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Basement-involved deformation overprinting thin-skinned deformation in the Pampean flat-slab segment of the southern Central Andes, Argentina

MARIA SILVIA JAPAS*†, GUILLERMO HÉCTOR RÉ*, SEBASTIÁN ORIOLO‡ & JUAN FRANCISCO VILAS*

*IGeBA, Universidad de Buenos Aires – CONICET, Departamento de Ciencias Geológicas, Pabellón II, Ciudad Universitaria (1428) Ciudad Autónoma de Buenos Aires, Argentina
‡Geoscience Centre, Georg-August-Universität Göttingen, Goldschmidtstraße 3, 37077 Göttingen, Germany

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Abstract – In the southern Central Andes, the Andean foreland was deformed due to Neogene shallowing of the Nazca slab beneath the South America plate. In this 27–33º S Pampean flat-slab segment, the N-trending Argentine Precordillera transpressional fold-and-thrust belt and the Sierras Pampeanas broken foreland developed as a consequence of inward migration of the orogenic front. At 28º S, a NNE-trending westward-dipping, thick Neogene synorogenic sequence is exposed in the Sierra de los Colorados, which shares deformation features of the Precordillera and the Sierras Pampeanas. Integration of new structural and kinematic data and available structural, kinematic, geophysical and palaeomagnetic information allows consideration of the Sierra de los Colorados area as part of the northern sector of the Precordillera during the middle Neogene. At *c.* 9 Ma, basement block exhumation started with the uplift of the Sierra de Umango-Espinal that was triggered by deformation along the NE-trending Tucumán oblique belt. This stage marked the beginning of compartmentalization of the incipiently deformed Vinchina foreland. Since *c.* 6.8–6.1 Ma, basement block uplift linked to the Miranda–Chepes and Valle Fértil NNW-trending sinistral transpressional belts, as well as kinking of the Neogene sequence by localized WNW-striking cross-strike structures, resulted in multiple segmentation that produced a complex mosaic of basement-block pieces. The overprint of these regional, basement-involved, oblique, brittle–ductile transpressional and cross-strike megazones could be related to high interplate coupling. Localized mechanical and rheological changes introduced by magmatism favoured this thick-skinned deformation overprint.

Keywords: Precordillera, Sierras Pampeanas, Sierra de Famatina, Sierra de los Colorados, Neogene, oblique brittle–ductile megashear zones, kinematics.

1. Introduction

Since the late Early Miocene, significant geodynamic changes have affected the 27–33° S Andean segment as a consequence of the shallowing of the Nazca plate (Ramos, Cristallini & Perez, 2002 and references therein; Fig. 1a). Deformation migrated inland, resulting in Andean foreland basin exhumation (Argentine Precordillera) and fragmentation by major block uplift (Sierras Pampeanas and Famatina broken foreland; Isacks *et al*. 1982; Jordan *et al*. 1983; Jordan & Allmendinger, 1986; Kay & Abbruzzi, 1996; Ramos, Cristallini & Perez, 2002). Declining arc-magmatism also migrated towards the foreland and was emplaced along WNW-trending corridors (Urbina & Sruoga, 2009; Japas, Urbina & Sruoga, 2010; Oriolo *et al.* 2014).

Regional transpressional deformation played a main role during Neogene deformation of the Argentine Precordillera (Japas, 1998; Ré, Japas & Barredo, 2001; Siame *et al*. 2005; Álvarez-Marrón *et al.* 2006; Oriolo *et al.* 2014, 2015; Japas *et al.* 2015) and the Sierras Pampeanas and Famatina broken foreland (Rossello *et al.* 1996; Japas, 1998; Ré, Japas & Barredo, 2001). Transpression was controlled by oblique convergence (N76° E defined by DeMets *et al*. 1990, onto an approximately N–S margin trend) affecting a strongly anisotropic upper plate (Rossello *et al.* 1996; Ré, Japas & Barredo, 2001; Japas, Ré & Barredo, 2002; Japas & Ré, 2012*a*, *b*; Oriolo *et al.* 2014, 2015; Perucca & Ruiz, 2014; Japas *et al.* 2015; Ortiz *et al.* 2015). These pre-Neogene major inherited structures in the upper plate (Alvarado, Beck & Zandt, 2007; Gans *et al.* 2011; Ammirati *et al.* 2013) resulted from a long history of accretion and amalgamation of different terranes (Ramos, 1999; Ramos, Cristallini & Perez, 2002).

The Argentina Precordillera (hereafter referred to as Precordillera) comprises a nearly N–S-trending fold-and-thrust belt (Baldis & Chebli, 1969; Ortiz & Zambrano, 1981; Baldis *et al*. 1982; Fig. 1). It consists of an E-verging thin-skinned domain (Western and Central Precordillera) and a W-verging thick-skinned domain (Eastern Precordillera; Baldis & Chebli, 1969; Ortiz & Zambrano, 1981; Baldis *et al*. 1982; Fig. 1b),

†Author for correspondence: msjapas@gl.fcen.uba.ar

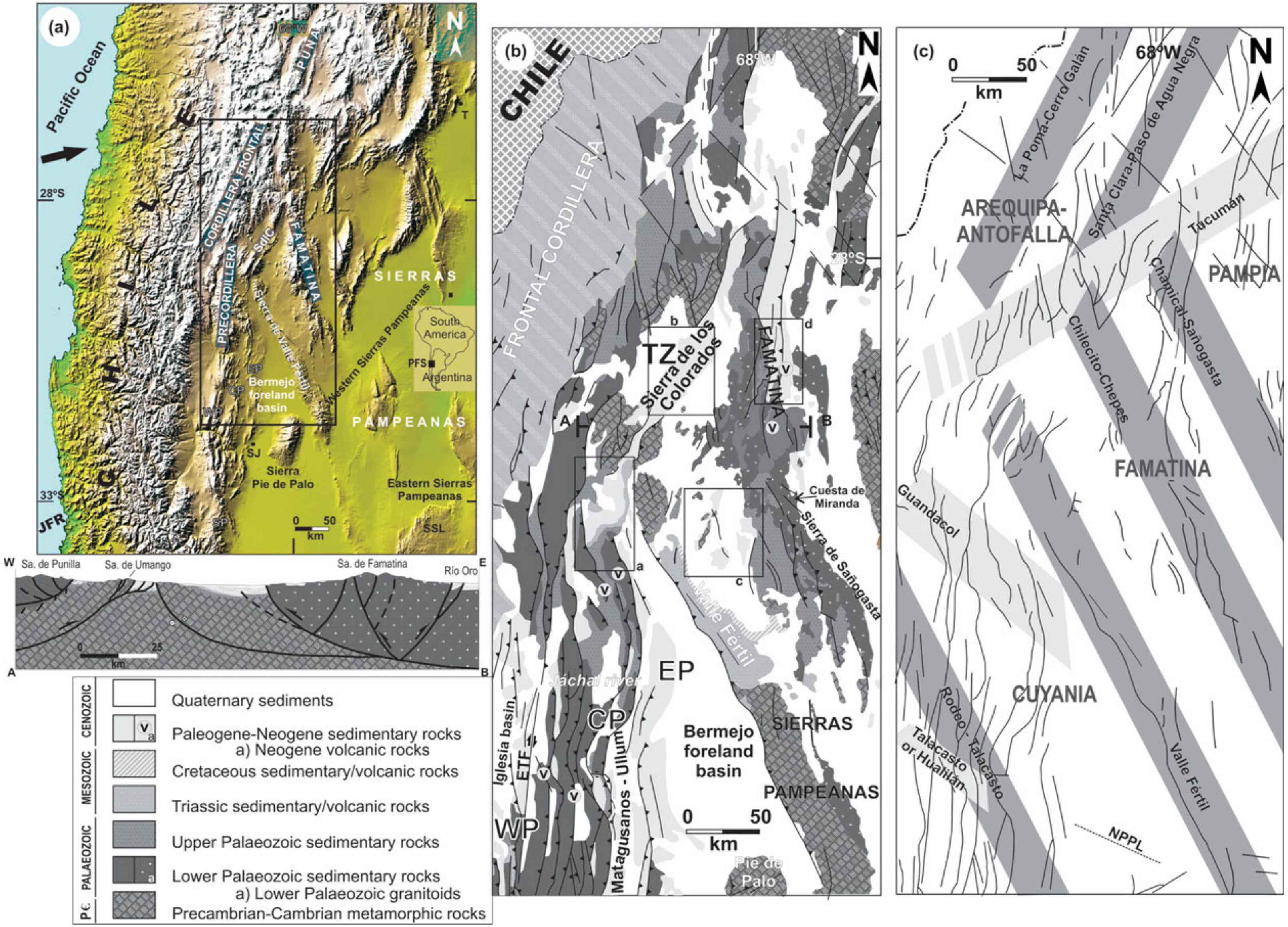

Figure 1. (a) (Colour online) The Sierra de los Colorados area (SdlC) in the regional context, southern Central Andes (Shuttle Radar Topography Mission image). PFS: Pampean Flat-Slab (27–33º S). SJ: San Juan city; T: Tucumán city. WP: Western Precordillera; CP: Central Precordillera; EP: Eastern Precordillera; SP: Southern Precordillera; ETF: El Tigre Fault; SSL: Sierra de San Luis. Courtesy NASA / Jet Propulsion Laboratory, California Institute of Technology: http://www2.jpl.nasa.gov/srtm/southAmerica.htm#PIA03388. (b) Simplified geological map from the area (after Caminos *et al.* 1993; Ragona *et al.* 1995; Zapata & Allmendinger, 1996; SEGEMAR, unpub. data, 2012, http://sig.segemar/gov.ar), and cross-section A–B (after Fauqué *et al.* 2016). Abbreviations as for Figure 1a. Rectangles indicated with letters a, b, c and d refer to the regions whose Neogene stratigraphy is summarized in Table 1 (northern Central Precordillera, Transitional zone, western Sierras Pampeanas and Famatina respectively). (c) Oblique transpressional and transtensional belts (modified from Ré, Japas & Barredo, 2001; Japas, Oriolo & Sruoga, 2012). NPPL: Northern Pie de Palo Lineament. Notice that main NNW-trending belts are coincident with and linked to ancient sutures (the different terranes are shown), recurrently reactivated since the Late Palaeozoic.

with a thick-skinned triangular zone developed in between (Zapata & Allmendinger, 1996). Along-strike segmentation allows to define two more morphostructural domains: (i) the Southern Precordillera that resulted from inversion and reactivation of Palaeozoic and Triassic NNW-striking major structures (Cortés, Pasini & Yamín, 2005; Cortés *et al.* 2006; Terrizzano *et al.* 2010), and (ii) the thick-skinned Northern Precordillera (28°15′–30° S; Cortés *et al.* 2014; Fig. 1b). In the Western and Central Precordillera, a first stage of Miocene thin-skinned highly partitioned transpressional deformation was followed by deformation along basement-involved WNW-trending transtensional cross-strike structures, and subsequent late Pliocene reactivation of pre-Andean NNW-striking structures. WNW-striking structures controlled the emplacement of the Miocene magmatism during its migration towards the foreland (Oriolo *et al.* 2014). In the case of the Eastern Precordillera, deformation only resulted from the late Pliocene stage (Japas *et al.* 2015).

The broken foreland comprises the Sierras Pampeanas and the Sierra de Famatina systems, part of a distal thick-skinned deformed foreland composed of basement blocks bounded by reactivated, NNW- and N-trending, high-angle reverse faults (Ramos, Cristallini & Perez, 2002; Hilley, Blisniuk & Strecker, 2005; Mortimer *et al.* 2007; Fig. 1a, b). Both regions share a similar Neogene geodynamical setting and basement block structure, differing in their pre-Cenozoic geological record (Petersen & Leanza, 1953). According to Dávila *et al.* (2004), Löbens *et al.* (2011, 2013*a*, *b*), Wemmer *et al.* (2011), Bense *et al.* (2013, 2014) and Ortiz *et al.* (2015), some parts of this foreland region underwent significant exhumation prior to widespread Late Miocene deformation.

To the north of the Pampean flat-slab segment of the Central Andes (Fig. 1a, b) the Sierra de los Colorados area shows a Neogene deformation history linked to the Precordillera and the broken foreland. Traditionally it was considered as part of the Sierras Pampeanas (Turner, 1964; Ramos, 1970; Ciccioli *et al.* 2011), but recent palaeomagnetic data by G. H. Ré (unpubl. Ph.D. thesis, Univ. de Buenos Aires, 2008) and Japas *et al.* (2015) allowed an early stage of thin-skinned transpressional deformation to be identified. Based on kinematic, structural and geophysical information, and available chronological data, this contribution will focus on the causes and temporal evolution of Mio-Pliocene thick-skinned deformation overprinting late Middle Miocene, thin-skinned structures in the Sierra de los Colorados area. In this two-staged deformation scenario, the significance of oblique transpressional and transtensional megazones in controlling Neogene deformation will also be analysed.

2. Geological setting

2.a. Geological record

In the Precordillera, unexposed basement rocks are considered as Grenvillian (Leveratto, 1968; Abbruzzi, Kay & Bickford, 1993; Kay, Orrell & Abruzzi, 1996). Palaeozoic rocks record the evolution from a Cambrian–Ordovician passive to a Silurian–Devonian active margin and culminated with a post-collisional history of Carboniferous–Permian active subduction. The Palaeozoic margin was successively deformed during the Middle to Late Ordovician, the Late Devonian and the Early Permian (Famatinian–Ocloyic, Famatinian–Chanic and San Rafael orogenies, respectively). During the Triassic, plate rearrangements resulted in regional rifting. From the inception of the Andean orogeny, this region evolved as part of the Bermejo foreland basin until it began to be deformed at *c.* 19 Ma (Jordan *et al.* 1993; Alonso *et al*. 2011; Table 1).

Pre-Cenozoic stratigraphy of the western Sierras Pampeanas consists of Precambrian to Early Palaeozoic metamorphic and plutonic rocks that represent the deeper parts of the Ordovician Famatinian Orogen. Carboniferous to Permian localized transtensional basin deposits (Fernández Seveso *et al.* 1993; Fernández Seveso & Tankard, 1995) were followed by Triassic – Early Jurassic and Cretaceous rifting sequences (Ramos, 1992; Schmidt *et al.* 1995). The Cenozoic record in the western Sierras Pampeanas in the study area is shown in Table 1.

In the Famatina, pre-Cenozoic rocks comprise a Middle to Late Cambrian metamorphic basement overlain by Early Palaeozoic volcano-sedimentary rocks (Aceñolaza, Millar & Toselli, 1996; Candiani *et al.* 2011), which are intruded by Middle to Late Ordovician igneous bodies resulting from continental-arc magmatism activity (Toselli, Saavedra & Rossi de Toselli, 1996; Rapela *et al.* 1999). Silurian post-orogenic granites were emplaced and deformed during the Late Devonian – Early Palaeozoic Chanic tectonic phase. Late Palaeozoic and Triassic extensional depocentres include more than 4000 m of continental sediments (Fernández Seveso *et al.* 1993). The Cenozoic record comprises *c.* 3500 m of alluvial deposits east of the Sierra de Famatina and also Early Pliocene volcanic rocks (Mogote Río Blanco Formation andesites; see Dávila & Astini, 2007; Zambrano *et al.* 2011; Table 1).

2.b. Regional structure

The main Neogene structure in these regions comprises NNE–NNW-trending thrusts linked to thin-skinned (Precordillera) and thick-skinned (Eastern Precordillera, Sierras Pampeanas and Famatina) deformation (Jordan & Allmendinger, 1986; Allmendinger *et al.* 1990; Cristallini & Ramos, 1995; Zapata & Allmendinger, 1996; Ramos, Cristallini & Perez, 2002). They are controlled and overprinted by localized, oblique- and cross-strike brittle–ductile megashear zones (Japas, 1998; Ré, Japas & Barredo, 2001; Cortés, Pasini & Yamín, 2005; Cortés *et al.* 2006; Japas & Ré, 2012*a*, *b*; Oriolo *et al*. 2014; Japas *et al.* 2015).

In the Precordillera, cross-strike and oblique structures consist respectively of WNW-trending sinistral transtensional zones (Guandacol; Talacasto or

Table 1. Cenozoic Stratigraphy of northern Central Precordillera, Sierra de los Colorados, western Sierras Pampeanas and Famatina areas. Data compiled from Malizia, Reynolds & Tabbutt (1995), Dávila & Astini (2007), Limarino, Ciccioli & Marenssi (2010), Ciccioli *et al.* (2014), Collo *et al.* (2014) and Fauqué *et al.* (2016).

TIME			UNITS			
			northern Central Precordillera	Sierra de los Colorados	western Sierras Pampeanas	Famatina
Quaternary	Holocene		Alluvial, colluvial, fluvial, and aeolian deposits			
	Pleistocene	L				
		E		Santa Florentina Fm.		Santa Florentina Fm.
Neogene	Pliocene	L		El Corral Fm.		
		E		**Toro Negro Fm**		
	Miocene	L	Zapallar Fm Vinchina Fm (upper section)	**Vinchina Fm** (upper section)	Desencuentro Fm.	El Durazno Fm. & Mogote Río Blanco Fm.
		M	Vinchina Fm (lower section)	**Vinchina Fm** (lower section)	Río Mañero Fm.	Santo Domingo Fm. Del Buey Fm. Del Abra Fm. Del Crestón Fm.
		E	Quebrada de la Montosa Fm			
Paleogene	Oligocene		Vallecito Fm. & Cerro Morado Fm.	Vallecito Fm.		
	Eocene		Puesto La Flecha Fm	Puesto La Flecha Fm		

Hualilán; Calingasta or San Juan; Paramillos; Ré, Japas & Barredo, 2001; Japas, Ré & Barredo, 2002; Oriolo *et al.* 2014) and NNW-trending sinistral transpressional belts (Valle Fértil; Rodeo–Talacasto; Mendoza Norte or Barreal–Las Peñas; Río Mendoza–Tupungato; Rossello *et al.* 1996; Ré, Japas & Barredo, 2001; Japas, Ré & Barredo, 2002; Cortés & Cegarra, 2004; Japas *et al.* 2015; Fig. 1c).

In the Sierras Pampeanas, the main cross-strike transtensional structures are the NE-trending Tucumán (Mon, 1976) and Catamarca (Rossello *et al.* 1996; Fig. 1c) structures, and the Tertiary Volcanic Belt in the Eastern Sierras Pampeanas (Urbina, Sruoga & Malvicini, 1995, 1997; Sruoga, Urbina & Malvicini, 1996; Sruoga & Urbina, 2008; Urbina & Sruoga, 2009; Japas, Urbina & Sruoga, 2010; Japas *et al.* 2011*a*, *b*). The main NNW-trending oblique Andean structures represent reactivation of major Early Palaeozoic structures, as is the case of the NNW-trending Valle Fértil (Rossello *et al.* 1996; Ré, Japas & Barredo, 2000, 2001; Introcaso & Ruiz, 2001; Ortiz *et al.* 2015), Chilecito–Chepes, Chamical–Sañogasta, Cruz del Eje–San Isidro and Rincón–Deán Funes transpressional belts (Ré, Japas & Barredo, 2001; Japas, Ré & Barredo, 2002).

The doubly vergent, NNW- to NNE-trending, high-angle basement thrusts of the Sierra de Famatina (Dávila & Astini, 2002, 2003; Ramos, Cristallini & Perez, 2002; F. M. Dávila, unpub. Ph.D. thesis, Univ. Nacional de Córdoba, 2003; Dávila *et al.* 2004; Candiani *et al.* 2011; Fig. 1) also resulted from reactivation of previous basement mechanical anisotropies (Fig. 1b). Uplift of Sierra de Famatina occurred along a set of reverse faults within the range rather than along a system of faults at the range boundary (de Alba, 1979; Jordan & Allmendinger, 1986). In spite of differences in pre-Cenozoic stratigraphy and structural pattern that includes the range's highest altitude (6200 m), the Sierra de Famatina was deformed and uplifted at the same time and in a mode equivalent to the Sierras Pampeanas. Main oblique structures affecting the Sierra de Famatina are the NNW-trending Chilecito–Chepes, Chamical–Sañogasta megazones (Ré, Japas & Barredo, 2001; Japas, Ré & Barredo, 2002; Chancaní from Rossello *et al.* 1996), the NNE-trending Santa Clara–Paso del Agua Negra and La Poma–Cerro Galán structures and the NE-trending Tucumán zone (Mon, 1976; Rossello *et al.* 1996; Urreiztieta, 1996; Fig. 1c).

3. Study area

The Sierra de los Colorados is located in La Rioja province, NW Argentina (Fig. 1a, b). Two topographic depressions are placed between this range and the Northern Precordillera to the west, and the Sierra de Famatina to the east. To the N-NE and S-SW, the Sierra de los Colorados is bounded by Sierras Pampeanas basement blocks (Sierra de Toro Negro and Sierra de Umango-Espinal, respectively; Fig. 1b).

As representative of the Neogene Vinchina basin fill, the foreland sequence at the Sierra de los Colorados

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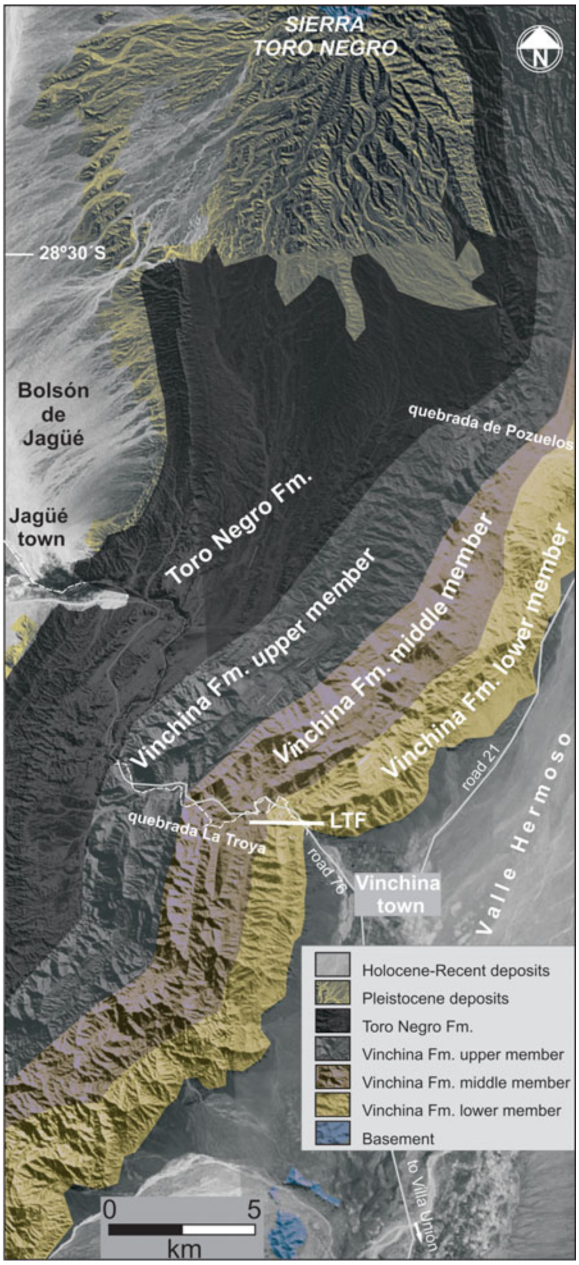

Figure 2. (Colour online) Geological map from the Sierra de los Colorados region (adapted from Marenssi *et al.* 2015). LTF: La Troya fault.

comprises a distal to proximal, thick synorogenic, alluvial sedimentary pile (Vinchina and Toro Negro Formations; Turner, 1964; Ramos, 1970; Fig. 2) that was deposited under semi-arid conditions (Tripaldi *et al.* 2001). This Neogene succession reaches an unusually large thickness that was attributed to a combination of flexural subsidence and alternative sublithospheric mechanisms (e.g. dynamic topography; Dávila, Astini & Jordan, 2005; Dávila *et al.* 2007; Dávila, Lithgow-Bertelloni & Giménez, 2010). Approximately 5500 m and *c.* 2000 m of sediments are documented for the Vinchina and Toro Negro Formations respectively in the quebrada de La Troya section. Along-strike thickness increments were also reported (Ramos, 1970; Marenssi *et al.* 2015).

The age of the Vinchina Formation rocks was constrained by magnetostratigraphic studies (Reynolds *et al.* 1990; Ré & Barredo, 1993) as well as by zircon fission-track (K. D. Tabbutt, unpub. Master's thesis, 1986) and U–Pb detrital zircon (Collo *et al.* 2011, 2014; Ciccioli, Limarino & Friedman, 2012; Ciccioli *et al.* 2014) ages. In the case of the Vinchina Formation lower member, a maximum sedimentation age of 15.6 ± 0.4 Ma was obtained (U–Pb chemical abrasion thermal ionization mass spectrometry (CA-TIMS) detrital zircon data; Ciccioli *et al.* 2014), whereas a depositional age of 9.24 ± 0.034 Ma was reported for the upper member based on U–Pb CA-TIMS data from volcanic zircons in a tuff layer (Ciccioli *et al.* 2014). Likewise, Collo *et al.* (2015) reported a maximum sedimentation age of 12.62 ± 0.4 Ma based on U–Pb laser altimetry–inductively coupled plasma–mass spectrometry (LA-ICP-MS) detrital zircon data from the lowest tuffaceous level at *c.* 5500 m depth. Defined as Late Miocene – Early Pliocene by Rodríguez Brizuela & Tauber (2006), the tuffaceous level 750 m below the top of the Toro Negro Formation was recently dated at 5.25 ± 0.23 Ma (U–Pb LA-ICP-MS in zircons; Collo *et al.* 2015). Unconformably overlying the Neogene sequence, the coarse-grained synorogenic deposits of the El Corral Formation (Furque, 1963) represent a diachronic intra-montane unit that resulted from cannibalization of the Neogene basin (Ciccioli *et al.* 2011). The flat-lying Pleistocene Santa Florentina Formation completes the local Cenozoic sedimentary column.

The timing of basement block exhumation in the area is not completely constrained, due to the lack of precise dating. The exhumation of the Neogene sequence as a whole was constrained at *c.* 3.4 Ma (Collo *et al.* 2011).

4. Methods

This contribution will focus on the structural fabric and kinematic analyses at both regional and outcrop scales. Field work was performed at eight accessible key areas of the Sierra de los Colorados region: Norte (N), quebrada de Pozuelos (QP), quebrada de La Troya (QLT), north of Vinchina town (NV), quebradas KB (KB), finca Buenavista (fB), road to Jagüé (rJ) and quebrada del Yeso (QY; Fig. 2). At the outcrop scale, the evaluated fabric elements comprised planar structures such as bedding, brittle–ductile shear zones (following Ramsay & Huber, 1987) and fractures (tensional, shear-extensional, etc.). Kinematics was established by the offset of structures, presence of releasing/restraining bends, distribution of en échelon gashes, tensional fractures, rough cleavage and/or Riedel structures (Fig. 3a). When possible, timing of minor structures was defined by cross-cutting, overprinting and reactivation relationships. Three-dimensional kinematic measurements on the minor structures that affect Neogene strata were performed in order to identify the different kinematic events (see Japas, Rubinstein & Kleiman, 2013). Data from kinematic indicators measured in the field were plotted

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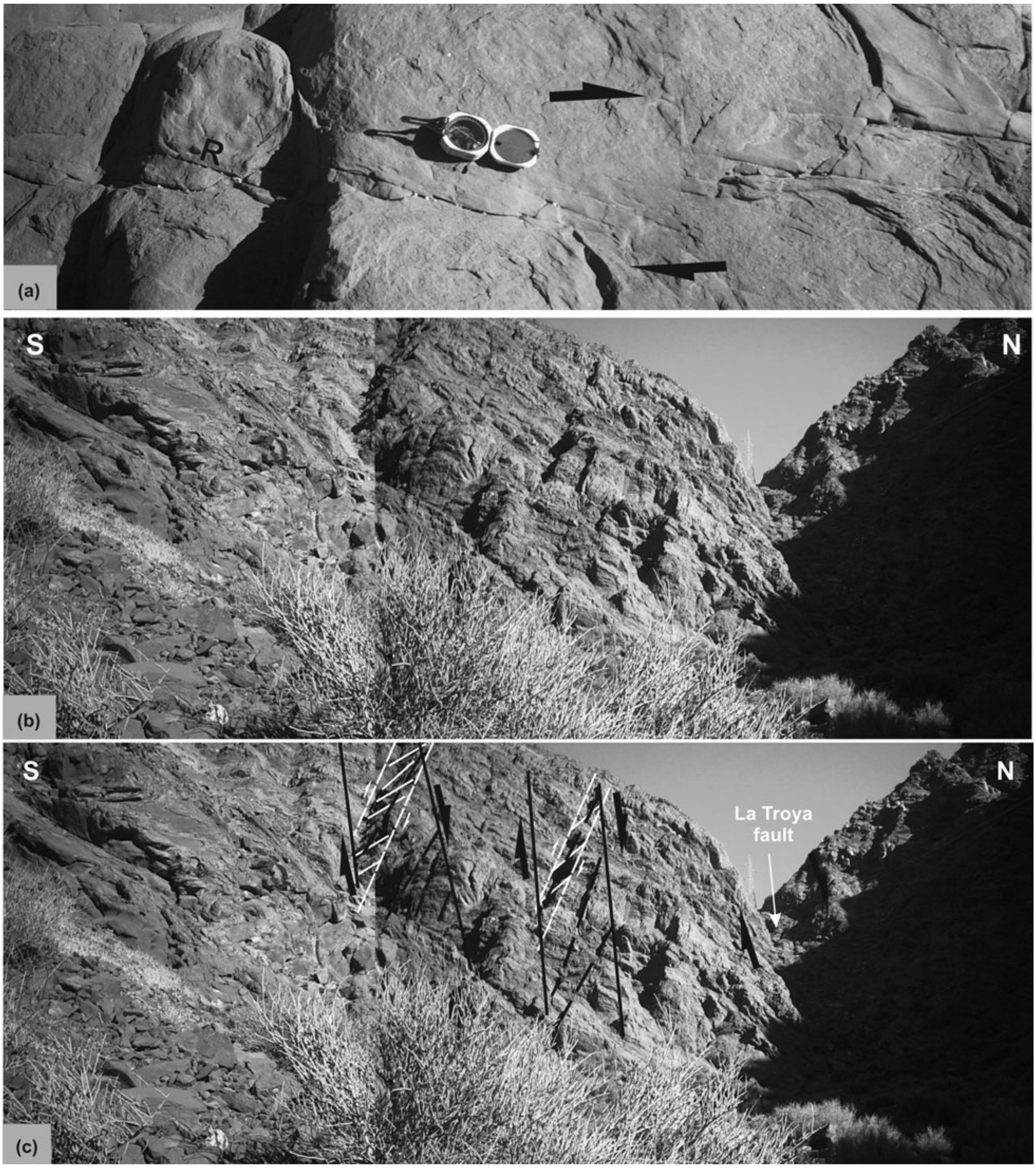

Figure 3. (a) Brittle–ductile shear zone at the outcrop scale. R: Riedel shear structure. (b) La Troya fault. (c) La Troya fault and related structures. Black lines show brittle–ductile shear zones parallel to La Troya fault and associated R structures. White lines show minor R shears within the main R structures in black.

using FaultKinWin software (R. W. Allmendinger, unpub. data, 2001).

5. Sierra de los Colorados structure

5.a. Bedding

The thick Neogene sedimentary pile exposed in the Sierra de los Colorados follows a NNE-trending strip, with beds showing localized and abrupt changes in strike (Fig. 2). Alternating NE–SW and nearly N–S-trending strata define a kink-like structure, in which four structural segments were defined (South, Central, North and North-northeast domains; Fig. 4a). East to the Sierra de Toro Negro, the North-northeast domain is the only exposed area showing NNW-trending beds (N in Fig. 4a).

The Neogene strata show W-directed decreasing dip angles towards the top of the sequence (Fig. 4b). Along the quebrada de La Troya section, the lowermost beds

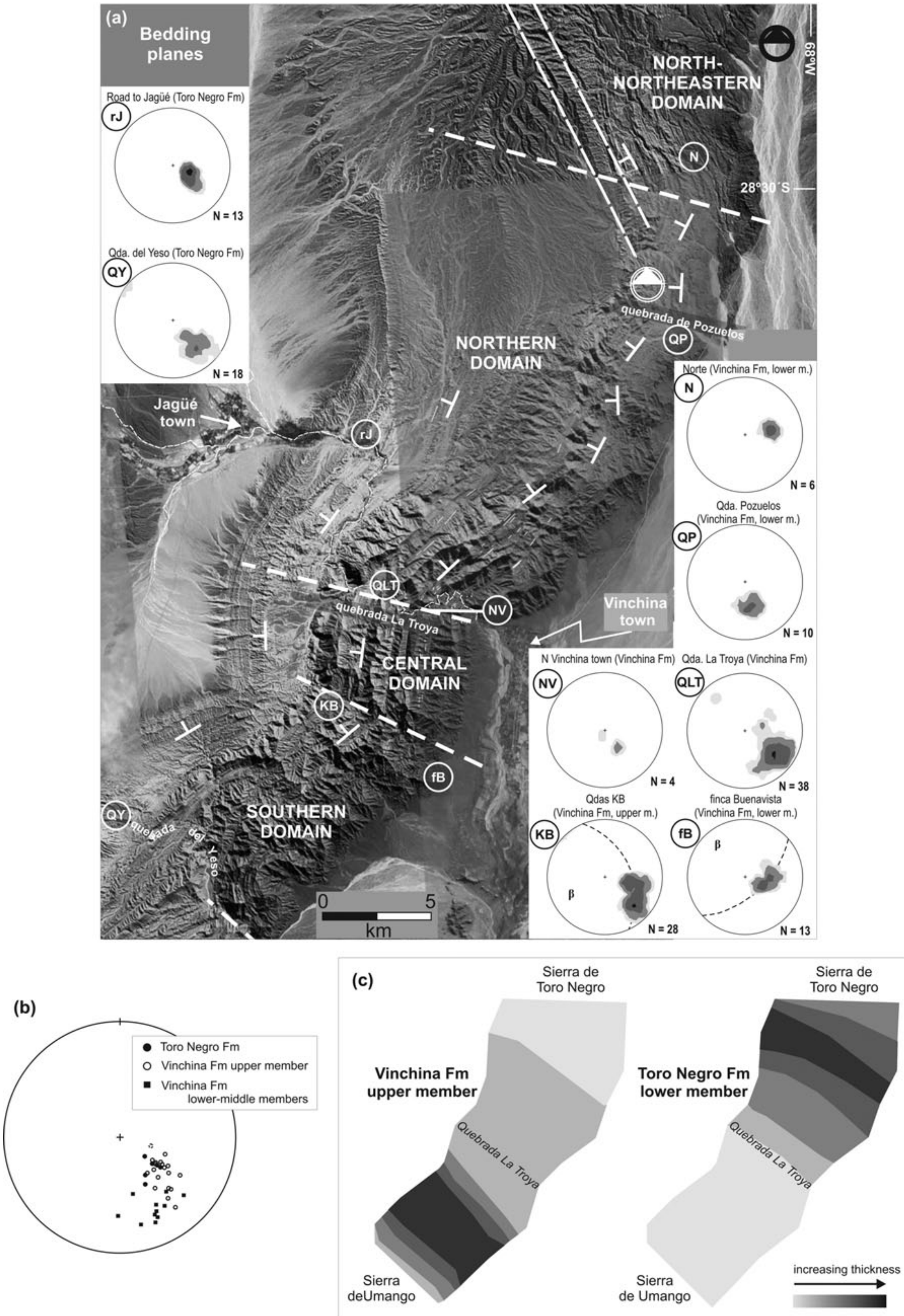

Figure 4. (a) Bedding in the Sierra de los Colorados domains (lower-hemisphere plot on equal-area stereonet; GEORIENT software by Holcombe, 2005). Sampled key areas are N: Norte; QP: quebrada de Pozuelos; QLT: quebrada de La Troya; NV: north of Vinchina town; KB: quebradas KB; fB: finca Buenavista; rJ: road to Jagüé; QY: quebrada del Yeso. Contours bounding shaded areas represent in **N**: 6–12 %, 12–24 %, >24 % (max. 41.18 %), **QP**: 10–20 %, 20–40 %, >40 % (max. 50 %), **QLT**: 3–6 %, 6–12 %, 12–24 %, >24 % (max. 26.32 %), **NV**: 25–50 %, > 50 % (max. 75 %), **KB**: 4–8 %, 8–16 %, 16–32 %, > 32 % (max. 35.71 %), **fB**: 8–16 %, 16–32 %, >32 % (max. 46.15 %), **rJ**: 8–16 %, 16–32 %, 32–64 %, > 64 % (max. 76.92), **QY**: 6–12 %, 12–24 %, > 24 % (max. 27.78 %). (b) Bedding showing decreasing dip angle towards the top of the Neogene sequence (lower-hemisphere plot on equal-area stereonet). (c) Isopach maps for the Vinchina Formation upper member and the Toro Formation lower member (after Ramos, 1970).

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of the Neogene sequence dip *c.* 60° W whereas the uppermost levels dip *c.* 40° W (respectively QLT and rJ in Fig. 4a; see also Fig. 4b).

Two bedding plane sets were discriminated at fB and KB localities (Fig. 4a). In fB, they represent minor kink-like structures that are constrained to a relatively wide zone that bounds the Central and South domains (internal kink-like bands; Anderson, 1974; fB in Fig. 4a). This local structure is geometrically concordant with the main kink-like structure as β-axis trends to the NW. At the Sierra de los Colorados scale, some incipient kink-like structures can be also observed in the North domain north of the quebrada la Troya, where minor WNW-trending fractures resemble a localized 'cleavage-like' fabric (Fig. 4a). Also linked to a sharp transition zone between domains (Central and South), the two observed sets in KB reflect a different pattern as β trends SW (KB in Fig. 4a).

Additionally, and constrained to the vicinity of the sierra de Umango-Espinal, there are some well-developed folds affecting the Vinchina and Toro Negro formations (southwestern South domain; Fig. 4a), whose amplitude diminishes towards the top of the Neogene sedimentary column.

5.b. Brittle–ductile shear zones

At the range scale, the described kink-like structure is delineated by WNW-trending brittle–ductile shear zones that define wide and narrow zones of localized deformation (Fig. 4a). A nearly E–W-trending normal-sinistral fault (La Troya fault; LTF in Fig. 2) is exposed at the easternmost sector of the quebrada de la Troya as part of the sharp transition zone between the North and Central domains (Fig. 3b, c). This fault disappears to the west where it is replaced by a brittle–ductile shear zone trending WNW. To the east, in locality NV (Fig. 5), lower member rocks of the Vinchina Formation also are affected by dominant WNW-trending brittle–ductile shear zones.

At the outcrop scale, diagrams in Figure 5 show that rocks from the Vinchina Formation lower and middle members display two main sets of brittle–ductile shear zones, one trending NNE and the other, NW–WNW. On the other hand, the Vinchina Formation upper member and the Toro Negro Formation are only affected by the WNW-trending set. In other words, NNE-trending structures were only found at the base of the Neogene sequence while NW- to WNW-trending structures are widely distributed.

6. Kinematic analyses

Figure 5 shows the kinematic axes that resulted from processing the kinematic indicators measured in the field. As previously mentioned, deformation was inhomogeneously distributed in space and time, and therefore the obtained kinematic axes will be described considering the units they affect (Fig. 5).

(1) In three of the five areas where Vinchina Formation lower and middle members were analysed, two main kinematic populations were recognized (A and B populations in N, QLT, fB; Fig. 5). In QLT and fB localities, shortening axes trend NE–SW (A-populations) and NW–SE (B-populations). In the case of locality N, the A-population shortening axis is SE-directed while the B-population shortening axis is SW-directed. In the two other areas, where the Vinchina Formation lower member was analysed (NV and QP in Fig. 5), measurements revealed kinematic axes belonging to the B-population. Dominant WNW-trending brittle–ductile shear zones in NV are linked to the La Troya fault and reveal normal-sinistral components of motions with a kinematic stretching axis trending to the NNE-NE.

(2) The lowermost levels from the Vinchina Formation upper member (western part of QLT) show the development of WNW-trending brittle–ductile shear zones with kinematic axes consistent with the B-population previously defined for the underlying members.

(3) On the other hand, when structures affecting rocks of the uppermost Vinchina Formation beds and the Toro Negro Formation are considered, a single and different kinematic population C could be observed, with kinematic axes disposed horizontally (T-axes; extension) and vertically (P-axes; shortening). The Bingham extension axis trends ENE in the Central domain (rJ), whereas it is oriented NNW in the Southern domain (KB and QY).

Although scarcely represented at the base of the Neogene sedimentary sequence, the C-population (only recognizable by its vertical P-axes; Fig. 5) shows a kinematic pattern coincident with that affecting the Toro Negro Formation which is linked to the position (convex or concave side) of the kink-like structure.

7. Interpretation and discussion

Data in sections 5 and 6 point to significant differences when comparing the lower-middle members of the Vinchina Formation with the Vinchina upper member and Toro Negro formations. From the two sets of NNE- and NW- to WNW-trending brittle–ductile shear zones identified at the base of the Neogene sequence, only the one that trends WNW affects the Vinchina Formation upper member (Fig. 5). This evidence, together with cross-cutting relationships, confirms NNE-striking structures pre-dating NNW-WNW ones.

This deformational scenario also agrees with palaeomagnetic data in the Sierra de los Colorados region since Vinchina Formation lower and middle members record the same number of clockwise rotations, indicating that deformation should have begun almost contemporaneously with the Vinchina Formation middle member deposition (∼11–12 Ma; G. H. Ré, unpubl. Ph.D. thesis, Univ. de Buenos Aires, 2008; Japas *et al.* 2015). Clockwise rotation at the base of the Neogene sequence in the Sierra de los Colorados was considered by Aubry *et al.* (1996) as the consequence of tectonic

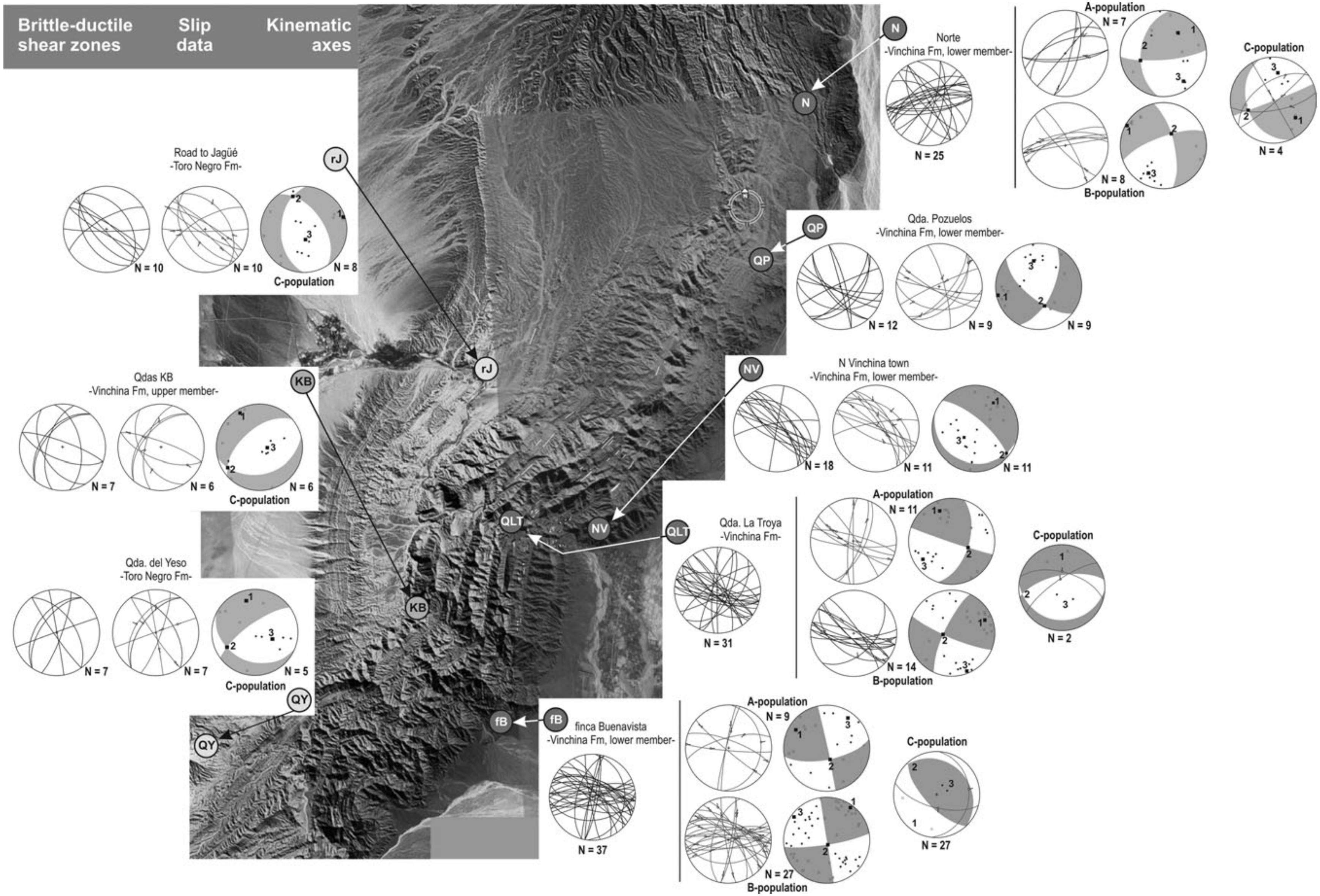

Figure 5. Brittle–ductile shear zones, slip data and kinematic axes measured in the Neogene sequence of the Sierra de los Colorados. Abbreviations as for Figure 4a. FaultKinWin software (R. W. Allmendinger, unpub. data, 2001). Notice that the main brittle–ductile zones affecting the Vinchina Formation lower member present in the N-NE domain is the same set as in other areas but rotated counterclockwise. This is concordant with preliminary palaeomagnetic results in the N-NE domain which reveal null rotation (G. H. Ré *et al.*, unpub. data). Two main populations (A and B) and a poorly defined one (C) were recognized for the lower-middle Vinchina Formation rocks. At the base of the Vinchina Formation, upper member B-population is present whereas the Toro Negro Formation rocks only record population C. In slip-data diagrams, arrows indicate movement of hanging wall. In kinematic diagrams, squares represent individual T-axes (extension), black circles individual P-axes (shortening); black squares 1 (shortening), 2 (intermediate), 3 (extension) refer to the calculated unweighted moment tensor (linked Bingham) axes (R. W. Allmendinger, unpub. data, 2001).

activity of the NE-striking Tucumán Zone. However, kinematic axes are more akin to the Central Precordillera kinematic picture because kinematic shortening axes are similar to the NE trend reported by Oriolo *et al.* (2014) and do not match the expected E-W referred to by Allmendinger (1986) and Sasso & Clark (1998) or the NW–SE determined by Urreiztieta (1996). This affinity with Central Precordillera deformation style is also supported by the time of the San Roque (*c.* 10.5 Ma) or Blanquitos (*c.*11.5 Ma) thrust initiation reported by Jordan *et al.* (1993) and Jordan, Schlunegger & Cardozo (2001) considering (e.g. Yáñez *et al.* 2001) or not (Suriano *et al.* 2015) a southern migration of the deformation front. Additionally, NNE-striking thrusts pre-dating deformation along NNW-WNW basement-controlled structures were reported by Oriolo *et al.* (2015) for the Precordillera.

Previous studies in the Central Precordillera reported an equivalent change from NNE-directed to WNW-directed shortening axes. This reorientation was linked to the inception of basement-involved deformation in the foreland (Japas *et al.* 2014, 2015; Oriolo *et al.* 2014), meaning that the appearance of basement-signature kinematics in the Sierra de los Colorados area occurred during deposition of the upper member of the Vinchina Formation (B-population). Regarding the timing of deformation involving basement, it started earlier in the Sierra de los Colorados area (28° S) than in the Central Precordillera at 31° S. Inception of basement deformation is confirmed by uplift of the Sierra de Umango-Espinal indicated by detrital zircon data (Ciccioli *et al.* 2011) and consequent local thickness increase of the Vinchina Formation upper member (Ramos, 1970) resulting from topographic loading subsidence (Fig. 4c).

Furthermore, west of the quebrada del Yeso, forced folds affect the whole sequence and become gentler towards the top of the sedimentary column (Ramos, 1970). These folds might be a result of progressive uplift of the Sierra de Umango-Espinal basement block that started during deposition of the upper Vinchina Formation member. Likewise, the presence of (a) three unconformity surfaces in the middle Vinchina Formation section (Marenssi *et al.* 2000), (b) changes in palaeocurrent patterns, from axial, NNE-directed to SE-directed (Limarino *et al.* 2001; Tripaldi *et al.* 2001), and (c) decreasing bedding-dip angle towards the top of the Neogene sequence (progressive unconformity; Fig. 4b), support the occurrence of a significant change at the beginning of deposition of the Vinchina Formation upper member.

During or shortly after deposition of the uppermost Vinchina Formation and the Toro Negro Formation, the kinematic scenario changed. This new kinematic field is represented by extension (C-population) and, although not yet completely understood, it is proposed that it could be related to kinematic conditions linked to the evolution of a kink-like structure (see Pimenta, 2008).

It is noteworthy that this kinematic scenario is characterized by three kinematic events (A: affecting the Vinchina lower and middle members; B: deforming all the Vinchina members; and C: affecting the whole sequence but mostly recognizable in the uppermost Vinchina upper member and the Toro Negro formations) and shows striking correspondences with coeval stages proposed by Ciccioli *et al.* (2011, 2013*a*, *b*; Table 2) based on tectonostratigraphic analysis.

7.a. Presence and role of brittle–ductile oblique megashear zones

7.a.1. Regional NNW- and NNE-trending transpressional structures

Regional NNW- and NNE-trending structures comprise transpressional brittle–ductile shear zones (Ré, Japas & Barredo, 2001; Cortés & Cegarra, 2004; Japas & Ré, 2012*a*, *b*; Oriolo *et al.* 2014; Japas *et al.* 2015; Fig. 1c). In the study area, the NNW-trending, sinistral transpressional Valle Fértil zone (linked to the Cuyania – Famatina/Pampia terrane boundary; Gimenez, Martinez & Introcaso, 2000; Introcaso & Ruiz, 2001), as well as shallow NNE-trending structures (considered as main dextral transpressional structures in the Precordillera region; Oriolo *et al.* 2015), were confirmed as major structures by gravimetric and magnetometric data by Porcher *et al.* (2004). In a more regional context, these structures as well as other oblique localized deformational belts can also be recognized by regional aeromagnetometry (SEGEMAR, unpub. data, 2012, http://sig.segemar/gov.ar; Fig. 6a). Some of the NNW-trending structures show neotectonic activity (Casa *et al.* 2011; SEGEMAR, unpub. data, 2012, http://sig.segemar/gov.ar).

Fault plane solutions of the 34 km deep Villa Unión earthquake (Fig. 6b) indicate a nodal plane steeply dipping to the ENE (Triep & Cardinali, 1984), sustaining the transpressional character of the NNW-trending structures as well as their sinistral strike-slip component of motion. Additionally, relative motions derived from scarce available GPS velocity data in the upper plate (Tinogasta and Guandacol sites in Fig. 6b; Brooks *et al.* 2003) confirm left-lateral (and thrust) displacements for the NNW-trending structures.

Based on structural elements at the Sierra de Famatina scale, two transpressional shear zones can be better constrained: the Miranda–Chepes and the Angulos–Patquía belts (Fig. 6c). These two structures substitute Ré, Japas & Barredo's (2001) Chilecito–Chepes and Chamical–Sañogasta zones from Figure 1c. The Angulos–Patquía zone seems to reactivate the western border of the 402–300 Ma Tinogasta–Pituil–Antinaco shear zone (TiPA belt; López & Toselli, 1993; Höckenreiner, Söllner & Miller, 2003). Although detailed structural mapping in the Sierra de Famatina is still scarce, regional structures reveal a possible Neogene flower structure controlled by both megashear zones

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Table 2. Tracking basement uplift in the Sierra de los Colorados and neighbouring areas based on stratigraphical and kinematic information.

Unit/member	Age (Ma)	Palaeo current	Subsidence/fill rate S/F	Source	Kinematic Population	Vertical axis rotation	Uplift	Deformation stage	Active oblique belt
Toro Negro Fm. upper									La Mejicana cross-strike
lower-middle	**5.5**				**C**	*ca.* 7° clockwise	Sa. Toro Negro		
lower	9–6		Paleovalley incision (localized thickness increase)	Pc+ CF + STN				Broken foreland	Miranda-Chepes transpressional belt
Vinchina Fm. upper	**9.24**	SE (higher dispersion)	Balanced S/F rate Localized thickness increase close to the Sa. Umango-Espinal	WVA	**B + C**	*ca.* 15° clockwise	Sa. Famatina & Sa. Toro Negro		
middle	10–12	SE	Higher subsidence Two unconformities	WVA	**A+B+C**	*ca.* 30° clockwise	Sa. Umango-Espinal	Embryonic thin-skinned	Tucumán cross-strike
lower	19 (?)–12	NNE (axial)	Underfilled Low subsidence	Metamorphic + FC					

Data compiled from Ramos (1999), Limarino *et al.* (2001), Tripaldi *et al.* (2001), G. H. Ré (unpubl. Ph.D. thesis, Univ. de Buenos Aires, 2008), Limarino, Ciccioli & Marenssi (2010), Collo *et al.* (2011, 2014), Ciccioli & Marenssi (2012), Ciccioli *et al.* (2013*b*), Japas *et al.* (2015). WVA: western volcanic arc; Pc: Precordillera; FC: Frontal Cordillera; STN: Sierra de Toro Negro.

(Fig. 7a, c). This flower structure explains an uplift associated with reverse faults within the range, and not along a fault system at the range boundary (see de Alba, 1979; Jordan & Allmendinger, 1986), and would also contribute to the higher altitude of the Sierra de Famatina compared to other ranges in NW Sierras Pampeanas.

7.a.2. Regional transtensional cross-strike structures

WNW-trending structures in the Precordillera region were referred to by Oriolo *et al.* (2014) as cross-strike discontinuities, consisting of broad, diffuse zones of faults and fractures cutting the entire fold-and-thrust belt at high angles to its regional strike. They are vertical structures usually originated by strike-slip reactivation of pre-existing basement faults that disrupt strike-parallel structural, geophysical, sedimentological and/or other patterns (Wheeler, 1980; Berger, 2001). Although frequently confused with other structures like tear faults and lateral ramps, they are different. Tear faults comprise small-scale individual strike-slip faults typically confined to a single thrust sheet dying out at the regional décollement, whereas lateral ramps consist of large-scale, high-angle (but not vertical; McClay, 1992) faults allowing the overriding thrust sheet to reach a higher stratigraphic level (Berger, 2001). In the Precordillera, these basement-involved cross-strike discontinuities were recognized as sinistral transtensional zones (Ré, Japas & Barredo, 2001; Oriolo *et al.* 2014; Yagupsky, Winocur & Cristallini, 2014; Japas *et al.* 2015) and therefore considered as preferred channels for the rise and extrusion of magma. In the Precordillera and Sierras Pampeanas they seem to be crucial structures controlling volcanism emplacement during the inland migration of arc magmatism, linked mineralization and also some present-day geothermal occurrences linked to convective hydrothermal systems (see Urbina, Sruoga & Malvicini, 1995, 1997; Sruoga, Urbina & Malvicini, 1996; Chernicoff & Nash, 2002; Pesce & Miranda, 2003; Sruoga & Urbina, 2008; Urbina & Sruoga, 2009; Japas, Urbina & Sruoga, 2010; Japas *et al.* 2011*a*, *b*; Oriolo *et al.* 2014). The link between magmatism emplacement and cross-strike structures is not restricted to the Pampean flat slab region but was also recognized in the Central and South Southern Volcanic Zone (Southern Andes; Lara *et al.* 2006), and the Puna region (Ré, Japas & Barredo, 2001; Riller *et al.* 2001; Chernicoff, Richards & Zappettini, 2002; Roy *et al.* 2006), where some of the authors also recognized extensional conditions (see also Sillitoe, 1997; Billa *et al.* 2004).

The WNW-trending structures in the Sierra de los Colorados show sinistral-normal displacements (NV in Fig. 4a). This WNW-trending brittle–ductile shear zone along the quebrada de La Troya is coincident with the Vinchina Lineament (Fig. 6a, b), a middle Proterozoic main sub-regional structure recognized by Porcher *et al.* (2004) based on regional aeromagnetic and gravimetric data. A similar structural discontinuity

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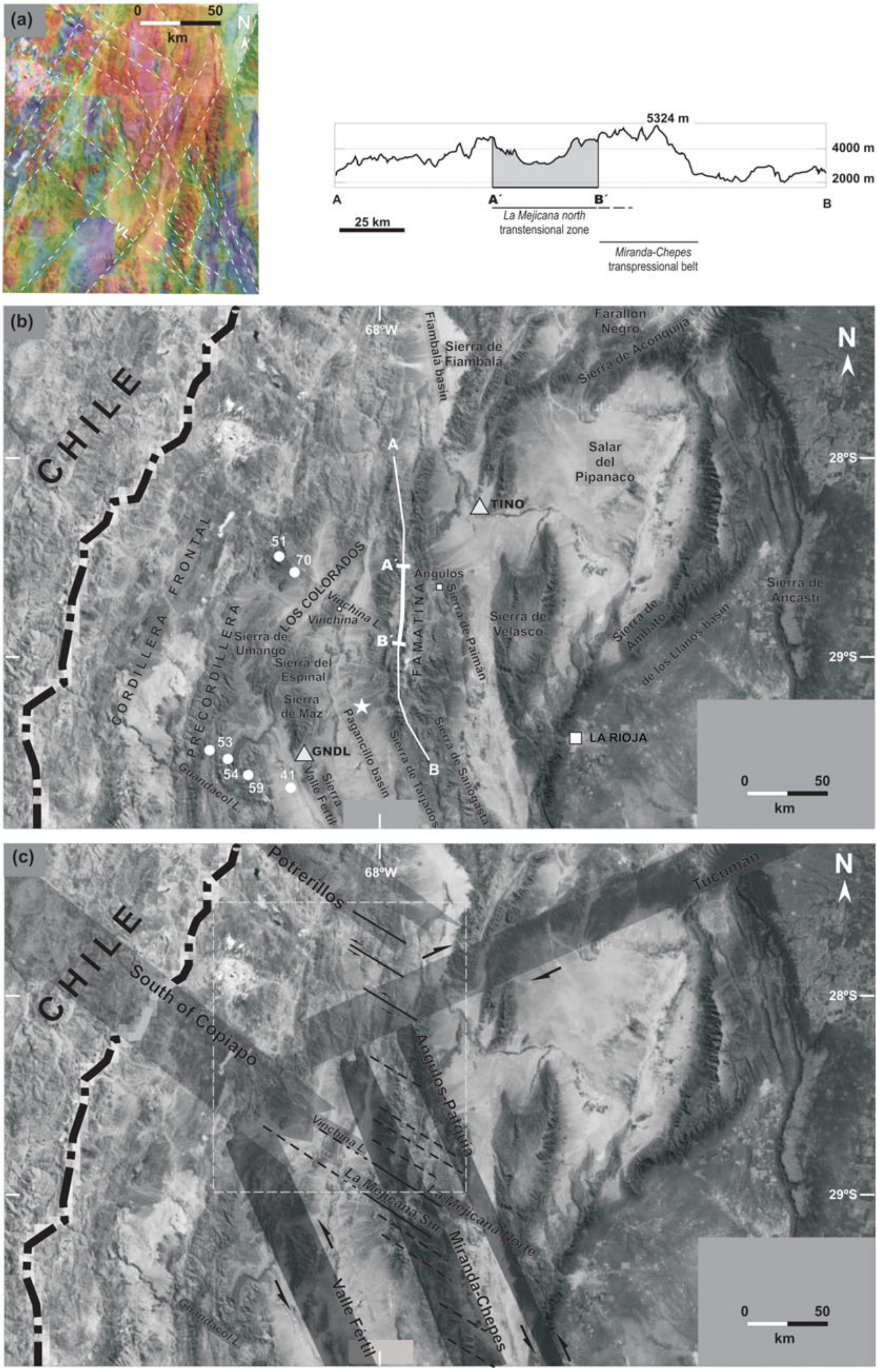

Figure 6. (Colour online) (a) Regional aeromagnetic map of the magnetic anomaly reduced to pole (SEGEMAR, unpub. data, 2012, http://sig.segemar/gov.ar) showing main lineaments. VL: Vinchina Lineament (Porcher *et al.* 2004). Location is shown in (c). (b) Sierra de los Colorados area in the regional context. Star shows the Villa Unión earthquake epicentre (Triep & Cardinali, 1984); white circles indicate earthquake epicentres (numbers refer to earthquake depth; United States Geological Survey database, earthquake.usgs.gov); triangles locate the GPS velocity datum sites from Brooks *et al.* (2003) (TINO: Tinogasta; GNDL: Guandacol). The Vinchina and Guandacol lineaments defined by Porcher *et al.* (2004) are shown. A–A′–B′–B locates the topographic profile. Notice that along-strike changes in altitude are strikingly coincident with the transtensional and transpressional structures referred in the topographic profile. (c) Main regional oblique brittle–ductile shear zones. Lateral components of motions are shown. Rectangle indicates area of (a).

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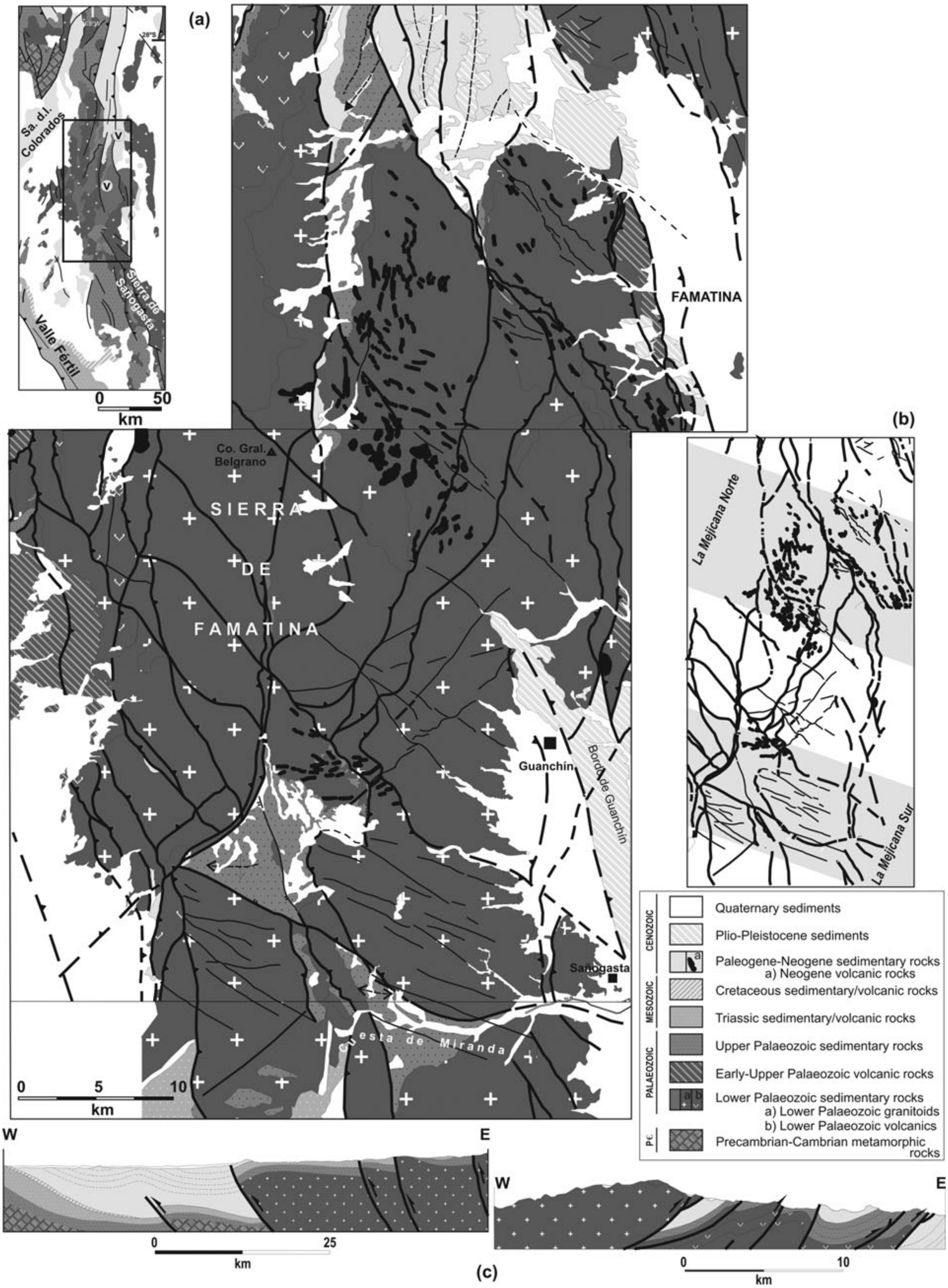

Figure 7. (a) Geological map of central Sierra de Famatina and northern Sierra de Sañogasta (after Candiani *et al.* 2011; Fauqué *et al.* 2016), and location map. (b) Exposures of Neogene volcanic rocks, fracture fabric and the La Mejicana cross-strike structures. Note in (a) the left-lateral displacement of Early Palaeozoic volcanic and the Late Palaeozoic sedimentary rock exposures at Cuesta de Miranda by the La Mejicana Sur structure. (c) E–W cross-sections: Sierra de Sañogasta (left; after Fauqué *et al.* 2016) and central Famatina (right; after Candiani *et al.* 2011).

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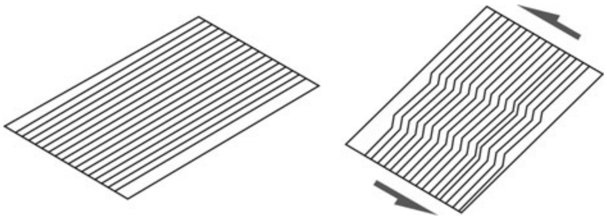

Figure 8. Origin of the Sierra de los Colorados kink-like structure (adapted from Reches & Johnson, 1976).

south of the Sierra de Umango represents a main structure in the northern Precordillera area that was detected by surface evidence (Guandacol Lineament from Porcher *et al.* 2004; see Ré, Japas & Barredo, 2000, 2001; Chernicoff & Nash, 2002; Oriolo *et al.* 2014; Japas *et al.* 2015; Figs 1c, 6b). The Vinchina and Guandacol WNW-trending structures separate basement blocks of different magnetic and gravimetric signatures and were referred to by Porcher *et al.* (2004) as representing Grenvillian age suture zones. During the Neogene, these basement structures reactivated, as confirmed by earthquake data showing hypocentres at 35–70 km depth along these structures (Fig. 6b), in contrast with the 15–21 km depth detachment level indicated for the thin-skinned fold-and-thrust belt by Allmendinger *et al.* (1990), Cristallini & Ramos (2000), Ammirati *et al.* (2013) and Ammirati, Alvarado & Beck (2015).

The localized WNW-trending cross-strike structures affecting the Sierra de los Colorados are responsible for the kinking of the thick Neogene foreland sequence. Average rheological properties of the Neogene sedimentary sequence in the Sierra de los Colorados permit this thick synorogenic pile to be considered as a composite foliated rock or multilayer. Experimental results by Cobbold, Cosgrove & Summers (1971), Gay & Weiss (1974) and Reches & Johnson (1976) reveal that, when compressed, the homogeneous anisotropic nature of such a package should induce internal instabilities and the formation of internal structures controlled by the high degree of anisotropy. These authors showed that at angles of *c.* 30–45º (Cobbold, Cosgrove & Summers, 1971) and 5–30º (Gay & Weiss, 1974) between compression and layering, a single set of kinks should develop. The single set of kinks that represents the Sierra de los Colorados conditions is equivalent to the structure in Figure 8, and could explain the apparent inconsistency between normal-sinistral WNW-trending structures and the *c.* 18 % along-strike finite shortening in the Sierra de los Colorados. The late development of this mesoscale kink structure is coherent with the observed vertical rotation pattern since results by G. H. Ré *et al.* (unpub. data) revealed null rotation in the Central domain where layering would have rotated counterclockwise.

To the east of the Sierra de los Colorados, the WNW-trending structures could be extended into the Sierra de Famatina. Here, two cross-strike discontinuities can be defined: the La Mejicana Sur and La Mejicana Norte structures (Figs 6b, c, 7b). They comprise broad and diffuse zones of faults and fractures controlling both the emplacement of the Mio-Pliocene volcanic rocks from the Mogote Río Blanco Formation and related mineralization (Roy *et al.* 2006) and the Pliocene thick volcaniclastic deposition in the Angulos area studied by Dávila & Astini (2007; Fig. 6b). As cross-strike structures, they disrupt strike-parallel geophysical (Fig. 6a) and structural patterns, as can be seen for example at Cuesta de Miranda (Fig. 7a, b), where structural differences between the Sierra de Sañogasta and Sierra de Famatina were early highlighted by de Alba (1979) and Durand, Toselli & Aceñolaza (1987). At a more regional scale, these WNW-trending oblique structures represent the inland prolongation of the main arc-transverse fault zones defined by Sillitoe & Perelló (2005): the La Mejicana Sur and La Mejicana Norte structures are strikingly aligned with the southernmost lineament south of Copiapó, while a similar brittle–ductile shear zone north of Famatina would correspond to the foreland extension of the Potrerillos Lineament (Fig. 6c).

A main regional NE-trending oblique belt in NW Argentina, the Tucumán Lineament (Mon, 1976) or Tucumán Transfer Zone (Rossello *et al.* 1996; Urreiztieta, 1996) would have been responsible for the Sierra de Aconquija, northern Famatina range, and the Sierra de Fiambalá uplift. Gravimetric and magnetometric data by Porcher *et al.* (2004) show significant NE-trending fracturing in the Sierra de Umango – Sierra de Maz area. This brittle–ductile structure is also associated with Neogene volcanism far from the trench (the Farallón Negro Volcanic Complex; Llambías, 1970, 1972; Sasso & Clark, 1998).

7.a.3. Neogene magmatism and cross-strike structures

The Mogote Río Blanco Formation volcanism (6.38 ± 0.37 to 4.24 ± 0.11 Ma, Ar–Ar ages; Toselli, 1996) and the epithermal alteration and vein systems linked to this volcanism (4 Ma, hydrogen isotope data by Taylor, McKee & Sillitoe, 1997; and 5.3 ± 0.1 to 4.0 ± 0.1 Ma, Ar–Ar plateau ages by Losada-Calderón, McBride & Bloom, 1994) constrain the age of La Mejicana cross-strike activation between 6 and 4 Ma.

In La Mejicana Mining District, Neogene dacitic porphyries were mostly emplaced along N–S-trending structures (Losada-Calderón & Bloom, 1990), whereas related mineralized veins and the distribution of alteration minerals trend dominantly NW–SE to WNW–ESE and E–W (A. Losada-Calderón, unpub. Ph.D. thesis, Monash Univ., 1992; Losada-Calderón & McPhail, 1996; Azcurra *et al.* 2005; Fauqué *et al.* 2006; Pudack *et al.* 2009; Candiani *et al.* 2011; Fig. 7a, b). These alteration trends reveal the control of tensional to shear extensional structures. A similar scenario characterized by two sets of structures controlling emplacement of magmatism and linked mineralization was described in different Neogene volcanic zones from the broken foreland. A first magmatism emplacement stage

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controlled by transpressive / strike-slip structures was immediately followed by a late one controlled by cross-strike transtensional fractures in the Farallón Negro region, in the Faja Volcánica Terciaria from San Luis (Sasso & Clark, 1998; Japas, Urbina & Sruoga, 2010; Japas *et al*. 2011*a*, *b*), but also in the Central Precordillera (Hualilán belt; S. Oriolo, unpub. Trabajo Final de Licenciatura, Univ. de Buenos Aires, 2012). Connection between tectonic and magmatic processes in oblique convergence systems was considered by Saint Blanquat *et al.* (1998) as linked in a positive feedback loop where deformation contributes to magma overpressuring and to connecting regions with pressure gradients (triggering its upward transport), and magma facilitates weakening of rocks and magma-induced deformation.

Cross-strike structures also produce localized accommodation spaces for coeval epi- and volcaniclastic rock accumulation, as was recognized in the Faja Volcánica Terciaria by Japas, Urbina & Sruoga (2010). In central Sierra de Famatina, localized subsidence associated with La Mejicana Norte cross-strike structure could thus be an alternative explanation to the volcanic-induced load proposed by Martina, Dávila & Astini (2006) for the volcanic depocentre near Angulos town (El Durazno Formation volcaniclastic rocks, 5.2 ± 0.85 Ma according to Tabbutt, 1990). Likewise, it could explain the palaeocurrent change reported by Dávila & Astini (2007) at the time of magmatism emplacement, as palaeocurrent turned towards the NE-NNE, perpendicular to the WNW-striking controlling faults. Source area composition also confirms this link as clasts from the underlying Del Buey Formation and Late Miocene – Pliocene volcanic-derived boulders contributed to the deposit (Dávila & Astini, 2007). The increase in clast size of the El Durazno Formation relative to the underlying sequences and the presence of contrasted compositions when compared with other contemporaneous deposits in the broken foreland (Dávila & Astini, 2007) would support the existence of a revitalized topography and basin fragmentation at a smaller scale, probably as a consequence of La Mejicana Norte activation.

The presence of Neogene magmatism far from the trench at 27–33º S would introduce a significant change in the foreland system as it should produce, at least locally, an increase in heat flow and some other magma-related softening processes of the crust. This seems to be concurrent with the fact that with magmatism emplacement, thick-skinned deformation started in the Sierras Pampeanas and Precordillera (Ramos, Cristallini & Perez, 2002; Japas, Urbina & Sruoga, 2010; Oriolo *et al.* 2014). Because information about uplift in the broken foreland comes from a still poorly constrained stratigraphy and low-temperature thermochronology (Nóbile & Dávila, 2012), the precise timing between magmatism emplacement and thick-skinned deformation could not yet be exactly established. One of the proposals about this suggests weakening of the crust enhanced by an increase in heat flow after magmatism emplaced, with consequent development of brittle–ductile transition within the crust and basement-involved deformation (Ramos, Cristallini & Perez, 2002). However, according to Collo *et al.* (2011, 2015) and Dávila & Carter (2013), the Neogene basin in the study area does not record any regional thermal increase at least until *c.* 3.4 Ma. Collo *et al.* (2015) reported a *c.* 26–42 mW m^{-2} (geothermal gradient of 15° C km^{-1}; Collo *et al.* 2011) to the east of the Precordillera, which is significantly lower than the heat flow of 60–80 mW m^{-2} required to position the depth of the brittle–ductile transition into the crust (Kusznir & Park, 1986; Ramos, Cristallini & Perez, 2002). On the other hand, Nóbile & Dávila (2012) demonstrated that the Sierra de Aconquija first uplift peak should have occurred at *c.* 12 Ma, the time of emplacement of the oldest volcanism in the Farallón Negro district. In the same way, La Mejicana district would also reveal simultaneous uplift and magmatism emplacement at *c.* 6.4 Ma. This concordance of magmatism and uplift ages would support melt-enhanced deformation ('tectonic surges' triggered by melt-lubricated shear zones; Hollister & Crawford, 1986) rather than heating-enhanced deformation (Coney, 1972; Burchfiel & Davis, 1975; Ramos, Cristallini & Perez, 2002). The active role of magmatism in increasing rock ductility is also supported by brittle–ductile shear zone substituting fault development (see also Kleiman & Japas, 2009; Japas, Urbina & Sruoga, 2010; Oriolo *et al.* 2014; Sruoga *et al.* 2014).

7.b. Compartmentalization of the Vinchina basin: timing of basement uplift

In the Sierra de los Colorados area, the Sierra de Umango-Espinal should have begun to be uplifted at *c.* 9 Ma based on sediment composition (Ciccioli *et al.* 2013*a*) and localized high thickness of the Vinchina Formation upper member (Ramos, 1970). This suggests an earlier onset of the broken-foreland stage than that constrained by Jordan, Schlunegger & Cardozo (2001) at 6.5 Ma, as previously supported by Dávila & Astini (2007), Dávila (2010) and Zambrano *et al.* (2011). Uplift of the Umango-Espinal block would also be active after 4.3 Ma (J. H. Reynolds, unpub. thesis, Dartmouth College, 1987; Ramos *et al.* 1988), revealing a long, recurrent and episodic history of uplift activity.

Considering the Sierra de Famatina region, fission-track age by Tabbutt (1990), and fission-track ages and magnetic polarity stratigraphy by Malizia, Reynolds & Tabbutt (1995) reported uplift at 6.8 Ma (Sierra de Famatina) and 6.1 Ma (Sierra de Tarjados, southern Sierra de Famatina; Fig. 6b), respectively. According to thermal modelling, Coughlin *et al.* (1998) indicate rapid cooling and exhumation of the Sierra de Famatina at *c.* 10–5 Ma based on apatite fission-track data. Based on the stratigraphic record in the Sierra de los Colorados, Limarino, Ciccioli & Marenssi (2010) and

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Ciccioli *et al.* (2013*a*, *b*, 2014) considered that the main Sierra de Famatina uplift phase correlates with the base of the Toro Negro Formation. The sharp incision at the base of the Toro Negro Formation in the quebrada de los Pozuelos area was interpreted as a palaeovalley that developed in response to a base level change triggered by uplift of the Sierra de Famatina (Limarino, Ciccioli & Marenssi, 2010). This occurred between 9 Ma (Vinchina Formation upper member) and 5.5 Ma (Toro Negro Formation lower-middle members), consistent with the previously considered age of *c.* 6.1–6.8 Ma. At this time the Sierra de Toro Negro also uplifted (Ciccioli & Marenssi, 2012), representing an additional source of subsidence. The Sierra de Toro Negro and the Sierra de Famatina basement blocks are aligned following the NNW-trending Miranda–Chepes transpressional belt that could be then considered active at 6.1–6.8 Ma.

WNW-trending cross-strike structures developed at the same time as, or immediately after, rocks of the Toro Negro Formation deposited. These structures affected the whole Neogene pile in the Sierra de los Colorados area and were contemporaneous with the Late Miocene to Early Pliocene volcanism emplacement in the Sierra de Famatina. To the north of the Sierra de Famatina, left-lateral WNW-trending structures displacing previous NNW-trending basement blocks would support this timing (Fig. 6c).

Thermochronological data constraining basement block exhumation in the broken foreland also confirm Neogene exhumation for the Western Sierras Pampeanas to some extent (Löbens *et al.* 2013*a*, *b*).

7.c. Proposed kinematic evolution

Identifiable deformation in the Sierra de los Colorados area began at *c.* 11–12 Ma, since both the lower and middle sections of the Vinchina Formation show the same amount of vertical axis rotation (*c.* 28° clockwise; G. H. Ré, unpubl. Ph.D. thesis, Univ. de Buenos Aires, 2008; Japas *et al.* 2015). This earlier signal of Andean deformation is interpreted as being related to the Precordillera thin-skinned deformation style because A-population kinematic shortening axes trend NNE and vertical axis rotation is clockwise (Fig. 9a). At *c.* 9 Ma, tectonic activity of the NE-trending Tucumán oblique structure triggered the Sierra de Umango-Espinal uplift (together with the Sierra de Aconquija, Sierra del Cajón and other related ranges; see Coughlin *et al.* 1998, Sobel & Strecker, 2003; Mortimer *et al.* 2007; Löbens *et al.* 2013*a*), inducing local topographic loading subsidence during deposition of the Vinchina Formation upper member (Fig. 9b). The activation of this regional oblique structure is also supported by the presence of both the kinematic B-population and the *c.* 14° clockwise vertical axis rotation. At about 6.1–6.8 Ma, the Miranda–Chepes belt activated and triggered the uplift of the Sierras de Sañogasta, Famatina and Toro Negro, and the left-lateral displacement of the Tucumán oblique megazone (Fig. 9c). At *c.* 6–4 Ma, the WNW-trending La Mejicana oblique belts controlled emplacement of the Mogotes volcanism in Famatina and induced the Neogene sequence of the Sierra de los Colorados to kink (Fig. 9d).

7.d. Thick-skinned overprinting thin-skinned deformation

Several examples of thick-skinned structures overprinting thin-skinned orogens were described in different contractional settings and linked to different causes (Mazzoli *et al.* 2000; Lacombe & Mouthereau, 2002; Molinaro *et al.* 2005; Madritsch, Schmid & Fabbri, 2008; Bailly *et al.* 2009; Maurin & Rangin, 2009; Sapin *et al.* 2009; Japas & Ré, 2012*a*, *b*; Japas *et al.* 2015). Some authors point directly to critical taper preservation conditions (Molinaro *et al.* 2005; Maurin & Rangin, 2009; Kraemer *et al.* 2011), to increasing friction due to large wedge development (Bailly *et al*. 2009), to the presence of structural obstacles (Japas *et al.* 2015) or/and to changes in subduction parameters (Sapin *et al.* 2009) such as those linked to ridge indentation and flat subduction (Japas & Ré, 2012*a*, *b*; Japas *et al.* 2015).

A Late Pliocene basement-involved oblique brittle–ductile shear zone was recognized in the northern sector of the thin-skinned Western and Central Precordillera, the Rodeo–Talacasto belt, based on vertical axis rotation data and structures (Japas *et al*. 2015). This late, NNW–SSE-trending left-lateral structure overprinted the regional Miocene N–S / NNE–SSW-trending, dextral transpressional fabric representative of the Central Andes Rotation Pattern (CARP of Somoza, Singer & Coira, 1996). Kinematic axes also confirmed the existence of these early thin-skinned and late thick-skinned stages, with E- and NNE-directed shortening (as partitioned; Siame *et al.* 2005; Oriolo *et al.* 2014), and WNW- to NW-directed shortening (F. M. Dávila, unpub. Ph.D. thesis, Univ. Nacional de Córdoba, 2003; Japas *et al.* 2014; Oriolo *et al*. 2014), respectively. Considering the above-mentioned uplift ages for the broken foreland together with data at the northern edge of the Sierra de Valle Fértil (Ortiz *et al.* 2015) and the 2.75 Ma age for the activation of the Rodeo–Talacasto belt (Japas *et al.* 2015), the younging-basement-block-uplift-to-the-west proposed by Malizia, Reynolds & Tabbutt, (1995) and Coughlin *et al.* (1998) is confirmed, at least in western Sierras Pampeanas.

Different kinematic shortening axes in the Sierras Pampeanas (see also Japas, Urbina & Sruoga, 2010) and in the Precordillera, as well as the GPS-derived velocity field from Brooks *et al.* (2003), reveal mechanical decoupling between the orogen and the broken foreland. Partitioning of motions is controlled by the Late Palaeozoic and Early Palaeozoic fabrics from the Precordillera and the Sierras Pampeanas respectively, which independently controlled the orientation and vergence of the Andean faults in each sector.

Basement-involved deformation involves reactivation of inherited structures, implying some lateral motion. Components of strike-slip displacement were recognized in Neogene structures in the Precordillera

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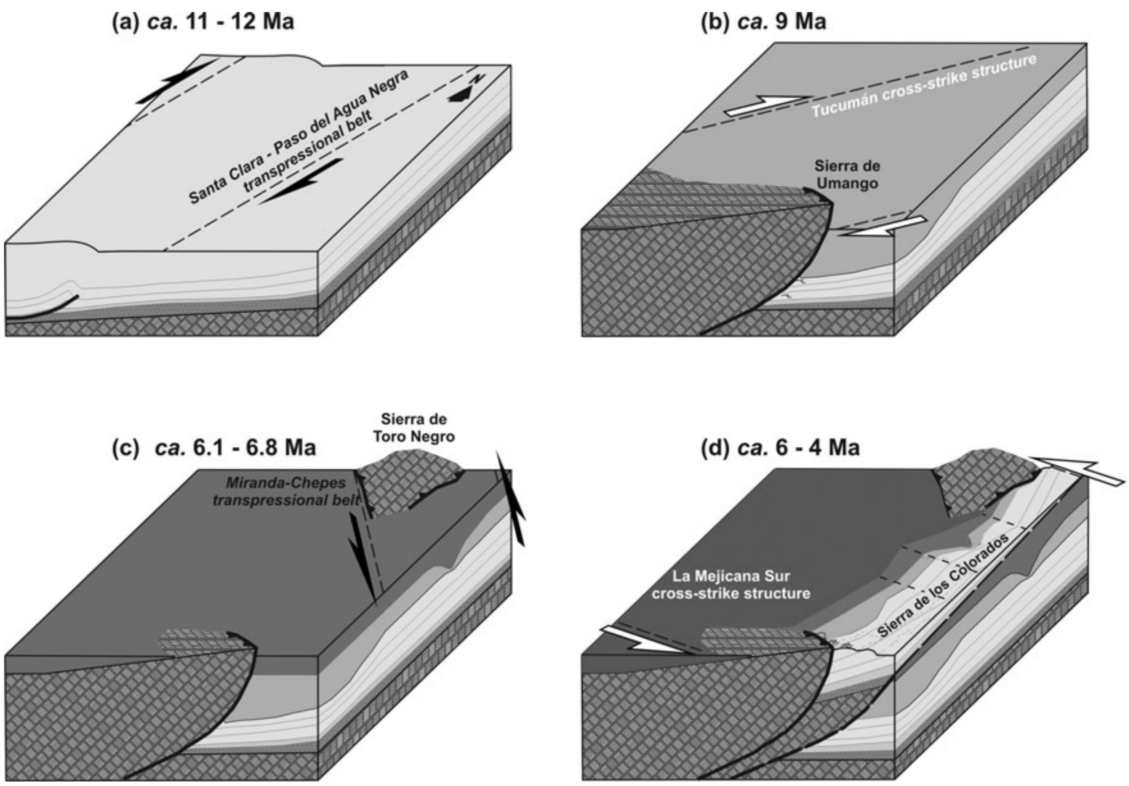

Figure 9. Schematic block-diagrams showing the Neogene evolution of the Sierra de los Colorados region at 28º S. (a) *c.* 11–12 Ma; (b) *c.* 9 Ma; (c) *c.* 6.1–6.8 Ma; (d) *c.* 6 to 4 Ma.

(Japas, 1998; Ré, Japas & Barredo, 2001; Cortés & Cegarra, 2004; Siame *et al.* 2005; Cortés *et al.* 2006; Japas & Ré, 2012*a*, *b*; Oriolo *et al*. 2014; Perucca & Ruiz, 2014; Japas *et al.* 2015) and also in the Sierras Pampeanas (Urreiztieta, 1996; Rossello *et al.* 1996; Japas, 1998; Ré, Japas & Barredo, 2000, 2001; Introcaso & Ruiz, 2001; Japas, Urbina & Sruoga, 2010). Although GPS data from Brooks *et al.* (2003) indicate a general ENE-trending convergence direction, some other kinematic indicators show WNW-trending shortening, at least since the Pliocene (Alvarado & Ramos, 2010, 2011; Japas, Urbina & Sruoga, 2010; Giambiagi *et al.* 2014). In the Sierras Pampeanas, Alvarado & Ramos (2010, 2011) explained the observed obliquity between the average P-axis of the seismic focal mechanism estimations and the GPS velocity orientation by slip partition, fault creeping and/or lower frequency of strike-slip recurrence compared to the *c.* 30-year instrumental measurement interval. In the Precordillera, this difference was linked to (a) local passive transport towards the ENE through a 10–12 km deep detachment level (Giambiagi *et al.* 2014), or (b) localized transpression associated with brittle–ductile megashear zones controlling basement-involved deformation (Japas *et al.* 2015).

The overprint of thick-skinned structures in the Sierra de los Colorados area reflects the advance of the orogenic front and the incorporation of the Sierras Pampeanas into the foreland deformation scenario since the Late Miocene – Pliocene. This overprint phenomenon occurred earlier in the Sierra de los Colorados region than in the Central Precordillera to the south, reflecting basement deformation migrating in the same direction as migration of the flat slab subduction. Pre-Cenozoic, major, favourably oriented basement structures have strongly controlled the Neogene deformation style in the Sierras Pampeanas, fragmenting the distal foreland into a group of inter-montane basins controlled by basement uplift.

8. Conclusions

Kinematic analyses in the Neogene Sierra de los Colorados sedimentary sequence report three kinematic populations. Represented by NNE-trending structures and NE-directed shortening, the oldest A-population sustains the occurrence of an embryonic thin-skinned deformation stage, lately overprinted by the second B-population (NNW-trending structures, WNW-directed kinematic shortening) starting the broken foreland phase. Although not yet fully understood, the youngest kinematic C-population potentially indicates a late extensional stage linked to strain adjustments associated with the kink structure that is interpreted as a consequence of late basement-involved WNW-trending cross-strike structures.

Kinematic and available palaeomagnetic results constrain the first thin-skinned deformation stage to the Vinchina Formation middle–upper member boundary (*c.* 11–12 Ma) and the beginning of the basement-involved stage to the Vinchina Formation upper member (*c.* 9 Ma). This two-staged deformational history indicates that this area is a transitional zone between the Precordillera and the Sierras Pampeanas.

Regional oblique brittle–ductile shear zones play a significant role in broken foreland deformation and during the thick-skinned overprint in the Precordillera region. They comprise the reactivation of inherited ancient structures. Internally, these brittle–ductile shear zones would have controlled the diachronic uplift and tilting of en échelon-distributed single basement blocks. Although also controlled by these Neogene megashear zones, differences in structural pattern in the Sierra de Famatina are linked to the development of a flower structure. This scenario explains the complex diachronic pattern of uplifted basement blocks.

The *La Mejicana* cross-strike structures are defined in the Famatina region and extended into the Sierra de los Colorados where they were responsible for the local late kink-like structure of the Neogene sequence. As in other regions in the foreland and broken foreland, La Mejicana Norte and La Mejicana Sur cross-strike structures controlled magma emplacement in the Pampean flat-slab segment.

The onset of basement deformation should result from magma-related softening processes and/or high interplate coupling, the latter being most consistent with a flat-slab scenario (with greater contact area between plates, and cooler temperatures / stronger rheology; Gutscher, 2002). Nevertheless, magma intrusion results in local softening of the crust and strain localization, even when small amounts of melt are introduced (Tommasi *et al.* 1994; Saint Blanquat *et al.* 1998). Once weakened the crust, diachronic uplift and exhumation are expected to be linked to both the southwestward regional migration of basement-involved foreland deformation, and to evolution of deformation within each regional brittle–ductile megashear zone.

In the Sierra de los Colorados area, the complex time-spatial interplay of different basement-controlling structures overprinting an early thin-skinned deformation stage results in a mosaic-style structural grain that could explain the heterogeneous pattern of some geological features (e.g. a tectonic block rotation pattern departing from the CARP).

The unusual thickness of the Neogene sedimentary pile in the Sierra de los Colorados area could alternatively be explained by the accumulative effect of recurrent episodes of subsidence, linked to both the Precordillera and the Sierras Pampeanas deformation stages. In this way, alternating regional flexural and local topographic load subsidence as well as sublithospheric mechanisms could have contributed to the thickest sediment accumulation within the Pampean flat-slab segment.

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