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The Paleozoic evolution of the Andes and its foreland: Introduction

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In the southern part of the Andean Cordillera and nearby areas of its foreland, located in the Bolivian, Chilean and Argentinian territory, there are Paleozoic basement relicts of variable extension, which formed part of the W and SW margin of Gondwana. This basement has been involved in orogenic events prior to the Andean orogeny (active from the Cretaceous to the present), some of which starts in the Neoproterozoic or reach the beginning of the Mesozoic. During the Paleozoic and according to Heredia et al. (2016, 2018), a set of continental fragments of variable extent and allochtony was successively accreted to the Gondwana margin, resulting in six Paleozoic orogenies of different temporal and spatial extension: Pampean (Ediacaran-early Cambrian), Famatinian (Middle Ordovician-Silurian), Ocloyic (Middle Ordovician-Devonian), Chanic (Middle Devonian-early Carboniferous), Gondwanan (Middle Devonian-middle Permian) and Tabarin (late Permian-Triassic). All these orogenies culminate with collisional events, with the exception of the Tabarin and the Gondwanan north of 39º S that are subduction-related.

The random distribution of Paleozoic outcrops along this segment of the Andes and the unclear separation between Paleozoic and Andean orogenic events did not facilitate the establishment of a coherent model of geodynamic evolution. In the last 30 years (1993-2023), the PaleoAndes Group has worked to characterize these Paleozoic orogenic events and to propose a geodynamic model for the Paleozoic evolution of the Chilean-Argentinian Andes, south of 21º S, and including the Antarctic Peninsula.

The PaleoAndes Group was constituted by researchers of the Instituto Geológico y Minero de España (IGME-CSIC), the Servicio Geológico y Minero Argentino (SEGEMAR), the University of Barcelona (UB) and the University of Oviedo (UNIOVI), institutions that led the research projects developed in these last 30 years. In these projects have also participated the Geosciences Barcelona (GEO3BCN-CSIC) and the Rey Juan Carlos University (URJC) from Spain, the national universities of La Plata, La Patagonia-San Juan Bosco, Rio Negro, Salta, Comahue, San Juan, the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) and the Instituto Antártico Argentino (IAA) from Argentina and the universities of Chile, Andrés Bello and Desarrollo from Chile.

The first works of the PaleoAndes Group in the Paleozoic basement of the Andes begin in the context of the project "Programa Nacional de Cartas Geológicas de la República Argentina", lead by the SEGEMAR and IGME and supported by the Agencia Española de Cooperación Internacional (AECI) between 1993 and 1997 (Areas 1, 6 and 16 in Fig. 1) and also in 2015 (Area 20, Tierra del Fuego, in Fig. 1A). Between 1998 and 2000 the University of Barcelona joined the works on the Paleozoic basement of the Andes, leading the TRANSCUYO Project (PB98-1189) (Fig. 1A). During 2001-2003 the IGME lead the TABARIN Project (REN2000-2959-E/ANT) in which the study of the Paleozoic basement of the northern Antarctic Peninsula were included (Fig. 1B). The next works of this Group in the Paleozoic basement of the Andes were developed between 2003 and 2015 and already included the University of Oviedo. These projects were supported by the Spanish I+D+i Plan and FEDER Founds of the EU and are from oldest to newest: the INVERANDES (BTE2002-04316-C03), PALEOANDES I & II (CGL2006-12415-CO3/BTE and CGL2009-13706-CO3) and TORANDES (CGL2012-38396-C03). Finally, during 2017 and 2020 SEGEMAR and IGME lead the MISAC Project (CANOA2722) (Fig. 1A) supported by an agreement between both institutions.

As results of these research projects, the members of the PaleoAndes Group are authors of several articles and book chapters on the Paleozoic basement of the Andean Cordillera. The main publications of this research group are collected in Heredia et al. (2016, 2018a, b) and Serra-Varela et al. (2022).

Previously to this Special Volume the PaleoAndes Group has published two other special volumes dedicated to the Andes, entitled respectively: “Geology of the Argentinian-Chilean Central Andes” (Busquets et al., 1997), edited by Acta Geológica Hispánica (now Geologica Acta) and “Palaeozoic geodynamics of the southwestern margin of Gondwana: controls on the present architecture of the Argentinian-Chilean Andes” (Colombo et al., 2014), edited by the Journal of Iberian Geology.

The present Special Volume “The Paleozoic evolution of the Andes and its foreland” publish the last data of the TORANDES project and also include contributions of other authors that work in the same or close areas of the PaleoAndes Group (Fig. 2). This volume also represents a tribute to Ferrán Colombo Piñol, Pere Busquets I Buezo (University of Barcelona) and Isabel Mendez Bedia (University of Oviedo) (Fig. 3), recently retired, and coordinators respectively of the sedimentological, stratigraphic and paleontological studies of the PaleoAndes Group. In addition, Ferrán Colombo has been main researcher in several projects (TRANSCUYO AND INVERANDES) and also in subprojects (UB subprojects of the PALEOANDES and TORANDES projects) of this research group.

This Special Volume contains articles on magmatic, sedimentary, metamorphic, tectonic and mineralization processes developed during the Palaeozoic in the south and southwestern margin of Gondwana, which is now preserved in the Bolivian, Chilean and Argentinian Andes and its foreland.

The article by **Cisterna et al.** (1 in Fig. 2) evaluate the depositional environment, provenance and tectonic setting of the metasedimentary rocks of the late Cambrian-early Tremadocian from the north of the Sierra de Narváez, developed at the upper-crustal section of the Famatinian Orogen, together with units of the same ages present at the central portion of this orogen. The metasandstone from the Sierra de Narváez, with abundance of quartz, feldspar and mainly volcanic fragments, are comparable with those related to a geochemical signature of magmatic arc influence. Taking into account geochemical data, the metasedimentary successions display similar characteristics to those from recent deep-sea turbidite developed in continental arc margins. The presence of black shales facies in the succession, record deepening of the depositional environment due to an overall sea-level rise, denoting an oxygen depletion characteristic of them. The remarkable involvement of volcanic components in the north of the Sierra de Narváez deposits, interbedded as riodacitic to basaltic effusions and as lithic clastic components with the same nature in the metasandstone, allow to indicate that they represent the beginning of the volcanic activity in a continental island arc.

Cristofolini et al. (2 in Fig. 2) study the Mesoproterozoic Laguna Amarga metamorphic complex, located in the Central Andes of Catamarca (Argentina). The Mesoproterozoic protolith ages (1119-1082 Ma), allow the correlation of this metamorphic complex with nearby basement detached from Laurentian realms. A point to highlight is the absence of Neoproterozoic ages reflecting a source in the Brasiliano-Pan-African orogenic belt that dominates detrital provenances in the West Gondwana margin. This metamorphic complex is composed by ortho-amphibolites, migmatites, schists, gneisses, marbles and calc-silicate intercalations, deformed in Middle Devonian times (metamorphic peak at 389 Ma). This Paleozoic deformation gave rise to an imbricate south-directed over-thrusting system and prevailing tectonic transport to the south, in response to progressive non-coaxial strains.

Dalenz et al. (3 in Fig. 2) study twenty-five genera of Silurian and Devonian Bivalves of the Bolivian central Andes and its palaeobiogeographic distribution. Twenty-two of these genera are considered cosmopolitan and three endemics of this western Gondwana area: *Notonucula*, *Pleurodapis* and *Andinodesma*. Discussions about dispersal *versus* vicariant distributions are presented, and different palaeoenvironmental strategies developed by Bivalves are analyzed.

De Barrio et al. (4 in Fig. 2) study early Carboniferous granitic rocks from the Bajo de La Leona (eastern Deseado Massif, Argentine) and their geological relationships with the Triassic-Jurassic magmatism. The Early Carboniferous Laguna Turbia Leucogranite shows a peneplanized landscape due to erosion processes and has microscopic evidence of solid-state deformation features. The geochemical signature is calc-alkaline, typical of magmatic arc environments. The high K contents and FI data are consistent with a crustal provenance. The Permian sediments of La Golondrina formation lye unconformably onto the early Carboniferous granites and is affected by a contact metamorphism related to the Late Triassic-Early Jurassic intrusions. This work also studies the relationships between the igneous rocks and Cu-Au mineralizations.

In the article of **Dicaro *et al.*** (5 in Fig. 2) the structure and metamorphism of the Cushamen Complex in the Sañico High (Southern Precordillera Neuquina, Argentine) is studied. In this area the Cushamen Complex is composed of migmatites, orthogneisses and calcsilicate rocks. Zircons from a migmatite mesosome were analyzed by U–Pb Q-ICP-MS yielding a maximum depositional age of 441.79 ± 1.68 Ma (early Silurian/Rhuddanian) indicating a probably sedimentation for the protholits of the Cushamen Complex during middle Silurian, age of the pre-orogenic successions of the Gondwanan cycle in Patagonia. The Cushamen Complex is affected by a Late Devonian regional metamorphic event, which is accompanied by the development of a pervasive tectonic foliation and associated isoclinal folds. Devonian-lower Carboniferous granites crosscut this foliation and produced contact metamorphism. The regional metamorphism can be related to the subduction-related Gondwanan orogeny in Patagonia. At least two more folding phases and related foliations were identified, probably related to the collisional event of the Gondwanan orogeny (late Carboniferous-early Permian).

Garcia-Sansegundo et al. (a) (6 in Fig. 2) study the polyorogenic Paleozoic structure of the San Rafael Block. The Paleozoic pre-Carboniferous rocks, located east of the Los Reyunos Gondwanan thrust, show Chanic structures (Late Devonian–early Carboniferous) with east vergence and generated in the absence of metamorphism. The rocks, located to the west of the Los Reyunos thrust, were deformed by two fold episodes developed under low to very low-grade metamorphic conditions, the first west verging and the second east verging. Therefore, the Los Reyunos thrust must be considered a reactivation of a Chanic structure during the Gondwanan orogeny (late Carboniferous–early Permian). The ancient Chanic thrust could be responsible for the overlay of the hinterland of the western branch of the Chanic Orogen on the foreland of its eastern branch.

In the other article of **Garcia-Sansegundo et al.** (7 in Fig. 2), the Paleozoic structures of the Maule river valley (Pacific coast, Chile) are studied. During the late Carboniferous–middle Permian, the basement of the Chilean Coastal Cordillera was deformed by the subduction-related Gondwanan orogeny. In the studied area, the following metamorphic rock units are distinguished: (i) Western Series (Cambrian to Carboniferous), formed by metabasites and metasediments mixed in a subduction channel (ii) Eastern Series (Carboniferous), consisting of metasediments of a fore-arc basin. In the Eastern Series two units are distinguished: the Eastern Pelitic Series and the Eastern Sandy Series. The Gondwanan deformation affected both series unequaly. In the Western Series, D1 structures consist of a foliation (S1) developed under HP-LT conditions, while in the Eastern Series it comprise tight east-verging folds, with the associated S1 developed under low PT metamorphic conditions. D2 structures are only present in the Western Series and Eastern Pelitic Series and represent the exhumation of the accretionary prism and its emplacement to the east over the fore-arc basin, with the development of east-verging recumbent folds and a thick shear-zone. The D3 deformation event, only well developed in the Eastern Sandy Series, and represented by a back-thrust with associated folds.

Heredia et al. (8 in Fig. 2) study the polyorogenic Paleozoic rocks of the Cuesta del Rahue (Precordillera Neuquina, Argentine), located north of 39º 30’ S. In the Cuesta del Rahue area, late Paleozoic turbiditic rocks with maximum depositional age of ca. 389 Ma were affected by three orogenic events. The oldest orogenic event is the Chanic orogeny (Late Devonian–early Carboniferous) that is characterized by folds with NNE vergence. This deformation is developed in low-grade to very low-grade metamorphic conditions, which allowed the development of a slaty/rough cleavage. The main Chanic structure is an asymmetric fold with a large normal limb tilted by the more recent orogenic events. The characteristics of the deformation and metamorphism allows us to assign the Cuesta del Rahue outcrop to the external hinterland of the western wedge of the Chanic Orogen. Early to late Carboniferous igneous rocks intruded the Paleozoic rocks of the Cuesta del Rahue area and crosscut the Chanic structures. After the Chanic orogeny, the subduction-related Gondwanan orogeny (late Carboniferous–early Permian) took place. The main structures of the Gondwanan Orogen are thrust and related folds with SSW vergence that fold the large Chanic normal limb and also affect Carboniferous igneous rocks. The Gondwanan deformation was developed under non-metamorphic conditions, and Permian igneous rocks crosscut the Gondwanan structures. This article is complementary to that of **Dicaro et al.,** since in the study area of these authors, located very close (40º S), the Chanic orogeny does not develops and the Gondwanan Orogen ends with a collisional event. This allows to verify the proposal of **Heredia et al**., who located the southern limit of the Chanic orogenic belt and the norther limit of the Patagonian collisional orogeny around 39º S and in the Huincul lineament, as previously proposed by Heredia et al. (2016, 2018b).

Limarino et al. (9 in Fig. 2) present the tectonosedimentary evolution of the Paleozoic Ancestral Andes between 33º a 25º S. This mountain range, here named Ancestral Andes, was formed during the Gondwanan orogeny (mainly Permian) and separated the Paleopacific Sea from the eastern retroarc basins in this part of South America. Three basement types are involved in the roots of the Ancestral Andes: 1. poorly exposed Mesoproterozoic-Neoproterozoic high-grade metamorphic rocks probably remains of the Chi-Cu terrane, 2. Cambrian-Silurian sedimentary and metamorphic rocks formed during the Famatinian orogenic cycle, and 3. Neoproterozoic to early Carboniferous sedimentary and metamorphic rocks originated during the Chanic orogenic cycle. According to tectonic activity, sedimentary facies, and magmatic record, the Gondwanan cycle comprises seven tectonosedimentary stages: 1) Late Mississippian-Early Pennsylvanian (post-Chanic orogeny marine sedimentation), 2) late Early Pennsylvanian (sea-level fall and progradation of sandy wedges in an extensional pre-orogenic period), 3) Middle-Late Pennsylvanian (sea level fluctuations at the end of the pre-orogenic phase), 4) latest Pennsylvanian-early Cisuralian (active tectonism during the beginning of the uplift of the Ancestral Andes during the Gondwanan orogeny, 5) middle Cisuralian (continental and shallow marine sedimentation during the main phase of the Ancestral Andes uplift), 6) late Cisuralian-Guadalupian (continental sedimentation and beginning of the post-orogenic volcanism), 7) late Guadalupian-Lopingian (most active post-orogenic volcanism).

Ortega et al. (10 in Fig. 2) study the VMS deposit of the La Colorada mine (Argentinian Puna). The massive sulfide ores of La Colorada mine (La Colorada-Limeca District, Salta province, NW Argentina) are hosted by a volcano-sedimentary sequence of Ordovician age with a complex history of superposing magmatism, hydrothermal alteration and metamorphism. La Colorada Mine is located 68 km N of San Antonio de Los Cobres at an average altitude of 3900 m a.s.l. In this study, based on the cores from three drill holes in the mine area, where petrographic and geochemical data of the host rocks and the sulfide ores are presented, analyzed and discuss, in the context of the lithostratigraphic sequence of the site. The studied ore levels consist of massive sulfides, with the metal association Fe–Cu–Pb–Zn. The sulfide mineral assemblage is dominated by pyrrhotite and pyrite, accompanied by sphalerite, galena, chalcopyrite, and minor amounts of arsenopyrite associated with Au/Ag-sulfosalts. The geochemical information about the ore lenses suggests classifying the deposit into the Au-rich volcanic massive sulfide (VMS) typology, with a Zn-rich lens, in a pelite-mafic subtype, while the geochemical data on interlayered volcanic rocks point towards a back-arc setting, in agreement with the regional geotectonic reconstructions of the Easter basin of Northern Puna.

Spalletti et al. (11 in Fig. 2) study the sandstone petrofacies, deformational events and the dynamic of the Valle Fértil Lineament during the late Paleozoic (Paganzo Basin, northwestern Argentina). In this study, three sandstones petrofacies were recognized in the Carboniferous and Permian Guandacol, Tupe and Patquía formations: quartzolithic (Q-L), quartzofeldspathic (Q-F), and lithic-volcanic (L-V). The vertical distribution of these petrofacies allows distinguishing four stratigraphic intervals. The first, which corresponds to the uppermost part of the Guandacol Formation and the lower Tupe Formation, displays a marked alternation between Q-L and Q-F petrofacies, indicating supply from the metamorphic basement of the local Umango-Maz Block (Q-L) and from granitoids of the Sierras Pampeanas System (Q-F). The second interval, corresponding to the upper Tupe Formation, is widely dominated by Q-F petrofacies owing to the progradation of arkosic wedges from the Sierras Pampeanas System and a limited contribution of the Umango-Maz Block. The third interval, the lower Patquía Formation, shows a sharp change in the composition of the sandstones since they are dominated by acidic and intermediate volcanic fragments (L-V petrofacies), suggesting the establishment of a volcanic field in the area. Finally, the fourth stratigraphic interval, the middle Patquía Formation, is again composed of the Q-F petrofacies indicating a new episode of progradation of arkosic wedges from the Sierras Pampeanas System. Evidence of tectonic activity during the deposition of the Guandacol Formation is also suggested by the presence of different scales of syn-sedimentary deformational structures, from small-scale soft-deformation to large-scale mass transport deposits. This deformational belt only occurs along the Valle Fértil Lineament and is not recorded in other localities of the Paganzo Basin.

Tapia et al. (12 in Fig. 2) study the Mississippian-Pennsylvanian El Imperial Formation, deposited into the San Rafael Basin (San Rafael Block, Mendoza province, Argentina). The generation of this basin took place afterward the Chanic orogeny and before the San Rafael orogeny (or Gondwanan orogeny). Although there is consensus about an extensional setting controlled the basin's inception, no crustal deformation corroborates this tectonic regime. This contribution is a first attempt to present geological and structural field evidence supported by preliminary kinematic analysis on the tectonic regime related to the formation of the San Rafael basin. From these new field observations, a NNE-SSW extensional deformation coetaneous to the deposition of the El Imperial Formation was recognized. The lateral thick variations and the normal faulting, mainly developed in the lower member of the El Imperial Formation, support this model.

Zimmermann et al. (13 in Fig. 2) study the petrography and geochemistry of successions from northwest Bolivia. The Paleozoic section in northwest Bolivia shows highly recycled quartz-arenites of Ordovician age followed by Silurian and Devonian successions mainly composed of subangular to surrounded detritus, moderately sorted, devoid of significant typical metamorphic detritus. During the late Paleozoic, the rocks tend to a larger variability, partly even poorly sorted, higher amount of angular grains and the occurrence of volcaniclastic debris. Geochemically the same trend can be observed, with strongly recycled successions during the Ordovician (Zr/Sc 20–200) followed by moderately recycled rocks (mainly Zr/Sc 10–20100) with typical trace element composition for unrecycled upper continental crust (UCC). During the Permian, sediments which are less weathered and slightly less fractionated in their overall geochemical composition, have been deposited. The geochemistry may point to the evolution of late Paleozoic volcanism, recorded in the overlying Triassic rocks. Significant increase or even typical UCC values of compatible elements or ratios are absent besides Cr and Ni increase in Ordovician rocks. The absence of any significant input of arc related detritus can be explained by not effective sediment dispersal system to transport arc related detritus into the depositional area. The low compositional and low to moderate textural maturity throughout the entire post-Ordovician stratigraphy implies relatively proximal sources and insignificant intra-basinal recycling. This together with the absence of metamorphic detritus, allows in proposing thick homogeneous sedimentary successions with low or no metamorphic overprint as major sources.

Acknowledgments

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FIGURE CAPTIONS

Figure 1. A) Digital elevation model of the southern part of South America with location of the geographic areas where the Paleozoic basement was studied in the PaleoAndes Group research projects. Red Squares: Programa Nacional de Cartas Geológicas de la República Argentina. Blue Square: TRANSCUYO Project. Purple Square: INVERANDES Project. White Squares: PALEOANDES I and II Projects. Black Squares: TORANDES Project. Orange Square: MISAC Project. Studied Areas: 1- Cordillera Oriental, 2- 22º S Transect, 3- Quevar volcano 4- Gualcamayo river, 5- Cordillera Frontal and Precordillera de San Juan, 6- Rodeo (1:250.000) and Castaño Viejo (1:100.000) SEGEMAR geological maps, 7- 32º S Transect, 8- TRANSCUYO section, 9- Cordón del Plata and Southern Precordillera, 10- Guarguaraz and Carrizalito ranges, 11-San Rafael Block, 12- Maule river section, 13- Cordillera del Viento, 14- Cuesta del Rahue and Piedra Santa range, 15- Lacar-Curruhué lakes, 16- San Carlos de Bariloche (1:250.000) SEGEMAR geological map, 17- 42º S Transect, 18- Esquel ranges, 19- Lago Viedma (1.250.000) SEGEMAR geological map, 20- Tierra del Fuego (1:250.000) SEGEMAR geological map. B) Digital elevation model of the Antarctica with location of the geographic areas where the Paleozoic basement was studied. Pink Square: TABARIN Project. Studied Area: 21- Northern Antarctic Peninsula and Southern Shetlands. Base maps taken from NASA Shuttle Radar Topography Mission (SRTM).

Figure 2. Digital elevation model of the southern part of South America with location of the geographic areas studied in this special volume. 1- Cisterna et al, 2- Cristofolini et al, 3- Dalenz et al., 4- De Barrio et al., 5- Dicaro et al., 6- Garcia-Sansegundo et al. (a), 7- Garcia-Sansegundo et al. (b), 8- Heredia et al., 9- Limarino et al., 10- Ortega et al., 11- Spalletti et al., 12- Tapia et al., 13- Zimmermann et al. Base map taken from NASA Shuttle Radar Topography Mission (SRTM).

Figure 3. From left to right: Raúl Cardó (SEGEMAR), **Ferrán Colombo** (University of Barcelona), Carlos Limarino (University of Buenos Aires), **Pere Busquets** (University of Barcelona) and **Isabel Méndez Bedia** (University of Oviedo), during field works in the Paleozoic of the Andean Frontal Cordillera. In bold type the honored researchers.

FIG.1


A
B
25°S
35°S
45°S
55°S
70°W
60°W
50°W
40°W
Asunción
Santiago
Buenos Aires
Montevideo
500 km
N
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
20

FIG.2


15°S
25°S
35°S
45°S
55°S
70°W
60°W
50°W
40°W
N
La Paz
13
3
10
Asunción
2
1
11
Santiago
9
7
6;12
Buenos
Aires
Montevideo
8
5
4
500 km

FIG.3