The Basement of the Central Andes: The Arequipa and Related Terranes

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Key Words

Grenville, Sunsás, accretion, dispersal, Famatinian orogeny

Abstract

The basement of the Central Andes provides insights for the dispersal of Rodinia, the reconstruction of Gondwana, and the dynamics of terrane accretion along the Pacific. The Paleoproterozoic Arequipa terrane was trapped during collision between Laurentia and Amazonia in the Mesoproterozoic. Ultrahigh-temperature metamorphism correlates with the collapse of the Sunsás-Grenville orogen after ∼1000 Ma and is related to slab break-off and dispersal of Rodinia. The Antofalla terrane separated in the Neoproterozoic, forming the Puncoviscana basin. Its closure was coeval with the collision of the eastern Sierras Pampeanas. The rift-drift transitions of the early Paleozoic clastic platform showed a gradual younging to the north, in agreement with counterclockwise rotation based on paleomagnetic data of Antofalla. North of Arequipa arc magmatism and high-grade metamorphism are linked to collision of the Paracas terrane in the Ordovician, during the Famatinian orogeny in the Sierras Pampeanas. The early Paleozoic history of the Arequipa massif is explained by a backarc, which further south changed to open oceanic conditions and subsequent collision. The Antofalla terrane reaccreted to the continental margin by the late Ordovician. These accretions and subsequent separations during the Mesoproterozoic, Neoproterozoic–early Cambrian, and late Cambrian–middle Ordovician are explained by changes in absolute motion of the Gondwana supercontinent during plate global reorganization.

INTRODUCTION

The old basement inliers along the Pacific coast of the Central Andes are important in the understanding of the tectonic evolution of the active margin. The Arequipa massif (see **Figure 1**), was considered an integral part of the South American continent (Cobbing et al. 1977) since the Andean arc erupted through a thick continental crust of Precambrian age (James 1971, Dalmayrac et al. 1977). However, these old ages posed some dilemmas on the crustal growth proposed for the South America basement by Cordani et al. (1973). Cordani et al. demonstrated, based on more than 1000 isotopic ages at that time, that the continent grew from an Archean core, surrounded by

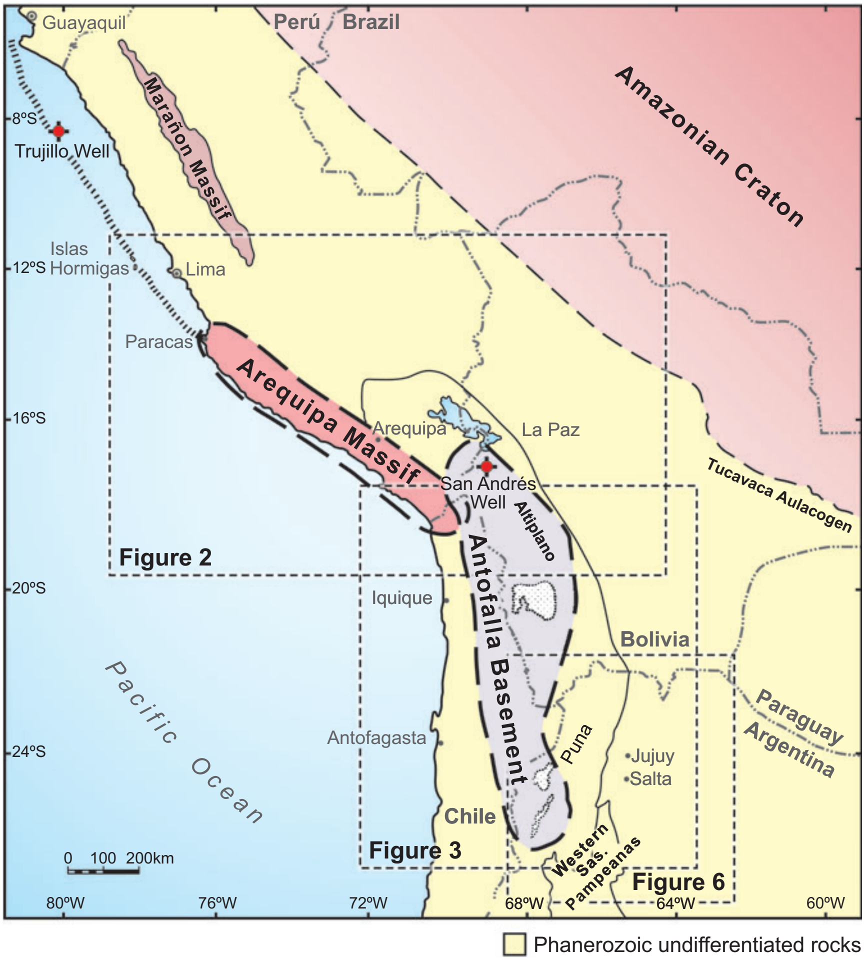

Figure 1

Main basement inliers of the Central Andes (modified from Dalziel & Forsythe 1985, Ramos 1988). Location of the exploration well in the Trujillo basin and outline of the offshore basement high (*dashed line* north of Paracas) after Thornburg & Kulm (1981).

trans-Amazonian belts in the Paleoproterozoic, later remobilized by Brasiliano Neoproterozoic belts. The models for the continental growth of the western Gondwana continent required younger metamorphic ages toward the continental margin, as pointed out by Almeida et al. (1977). This fact led to the proposal of these old basement blocks, such as the Arequipa Massif as a suspect terrane (e.g., Monger et al. 1982) by Coira et al. (1982) and Ramos (1986) (see Terrane and Crustal Growth sidebar).

The ensialic evolution was described by Dalmayrac et al. (1980), where the Arequipa basement was an integral part of South America, and the mobilistic approach, which interpreted Arequipa as a suspect terrane (Coira et al. 1982), was evaluated by Dalziel & Forsythe (1985). These contrasting interpretations of the pre-Andean tectonic evolution of the western margin of South America opened a long-lasting discussion in the following decades. The purpose of this article is to review the existing data and interpretations on the tectonic history of the basement of the Central Andes to evaluate the potential presence of exotic or displaced terranes, and to propose a revised early evolution of the proto-Andes. **Figure 1** illustrates the main basement blocks and the localities discussed in the text.

TERRANES AND CRUSTAL GROWTH

There are two distinct types of orogenic belts, the collisional orogen (Wilson 1966) and the accretionary orogen (Cawood 2005). The crustal growth in a mountain belt in a collisional orogen is formed by convergence and collision of two continents, as in the mountain systems of the Alps and the Himalayas. On the other hand, crustal growth in mountains generated along an active continental margin under subduction may record the accretion of terranes through time and are known as accretionary orogens (Vaughan et al. 2005). The addition of smaller crustal fragments, known as terranes, may end with a continental collision, or may last for hundreds of millions of years, as the Terra Australis orogen along the Pacific margin. There are different types of terranes:

Terrane: a crustal block or fragment that preserves a distinctive geologic history that is different from the surrounding areas and that it is usually bounded by faults.

Accreted terrane: terranes that become attached to a continental margin as a result of tectonic processes, as in western North America (Coney et al. 1980).

Allochthonous terrane: accreted terranes that were emplaced in the present setting derived from other regions, as indicated by the paleomagnetic data and geologic constitution.

Exotic terrane: a terrane whose characteristics are strikingly different from the surrounding areas, for example, the Madre de Dios terrane, in southern Chile. There, a fragment of a low-latitude tropical limestone developed on an oceanic plateau was accreted to the continental margin surrounded by glacigenic deposits (Mpodozis & Forsythe 1983). The exotic terranes are derived from other continents or oceanic realms, and are not native from the continent where they have been accreted.

Para-autochthonous terrane: a fragment detached from the continental margin through a period of rifting and formation of oceanic crust, and later accreted to the same continental margin.

Autochthonous terrane: a fault–bounded crustal fragment that has always been within a few kilometers of its current position.

MAIN BASEMENT BLOCKS ALONG THE PACIFIC MARGIN

There are several basement inliers in the forearc of the Central Andes between 8°S and 26°S latitudes. These inliers are discussed because of their importance and our present knowledge.

The Arequipa Massif

The best preserved basement inlier, named the Arequipa massif by Cobbing & Pitcher (1972), is exposed along the coastal region of southern Perú and northern Chile. This massif has a magmatic and metamorphic polycyclic complex evolution from early Proterozoic to early Paleozoic times.

Proterozoic basement. These rocks are known as Paleoproterozoic based on preliminary U-Pb ages in zircons from granulites of Mollendo area [1910 ± 36 Ma (Dalmayrac et al. 1977)]. The age of metamorphism was based on Rb-Sr isochrones: 1811 ± 39 Ma (Cobbing et al. 1977) and 1918 ± 33 Ma (Shackleton et al. 1979).

Basement outcrops stretch along the Pacific coast for 800 km and extend inland for approximately 100 km (see **Figure 2**). The Mollendo gneisses are preserved in granulite facies associated with dioritic gneisses and meta-igneous basic rocks strongly foliated. Foliated migmatites are also exposed between Quilca and Camaná. Further north at Ocoña, the rocks are intensively deformed constituting phyllonites, where mylonites are frequent (Shackleton et al. 1979). Inland of the previous outcrops, north of the city of Arequipa, similar gneisses, known as the Charcani gneisses, have been dated at 990 Ma (Rb-Sr) by James & Brooks (1976).

More recently, Wasteneys et al. (1995) identified a Mesoproterozoic age based on U-Pb ages from zircon in gneisses from Quilca (1198 ± 4 Ma) and north of Mollendo (approximately 970 Ma). The dating of Loewy et al. (2004) identified a protolith in the northernmost segment with juvenile magmatism and metamorphism between 1.9 and 1.8 Ga (**Figure 2**), whereas the central domain has juvenile magmatism at 1.5–1.4 Ga with metamorphism at 1.2–1.0 Ga. Inherited zircons in both domains suggest an approximately 1900 Ma age for the protolith of the Arequipa massif, as indicated by previous works.

To constrain the age of high-grade metamorphism in the central segment, Th-U-Pb chemical age determinations on monazite were made by in situ microprobe measurements (Martignole & Martelat 2003). The metamorphic ages range from 1064 ± 45 Ma to 956 ± 50 Ma and confirm that an old protolith of 1900 Ma was rejuvenated around 1000 Ma during a regional high-grade metamorphic event. The study indicates an ultrahigh-temperature metamorphic event in the Mesoproterozoic. Two types of heat perturbations have been advocated to explain the ultrahigh-temperature: advection of heat owing to emplacement of mafic or superheated silicic magmas and the upwelling of asthenospheric mantle at the base of continental crust. The Mollendo-Camaná region shows the ultrahigh-temperature event for more than 100 km along coast, implying a thermal influx that can hardly be attributed to local emplacement of magmas. An upwelling of asthenospheric mantle into an already

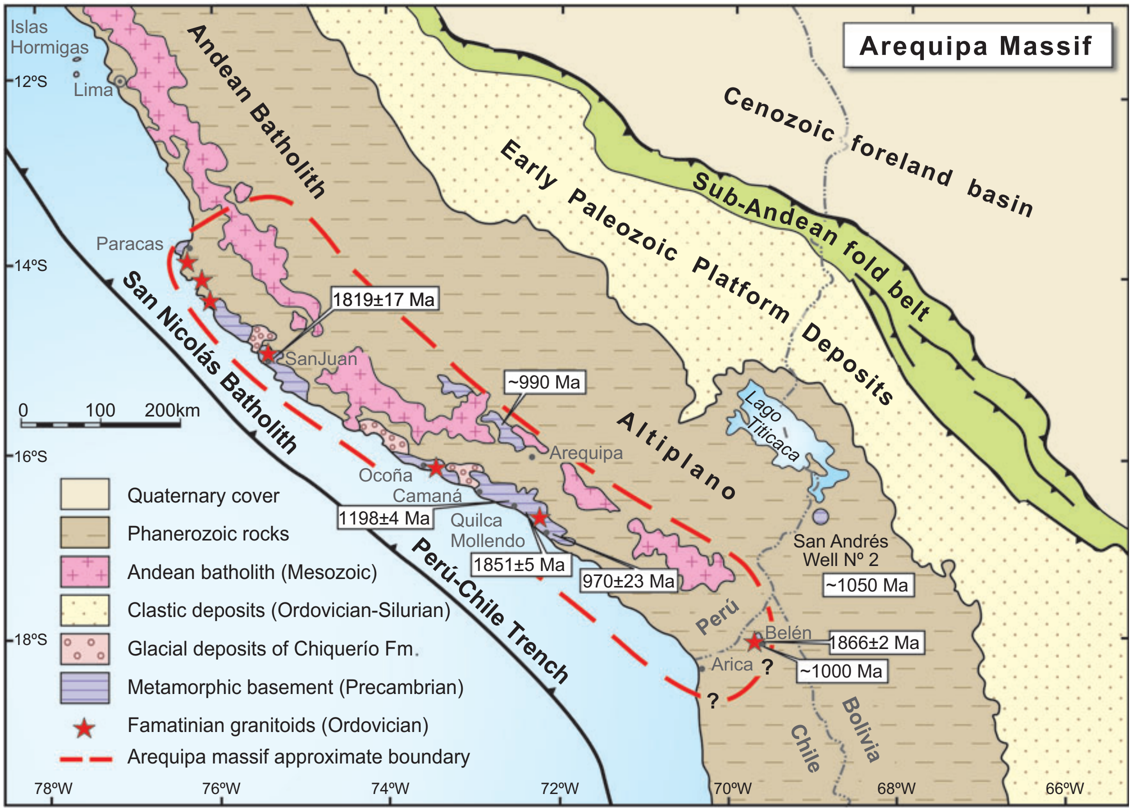

Figure 2

Main outcrops of the metamorphic basement of the Arequipa Massif and its inferred extension along the Coastal Cordillera of Perú (data from Loewy et al. 2004, Wasteneys et al. 1994, Chew et al. 2007a). Also shown is the location of San Andrés well in the Altiplano of Bolivia, south of Lago Titicaca (Lehman 1978). The red stars indicate the intrusions of Ordovician calcalkaline granitoids (Loewy et al. 2004). The outcrops of Chiquerío Formation are shown to emphasize the local derivation of the Grenvillian-age clasts (Chew et al. 2007b). The present extension of early Paleozoic platform sedimentary rocks is also indicated as well as the location of the Andean magmatic arc expressed by the Andean batholith.

overthickened crust is thus the more likely source of heat (Martignole & Martelat 2003).

Lead isotope data available from the Arequipa basement show that it is mainly unradiogenic, with low $^{206}Pb/^{204}Pb$ values ranging from 16.083 to 18.45, $^{207}Pb/^{204}Pb$ from 15.606 to 15.636, and $^{208}Pb/^{204}Pb$ from 36.712 to 38.625, typical of an ancient, high-grade terrane (Mamaní et al. 2007). These data combined with Pb-isotopes from Cenozoic volcanic rocks outline the Arequipa domain, characterized by a basement lead signature from 15°S to 21°S (see **Figure 3**), under a thick cover of Paleozoic to Cenozoic rocks. This new compilation improves the previous lead provinces recognized by Tosdal (1996), Wörner et al. (2000), and Loewy et al. (2004).

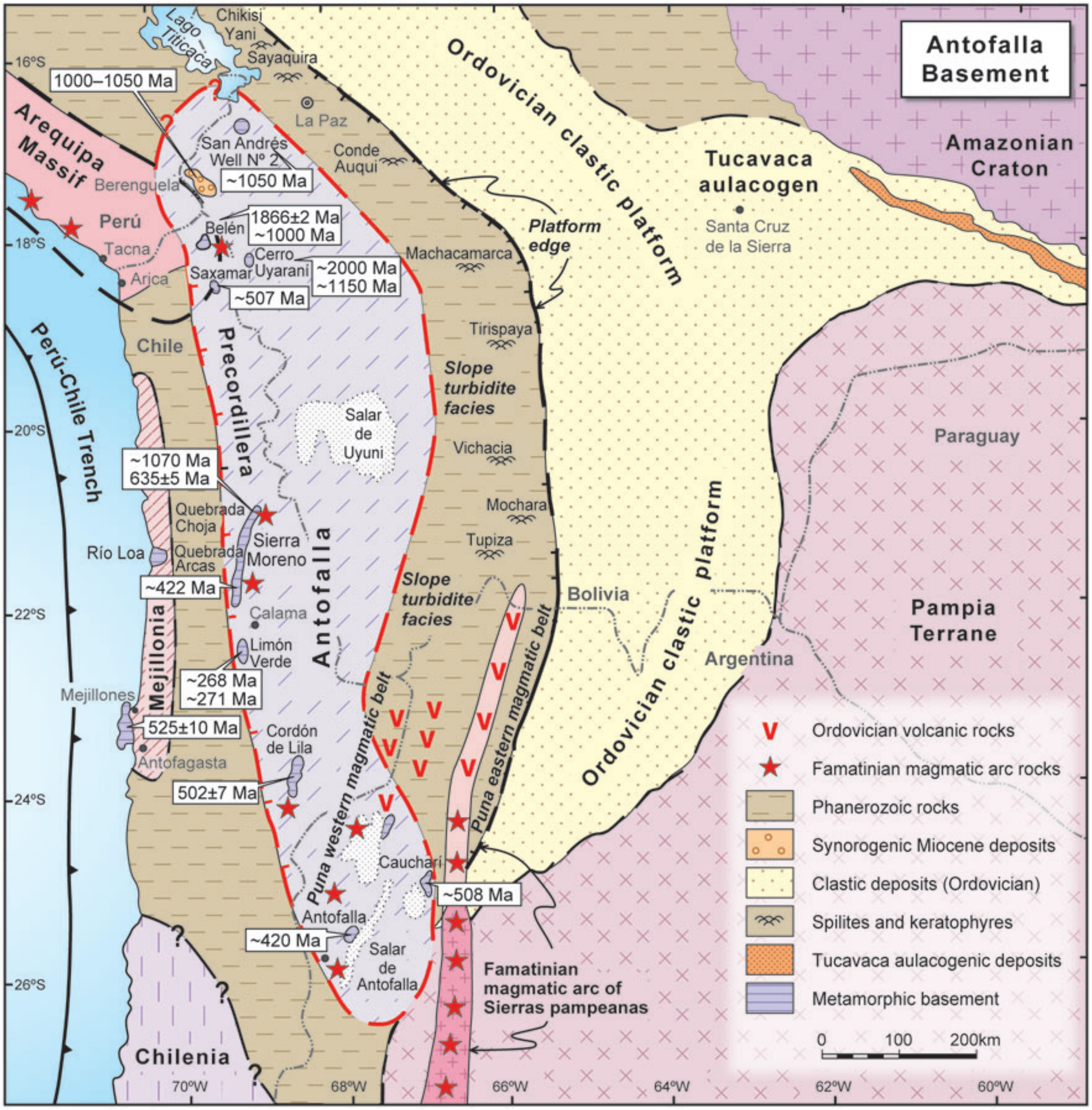

Figure 3

The Arequipa-Antofalla massif in northern Chile and northwestern Argentina. Ages based on Pacci et al. (1981), Hervé et al. (1985), Palma et al. (1986), Basei et al. (1996), Tosdal (1996), Lucassen et al. (2000, 2001), and Loewy et al. (2003, 2004). Terrane boundaries modified from Ramos (1988, 2000) based on gravimetric data of Götze et al. (1994) and Omarini et al. (1999a). Mejillonia and Chilenia basement terranes after Ramos (1988). San Andrés well after Lehmann (1978). Ordovician spilitic and keratophyric rocks associated with slope deposits in Bolivia after Avila Salinas (1992).

These gneisses and granites are covered by the Chiquerío Formation tillite, with clasts with U-Pb ages of 1168 ± 8 Ma, 1162 ± 6 Ma, and ~1165 Ma (Loewy et al. 2004). Recent U/Pb detrital zircons dating in these clasts constrained the maximum ages at 932 ± 28 Ma and 955 ± 18 Ma (Chew et al. 2007a).

Early Paleozoic intrusions and deformation. The Precambrian basement of the Arequipa massif has been emplaced by Ordovician granitoids in the coastal batholith of Perú and northern Chile. Geochemical and isotopic studies in the San Nicolás batholith (**Figure 2**) indicate a calc-alkaline arc character (Mukasa & Henry 1990). U-Pb ages from zircons showed that the calc-alkaline granitoids were formed at 468 ± 4 Ma at Mollendo, 464 ± 4 Ma at Ocoña, ~468–440 at San Juan, and 473 ± 3 Ma and 472 ± 2 Ma at Belén (Loewy et al. 2004). These granitoids with arc-affinities are foliated and are represented by orthogneisses and strongly deformed granites. The younger ages (440–339 Ma) may represent late- to post-tectonic magmatism in southern Perú and northern Chile (Loewy et al. 2004). This magmatism and associated metamorphism are part of a larger event recognized further south as the Famatinian continental arc. This arc developed on the western margin of South America from 515 to 450 Ma, and was followed by a postorogenic magmatism during Devonian and Carboniferous times (Quenardelle & Ramos 1999).

The Antofalla Basement and Other Metamorphic Inliers

Along the coast of northern Chile and in the adjacent Precordillera, as well as in the western Puna of Argentina, there are basement exposures of different ages preserved in mid- to high-grade metamorphic facies.

Proterozoic-early Cambrian basement. The finding of high-grade metamorphic basement in western Puna (**Figure 3**) (Segerstrom & Turner 1972) opened a discussion on its tectonic meaning (Coira et al. 1982). The first attempts joined these outcrops with the Arequipa inliers, assuming a single coherent basement, the Arequipa-Antofalla massif (Ramos 1988). The studies of Baeza & Pichowiak (1988) recognized a belt of metamorphic basement in the Precordillera of northern Chile (~18° to 23°S lat.) along the Belén, Choja, Sierra Moreno, and Limón Verde outcrops, assigned to the Mesoproterozoic based on preliminary U-Pb ages. Recent studies of Loewy et al. (2004) recognized three distinctive domains in the Arequipa-Antofalla basement. The northern domain restricted to the Arequipa massif (14° to 18°S) is characterized by juvenile magmatism and metamorphism between 1.9 to 1.8 Ga, and a magmatic arc around 0.5–0.4 Ga (**Figure 2**). The other two domains are part of the Antofalla segment. The central domain has juvenile magmatism at 1.5–1.4 Ga, metamorphism at 1.2–1.0 Ga, and later magmatism between 0.5–0.4 Ga, extended through northern Chile between Belén and Sierra Moreno. The southern domain with juvenile material between 0.7–0.6 Ga and magmatism and metamorphism between 0.5–0.4 Ga is exposed from Limón Verde in northern Chile to Antofalla in western Argentine Puna (22°–26°S) (see **Figure 4**). The northern and central domains have a low radiogenic lead isotope signature (Mamaní et al. 2007). This basement also has a conspicuous

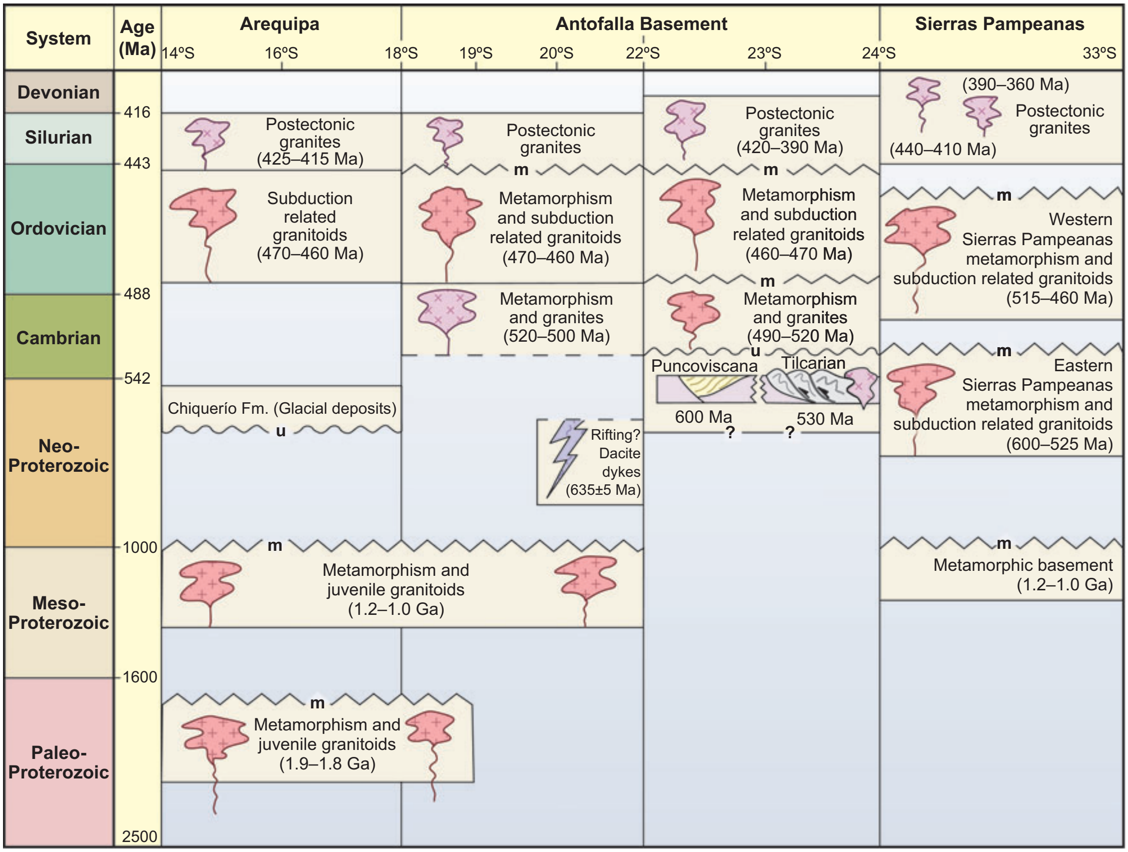

Figure 4

Tectonostratigraphic chart of the Arequipa-Antofalla Massif with main characteristics of the northern, central, and southern domains (modified from Loewy et al. 2004).

Bouguer gravity anomaly that outlines the extension of the sialic basement beneath the thick volcaniclastic cover (Götze et al. 1994).

The northernmost outcrops of the metamorphic basement in Chile (**Figure 2**) are exposed in Belén (Pacci et al. 1981), with a protolith formed by amphibolites and gneisses with U-Pb ages in zircons of 1745 ± 27 Ma, 1877 ± 130 Ma (Wörner et al. 2000), and 1866 ± 2 Ma (Loewy et al. 2004). Orthogneisses of 507 ± 48 Ma were recorded in the Saxamar area further south by the same method (Basei et al. 1996). Another outcrop has been dated by Wörner et al. (2000) in Cerro Uyarani in northwestern Bolivia by U-Pb in zircons with an upper intercept of 2024 +133/–11 Ma, and a lower intercept of 1157 +49/–62 Ma. Proterozoic rocks are also exposed in the east-west–trending Quebrada Choja (**Figure 3**), where migmatitic gneisses containing quartz-biotite paragneiss and granodioritic orthogneiss are cut by dacitic dikes that yielded a crystallization U-Pb age of 635 ± 5 Ma (Loewy et al. 2004). This is the only igneous rock of this age known in the Antofalla basement that may be related to Pampean events. The oldest protolith is indicated by an upper interception of a U-Pb concordia diagram in zircons of 1697 ± 48 Ma (Loewy et al. 2004). The Belén, Cerro Uyarani, and Quebrada Choja metamorphic basements have Paleoproterozoic protoliths with similar ages to the Arequipa massif.

The Mesoproterozoic granulite-facies metamorphism of Cerro Uyarani zircons is similar to the Grenvillian age granulite-facies ranging from 1200 to 970 Ma of the Arequipa massif (Wasteneys et al. 1995), and confirmed by Martignole & Martelat (2003). These last ages coincide with the 1008 ± 16 Ma Sm-Nd and 982 ± 2 Ma Ar-Ar ages of high-grade rocks obtained by Wörner et al. (2000) for the Cerro Uyarani. The existence of Grenville crust beneath the Altiplano was confirmed by the San Andres drill core, with an ∼1050 Ma Rb-Sr whole-rock age (Lehmann 1978), and by U-Pb zircons aged 1150 and 1100 Ma for ortho- and paragneiss clasts, respectively, in Miocene sedimentary deposits of the Berenguela area (Tosdal 1996).

Igneous rocks with similar ages are in the Quebrada Choja [1067 ± 4 Ma for orthogneiss, 1024 ± 5 Ma for granite, and ∼1070 Ma for tonalite (Loewy et al. 2004)]. These ages indicate a magmatic calc-alkaline suite associated with high-grade metamorphism of Grenvillian ages in northern Chile, somewhat similar to the Arequipa massif northern segment. Based on petrological, geochemical, and isotopic considerations, Franz et al. (2006) emphasize the important crustal reworking of these Proterozoic events, with little addition of juvenile material, which produced a quite homogeneous continental crust.

The metamorphic basement of the Precordillera of northern Chile is somewhat different at Limón Verde outstanding exposures. This basement has two distinctive units (Baeza 1984). The western unit is formed by garnet amphibolites and high-pressure gneisses, which are in tectonic contact with gabbros, diorites, and granitoids of the eastern unit. Geochemistry indicates a tholeiitic composition for the metabasites and a calc-alkaline trend for the granitoids. The K-Ar dating of the metamorphic complex yielded late Paleozoic ages (312 to 282 Ma in hornblende), as well as the granitoids (biotite ages between 305 ± 4 Ma and 267 ± 6 Ma) (Hervé et al. 1985). A more precise U-Pb zircon age of 298 ± 1.5 Ma from intrusives confirms these ages (Damm et al. 1990). The petrologic studies of Lucassen et al. (1999a) identified a high-pressure metamorphism for the metabasites, with P-T conditions of 13 ± 1 kbar and approximately 660–720°C, west of the major fault that separates both complexes. These high pressure–low temperature (HP-LT) rocks correspond to a depth of 45 km. These rocks contrast with the high temperature–low pressure (HT-LP) rocks east of the fault, in conditions that are very similar to the gneisses and migmatites exposed in the Sierra Moreno and further north. The HP-LT conditions led Hervé et al. (1985) to interpret these rocks as corresponding to a typical accretionary subduction setting for the late Paleozoic. However, Lucassen et al. (1999b) rejected a collision- or subduction-related accretionary complex, favoring a strike-slip setting. This setting is disregarded here, as there is no structural evidence of strike-slip displacements. Furthermore, it is hard to explain a local exhumation of 45 km of the crust prior to the emplacement of undeformed Triassic granites at ∼218 Ma and the deposition of the late Triassic sedimentary cover by this mechanism.

West of the Limón Verde, two isolated basement outcrops are exposed in the Mejillones Peninsula and in Río Loa along the coast (**Figure 3**). Gneisses and schists of upper amphibolite facies with minor intercalations of garnet-amphibolite are exposed in the central part of the peninsula (Baeza 1984).

In the western part of the Argentine Puna, major occurrences of high-grade metamorphic rocks of upper amphibolite facies are known (**Figure 3**) (Segerstrom & Turner 1972, Allmendinger et al. 1983, Viramonte et al. 1993, Hongn 1994, Becchio et al. 1999). There are also low-grade equivalents of the same lithological units. Rock types consist of metasediments and orthogneiss of granitoid composition, exposed west of the Salar de Antofalla, east of Salar Centenario, and in El Jote areas. All these rocks have a dominant north-south-trending foliation, and they were thrust on Ordovician sediments and their low-grade equivalents during Ocloyic deformation (Ramos 1986, Hongn 1994, Mon & Hongn 1996). Recent petrological and geochronological studies show some common characteristics in these rocks (Becchio et al. 1999, Lucassen et al. 2000). They consist of high-grade metamorphic rocks, formed at mainly LP-HT conditions [3.5 to 6 kbars and 550–630°C (Becchio et al. 1999)]. The metamorphic peak has been dated by Nd-Sm isochrones in 525 ± 10 Ma at Mejillones; 509 ± 1 Ma at Salar de Hombre Muerto; and 505 ± 6 Ma at Quebrada Choja, north of Sierra Moreno (**Figure 3**). The Sm-Nd mineral isochron age of the Salar de Hombre Muerto (509 Ma) is confirmed by a U-Pb age of 508 ± 19 Ma from an orthogneiss in the same area (Becchio et al. 1999), which could indicate the age of intrusion or metamorphism. These ages correspond to the Pampean orogeny (Aceñolaza & Toselli 1981), indicating an important episode of magmatism and deformation in the early to middle Cambrian with a dominant north to north-northeast trend.

Early Paleozoic intrusives and deformation. Granitoids emplaced into the metamorphic basement of northern Chile have yielded Ordovician U-Pb zircon ages of 473 ± 3 and 472 ± 2 Ma (Loewy et al. 2004). These rocks are foliated and an available K-Ar age of 444 ± 14 Ma may indicate the age of the metamorphic event (Pacci et al. 1981). This is confirmed by the 450–460 Ma U-Pb zircon lower intercept ages and K-Ar hornblende ages of the upper amphibolite-facies metamorphism related to the Ocloyic phase by Wörner et al. (2000). This event identifies an important deformation by the end of the Ordovician (Ramos 1986).

Further south in Quebrada Choja, the lower intercept of U-Pb zircon data of a migmatite at 466 +8/–7 Ma and of an orthogneiss at 415 +36/–38 Ma were interpreted as ages of high-grade overprint by Damm et al. (1990, 1994). Similar ages between 490 and 470 Ma representing the Famatinian cycle in northern Chile and the Argentine Puna are well known in the western Faja Eruptiva de la Puna (Palma et al. 1986, Niemeyer 1989, Coira et al. 1999) and in the eastern Faja Eruptiva de la Puna (Coira et al. 1982, 1999; Ramos 1986; Bahlburg & Hervé 1997). The Puna western belt has geochemical and isotopic characteristics typical of a magmatic arc. However, the Puna eastern belt, the northern continuation of the Famatina late Cambrian-Ordovician magmatic arc of Sierras Pampeanas (Ramos 1988, Pankhurst & Rapela 1998, Quenardelle & Ramos, 1999), looses its typical continental arc signature and

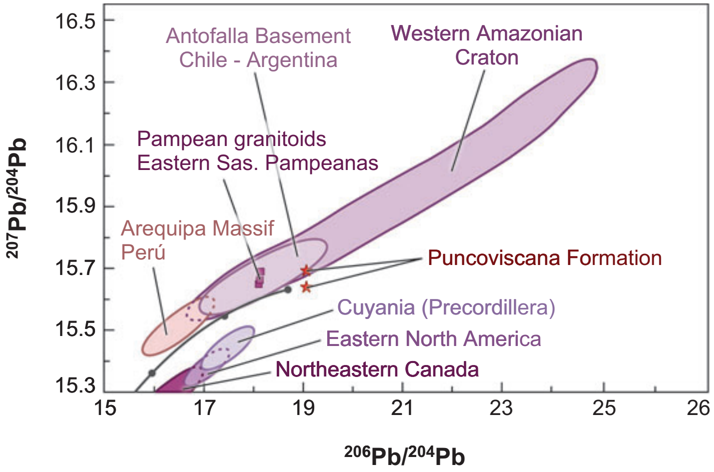

Figure 5

Pb-isotopic signatures of the different basement blocks of the study area (data modified from Tosdal 1996 and Schwartz & Gromet 2004). The main isotopic composition of the main Pampean granitoids of eastern Sierras Pampeanas and rocks from Puncoviscana Formation are also indicated based on Bock et al. (2000).

dies out to the north, changing to extensional bimodal suites of dacites and alkaline pillow basalts (Coira et al. 1999).

The igneous and sedimentary rocks were affected by an important deformation during the middle to upper Ordovician, ranging from south to north, from high-grade metamorphism to greenschists facies (Aceñolaza & Toselli 1981), which were identified by Ramos (1986) as the Ocloyic collisional orogeny.

The Pb-isotopic signature of Antofalla has some gradual differences with the Arequipa basement. **Figure 5** shows the general enriched trend of the Arequipa-Antofalla-Western Amazonia isotope signatures, mainly in comparison with the more depleted Pb-isotope signatures of Cuyania (Precordillera) terrane and eastern North America (see discussion in Schwartz & Gromet 2004). Recent isotopic studies of Mamaní et al. (2007) emphasized these differences.

THE NEOROTEROZOIC–EARLY PALEOZOIC SEDIMENTARY BASINS

The Central Andes from southern Perú to northern Chile and Argentina (8°S–26°S lat.) consist of a series of successive sedimentary basins whose evolution is linked to igneous and metamorphic rocks. There are two main sedimentary cycles, a Neoproterozoic to early Cambrian assigned to the Puncoviscana basin and its northern extension in the Tucavaca aulacogen (**Figure 3**), and a widespread continental platform developed between late Cambrian and Ordovician along the protomargin of west Gondwana.

The Puncoviscana Basin

A belt of very low-grade metamorphic sediments, grading from slates to schists, is recorded in the Puna and adjacent Eastern Cordillera (northwestern Argentina and southernmost Bolivia). This belt extends over 800 km north-south and 150 km east-west (**Figure 6**), and outcrops are preserved from the city of Tucumán at 27°S in the south to the Bolivian border north of 22°S. The several-thousand-meters-thick sedimentary sequence, known as the Puncoviscana Formation, is composed of siliciclastic flysch-like turbidites, pelagic clays, and minor shallow-water limestones, with locally thick lenses of conglomerate at the base. The rocks of the Puncoviscana Formation are gradually overlain to the north by a Paleozoic sedimentary cover. In southern Bolivia, the Puncoviscana Formation is contiguous with the San Cristóbal Formation (Omarini et al. 1999) and based on the ichnofossils correlated with the Tucavaca Group (Durand 1993).

Volcanic rocks interbedded with the Puncoviscana Formation are known from several localities (Coira et al. 1990). There are two different groups: an intraplate mafic alkaline suite at the base with oceanic affinities, and a more tholeiitic suite up in the Puncoviscana section (Omarini et al. 1999). The petrotectonic setting of these rocks suggests a rift regime at the base, which evolved up-sequence to an oceanic realm. The Puncoviscana Formation is emplaced by tonalites and granodiorites in the Santa Victoria and Tastil batholiths, and by more evolved granites such as the Tipayoc and Fundiciones stocks (Toselli 1992). These granitoids were interpreted as immature arcs and are separated by a strong angular unconformity, which developed during the Tilcarian orogeny from the orthoquartzites of the Upper Cambrian Mesón Group (Omarini et al. 1999).

The age of this unit was interpreted as Neoproterozoic based on the ~530–550 Ma age of some Pampean granitoids that are emplaced in deformed graywackes of Puncoviscana Formation (Omarini 1983). However, based on some ichnofossils such as *Oldhamia*, an Ediacaran to Early Cambrian age has been proposed (Durand 1993, Buatois et al. 2000, Aceñolaza & Tortello 2003). This last age is constrained on geochronological grounds by the granitic intrusives emplaced in the Puncoviscana Formation, with ages of 535 and 536 Ma (U-Pb, Bachmann et al. 1987), detrital zircons from 560 to 530 Ma (U-Pb, Lork et al. 1989), and the regional metamorphism ages between 535 and 540 Ma (K-Ar, Adams et al. 1990). A recent U-Pb detrital zircon analysis from classic sequences of this unit confirmed a maximum age of Early Cambrian based on the younger zircons population of approximately 523–534 Ma (**Figure 6**, see ***a*** and ***b***) (Adams & Miller 2007). These younger populations are formed by clean euhedral zircons derived from a volcanic source. These ages coincide with the SHRIMP U-Pb zircon ages of the postcollisional rhyolite developed in northern Sierras Pampeanas after the collision of the Pampia block against the Río de La Plata craton (Leal et al. 2004, Escayola et al. 2007). This provenance from the east is in agreement with the paleocurrents of Puncoviscana Formation measured by Jêzek et al. (1985). In addition to these Pampean ages, the detrital zircons show provenance from the eastern Sierras Pampeanas belt (Ramos 1988, Rapela et al. 1998) and/or from the Sunsás magmatic and metamorphic belt and their continuation in the western Sierras Pampeanas belt (Brito Neves & Cordani 1991, Ramos et al. 1993), and a minor amount of older zircons from the surrounding cratons (Adams & Miller 2007). Although data from detrital zircons from the eastern Sierras Pampeanas are scarce, the available data show two conspicuous peaks, one Pampean (~530 Ma) and the other at approximately 1000 Ma (Schwartz & Gromet 2004), matching the

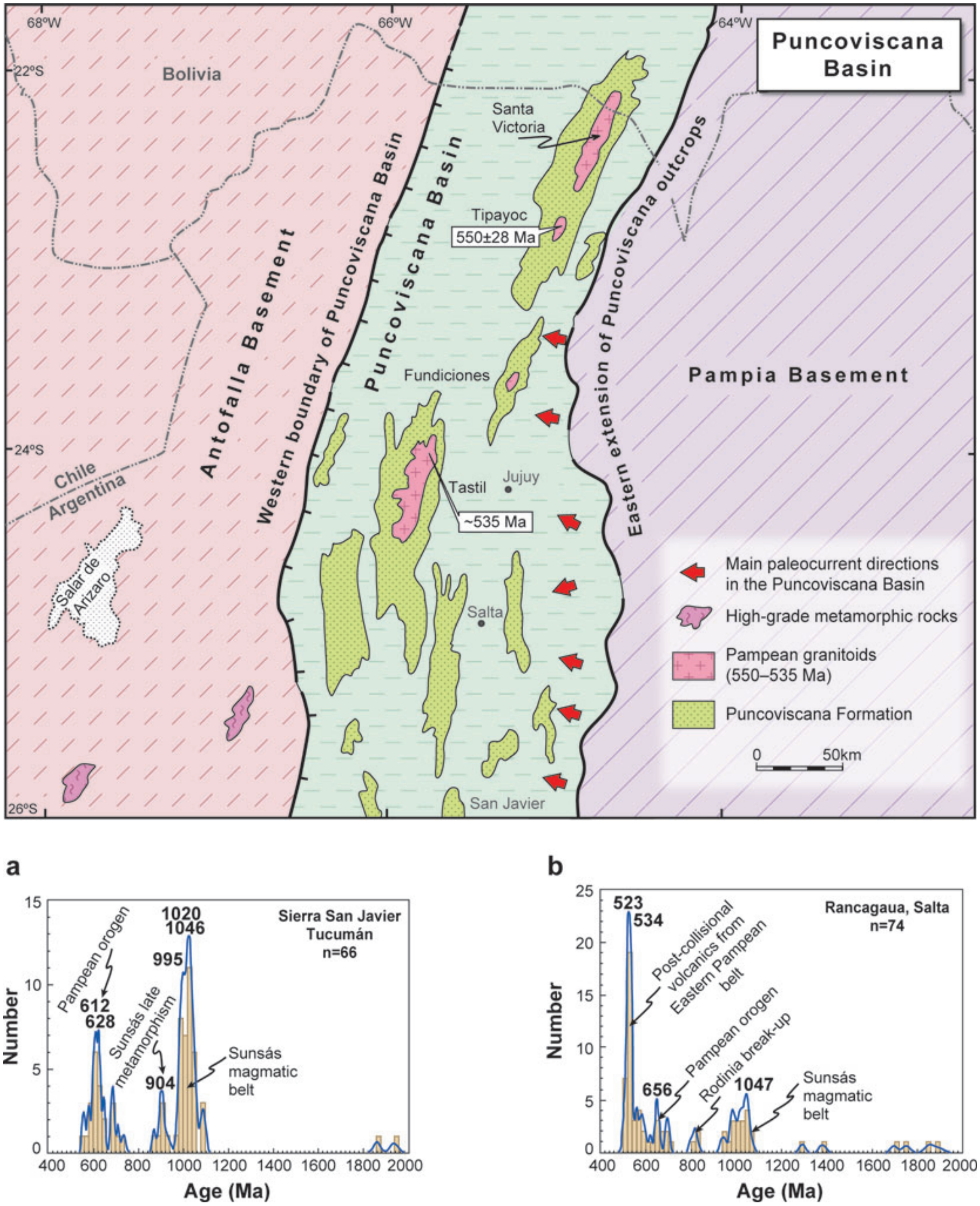

Figure 6

Present exposures of the Puncoviscana Formation and related Pampean granitoids (modified from Jêzek et al. 1985, Omarini et al. 1999a). Detrital zircons from *a* and *b* based on Adams & Miller (2007).

zircon peaks obtained from rocks of Puncoviscana Formation by Adams & Miller (2007).

The provenance study, based on sedimentary petrography and geochemical data from the siliciclastic sequence of the Puncoviscana Formation, shows a composition comparable to foreland basin successions, fed from an eastern fold and thrust belt, but including relicts of pre- and syncollisional magmatic activity as well (Zimmermann 2005). This evidence supports the proposal that the Puncoviscana Formation was a peripheral foreland basin related to the collision of the Pampia block along the eastern Sierras Pampeanas with the Río de La Plata (Kraemer et al. 1995, Keppie & Bahlburg 1999, Escayola et al. 2007). The Pb-isotope study of the sediments by Bock et al. (2000) also found that the Arequipa massif was not a major source for the Puncoviscana Formation. The Pb-signature is closer to western Amazonia or the Antofalla basement, which could be the sources of Puncoviscana debris (see **Figure 6**).

The Early Paleozoic Clastic Platform and Subsequent Foreland Basin

Most of the proto-margin of western Gondwana was characterized by a clastic platform that shows a progression in the ages of the rift-drift transition from north to south along the eastern foothills of the present Andes. The basement of this platform has been described in the Eastern Cordillera of Bolivia by Suárez Soruco (2000), where near Cochabamba city, a sequence of evaporites, conglomerates, and shales of the Avispas Formation may represent the synrift deposits associated with the early opening of the Altiplano basin.

The range of rift-drift transition age along the early Paleozoic platform of the Central Andes is based on the studies of Moya (1988): pre-Llanvirn in the northern sector along the Peruvian foreland (8°–18°S lat.), pre-Llanvirn in the north to pre-Arenig in the south in the Bolivian platform (18°–22°S), and pre-Tremadoc to Late Cambrian further south in Argentina (22°–24°S). These ages clearly indicate that the thermal subsidence starts in the south at approximately 500 Ma, steps forward into Bolivia at 490 Ma, and progresses into the Perú platform at 475 Ma. These old stage names were correlated with numerical ages after Gradstein et al. (2004) and following Astini (2003). The sedimentation was interrupted almost synchronously at the end of Caradoc (after 460 Ma) in the entire segment.

The subsidence studies of Bahlburg (1990) in northern Argentina and Chile identified two different stages in the Late Cambrian–Ordovician. An early stage of thermal subsidence in a clastic platform was followed by a strong flexural loading in a foreland basin as a result of the tectonic staking in the western region during Caradoc times. These two stages are also recognized in the Ordovician of the Altiplano backarc basin of Bolivia, where after middle Caradoc times, there is no deep facies sedimentation as a result of the first compressive deformation at the end of the middle Ordovician. Evidence of contraction is more obvious to the south, as recognized by Sempéré (1995). The same conditions have been recognized in the clastic platform of Perú, where sedimentation also ends in Caradoc times [see review by Moya (1988)].

In a complete synthesis of the Ordovician proto-Andean basins of Argentina and Chile, Astini (2003) presented a detailed paleogeography of the sedimentation well-time-constrained by a rich fauna of graptolites, trilobites, and brachiopods (Benedetto 2003). The west-facing clastic platform during the early to middle Ordovician, with transport directions from the east, contrasts with the middle to late Ordovician turbiditic facies. This Puna Turbidite Complex defined by Bahlburg (1990) marked the beginning of the flexural loading in the western region. This was interpreted by Bahlburg & Hervé (1997) as evidence of the collision of the Arequipa-Antofalla terrane. The tightly folded late Ordovician sequence of the western region of the Puna basin was interpreted also as an Andean fold and thrust belt by Astini (2003). These deformed rocks, accompanying important crustal thickening and shortening, gave rise to the fold belt that in the Sierra de Rinconada is hosting typical gold orogenic deposits dated by Ar/Ar as late Ordovician and Silurian (Bierlein et al. 2006).

The deposits of the Puna basin are interbedded with the calc-alkaline volcanics of the Puna western and eastern belts of early to middle Ordovician age (Coira et al. 1999). Recent studies of the geochemical and isotopic characteristics of the basic rocks have shown contrasting signatures (Coira et al. 2007). The Puna eastern belt is the northern part of the Famatinian belt of the western Sierras Pampeanas (33°S to 26°S) of central Argentina, a typical late Cambrian to middle Ordovician magmatic arc (Ramos 1986, 1988, Pankhurst & Rapela 1998, Quenardelle & Ramos 1999, Dahlquist & Galindo 2004). This belt in the Puna is identified by strongly deformed orthogneisses and granitoids from 26°30′S to 24°30′S, which, north of Cumbres of Luracatao, is exposed at a different structural level, being represented by dacites and rhyolites and minor basaltic pillow lavas (Mendez et al. 1972, Coira et al. 1982, Ramos 1986). This change is also reflected in the geochemistry: to the north it varies from calc-alkaline with subtle arc characteristics to a within-plate alkaline signature (Coira et al. 1999). The Puna western belt has a dominant arc signature in the granitoids and volcanic rocks (Palma et al. 1986) and is associated with oceanic rocks like the Calalaste ophiolites to the east (Zimmermann & van Staden 2002) and the Cordón de Lina tholeiitic basalts (Niemeyer 1989, Damm et al. 1990, 1994). The magmatic rocks represented by the Puna Volcanic Complex of Bahlburg (1990) indicate the presence of a thin crust and oceanic rocks in the central western Puna during the early to middle Ordovician.

Recent geochemical and isotopic studies of Bock et al. (2000) through the entire Puna and Eastern Cordillera of northwestern Argentina show juvenile Nd isotope compositions only for early and middle Ordovician times. The Puna Turbidite Complex, as well as the granitoids of the Puna western belt, has high negative Nd isotope compositions. These led Bock et al. (2000) to conclude that between 20° and 26°S latitude, these rocks are the result of a complete recycling of the continental crust as proposed by Lucassen et al. (1999b) and Franz et al. (2006). These authors have interpreted this orogen as a typical mobile belt.

EVOLUTION OF THE WESTERN GONDWANA CONTINENTAL MARGIN

The evolution of the continental margin of Gondwana in the Central Andean region has two contrasting models. The mobile belt model was proposed mainly along the

Arequipa-Antofalla segment through extensive geochemical and isotopic studies of the Neoproterozoic and early Paleozoic rocks. Igneous activity, sedimentary basin formation, and deformation in this model were part of a mechanism of crustal recycling of the present continental crust, without continental collisions, sutures, and exotic terranes, where the minor patches of oceanic relics were negligible. The region was always an integral part of the Gondwana continent, where its crust has been homogenized through a wide, long-lasting mobile belt as proposed by Becchio et al. (1999); Lucassen et al. (1999b, 2000, 2001); Bock et al. (2000); Lucassen & Franz (2005); and Franz et al. (2006), among others (see Mobile Belts sidebar).

However, several authors have proposed the accretion of allochthonous terranes at different times, in particular the Arequipa-Antofalla terrane (Coira et al. 1982; Ramos 1986, 1999; Ramos et al. 1984, 1986, 2002; Hervé et al. 1987; Forsythe et al. 1993; Loewy et al. 2004). The isolated and discontinuous patches of oceanic rocks (ophiolite) provide evidence for ancient oceans that have been closed during the orogenic movements.

The regional tectonic evolution of the western margin of Gondwana shows a large orogen known as the Terra Australis Orogen that surrounded the present Pacific margin of South America during most of the Paleozoic (Cawood 2005). The accretion took place through a series of basement blocks of either continental or oceanic character that can be further subdivided on the basis of preorogenic geographic affinity

MOBILE BELTS

The term mobile belt was coined by Anhaeusser et al. (1969) to characterize the Precambrian orogenic belts, based on some conspicuous characteristics. Because these fold belts are frequently preserved at middle-lower crustal levels, to understand them, precise petrology and metamorphic studies are required. As pointed out by Trompette (1994), mobile belts consist of particular types of fold belts surrounded by cratons, where metamorphosed and granitized basement is often associated with fragments of reactivated polycyclic basement. The previous authors thought, based on the previous characteristics, that the tectonic regime was ensialic, with dominant vertical movements and conspicuous shear zones. The term mobile belt is also used as an end-member of an orogen, as opposed to modern orogens. The modern orogens show prevailing horizontal displacements, associated with oceanic crust consumption, and are dominated by plate tectonics. Several recent studies have recognized mobile belts in the evolution of northern Argentina and Chile to characterize deformed belts where the polycyclic reworking of ensialic orogens did not have juvenile material, and therefore no apparent evidence of subduction-related magmatism was required. Through these processes, the crust was reworked and homogenized. See, for example, the proposals of the Pampean mobile or early Paleozoic belts of Lucassen et al. (1999 b), Becchio et al. (1999) and the most recent studies of Lucassen & Franz (2005) and Franz et al. (2006).

However, a number of studies have shown that plate tectonics has played an important role in the development of Proterozoic fold belts (Hoffman 1980, Cawood et al. 2006). It was clearly demonstrated that even the mobile belts required subduction of oceanic crust, and the apparent cratonic or entirely ensialic origin is the result of collisional tectonics (see Hoffman 1988 and Cawood 2005).

(Laurentian versus Gondwanan) and proximity to inferred continental margin sequences, such as the peri-Gondwanan terranes.

Along the Pacific margin of Gondwana, the presence of exotic terranes can be detected. One of such is the Cuyania terrane, where the basement, the fauna, the Pb-isotope character, the paleomagnetic poles, and the paleoclimatic conditions of the sedimentation, among other characteristics, suggest an allochthonous origin that subsequently collided against the margin of Gondwana [see reviews by Thomas & Astini (1996), Astini & Thomas (1999), and Ramos (2004)]. During terrane accretion, magmatic arc activity migrates first inboard as terrane accretion causes contraction, and then jumps outboard as a new subduction zone is established (Ramos et al. 1986, Astini et al. 1995).

However, there are para-autochthonous terranes, such as Famatina, Pampia, and Arequipa-Antofalla described by Ramos & Basei (1997), where the colliding terrane has been previously derived from Gondwana through a period of rifting and formation of oceanic crust. The terranes in these cases have Gondwanan affinities and record isotopic and geochemical evidence, as well as previous common orogenies, which can be traced through paleomagnetic data and provenance studies. Recent studies demonstrate that this setting is controlled by tectonic plate reorganization involving changes in convergence direction, including rapid increases in the absolute motion of the overriding plate (Cawood & Buchan 2007). Modification in the absolute motion of the overridden plate is clearly seen during the Mesozoic in the present Andes. Changes in the absolute motion of South America after the separation from Africa produced a change from negative to positive trench roll-back velocity, and a consequent regime modification (Ramos 1999). Widespread regional extension gave place to a compressional regime and the beginning of Andean uplift in the Late Cretaceous (Ramos & Aleman 2000).

Based on these premises, the tectonic evolution of the protomargin of Gondwana will be analyzed during Mesoproterozoic, Neoproterozoic–Early Cambrian, and Ordovician times.

The Grenville-Sunsás Orogeny

Since the early proposals of Rodinia assembly (Hoffman 1991, Dalziel 1997), it was evident that western South America was part of the Rodinia supercontinent. The tectonic scenario that interpreted the Grenville front of North America as a consequence of the collision with Amazonia (see **Figure 7**) was introduced by Sadowski & Bettencourt (1996). The original hypothesis that western Amazonia was the magmatic arc developed along the Sunsás belt, and that Laurentia was the lower plate passive margin, was enhanced by subsequent papers (Dalziel 1997, Cordani et al. 2000, Jaillard et al. 2000, Brito Neves 2003, Fucks et al. 2008). The main drawback of the original proposal was that the magmatic arc was developed many hundreds of kilometers away from the potential suture. Therefore, the existence of an intermediate block, such as the Arequipa-Antofalla terrane (see **Figure 7**), with a magmatic arc (Loewy et al. 2004) not longer than 300 km away from the trench is a more realistic

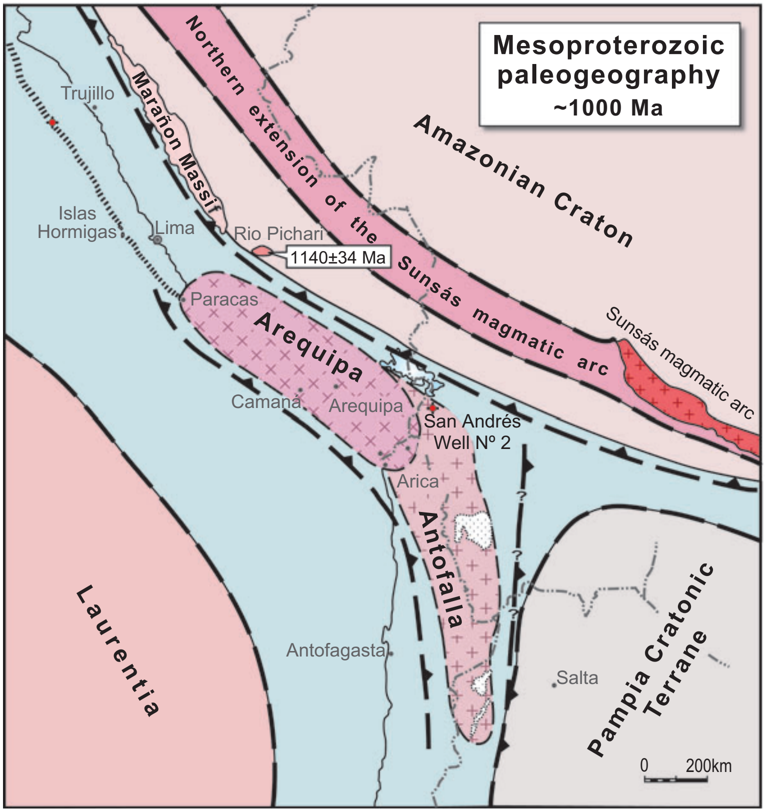

Figure 7

Proposed paleogeography during Mesoproterozoic times that led to the accretion of the Arequipa-Antofalla basement to the Amazonian craton and Pampia cratonic terrane (modified from Ramos 1988, Ramos & Vujovich 1993, Loewy et al. 2004, Fucks et al. 2007).

scenario because present magmatic arcs in the Andes vary from 250 to 300 km from the trench (Ramos & Aleman 2000).

There is consensus among most authors that Laurentia and western Gondwana were amalgamated during the formation of Rodinia. However, there are differences in the amount of continental blocks, outline of the potential terranes, and in the exact relative position between the two continents (Loewy et al. 2003, 2004; Santos et al. 2000). Some authors claim the need of an intermediate terrane, such as the Paragua block between Amazonia and Arequipa-Antofalla (Boger et al. 2005), whereas others locate Amazonia in a different position relative to Laurentia (Cawood et al. 2006, Thover et al. 2006).

The early Pb-isotopes studies interpreted the Arequipa-Antofalla terrane as a para-autochthonous block derived from Amazonia (Tosdal 1996). However, based on a larger database and new U-Pb geochronology, Loewy et al. (2004) favored that Arequipa-Antofalla was an allochthonous terrane owing to the different age patterns between the two cratonic blocks. If we accept the allochthonous character of the Arequipa-Antofalla basement, two different mechanisms are possible to transfer this terrane. A larger continent-continent collision between Laurentia and Amazonia, that

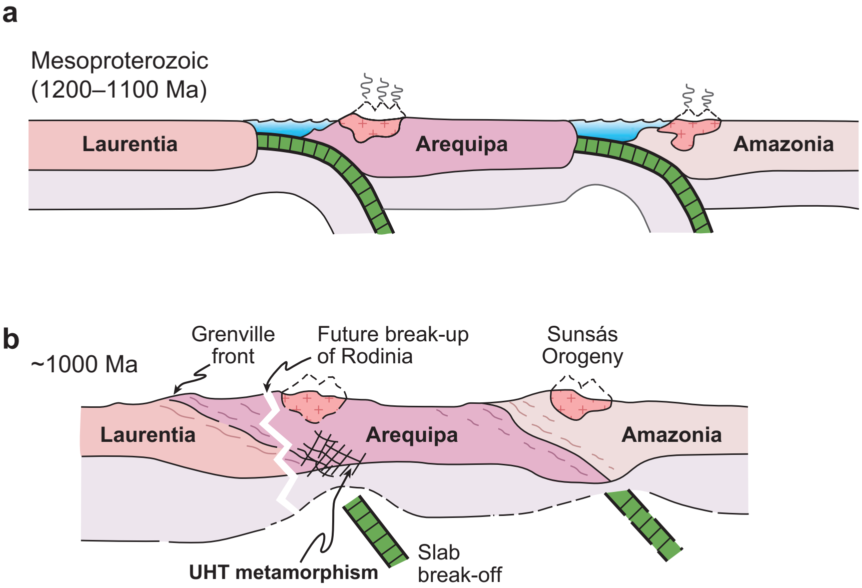

Figure 8

Schematic evolution of the Arequipa basement during the Mesoproterozoic. (*a*) Formation of juvenile magmatic arcs in Arequipa and Sunsás belts. (*b*) Collision during the Grenville-Sunsás orogeny and evidence of asthenospheric upwelling during slab break-off. Future rupture of Laurentia during Rodinia dispersal is also indicated.

left behind the terrane in the Amazonian side during the separation, or the collision of a microcontinent. The frequent Grenville signature of different inliers of the Andes between Colombia and Patagonia and the great variety of isotope composition, chronology, and distribution favor that independent pieces were accreted during the assembly of Rodinia between the two continents as depicted in **Figure 8** (Ramos & Keppie 1999, Cordani et al. 2005, Cawood et al. 2007, Fucks et al. 2008).

The juvenile igneous activity in the Arequipa-Antofalla terrane and the metamorphic peak indicate that docking occurred during the Sunsás orogeny at approximately 1.05 Ga (Loewy et al. 2004). However, it is not clear if the docking occurred only against the Amazonia craton or a more complex setting. The present outline of the Pampia cratonic block indicates that the Puncoviscana basin developed on sialic substrate (Ramos & Vujovich 1993, Omarini et al. 1999). The basement of the basin is not known, but recent U-Pb zircon provenance studies indicate a conspicuous Grenville source (Adams & Miller 2007). The 1020–1046 Ma peak at San Javier (26°S lat.) and the 1047 Ma peak at Rancagua (25°S lat.) of the Puncoviscana basin (see **Figure 6**), together with paleocurrents from the east and southeast obtained by Jêzek (1990), point to a Grenville age basement in the eastern side of the basin. Therefore, it is feasible that in the western side of the Pampia cratonic block there is a Mesoproterozoic basement that interacts with the Antofalla allochthonous terrane. Based on these premises, it can be concluded that the Arequipa-Antofalla basement collided against Amazonia and Pampia, and the amalgamation between Pampia and Amazonia may have occurred at the Mesoproterozoic.

The autochthonous northern extension of the Sunsás belt (Litherland et al. 1985) has a minor exposure in Río Picharí (**Figure 7**), described and dated by Dalmayrac et al. (1980). The authors indicate a possible crystallization age of 1140 ± 34 Ma, and an important lead loss near 1000 Ma of these high-grade metamorphic rocks. This coincides with the time of collision of the Arequipa block. Further north, there is no evidence east of the Marañón massif of Grenville ages in the basement, and according to Mamaní et al. (2007), the isotopic character of the Arequipa domain ends here. Zircons from Paleozoic igneous rocks from the Marañón massif have Grenville inheritance as the main source approximately 1.0–1.3 Ga (Cardona et al. 2005, 2007; Chew et al. 2007b). This indicates that the Amazonian margin north of Arequipa was part of the Grenville-Sunsás orogen. This orogeny led to the formation of the Rodinia supercontinent with the amalgamation of different terranes between Laurentia and the present western margin of Amazonia and Pampia, from Colombia to Chile along the Pacific margin of the continent.

The Pampean-Brasiliano Orogeny

Major plate reorganization took place during the Rodinia break-up. Ultra-high temperature metamorphism, probably related to superheated silicic magmas and the upwelling of asthenospheric mantle at the base of continental crust (Martignole & Martelat 2003) occurred after collision along the Arequipa massif associated with the slab break-off (**Figure 8**). This led to a rifting event probably involving the partial detachment of the Arequipa-Antofalla basement. Dacitic dikes at approximately 635 Ma (Loewy et al. 2004) may indicate the beginning of the rifting in the upper plate block. This time coincides with the age rifting of Laurentia between 625 Ma and 555 Ma as envisaged by the early work of Bond et al. (1984) and Cawood et al. (2001). Although the Arequipa massif has no evidence of detachment, further south along the Antofalla block, an important separation took place (**Figure 9*a***) with the development of the Neoproterozoic–Early Cambrian Puncoviscana basin. Early rifting gave way to the formation of oceanic tholeiitic rocks in the western part of the basin (Omarini et al. 1999). Sediment supply to the basin was enhanced by the collision of Pampia against the Río de la Plata Craton and the formation of a large foreland basin (**Figure 9*b***) (Kraemer et al. 1995, Keppie & Bahlburg 1999). This collision produced the eastern Sierras Pampeanas orogen at approximately 530 Ma (Ramos 1988, Pankhurst & Rapela 1998, Zimmermann 2005). Recent U-Pb detrital zircon studies show that at approximately 523–534 Ma euhedral zircons from volcanic sources were derived from the eastern part of the basin (Adams & Miller 2007) (**Figure 6**). At this time, an important rhyolitic-dacitic province was developed in the northern region of eastern Sierras Pampeanas belt, formed by orogenic collapse of the orogen probably during slab break-off (Leal et al. 2004).

The Early Cambrian was a major time of plate reorganization related to collision and amalgamation that led to the final assembly of Gondwana and the switch from passive margin to subduction along the Pacific margin (Cawood & Buchan 2007). At

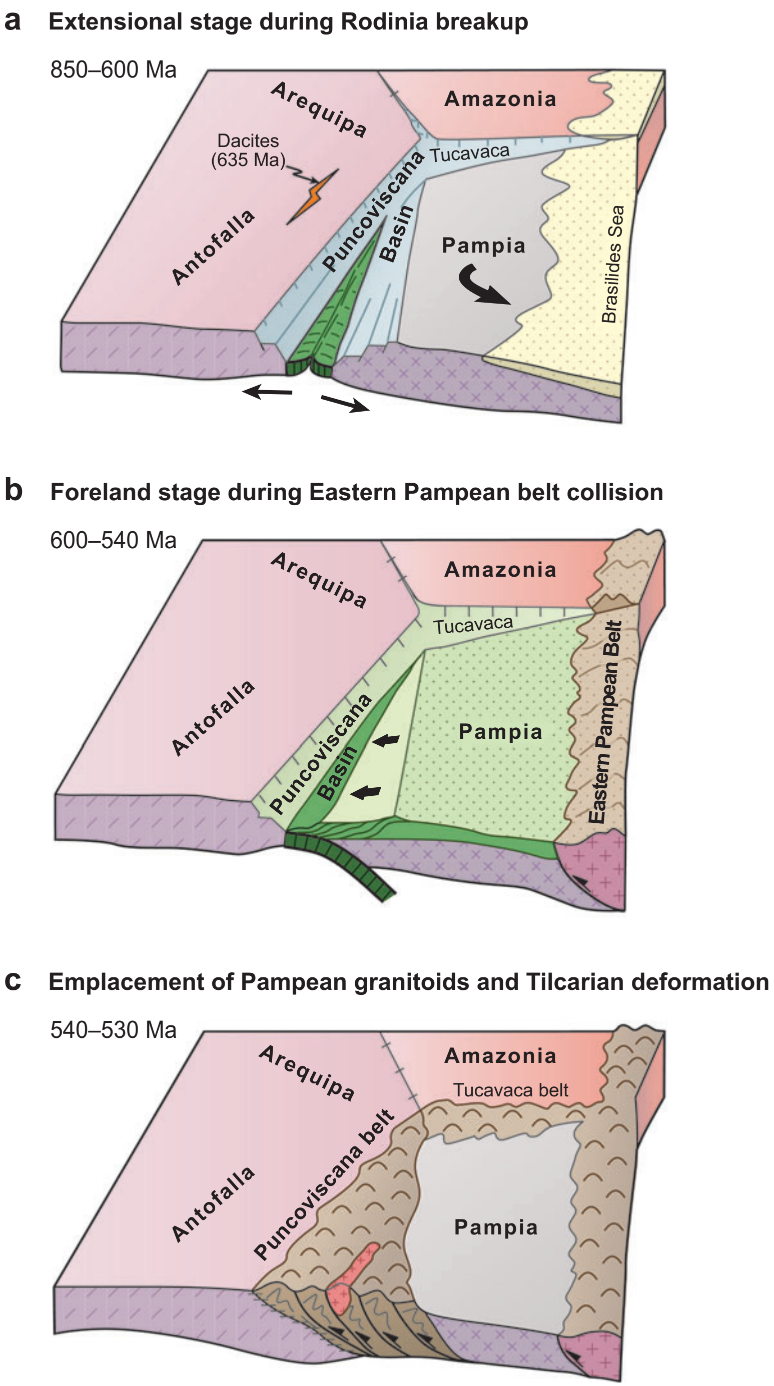

Figure 9

Neoproterozoic evolution of the Puncoviscana belt. (*a*) Synchronous opening of the Tucavaca aulacogen and the Puncoviscana basin. (*b*) Oceanic rocks in the western margin of the basin and beginning of subduction. (*c*) Closure of the Tucavaca aulacogen and formation of the Puncoviscana belt with late emplacement of Pampean granitoids (based on Ramos 1988, Omarini et al. 1999a).

that time, the Puncoviscana basin was closed and the Puncoviscana belt was formed (**Figure 9*c***). Tight folding and low-grade metamorphism precede the emplacement of the calc-alkaline postorogenic Santa Rosa and Tastil batholiths and associated granites (Toselli et al. 1992). These events were probably related to a short period of subduction as proposed by Omarini et al. (1999). A strong angular unconformity, represented by the Tilcarian movements of the Pampean orogeny, separates these rocks from the late Cambrian quartzites of the Mesón Group. This peripheral orogen of the Puncoviscana belt was preserved in low-grade facies, contrasting with the interior eastern Sierras Pampeanas belt where high grade metamorphic rocks are exposed associated with the collision of Pampia with the Rio de la Plata craton in a more interior setting (Ramos 1988).

There is no clear evidence in Perú of the Pampean orogeny. Some isolated and poorly defined Neoproterozoic ages (Dalmayrac et al. 1980, Chew et al. 2007b) should be reexamined, and may be related to the subsequent reaccretion of the Arequipa block against Gondwana. The lack of positive evidence for rifting in the northern segment of the Arequipa-Antofalla terrane, in comparison with what had happened in the southern segment, raises the question of if both basements were a single terrane. The opening of the Puncoviscana basin can be explained by relative rotation of the Pampia cratonic block, which at that time was not attached to the Río de la Plata craton (**Figure 9**). However, it could be that the Antofalla block was an independent block during the Neoproterozoic.

The Famatinian Orogeny

After the reaccretion of the Antofalla terrane against the margin, and the widespread Pampean contractional deformation in central and northwestern Argentina and Chile, a new period of collapse and opening started. The diachronic development of the rift-drift transitions in the clastic platforms through the whole western margin of western Gondwana began at Antofalla at approximately 500 Ma, continued into Bolivia and southern Perú at ∼490 Ma, and progressed north of the Arequipa massif in northern Perú platform at ∼475 Ma. On this basis, three distinctive segments can be recognized (**Figures 10*a*–*c***).

North of Arequipa at the latitude of Marañón massif. Recent studies by Cardona et al. (2005, 2007) and Chew et al. (2007b) have demonstrated that the northern segment (north of Arequipa at the latitude of Marañón massif) was affected by an important early Paleozoic metamorphism preserved in low- to high-grade facies. Their studies have shown for the first time that the high-grade metamorphic rocks of the Marañón massif were not Precambrian, as proposed by the early work of Audebaud et al. (1971). The U-Pb dating of zircon overgrowths from amphibolite-facies schists reveals metamorphic events at approximately 478 Ma (Chew et al. 2007b). They also found a subduction-related magmatic belt (474–442 Ma) in the Eastern Cordillera of Perú and regional orogenic events that pre- and postdate this phase of magmatism. These subduction-related rocks and their metamorphism have a similar geological

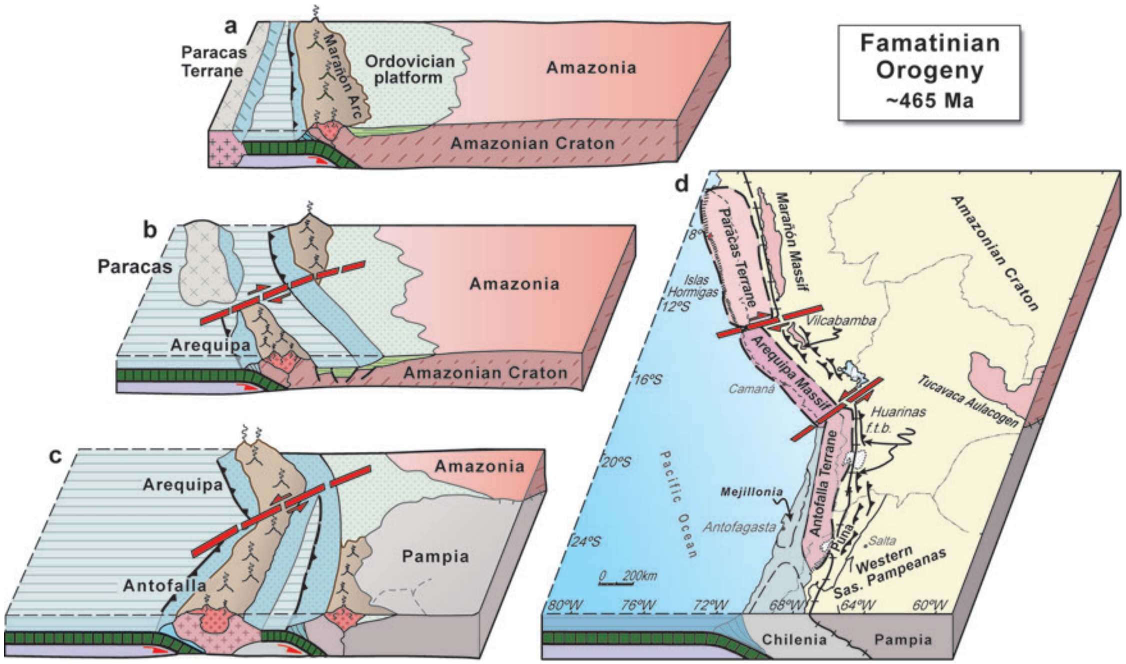

Figure 10

Segmented nature of the evolution of the Paleozoic basement of the Central Andes during the opening of the early Paleozoic basins (*a–c*), and after the closure of the basins during the late Ordovician Famatinian orogeny (*d*). (*a*) Northern segment at the latitude of the Marañón massif; (*b*) central segment at the latitude of Arequipa massif; and (*c*) southern segment at the latitude of Antofalla basement.

and geochronological character to the typical Famatinian rocks of the western Sierras Pampeanas (Pankhurst & Rapela 1998, Quenardelle & Ramos 1999).

Polliand et al. (2005) support the hypothesis that the basement of the Western Cordillera north of 14°S is represented by accreted oceanic material, as it is unexposed. Chew et al. (2007b) suggest that the change in strike of the magmatic belt results from the presence of an original embayment on the western Gondwanan margin during the early Paleozoic, which was then filled by subsequent accretion of oceanic material.

The presence of sialic basement in the offshore platform of central Perú north of 14°S, between the localities of Paracas and Trujillo, is well established (Thornburg & Kulm 1981). The nature of an outer shelf basement high that divides the outer from the inner off-shore basins is validated by (*a*) island exposures of crystalline rocks and metasediments along the ridge in Las Hormigas de Afuera Islands (12°S, 77.8°W) at the latitude of Lima (**Figure 2**); (*b*) borehole data in the Trujillo basin (9°S) that indicate a metamorphic basement (see location in **Figure 1**); and (*c*) gravimetric and refraction data showing a high density (2.7 to 2.8 g cm^{-3}), and a high velocity (5.9 to 6.0 km s^{-1}) ridge continuous along the off-shore platform (Thornburg & Kulm 1981).

The interpreted negative Bouguer anomalies contrasted with the positive anomalies to the west, which are related to the oceanic basement, and the onshore positive anomalies to the east, which are related to the Huarmney basin fill. This Cretaceous basin was filled by up to more than 9 km of mafic pillow lavas and pyroclastic rocks interfingered with limited packages of marine sediments. This clearly indicates that the intra-arc Cretaceous basin was developed by attenuation of preexisting sialic crust, which is still preserved in the offshore platform (Ramos & Aleman 2000).

This attenuated crust, known as the Paracas high, is here interpreted as the Paracas sialic terrane that collided against western Gondwana in middle to late Ordovician times to form the Marañón orogen during the Famatinian cycle. Neither geochemical nor isotopic data are known from these metamorphic rocks, although the studies of Mamaní et al. (2007) indicate a different Pb-isotopic composition north of the Arequipa domain. The Paracas terrane could be interpreted either as a para-autochthonous terrane, such as the Arequipa-Antofalla (Ramos & Basei 1997), and therefore a continuation of the Grenville basement further south, or as an exotic terrane.

Although no geochronological data are available, it is interesting to note the hypothesis of Keppie & Ortega-Gutiérrez (1999), who proposed the location of the Oaxaquia terrane north of Paracas to explain the gap of Grenvillian terranes along the margin between the Arequipa Massif and the Chibcha and related terranes of Colombia (see location of Oaxaquia in figure 2 of Ramos & Aleman 2000). This proposal was based on the geochemical and isotopic composition and Grenville age of Oaxaquia in comparison with the Arequipa basement. In addition, the early Ordovician cover of Oaxaquia reinforces this interpretation. The correlations of Moya et al. (1993) show that the trilobites of late Cambrian–early Ordovician age in Bolivia and northwestern Argentina have several species in common with the Tiñú Formation in Oaxaca, Mexico. This endemic Gondwana fauna is exotic to Laurentia and restricted to a small sector of western Gondwana (Moya et al. 1993, Sánchez Zavala et al. 1999).

Based on these facts, plus the morphology and length of this 1000-km-long coastal segment and the postulated affinities of the basement, Ramos & Aleman (2000) proposed that the basement of the Oaxaquia terrane has been detached from this coastal sector of central Perú. Therefore, the western margin of the Paracas terrane could be the conjugate margin of Oaxaquia terrane left behind on the Gondwana margin during the late Ordovician after the Famatinian deformation recorded in the Marañón arc by Chew et al. (2007b).

At the Arequipa latitude. The rift-drift transition at ~490 Ma of the Bolivian clastic platform at the latitude of Arequipa indicates the end of an extensional regime by the latest Cambrian. The attenuated crust may be associated with spilitic and keratophyric lavas in slope deposits of Bolivia and southern Perú (**Figure 3**) with lower to middle Ordovician age (Ávila Salinas 1992, Sempéré 1995). The Marañón orogen vanished to the south, where the only evidence of it is the low-grade metamorphic rocks of the Cordillera de Vilcabamba near Cuzco (**Figure 10*b***) (Dalmayrac et al. 1980) and some minor occurrences of arc-related volcanics described by Bahlburg et al. (2006). These are subaqueous calc-alkaline rocks recorded near Cuzco and Puno, interbedded with the Ordovician sequences in the Eastern Cordillera and the Altiplano of Perú. The Ordovician rocks in Bolivia were deformed by the Ocloyic orogeny (Allmendinger & Gubbels 1996) but do not have metamorphism.

The tectonic setting of this segment for the early Paleozoic is interpreted as a magmatic arc developed on the Arequipa massif and a backarc basin in an attenuated crust (**Figure 10*b***), represented by the Bolivian clastic platform (Ramos 1988, Sempéré 1995, Bahlburg et al. 2006).

At the Antofalla latitude. At the beginning of the early Paleozoic, the clastic platform shows evidence of an extensional regime at the latitude of Antofalla. The oldest magmatic rocks are basic alkaline within plate sills and lavas emplaced in the Mesón Group Upper Cambrian quartzites in northern Argentina (Coira et al. 1990). This extension reached a climax during the Arenig, when Bock et al. (2000) registered juvenile material derived from the mantle, based on Nd-isotopes. This was a unique time in the Pampean and Famatinian orogenies, when juvenile material was added to the crust. Oceanic rocks of tholeiitic composition have been described during early Ordovician times in western Puna, at the time that pillow lavas of basaltic and andesitic compositions were interbedded with Tremadoc sediments in the Puna western belt (Niemeyer 1989, Coira et al. 1999). This shows an important crustal thinning during the early Ordovician along the central and western sectors of the Puna.

Along the Puna eastern belt, the strong arc signature of the Famatinian belt of western Sierras Pampeanas waned to the north, giving place to an intraplate extensional magmatism (Coira et al. 1999). Evidence of arc magmatism resumes further north in the northern sector, east of the Arequipa Massif in the Peruvian Altiplano and Eastern Cordillera (Bahlburg et al. 2006). However, another relevant set of data come from geophysical studies of northeastern Puna. Detailed gravimetric surveys between 23°–24°S latitude show a high positive Bouguer anomaly beneath the eastern Puna magmatic belt, which requires ultrabasic and basaltic rocks near the surface, interpreted as the roots of the magmatic belt (Gangui & Götze 1996).

Preliminary paleomagnetic data from Sierra de Almeida in western Puna of northern Chile indicate for the late Cambrian–early Ordovician a separation of the Antofalla basement of the order of 1000 km form western Gondwana margin (Forsythe et al. 1993). New paleomagnetic data have been obtained in northwestern Puna from early to middle Ordovician volcanic and plutonic rocks of the Antofalla block (see review of Rapalini 2005). These studies confirm the counterclockwise rotation prior to late Ordovician, and a possible latitudinal displacement. These data also indicate a common polar wandering path with Gondwana after the latest Ordovician to the Devonian.

Through the entire margin of the Central Andes during Caradoc times (Late Ordovician) an interruption of the sedimentation is observed with important deformation in the northern, central, and southern segments (**Figure 10*d***). Along the Antofalla segment, the uplift of the proto-Puna is well documented, as proposed by Bahlburg (1990) and Ramos (2000), and the subsequent migration of the foreland basins to the east during the early Paleozoic are also well documented. Even the

Puncoviscana belt has a low-grade metamorphic peak superimposed on the Pampean Neoproterozoic metamorphism, and dated in 450 Ma (Toselli et al. 1992).

The tectonic evidence of this segment indicates that the Antofalla terrane, after an important period of extension, was separated from Gondwana, and it was later accreted to the continental margin. Paleomagnetic data shows counterclockwise separation that may favor rotation and explain why only the southern area had developed oceanic crust. Therefore, during the subsequent docking of Antofalla, the magmatic arc waned to the north along the eastern Puna magmatic belt resulting in the Ocloyic deformation at Caradoc times. This fact may indicate that the Arequipa-Antofalla terrane of Ramos (1988), may have been at least two independent blocks during Cambrian and early Ordovician times (Bahlburg & Hervé 1997, Rapalini 2005).

The presence of late Paleozoic oceanic rocks related to high-pressure metamorphism between the early Cambrian metamorphic rocks of the Mejillones peninsula and the Sierra de Limón Verde may indicate that this process of separation and reaccretion may have lasted until the end of the Paleozoic in western Gondwana.

CONCLUDING REMARKS

The analysis of the evolution of the basement of the Central Andes from Perú to northern Chile shows a series of processes that affected the whole length of the orogen almost synchronously during the Mesoproterozoic and the early Paleozoic.

The entire Pacific margin of South America shares a common Grenville-Sunsás orogeny as a result of the amalgamation of Rodinia (Hoffman 1991, Dalziel 1997). The Arequipa and Antofalla blocks were trapped between Laurentia and Amazonian and Pampia cratons during Mesoproterozoic times. Juvenile material and metamorphism show that these terranes developed an independent magmatic arc parallel to the Sunsás magmatic arc (Sadowski & Bettencourt 1996). Evidence of this Mesoproterozoic orogeny can be recorded from northern Colombia to Patagonia.

The breakup of Rodinia and the subsequent dispersal was not that homogeneous. Some of the accreted blocks remained amalgamated, whereas others went away. After 635 Ma, the previously accreted blocks acted as para-autochthonous (Cawood & Buchan 2007) or peri-Gondwanan (Ramos & Basei 1997). These terms are used to emphasize that the terranes have been partially or totally rifted away from Gondwana and later on reaccreted to the margin as described by Vaughan et al. (2005). They are not truly exotic as, for example, the Cuyania terrane derived from Laurentia further south (see Thomas & Astini 1996, Ramos 2004).

The synchronicity of the magmatic and tectonic evolution of northern Perú and central Argentina in early Paleozoic times is striking, despite most of Bolivia having a different history. These facts may indicate that subduction and subsequent accretion of the Paracas terrane in the north, and the Antofalla and Cuyania terranes in the south, are consequences of more global processes that encompassed the whole Gondwana, rather than local accidents along the margin. Changes in absolute motion of Gondwana associated with global plate reorganizations as proposed by Cawood & Buchan (2007) may control the coeval time of orogenesis.

Therefore, it is favored that periods of rifting, separation, and reaccretion as documented in the Antofalla segment during Neoproterozoic-Cambrian and late Cambrian–late Ordovician times are the result of changes in plate dynamics at a continental scale. Repeated successions of extensional and contractional regimes are better understood at this scale. The final results of these regimes will be locally controlled by the rheology and thermal state of the continental crust. For example, some blocks are rifted away, as Oaxaquia that left behind the Paracas block, whereas others are reamalgamated to the margin as the Antofalla. Others, such as the Arequipa margin, once accreted to Gondwana had a minor rifting and development of a backarc basin, but stayed together with the Amazon craton.

As a final remark, it is emphasized that the accretionary tectonics along the Pacific margin required oceanic plate subduction, and that docking of terranes is a process that involves transportation by oceanic lithosphere, more than the result of static mobile belts that reworked the continental crust.

DISCLOSURE STATEMENT

The author is not aware of any biases that might be perceived as affecting the objectivity of this review.

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