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The Choiyoi volcanic province at 34°S–36°S (San Rafael, Mendoza, Argentina): Implications for the Late Palaeozoic evolution of the southwestern margin of Gondwana

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ABSTRACT

The Choiyoi rhyolitic province of Chile and Argentina (23°S–42°S) was emplaced at the SW margin of Gondwana during the Permian. The San Rafael Massif (Mendoza, Argentina, 34°–36°S), is a key area to analyse the relative timing of Choyoi magmatism and related deformation as it bears one of the most complete and well exposed succession. Stratigraphic, structural and magmatic studies indicate that major changes of geodynamic conditions occurred during the Permian since arc-related sequences syntectonic with transpression (lower Choiyoi) were followed by transitional to intraplate, postorogenic suites coeval with transtension (upper Choiyoi). During the Early Permian, a major event of N–NNW dextral transpressional motions deformed the Carboniferous foreland basin in the San Rafael Massif. This event is attributed to the first episode of the San Rafael orogeny and can be related to oblique subduction (Az. 30°) of the Palaeo-Pacific plate. Ca. 280 Ma the inception of voluminous calc-alkaline volcanism (lower Choiyoi) syntectonic with WNW sinistral transpression of the second episode of the San Rafael orogeny, is associated with an eastward migration of the magmatic arc at this latitude. To the southeast of San Rafael, magmatism and transpression continued to migrate inland suggesting that a progressively younger, WNW, sinistral, thick skinned deformation belt broadens into the foreland and can be traced from San Rafael to Sierra de la Ventana, linking the San Rafael orogeny with the Gondwanide orogeny of the Cape Fold Belt in South Africa. This distribution of magmatism and deformation is interpreted as being the consequence of a progressive shallowing of the Palaeo-Pacific plate starting to the north of San Rafael, and culminating with a flat-slab region south of 36°S. Ca. 265 Ma the onset of predominantly felsic volcanism (upper Choiyoi) in San Rafael occurred in a Post-San Rafael extensional setting. Kinematic indicators and strain fabric analyses of San Rafael orogeny transpression and Post-San Rafael extension show a tectonic reversion. The Post-San Rafael event could be the result of the extensional collapse of the San Rafael orogen, triggered by continental-scale clockwise rotations. These rotations would account for subduction ceasing earlier in the north (31°S–36°S) than in the south, thus explaining the coexistence, after ~265 Ma, of extension in San Rafael with compression in the Sierra de la Ventana–Cape Fold Belt area.

1. Introduction

The southern portion of South America formed part of the supercontinent of Gondwana during most of the Palaeozoic and Early Mesozoic. Between approximately 350 and 230 Ma, Gondwana magmatism spanned the change from a convergent plate margin to an extensional regime (Uliana and Biddle, 1988; Mpodozis and Kay, 1992; Llambías et al., 1993; Kleiman, 1993; Kleiman and Japas, 2002, 2005). Based on age data frequency, two periods were constrained (Ramos and Ramos, 1979): a) Carboniferous–Early Permian and b) Late Permian–Triassic. Calc-alkaline I-type arc sequences of the first period are related to the subduction of the Palaeo-Pacific plate under the continent (Frutos and Alfaro, 1985; Hervé, 1988) whereas granitoids and volcanics of the second period are transitional sequences that ended with bimodal suites erupted during Triassic rifting (Mpodozis and Kay, 1992).

As a part of Gondwana magmatism, the Choiyoi is a large silicic volcanic province that extends from 23°S to 42°S in Chile and Argentina. South of 36°S, outcrops of this sequence divide into two different belts: a nearly NS and a WNW one (Fig. 1). The relative timing of magmatism, deformation as well as the tectonic setting of the Choiyoi province remains controversial. Traditionally, it was assigned to the Late Permian–Triassic age period (Ramos and Ramos, 1979) and related to an extensional setting following the major deformation

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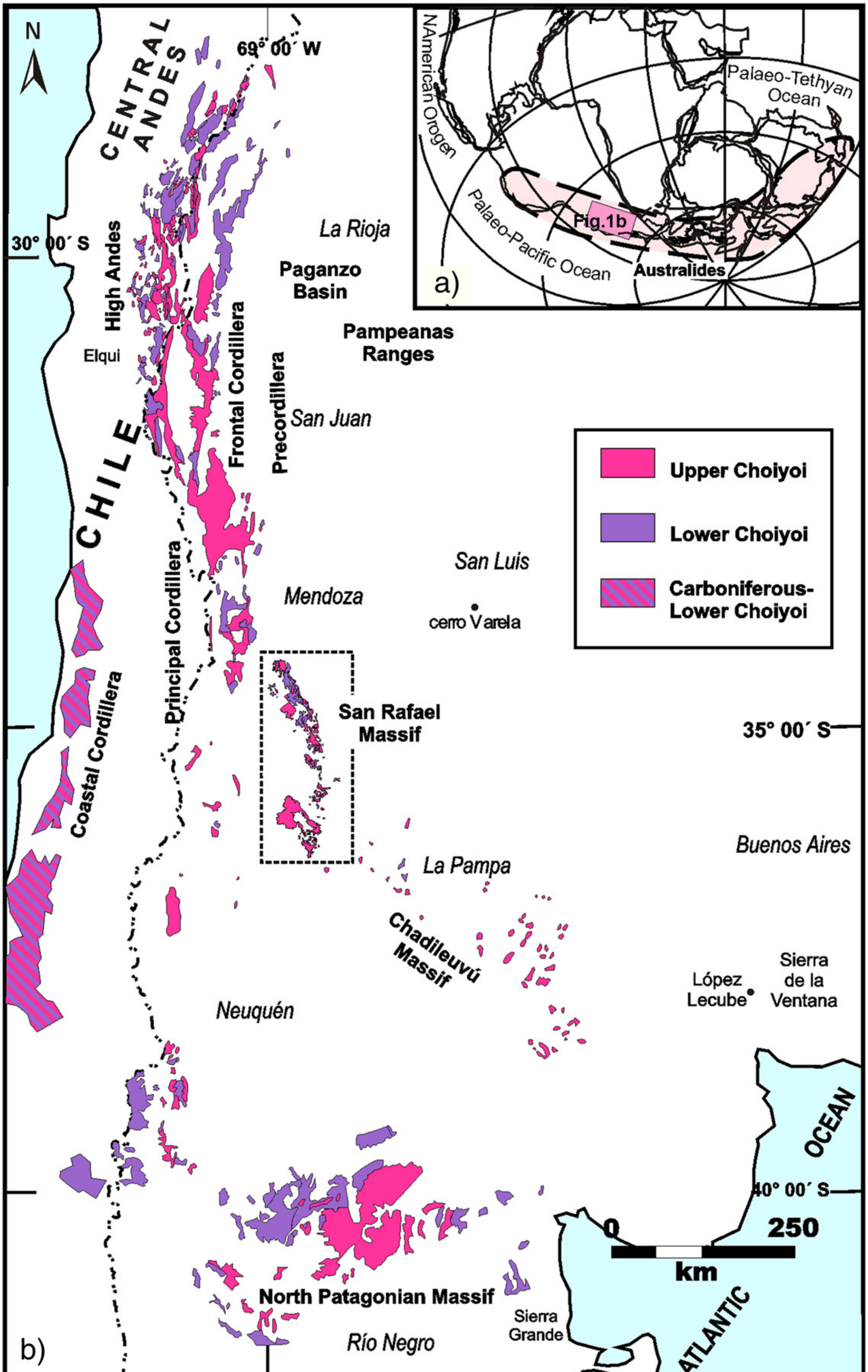
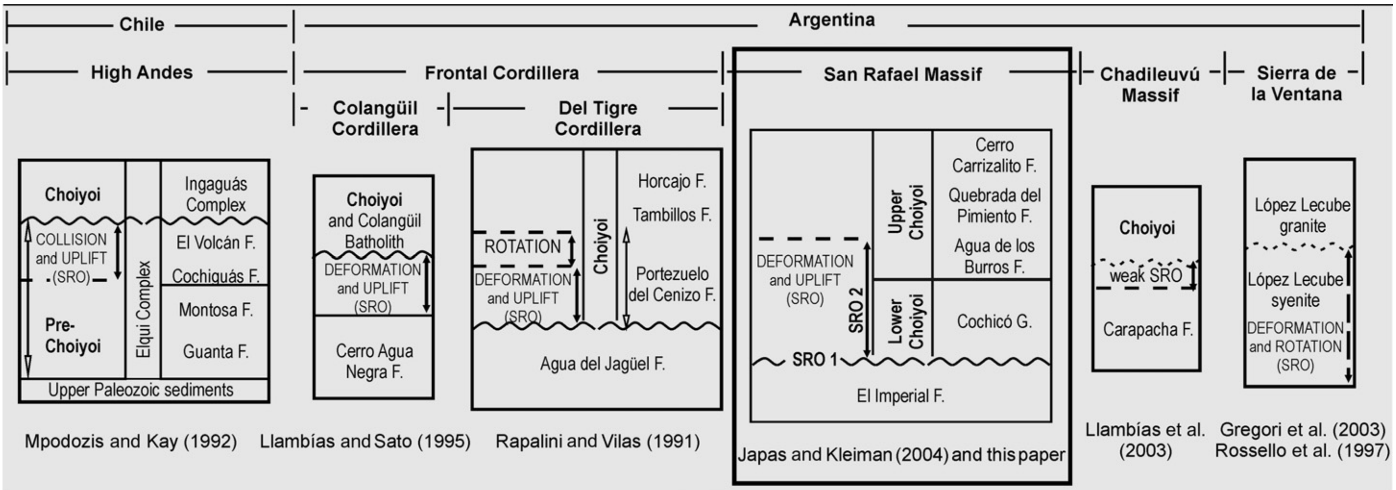


Fig. 1. a) Reconstruction of Gondwana from Vaughan et al. (2005) with the Australides of Cawood (2005) and the location of b). b) Distribution of the Choiyoi volcanic province south of 28°S and equivalent Late Palaeozoic magmatic rocks in Argentina and in Chile. The box outlines the San Rafael Massif. Sources: Mapa Geológico de la República Argentina 1:500.000 (1996), Mapa Geológico de Chile (2003), Mpodozis and Kay (1992), Llambías et al. (2003), Pankhurst et al. (2006).

Table 1
A comparative scheme to illustrate the relative timing of Permian magmatism and deformation in this portion of the Gondwana margin as it was originally set by different authors.



Time markers and scales are not shown as radiometric data are not well constrained.

event of the San Rafael orogeny (Llambías and Sato, 1990, 1995; Llambías et al., 1993; Heredia et al., 2002). However, this volcanism not only straddled both age periods, as it was dated between ~280 Ma (Rocha-Campos et al., 2006) and 240 Ma (Llambías and Stipanicic, 2002) but it also spanned the change of geodynamic conditions, since the basal sequences were syntectonic with this orogeny (Kleiman and Japas, 2002; Japas and Kleiman, 2004).

During the Early Permian the San Rafael orogeny deformed Carboniferous–Early Permian marine and continental sedimentary sequences in Chile and western Argentina when plate convergence was still active to the west (Azcuy and Caminos, 1987; Ramos, 1988a). Paleomagnetic data suggest that this deformation event expanded to the south and to the east (Rapalini, 1998; Tomezzoli and Vilas, 1999; Fig. 1, Table 1) and it may be linked with the Gondwanide orogeny which extended from Sierra de la Ventana through the Cape Fold belt in south Africa, to Antarctica, Australia and New Guinea (Mpodozis and Kay, 1992; Veevers et al., 1994). Age data sets of both orogenies suggest diachronism of these events. The main peak of deformation occurred before ~280 Ma in western South America (Japas and Kleiman, 2004) and at ~260 Ma in South Africa (Hälbich et al., 1983; Gresse et al., 1992). Compression also ceased earlier in South America than in South Africa, where it lasted until ~230 Ma.

Diverse geodynamic scenarios were proposed to explain both magmatism and deformation of this part of the Gondwana margin during the Late Palaeozoic (Lock, 1980; Forsythe, 1982; Ramos, 1984; Uliana and Biddle, 1988; Dalziel et al., 2000; Pankhurst et al., 2006), a controversy that will persist until diachronism and other factors are not better constrained.

We undertook structural, stratigraphic and geochemical studies in the San Rafael Massif (southern Mendoza, Argentina, 34°–36°S, Fig. 1) in order to analyse the relationship between Choiyoi magmatism and changes in the stress regime. This is a key area to understand the evolution of the Choiyoi province since it bears one of the most complete sequences ranging from Lower Permian continental-arc volcanics (lower Choiyoi) to Upper Permian transitional to intraplate volcanic and subvolcanic rocks (upper Choiyoi). In an attempt to constrain the Late Palaeozoic evolution of this portion of the Gondwana margin we compared our results with the regional framework, thus providing an insight into the timing of magmatism and deformation in this area.

2. Geologic setting

The geologic history of this part of South America can be divided into several cycles: Grenvillian (Precambrian), Famatinian (Early Palaeozoic), Gondwanian (Late Palaeozoic–Early Mesozoic) and Andean (Tertiary to Present). Rocks exposed in the San Rafael Massif range from Precambrian amphibolites to Pleistocene Andean volcanics.

Grenvillian metamorphic rocks (Cingolani et al., 2005) are overlain by Ordovician carbonate platform sequences (Bordonaro et al., 1996) which could be related to the accretion of exotic terranes to the western margin of Gondwana during the Early Palaeozoic (Ramos, 1988b). Ultramafic rocks in the San Rafael Massif were assimilated into the Famatinian ultramafic belt and interpreted as the result of continent–continent collisions at the same margin (Haller and Ramos, 1993).

Extensive thick sequences of Siluro-Devonian metasediments and turbidites were severely deformed at the end of the Devonian, as the consequence of the collision of the allochtonous Chilenia terrane (Ramos et al., 1984).

The Gondwanian cycle in the San Rafael Massif is represented by upper Carboniferous–Lower Permian sediments of the El Imperial Formation, Lower Permian–Lower Triassic (?) Choiyoi volcanism and associated sedimentary rocks, and the Triassic Puesto Viejo rift sequences (Fig. 2 and Table 2).

The El Imperial Formation represents the filling of a foreland basin and comprises siliciclastic, glaciomarine deposits which grade upwards into fan deltas and braided-fluvial systems (López Gamundi et al., 1989; Espejo, 1990). This sequence was deformed during the San Rafael orogeny (Ramos, 1993). As the Choiyoi volcanism unconformably overlies the Carboniferous sequences in various localities, this unconformity was interpreted as a regional erosional surface (Llambías et al., 1993). In contrast to the Precordillera and Frontal Cordillera, magmatic rocks of Carboniferous age are unknown in San Rafael, implying that at this latitude the magmatic arc was situated farther to the west (Figs. 1 and 2).

The lower Choiyoi in San Rafael comprises the Cochicó Group, a volcano-sedimentary sequence deposited following a NNE trending trough, which was also deformed by the San Rafael orogeny (Kleiman, 1999; Cortés and Kleiman, 1999; Japas and Kleiman, 2004). Recent U/Pb SHRIMP dating of zircons from an ignimbrite at the base of the sequence yielded an age of 281.4 ± 2.5 Ma (Rocha-Campos et al., 2006).

The Cochicó Group is unconformably overlain by the upper Choiyoi sequences, which in this area include the Agua de los Burros, Quebrada del Pimiento and Cerro Carrizalito Formations (González Díaz, 1972). The first unit is an increasingly acid volcaniclastic succession dated at 265.0 ± 2.6 Ma by U/Pb (SHRIMP) in zircons (Rocha-Campos et al., 2006). It filled and overlapped the Lower Permian trough and it is also slightly folded by the San Rafael orogeny. The Agua de los Burros

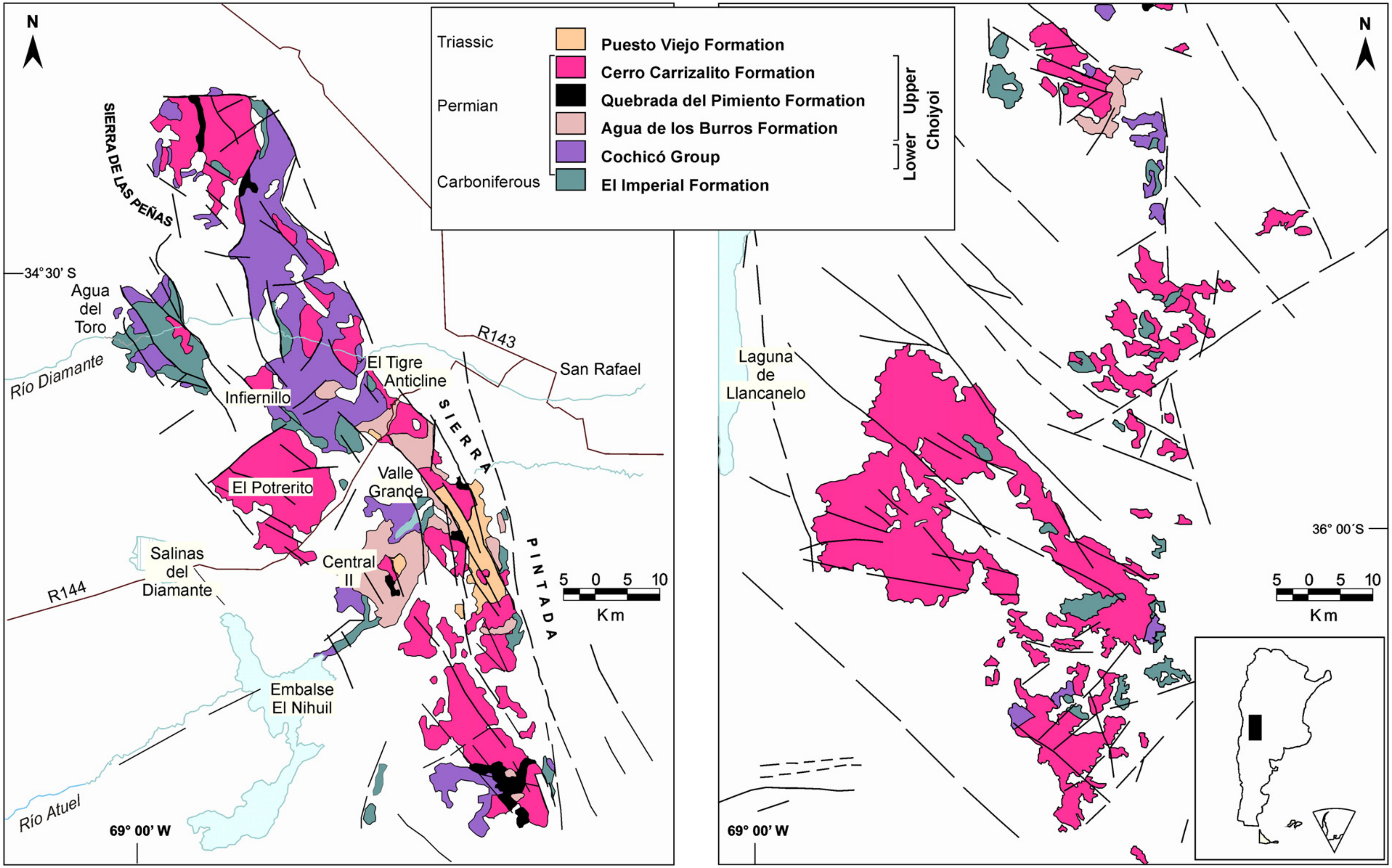


Fig. 2. Geologic map of the San Rafael Massif. Only the distribution of upper Palaeozoic and Triassic rocks are shown. Sources: Kleiman (1999), Mapa Geológico de la República Argentina 1:500.000 (1996).

ignimbrites were intruded by andesitic dykes of the Quebrada del Pimiento Formation following normal faults. Whole rock K/Ar ages for these andesites range from 271 ± 10 Ma (Linares et al., 1979) to 263 ± 10 Ma (Núñez, 1979). The Cerro Carrizalito Formation which includes products of several rhyolitic volcanic centres, represents the upper portion of the Choiyoi volcanism. U/Pb SHRIMP data on zircons near the top of the sequence gave an age of 252.3 ± 3.8 Ma (Rocha-Campos et al., 2006).

Triassic sequences of the Puesto Viejo Formation (González Díaz, 1972) consist of synrift-continental successions interbedded with rhyolites, ignimbrites and basalts. They rest unconformably on Upper Choiyoi volcanics and correspond to the final stage of the Gondwana magmatism in the San Rafael Massif (Kleiman and Salvarredi, 2001). Whole-rock K/Ar ages of the silicic ignimbrites ranged from 241 ± 10 to 235 ± 10 Ma, whereas an age of 237 ± 4 Ma was determined for the basalts (Valencio et al., 1975). After the Triassic the area was uplifted and remained positive until the Miocene.

3. Late Palaeozoic volcanism in the San Rafael Massif

3.1. Description of the sequences

3.1.1. Lower Choiyoi

The Cochicó Group is a volcano-sedimentary succession, 1400 m thick, made up of conglomerates, ignimbrites (up to 200 m thick) interbedded with eolian sandstones (up to 100 m thick), andesitic breccias (debris flow deposits) and auto-brecciated andesitic lavas. Dacitic to rhyodacitic ignimbrites are mainly high aspect-ratio, poorly welded and crystal-rich (up to 50%), containing plagioclase, quartz, sanidine, biotite, magnetite, apatite and zircon. They share characteristics with monotonous-intermediate ignimbrites of Hildreth's (1981) classification (Kleiman, 2005). The volume and acidity of the ignimbrites diminish towards the top of the sequence, in which andesitic breccias and andesites predominate. Eruptive centres for the lower Choiyoi have not been identified yet.

3.1.2. Upper Choiyoi

At the base of the upper Choiyoi, the Agua de los Burros Formation comprises conglomerates, andesitic breccias, dacitic to rhyolitic, crystal-poor (18%), moderately welded ignimbrites, flow-banded rhyolitic lavas, tuffaceous sediments and tuffs. These are intruded by subvolcanic bodies (dykes and domes) of dacitic composition. The sequence ends with co-ignimbritic breccias and rhyolitic ignimbrites, which are predominant. These ignimbrites contain up to 30% crystals of quartz, feldspar, biotite, amphibole, and accessory magnetite, apatite and zircon; they are moderately welded, with some eutaxitic textures, and show columnar joints.

The Quebrada del Pimiento Formation consists of andesitic dykes, lavas and sills, which intrude or cross-cut the Cochicó Group and the Agua de los Burros sequences. They are dark, greenish grey, aphanitic rocks with andesine, amphiboles and pyroxenes.

The Cerro Carrizalito Formation includes a complex set of rocks with variable compositions, which are the product of different volcanic centres, so that their stratigraphic relations are not easily inferred (Kleiman, 1999). One of these centres (El Potrerito) has been described as a caldera (Salvarredi, 1996; Kleiman et al., 2005). Rhyolitic lavas, dykes and ignimbrites, coarse-grained, dacitic to rhyodacitic intrusions, and fine-grained, rhyolitic subvolcanic bodies, some of them bearing garnet and topaz, are the main lithologies. Ignimbrites are moderately to highly welded with columnar joints. They are crystal-rich (21–45%) with various proportions of quartz, sanidine, oligoclase, biotite, amphibole and/or pyroxenes. The last stages of Choiyoi magmatism in the area are represented by basandesitic lavas and dykes interbedded in the sequence at the El Potrerito caldera, indicating a bimodal trend (Kleiman et al., 2005).

3.2. Geochemistry

Whole-rock major and trace element data were evaluated in order to characterize the lower and upper Choiyoi sections in the area of San Rafael. Analytical data of some representative samples are shown in Table 3.

Table 2
Synopsis of the stratigraphy, geochemistry, structure and tectonic setting of the Gondwanian cycle in the San Rafael Massif.

Ma	Age				Stratigraphy	Lithology	Geochemistry		Tectonic setting	Mesoscopic Structures	Shear Zones
241,7	Triassic	Mid			Puesto Viejo Formation ~241–235 Ma	Rhyolites (high SiO_2), dacites, basalts			Rift Basin		
		Early									
248,2	Permian	Late	Choiyoi magmatism	Upper Section	Cerro Carrizalito Formation ~252 Ma	Rhyolites (high SiO_2), dacites, basalts	High K K_2O/$Na_2O>1$	Intermediate to low LILE/HFS Ba/La La/Yb	Transitional to Intraplate	Normal faulting **POST-SRO**	Tt
256,0		Early			Quebrada del Pimiento Formation	Andesites					
					Agua de los Burros Formation ~265 Ma	Rhyolites (high SiO_2)				Folding and inverse faulting **SRO** Normal faulting **POST-SRO**	Tp and Tt
				Lower Section	Cochicó Group ~281 Ma	Andesites, dacites, low SiO_2 rhyolites	Medium to high K K_2O/$Na_2O<1$	High LILE/HFS Ba/La La/Yb	Volcanic Arc		
290,0	Carboniferous	Late			El Imperial Formation	Shales, sandstones			Retroarc foreland Basin	Folding and inverse faulting **SRO** Normal faulting **POST-SRO**	Tp and Tt

See text for age data sources. SRO: San Rafael orogeny, Post-SRO: post-San Rafael orogeny, Tp: transpression, Tt: transtension.

Table 3
Analytical results of some representative samples of the Choiyoi magmatism in the San Rafael Massif.

	LCA1	LCA2	LCI1	LCI2	LCI4	LCI5	LCI6	LCI7	LCI8	AB1	AB2	QP1	QP2	CCI1	CCI2	CCG1	CCR1	CCR2
SiO_2	63.24	59.11	63.70	66.37	67.80	68.43	68.59	69.71	67.09	71.07	75.94	60.08	56.70	71.85	76.04	70.62	74.27	76.07
Al_2O_3	16.73	17.28	15.40	14.98	15.74	15.33	15.01	14.47	15.94	15.26	12.87	16.99	15.45	13.81	12.30	12.94	14.36	12.91
Fe_2O_3	1.76	6.08	2.67	2.91	3.20	2.29	2.65	2.55	2.44	3.28	1.23	1.18	7.07	2.85	0.95	3.01	0.94	0.70
FeO	2.20	1.04	0.87	0.15	0.18	0.31	0.20	0.22	0.49	0.00	0.06	4.42	0.00	0.69	1.64	1.24	0.28	0.37
MgO	1.30	1.72	1.24	0.90	0.73	0.67	1.00	0.26	0.78	0.35	0.02	2.86	3.84	0.10	0.11	0.44	0.11	0.15
CaO	3.20	4.52	3.64	2.50	2.60	2.08	1.33	2.54	2.43	0.52	0.31	5.96	3.75	1.13	0.72	1.58	1.00	0.54
Na_2O	3.35	4.09	3.22	4.05	3.39	4.89	4.38	3.83	4.03	0.56	4.33	3.49	3.88	3.13	2.88	2.89	3.69	2.41
K_2O	3.36	2.91	2.46	3.55	3.79	2.91	3.28	2.98	3.46	4.54	4.48	1.83	2.61	5.48	4.67	4.81	3.54	4.49
TiO_2	0.73	0.83	0.50	0.43	0.50	0.34	0.30	0.45	0.49	0.41	0.12	0.94	0.92	0.38	0.12	0.45	0.10	0.04
MnO	0.07	0.13	0.06	0.04	0.06	0.02	0.05	0.06	0.05	0.03	0.02	0.13	0.10	0.04	0.03	0.09	0.02	0.03
P_2O_5	0.22	0.37	0.13	0.18	0.20	0.09	0.15	0.10	0.14	0.11	0.01	0.22	0.36	0.07	0.02	0.09	0.05	0.01
L.O.I.	3.85	1.92	2.21	2.60	2.00	2.85	2.35	2.88	2.28	3.87	0.61	1.90	5.32	0.46	0.52	1.84	1.63	2.29
U	0.9	1.1	1.45	0.35	1.57	1.82	1.04	2.07	1.34	1.8	2.84	1.5	3.71	3.61	3.3	4.3	2.42	2.09
Th	7	5	8.07	6.51	10	6.64	6.65	6.7	7.15	18.4	16.6	6	11.2	20.1	17	14.6	10.1	10.9
Rb	120	66	101	93	133	81	97	82	105	197	141	115	86	220	148	161	159	200
Sr	460	904	495	688	708	723	776	691	665	140	18	361	1020	128	37	47	208	20
Ba	875	1271	626	1070	1439	1256	1302	852	1055	900	181	965	1496	1080	117	395	696	74.9
Nb	13	11	13	2	6	11	7	5		13.1	20	13	9.78	15	15	32	15	23
Zr	183	182	90	75	80	75	65	84	92	306	141	240	209	327	122	711	89	115
Y	33	25	15.3	13.2	15	13.1	13.3	12.4	14.6	37.5	36	33	26.3	38.9	29	74	8.1	48
Ni	7	5	28		10			14		14	10	9	43	10	6	16	14	17
Co	55	23	15.9							22.1	57.5	63	31.6	81.4	52	37.2	39.8	32.8
Cr	11	12	22	36	26	32	26	33	30			13	43		11	12		
V	92	121	78	69	74	58	62	58	61	23		162	412	9	3	13	7	
Cu	10	11	20							13	27	10	73	11	3	12	11	9
Zn	74	80	75							50	33	81	91	56	30	132	15	77
Pb	18	11	22							32	12	14	6	28	16	25	23	33
Ga	19	22	24							22	18	20	24	21	15	27	20	24
Ge			1.3							1.7	1.3		1.5	1.5		1.9	1.3	1.6
As										49				22		9		41
Mo			0.6							1.81	0.66		0.55	1.94		2.98	0.71	0.44
Sn			3.1							2.7	1.2		1.6	3.8		4.2	3.4	2.8
Sb			0.43							1.3	1.16		0.8	1.74		0.48	0.49	0.49
Cs			34.5							9.42	2.07		10.6	10.9		2.87	3.74	6.86
La	34.9	31	29.3	25.9	27.2	27.8	26.6	26.2	28.6	54.6	32.4	27.6	58.8	51.8	25.8	84.8	29.9	11.7
Ce	70.1	70.2	56.9	51.9	57.7	54.3	53.5	52	57.5	112	73.4	63.7	116	106	60	183	57.5	30.4
Pr			7.81							12.8	8.56		13.7	12.2		21.9	6.32	3.86
Nd	33.6	34.3	27.6	27	27.4	26.8	25.7	25.8	29.3	46	31.2	28	51.2	43.3	30.2	82.8	21.4	15.6
Sm	6.88	6.42	5.32	5.02	5.28	5.06	4.85	4.72	5.37	8.68	6.93	5.69	9.64	8.43	7.2	15.7	3.91	5.63
Eu	1.4	1.77	1.48	1.29	1.28	1.18	1.37	1.21	1.4	1.45	0.35	1.47	2.2	1.3	0.5	1.67	0.73	0.24
Gd	6.44	5.44	4.24	3.7	4.09	3.69	3.41	3.28	3.92	7.62	6.68	5.55	6.98	7.42	6.16	14	2.68	7.39
Tb			0.59							1.26	1.1		0.99	1.27		2.26	0.37	1.36
Dy	5.27	4.09	2.54	2.21	2.6	2.28	2.15	2.07	2.42	6.2	5.54	4.81	4.5	6.41	5.14	11.2	1.4	7.14
Ho			0.47							1.34	1.2		0.91	1.38		2.36	0.24	1.55
Er	2.54	2.13	1.17	1.02	1.18	1	1.01	1.03	1.13	3.93	3.77	2.36	2.65	4.31	2.54	7.36	0.66	4.81
Tm			0.19							0.62	0.61		0.39	0.66		1.15	0.1	0.77
Yb	2.7	1.99	1.16	1	1.12	1.01	1.02	1.06	1.16	3.64	3.61	2.58	2.48	4.13	2.9	7.2	0.66	4.56
Lu	0.4	0.3	0.16	0.18	0.18	0.2	0.15	0.15	0.17	0.53	0.55	0.38	0.35	0.62	0.42	1.07	0.1	0.66
Hf			4.02							8.66	3.78		5.41	8.53		16.8	2.69	3.78
Ta			1.17							1.28	1.75		0.64	2.23		2.27	1.67	1.74
W			97.1							153	390		68.1	662		387	475	351
Tl			0.61							0.79	0.53		0.08	0.86		0.85	0.81	1.04

LC, lower Choiyoi, AB: Agua de los Burros, QP: Quebrada del Pimiento, CC: Cerro Carrizalito. Major elements (wt.%) and trace elements (ppm): XRF and ICP-MS, Actlabs, Canada.

Lower Choiyoi rocks are andesites, dacites and rhyolites with SiO_2 contents ranging from 60 wt.% to 72 wt.%. They are medium to high K, and follow a calc-alkaline trend. The silicic rocks are metaluminous to peraluminous. In contrast, upper Choiyoi volcanics are predominantly high silica rhyolites (SiO_2: 72–79 wt.%), with interbedded andesites (Quebrada del Pimiento SiO_2: 58–61 wt.%), dacites (SiO_2: 64–66 wt.%) and alkaline basaltic andesites (SiO_2 54–59 wt.%), so some compositional gaps are observed within this sequence. Upper Choiyoi rocks are high K and follow a Fe-enrichment trend. Upper Choiyoi rhyolites are predominantly peraluminous.

Lower Choiyoi dacites and rhyolites show lower K_2O/Na_2O, TiO_2/MgO, FeO*/MgO, NK/A ratios than upper Choiyoi rhyolites (Fig. 3a).

As a whole, the lower Choiyoi silicic rocks are depleted in K, Rb, Th, U, Nb, Y, and enriched in Sr, Ba, P, Ti, relative to the upper Choiyoi analogues. They are also depleted in Rare Earth Elements (REE), and show higher La/Yb ratios in relation to the upper Choiyoi equivalents with the exception of some garnet-bearing upper Choiyoi rhyolites which have extremely high La/Yb ratios. Both Ba/La and La/Nb are lower in the upper Choiyoi sequences considering samples with no important fractionation of accessory minerals that could substantially modify these ratios (Fig. 3b). Spiderdiagrams normalized to chondrite (Thompson et al., 1984) of the lower Choiyoi samples show a strong decoupling of the Light Ion Lithophile Elements (LILE) and High Field Strength Elements (HFSE) abundances together with a Nb or Nb–Ta trough. This decoupling decreases gradually in the upper Choiyoi volcanics (Fig. 4).

Both basaltic andesites and andesites from the two suites are highly fractioned (MgO ≤4 wt.%), and with the exception of some samples of the Quebrada del Pimiento Formation (Ni = 43 ppm, Cr = 43 ppm), they also have very low Ni (5–15 ppm) and Cr (5–11 ppm) contents denoting substantial modification from mantle derived liquids. Both the lower Choiyoi and the Quebrada del Pimiento andesites have very similar chemical compositions.

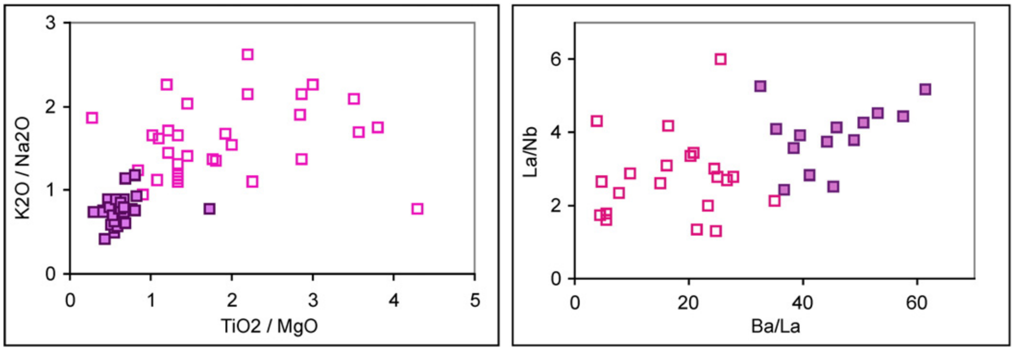


Fig. 3. The lower (black squares) and upper Choiyoi (empty squares) suites of San Rafael are discriminated in plots of a) TiO_2/MgO vs. K_2O/Na_2O and b) Ba/La vs. La/Nb.

Silicic rocks from the two suites can be discriminated on the basis of their Nb, Y and Zr contents using the diagrams of Pearce et al. (1984) (Fig. 5a) and of Macdonald et al. (1992) (Fig. 5b). In most of these diagrams the lower Choiyoi rocks plot in the field of active continental margins, whereas the upper Choiyoi samples are displaced towards the field of intraplate settings. Some of the upper Choiyoi rhyolites have an alkaline affinity with high Zr (>400 ppm) contents.

4. Late Palaeozoic deformation in the San Rafael Massif

Minor and mesostructures as well as kinematic indicators measured in five key areas (Fig. 6) show that the El Imperial, Cochicó and Agua de los Burros sequences were affected by two contrasting regimes of deformation at the regional scale: a) transpression related to NNE oblique convergence during the San Rafael orogeny and b) transtension associated with NNE regional extension after the San Rafael orogeny (Table 2). The Quebrada del Pimiento, Cerro Carrizalito and Puesto Viejo Formations record only the latter deformation event, i.e. Post-San Rafael orogeny transtension.

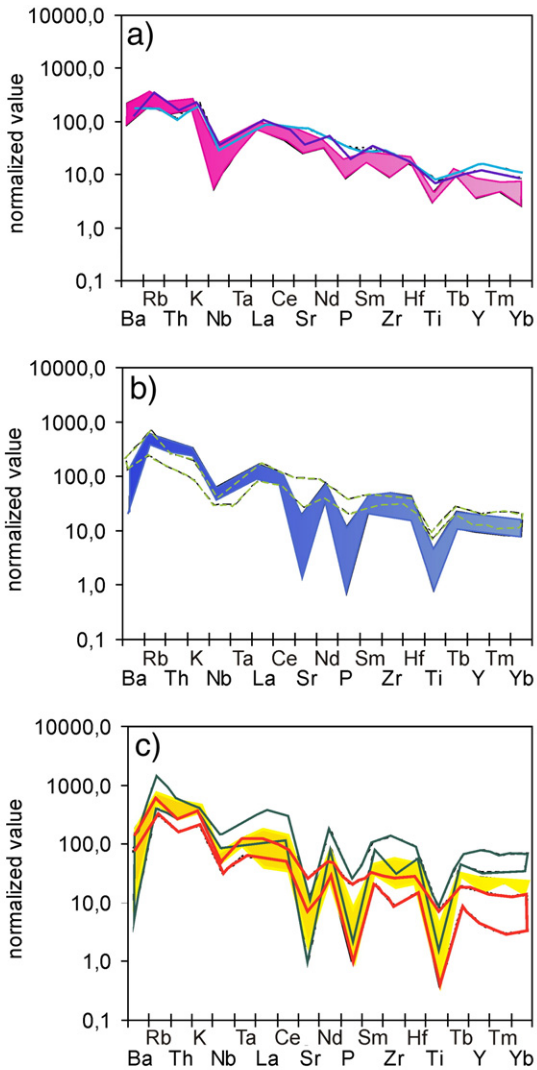


Fig. 4. Spiderdiagrams normalized to chondrite (Thompson et al., 1984) showing the range of a) lower Choiyoi dacites and rhyolites (grey) and andesites (dashed lines), b) Agua de los Burros rhyolites (gray) and Quebrada del Pimiento andesites (dashed lines), c) three suites within the upper Choiyoi rhyolites.

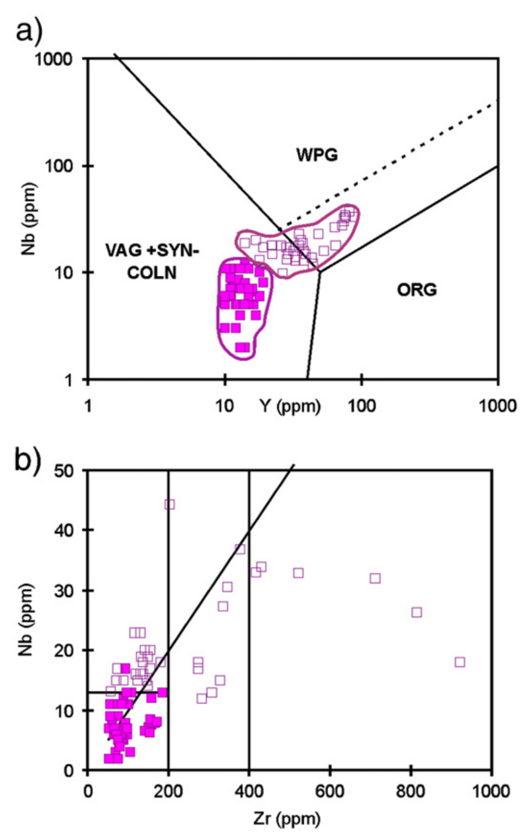


Fig. 5. The lower and upper Choiyoi suites of San Rafael in a) Pearce et al. (1984) tectonic discriminant diagram and b) in Macdonald et al. (1992) discriminant diagram. Only samples with SiO_2 > 60 wt.% were plotted. Symbols are the same as in Fig. 3.

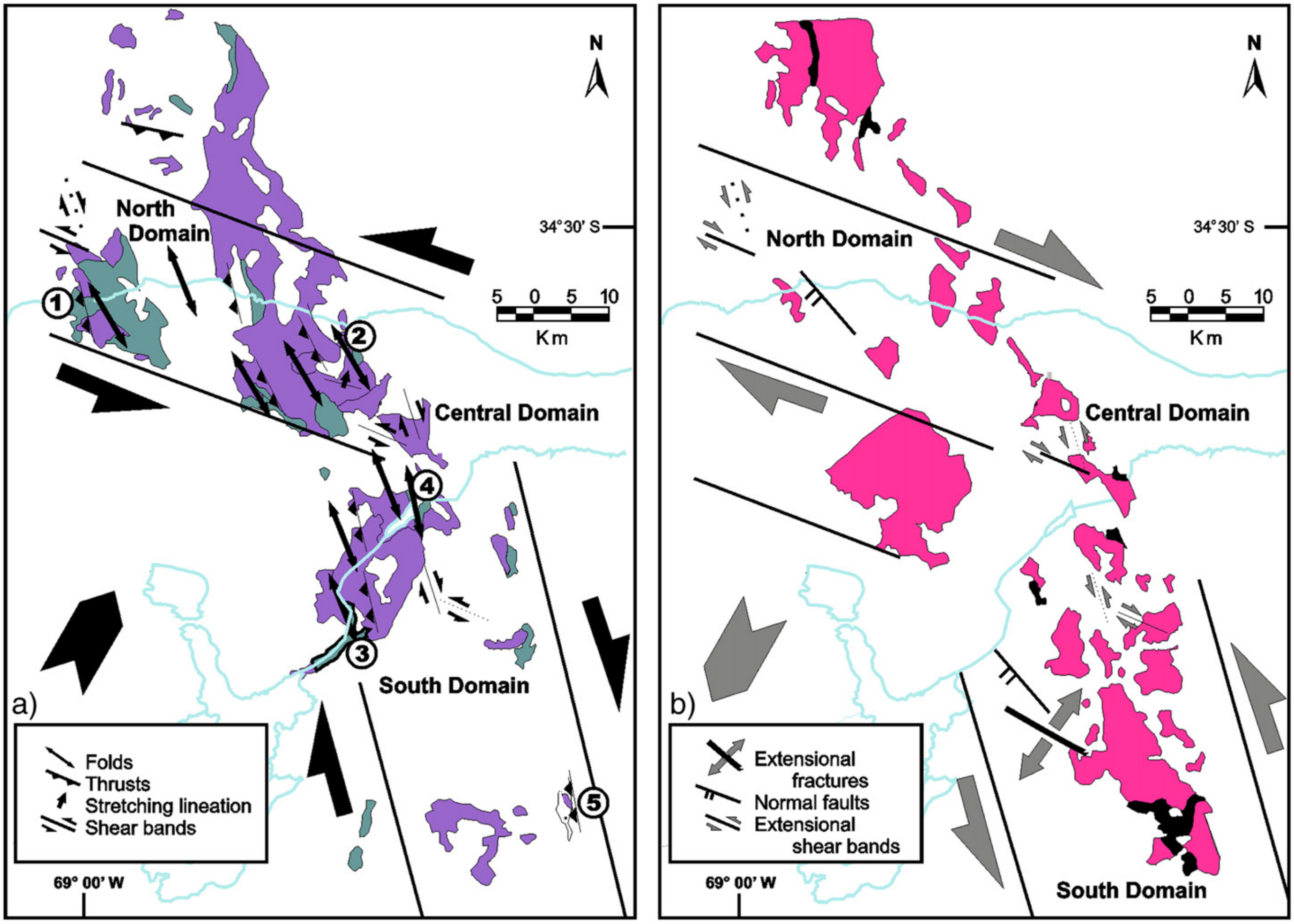


Fig. 6. Schematic distribution of main structures in the three domains with the location of the five measured areas. a) structures related to the San Rafael orogeny, b) structures related to the post-San Rafael extension. 1: Agua del Toro, 2: Yacimiento Dr. Baulíes, 3: El Nihuil, 4. Valle Grande, 5: Ponón Trehué.

4.1. Structures related to the San Rafael orogeny

NNW to NW striking faults and folds are the most conspicuous structures related to the San Rafael orogeny. They involve some of the basement rocks (Moreno Peral and Salvarredi, 1984) as the result of regional thick-skinned deformation. At the regional scale, folds and faults display an *en-échèlon* geometry which follows WNW and N–NNW major structural trends (Fig. 6a). Extensional, NNE to NE trending fractures define the direction of maximum stretching as horizontal and almost perpendicular to fold axis, indicating regional N to NNW dextral motions. At the scale of the San Rafael Massif, these extensional structures controlled the emplacement and deposition of the lower Choiyoi and the Agua de los Burros units, implying the syntectonic onset of volcanism during the San Rafael orogeny (Fig. 6a). The main evidence of this syntectonic emplacement is folding of the Cochicó Group (Moreno Peral and Salvarredi, 1984), which can be interpreted as growth folding related to growth faults (Cortés and Kleiman, 1999). Ignimbrites of the Agua de los Burros Formation, although rest unconformably over the Cochicó Group, are weakly folded (Fig. 7a) indicating the persistence of the San Rafael orogeny.

Localized strain bands are widespread over the region. Two sets of shear bands (NNW right-lateral and WNW left-lateral) show components of lateral movement along strike, with subsidiary thrusting towards the NNE. South of the El Tigre anticline (Fig. 2, locality 2 Fig. 6a), kinematic indicators measured in sandstones and ignimbrites of the Cochicó Group present top-to-the-NE thrusts.

Cleavage is not well developed and, where present, it is widely spaced and rough. Both fracture and cleavage inside strain bands suggest a brittle–ductile behaviour of the rocks (c.f. Ramsay and Huber, 1987) during the San Rafael orogeny deformation.

Systematic changes of the San Rafael orogeny structures (folds, faults and shear zones) define three different kinematic domains which delineate a regional antitaxial bend (c.f. Marshak, 1988) (Fig. 6a): North (WNW trend, sinistral transpression), South (NS, dextral transpression) and Central (NW, thrust overprinting dextral and sinistral transpression) (Japas and Tomezzoli, 2001; Japas and Kleiman, 2004). This relatively high partitioning of transpressional motions could have been conditioned by the anisotropy of previous Precambrian E–W and Early Palaeozoic NS and NE structures (Japas and Kleiman, 2004).

In the North Domain, shales and sandstones of the El Imperial Formation are folded into NW striking *en-échèlon* cylindrical folds (Amos, 1980) (locality 1 Fig. 6a), indicating WNW sinistral tranpression. High angle NW-trending reverse faults cross-cut both the El Imperial and the Cochicó rocks. WNW left-lateral shear bands and faults are predominant in this domain (Figs. 6a and 8b).

In the South Domain, deformation is heterogeneously distributed. Folds striking at Az. 170° are aligned within a ~4 km wide belt striking 175°, which defines an area of more intense deformation (locality 4 Figs. 6a and 8a). Following this belt, sedimentary rocks of the El Imperial Formation are more strained and tightly folded than in the other areas, producing a strong angular unconformity with the overlying volcanic sequences (locality 4 Figs. 6a and 7a). Since deformation is heterogeneous,

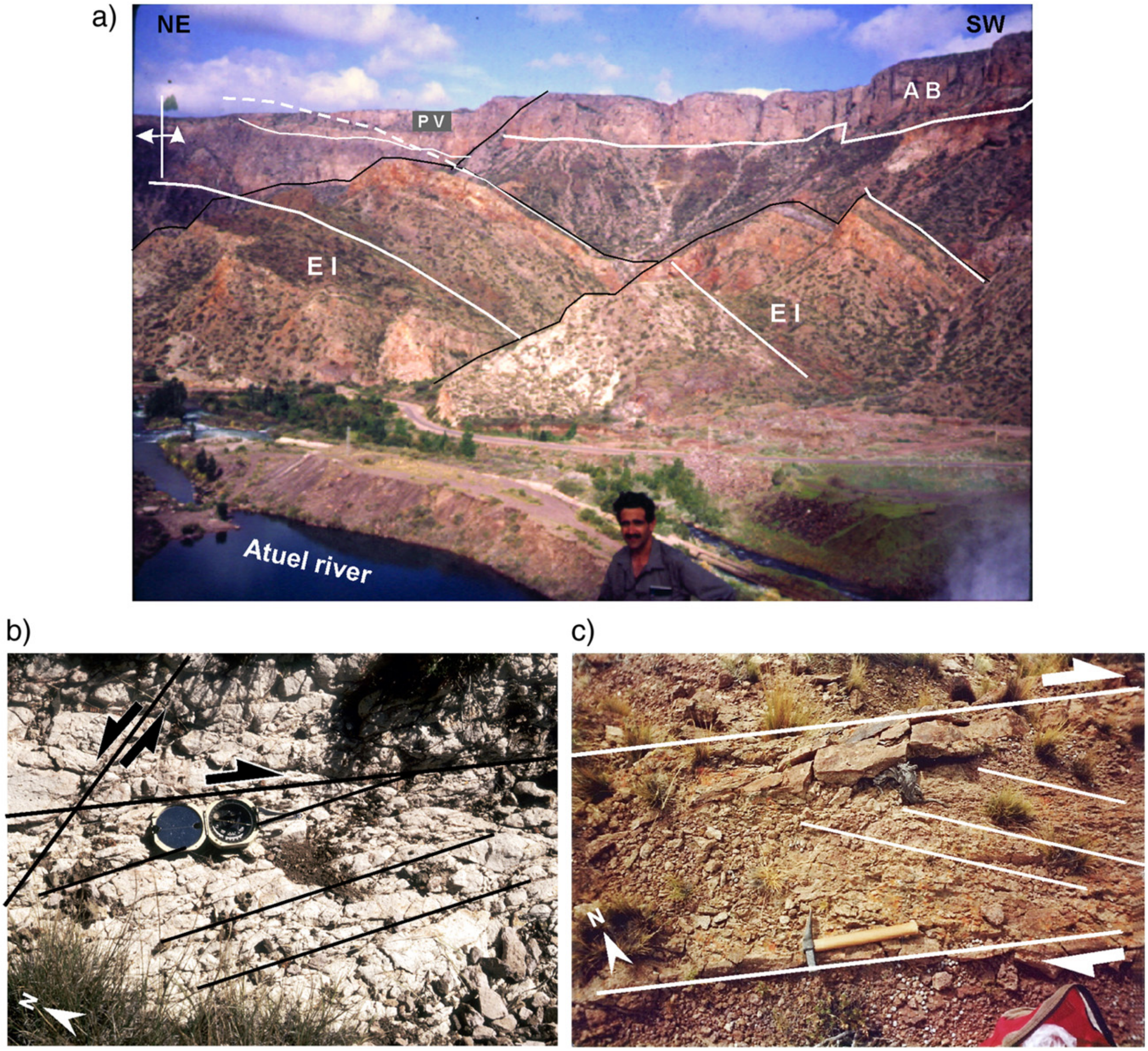


Fig. 7. a) Angular unconformity between tightly folded the El Imperial sediments and the Agua de los Burros ignimbrites. Some scattered basal conglomerates of the Agua de los Burros Formation fill the relief cut in the El Imperial folded rocks. b) Dextral NNW transpressional shear band affecting rocks of the Agua de los Burros Formation near the Central II (Río Atuel). This band is overprinted by Andean (Cenozoic) deformation. c) Cerro Carrizalito volcanics showing major Post-San Rafael dextral, transtensional, WNW bands bounding minor NW tensional structures. This setting indicates a negative reversion.

this unconformity is not easily observed elsewhere. Both the El Imperial and the Cochicó sequences are affected by *en-échèlon* folds, which follow a NNW trend, defining local NNW dextral transpression. Southwards, high angle reverse faults follow NNW and NS directions and cross-cut the El Imperial sandstones (locality 5 Fig. 6a). Although sinistral WNW shear bands are still predominant in the South Domain, NNW right-lateral faults and dextral, transpressional shear bands are more frequent in this area (Fig. 8b). Strikes of WNW transpressional structures are constant whereas those of NNW structures are variable depending on their position relative to the more strained Az. 175° zone of locality 4 (Fig. 8b), implying that they developed at a later stage. The Agua de los Burros Formation display some of these dextral, NNW shear bands (Fig. 7b), providing further evidence that the San Rafael orogeny also disturbed the base of the Upper Choiyoi.

In the Central Domain, a NW-trending growth fold structure (El Tigre anticline, Fig. 2) affected the El Imperial, Cochicó and Agua de los Burros sequences. This structure is cross-cut by a set of NE normal fractures (Moreno Peral and Salvarredi, 1984; Lardone and Giordano, 1984) which represent the San Rafael orogeny extension. Southwards, gently dipping, WNW (Azimuth 120°) shear planes with a top to the NNE thrusting component, cross-cut both the Cochicó and the Agua de los Burros rocks, overprinting NNW fold structures.

Different states of finite strain occur within each domain, strongly suggesting that, at this scale, the intensity of deformation was heterogeneous and strain was moderately partitioned; this is observed mainly in the South Domain (Fig. 6a). An integration of strain fabric data from the three domains (Fig. 6a) indicates a NNE direction of shortening and a WNW direction of extension.

As San Rafael orogeny deformation is brittle–ductile and these structures have undergone subsequent reactivations (Japas and Kleiman, 2004), kinematic indicators are not easily depicted. The kinematics was calculated using shear criteria based on minor structures, both in the horizontal and in the vertical planes and assuming plane strain (Fig. 9a). The results of these analyses confirm the NNE direction of shortening obtained from the strain fabric analyses, and show a low degree of strain partitioning. The kinematic solution indicates that the same motions controlled by WNW sinistral transpression are predominant in the three domains regardless of the different strain fabric which characterizes each one of them. This can be interpreted as the result of the superposition of

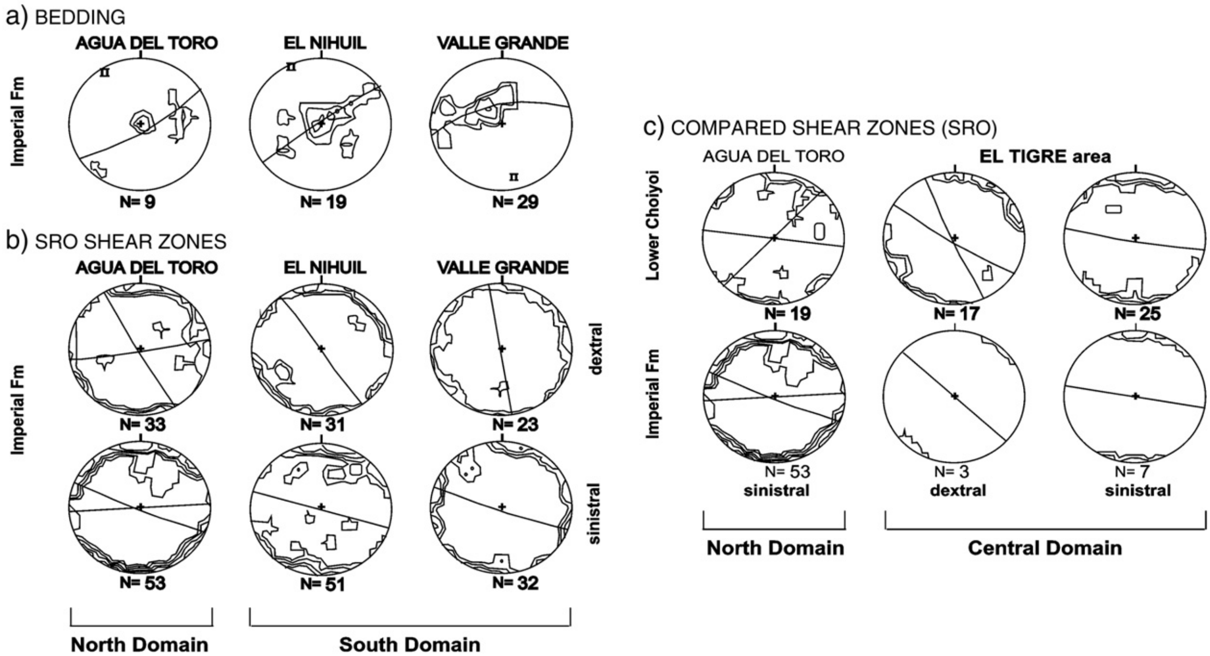


Fig. 8. Lower-hemisphere plots on equal-area stereonets. a) Poles of bedding planes in the El Imperial Formation. b) Poles of shear bands affecting the El Imperial sediments, c) comparison between shear bands measured in the El Imperial Fm. and Cochicó Group rocks (SRO: San Rafael orogeny). GEORIENT software (Holcombe, 2005).

two stages of deformation within the San Rafael orogeny: a first main stage of N–NNW dextral transpression with moderate strain partitioning was followed by a second stage of WNW sinistral transpression with low strain-partitioning. Although the second stage of deformation is more homogeneously distributed all over the study area, it is more evident in the North Domain.

4.2. Post-San Rafael structures

In contrast to the brittle–ductile behaviour of the San Rafael orogeny structures, Post-San Rafael strain is brittle. Strain fabric and kinematic indicators show that Post-San Rafael extension inherited the direction of previous NNE San Rafael orogeny convergence (Figs. 9 and 10), strongly suggesting that these structures are the result of the transtensional reactivation of previous major San Rafael orogeny trends. Tensional and trantensional fractures controlled the emplacement of most of the upper Choiyoi volcanism and persisted during most of the Triassic (Fig. 6b).

The Quebrada del Pimiento dykes filled NNW and WSW tensional fractures, which are the first clear evidence of the change in stress regime. Ignimbrite deposits and subvolcanic bodies of the Cerro Carrizalito Formation followed the trend of NNW and E–W transtensional faults with displacements of about 1 km (Kleiman, 1999). A WNW zone of major Post-San Rafael extension could be defined along the El Potrerito–Puesto Viejo basin lineament (Japas et al., 2005; Fig. 6b).

During Post-San Rafael times the same three domains remained active as deformation followed San Rafael structures. Both, in the North and in the South domains strain fabric and kinematic indicators point to a transtensional setting. NNW–NW striking Post-San Rafael transtensional faults and shear bands, affecting rocks of the Quebrada del Pimiento and Cerro Carrizalito Formations, are left-lateral, whereas WNW conjugate structures are right-lateral. Although they are widespread in the whole study area, NW trending (Az. 130°) tensional structures are predominant in the Central Domain. They show vertical slip motions indicating NNE extension (Fig. 7c).

In the North Domain, WNW dextral transtension is predominant (Fig. 6b) as igneous bodies of the Cerro Carrizalito Formation follow an *en-échèlon* WNW trend. The relationship between San Rafael orogeny and Post-San Rafael structures shows that WNW sinistral transpression was replaced by dextral transtension. For instance, at Infiernillo (Fig. 2) NNE mineralized veins related to the San Rafael orogeny are cross-cut by barren NW Post-San Rafael ones (Japas and Rubinstein, 2004).

In the South Domain, strain fabric analysis indicates that NNW sinistral transtension followed San Rafael orogeny NNW dextral transpression (Figs. 6b and 10). Post-San Rafael tensional fractures are nearly parallel to San Rafael orogeny fold axes (Figs. 6b and 10).

The Central Domain is characterized by NW tensional fractures and a conjugate NNW and WNW-trending transtensional system, which controlled the emplacement of upper Choiyoi volcanism (Fig. 6b). In this domain, NNE contractional structures of the San Rafael orogeny were reactivated as NNE tensional ones.

Kinematic analyses of Post-San Rafael structures indicate a particular case of negative tectonic inversion, (tectonic reversion in this paper), as the direction of maximum extension is coincident with that of maximum compression of the San Rafael orogeny (Fig. 9b).

5. Discussion

The geochemical and structural information obtained in this study suggests that inception of Choiyoi sequences in the San Rafael Massif occurred under changing geodynamic settings. Lower Choiyoi magmatism is calc-alkaline with typical continental subduction-signatures and emplaced syntectonically with transpressional deformation, constraining the tectonic environment to an active continental margin under an oblique subduction regime for this time. Upper Choiyoi magmatism is transitional between a calc-alkaline and an alkaline bimodal suite typical of an intraplate anorogenic setting, and emplaced during transtensional deformation that could be associated with either waning or post-convergence conditions.

In the following sections we compare the information of the San Rafael Massif with the regional framework in an attempt to understand how the change of geodynamic scenarios occurred during the Permian in this portion of the Gondwana margin.

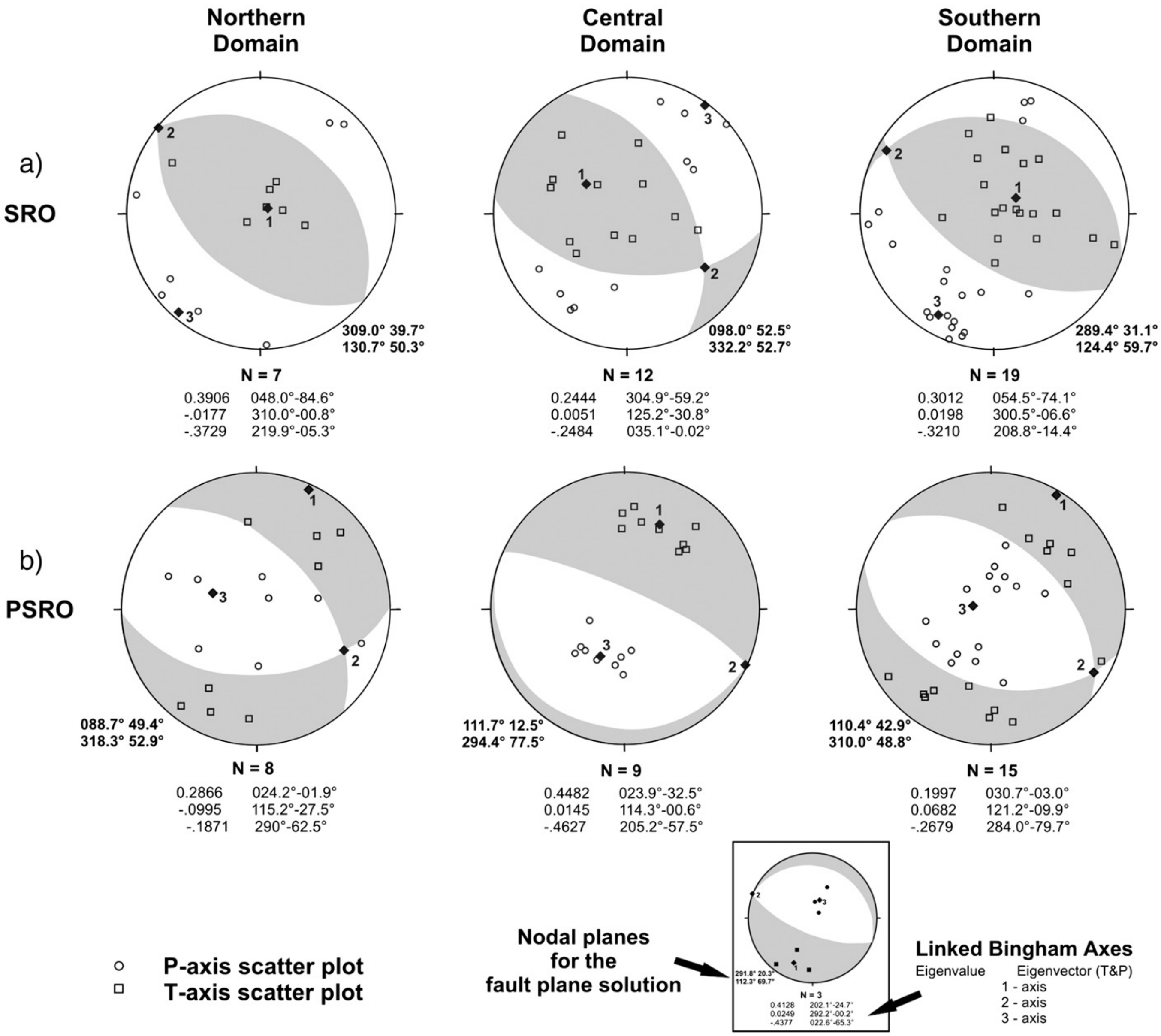


Fig. 9. Kinematic analyses of a) San Rafael orogeny (SRO) and b) Post-San Rafael structures (PSRO) after Allmendinger's (2001) FaultKinWin program showing nearly coincident orientations of contractional (San Rafael orogeny) and extensional (post-San Rafael) kinematic axes.

5.1. The San Rafael orogeny and Post-San Rafael extension

As it was described in Section 4, the styles of deformation in the San Rafael Massif changed significantly during the Permian. The San Rafael orogeny involved regional dextral transpression as a consequence of NNE oblique convergence of the Palaeo-Pacific plate under the South American plate, as previously suggested for this portion of the Gondwana margin (Fuentes et al., 1986; Rapalini and Vilas, 1991; Mpodozis and Kay, 1992; Trouw and de Wit, 1999; Japas and Kleiman, 2004). The partition of deformation into discrete domains is consistent with oblique plate convergence and suggests the presence of an anisotropic upper plate (Jones and Tanner, 1995; Cembrano et al., 2002; Claypool et al., 2002). In contrast, the Post-San Rafael extensional event consisted mainly of regional sinistral trantension.

Evidence of early movements of the San Rafael orogeny, such as a reversion of the basin paleo-slope from NE to SW, was found in the San Rafael Massif, at the final stages of deposition of the El Imperial sequence (Espejo, 1990). However, the main shortening event dominated by N–NNW dextral transpression (first stage of the San Rafael orogeny), took place after the whole sequence was deposited and before the onset of the lower Choiyoi volcanism. The inception of this volcanism could be related to either the migration or the expansion of the Carboniferous–Lower Permian magmatic arc to the east, reaching the area of San Rafael by the Early Permian (Kleiman, 1999; Cortés and Kleiman, 1999; Kleiman and Japas, 2002). The transpressional regime continued for most of the Permian, during the emplacement of the lower Choiyoi and of the upper Choiyoi basal units (Agua de los Burros Formation) but governed by WNW sinistral transpression (second stage of the San Rafael orogeny).

Based on data of the San Rafael Massif a rough estimation of the direction of convergence of the Palaeo-Pacific plate during the Late Paleozoic could be inferred using the θ *vs* strike-slip partitioning diagram of Tikoff and Teyssier (1994).

Although the parameters of this diagram are not easily constrained in ancient sequences, a θ of ~25° (angle between the maximum horizontal instantaneous strain axis and the plate margin) was calculated considering the axis-orientation of the less deformed folds (Az 155°, locality 3 Fig. 6a) and a NS-trending margin during the first

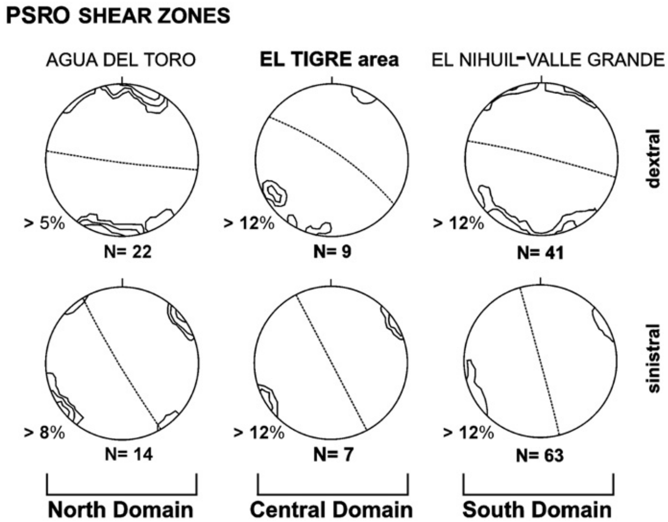


Fig. 10. Lower-hemisphere plots on equal-area stereonets. Poles of shear bands affecting upper Choiyoi rocks. Holcombe's GEORIENT software.

stage of the San Rafael orogeny (Fig. 11). Our data plotted into this diagram resulted in a direction of convergence of Az ~30°, being α~30° (angle between the plate margin and the plate-motion vector). As strain partitioning decreases during the second stage of the San Rafael orogeny (Section 4.1), changes in both α and θ values are to be expected. A maximum horizontal instantaneous strain axis oriented at 120° was calculated for the second stage of the San Rafael orogeny, based on tensional fractures and fold axes. This orientation would yield a θ of 60°, which is not viable as this value should be less than 45° (Fig. 11a) and α should be at least 30° in order to sustain the subduction regime. Thus, the decrease of strain partitioning could be caused by a lower degree of obliquity of plate convergence (90° − α) (see Cembrano et al., 2002), implying a change in the margin trend and/or in the direction of convergence (Fig. 11). Given the lack of structural evidence for a change in the direction of convergence to the north or to the south of San Rafael, a curvature of the upper plate margin is a more likely hypothesis. Major regional WNW sinistral transpressional structures of the second stage of the San Rafael orogeny, could account for a margin shift from N–S to NNW–NW south of 34°S. South of 36°S the margin might have deviated farther to the NW–WNW due to major development of these sinistral transpressional structures, in coincidence with a margin deviation as it was previously suggested (Martin et al., 1999).

The date of the San Rafael orogeny is still a subject of debate. Regional age discrepancies of this deformation could either be attributed to a relatively poor age data base, to different methodologies used for radiometric dating or to diachronism of this event. The U/Pb zircon (SHRIMP) data of the Choiyoi volcanism in San Rafael (Rocha-Campos et al., 2006) indicates that the first stage of the San Rafael orogeny finished before than ~281 Ma, whereas the second stage was restricted to a time span of about 15 Ma, between the initial eruptions of the Cochicó Group and the final emplacement of the Agua de los Burros ignimbrites (i.e. slightly before ~281 Ma and lasting until ~265 Ma).

The San Rafael orogeny had a wide regional distribution both in Chile and in Argentina. Major crustal thickening recorded during the emplacement of some of the granitoids of the Elqui complex in Chile (31°S) was related to this deformation (Mpodozis and Kay, 1992; Martin et al., 1999). Farther to the east in the Paganzo Basin evidence of this deformation event was also verified (Geuna and Escosteguy, 2004) (Fig. 1). Paleomagnetic data for the Frontal Cordillera (32°S) showed that lower Choiyoi and older sequences were affected by clockwise block rotations (Rapalini and Vilas, 1991), movements that could be ascribed to this orogeny.

To the SE of San Rafael, paleomagnetic and structural data for the Chadileuvú Massif (La Pampa), Sierra de la Ventana (Buenos Aires) and Sierra Grande (North Patagonian Massif) also suggest that this deformation extended into the inland regions (Japas, 1988, 1989, 1998, 2001; Rossello et al., 1997; Rapalini, 1998; Tomezzoli and Vilas, 1999) (Fig. 1).

Although radiometric age data sets are still insufficient to confirm the timing of inland migration of magmatism and deformation, diachronism is suggested based on paleomagnetic data from La Pampa and Sierra de la Ventana (Tomezzoli, 2005). If so, a progressively younger WNW, sinistral, thick-skinned deformation belt, broadening into the foreland, can be traced from San Rafael, to La Pampa and to Sierra de la Ventana and could be linked with the Cape Fold Belt of South Africa (Fig. 1).

The cessation of the San Rafael orogeny might be related to a major change in kinematics of structures when transpression was replaced by transtension, producing a negative tectonic reversion. A similar case was described in the Cape Fold of South Africa in which Mesozoic extensional structures are parallel reactivations of Late Paleozoic compressional ones (Paton, 2006). The postorogenic (diachronic?) generalized extension and the abundant silicic magmatism of the upper Choiyoi, with a wide distribution in Chile and Argentina (Fig. 1) also followed this WNW belt in which it waned as it migrated inland.

5.2. Choiyoi magmatism

The change in kinematics affecting the Choiyoi province was coupled with a variation of magmatism (Kay et al., 1989; Llambías

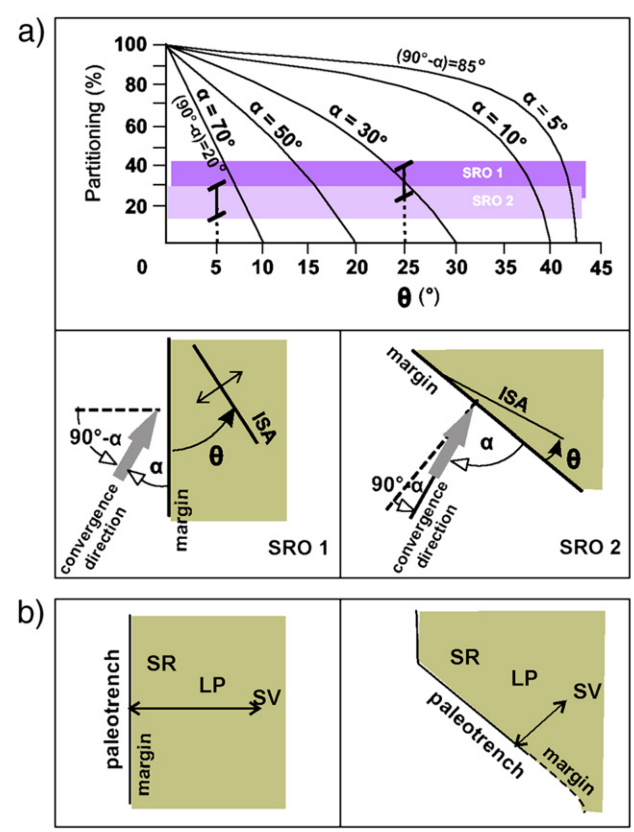


Fig. 11. Estimation of the direction of convergence of the Palaeo-Pacific plate during the Late Paleozoic using the θ *vs* strike-slip partitioning diagram of Tikoff and Teyssier (1994), for both stages of the San Rafael orogeny (SRO 1 and SRO 2). θ: angle between the maximum horizontal instantaneous strain axis — ISA — and the plate margin; α: angle between the plate margin and the plate-motion vector; (90° − α): obliquity of plate convergence (c.f. Cembrano et al., 2002).

et al., 1993; Kleiman, 1993, 1999) as well as of styles of volcanic eruptions (Japas and Kleiman, 2004).

In San Rafael, the lower Choiyoi calc-alkaline sequences with strong subduction signatures erupted syntectonically with the second stage of the San Rafael orogeny. At 31°S equivalent calc-alkaline magmatism in Chile comprises the younger granitoids of the Elqui complex, considered as pre-Choiyoi (Mpodozis and Kay, 1991, 1992).

South of 36°S, the alkaline basal sequences of La Pampa and López Lecube (Buenos Aires), although emplaced in an intraplate setting at a large distance to the east of the paleotrench (Llambías et al., 2003; Grégori et al., 2003) show subduction signatures suggesting that they could be related to the lower Choiyoi. If so, an U/Pb SHRIMP age in zircons of ~260 Ma for the López Lecube syenite (Pankhurst et al., 2006) would stand for diachronism of the lower Choiyoi.

Changing geochemical signatures of lower Choiyoi and equivalent rocks emplaced in Chile, San Rafael, La Pampa and Buenos Aires can be observed in a plot of La/Sm versus Sm/Yb ratios, which are indicative of magma source regions and equilibrated residual mineralogy (Fig. 12). Higher Sm/Yb ratios in some Elqui granitoids in Chile indicate the effect of crustal thickening due to the San Rafael orogeny (Mpodozis and Kay, 1992). Sm/Yb ratios progressively increase in San Rafael and in La Pampa where the basal shoshonitic suite (Llambías et al., 2003) reaches a maximum (Fig. 12a). These shoshonites have geochemical characteristics that resemble Andean adakite-like rocks described by Kay and Mpodozis (2002) and their occurrence could thus imply crustal thickening in association with a flat-slab geometry.

In San Rafael the upper Choiyoi section (Llambías et al., 1993) consists mainly of silicic volcanic rocks which are transitional to an intraplate setting, akin with the Choiyoi volcanism as it has been conventionally described. Although the Agua de los Burros ignimbrites were emplaced during the final stages of shortening, probably when the crust reached the maximum thickness in the area, they are undistinguishable from the upper Choiyoi felsitic rocks. This apparent inconsistency would either indicate a higher level of melting of the crust for the Agua de los Burros volcanism which is also sustained by synchronous brittle structures, or a longer residence of this magma into the crust to achieve stronger differentiated end members. The Quebrada del Pimiento andesitic dykes are calc-alkaline with strong subduction signatures, a common feature of the first magmas erupted during the onset of extension, shortly after a subduction regime waned or ended.

An ignimbrite "flare-up", some of which could be associated with calderas, and the emplacement of subvolcanic bodies (Cerro Carrizalito Formation), both more silicic than the lower Choiyoi, were concurrent with progressive transtension that preceded Triassic rifting. The presence of garnet bearing dacites and rhyolites suggests S-type magmas coexisting with highly evolved I-type and final A-type products (Kleiman, 1999, 2002) which would indicate important contribution from crustal melts. Isotopic analysis (in progress) will help to constrain the petrogenesis of these rocks.

High silicic sequences in Chile (Ingaguas complex), in the Frontal Cordillera, in La Pampa and in López Lecube show similar geochemical signatures than upper Choiyoi rocks of San Rafael. This is apparent in a La/Sm vs Sm/Yb plot in which all these ratios overlap and show an important decrease of Sm/Yb with respect to lower Choiyoi rocks, suggesting an important crustal thinning consistent with an extensional setting (Fig. 12b). As the crust stretched, magma chambers were emplaced at higher crustal levels and crustal assimilation and/or crustal melting might be a main process in the genesis of these magmas (Kleiman, 2002).

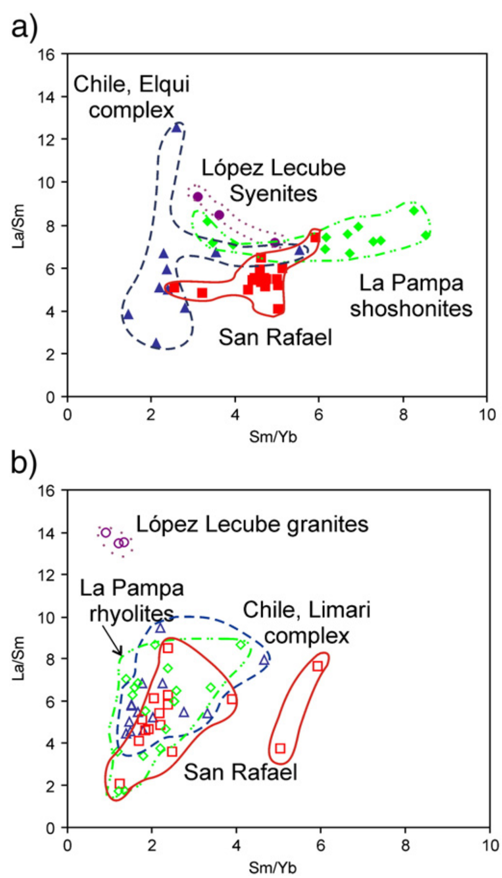


Fig. 12. Plot of La/Sm versus Sm/Yb for a) lower and b) upper Choiyoi and equivalent units. Data sources: this paper (squares), Mpodozis and Kay (1992) (triangles); Llambías et al. (2003) (diamonds), Grégori et al. (2003) (circles). The variation of Sm/Yb ratios of the lower Choiyoi suites from Chile to the SE would be consistent with crustal thickening related to progressive slab shallowing. Overlapping of the upper Choiyoi suites would indicate generalized crustal thinning.

5.3. Constraining a tectonic model for this segment of Gondwana

In order to constrain a tectonic model for the emplacement of the Choyoi province, we considered the following observations: 1) Oblique subduction of the Palaeo-Pacific plate with a NE (~30°) direction of convergence. 2) Basal Choiyoi sequences were syntectonic with dextral transpression of the San Rafael orogeny 3) upper Choiyoi sequences were emplaced during postorogenic sinistral transtension 4) The direction of maximum extension during post-San Rafael deformation is coincident with that of maximum contraction of the San Rafael orogeny. 5) Choiyoi magmatism progressively varied, showing overall declining subduction-signatures. 6) Although insufficient, ages of the Choiyoi province seem to decrease both to the south and to the east of San Rafael implying that extensional disruption in the Palaeo-Pacific margin was contemporaneous with compressional deformation in the Sierra de la Ventana–Cape Fold Belt area.

In Carboniferous times (Fig. 13a), as the marine and continental sediments of the El Imperial sequence were deposited in the San Rafael foreland basin, a magmatic arc was active to the west in the Palaeo-Pacific margin (Lock, 1980; Forsythe, 1982; Uliana et al., 1985; López Gamundi et al., 1995). The remains of this arc are currently represented at the same latitude by several plutons of the Coastal Batholith in Chile (Parada et al., 1991). North of 31°S, the Late Carboniferous belt (Guanta unit of the Elqui complex) is displaced inland and crops out in the High Andes near the Argentine border (Parada, 1990; Mpodozis and Kay, 1992). In the Frontal Cordillera (Argentina) Late Carboniferous granitoids are restricted to a N–S narrow belt extending from 28°S to 34°S (Dessanti and Caminos, 1967; Llambías, 1999).

During the Early Permian at 31°S arc magmatism remained active as it was emplaced in the Elqui and in the Colangüil (Frontal Cordillera) batholiths. At this time in San Rafael, the El Imperial sedimentary sequence was folded by the main shortening event of the San Rafael orogeny. Then, the magmatic arc, which during the Late Carboniferous was located at the Coastal Cordillera in Chile started to migrate to the east (Fig. 13b) reaching the area of San Rafael at ~280 Ma. Thus,

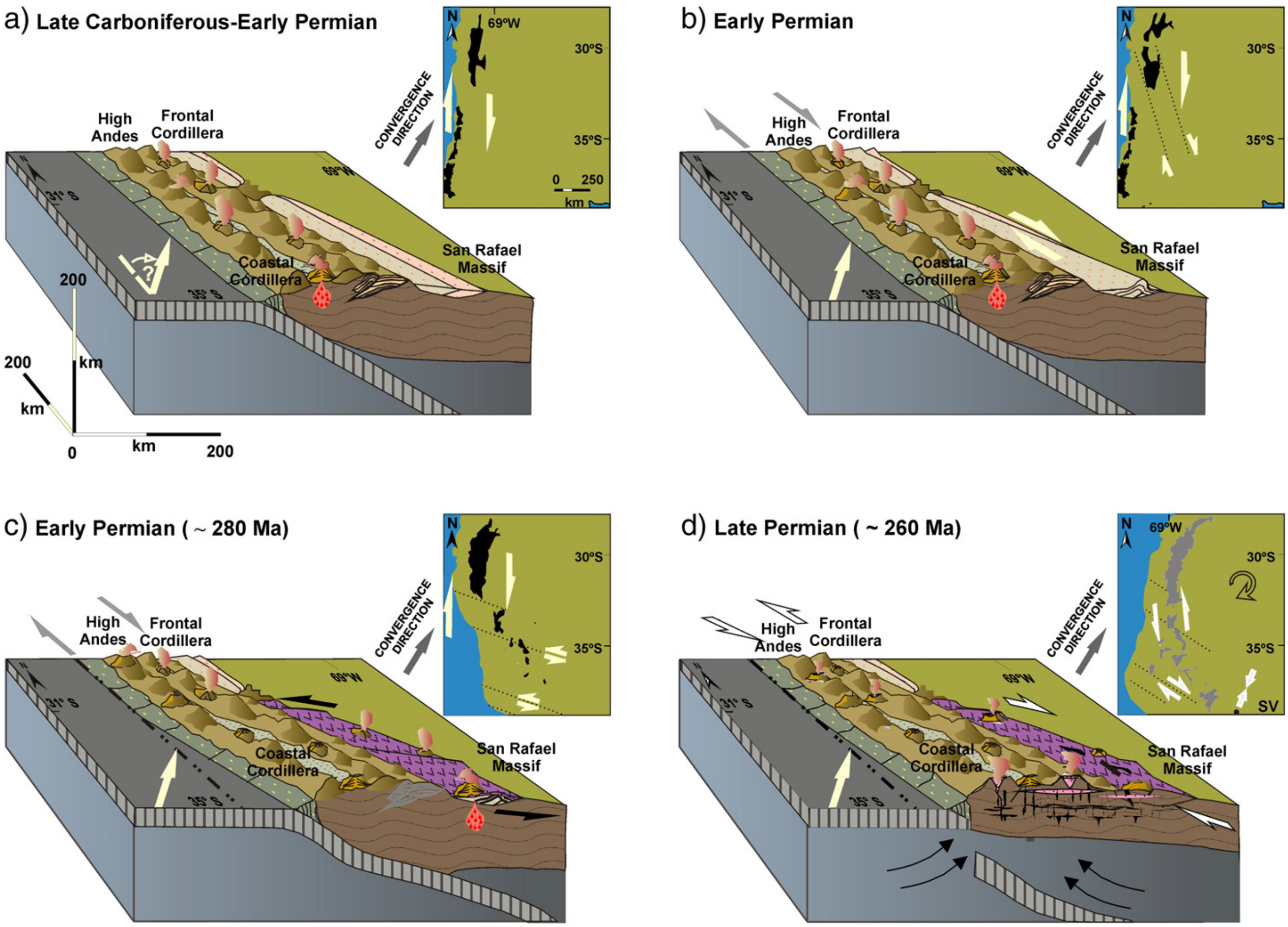


Fig. 13. Block-diagrams showing the Late Palaeozoic evolution of the SW Gondwana margin between 30° and 35°S in South America. A regional paleogeographic scheme is presented with each diagram (arc-related sequences in black, post-orogenic suites in grey). Scales are the same as in a). a) Late Carboniferous: the magmatic arc is parallel to the margin. Notice the advancing fold and thrust belt and the deposition of sediments into foreland basins. b) Early Permian: the first episode of the San Rafael orogeny deforms the foreland sequences. c) Early Permian: South of 34°S the margin is curved. Progressive shallowing of the oceanic plate resulted in inland arc migration with inception of volcanic eruptions syntectonically with the second episode of the San Rafael orogeny. d) Late Permian: Continental dextral block rotations will situate the margin near parallel to the direction of convergence, north of 36°S. This will cause the arrest of subduction, and the extensional collapse of the orogen in which San Rafael orogeny structures reverted to Post-San Rafael extensional deformation. Slab removal will allow astenospheric upwelling, concurrent profuse melting of the crust and the inception of the upper Choiyoi volcanism. South of 36°S as subduction continued, compression was still active in Sierra de la Ventana (SV).

between 34°S and 36°S, the locus of arc magmatism and related deformation shifted ~350 km inwards from the trench. This is apparent by the inception of voluminous volcaniclastic eruptions filling the basin in the San Rafael Massif, syntectonic with the second stage of deformation of the San Rafael orogeny (Fig. 13c), precluding a stationary slab situated in the western margin, in which only reduced melt volumes are expected to erupt inland. Further evidence of such arc migration is given by the absence of magmatic rocks aged between 270 Ma and 230 Ma in the Coastal Batholith of Chile (Drake et al., 1982) indicating a magmatic gap to the west of San Rafael. This inland shifting should have started south of 31°S as it is suggested by the presence of continental arc volcanism in Argentina at 32°S (Koukharsky and Etcheverría, 2006). To the southeast of San Rafael (south of 36°S), the basal sequences of La Pampa and López Lecube which are deformed by the San Rafael orogeny, are likely related to the lower Choiyoi of San Rafael. An association of this magmatism with subduction at a rather distant Palaeo-Pacific margin appears to be inconsistent; however the hypothetical margin curvature we suggested above would have considerably shorten this distance (Fig. 11b).

Although controversial (English et al., 2003), major shallowing of the slab dip seems to be crucial for both arc-related magmatism and transpressional deformation to migrate distances larger than 600 km inboard from the trench (Gutscher et al., 2000). In addition, increasing convergence rates and tectonic erosion of the crust in the forearc, may have also played an important role in arc migration (Kay and Mpodozis, 2002). Our observations would suggest a slab with a progressively decreasing dip from 31°S to 36°S. This segment, which encloses the San Rafael Massif (Fig. 13c), could be considered as a transitional zone between different subduction segments. To the North subduction was normal, to the south major shallowing occurred with the establishment of a flat-slab region. The presence of adakite- like rocks in La Pampa, implying crustal thickening related to major crustal shortening, and the absence of magmatism (volcanic gap) after 270Ma in Chile (Drake et al.,1982) would both support slab shallowing. The subduction of buoyant aseismic ridges is considered an important factor for triggering shallow subduction zones (Pilger, 1981; Gutscher et al., 2000; English et al., 2003). The southeastward progression of events and the margin curvature described above would be consistent with the subduction of an aseismic ridge striking oblique (Az 10°–25°) with respect to the direction of convergence of Az. 30°.

During the Late Permian (Fig. 13d) the onset of voluminous silicic magmatism of the upper Choiyoi concurrent with extension indicates major geodynamic changes for this region, which were traditionally attributed to cessation of active subduction (Kay et al., 1989; Llambías and Sato, 1995). Age data sets indicate that arc-related rocks of Late Permian age are unknown both in Chile and in western Argentina whereas extension-related magmatism is absent in many areas of Chile until the Triassic.

Abundant felsic magmatism implies major crustal melting. This could be associated with a thermal raise through a thinning crust, which results from lithospheric thinning due to melting in the mantle. Extension would also allow the invasion of mantle derived magmas as sills or dykes into the lower crust, causing widespread and rapid melting of crustal rocks (Huppert and Sparks, 1988). The access of mantle derived magmas and of higher heat flow into the base of the crust would need of some mechanism to either tear or remove the subducting slab. The end of subduction would cause slab detachment and postorogenic extensional collapse (Fig. 13d) as it was previously suggested (Llambías and Sato, 1995; Franzese and Spalletti, 2001).

The coexistence of extension and silicic volcanism in San Rafael with compression in the Sierra de la Ventana–Cape Fold Belt area after ~265 Ma would indicate that subduction might have ceased earlier in the north than in the south. This could be related to Late Permian clockwise rotations of Gondwana megablocks at the continental scale (Visser and Praekelt, 1998) that could shift the whole margin. As the margin was previously curved (Section 5.1), differential decrease of α (angle between the plate margin and the plate-motion vector) are to be expected. Thus, north of 34°S the originally NS margin rotated clockwise, turning nearly parallel to the convergence direction and producing the arrest of subduction. Between 34°S and 36°S, deviation of the NNW–NW trending margin would produce a similar situation. south of 36°S, the previous NW-WNW oriented margin did not attain such parallelism with the direction of convergence, and subduction continued to be active. Later on, the onset of highly silicic volcanism and related extension south of 36°S could probably be associated with episodes in the North Patagonian Massif.

Extension in San Rafael increased progressively during the final stages of the upper Choiyoi (El Potrerito) and during the inception of the Triassic Puesto Viejo rift basin in which rhyolites and OIB-type basalts erupted (Kleiman and Salvarredi, 2001). Then, the locus of extension migrated from San Rafael to the east and to the south where it continued during Triassic and Early Jurassic times (Martin et al., 1999; Franzese and Spalletti, 2001). These last extensional episodes could be related to changes in plate interactions and stress regimes in the Palaeo-Pacific margin (Franzese and Spalletti, 2001) as well as to the opening of the South Atlantic (see Vaughan and Livermore, 2005 for a review). A global reorganization of lithospheric plate boundaries and plate kinematics that followed the end of the Palaeozoic suturing of Pangea and marked the beginning of its disintegration could ultimately be the cause of the build-up of regional extensional stresses in several areas of the supercontinent (Nikishin et al., 2002).

6. Conclusions

The Choiyoi volcanic province shows concurrent variations in magmatic composition and kinematics of structures, indicating major geodynamic changes during the Late Paleozoic in this portion of the Gondwana margin. Our structural results allowed to estimate an Az 30° direction of convergence for the Paleo-Pacific margin and to define two stages of transpression of the San Rafael orogeny. South of 34°S, differences in strain partitioning and angular relationships between the margin and the maximum horizontal instantaneous strain axes in both stages would be consistent with a margin shifting during the second stage of the San Rafael orogeny.

Calc-alkaline lower Choiyoi volcanic suites of San Rafael are similar to Lower Permian granitoids found in Chile and in Argentina to the north of this area. To the SE of San Rafael, basal shoshonitic and syenitic sequences of La Pampa and Buenos Aires keep subduction signatures although emplaced in an intraplate setting at a large distance from the Palaeo-Pacific margin. These sequences seem to be related to the lower Choiyoi of San Rafael as they are also deformed by the second stage of the San Rafael orogeny. Age data sets suggest that arc-related magmatism ceased in the western margin in Chile (Coastal Cordillera) at ~270 Ma whereas was still active to the east in San Rafael until ~265 Ma and until ~260 Ma in Buenos Aires, indicating that both magmatism and related transpressional deformation migrated inland. This progressive eastward migration is documented starting at about 31°S and reaching the latitude of San Rafael by 280 Ma. This distribution suggests an increasing slab shallowing south of 31°S and the establishment of a flat-slab segment south of 36°S. A negative tectonic reversion, in which dextral transpression was replaced by sinistral transtension took place after 265 Ma in the area of San Rafael and later in the east. Concomitant onset of abundant crustal melting produced the predominantly felsic magmatism of the upper Choiyoi series with transitional to intraplate signatures. We speculate that clockwise rotations of continental blocks in relation to the proposed curved margin will produce the earlier shut of subduction in the north than in the south of San Rafael, with the subsequent gravitational collapse of the oceanic plate and related extensional collapse of the San Rafael orogen.

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