THE HIGH ANDEAN CORDILLERA OF CENTRAL ARGENTINA AND CHILE ALONG THE PIUQUENES PASS-CORDON DEL PORTILLO TRANSECT: DARWIN'S PIONEERING OBSERVATIONS COMPARED WITH MODERN GEOLOGY

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ABSTRACT

The geological observations made by Darwin in 1835 during his crossing of the Andes from Santiago to Mendoza via the Piuquenes Pass and Cordón del Portillo are compared with the present geological knowledge of the Cordillera Principal and Cordillera Frontal at 33°-34°S. The analysis of the complex stratigraphy of the Cordillera Principal, the imbricated structure of the Aconcagua fold and thrust belt, as well as the stratigraphy and structure of the inter mountain foreland Tunuyán Basin, allows to assess the pioneer observations of Darwin. He recognized the old metamorphic basement and the granitoids and volcanic sequences of late Paleozoic to Triassic age of the Cordillera Frontal, established the Cretaceous age of the marine successions cropping out along the eastern Cordillera Principal and studied the conglomeratic deposits associated with the uplift of the Cordillera in the Alto Tunuyán Basin. Based on the study of clast provenance of the synorogenic deposits of the Alto Tunuyán Basin, Darwin recognized that the Cordillera Frontal was uplifted later than the Cordillera Principal. The present knowledge of this sector of the Andean Cordillera confirms his pioneer observations and show that Darwin was one of the first scientists ever in realizing that in an orogenic system the sequence of uplift and deformation proceeds from hinterland towards foreland, according to a process that is exceptionally well-illustrated along the Piuquenes-Cordón del Portillo transect.

Keywords: *Uplift, Provenance, Structure, Metamorphic rocks, Synorogenic deposits.*

RESUMEN: *La Alta Cordillera de los Andes del centro de Argentina y Chile a lo largo de la transecta del Paso Piuquenes-Cordón del Portillo: Las observaciones pioneras de Darwin comparadas con la geología moderna.* Las observaciones geológicas efectuadas por Darwin en 1935 durante su cruce de la Cordillera de Los Andes entre Santiago y Mendoza realizado en 1835 a través de los pasos del Portillo y Piuquenes son examinadas y comparadas con el conocimiento actual existente de las Cordilleras Principal y Frontal entre los 33°-34°S. El análisis de la compleja estratigrafía de la Cordillera Principal, la estructura de las diferentes láminas imbricadas de la faja plegada y corrida del Aconcagua y la cuenca de antepaís intermonatana del Tunuyán, permiten ponderar las pioneras observaciones de Darwin, quien reconoció el basamento metamórfico y los granitoides y secuencias volcánicas neopaleozoicas a triásicas de la Cordillera Frontal, estableció la edad cretácica de las sucesiones marinas del sector oriental de la Cordillera Principal y describió e interpretó los depósitos conglomerádicos asociados al levantamiento de los Andes en el Alto Tunuyán. Sobre la base del estudio de la proveniencia de los clastos de los depósitos sinorogénicos de la cuenca del Alto Tunuyán pudo reconocer que la Cordillera Principal, fue alzada con anterioridad a la Cordillera Frontal, la que a través de varios pulsos adquirió su altura actual en épocas más recientes. Darwin fue uno de los primeros en reconocer que en un sistema orogénico, la secuencia de deformación asociada al levantamiento orogénico comienza en su región interna desde donde avanza progresivamente hacia el antepaís, como lo demuestran sus brillantes observaciones efectuadas ya hace más de 150 años.

Palabras clave: *Levantamiento, Procedencia, Estructura, Rocas metamórficas, Depósitos sinorogénicos.*

INTRODUCTION

Charles Darwin, a naturalist who thought of himself as a geologist, crossed the Piuquenes and Portillo passes in 1835, during his voyage on board HMS Beagle. The trip, which lasted from March 19th to March 24th, was a milestone in his knowledge of Andean geology. It was in this sector of the Andes that Darwin suspected that the giant mountains were uplifted as late as in the Cenozoic. The idea was a radical one, as well as the interpretation that the different ranges were uplifted one after the other, being the easternmost one the youngest. Later generations of geologists demonstrated that he was essentially right in both concepts.

The Piuquenes and Portillo passes are situated in the southern Central Andes, at 33°40´S (Fig. 1). At these latitudes the Andes are formed by the Cordillera Principal and the Cordillera Frontal. The Piuquenes Pass is situated in the Cordillera Principal, at the border between Argentina and Chile, and the Portillo Pass is located in the high summits of the Cordillera Frontal to the east (Fig. 2). At the time Darwin crossed the Andes through the Piuquenes Pass, this sector of the Cordillera Principal was known as the Peuquenes range or western line, and the Cordillera Frontal, as the Portillo range. These two ranges are separated, by a wide valley filled by Neogene sediments (*Depresión Intermontana del Alto Tunuyán*, Polanski 1957). The Cordillera Principal can be subdivided into a western sector, formed by a thick sequence of Oligocene and Miocene volcanic rocks and intrusives, and an eastern zone corresponding to the strata of Mesozoic sedimentary rocks deformed into the Aconcagua fold and thrust belt (Ramos 1988, Cegarra and Ramos 1996, Ramos *et al.* 1996a). It was observing these rocks that Darwin became astonished to see "*shells which were once crawling on the bottom of the sea, now standing nearly 14,000 feet above its level*" (Darwin 1845, p. 320).

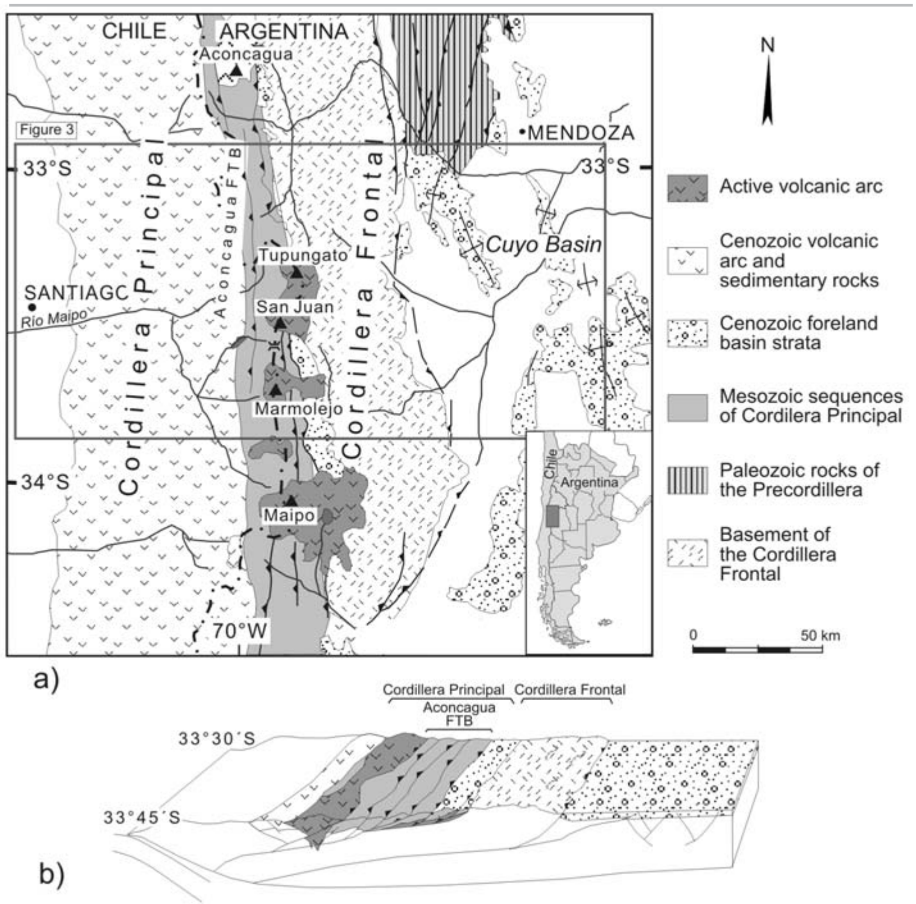

Figure 1: a) Location map of the High Andes with main geological provinces and lithological sequences between Santiago (Chile) and Mendoza (Argentina); b) Block diagram showing the main structures of the Cordillera Principal and Cordillera Frontal with location of the Aconcagua fold and thrust belt.

TECTONIC SETTING

The Andes of central Argentina and Chile are a linear orogenic belt formed at the convergent plate margin between the Nazca and South American plates. At 33°-34° S the Nazca plate subducts beneath the South American plate at a relative velocity of nearly 10 cm/yr (Pardo-Casas and Molnar 1987). The distribution of seismicity suggests that the Nazca Plate is characterized by alternating flat and normal segments of subduction (Barazangi and Isacks 1976, Cahill and Isacks 1992, Pardo *et al.* 2002). Several features of the Andes orogenic system appear to correlate with these changing subduction geometries, such as volcanism and distribution of morphostructural belts and tectonic style (Isacks *et al.* 1982, Jordan *et al.* 1983). North of 33°S, the flat subduction segment lacks active arc magmatism and underlies the Cordillera Principal, Cordillera Frontal, Precordillera and Sierras Pampeanas structural provinces while south of 34°S the "normal" subduction segment of south-central Argentina and Chile shows the active volcanism of the Southern Volcanic zone (see Hildreth and Moorbath 1988, Stern *et al.* 2007) and the orogenic system is much narrower and formed only by the Cordillera Principal and Cordillera Frontal. The study area (33°-34°S) is located along the transition zone between the flat and normal subduction segments (Fig. 3).

STRATIGRAPHY

The stratigraphy, examined in many previous studies such as those of by Polanski (1964), Thiele (1980), Charrier *et al.* (1997), Ramos *et al.* (2000), Jordan *et al.* (2001), Giambiagi *et al.* (2001, 2002), Tunik (2003), Tunik *et al.* (2004), Kay *et al.* (2005), Fock (2005) and Farías *et al.* (2008) includes seven main major tectono-stratigraphic units (Fig. 4): (1) Proterozoic to Lower Triassic metamorphic, volcanic and intrusive rocks; (2) Triassic and Jurassic rift sequences; (3) Titho-Neocomian marine strata; (4) Cretaceous to Paleogene marine and non marine

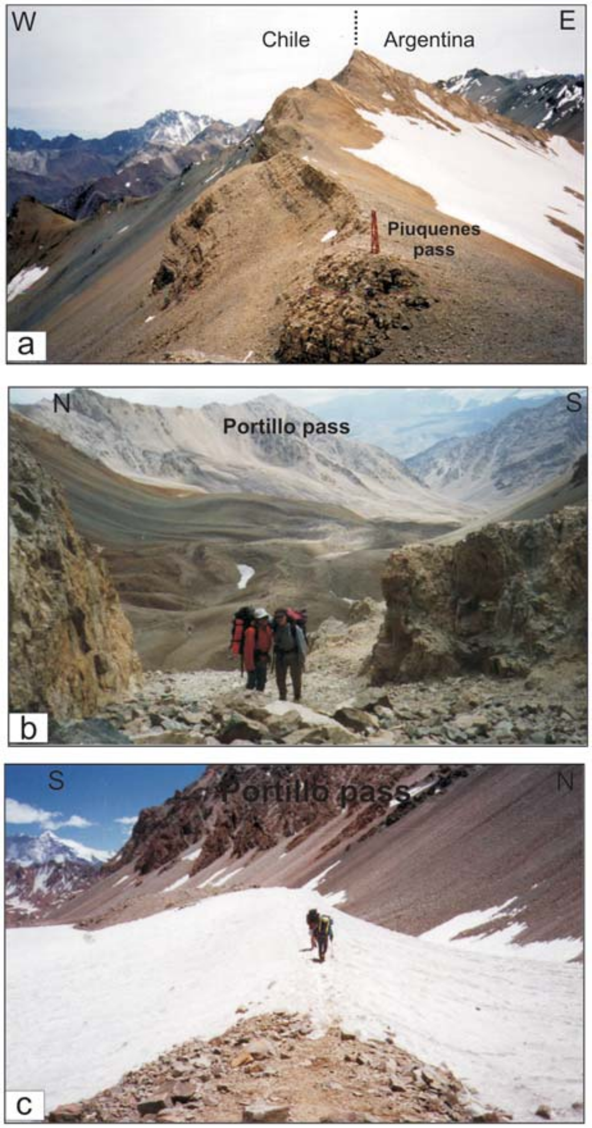

Figure 2: a) Water divide between Chile and Argentina with indication of the Piuquenes Pass. The international landmark (hito) is located on Neocomian limestones; b) Portillo Pass across the Cordillera Frontal. Glacial deposits are overlying late Paleozoic granites; c) Approaching the international boundary along Darwin's trail.

sedimentary rocks; (5) Eocene?-Oligocene to Lower Miocene volcanics; (6) Upper Cenozoic foreland basin deposits; and (7) Upper Cenozoic intrusives and volcanic-arc rocks.

The oldest rocks correspond to Proterozoic mica-schists cropping out at Cordón del Portillo, in the Cordillera Frontal. These rocks were examined by Darwin at the "*base of the Portillo range, ...at a place called Mal Paso. The mica-schist here consists of thick layers of quartz, with intervening folia of finely-scaly mica, often passing into a substance like black glossy clay-slate: in one spot, the layers of quartz having disappeared, the whole mass became converted into glossy clay-slate. Where the folia were best defined, they were inclined at a high angle westward, that is, towards the range... I think it more probable, considering its more perfect metamorphic character and its well-pronounced foliation, that it belongs to an anterior epoch*" (Darwin 1846, p. 184). These rocks are unconformably overlain by Upper Paleozoic marine black shales and sandstones and are intruded by Carboniferous to Permian granitoids (Polanski 1964). These granitoids were clearly identified by Darwin who stated that "*the red granite, from being divided by parallel joints, has weathered into sharp pinnacles, on some of which, even on some of the loftiest, little caps of mica-schist could be clearly seen: here and there isolated patches of this rock adhered to the mountain-flanks, and these often corresponded in height and position on the opposite sides of the immense valleys. Lower down the schist prevailed more and more, with only a few quite small points of granite projecting through. Looking at the entire eastern face of the Portillo range, the red color far exceeds in area the black; yet it was scarcely possible to doubt, that the granite had once been almost wholly encased by the mica-schist*" (Dar-win 1846, p. 184).

Permian-Triassic intermediate and acid volcanic rocks unconformably overlie the previously deformed rocks. As Darwin pointed out, these volcanics reach a thickness of more than 1,700 m. He described these rocks and assigned them a relative age based on their metamorphism and vein intrusion. Rifting was widespread in central Argentina and Chile during Triassic - Early Jurassic times. This was a consequence of extensional processes linked to the initial stages of the fragmentation of Gondwana and the opening of the South Atlantic (Uliana *et al.* 1989). A series of NNW trending rift systems was formed at this time along the western margin of Gondwana (Charrier 1979, 1984, Uliana *et al.* 1989). In the Cordillera Principal, these rift basins, which at this latitude only crop out in the Chilean side of the Cordillera Principal, were filled by Lower to Middle Jurassic black shales (Godoy 1993, Alvarez *et al.* 1997, 1999). In the Argentinean side, a thick layer of evaporites (Auquilco Formation) unconformably rests upon Jurassic marine strata. This was observed by Darwin who was stunned by its more than 600 m thickness. The evaporites grade into the red sandstones and claystones with subordinated conglomerates of the Kimmeridgian Tordillo Formation.

The Jurassic units in the Cordillera Principal are capped by black shales, mudstones, limestones and sandstones, deposited on a stable marine platform during Titho Neocomian thermal times (Biro 1964, Polanski 1964, Aguirre-Ureta 1996). These sedimentary rocks, now grouped into the Mendoza Group, were described in detailed by Darwin who assigned them a Neocomian age based on his collection of invertebrate fossils (see Aguirre-Urreta and Vennari, 2009).

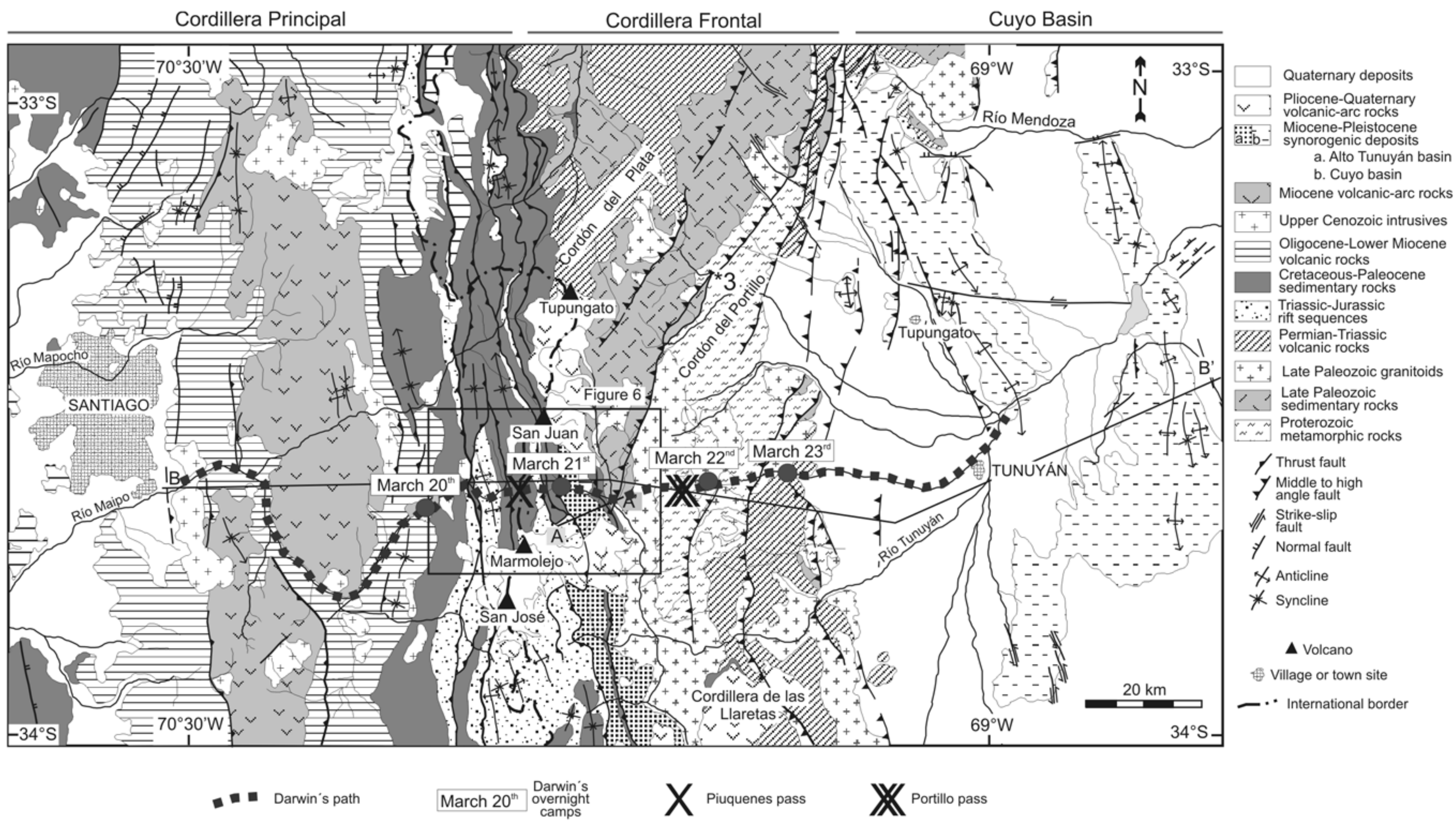

Figure 3: Geologic map of the Cordillera Principal and Cordillera Frontal between Santiago (Chile) and Mendoza (Argentina) based on Giambiagi *et al.* (2003). The trail followed by Darwin, as well as the different camps, are indicated day by day following Darwin's (1845) description.

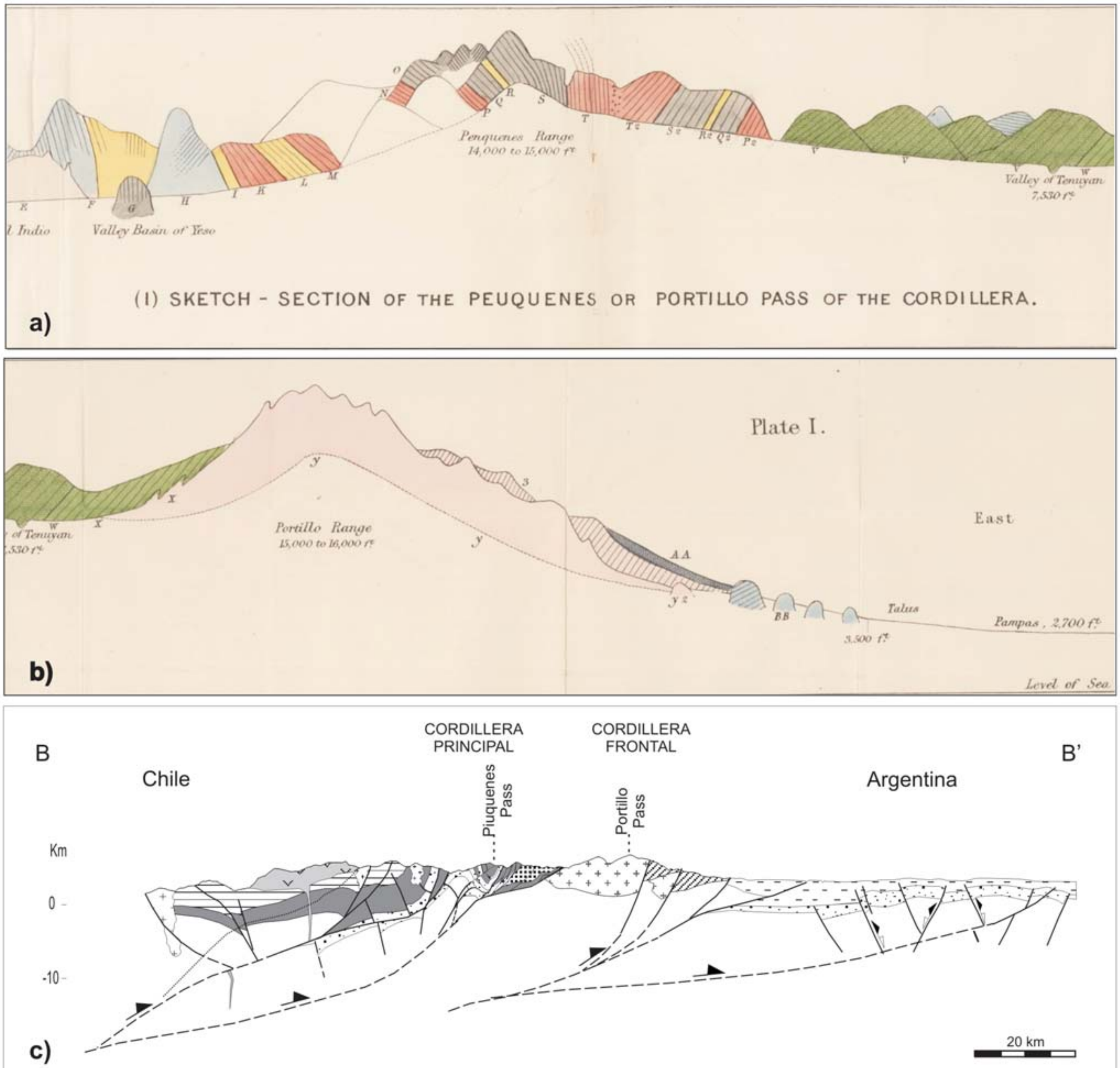

Figure 4: Structural cross sections across the High Andes: a) Section of the Piuquenes pass and b) Portillo pass after Darwin (1846); c) Modern structural cross-section based on Giambiagi and Ramos (2002). Location of the section in figure 3.

The Upper Cretaceous strata, se-parated from the Lower Cretaceous units by an erosional unconformity, consist of conglomerates, sandstones and volcaniclastic rocks. The presence of a continuous interval of Maastrichtian to Da-nian siltstones and limestones deposited during an Atlantic ingression that reached up to the eastern slope of the present-day Cordillera Principal (Tunik 2003, Tunik *et al.* 2004) indicates a subdued relief close to sea level for this region at that time.

After at least 10 Ma of magmatic quiescence, volcanic activity considerably increased in the western Cordillera Principal during the Eocene?-early Miocene (Godoy *et al.* 1996, Charrier *et al.* 1997, Jordan *et al.* 2001, Kay *et al.* 2005, Fock 2005). This volcanic event corresponds to the Abanico and Coya Machalí Formations of Late Eocene to Middle Miocene age (Wyss *et al.* 1990, Flynn *et al.* 1995, Gana and Wall 1997, Charrier *et al.* 2002, Farías *et al.* 2008). that crop out in two north-trending belts made up of basic lavas, tuffs and intermediate pyroclastic rocks, interbedded with sedimentary rocks totalling at least 2,000 m thick. Eocene ages are reported only on the western belt while, in general, volcanic rocks have a primitive isotopic signature indicating crustal thinning and high paleothermal gradient (Nystrom *et al.* 1993, Vergara *et al.* 1988, 1999) during the accumulation of these sequences, probably

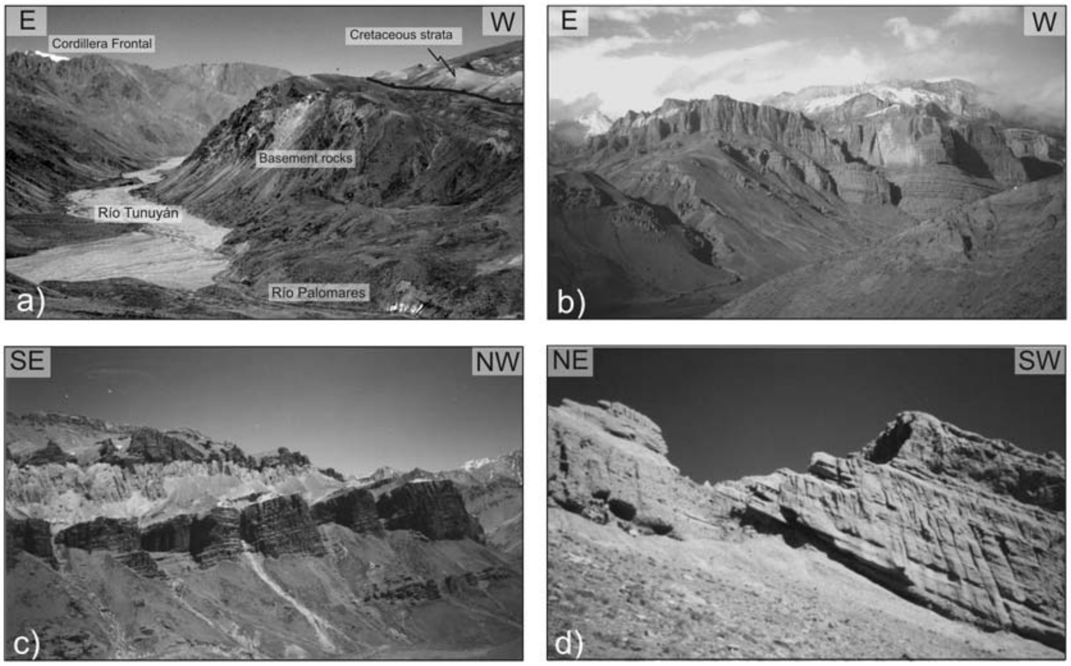

Figure 5: a) Tunuyán and Palomares rivers, looking southward. Cretaceous marine strata unconformably rest over the Paleozoic basement rocks of the Cordón del Portillo; b) Tunuyán Conglomerate in the Palomares river; c) Tuffs and conglomerates of the Palomares Formation unconformably resting over the Tunuyán Conglomerate; d) Butaló Formation.

in a volcano-tectonic extensional /transtensional basin (Charrier *et al.* 1997, 2002, Godoy *et al.* 1999, Jordan *et al.* 2001, Fock 2005). The Abanico and Coya Machalí Formations are covered by 2,000 m of Miocene calc-alkaline andesitic lava and acid pyroclastic flows of the Farellones Formation from which radiometric ages spanning from 20 Ma to 7 Ma have been reported (Rivano *et al.* 1990). This unit is intruded by several epizonal granitoid plutons and stocks, some of them associated with the giant copper-porphyry copper deposits of Río Blanco and El Teniente with show radiometric ages constrained between 10 to 6 Ma (Cornejo and Mahood 1997, Kurtz *et al.* 1997, Maksaev *et al.* 2004, Deckart *et al.* 2005). During this journey across the Cordillera Principal Darwin observed massive rocks which "*rarely contain any quartz*" intruded among the volcanic strata that probably correspond to sub volcanic dykes and sills emplaced in the volcanic sequences. Finally, the youngest geological units of the Cordillera Principal at this latitude correspond to large composite Quaternary stratovolcanoes such as the Tupungato, San Juan, Marmolejo and San José, being these the northernmost volcanic centers of the Southern Volcanic Zone (SVZ) of the Andes (Hildreth and Moorbath 1988, Stern *et al.* 2007).

Along the eastern slope of the Cordillera Principal, in Argentina, the oldest Cenozoic volcanic unit is the Contreras Formation, exposed at the base of a thick sequence of Neogene synorogenic deposits, and consisting of basaltic lava flows and breccias. A sample from the middle sector of this unit yielded a whole rock K-Ar age of 18.3 Ma (Giambiagi *et al.* 2001). Its geochemistry suggests a retroarc setting in a thickening crust during its extrusion (Ramos *et al.* 1996b). Late Cenozoic foreland clastic deposits occur to the east of the Cordillera Principal. Miocene sedimentary rocks filling the Alto Tunuyán Basin include three units. The oldest Tunuyán Conglomerate consists of up to 1,400 m of conglomerates and sandstones deposited in an alluvial-fan setting (Fig. 5b).

The vertical variation in clast composition and paleocurrent data reflect the progressive erosion and unroofing of the Aconcagua fold and thrust belt (Giambiagi 1999). The synchronism of deposition of the upper 400 m of this unit with the emplacement of thrusts within the basin is documented by syntectonic unconformities. Deposition of the Tunuyán Conglomerate started around 18 to 17 Ma, and continued to ~10 Ma. The intermediate Palomares Formation filled a gentle paleorelief in the Tunuyán Conglomerate between 8.5 and 7 Ma and consists of 200 m of volcaniclastic and clastic sediments deposited in an alluvial-fan setting (Fig. 5c). The Cordillera Frontal was the main source area of this unit, as indicated by clast composition, paleocurrent measurements and syntectonic geometries (Giambiagi *et al.* 2001). The Butaló Formation records the final infilling of the sedimentary trough, reaching a thickness of more than 300 m, and is made up of fluvial and lacustrine deposits (Fig. 5d). It is unconformably overlain by andesitic volcanic rocks dated at 5.9 Ma (whole rock K/Ar age, Ramos *et al.* 2000). Darwin's description of the Conglomerate of Tenuyan (*sic*) indicated that "*the included pebbles are either perfectly or only partially rounded: they consist of purplish sandstones, of various porphyries, of brownish limestone, of black calcareous, compact shale precisely like that in situ in the Peuquenes range, and containing some of the same fossil shells; also very many pebbles of quartz, some of micaceous schist, and numerous, broken, rounded crystals of a reddish orthitic or potash feldspar (as determined by Professor Miller), and these*

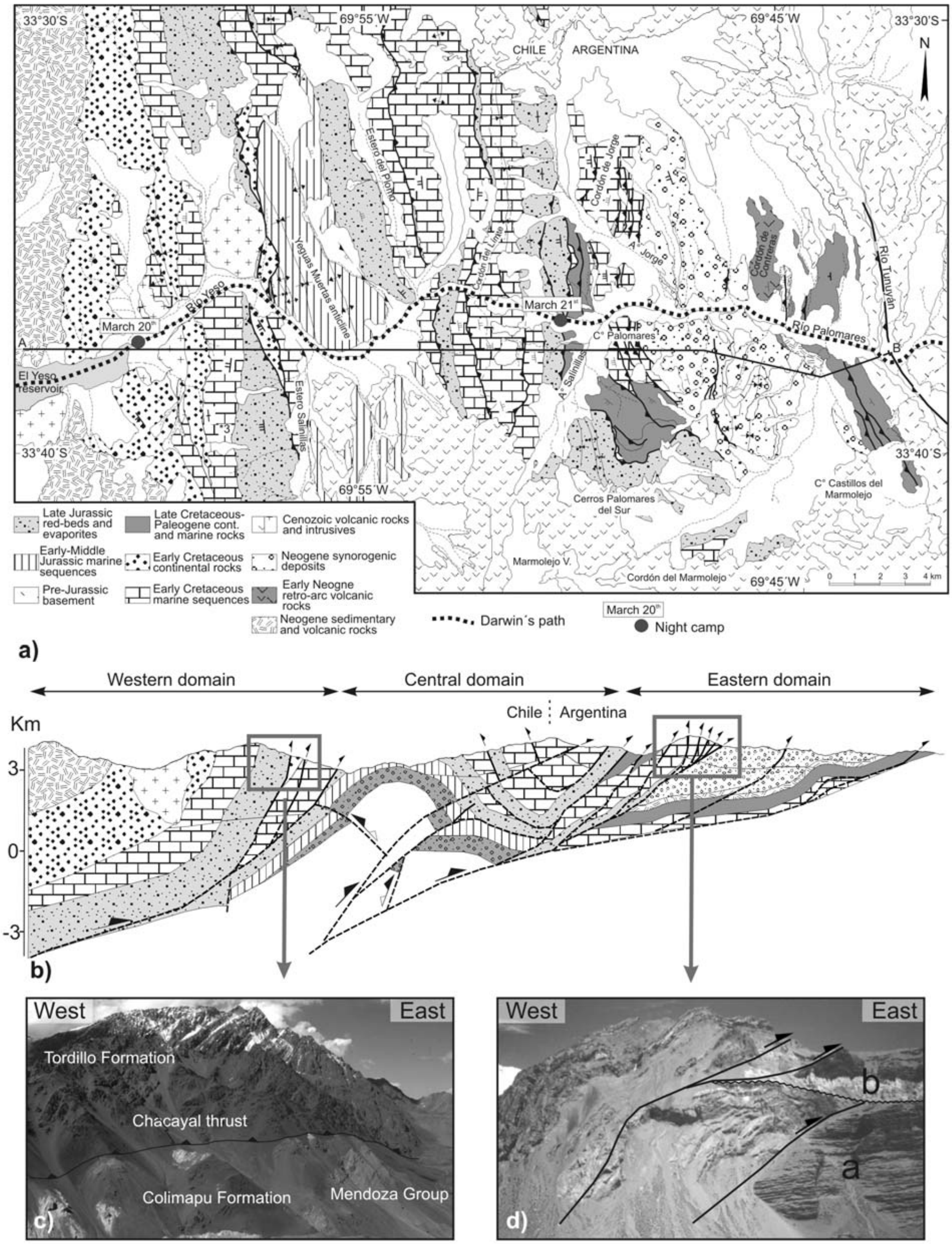

Figure 6: a) Geological map of the Aconcagua fold-and-thrust belt in the Yeso and Palomares river (modified from Giambiagi *et al.* 2003) See location in figure 3; b) Structural cross-section A-B (Giambiagi and Ramos 2002); c) The Chacayal thrust in the Chilean slope of the Cordillera Principal, uplifting Late Jurassic red beds (Tordillo Formation) over Early Cretaceous continental and marine sequences (Colimapu Formation and Mendoza Group); d) Southern view of the Cerro Palomares. The Palomares fault system uplifts Cretaceous limestones over the Neogene synorogenic strata of the Tunuyán Conglomerate (a) and the Palomares Formation (b).

from their size must have been derived from a coarse-grained rock, probably granite. From this feldspar being orthitic, and even from its external appearance, I venture positively to affirm that it has not been derived from the rocks of the western ranges; but on the other hand it may well have come, together with the quartz and metamorphic schists, from the eastern or Portillo line, for this line mainly consists of coarse orthitic granite. The pebbles of the fossiliferous slate and of the purple sandstone, certainly have been derived from the Peuquenes or western ranges." (Darwin 1845, p. 182).

STRUCTURE

Aconcagua Fold and Thrust Belt

During his ride through the Piuquenes Pass Darwin felt admiration for the inclined to overturned Mesozoic layers which had been formed undersea and later uplifted and deformed in an "*extraordinary manner*", reaching an altitude of more than 4,000 m (Figs. 4 a and b). Presently, the Argentine eastern sector of the Cordi-llera Principal is interpreted to form part of the Aconcagua fold-and-thrust belt. This belt can be divided into two do-mains (Fig. 6b, c).

The structure of the western domain is dominated by open NNW trending folds and N-S thrust faults. The majority of these thrusts cut the previously developed fold structures and show an eastward vergence, with the exception of a belt of west verging back-thrusts located at the border between Argentina and Chile (Fig. 4c). Although the basement does not crop out, its involvement is deduced from the geometry of the structure and significant thickness variations of the deformed Mesozoic successions (Giambiagi *et al.* 2003). The eastern domain is broad and narrows towards the south until it disappears south of Volcán Marmolejo. This domain is characterized by a dense array of imbricate low-angle thrusts which exhibits flat and ramp geometries, with flats corresponding to *decóllement* levels located on the Late Jurassic evaporites and Early Cretaceous shales. In this sector of the belt it is common to observe thrusts cutting previously developed structures, some of them showing younger-over-older relationships. This is the reason why it is interpreted as evolved by a forward propagating thrust sequence with periods of out-of-sequence thrusting

The Alto Tunuyán Foreland Basin

The Alto Tunuyán Basin is a Neogene foreland basin located between the Cordillera Principal and the Cordillera Frontal, from 33°30´ to 34°S. The basin was generated by lithospheric flexure as response to thrust belt load of the Aconcagua fold and thrust belt and was filled with more than 1,800 m of continental synorogenic deposits of the Tunuyán Conglomerates and the Palomares and Butaló Formations. These strata were deformed as the Aconcagua fold-and-thrust belt deformation migrated eastward and cannibalized the foreland basin. One of Darwin's first geological observation was that the constitutions of the two ranges are totally different and that "*one part of the double line of mountains* (Cordilleras Principal and Frontal) *is of an age long posterior to the other*", which is nowadays known as the normal sequence of deformation and uplift of an orogenic system, from the hinterland to the foreland. It is interesting to remark how Darwin, based on a provenance analysis of conglomeradic clasts, was able to infer the order and the relative uplift age of each mountain chain across this section of the Andes. He noted that between the two main ranges "*there rest beds of a conglomerate several thousand feet in thickness, which have been upheaved ... and dip at an angle of 45° towards the Peuquenes line. I was astonished to find that this conglomerate was partly composed of pebbles, derived from the rocks, with their fossil shells, of the Peuquenes range; and partly of red potash granite, like that of the Portillo. Hence we must conclude, that both the Peuquenes and Portillo ranges were partially upheaved and exposed to wear and tear, when the conglomerate was forming; but as the beds of the conglomerate have been thrown off at an angle of 45° by the red Portillo granite ..., we may feel sure, that the greater part of the ... upheaval of the already partially formed Portillo line, took place after the accumulation of the conglomerate, and long after the elevation of the Peuquenes ridge. So that the Portillo, the loftiest line in this part of the Cordillera, is not so old as the less lofty line of the Peuquenes. Evidence derived from an inclined stream of lava at the eastern base of the Portillo, might be adduced to show, that it owes part of its great height to elevations of a still later date. ... In most parts, perhaps in all parts, of the Cordillera, it may be concluded that each line has been formed by repeated upheavals*" (Darwin 1845, p. 320). These conglomerates are now part of the Alto Tunuyán Basin (Polanski 1957), an intermontane basin studied by Giambiagi (1999), who confirmed the uplift sequence by means of precise provenance studies. The Alto Tunuyán Basin structure comprises thin-skinned fold-thrust sheets above a *decóllement* developed in Late Cretaceous siltstones. Within this zone, faults related to syntectonic unconformities recorded in the upper part of the Tunuyán Conglomerate indicate sedimentation above an active thrust (Giambiagi *et al.* 2001). Other faults indicate activity after deposition of the Neogene units. The structure in this domain intrigued Darwin, who observed that the newer coarse conglomerates dipped directly under the much older beds of gypseous and limestone units. He stated that the Mesozoic strata has been broken up by "*several, distinct, parallel, unilinal lines of elevation*" and estimated a vertical throw of over 600 m. These lines of elevation represent the complex thrust system of the Cerro Palomares (Fig. 6d).

Cordillera Frontal

The Cordillera Frontal consists of several basement blocks uplifted east of the Aconcagua fold-and-thrust belt. During the Late Cenozoic compression - at the latitude of the Portillo Pass- it behaved as a rigid block disrupted by medium to high angle faults showing two regional trends of structures, i.e., NNE-trending faults in the northern region and N to NNW-trending faults in the southern half, related to Late Paleozoic structures. A deep crustal detachment level is required in order to propagate shortening within the Cordillera Frontal. This detachment is inferred to be located between 15 and 20 km deep, probably within a brittle-ductile transition.

GEOMORPHOLOGY

Darwin stated "*in the course of ages in this* (referring to the Cachapoal) *and other valleys, events may have occurred like between, but even on a grander scale than, that described by Molina, when a slip during the earthquake of 1762, banked up for ten days the great river Lontué, which then bursting its barrier inundated the whole country and doubtless transported many great fragments of rocks*" (Darwin 1846, p. 66-67). However, "*not withstanding this one case of difficulty*" he then claimed that "*one of the most important conclusions to which my observations on the geology of South America have led me*", is his lengthily exposed conviction that the "*terrace-like fringes, which are continuously united with the basin-shaped plains at the foot of the Cordillera, have been formed by the arrestment of river-borne detritus at successive levels, in the same manner as we see now taking place at the heads of all those many, deep, winding fiords intersecting the southern coasts*." Due to this view Darwin failed to recognize the Meson Alto landslide and the plain in the Yeso valley (Embalse El Yeso in Fig. 6a) and refers to it as "*the one exception in which a range was dislocated by a great and abrupt fault*" In page 178 this plain is described as a "*drained lake*", yet once more no relation to a landslide is mentioned. The dam of this paleolake was later described as a moraine and only recently has it been recognized as part of a big landslide derived from the granitic southern slopes of the Yeso valley (Abele 1981).

STRUCTURAL EVOLUTION OF THE ANDES AT 33°40´S

Here we integrate recent structural and sedimentological studies carried out at 33°-34° S (Godoy 1993, Godoy *et al.* 1996, 1999, Ramos *et al.* 1996b, 1997, Giambiagi *et al.* 2001, Giambiagi and Ramos 2002, Giambiagi *et al.* 2003) as a way to understand what was envisaged by Darwin's during his early observations.
During the early Miocene - between 20? and 15 Ma - shortening associated with inversion of the Mesozoic and Early Cenozoic extensional systems started diachronically in the Cordillera Principal. At around 18 Ma deformation and uplift generated a western sediment source for the lower part of the foreland Tunuyán Conglomerate, which at 15 Ma shows an abrupt change in clast composition indicated by the first appearance of Mesozoic sedimentary debris (Giambiagi 1999, Irigoyen *et al.* 2000). This is considered as evidence for a second phase of deformation, linked to E-W shortening along the eastern Cordillera Principal. Continued migration of deformation toward the foreland is documented by the occurrence of growth structures in the upper section of the Tunuyán Conglomerate. At that time basement thrusts transported eastwards earlier Cordillera Principal thrusts and folds, forming thus a hybrid thin and thick-skinned belt of deformation.
Overprinting relationships indicate that the fold and thrust belt evolved by means of a forward propagating thrust sequence including periods of out-of-sequence thrusting. The denudation of the fold and thrust belt provided the material for the uppermost levels of the Tunuyán Conglomerate. The unconformity that separates the Palomares Formation from the Tunuyán Conglomerate, the changes in paleocurrents measured in the former unit, and the occurrence of locally derived conglomerates, provide evidence for the beginning of a third phase of deformation, associated this time with the onset of uplifting in the Cordillera Frontal. This is recorded by the regional influx of thick coarse conglomerates, the generation of a broken foreland basin system, and the accumulation of the wedge of proximal synorogenic deposits of the Palomares and Butaló Formations.
The uplift of the Cordillera Frontal generated a sticking point, preventing the propagation of the thrust belt towards the foreland. As a result, a series of out-of-sequence thrusts developed in the eastern Cordillera Principal and the Alto Tunuyán foreland basin was partially cannibalized by the advancing thrust sheets. After the emplacement of granitoids with isotopic signatures indicating magmas sources in a thickened crust (Kurtz *et al.* 1997, Kay *et al.* 2005) in the western Cordillera Principal, magmatism shifted eastward to its present position along the active volcanic front of the Tupungato-San José line. Thrusting along the Cordillera Principal ended by ~4 Ma and subsequently the deformation front migrated to the Precordillera - north of 33°S- and to the Cuyo Basin and the eastern Cordillera Frontal foothills south of 33°S. Folding in the Cuyo Basin started after the beginning of deposition of the Mogotes Formation at ~ 3.0 Ma (Yrigoyen 1993, Chiaramonte *et al.* 2000). The last phase of deformation accommodating ESE-WNW and ENE-WSW shortening concentrated in the Cuyo Basin and in the La Carrera thrust system in the Cordillera Frontal. Earthquake focal mechanisms and neotectonic activity indicate that the eastern border of the Precordillera and the Cuyo Basin are still active (Cortés *et al.* 1999, Chiaramonte *et al.* 2000).

CONCLUDING REMARKS

Darwin was the first geologist to describe the stratigraphy of the Cordillera Principal and the Cordillera Frontal of central Chile and Argentina recognizing the presence of an old metamorphic basement - much older than its "red granites" - presently considered to be late Paleozoic intrusives in the Cordillera Frontal. He correctly assigned a Cretaceous age to the marine sediments cropping out along the eastern Cordillera Principal and also showed that the uplift of the Andean range was much younger than the marine sedimentation of the Cretaceous deposits. By studying the composition of clasts included in Tertiary sediments of the Alto Tunuyán Basin he was able to establish the relative uplifting times for the Cordillera Principal and Cordillera Frontal conluding that the Piuquenes range (Cordillera Principal) was uplifted before the Portillo range (Cordillera Frontal). To explain the drainage pattern of the Tunuyán-Cordón del Portillo region, he proposed a gradual elevation of the Cordón del Portillo after the uplift of the Piuquenes range, which allowed the waters of the Tunuyán Depression to cut a deep canyon through the latter as the range was been uplifted. As a tribute to his exceptional observational skills we should emphasize that the progressive advance of an orogenic deformation front from hinterland towards foreland, now considered a common process in most mountain chains, was early envisaged by Darwin more than 150 years ago during is historic 1835 journey across the Andes.

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