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Magmatism coeval with lower Paleozoic shelf basins in NW-Argentina (Tastil batholith): Constraints on current stratigraphic and tectonic interpretations

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ABSTRACT

The Tastil batholith (Eastern Cordillera, NW Argentina) holds relevant keys for interpreting the tectonic evolution of the Central Andes basement since it has always been interpreted as the subcrop of the Cambrian and Lower Ordovician basins in the Eastern Cordillera. However, in the Angosto de la Quesera section, the batholith intrudes sandstones underlying a fossiliferous Lower Tremadocian conglomerate containing Tastil granite pebbles. The precise assignation of the sandstones intruded by the granite to Cambrian Mesón Group or to the Uppermost Cambrian–Lower Tremadocian Santa Victoria Group is a key for refining the relationships between magmatic and sedimentary units. The ages of 526 Ma and 517 Ma (U/Pb, zircons) obtained from two facies of the batholith are coherent with the proposal of including these sandstones in the Mesón Group. However, the lithologic features and fossil content point to an affinity with the basal units of the Santa Victoria Group according to sedimentologic and stratigraphic studies ruled out by other authors. The intrusive relationships between the Tastil batholith and the Lower Paleozoic sandstones indicates the batholith is coeval with the Mesón and/or Santa Victoria groups basins instead of being its subcrop, which strongly contradicts previous proposals about basement evolution along the Lower Paleozoic margin of Gondwana. Therefore, the genesis and emplacement of the Tastil batholith must be related to the development of the Lower Paleozoic shelf basins rather than with the final stages of Puncoviscana-type basin evolution. The basement of central and northern Argentina records a wide spectrum of sedimentary, deformational, magmatic and metamorphic processes at a variety of crust levels during the Early Paleozoic. Tastil batholith emplacement and exhumation in the Eastern Cordillera represent shallower crustal expressions of the plutonic and high-T–low-P metamorphic events at deeper levels in the basement now exposed mainly in eastern Puna and Pampean Ranges.

1. Introduction

Geodynamic hypotheses linking Laurentia and South America during the Precambrian and Lower Paleozoic (Dalla Salda et al., 1992; Dalziel, 1997; Pankhurst and Rapela, 1998a; Ramos, 2008) have renewed interest about the Argentine basement in recent years because most of the Neoproterozoic–Lower Paleozoic basement of the central Andes is located in western regions of central and northern Argentina (Fig. 1). In this context, the Puncoviscana basin, the Pampean cycle and the Pampean magmatic arc are keys for understanding the evolution of the western margin of Gondwana during the Neoproterozoic–Early Paleozoic (Omarini et al., 1999; Cawood, 2005; Ramos 2008; see papers in Pankhurst and Rapela, 1998b; González Bonorino et al., 1999; Ramos and Keppie, 1999).

On the basis of the spreading of Cambrian and Ordovician sedimentary sequences, two basement domains are distinguished in NW Argentina, the Eastern Cordillera to the east and the Puna and Pampean Ranges to the west and south, respectively (Fig. 1). Due to the wide distribution of Cambrian–Ordovician sedimentary successions and the weak imprint of Lower Paleozoic deformations, the Eastern Cordillera shows well-preserved stratigraphic relationships between intensely deformed Neoproterozoic–Lowermost Cambrian rocks of low metamorphic grade (Puncovisna-type basement) and the overlying sedimentary Cambrian–Ordovician rocks, preserving key geological relations to decipher the Neoproterozoic–Lower Paleozoic geological evolution. In contrast, the neighbor Puna and Sierras Pampeanas domains (Fig. 1: insert) are

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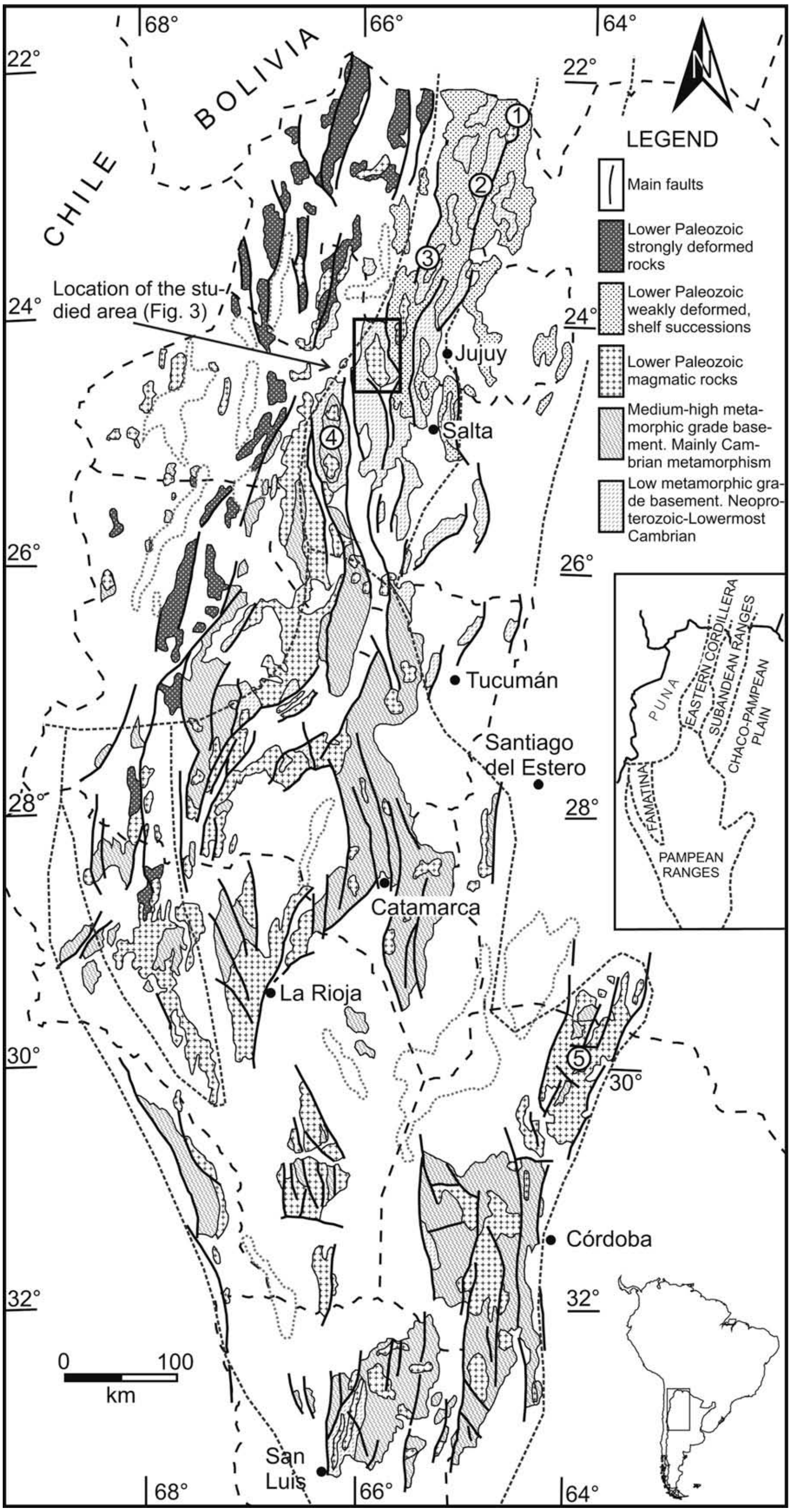

Fig. 1. Simplified map of the main outcrops of the Upper Neoproterozoic–Lower Paleozoic basement in central and northern Argentina showing the location of the Tastil area. Outcrops of the westernmost Pampean Ranges are not included due to they are strongly suspected of being allochthonous and akin to Laurentia. Geologic regions limited by dashed gray line identified in box at the right side. Modify from SEGEMAR (1999). Numbers identify main places mentioned in text: 1 – Cañani; 2 – Tipayoc; 3 – Fundiciones; 4 – Cachi; 5 – Norte-Ambargasta-Sumampa.

less favorable to do that, since Cambrian–Ordovician sedimentary rocks are much more scarce, specially in the Pampean Ranges (Gordillo and Lencinas, 1979; Caminos, 1979; Ramos, 1999), and strong and younger, mainly Ordovician, magmatic and tectonometamorphic events play against the recognition of the older stratigraphic relationships. Although profuse data constraining main episodes of metamorphism, magmatism and deformation in the Puna and Pampean Ranges have been lately published (Lucassen and Becchio, 2003; Buttner et al., 2005; Ramos, 2008; see also papers in Pankhurst and Rapela, 1998b; González Bonorino et al., 1999; Ramos and Keppie, 1999), most of them came from crystalline rocks in which original stratigraphic relationships have been intensely reworked (Pampean Ranges) or from lithological sequences in which the preserved stratigraphic relationships are mainly of Ordovician ages (Puna).

The genesis of the Neoproterozoic–Lower Paleozoic basins and subsequent deformational events in the Eastern Cordillera have been correlated with tectonometamorphic events of similar age in the remaining geological provinces with basement exposures (Puna and Pampean Ranges; see papers in Pankhurst and Rapela, 1998b; Ramos and Keppie, 1999). In this regard, the Tastil batholith (Fig. 1) stands out as one of the mainstays to correlate the Eastern Cordillera with other Argentinean basement ranges, the Pampean Ranges in particular. Since the pioneering studies by Keidel (1937, 1943), the Tastil batholith has always been described as a two facies plutonic suite (gray granodiorite and red granite) and interpreted as part of the basement that is discordantly covered by shelf sandstones included either in the Lower-Middle Cambrian Mesón Group or in the Upper Cambrian–Lower Ordovician Santa Victoria Group (Turner, 1970; Kilmurray and Igarzábal, 1971; Turner and Mon, 1979; Moya, 1988; Omarini et al., 1999; Aceñolaza et al., 2000; Astini, 2005). Thus, the stratigraphic relationships around the Tastil batholith, specifically those observed in the Angosto de la Quesera area, became a geological paradigm for the evolution of the pre-Andean basement. In accordance with these interpretations, the Tastil area (Fig. 2a) shows a weakly metamorphosed and intensely folded metaturbidite sequence, referred to as the Puncoviscana Formation, intruded by the Tastil batholith, both of which are overlain by the Lower Paleozoic shelf sandstones. This section formed the basis for proposals about tectonic events: Tilcaric phase (Turner and Méndez, 1975), Pampean and Famatinian orogenic cycles (Aceñolaza and Toselli, 1976) in NW Argentina, which with their original meaning or in weakly modified form were and/or are widely applied to the Gondwana border (see papers in: Aceñolaza et al., 1990; Pankhurst and Rapela, 1998b; González Bonorino et al., 1999; Ramos and Keppie, 1999; Vaughan et al., 2005). Taking into consideration the accepted critical stratigraphic position of the Tastil batholith, which postdated the Puncoviscana Formation folding and predated the Lower Paleozoic basins (Fig 2a), the absolute age determinations on the Tastil batholith were a useful tool for constraining the minimum age of the Puncoviscana Formation and the maximum age of the Mesón Group since these stratigraphic units do not hold any diagnostic fossils. The U/Pb ages of 535–536 Ma (Bachman et al., 1987) are the most widely accepted and from them the hypotheses claiming a deposition age for the Puncoviscana Formation until the Lower to Middle Cambrian and for the Mesón Group from the Middle to Late Cambrian became stronger (Lork et al., 1989; Aceñolaza et al., 1990; Aceñolaza et al., 2000).

The present work encompasses field mapping, structural, petrographic, geochemical and geochronological data in the Tastil area. Such complementary data provide a new view of the Tastil batholith, since they demonstrate that the Tastil batholith intrudes sandstones of the Lower Paleozoic shelf deposits (Fig. 2b) instead of being its basement (Fig. 2a) as it was interpreted until now. Additionally, they result in a new and very different cartography of the magmatic rocks in the Tastil area because we have identified two different magmatic suites among the rocks previously included in the Tastil batholith: a Cambrian suite composed of gray granodiorite, dacite porphyry and red granite, henceforth referred to as the Tastil batholith, and Miocene monzodiorite plutons (Fig. 3). This new stratigraphic framework contradicts previous hypotheses, especially those that take the nonconformity between Lower Paleozoic sedimentary levels and the batholith as a feature of regional significance along the Gondwana border (e.g. Rapela et al., 1998; Omarini et al., 1999; Aceñolaza et al., 2000). This paper synthesizes the observations and data regarding the new stratigraphic interpretation of the Tastil batholith and discusses how it constrains current geodynamic models and stratigraphic syntheses on Eastern Cordillera basement in particular and on the basement of the west Gondwana margin in general. Albeit the aim of this paper is not to discuss global plate-tectonic scenarios for the Lower Paleozoic time, the presented data can form the basis for reviewing current models involving the proto-Andean margin of Gondwana. Some of these results were partially advanced by Tubía et al. (1999) and Hongn et al. (2001a, 2001b, 2005).

2. The Tastil batholith

The Tastil batholith, located in the Eastern Cordillera, spreads over more than 500 square kilometers at Salta, in the northwestern

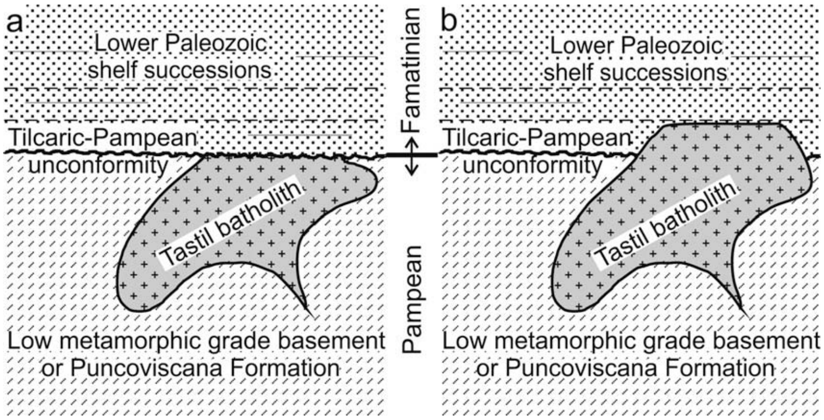

Fig. 2. Sketches summarizing the two interpretations of the contact between the sandstone and red granite of the Tastil batholith, in the Angosto de La Quesera: unconformity, according to previously accepted interpretations (a) versus the intrusive contact proposed in this work (b).

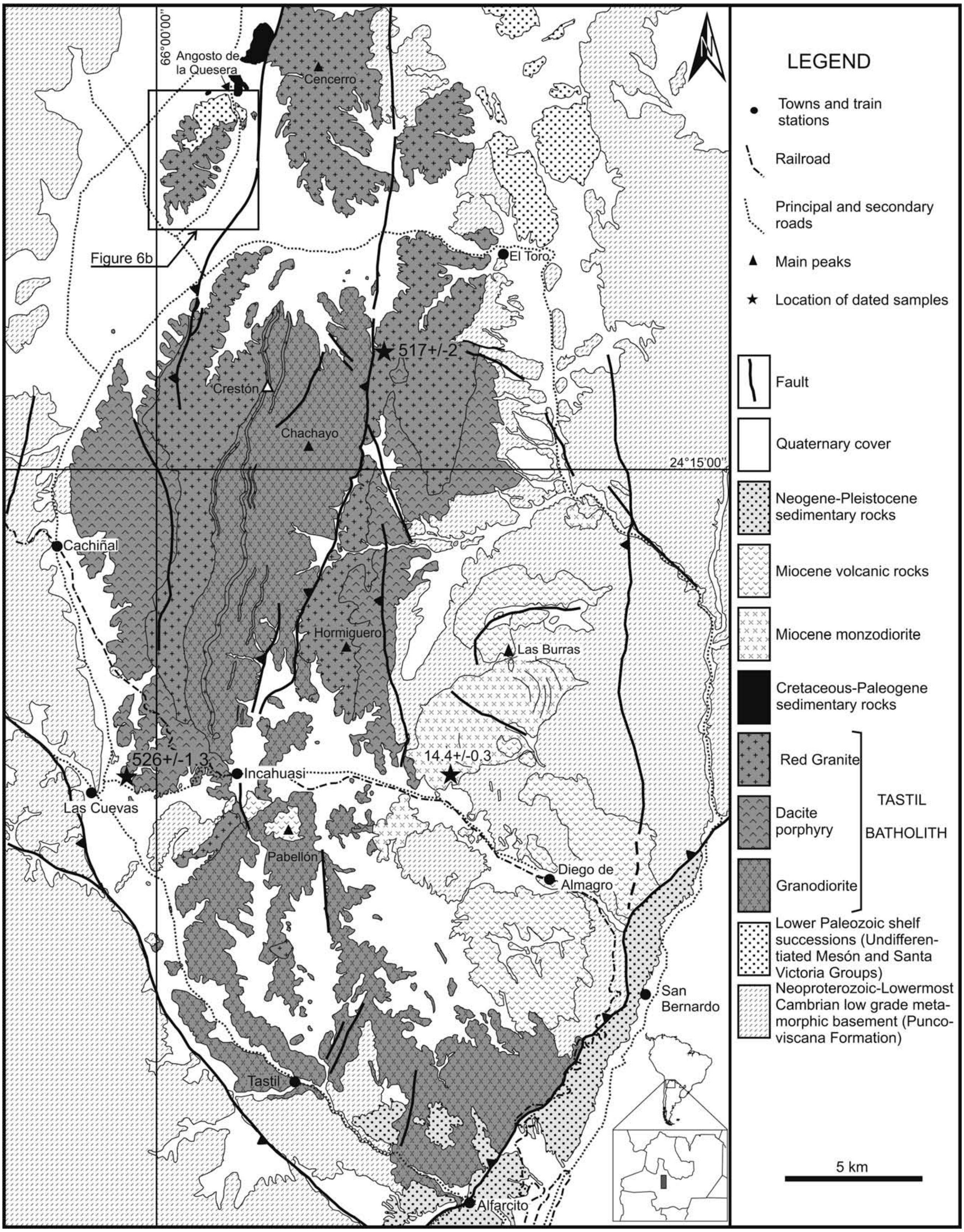

Fig. 3. Geological map of the Tastil batholith.

corner of Argentina (Figs. 1 and 3). The main geological features (lithology and geochemistry, structure, facies relationships and geochronological data) of the batholith are described in the following subdivisions.

2.1. Lithology and geochemistry

Fig. 3 shows the map of the Tastil batholith. In addition to the gray granodiorites and red granites described by Kilmurray and Igarzábal (1971), this map includes a facies of dacite porphyry first recognized by Hongn et al. (2001b). We have also separated the small plutons located to the east of the batholith since they do not correspond to gray granodiorite, as shown on previous maps, but to monzodiorite of Miocene age (Fig. 3).

The gray granodiorite is a medium- to coarse-grained, equigranular rock composed of quartz, plagioclase, K-feldspar and biotite (Fig. 4b). Idiomorphic crystals of cordierite have been observed in a few samples from the southeastern part of the gray granite. Zircon and magnetite do very often appear as inclusions in biotite. The red granites are concentrated in two N–S striking belts separated by the granodiorite central body (Fig. 3). The primary, magmatic mineralogy of the red granite is quartz, K-feldspar, plagioclase and biotite. The content of K-feldspar is larger and the amount of biotite is lower than in the gray granodiorite. In wide areas, mainly from the western belt, the red granite has been strongly modified by late hydrothermal processes, leading to significant replacements of most of their primary minerals by chlo-

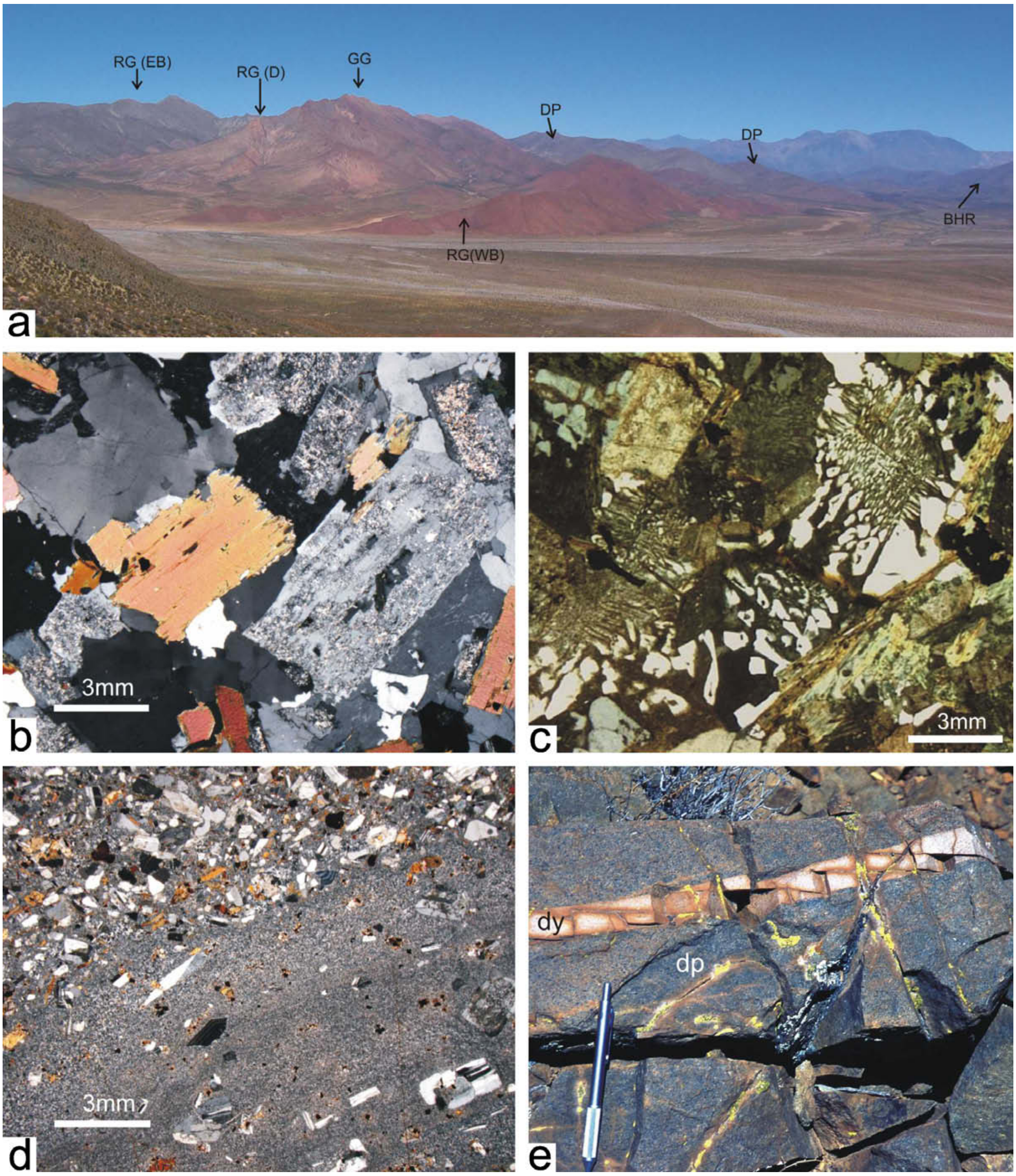

Fig. 4. Lithological features of the Tastil batholith. (a) Main facies of the Tastil batholith (RGEB – red granite eastern belt; RGWB – red granite western belt; RGD – red granite dyke; GG – gray granite; DP – dacite porphyry; BHR – basement host rock); view in south direction from the Angosto de la Quesera area; (b) granular texture in gray granodiorite; (c) red granite showing quartz and K-feldspar with granophyric intergrowths and graphic textures; (d) dacite porphyry with subvolcanic texture; (e) red granite dyke (dy) intruded in the dacite porphyry (dp). (b–d): Photomicrographs from thin sections with crossed polarizers.

rite, epidote and hematite clusters. Zircons were also affected by this alteration. Where fresh samples are preserved, mostly along the eastern outcrops, they mainly show coarse-grained equigranular texture; porphyritic textures are restricted to narrow corridors near the contacts with host rocks (e.g., in Angosto de la Quesera area) and quartz and K-feldspar show granophyric intergrowths and graphic textures (Fig. 4c), which along with miarolitic cavities point to a very shallow emplacement level. The dacite porphyries show a wide range of textures indicating different emplacement levels, from plutonic up to volcanic–subvolcanic ones. They are generally fine grained and locally have a lamprophyric texture defined by phenocrysts of plagioclase, biotite, amphibole and/or pyroxene in a very fine grained to microcrystalline matrix in which quartz, plagioclase and biotite are distinguished (Fig. 4d). These rocks are characterized by a well-defined magmatic foliation, which is outlined by the preferred orientation of the amphibole and pyroxene megacrysts and is enhanced by the parallel arrangement of very fine-grained to microcrystalline lenses and elongated fragments of the Puncoviscana Formation.

The geochemistry of magmatic rocks in the Tastil area defines a sharp separation between the facies belonging to the Cambrian batholith and those related to Miocene plutons. Red granite and gray granodiorite have Si_2O contents ranging from 65% to 77%, high-K calc-alkaline trends and weakly peraluminous compositions (A/CNK is 0.96 in one sample and between 1.01 and 1.03 in the remaining four samples). Dacite porphyry is characterized by Si_2O varying between 54% to 67%, a high-K calc-alkaline to shoshonitic trend and strong variations in the alumina ratio (A/CNK between 0.92 and 1.09). The REE pattern is very close to the average of the upper crust (Fig. 5) like in most of the Famatinian plutons (Kaseman et al., 2000; Coira et al., 1999; Viramonte et al., 2007), which is consistent with the finding of cordierite in the gray granodiorite.

2.2. Structure and contact relationships between facies and with the country rocks

The main structures in the country rocks of the Puncoviscana Formation are a set of tight folds with angular geometry, which only locally develop a spaced axial-planar cleavage. Fold axes plunge 30° to N350°. The dominant northward strike of the bedding within the Puncoviscana Formation is parallel to the batholith's elongation.

The gray granodiorite, porphyrytic dacite and red granite form roughly concordant sheeted bodies that display N–S strikes and variable dips. Along the northwestern side of the batholith, the red granite/gray granodiorite contact dips nearly 40° west, as do the sheets of red granite intruded into the gray granodiorite and the magmatic foliation observed in granite with porphyritic texture; these structural features support the magmatic origin of that contact, as interpreted by Kilmurray and Igarzábal (1971). In contrast, at the eastern side of the batholith, the contact between the same two facies is a west-dipping reverse fault responsible for the overthrusting of gray granodiorite over red granite (Fig. 3). This reverse fault can be linked to the Andean tectonics, as other faults with the same orientation and kinematics found in some western hills of the batholith (Ramos, 1973) result in the imbrication of conglomerate and calcareous beds of the Upper Cretaceous–Lower Tertiary Yacoraite Formation within red granites. Along the easternmost band of the batholith, the red granite is coarse-grained and equigranular, so it is very difficult to recognize the foliation with the naked eye. Fortunately, this sector is very rich in tabular xenoliths from the Puncoviscana Formation, which help to identify a mean planar structure dipping about 55° east. After restoration of the west and east dipping zones to a horizontal position, the Tastil batholith would display the shape of a composite laccolith. The existence of low-angle thrust faults in the batholith militates in favor of its laccolithic geometry (Tubía et al., 2005a), as the propagation of such faults through sheeted intrusions would require lower resolved-shear stress than in balloon-shaped plutons.

The structure of the igneous rocks provides additional arguments to segregate a small pluton, referred to as the Las Burras monzodiorite (Hongn et al., 2001b) which was mapped as part of the granodiorite facies of the Tastil batholith by Kilmurray and Igarzábal (1971). The Las Burras monzodiorite outlines an elliptical intrusion with an elongation, N60°E, oblique to the N–S grain of the Puncoviscana Formation and the dominant north striking structure of the Tastil batholith (Fig. 3). A magmatic layering defined by monzodiorite and granodiorite layers helps to define the structure of an asymmetric dome with its center located at the SE quarter of the massif.

The three facies of the Tastil batholith are in contact with the Puncoviscana Formation (Fig. 3) and their contacts are concordant with the country rocks. The gradual curvature of the contact, from NNE-strikes in northward sectors to SE-strikes along its southern border, is accompanied by an equivalent rotation of the bedding and cleavage of the country rocks. These contacts with the country rocks are usually sharp, except along the easternmost contact zone of the dacite porphyry, where there are numerous metaturbidite enclaves in dacite. The emplacement sequence is: (1) gray granodiorite, (2) dacite porphyry and (3) red granite. The gray granodiorite intruded the Puncoviscana Formation and is intruded by the red granite (Keidel, 1943; Kilmurray and Igarzábal, 1971). The relationships between red granite and dacite porphyry are complex, as red granite dykes cut the porphyry frequently (Fig. 4e), but inclusions of red granite with different stages of assimilation in dacite porphyry are observed locally too; this latter relationship is more common where the porphyry exhibits subvolcanic texture (Fig. 4c). These variable relationships between red granite and dacite porphyry suggest the existence of several magmatic pulses of dacite porphyries. The dacite porphyry also intruded the intensely folded Puncoviscana Formation.

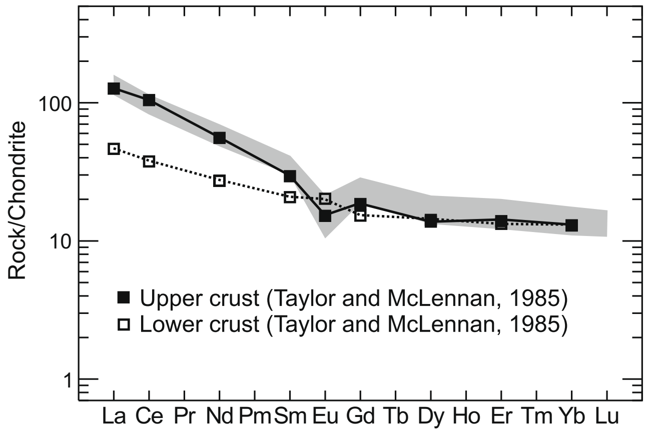

Fig. 5. Chondrite-normalized REE distribution pattern comparing the Tastil samples (gray field defined by integration of seven samples from the three facies of the batholith) with average compositions of the lower and upper crust according to Taylor and McLennan (1985). The Tastil batholith is akin to the upper crust.

2.3. New U/Pb zircon ages

Fig. 6a summarizes previously published ages of the Tastil batholith and its metamorphic aureole. We present here two new U/Pb zircon (TIMS) ages for a dacite (Sample RT-18, 24°21′02.3″SL, 66°00′31.8″WL) and a red granite (Sample RT-24, 24°12′54.9″SL, 65°54′57.1″WL) (see map of Fig. 3 for sample location). Samples

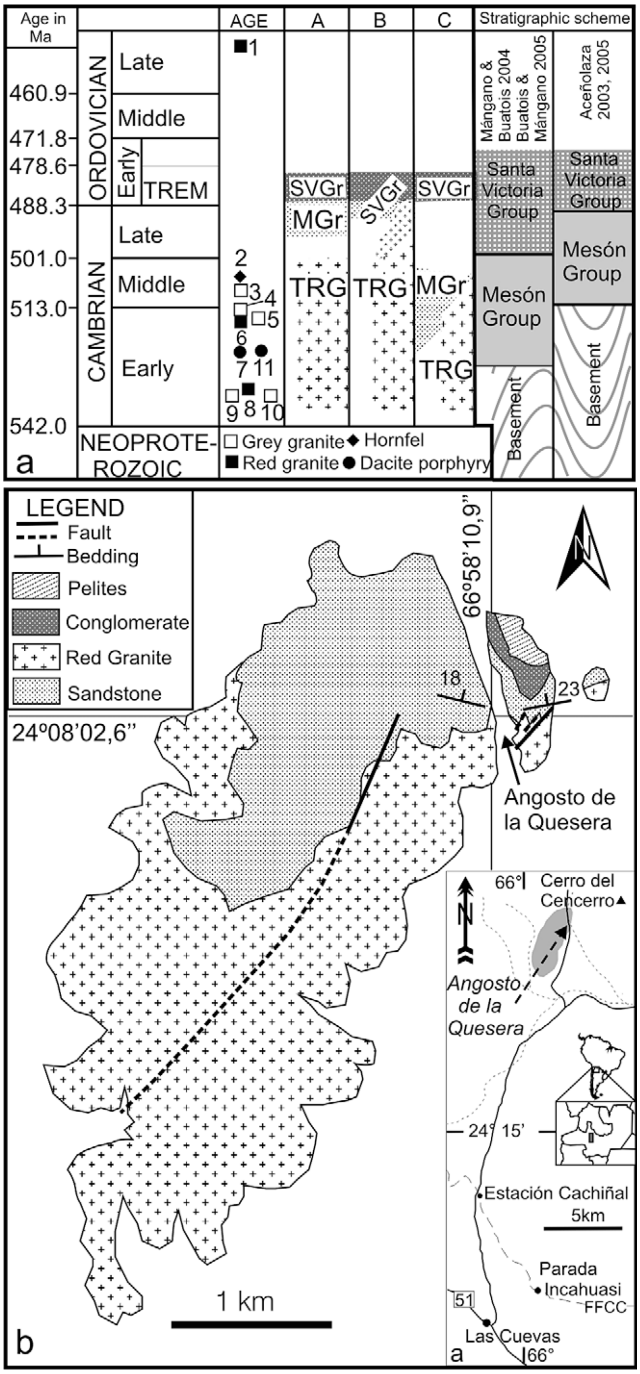

Fig. 6. (a) Synthesis of hypothesis concerning the stratigraphic framework of the Tastil batholith (in particular red granite, TRG). The age column synthesizes absolute ages on the granites and its hornfel. Data from: Cordani et al. (1990) (1 – Rb/Sr, whole rock; 2 – K/Ar, whole rock; 3 – K/Ar; biotite); Bachman et al., 1987 (4 – Rb/Sr, four points isochrone; 8/9 – U/Pb, zircon); Melick, 1999 (5 - Ar/Ar, biotite); Matteini et al. (2008) (10/11 – U/Pb, zircon); this paper (6/7 – U/Pb, zircon). Right column reproduces main proposals about regional stratigraphic relationships among Puncoviscana-type basement and Mesón and Santa Victoria Groups. Time scale from Gradstein et al. (2004). (A) Lower Paleozoic clastic sequences resting on the red granite through a nonconformity surface. (B) Sandstones intruded by the red granite belong to the Upper Cambrian–Low Ordovician Santa Victoria Group (SVGr). (C) Sandstones intruded by the red granite belong to the Cambrian Mesón Group (MGr). (b) Detailed map of Angosto de la Quesera area.

were processed and analyzed with standard laboratory procedures reported previously by Krogh (1973) and Dube et al. (1996).

Sample RT-24 yielded large clear euhedral zircon prisms and four analyses were carried out (Table 1) of small numbers of grains that were strongly abraded following the procedure of Krogh (1982). These display a linear array (Fig. 7a) with an inherited Proterozoic age component and define a line from 1681 ± 13 Ma to 517 ± 2 Ma (95% confidence interval (CI), 21% probability of fit). Analysis Z3 is significantly outside the boundaries of the plot.

Sample RT-18 also yielded a large amount of euhedral igneous zircon and two analyses of small numbers of needles are overlapping each other on concordia (Fig. 7b). These yield an age of 526 ± 1.3 Ma as the weighted average of the $^{206}Pb/^{238}U$ ages using ISOPLOT (95%CI, MSWD = 0.57).

We tried to date an additional sample of red granite extracted from the outcrops that are in contact with the overlying sandstone in the Angosto de La Quesera, but the strong hydrothermal alteration of this western portion of red granite had affected the zircon, preventing its use for radiometric dating. However, it is worth noting that their similar texture, mineralogy and geochemistry points to a unique origin for the two belts of red granite. However, in view of the beds it intrudes in the Angosto de la Quesera may belong to the Santa Victoria Group (Keidel, 1943; Moya, 1999; Astini 2005; Pinilla et al., 2008), we consider the western belt could be younger than the eastern one.

Ages on the gray granodiorite (Fig. 6a) cluster around 535–530 Ma (U/Pb, zircon, Bachman et al., 1987; Matteini et al., 2008) and around 510–515 Ma (Rb/Sr; Bachman et al., 1987; Cordani et al., 1990; Ar/Ar, Melick, 1999)

Monzodiorite sample RT-85 yielded sharp euhedral zircon prisms and three analyses were carried out of small numbers of euhedral prisms or prism tips (Fig. 7c). These yielded $^{206}Pb/^{238}U$ ages ranging from 13.7 to 14.6 Ma that do not all overlap within 2 sigma uncertainties. An age of 14.4 ± 1.2 Ma is calculated as the weighted average of the two older analyses using ISOPLOT (95% CI, MSWD = 2.0) and this covers the younger analysis as well. This Cenozoic age confirms that this intrusive is not part of the Tastil Batholith as indicated by lithological and structural features as well as field relationships (Fig. 3).

3. The Angosto de la Quesera contact

The contact between the red granite and the Lower Paleozoic sandstones is only exposed along the banks of the Angosto de la Quesera pass, at the northwest corner of the batholith (Figs. 3 and 6b). In spite of its reduced extent, this area deserves special attention because it is the type outcrop where Keidel (1937, 1943) first described the apparent unconformity between the red granite and the overlying sandstones and, hence, concluded that the Tastil batholith was older than the sandstone.

Four main lithological units can be recognized at the Angosto de la Quesera, from bottom to top these are: red granite, quartzitic sandstone, discontinuous levels of conglomerate and, finally, green sandstones and pelitic rocks up-section (Fig. 6b; see Moya, 1988; Aceñolaza et al., 2003; Astini, 2005; Pinilla et al., 2008 for detailed lithologic description). No basal conglomerate is found in contact with the granite. A large overview from the slopes of the pass shows that the granite contact, dipping nearly 20° in north direction, is concordant as a whole with the bedding of the sandstone (Fig. 8a). However, a detailed inspection of the contact zone reveals that: (1) there are protrusions of granite in the sandstone (Fig. 8b); (2) the granite bears xenoliths of sandstones (Fig. 8b and c); (3) very thin quartz–feldspar dikes are found in hand samples traversing the granite/sandstone boundary (Fig. 8c); and (4) granite intrudes in fractured sandstone beds (Fig. 8d). These data definitely support the intrusive nature of the contact between the red granite and the sandstone. In addition, the sandstone is a fine-grained rock mainly formed by interlocked grains of quartz with scarce muscovite flakes and microcline grains. Nearly 30 m away from the con-

Table 1
U/Pb data.

Fraction	Weight (mg)	Concentration		Measured		Corrected atomic ratios[a]							Age (Ma)		
		U (ppm)	Pb rad (ppm)	total common Pb (pg)	206Pb	208Pb	206Pb	±	207Pb	±	207Pb	±	206Pb	207Pb	207Pb
					204Pb	206Pb	238U		235U		206Pb		238U	235U	206Pb
RT-24 Red granite															
Z1 clr prisms abr	0.033	171	15.8	30	1005	0.2213	0.08403	32	0.6722	28	0.05802	12	520	522	531
Z2 clr prisms abr	0.019	134	12.8	36	395	0.2392	0.08571	78	0.6927	64	0.05862	50	530	534	553
Z3 6 lrg clr euh abr	0.016	101	14.2	3.6	3574	0.2263	0.12494	50	1.3540	50	0.07860	18	759	869	1162
Z4 25 clr euh abr	0.028	150	14.0	6.2	3681	0.2055	0.08553	30	0.6984	26	0.05922	10	529	538	575
RT-18 Dacite porphyry															
Z1 20 needles abr	0.025	210	17.7	41	697	0.0941	0.08505	30	0.6789	30	0.05790	14	526	526	526
Z2 needles abr	0.023	190	16.1	40	607	0.0997	0.08489	30	0.6775	30	0.05788	14	525	525	525
RT-85 Monzodiorite															
Z1 14 clr euh tips abr	0.019	385	0.9	4.3	254	0.2071	0.00226	3	0.0150		20.04816	78	14.6	15.2	107
Z2 6 clr euh abr	0.006	91	0.3	2.7	48	0.7771	0.00223	3	0.0150	22	0.04898	696	14.3	15.2	147
Z3 6 clr euh abr	0.007	233	0.6	2.5	99	0.2648	0.00213	3	0.0137	8	0.04658	260	13.7	13.8	28

Notes: Z, zircon; clr, clear; lrg, large; euh, euhedral; abr, abraded (cf. Krogh, 1982), mg, milligrams; pg, picograms.

[a] Atomic ratios corrected for blank, spike, initial common lead at the age of the sample calculated from the model of Stacey and Kramers (1975). 2 sigma uncertainties are reported after the ratios and refer to the final digits.

tact, the grains of quartz are elongate, display round borders and preserve older subgrain boundaries. In contrast, close to the granite, many grains of quartz have larger size, are devoid of subgrain boundaries and show polygonal shapes with triple point junctions with the neighbor grains (Fig. 8e). These microstructures point to grain coarsening induced by heating of previous sedimentary fabrics, an interpretation which is supported by the preservation of ghost detrital cores in many polygonal grains (Fig. 8e). Similar microstructures of quartz grain coarsening in the Appin Quartzite (Scottish Highlands) has been reported by Buntebarth and Voll (1991), related to the intrusion of the Caledonian Ballachulish igneous complex in Scotland. The high content in quartz of the sandstone explains the scarceness of minerals formed by static heating during contact metamorphism. The same problem arises when the metaturbidites of the Puncoviscana formation are in contact with the red granite. Fig. 8f shows a pelite-sandstone sample with abundant andalusite spots in metapelitic bands but only quartz coarsening in the adjacent sandstone. The strong cohesion of the contact at the scale of thin section (see Fig. 1f in Hongn et al., 2001a) is also consistent with the intrusive nature of the contact.

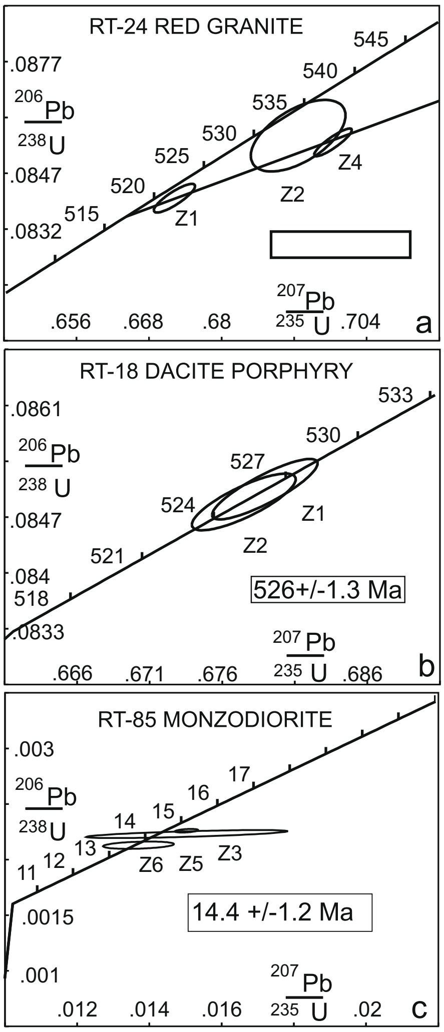

Fig. 7. Concordia diagrams. U/Pb age determinations. (a and b) Tastil batholith Cambrian facies; (c) Cenozoic Las Burras Monzodiorite.

The intrusion of red granite into the sandstones (Tubía et al., 1999; Hongn et al., 2001a, 2001b, 2005) has been questioned by other authors (Aceñolaza et al., 2003; Moya et al., 2003; Astini, 2005). Following Moya et al. (2003), Astini (2005) relates the quartz–feldspar veins emanating from the granite into the sandstone (Fig. 8c) to a hypothetical far-away Cenozoic volcanic source with no additional evidence in the zone under discussion. He also considers that part of the sandstones mapped by Hongn et al. (2001a) in contact with the red granite are silica-rich magmatic injections due to its polygonal fabric, but his interpretation is invalidated by the preservation of ghost detrital grains in the core of many polygonal grains (Fig. 8e), demonstrating the sedimentary origin of such fabric. Thus, the contact we describe (Fig. 8a) involves red granite and the sandstones that Astini (2005) has included in the Cardonal Formation. Finally, Fig. 8b shows xenoliths of sandstone with bent boundaries completely surrounded by red granite which cannot be explained by vertical slip along fractures as Astini did (2005).

4. A new stratigraphic framework for the Tastil batholith

The conglomerate that rests over the sandstone intruded by the red granite in the east side of the Angosto de la Quesera pass

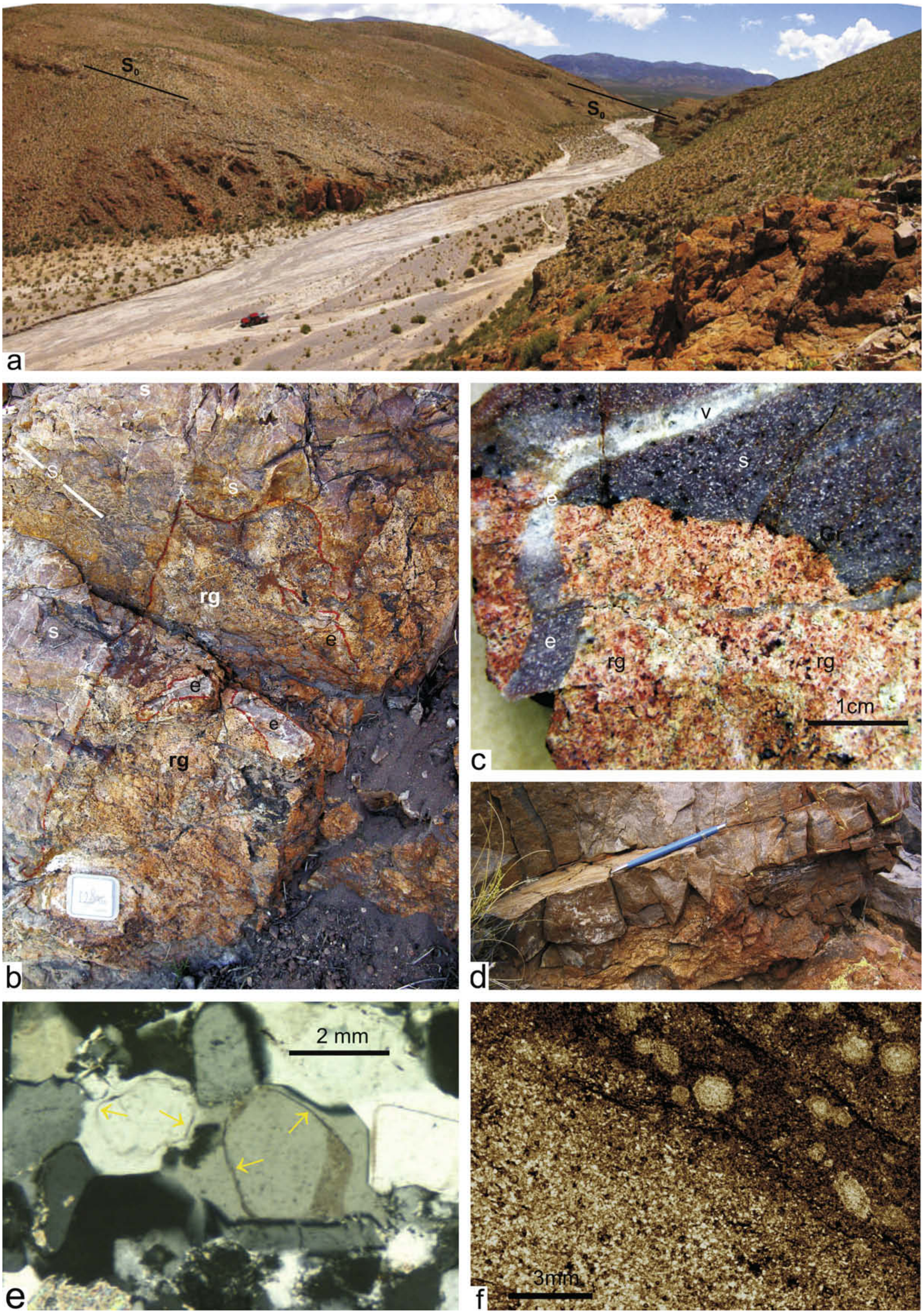

Fig. 8. Photos showing the main evidences for the intrusive nature of the contact between red granite and sandstones (further explanation in text). (a) Granite intrusion parallel to sandstone bedding; view in north direction; (b) Protusion of red granite in sandstones and sandstone enclaves in granite (rg – red granite, s – sandstone, e – sandstone enclaves, S0 – sandstone bedding); (c) Contact in polished hand sample (rg – red granite, s – sandstone, e – sandstone enclaves, v – vein); d – fractured sandstone intruded by red granite. Note that fractures do not displace sandstone bedding, therefore granite intruded fracture-bound spaces; e – Quartz triple points related to static recrystallization upon heating. Arrows indicate original grain borders before heating. Crossed polarizers; g – Red granite hornfel from laminated turbidite of the Puncoviscana-type basement. Andalusite spots grow in pelitic domains. However, no evident transformation occurs in sandstone domains. Plane polarized light.

mainly contains clasts from the sandstone formation and large blocks of red granite are also common. This conglomerate holds several limestone ribbons with Tremadocian fossils (Keidel, 1943; Moya, 1988) representative of the Kainella meridionalis biostratigraphic zone attributed to the Uppermost Cambrian–Lower Ordovician Santa Victoria Group (Moya, 1988, 1999; Aceñolaza, 1998; Bahlburg et al., 2000, Astini, 2005). Since the age of the underlying sandstones is poorly constrained due to the lack of diagnostic fossils, these rocks have been correlated with either the Cambrian Mesón Group (Kilmurray and Igarzábal, 1971; Ramos, 1973; Hongn et al., 2001b; Aceñolaza et al., 2003) or the younger Santa Victoria Group (Moya, 1988, 1999; Moya et al., 2003; Bahlburg et al., 2000; Kumpa and Sánchez, 1988; Astini, 2005; Pinilla et al., 2008). From the first work of Keidel (1937, 1943), lithological descriptions suggest these sandstone levels belong to the Santa Victoria Group (Moya, 1988, 1999; Astini, 2005). Pinilla et al. (2008) found an Upper Cambrian fossil association in shales intercalated in sandstones from the northern end of the Angosto de la Quesera outcrops; bad expositions of the fossiliferous levels avoid determining precisely their relationships with the sandstones intruded by the granite. However, they cover the sandstones and are partially eroded by the conglomeradic levels, which contain granite and sandstone pebbles and rest directly on the sandstone in the eastern side of the Angosto de la Quesera pass (Aceñolaza et al., 2003). The fossil content described by Pinilla et al. (2008) supports the inclusion of the sandstones intruded by the granite in the Santa Victoria Group.

Published data and interpretations allow three possible different stratigraphic schemes for the Tastil batholith red granite (Fig. 6a). Fig. 6a-A represents the most accepted hypothesis, it includes an unconformity or non conformity between the red granite and the siliciclastic sequences, Mesón or Santa Victoria Groups. This model is not supported here because of the good evidence for an intrusive contact as described in the previous section. Fig. 6a-B-C shows two possible schemes considering the sandstones intruded by the red granite as part of the Santa Victoria Group (B) or the Mesón Group (C). Absolute ages on the Tastil batholith and both lithologic and geochemical similarities between the two belts of red granite outcrops points to the three facies here included in the batholith being of Lower to Middle Cambrian age and consequently the sandstones should be part of the late Lower to Middle Cambrian Mesón Group (Kilmurray and Igarzábal, 1971; Ramos, 1973; Hongn et al., 2001b; Aceñolaza et al., 2003). In this framework, the time elapsed between the deposition of the quartz-bearing sandstone intruded by the red granite and the deposition of the Tremadocian polymictic conglomerate must have been long enough to encompass the processes of intrusion, exhumation and erosion of the red granite. Besides, a brittle deformation episode took place after the deposition of the sandstones and before the intrusion of the red granite, according to the existence of fractures in the sandstone that are sealed by the underlying granite (Fig. 8d). This sequence of events requires more time than just a brief interruption in the sedimentary record, as it is implicitly postulated when interpreting the quart-bearing sandstone as part of the Santa Victoria Group. However, in the case of accepting arguments in favor of assigning the sandstones to the Santa Victoria Group (Keidel, 1943; Moya, 1988; Astini, 2005; Pinilla et al., 2008), the red granite outcropping in the western belt whose northern end corresponds to the Angosto de la Quesera area has to be distinguished as a new facies of the batholith whose age should be around 500–490 Ma since it intrudes the Upper Cambrian beds (Pinilla et al. 2008) and supplies boulders to the Lower Tremadocian conglomerate. In this scheme, the Tastil batholith would consist of four facies: three of Lower to Middle Cambrian age (gray granite, dacite porphyries and red granite of the eastern belt) and the remaining (and hypothetical) one of Uppermost Cambrian to Early Tremadocian age (red granite of the western belt). This last hypothesis has the virtue of reconcile most of the available and apparently contradictory information. Additional datations on the granite and its host rock in the Angosto de la Quesera area will refine the stratigraphic knowledge of this reference area. However, it must be remarked that in the Angosto de la Quesera area, the only zone in which relationships between the Tastil batholith and the Lower Paleozoic sandstones are preserved, the red granite intrudes the sandstones instead of being their basement.

5. Discussion

Figs. 6a and 9 synthesize available ages on magmatic rocks in Eastern Cordillera and Puna eastern border. The ages of the Puncoviscana type basement and Mesón and Santa Victoria Groups is a matter of current debate (e.g. Buatois and Mángano, 2005; Aceñolaza, 2005). According to Mángano and Buatois (2004), Buatois and Mángano (2005) and Buatois et al. (2006), the youngest sedimentation of the basement is Lowermost Cambrian, the sedimentation of the Mesón Group begins in the Lower Cambrian (Tommotian) and the sedimentation of the Santa Victoria Group starts in the Upper Cambrian times. The new data presented in this work are consistent with this proposal. In this framework, most of the ages on the Tastil batholith and other Lower Paleozoic plutons in the Eastern Cordillera show the intrusions are contemporaneous with the deposition of the Mesón and Santa Victoria Groups, which is coherent with our observations in the Angosto de Quesera area. However, U/Pb ages on the gray granodiorite facies of the Tastil batholith concentrate around 535 Ma, an older age than the oldest levels of the Mesón Group. Our field observations and geochemical features suggest the Cambrian facies of the Tastil batholith are so closely related that they should be considered as part of a continuous batholith construction including several steps between the Lower-Middle Cambrian up to the Upper Cambrian. In this context, the emplacement of the granodiorite facies (*ca.* 535–530 Ma.) represents the first stage of the batholith construction. The emplacement of this initial magmatic pulse probably took place short before the development of the Mesón basin at the beginning of extensional episodes subsequent to the orogenic thickening of the Puncoviscana-type basement. The scattered radiometric ages obtained from the different facies of the Tastil batholith are in line with a long-lived magmatic activity. However, considering that most of the available U/Pb ages were obtained by convectional methods, variable components of crustal heritage must not be discharged when interpreting the time construction of the batholith.

5.1. Emplacement setting of the Tastil batholith

Previous syntheses about the basement evolution of the Central Andes (Omarini et al., 1999; Keppie and Bahlburg, 1999; Aceñolaza et al., 2000; Ramos, 2008) have related the origin and emplacement of the Tastil batholith to the closure and deformation of the Puncoviscana basin in a contractional tectonic setting. However, the batholith is nearly contemporaneous with the deposition of the Mesón and/or Santa Victoria Groups, which records the infilling of basins developed in an extensional tectonic setting according to most of the authors that investigated this unit and its related volcanism (Salfity et al., 1975; Aceñolaza et al., 1982; Mon and Salfity, 1995; González Bonorino and Llambías, 1996; Moya, 1998; Sánchez and Salfity, 1999; Sureda and Omarini, 1999; Coira et al., 1999; Bahlburg 1990; Bahlburg and Hervé,1997; Ramos, 2008). The alkaline signature of the volcanic rocks intercalated in the Mesón Group points to a rift-related, intraplate extensional setting (Manca et al., 1989; Coira et al., 1999).

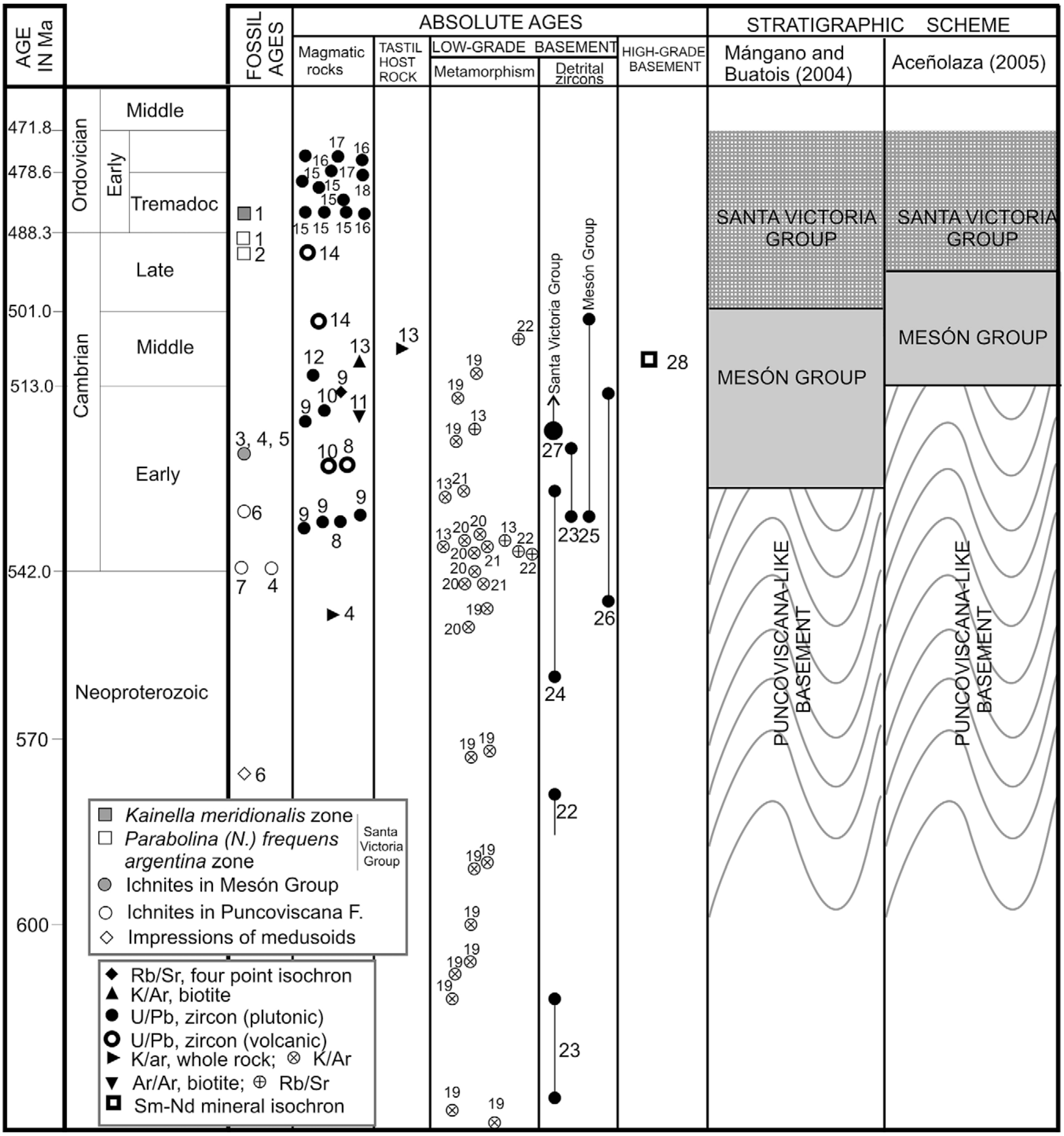

Fig. 9. Synthesis of absolute and fossil ages on Neoproterozoic–Lower Paleozoic rocks of the Eastern Cordillera and neighboring regions. Ages on Santa Victoria Group just include data from Angosto de la Quesera and close areas. Stratigraphic scheme show current proposals on ages of Puncoviscana Formation and Mesón and Santa Victoria Groups. Further explanation in the text. Timescale from Gradstein et al. (2004). Data from 1 – Moya (1998); 2 – Pinilla et al. (2008); 3 – Alonso and Marquillas (1981); 4 – Omarini et al. (1999); 5 – Mángano and Buatois (2004); 6 – Aceñolaza et al. (1999); 7 – Sureda and Omarini (1999); 8 – Matteini et al. (2008); 9 – Bachman et al. (1987); 10 – this paper; 11 – Melick (1999); 12 – Zappettini et al. (2008);13 – Cordani et al. (1990); 14 – Hauser et al. (2008); 15 – Haschke et al. (2005); 16 – Viramonte et al. (2007); 17 – Lork and Bahlburg (1993); 18 – Coira et al. (2009); 19 – Do Campo (1999); 20 – Adams et al. (1990); 21 – Do Campo et al. (1994); 22 – Adams et al. (2005); 23 – Adams et al. (2007); 24 – Lork et al. (1990); 25 – Adams et al. (2008a); 26 – Adams et al. (2008b); 27 – Di Cunzolo and Pimentel (2008); 28 – Lucassen et al. (2000).

Fig. 10 summarizes the emplacement history of the Tastil batholith in an extending continental crust, resembling the tectonic scenario proponed by Richards and Collins (2004) for the emplacement of granites in initial to moderate stages of a rift development. The sequence of magmatic pulses evidenced by field relationships (Fig. 4) and isotopic ages (Figs. 6a, 7 and 9) is from older to younger: gray granodiorite, dacite porphyry and red granite. The first sketch (Fig 10a) represents the intrusion of dacite porphyry, some 526 Ma ago, and its storage between the granodiorites and the Puncoviscana Formation. The widespread presence of subvolcanic textures is consistent with a very shallow emplacement level. This event probably took place at initial stages of crustal extension and exploiting the same ascent conduit as the older granodiorite, as suggested by the concentration of dacite porphyries to the north of the batholith's root located between the Tastil village and the Incahuasi and Diego the Almagro railway stations (Fig. 3; Tubía

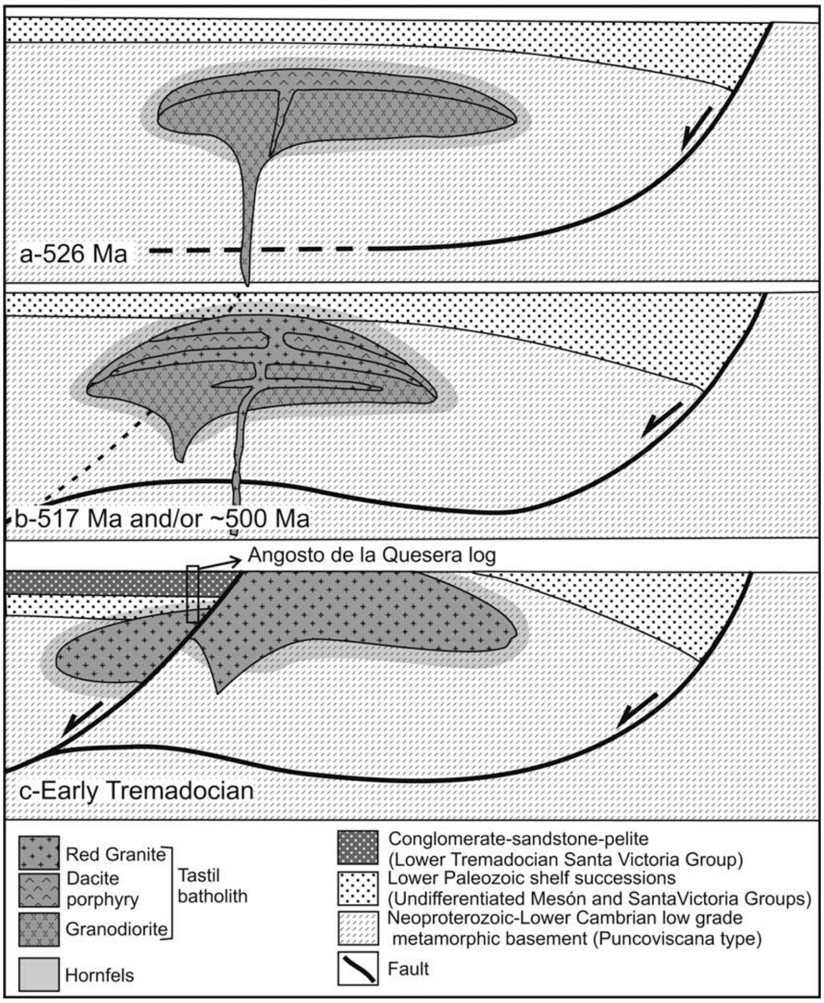

Fig. 10. Sketch of emplacement history of the Tastil batholith. Further explanation in text.

et al., 2005a). The intrusion of red granites produced changes in both the structure of the batholith and the intrusion level (Fig. 10b). The red granite could include two pulses, of *ca.* 517 Ma and *ca.* 500 Ma, if the platform sandstones it intrudes belong to the Upper Cambrian–Lower Ordovician Santa Victoria Group. Regarding the structure of the batholith, it is worth noting that the red granite is usually sandwiched between granodiorites and dacite porphyries although it also comes in contact with the Puncoviscana Formation and with the Paleozoic sandstones of the Angosto de la Quesera finally (Fig. 3). Such contact relationships suggest that the granite magma ascended through the granodiorite as indicated by the existence of concordant sheets of red granite in the granodiorite and then spread laterally along the granodiorite/dacite contact. After some inflation, the fracturing of the dacite cover permitted the ascent of granite magma to uppermost levels. The common presence of corroded grains of quartz and miarolitic cavities in the red granite (Tubía et al., 1999) indicates its shallow level of emplacement, which could have been enhanced by the upwards bending of the thinned continental crust during the ongoing extensional deformation. In the same way, we propose that the water supplied by the cover of Paleozoic sediments promoted the strong hydrothermal retrogression observed in the red granites. Finally, Fig. 10c features the activation of a new extensional listric fault leading to the erosion of the Paleozoic sandstone cover and the underlying red granite during the deposition of the Lower Tremadocian conglomerates of the Santa Victoria Group.

5.2. Regional implications

The Tastil batholith is one of the mainstays for models of the Pampean and Famatinian orogenic cycles in NW Argentina (Aceñolaza and Toselli, 1976) and even most of the tectonic correlations at regional and continental scales rely partially on the previously widely accepted non conformity between the Tastil batholith and the Lower Paleozoic shelf deposits (see papers in Aceñolaza et al., 1990; Pankhurst and Rapela, 1998b; Ramos and Keppie, 1999; González Bonorino et al., 1999). However, the outcrops of the Angosto de la Quesera area show the Tastil batholith intruded into the Lower Paleozoic basins of the Eastern Cordillera of the Central Andes and can not be longer interpreted as the basement of such basins; this seemingly simple statement is of paramount relevance for current interpretations of the evolution of the Neoproterozoic to Lower Paleozoic basement in the Eastern Cordillera in particular and for the tectonic evolution of the overall Central Andes too. This relationship impacts on the analyses of the Lower Paleozoic geological evolution of the Eastern Cordillera.

The ages of the Mesón Group and the underlying Puncoviscana Formation have been a matter of discussion for forty years. Initial hypotheses (Turner, 1970) postulate Precambrian and Cambrian ages for the lepto-metamorphic basement and the Mesón Group, respectively. Based on the Lower Cambrian age indicated by trace fossils for the sedimentation of the basement, Aceñolaza and Toselli (1976) defined the Pampean and Famatinian cycles, which correspondingly encompass the development of the Puncoviscana

Formation (Upper Neoproterozoic–Lower Cambrian) and the Paleozoic basins (from Middle Cambrian onwards). The Tastil batholith is considered as part of the Pampean arc (e.g. Omarini et al., 1999) formed by the accretion of the Antofalla and Pampia terranes (Ramos, 2008). However, the new data presented here show that the intrusion of the Tastil batholith and the development of the Cambrian–Ordovician basins (Mesón and Santa Victoria Groups) were coeval processes which are to be related with initial stages of the younger Famatinian cycle in NW-Argentina, so it should not be integrated in the Pampean magmatic arc.

In addition to Tastil, other plutons considered as part of the Pampean arc in the Eastern Cordillera (intrusives of the Cachi-Palermo ranges, Tastil, Fundiciones, Tipayoc and Cañañí; e.g. Omarini et al., 1999) show features indicating they are Famatinian granites, or even younger as it happens with the Fundiciones granite (Gorustovich et al., 1996; Haschke et al., 2005) and not Pampean ones. Plutons of the Cachi mountains, located to the south of the Tastil batholith, have been grouped in two magmatic suites with different geochemistry, field relationships and ages (Gallisky, 1983, 2007; Gallisky et al., 1990; Hongn et al., 1999; Méndez et al., 2006). Several plutons of granodiorite and trondhjemite intruded at different structural levels (Tubía et al., 2005b, 2008) within the La Paya Formation, a medium- to high-grade metamorphic equivalent of the Puncoviscana-type unit (Aceñolaza et al., 1976). Based on a detailed structural mapping along with geochronologic and petrographic data, Tubía et al. (2005b, 2008) interpret that positive inversion tectonics within intermediate crustal levels took place during the Early Ordovician. The metamorphic evolution and the formation of sheeted plutons are consistent with a Lower to Middle Cambrian extensional event, whereas the younger E-vergent folds provide evidence for the overprint of a Lower Ordovician shortening episode.

The plutonism and high-T–low-P metamorphism recorded in the Cachi-Palermo ranges postdate the Pampean or Tilcaric deformation imprinted at low-temperature conditions in Puncoviscana-type units, but they predate the plutonism of the Faja Eruptiva de la Puna Oriental, a magmatic belt distributed all along the Puna eastern border (Méndez et al., 1973) composed of plutons ranging in age between 470 and 490 Ma (see Fig. 9 and references therein). Most of these plutons are thought to be emplaced under active deformation with main shortening and subordinate strike-slip components (Hongn et al., 1996; Tubía et al., 2005b; Hongn and Riller, 2007) in a back-arc tectonic setting similar to that proposed by Coira et al. (2009). The assignment of the Cachi plutons to post-Tilcaric events was proposed by Gallisky et al. (1990), Coira et al. (1999) or Méndez et al. (2006) previously.

The compilation of published ages from different basement rocks or events in the Eastern Cordillera and nearby areas like the eastern border of the Puna (Fig. 9) reflects some interesting features, among them: (1) ages of granite rocks in the Eastern Cordillera are consistent with magma intrusion contemporaneous with the sedimentation of the Mesón Group according to updated regional stratigraphic analysis (e.g. Mángano and Buatois, 2004). (2) The deposition of the Mesón and Santa Victoria Groups, the intrusion of plutons and high-T and low-P metamorphism are coeval processes that took place at different crustal levels of the Eastern Cordillera. (3) Geochronological data of low-grade metamorphism and detrital zircons in Puncoviscana-type units (see references in Fig. 9) support previous hypotheses proposing that more than one tectono-metamorphic domain can be differentiated in the Puncoviscana-type units (Mon and Hongn, 1988, 1991; Moya, 1998; Mángano and Buatois, 2004) and suggest that the last main deformation and low-grade metamorphism took place *ca.* 530 Ma ago. (4) Ages on younger detrital zircons in the Puncoviscana-type basement are in some cases younger than ages dating low-grade metamorphism and contemporaneous with ages yielded by granites intruded in this basement after deformation and low-grade-metamorphism, and (5) ages of plutons from the Faja Eruptiva cluster around 485–475 Ma.

5.3. Large extent of the Lower Paleozoic extensional tectonics

The high-T and low- to medium-P metamorphism in the basement of the Puna, dated at *ca.* 510 Ma (Sm ± Nd mineral isochrones; Lucassen et al., 2000), and the Cambrian–Lowermost Ordovician high-T low-P metamorphism and related sheeted plutons in the Cachi ranges (Tubía et al., 2008) could reflect the same Lower Paleozoic extensional event described for the Tastil region but at deeper crustal levels. The extensional conditions vanished in the eastern Puna at around 480–470 Ma (Fig. 9 and references there), when great volumes of crustal granites formed the Faja Eruptiva of the Puna. Minor participation of juvenile material related to mantle sources (Coira et al., 1999, 2009; Bock et al., 2000; Viramonte et al., 2007) points to a complex back-arc setting, where thinned continental crust started to be shortened in Tremadocian–Lower Arenigian times. The *ca.* 480–470 Ma shortening resulted in ductile deformation at intermediate crustal levels in the eastern Puna (Hongn et al., 1996; Hongn and Mon, 1999; Domínguez et al., 2006; Viramonte et al., 2007; Tubía et al., 2008) and at shallower levels in stratigraphic discontinuities in basins like Tumbaya (Moya, 1997), Guandacol (Salfity et al., 1984) and Los Colorados (Astini, 2003), albeit the Tremadocian Tumbaya discontinuity may be related to the latest extensional event. The overprint of ductile contractional deformation obliterated most evidence of the older extensional event. However, as in the Eastern Cordillera the contractional deformation vanished eastward, so the Cambrian extension can still be recognized at middle crustal levels in the Cachi region and at shallow levels in the Tastil area. Considering ages and the preservation, or overprint, of tectonics events, some belts can be delineated in northwest Argentina (Fig. 11). The eastern zone (Eastern Cordillera) preserves the Lowermost Cambrian contractional deformation and metamorphism characterizing the Puncoviscana-type basement and the shelf basins along with contemporaneous magmatism (Mesón and Santa Victoria Groups and Tastil batholith). Westward and south of 24°S, in the Calchaquí valley, the basement of the Puna–Eastern Cordillera transition shows the best evidence of the Cambrian extension at intermediate crust levels. Along the eastern border of the Puna the record of ductile deformation during Lower Ordovician shortening (nearly 480–470 Ma) is well preserved, while sedimentary deposits accumulated in syntectonic basins along the central portion of the Puna at the middle and end of the Ordovician (Bahlburg, 1990).

The Middle Cambrian to Lower Ordovician extensional tectonics was initiated after the Tilcaric or Pampean main contraction. Whether extension was promoted by gravitational collapse alone (Pankhurst and Rapela, 1998a) or induced by plate tectonics (Ramos 2008) is not yet well constrained. Likely, an initial extension related to orogen collapse was followed by further extension related to plate tectonics due to separation of continental masses or back-arc extension associated with the slab–upper plate system (retreated or advanced upper plate). The development of a magmatic arc from the Upper Cambrian in the northern Chile and northern Puna (Palma et al., 1986; Breitkreuz et al., 1989; Omarini and Sureda, 1994; Bahlburg and Hervé, 1997; Coira et al., 1999; González et al., 2007) seems to support extension in an active back-arc setting between Upper Cambrian and Lower Ordovician times.

It is worth noting that some magmatic rocks of the Pampean Sierras de Córdoba, nearly 800 km to the south of the Tastil batholith, have been linked to post-collisional extension and correlated with the Tastil batholith (Rapela et al., 1992; see papers in Pankhurst and Rapela, 1998b; González Bonorino et al., 1999; Ramos

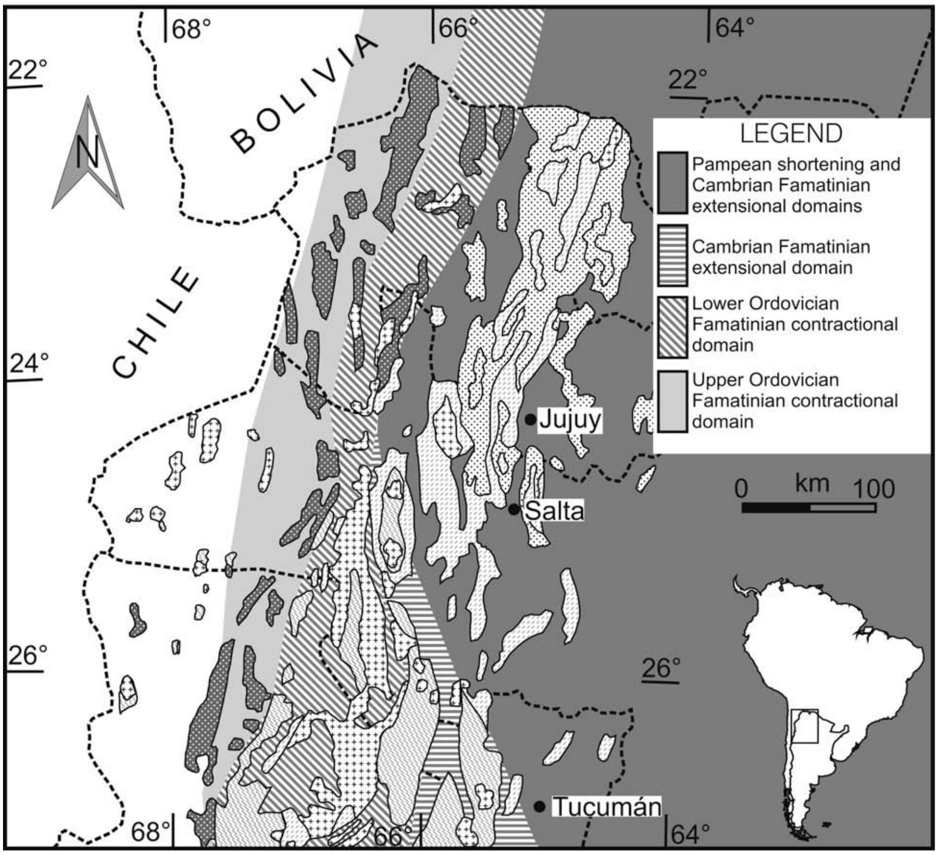

Fig. 11. Lithotectonic belts delineating the Latest Neoproterozoic–Lowermost Cambrian Pampean intense contraction, Cambrian extensional Famatinian and Ordovician contractional Famatinian domains. The Ordovician contractional belt is displaced toward west in relation to the older ones. References as in Fig. 1. Modified from SEGEMAR (1999).

and Keppie 1999). The high-T and low- to medium-P metamorphism did develop during final stages of the Pampean orogeny in both Pampean Ranges and Puna (Rossi et al., 1992; Grissom et al., 1998; Pankhurst et al., 1998; Rapela et al., 1998; Sims et al., 1998; Stuart-Smith et al., 1999; Lucassen et al., 2000; González et al., 2002). According to Rapela et al. (1998), the metamorphic peak at about 525–519 Ma would represent a younger overprint recording an isothermal decompression linked to the extensional collapse of the Pampean orogen. The intrusion of strongly peraluminous granites in the Sierras de Córdoba took place during such an extensional event. In line with this interpretation, magmatic activity between Middle Cambrian to Lower Ordovician, with a well-defined cluster around 530–510 Ma, has been also reported for the Ambargasta, Sumampa and Norte ranges (Castellote, 1982, 1985; Rapela et al., 1991; Stuart-Smith et al., 1999; Massabie et al., 2002; Koukharsky et al., 2003; Leal et al., 2003; Llambías et al., 2003; Schwartz et al., 2008) and in some cases interpreted as post-collisional magmatism (e.g., Leal et al., 2003). Albeit the aim of this paper is not to discuss global plate-tectonic scenarios for the Lower Paleozoic time, the new data presented here suggest that magmatic events interpreted as Pampean episodes in the Pampean Ranges should be reviewed since many granites included in the Pampean arc are in fact associated with Cambrian–Lower Ordovician extension tectonics.

6. Concluding remarks

Several facts that should be included in further investigations on the basement of central and northern Argentina and consequently on the Gondwana margin emerge from our revision of the Tastil batholith, as follows:

- The Tastil batholith was emplaced during a magmatic episode coeval with the development of the Lower Paleozoic basins and is not basement to them as previously interpreted. This fact changes radically the focus on the basement analysis since it is the oldest magmatic record of the Famatinian cycle and not the youngest Pampean plutonic event in the Eastern Cordillera.
- A well-defined extensional tectonic setting controlled the start and first stages of the Famatinian cycle during the Cambrian. Basin development, high-T/low-P metamorphism, peraluminous magmatism with geochemical signals pointing at recycling of the crust and extensional ductile shear zones took place contemporaneously during the Cambrian at different levels of the crust in Eastern Cordillera, Puna and likely in Pampean Ranges. The Tilcaric–Pampean orogeny results in the amalgamation of Laurentia, Amazonia and Pampia involving minor cratonic terranes such as Arequipa–Antofalla during the Late Neoproterozoic–Early Cambrian (Ramos 2008) then the Lower Paleozoic extensional tectonic setting in the western Gondwana margin is related to the late orogenic extension of the Pampean orogen (Rapela et al. 1998; Sureda and Omarini, 1999) and to the plate tectonics (Ramos 2008). The long-lived extensional deformation lasted from the Early Cambrian up to the Late Cambrian–Early Ordovician and was sandwiched by two contractional episodes, the older was the Tilcaric–Pampean orogeny and the younger related to the installation of the Famatinian active margin from Late Cambrian–Early Ordovician.
- The initiation of subduction-collision systems on the western border of Gondwana at *ca.* 500 Ma produces intense magmatic, metamorphic and deformation processes that overprint the Pampean and initial Famatinian records. The Ordovician Fama-

tinian contractional overprint defines a N–S belt in which Pampean and extensional Famatinian lithotectonic associations are reworked making difficult the restoration of the Pampean and first stages of the Famatinian cycles in some areas like the eastern Puna or Pampean ranges. This led some authors to propose a mobile belt in which a long-standing thermal anomaly controlled magmatism, deformation and metamorphism in an almost continuous form (Lucassen et al., 2002; Lucassen and Becchio, 2003). However, the Ordovician Famatinian lithotectonic belt is clearly displaced to the west in relation to the Pampean and extensional Famatinian ones in NW-Argentina (Fig. 11) so that the easternmost outcrops in Eastern Cordillera better preserve the Pampean and Cambrian Famatinian events (e.g., intensely deformed and weakly metamorphosed Puncoviscana-type basement, Lower Paleozoic basins – Mesón and Santa Victoria Groups – and related magmatism –Tastil batholith–).

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