

Ordovician metamorphic event in the carbonate platform of the Argentine Precordillera: Implications for the geotectonic evolution of the proto-Andean margin of Gondwana

Gustavo G. Voldman^{1*}, Guillermo L. Albanesi¹, Víctor A. Ramos²

¹CONICET—Museo de Paleontología, Universidad Nacional de Córdoba, Córdoba X5000FCO, Argentina

²CONICET—Laboratorio de Tectónica Andina, Universidad de Buenos Aires, Buenos Aires C1428EHA, Argentina

ABSTRACT

An Ordovician metamorphic event is recorded by means of conodont paleothermometry in the slope sedimentary sequences of the Western Precordillera. Allochthonous conodonts from reworked deposits of the eastern carbonate platform with CAI 4.5–5 and autochthonous conodonts from the olistostrome matrix with CAI 3 allow for constraining the metamorphic age within the *Paltodus deltifer* and *Lenodus variabilis* zones (i.e., ca. 480–465 Ma). The conodont data support an Ordovician instead of an alternative Devonian collision for the Cuyania terrane with the proto-Andean margin of Gondwana, which is consistent with the earlier proposed, but still contentious, microcontinent model. In the latter scenario, the collision of the Cuyania terrane caused unroofing and cannibalism of the leading edge of the carbonate succession and basement rocks. The erosion of these rocks supplied detritus and metamorphosed conodonts to the deeper basinal settings of the Western Precordillera. As the deformation front migrated into the peripheral foreland of the Eastern and Central Precordillera, nonmetamorphosed conodonts were eventually incorporated into the west-prograding synorogenic clastic wedge. The occurrence of allochthonous and autochthonous conodonts in the slope facies of the Western Precordillera provides a time constraint for the early accretion of the Cuyania terrane and its transition to an evolving foreland mountain system in the Ordovician period.

INTRODUCTION

The Argentine Precordillera plays a key role in a number of West Gondwanan tectonic reconstructions for the early Paleozoic, where it stands at the external zone of the Famatinian orogen (e.g., Ramos et al., 1998; Keller, 1999) (Fig. 1). Its Cambrian-Ordovician carbonate platform sequence is unique to South America and makes up part of a larger region of the Andean foothills of northwestern Argentina that is referred to as the Cuyania composite terrane (Ramos et al., 1998). Contrasting interpretations of the tectonic history of Cuyania focus on its origin, boundaries, timing, and mode of accretion. According to prevailing hypotheses, Cuyania is a Laurentia-derived fragment rifted in the Early Cambrian and accreted to the proto-Andean margin of Gondwana in the Middle to Late Ordovician (summary in Thomas and Astini, 2003; Ramos, 2004). Subsequently, the Siluro-Devonian accretion of the Chilenia arc terrane to the proto-Pacific margin of Cuyania significantly overprinted the previous geologic history, resulting in a complex deformation and low-grade metamorphism that affected particularly the Western Precordillera (e.g., Davis et al., 1999). Earlier proposals about Cuyania as an accreted fragment (Dalla Salda et al., 1992), or as a marginal plateau (Dalziel, 1997), left behind after a Laurentia–West Gondwana continent collision in the Ordovician, are difficult to reconcile with the faunal, isotopic, paleomagnetic, geochronological, and stratigraphic evidence. Other alternative hypotheses propose that Cuyania was either a marginal plateau adjacent to Laurentia (Keller, 1999) or an Ordovician terrane derived from Gondwana through large-scale transform displacements, which collided with the latter paleocontinent in the Devonian (Acefózola et al., 2002; Finney, 2007).

We report an Ordovician metamorphic event by means of the conodont color alteration index (CAI), preserved in rocks from the western slope sedimentary sequences of the Precordillera. The investigated conodonts not only give insight into the paleothermometry but also allow rela-

tive dating of the metamorphism, being constrained within the *Paltodus deltifer* and *Lenodus variabilis* Zones (i.e., ca. 480–465 Ma; Ogg et al., 2008), which we relate to the collision of Cuyania with the proto-Andean margin of Gondwana.

GEOLOGICAL SETTING

The Precordillera has typically been defined as a high-level fold-and-thrust belt that extends between 29°S and 33°S in the Andean foothills, above the shallow subduction segment of the Nazca plate (Ramos et al., 2002). The Bermejo and Jocolí basins separate the Precordillera from fault-bounded crystalline basement uplifts of the Sierras Pampeanas to the east, whereas the Uspallata-Calingasta-Iglesia Basin covers the structural boundary with the Cordillera Frontal to the west. Eastern, Central, and Western domains have classically been distinguished on the basis of structural and stratigraphical criteria (Fig. 2). The Eastern and Central Precordillera represent an important Cambrian to Middle Ordovician carbonate platform, which is covered by siliciclastic foreland deposits with paleocurrents to the west. The Western Precordillera exhibits deeper environments, with slope to ocean floor sedimentary rocks that include pillow lavas and mafic-ultramafic bodies in the westernmost sections. The occurrence of early Paleozoic platform deposits changing westward to slope and ocean floor facies allows for the reconstruction of an ancient continental margin in the western part of the Precordillera (e.g., Spalletti et al., 1989; Astini, 1998).

The collapse of the Cuyania carbonate platform in the Middle Ordovician was associated with an important paleogeographical rearrangement of depocenters and source areas. A large influx of fine-grained clastics filled rapidly subsiding marine basins, punctuated by local deposition of olistostromes, debris flows, conglomerates, and turbidites (e.g., Astini et al., 1995; Keller, 1999). Although the foreland basin on the shelf provided sediments as a primary source, medium- to coarse-grained siliciclastic deposits of an extrabasinal orogenic source were funneled into slope settings through canyons or tectonic troughs, linking the eastern and western basins of the Precordillera (Spalletti et al., 1989; Astini, 1998). Nd-Pb

*E-mail: gvoldman@efn.uncor.edu

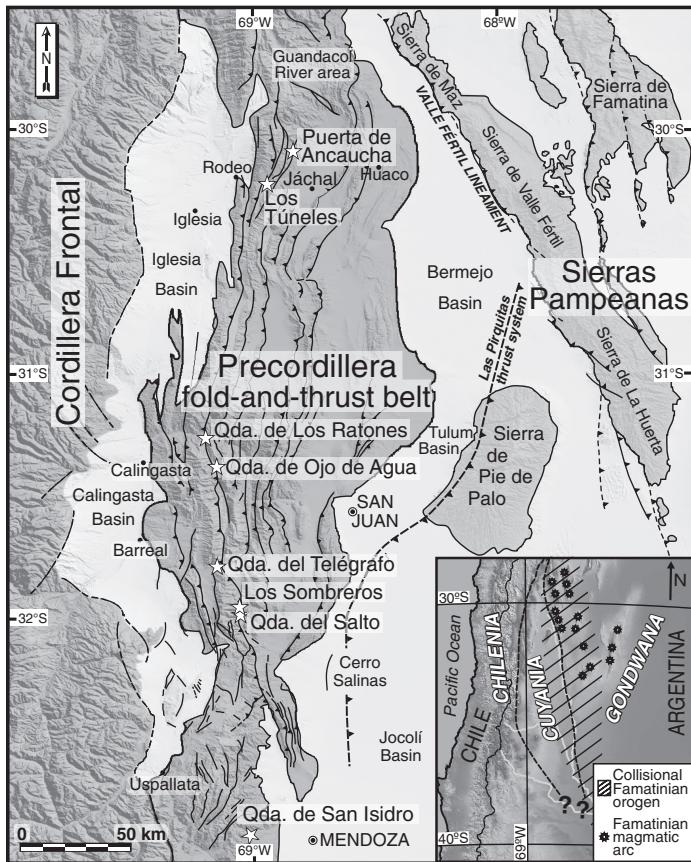


Figure 1. Location map of the Argentine Precordillera fold-and-thrust belt, as part of the Cuyania terrane, superposed on shaded relief map derived from Shuttle Radar Topography Mission (SRTM). Stars—studied localities; Qda.—Quebrada.

isotopic and U-Pb detrital zircon data confirm that the outer slope/basinal facies of the Western Precordillera received detritus from a recycled Pre-cordillera platform and basement source (Gleason et al., 2007).

STRATIGRAPHY AND SAMPLING

At the continental slope and rise, to the west of the Precordillera carbonate platform, the Ordovician Los Sombreros Formation includes a diverse array of rocks derived from the platform, slope, and basement (Fig. 2) (Keller, 1999, and references therein). This mud-dominated deepwater olistostrome-bearing unit displays ubiquitous extensional structures related to submarine sliding by gravitational collapse (Alonso et al., 2008). This phenomenon is ascribed to the Guadacol tectonic phase of the Middle to Upper Ordovician Ocloyic orogeny, when the Cuyania terrane entered an east-dipping subduction zone beneath West Gondwana (Astini et al., 1995).

The Los Sombreros Formation contains blocks as large as hectometer scale of Lower Cambrian to Lower Ordovician limestones, as well as arkosic sandstones and conglomerates with rounded basement-derived clasts from metamorphic and igneous sources. These composite deposits record fragmentation of the outer edge of the carbonate platform along with the underlying synrift and basement rocks by slope-collapse faults or submarine canyons (Thomas and Astini, 2003). The temporal range of the Los Sombreros mélange is constrained by graptolite and conodont species recovered from the matrix, which span from the late Tremadocian (Voldman et al., 2008) to the early Sandbian (Cuerda et al., 1986). This succession is equivalent to the olistostromic Estancia San Isidro Formation in Mendoza, which exhibits giant Cambrian limestone blocks immersed in a green shaly matrix of Darriwilian age (Heredia and Beresi, 2004; Ortega et al., 2007). The latter stratigraphic unit is unconformably

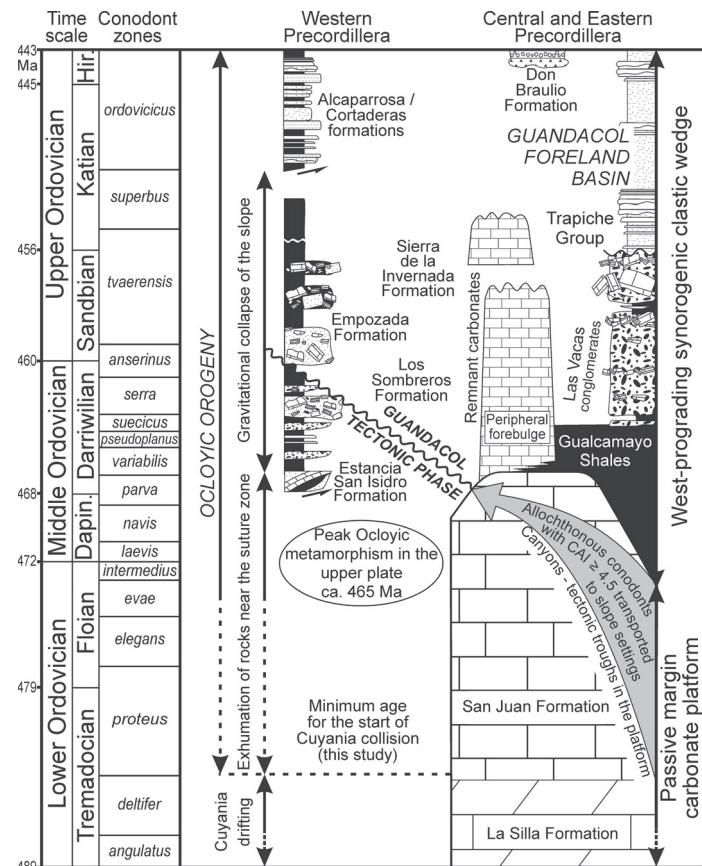


Figure 2. Summary tectonostratigraphic diagram for the Ordovician of the Argentine Precordillera. IUGS time scale (Ogg et al., 2008). Dapin.—Dapingian; Hir.—Hirnantian.

overlain by the Katian Empozada Formation, a unit consisting of partly calcareous sandstones and siltstones with intercalated debris-flow deposits that yielded diverse intra-Ordovician transported graptolite and conodont faunas (Ortega et al., 2007). The unconformity records the later pulses of the Ocloyic orogeny in the Western Precordillera (Astini et al., 1995).

One decisive parameter, hitherto not explored, through which the tectonic history of the Cuyania terrane can be evaluated, is the thermal maturation history of its carbonate platform. Autochthonous and allochthonous conodont CAIs provide constraints on the tectonothermal history of Cuyania and thus shed light on its transfer to the Gondwana margin. For this purpose, 61 conodont samples from the Los Sombreros Formation were processed in 10% acetic acid solution following the standard techniques described by Stone (1987). Subsequently, their textural alterations and CAI values were measured by direct comparison with a standard conodont CAI set provided by A. Harris (USGS), and transformed into paleotemperatures according to the schemes proposed by Epstein et al. (1977) and Rejebian et al. (1987). The studied conodont specimens are stored in the Museo de Paleontología, Universidad Nacional de Córdoba, with repository code CORD-MP.

RESULTS

Conodont assemblages from the *Cordylodus proavus* Zone of the upper Furongian (Upper Cambrian) (Fig. DR1 in the GSA Data Repository¹) were recovered from clasts immersed in a calcareous megabreccia

¹GSA Data Repository item 2009081, Figure DR1 (conodont plate), is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

of the Los Sombreros Formation at the Quebrada de Ojo de Agua, at the eastern slope of the Sierra del Tontal (Fig. 1). In addition, we obtained allochthonous conodont assemblages referable to the *Paltodus deltifer* Zone (early late Tremadocian) from resedimented gravity flows of the same stratigraphic unit at the Los Túneles section, Quebrada del Telégrafo, and Quebrada del Salto (Fig. 1). The *P. deltifer* Zone is represented by typical species from the shallow, warm-water domain (*Scolopodus floweri*, *S. krummi*, *Ulrichodina quadruplicata*) and the open, cold-water domain (*P. deltifer*, *Drepanodus arcuatus*, *Paroistodus numarcuatus*) (Fig. DR1). All studied specimens from the *C. proavus* and *P. deltifer* Zones display CAI values in the range of 4.5–5 (~300–480 °C paleotemperature) and appear slightly folded and corroded. Those features are persistent in allochthonous elements of the *C. proavus* association described by Lehnert (1994) from the Los Sombreros section, as well as in conodonts from the *Proconodontus tenuiserratus* Zone (Upper Cambrian) yielded by the olistostromic Estancia San Isidro Formation (Heredia, 1994).

Conversely, the distributional pattern of paleotemperatures from coeval in situ sedimentary rocks of the Eastern and Central Precordillera hardly exceeds the diagenetic zone (Keller et al., 1993; Voldman and Albanesi, 2005). Transported conodont elements (*P. deltifer* Zone) from blocks of the basal conglomerate of the Empozada Formation display a CAI 3 (Heredia, 1994).

Autochthonous conodonts from the Los Sombreros Formation were recovered from the mudstone matrix at the Los Túneles section and calcarenite channel fills at the Puerta de Ancaucha (Fig. 1). The fauna represents the *Lenodus variabilis* Zone (middle Darriwilian), including *L. variabilis*, *Fahraeusodus marathonensis*, *Paroistodus horridus*, and *Periodon macrodentata*, among many others. These conodonts are well preserved, with no visible textural alterations (e.g., dissolution or mineral overgrowths), and exhibit a CAI 3 (~110–200 °C) (Fig. DR1). In addition, autochthonous conodonts from the Estancia San Isidro Formation are similarly preserved (Ortega et al., 2007).

Consequently, our conodont data record the oldest known metamorphic event in the Precordillera carbonate platform so far, which can be constrained between the *P. deltifer* and *L. variabilis* Zones (across the latest Tremadocian–earliest Darriwilian, ca. 480–465 Ma) (Fig. 2). Tremadocian limestones of the Mahuidas Block, southernmost Cuyania, yielded in situ deformed and corroded conodonts with CAI 5 (Albanesi et al., 2003), probably reflecting the same deformational event.

TECTONIC IMPLICATIONS

Several lines of evidence have been interpreted as the onset of deformation related to the accretion of Cuyania during the Middle to Late Ordovician (Ocloyic orogeny): (1) drowning of the carbonate platform and introduction of a synorogenic clastic wedge in the basin (Astini et al., 1995), (2) peak Ocloyic metamorphism (ca. 470–460 Ma) of crystalline rocks and their metasedimentary cover in the Sierras Pampeanas and Famatina (e.g., Casquet et al., 2001; Vujovich et al., 2004), (3) cessation of subduction-related Famatian magmatic arc activity (Ramos, 2004, and references therein), and (4) the vestiges of a west-vergent Ocloyic thin-skinned thrust belt overprinted by the Andean deformation at the Guandacol River area (Thomas and Astini, 2007), among others (Fig. 3).

The continental slope along the western margin of Cuyania underwent local infill of Cambrian-Ordovician olistoliths coeval with the west-prograding clastic wedge that formed as a result of Cuyania docking against the proto-Andean margin of Gondwana (Astini et al., 1995). In the eastern part of the terrane, the Sierra de Pie de Palo (Fig. 1) records top-to-the-west imbricate ductile thrusting along the Las Pirquitas thrust system, which places Grenville-age basement rocks over the metacarbonate-bearing Caucete Group (Ramos et al., 1998; Vujovich et al., 2004). These latter rocks are interpreted to be Cambrian in age based on Sr, Sm/Nd, C, and O isotopic signals, which are similar to Precordillera platform deposits and correlative carbonates of the Cerro Salinas and the Cerro Pan de Azúcar to

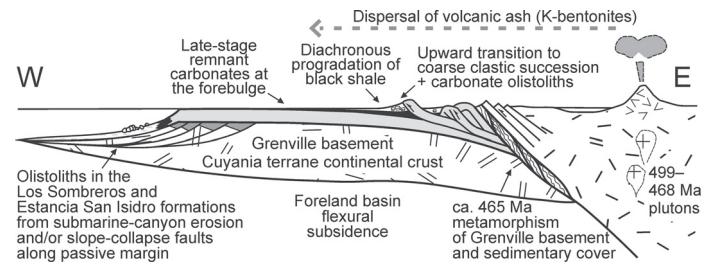


Figure 3. Schematic cross section (not to scale) showing the collision of Cuyania with the Famatinian magmatic arc along the western margin of Gondwana during the Middle Ordovician (modified from Thomas and Astini, 2003).

the east (Naipauer et al., 2005). Rapid exhumation of the Caucete Group has been proposed on a structural basis by its position in the subduction channel of the collision zone (van Staal et al., 2005). These authors identified an early deformation between 490 and 460 Ma, partially coeval with the evidence presented here.

We suggest that the proposed collision of Cuyania caused unroofing and cannibalism of the downwarping carbonate platform shortly after it was thrust beneath the Pie de Palo complex by the Las Pirquitas thrust system. After burial-related metamorphism and rapid extrusion-related exhumation of carbonate platform levels at the subduction wedge (e.g., Ring and Reischmann, 2002), some conodont elements were eroded from unroofed limestones situated near the suture zone to be redeposited in the slope settings farther to the west. This process provides the relative dating of the accretion of the Cuyania passive margin carbonate platform and its transition to an evolving foreland mountain system.

As the deformation front migrated into the peripheral foreland of the Eastern and Central Precordillera (Thomas and Astini, 2007), weakly metamorphosed to nonmetamorphosed conodonts (CAI 3) were eventually incorporated into the west-prograding synorogenic clastic wedge. This is consistent with the Nd-Pb isotopic and U-Pb detrital zircon data of provenance, which suggests rapid unroofing of the forefront platform succession and basement rocks that were thrust back onto the platform through a series of stacked sheets (Gleason et al., 2007).

Alternative solutions involve a western Cordilleran source or an Ordovician rifting phase as proposed by Keller (1999). The first solution is not compatible with the west-facing continental slope of the Precordillera and its sedimentary dispersal patterns (Spalletti et al., 1989; Thomas and Astini, 2003), whereas the second solution is not consistent with the time span necessary (tens of millions of years) for the heat to advect upwards (Ziegler and Cloetingh, 2004), which would have affected the Darriwilian conodonts as well.

CONCLUSIONS

The conodont data discussed herein record the oldest known metamorphic event that affected the carbonate platform, which is constrained between the *Paltodus deltifer* and *Lenodus variabilis* Zones (i.e., across the latest Tremadocian–earliest Darriwilian, ca. 480–465 Ma). Together with the thermal history of the basin, our data support an Ordovician rather than Devonian accretion for the Cuyania terrane, which is consistent with the microcontinent model. In this scenario, the Cuyania terrane would have drifted from a low-latitude position in the Cambrian to collide against the proto-Andean margin of Gondwana by the Middle Ordovician.

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