The Ordovician System in the Argentine Eastern Cordillera

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Introduction

The purpose of this chapter is to offer a synthesis on the main geological features of the Ordovician deposits that crop out in the Eastern Cordillera (Cordillera Oriental) of northwestern Argentina. The regional and interregional geological framework that controlled the Ordovician sedimentation is considered by following previous works (Moya, 1999a, 2002), and including recent observations referred to the localities or sections to visit.

Geologic Framework

Ordovician deposits in the Argentine Eastern Cordillera correspond to marine–clastic facies with index fossils of high to middle paleolatitudes. Similar facies and fossils characterize all Ordovician deposits of the Andean Belt, from Colombia and Venezuela to the north, to the Famatina System to the south (Figure 1). All of these terranes show strong evidences of being autochthonous since late Proterozoic to early Cambrian times, when the cratonic areas of South America were accreted to the western Gondwanan margin (Pan–African/Brasilian/Pampean Cycle). In present generalities, terranes under suspicion of being allochthonous or parautochthonous, such as the Precordillera and San Rafael Block (Figure 1), are excluded. The linkage of these terranes with the rest of Ordovician basins of South America is unquestionable from the Middle–Upper Ordovician.

Tectonic processes that occurred in the Gondwana western border during the Pan–African/Brasilian/Pampean Cycle were strongly diachronic, including multiple collisions followed by extensional collapse events. The last ones would have generated the clastic Cambrian and Ordovician basins of South America (Brito Neves *et al.,* 1999). In these basins, it is possible to recognize wide and stable marine shelves developed on the western margins of South American cratons, which embraces the Eastern Cordillera, Subandean Ranges (Sierras Subandinas) and the underground of continental pericratonic plains (Figure 1). Deep marine depositional areas were developed through the west of these shelves, which are recognized in the Colombian Central Cordillera, Peruvian–Bolivian Altiplano, and Argentine–Chilean Puna (Figure 1). Deposits do not show an exposed base, and they are associated to synsedimentary volcanism and intruded by plutonic bodies.

The general scheme mentioned above is applicable to the Cambro–Ordovician basins of northern Argentina, which were developed on the margins of the Pampean Craton (Pampean Domain, Figures 2c–2f). The annexation of Pampean Domain terranes to Gondwana would have been previous to that of the basement of the Eastern Cordillera (Pan–American Domain,

Figure 2c). Plutonic rocks and medium to high–grade metamorphic rocks characterize the Pampean Domain basement. Folded sedimentary rocks, affected by low to very low–grade metamorphism and intruded by plutonic bodies, compose the Pan–American Domain basement. Two magmatic–metamorphic episodes could have been registered in both domains; an older one of 560–540 Ma (Vendian), and a younger of 525–505 Ma (Lower to Middle Cambrian) (Toselli & Toselli, 1990; Becchio *et al.,* 1999).

In the Eastern Cordillera, metamorphic and plutonic rocks of the basement underlie the Mesón Group deposits (MG, Upper Cambrian) through a strong angular unconformity (Tilcara unconformity). This contact points out the end of the sedimentary, metamorphic and tecto–magmatic events that occurred during the Pan–African/Brasilian/Pampean Cycle.

The Mesón Group begins with the Famatinian Cycle (Upper Cambrian–Upper Devonian). The deposits of the Famatinian Cycle are siliciclastics and have been accumulated in a marine shelf environment. Deep basin facies are restricted in time (Ordovician) and space (Famatinian Domain, Figure 2c).

The Famatinian Domain includes the Argentine–Chilean Puna, where the Pampean Cycle rocks are poorly represented. In this region, Ordovician deposits do not expose their bases, by representing the stratigraphic core. The Famatinian Domain was a tectonically unstable area affected by volcanism during the Lower Ordovician (Figures 2d, 2e). The deposits of this age integrate volcano–sedimentary successions (CVP, Figure 3) accumulated in shelf–marine environments (Altiplano Shelf, Figure 2d). A pronounced subsidence recorded in the Upper Arenig gave place to the accumulation of thick volcaniclastic turbidite successions (CTP, Figure 3; Upper Arenig–Caradoc). In the Famatinian Domain, Silurian–Devonian deposits are restricted to the western border of the Puna, where they unconformably underlie Upper Carboniferous red beds (Figures 2b,3).

Paleozoic of the Eastern Cordillera and Chaco Shelf

Most complete Cambrian–Ordovician successions of northern Argentine Andes crop out in the Eastern Cordillera (Figure 3). Similar successions are presented in the Subandean Ranges (Figure 3) being extended toward east (outside of the limits of the Figure 2b), in the underground of the Chaco Plain.

These regions were part of a wide marine shelf during all of the Famatinian Cycle (the Chaco Shelf, Figure 2d). An emerged to submerged structure (the Lipán Swell, Figures 2d–f) divided the Chaco Shelf into an eastern and western area. The western area was bounded to the west by the Cobres High, only active during the Cambrian–Lower Tremadocian (*cf.*, Figures 2d and 2e–f). The Cobres High is an extension of the Pampean Craton, being its western limit an old and important tectonic front (Figure 2d).

The evolution of the Famatinian Cycle in the Chaco Shelf was mainly controlled by relative sea–level changes; *i.e.,* the development of three–second order tectono–eustatic cycles limited at base and top by significant unconformities, which bound to the Mesonian, Victorian and Cordilleran cycles. The Paleozoic cycles of the Chaco Shelf discordantly cover the basement of the Pan–American Domain (Figure 2c).

The Eastern Cordillera presents two particular stratigraphical features that distinguish it from the rest of the northern Argentine regions: 1) It is the only region that exposes an angular unconformity that separates the metamorphic basement (Upper Proterozoic – Lower Cambrian) from almost undeformed Cambrian sequences (Mesón Group). 2) The Eastern Cordillera is the only region that exposes the unconformity that separates the Mesonian and Victorian cycles (Iruya unconformity).

The basement (Upper Proterozoic – Lower Cambrian)

The basement of the Eastern Cordillera is generally identified as the Puncoviscana Formation (Turner, 1960). However, the stratigraphic core of the region is constituted by a heterogeneous group of clastic units of different ages, which were affected by low to very low–grade metamorphism. Plutonic events that occurred during the Vendian and the Lower–Middle Cambrian affected to some units of the basement.

The definition, distribution and regional characterization of the stratigraphic and tectono–metamorphic units of the basement are topics of permanent investigation and discussion. However, available information is abundant and allows us to recognize, at least, two groups of rocks with different deformational degree.

i) The less deformed group –Guachos Formation (Moya, 1998)– is composed by intermediate and distal turbidites that preserves sedimentary structures, and contain frequent trace fossils on beddin plane surfaces. The ichnofaunas were assigned to the Lower Cambrian by Aceñolaza *et al.* (1999); age that is consistent with radimetric values obtained for sedimentary deposits (527–530 Ma; Lork *et al.,* 1990). This group presents scarce deformation, the cleavage is not very marked, and folds are wide.

ii) Another group is assigned to the Upper Proterozoic, which is integrated by shales (Sancha Formation), sandy–pelitic turbidites (Puncoviscana Formation) and calcareous rocks (Volcán / Las Tienditas formations) (Turner, 1960; Salfity *et al.,* 1975; Baldis & Omarini, 1984; Jêzek, 1990). The rocks of this group are more deformed, with tight folds, intense cleavage, and are frequently crossed by quartz veins.

In all cases, the contact between both groups is tectonic. Apparently, the faults that separate them took advantage of an old unconformity surface.

The Mesonian Cycle (Middle? – Upper Cambrian)

It is developed above the Tilcara unconformity, being represented by the Mesón Group (MG). The MG is integrated from base to top by the Lizoite (K1), Campanario (K2) and Chalhualmayoc (K3) formations (Keidel, 1943; Turner, 1960). K1 and K3 are quartzose sandstone bodies, and K2 consists of bioturbated sandstones and siltstones. The MG do not bear a diagnostic fauna; its Cambrian age is established on the base of its stratigraphic relationships. It covers to the basement (Upper Proterozoic – Lower–Middle Cambrian) and is underlain by Upper Cambrian – Lower Tremadocian deposits of the Santa Victoria Group (SVG). The trace fossils point out to a Cambrian *sensu lato* age (Aceñolaza *et al.,* 1982, Buatois & Mángano, pers. com.).

The Mesonian Cycle includes two transgresive–regresive episodes. The first episode corresponds to the prograding sequence integrate by the K1 and K2. Deposits of the second episode (K3) are truncated by the Iruya Unconformity (Figure 3). The MG deposits was accumulated on tide–dominated paleoenvironments (sub–, inter– and supratidal environments), being characterized by a high mineralogical and textural maturity. The latter indicates that the MG was deposited under conditions of high stability of the basement.

The MG basin is restricted to the Eastern Cordillera (Figures 2d, 3). Its genesis is linked to extensional processes that concluded the Pampean Cycle.

The Victorian Cycle (Upper Cambrian – Caradoc)

It is represented by the Santa Victoria Group (Eastern Cordillera) and by the Tamango Group (Subandean Ranges). This cycle is limited at base and top by two erosional unconformities (Iruya and Ocloya unconformities; Figure 3). These unconformities were generated by relative see–level falls, during which wide areas of the Chaco Shelf were exposed to subaerial erosion. These events correspond, respectively, to the Lange Ranch Eustatic Event (LREE, Upper Cambrian) and the Hirnantia Regressive Even (HRE, Ashgill), which were recorded in other regions of the world.

The Victorian Cycle includes cycles of third and fourth order, representing transgressive–regressive episodes. The resulting succession is composed by alternating sandstone and shale bodies (Ss1, Sh1, Ss2, Sh2, Ss3, Sh3, Ss4, Sh4 and Ss5, Figure 3).

Recent information regarding these units allowed for defining seven stratigraphic intervals characterized by distinctive fossil assemblages. Following this, Moya *et al.* (2003a) present a more detailed correlation scheme (I–VII, Figures 3, 4). The scheme is valid for the Cambrian–Tremadocian deposits of the Santa Victoria Group allowing for a better control of the regional correlation chart (Figure 3).

Although the stratigraphic arrangement of the Chaco Shelf deposits is remarkably different from that of the Puna Ordovician successions (CVP, CTP, Figure 3), fossiliferous assemblages pointed out in the Figure 3 and those mentioned by Moya *et al.* (2003a) allow us to discuss the relationship among tectonic, eustatic and sedimentary processes that occurred in the Ordovician basin of northern Argentina. The base of the discussion is the recorded transgressive–regressive cycles, whose limits are sedimentary discontinuities of different magnitude and regional expression. These discontinuities represent relative sea–level falls and they would be equivalent to the events LREE (*Lange Range Eustatic Event*), ARE 1 and ARE 2 (multiple *Acerocare Regressive Event*, *sensu* Cooper & Nowlan, 1999), BMEE (*Black Mountain Regressive Event*), GARE (*Grés Armorican Regressive Event*), VRE (*Vallhallfonna Regressive Event*), and HRE *(Hirnantia Regressive Event*) (Figures 3, 8, 11). The paleontological control still does not allow us to specify if identified local events, as the *Kainella Regressive Event* (KRE) and the *Notopeltis Regressive Event* (NORE), correspond to the *Peltocare Regressive Event* (PRE) and the *Ceratopyge Regressive Event* (CRE), respectively.

The SVG begins with alluvial coarse deposits (sandstones and conglomerates) attributed to braided rivers and bradplains of a paraglacial environment. The remaining deposits of the SVG consist of marine shelf facies, changing from coastal marine to intermediate and distal outer shelf environments. The Sandstone 1 and Sandstone 4 were accumulated on tide–dominated environments, as long as the Shale 1, Sandstone 2, Shale 2, Sandstone 3, and Shale 3 were deposited on storm–dominated environments, whose evolution was synchronous with volcanic events in the Puna. Starting with the Llandeilian?–Lower Caradoc, the eastern part of the region is isolated; the Shale 4 deposits in this part, denote restricted circulation and slow sedimentation conditions. The erosional lapse of the Ocloya unconformity was preceded by the shallowing represented by Sandstone 5 (Caradoc). The genesis of the Ocloya unconformity is linked with early Ashgill glacioeustatic events that affected a great part of the Andes.

Although the sedimentation in the Chaco Shelf was dominated by eustatic fluctuations, the shelf also suffered the tectonic events of the Tumbaya Phase (upper Tremadocian). During the Tumbaya Phase, the Chaco Shelf tilted toward west, causing bathymetric modifications in the Ordovician basin. So, the western part of the Eastern Cordillera was a shallow shelf during the Upper Cambrian and Tremadocian, while during the Lower–Middle Arenig it was notably deepened. The effects of the Tumbaya tectonism probably also impacted in the Puna and in the Famatina System (Moya, 1999a).

The Cordilleran Cycle (upper Ashgill – Upper Devonian)

This cycle was defined in Bolivia (*fide* Suárez Soruco, 2000). In northern Argentina, the Cordilleran Cycle is better represented in the Subandean Ranges (Figure 2b), where it is limited at base and top by the Ocloya and Chánica unconformities, respectively. The oldest deposits of the Cordilleran Cycle are represented by the Zapla Formation (upper Ashgill), which starts the Cinco Picachos Supersequence (upper Ashgill – Lower Devonian). The latter represents the first of three third order cycles that characterize the Silurian–Devonian successions in the Subandean Ranges (Vistalli, 1999).

Up to the present, deposits of the Cordilleran Cycle were only found in two areas of the Eastern Cordillera (Fig. 4): NW of Santa Victoria (Turner, 1960) and E–NE of Los Colorados (Moya & Monteros, 1999). The last authors indicate that in Los Colorados area the relationship between the Victorian and Cordilleran cycles lacks angularity, and they highlight the erosive but not tectonic nature of the Ocloya unconformity.

As it occurs in the rest of the Central Andes, the Zapla Formation (and equivalent units) is represented by diamictites, which are occasionally interbedded with dark shales that contain typical hirnantian faunas (Baldis & Blasco, 1975; Monaldi & Boso, 1987; Benedetto, 1991).

The stratigraphic relation between the Zapla Formation and the remaining units of Cinco Picachos Supersecuence is considered transitional (Benedetto *et al.,* 1992) or paraconformable (Monteros *et al.,* 1993; Moya and Monteros, 1999).

Finally, in the Eastern Cordillera, the SVG generally underlies red beds, shales, lacustrine and marine limestones of the Salta Group (Cretaceous–Eocene) through a low angular unconformity. Cordilleran Cycle deposits interpose between Ordovician and Cretaceous–Tertiary successions only in two areas of the Eastern Cordillera. Tertiary deposits (Orán Group and equivalent units) have a tectonic relation with Paleozoic successions (MG, SVG, ZF) and basement units.

A chrono–biostratigraphic chart of the Ordovician System of Argentina and global reference schemes is attached as Figure 40.

The Recent Eastern Cordillera

Eastern Cordillera boundaries depicted in Figure 4 coincide with old structures, which would have regulated the geometry of the MG and SVG basins. These limits are partially coincident with those proposed by Baldis *et al.* (1976a), who priorized the Paleozoic history occurred to the north of El Toro Lineament. Alternatively, Turner & Mon (1979) and Ramos (1999) extended the southern limit of the Eastern Cordillera to the Tucumán latitude (Figure 2a,b), emphasizing andean structural features and incorporating a region that was a non depositional area during the Cambrian (Northern Pampean Ranges, Figure 4a).

The most striking morphological feature of the Eastern Cordillera is its marked relief, with high mountain chains and deep intermountain valleys with steep slopes. The maximum altitude overcome the 6000 m (Cerro Chañi, 6250 m), registered in the Maximum Imbrication Zone, where the average altitude of the mountain chains is 4000 m. Main populations of Salta and Jujuy provinces are located in the intermountain valleys, where the altitude decreases from north to south and west to east. So, the altitude of the Río Grande Valley in the confluence with the Purmamarca River is 2200 m, as long as the bottom of the same valley in San Salvador of Jujuy, does not reach 1300 m.

The morphology of the Eastern Cordillera, whose main structures have N–S direction, is a consequence of the Cenozoic tectonics (Andean Orogeny). Generally, the crossed structures to this general direction are older.

The Andean Orogeny starts with the Inca Phase (Late Eocene – Early Oligocene), which interrupted the sedimentation of the Salta Group (Cretaceous–Eocene). The Quechua II (Late Miocene) and Diaguita (Pleistocene) phases of the Andean Orogeny inverted the Salta Group basin (Salfity & Marquillas, 1999).

Important tectonic fronts are the boundaries of large complex folds or overthrust sheets. These structures include basement rocks and the cover, which is integrated by Cambrian, Ordovician (occasionally Silurian–Devonian), and Cretaceous deposits.

Cenozoic continental basins of the Andean foreland were developed to the east of these tectonic fronts and they were also folded because of the intensity of the tectonism, which progressively increased (Mon & Salfity, 1995). This is the case of the Eastern Ocloyic, Río Grande and Punic tectonic fronts (Figures 4 and 6) that in the southern tract of the Eastern Cordillera limit to the west the Sianca, Quebrada de Humahuaca – Lerma Valley, and Guayatayoc – Salinas Grandes depressions, respectively. In these depressions, post–Inca deposits of the Orán Group (and equivalent units) reach the maximum registered thickness in the region, and exhibit typical coarsening upward stratigraphic arrangements related to their genesis during the evolution of the Andean foreland.

The activity of the main tectonic fronts with N–S orientation and some lineaments across this direction, goes back to previous times of the Andean Orogeny. It is even possible to deduce the structural control produced during the evolution of the Cambrian and Ordovician basins (Figures 2d, 4 and 6):

The Punic Front and El Toro Lineament conformed borders of the MG basin; on whose proximities the SVG directly lies on the basement. At the same time, the Punic and the Eastern Ocloyic Fronts defined a particularly unstable area (Cobres High, Figure 2d). The Cobres High was a positive structure during the Upper Cambrian – Lower Tremadocian, after that a strong subsidence started from the Upper Tremadocian (Figures 2d–e). It is interesting to stand out that the Western Ocloyic Front constituted the western boundary of the lands that were linked with the Pampean Craton during the Lower Paleozoic (Chaco Shelf). Previous discussions evidenced that the activity of these tectonic fronts, such as the El Toro Lineament, dates at least from the Upper Cambrian (Moya, 1988a, 1999a, Hongn, 1994).

Less evident is the activity of the Eastern Ocloyic Front during same time interval. Although a great part of the outcrops of the MG are controlled by this tectonic front, in the northern part of the Eastern Cordillera the Cambrian deposits continue to the east of the Eastern Ocloyic Front with remarkably lower thickness (Zenta Range vs. Iruya Area). Therefore, it is considered that at least in the mentioned districts, the Eastern Ocloyic Front would not have constituted a border of the Cambrian basin.

The scarce Silurian and Lower Devonian deposits of the Eastern Cordillera testify that the region was not a non deposition area during these times. The Silurian–Devonian basin is very well–preserved in the neighboring Subandean Ranges region, where deposits are covered by Upper Palaeozoic rocks (absents in the Eastern Cordillera). The isopach information of Mingramm *et al.* (1979) shows that one of the borders of the Carboniferous basin may coincide with the Eastern Ocloyic Front. This feature evidences the activity of the structure during the Chanic Phase (Upper Devonian–Lower Carboniferous). It is probable that great part of the Eastern Cordillera remained emerged, starting from this time. It would explain the scarce Siluro–Devonian deposits and also the erosional truncation of the SVG. The oldest erosional levels of the SVG are present in the eastern belt of the region. In the western belt, lower Paleozoic deposits are better preserved. For example, in the eastern flanks of Alfarcito and Tilcara ranges (Tilcara latitude), the Yacoraite Formation lies on deposits of the MG and shales of the SVG, late Early Tremadocian in age. On the contrary, in Los Colorados area (western belt of the region), the SVG is covered by Ashgill deposits of the Zapla Formation. The uncomformity that separates these units is clearly erosional, without evidences of Ocloyic folding (Moya & Monteros, 1999).

In the Eastern Cordillera, the Paleozoic units do not present deformational evidences of the Ocloya Phase, or other preandean testonism. It is noteworthy the low angular relationship of MG and SVG deposits in relation with the Salta Group. Thus, it seems that the Paleozoic deposits were only subject to a block tectonics, and later folded together with Cretaceous deposits by the Andean Orogeny. Previous consideration is reinforced by analyzing the stratigraphic arrangements of the Cambro–Ordovician and Cretaceous successions. From this assertion, it is possible to deduce a heritage of structures and/or tendencies of emersion/subsidence of certain areas through geologic time (Moya, 1999 b).

In some intermountain valleys of the Eastern Cordillera and Puna, Tertiary post–Inca deposits are absent. This fact suggests that the Andean thrusts began with the Inca Phase (González *et al.,* 1996).

Parts of the positive area, such as Cretaceous and Tertiary highs in the Eastern Cordillera (Salfity & Marquillas, 1999), coincide with an old positive structure called the Lipán Swell (Figure 2), which was effective during the whole Lower Paleozoic. It is probable that the intense deformation of the Maximun Imbrication Zone (Figure 6) was a result of the smaller thickness of Paleozoic and Cretaceous deposits that accumulated in the flanks of the Lipán Swell.

The pre–Hispanic cultures in the Eastern Cordillera

In the journey across the Eastern Cordillera, we will look at the Tilcara, Iruya, Tumbaya and Ocloya unconformities, whose names, as it is traditional in geology, evoke native communities of northern Argentina.

The Eastern Cordillera holds an extraordinary cultural richness of pre–Hispanic tribes that inhabited the region. Intermountain valleys offered favourable frameworks for the establishment of these populations, whereas they were natural roads of communication for economic and cultural exchange.

Although all the communities had cultural and ethnic likeness, it is possible to recognize groups of tribes called "nations" that occupied particular geographical areas, even distinguished by they own languages. In this scenario, the Atacama, Omahuaca and Diaguita pre–Hispanic nations occupied the southern part of the Eastern Cordillera. The boundaries of their territories were physical ones, such as topographic barriers or climatic and edaphic factors.

The Atacama Nation occupied the Atacama Puna (Chile), which extended through the Argentine Puna and the western flank of the Eastern Cordillera. The Atacamas spoke the *Cunza* laguage and maintained commercial links with Chilean tribes and their neighbors, diaguitas and omahuacas; their main activity was the *llamas* breeding that not only provided a nutritious resource, but also clothes and transport.

The Omahuaca Nation occupied the Quebrada de Humahuaca and surrounding mountains. Their inhabitants spoke an *Aimara* dialect (*Omahuaca*), with a strong influence from neighboring and *Quechua* languages. The Omahuacas were farmers, shepherds, potters and weavers. They worked metals, mainly gold, silver and copper, for handicrafts. The names of their tribes have been as stamp of their step by these lands: Jujuis, Purmamarcas, Maimaras, Fiscaras or Tilcaras, Uquias, Omahuacas, Ocloyas, etc. The Omahuacas were battle–tested, building forts (= pucaras) to defend their territory. The Huajra, Juella and Tilcara pucaras are some of the silent testimonies of conquered resistances.

The Atacama and Omahuaca nations limited to the south with the Diaguita Nation, which occupied the Lerma and Calchaquí valleys in Salta Province, as well as all intermountain valleys of Tucumán, Catamarca and La Rioja provinces. Chicoanas, Pulares, Huachipas, Colalaos, Amaichas, Aldalhualas, Catamarcas, Famatinas, Famaifiles and Guandacoles are some of the tribes that engraved their names in Andean towns of northern Argentina. All of these tribes spoke Cacán, an extinguished language. The diaguitas were farmers and weavers, but mainly outstanding artists; musicians and ceramists decorated their works with diverse paintings. They did also work metal and stones, wood and bone. In all their cultural and artistic manifests a marked Inca influence is noticed.

The election of Salta and Tilcara as strategic points in the journey are not casual; these centers still live the encounter of two cultures. The white man culture, which allows the insertion of the region in the global world, and the ancestral one of rites and not well–known customs, with artistic expressions that evoke the communion of the Andean man and the landscape.

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