The Angosto del Moreno Area, Eastern Cordillera, Jujuy Province

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Introduction

Ordovician and Silurian rocks exposed in the western belt of the Eastern Cordillera of Jujuy Province will be discussed during the journey through the provincial road 16, which connects the Purmamarca Village with the Angosto del Moreno locality. Following stops refer to diverse geological aspects of the region.

Stop 1. Lipán High.

View of Quaternary deposits on the northern slope of the Purmamarca creek. An old glacial valley is dissected by a modern fluvial course.

Stop 2. Potrerillos Cove.

View of a well exposed stratigraphic interval with the Tilcara unconformity.

Stop 3. Western flank of the Lipán High. Panoramic view of the Agua Blanca Valley (Figure 16).

View of a typical delta structure, limited to the east by the Pives Front and toward west by the Alumbrillo Front, which suppresses the SVG roof and the base of the Salta Group (Pirgua Subgroup). In the centre of the structure, Cretaceous–Tertiary deposits are folded in a complex syncline. In the Alumbrillo Range, the homonymous mining district (baritina and lead) is placed. The tunnels (pits) are located along the Chueca fault, whose plane is partially coincident with the Tumbaya unconformity surface that separates early Tremadoc deposits from others of early Arenig age. To the east of the Chueca fault, Ordovician strata are inverted.

Stop 4. Just to point out the road to Los Colorados, one of the two localities with Ashgill–Silurian deposits in the Eastern Cordillera.

An extensive fossiliferous Ordovician – Silurian succession including the Acoite (Arenig), Sepulturas (Llanvirn – Caradoc), Zapla (Hirnantian?), and Chamarra (Silurian) formations is exposed in the Los Colorados area. A rich and diverse fauna (trilobites, brachiopods, ostracods, conodonts, graptolites, and pteraspidomorphs) was recorded from this sequence (*e.g.* Benedetto & Malanca, 1975; Ottone *et al.*, 1992; Toro, 1994, 1995; 1997; Moya & Monteros, 1999; Albanesi & Moya, 2002).

The black and gray–green shales of the Acoite Formation in the mentioned area bear a graptolite assemblage that allowed us to recognize the *Tetragraptus phyllograptoides, Tetragraptus akzarensis, Baltograptus deflexus*, and *Didymograptellus bifidus* zones of the Lower–Middle Arenig (Toro, 1997).

The heterolitic succession of the upper member of the Sepulturas Formation (*sensu* Astini, 1994) at Los Colorados area yielded conodonts of *Erismodus, Erraticodon*, and *Plectodina* genera, and first remains of pteraspidomorphs (*Sacabambaspis janvieri* Gagnier *et al.*), which provides new linkages for the paleogeography of the western margin of Gondwana (Albanesi & Moya, 2002; Albanesi & Astini, 2002).

At Los Colorados, the Ocloya unconformity (erosional, not angular unconformity) separates Caradoc SVG deposits (Sepulturas Formation) from the Zapla Formation (Hirnantian?) (Figure 17). Studied paleocurrents of the conglomerate and fluvial facies present in the lower part of the Zapla Formation suggest E–SE source areas (Lipán Swell), indicating a linkage with the Silurian Sica–Sica sub–basin for the western border of the Eastern Cordillera. On the contrary, the Zapla Formation of the Santa Victoria range, in the eastern border of the Eastern Cordillera, would be related to the Hirnantian – Silurian Subandean sub–basin (Moya & Monteros, 1999). The Chamarra Formation (Moya & Monteros, 1999) conformably overlies the Zapla Formation. The lower shaly member of this unit contains shelly fauna and monograptids. The upper member is mainly composed of sandstones. The Chamarra Formation is equivalent to the Lipeón Formation of the eastern successions (Santa Victoria range and Subandean Ranges). The record of *Clinoclimacograptu retroversus* Bulman & Rickards and *Stimulograptus sedwickii* (Portlock) suggest a Middle Llandovery age for the lower part of the unit (Toro, 1995).

Angosto del Moreno area

The most significant section of the Santa Victoria Group in the western flank of the Eastern Cordillera is located in the Angosto del Moreno area (Figure 18). This section is exceptional in terms of the quality of exposures, continuity of deposits, fossil wealth, and accessibility. Diverse aspects concerning the Ordovician geology of this study area have been discussed by Moya *et al.* (1994, 1998), Moya & Albanesi (2000), Moya & Monteros (2000), Malanca & Brandán (2000), Gómez Martínez *et al.* (2002), and Buatois *et al.* (2003). Previous data and recent paleontological collections enable a preliminary biostratigraphic scheme for the Upper Cambrian to Arenig units of the Santa Victoria Group, which include the Padrioc (sandstone), Lampazar (shale), Cardonal (sandstone), Saladillo (shale), and Acoite (shale) formations (Moya *et al.*, 2003) (Figure 19, 20).

In contrast to other regions of the Eastern Cordillera, the Angosto del Moreno succession is mostly undeformed and a continuous section can be measured (Moya and Albanesi, 2000; Buatois *et al.*, 2003).

Stop 5. Campanario Formation (Mesón Group) – Padrioc Formation (Santa Victoria Group).

At this place it is possible to look at the Upper Cambrian Mesón Group and the angular unconformity that separates it from the regional metamorphic basement (Tilcara unconformity), and the Iruya unconformity which is placed between the Mesón and Santa Victoria groups.

The base of the succession is represented by fine–grained, heterolithic deposits of the Campanario Formation, middle unit of the Cambrian Mesón Group (Figure 20). In the analyzed section, the Campanario Formation is 40 m thick and consists essentially of fine– to very fine–grained sandstone and mudstone with flaser, wavy and lenticular bedding deposited in intertidal areas of a macrotidal depositional system (Moya, 1998; Mángano and Buatois, 2000).

The contact between the Mesón and Santa Vicoria groups is a clear unconformity surface (Iruya unconformity), which is probably linked to the Lange Range Regresive Event (LREE) (Moya *et al.*, 2003).

The SVG begins with the the Padrioc Formation, which is represented by clean sandstone facies of clear color, with greenish and brown–yellowish tints by weathering. The latter is due to the oxidation of the rich matrix in chlorite. The presence of dispersed reddish brown small stains in the sandstone denotes the presence of scarce ferruginous cement. The appearance of *Parabolina (Neoparabolina) frequens* is registered in the upper part of the Padrioc Formation.

These fine–grained deposits of the Campanario Fromation are replaced upwards by a sandstone unit that traditionally has been referred to as the Padrioc Formation (Figure 19, 20). This unit is 30 m thick and dominated by large scale tabular and trough cross-stratified, well-sorted, medium– to fine-grained quartzose sandstone beds that record deposition in subtidal sandbars. Correlation of this sandstone body is problematic due to the scarcity of body fossils. The presence of *Parabolina (Neoparabolina) frequens argentina* (Kayser) in the upper part of the Padrioc Formation (Moya and Monteros, 2000) suggests that this unit is the basal sandstone of the Late Cambrian–Early Ordovician sedimentary cycle.

Lampazar Formation. Tide–dominated sandstones of the Padrioc Formation are abruptly overlain by a mudstone–dominated succession referred to as the Lampazar Formation (Figure 20). This unit is 70 m thick and is characterized by parallel laminated mudstone and thin, very fine–grained sandstone beds with combined–flow ripple cross–lamination and microhummocky cross–stratification. Thin to moderately thick, non–amalgamated, hummocky cross–stratified, fine to very fine–grained sandstone and shell beds occur towards the top of the interval. The shelly fauna increases notably within the highstand systems tract in middle and upper intervals of the unit. Sandstone and coquina beds that characterize this part of the succession contain *P (N.) frequens argentina* together with olenids and agnostids, some of which range up to the Saladillo Formation. One of the younger coquinas yielded conodonts of the *Hirsutodontus hirsutus* Subzone (*Cordylodus proavus* Zone), indicating a Late Cambrian age (Moya and Albanesi, 2000; Moya et al., 2003). This interval is represented by *Cordylodus proavus* Müller, *C.* cf. *proavus, C. primitivus* Bagnoli *et al*., *C. andresi* Viira, *Eoconodontus notchpeakensis* (Miller),*Hirsutodontus hirsutus* Miller, *Proconodontus muelleri* Miller, *Furnishina* sp., and *Prooneotodus* sp. (Figure 27).

The Lampazar Formation mostly represents alternating sediment fallout and storm deposition in wave–dominated, lower offshore to offshore transition environments. The lowermost parasequences display a retrogradational stacking pattern (transgressive systems tract), reflecting a transgressive episode that blanketed subtidal sandbar deposits of the Padrioc Formation. Above the maximum flooding interval, the middle and upper intervals of the Lampazar Formation show an arrangement of progradational parasequence sets, representing a highstand systems tract (Buatois *et al*., 2003).

Cardonal Formation. Fine–grained deposits of the Lampazar Formation are abruptly overlain by another sandstone–dominated package of the Cardonal Formation (Figure 20). This unit is 90 m thick and can be divided into three distinct intervals, a lower sandstone–dominated interval, a middle mixed sandstone and mudstone interval and an upper sandstone–dominated interval (Buatois *et al*., 2003; Moya *et al*., 2003). The lower and upper intervals are composed of hummocky cross–stratified, fine–grained sandstone. Sandstone beds are commonly amalgamated and internal second–order erosion surfaces separating hummocky cross–stratified laminasets are present. Proximal storm beds deposited in lower to middle shoreface environments are represented by thick amalgamated hummocky cross–stratified sandstones. Hummocky cross–stratified sandstone bedsets occasionally pass upwards into fine–grained, trough cross–stratified sandstone units that record migration of three dimensional dunes in the upper shoreface. Amalgamation of hummocky cross–stratified beds and scarce bioturbation represented by opportunistic *Skolithos* suites indicate that the shoreface deposits of the Cardonal Formation were strongly storm–dominated.

The middle member consists of interbedded parallel laminated mudstone and thin to rarely thick, fine– to very fine–grained sandstone beds with combined–flow ripple cross–lamination, microhummocky cross–stratification and hummocky cross–stratification. *Skolithos* occurs as endichnia in storm sandstone beds, while *Cruziana* is common as positive hyporelief and, very rarely, negative epirelief. Arthropod trackways are common on top of hummocky sandstone layers. The presence of *P. (N.) frequens argentina* associated with the first shumardids and pelturids and new olenids is recorded in the middle of the Cardonal Formation. Neither conodonts nor graptolites were found in these strata at the present. This interval mostly records alternating sediment fallout and storm deposition in upper offshore to offshore transition environments, although shoreface deposits are locally present also. The lower shoreface unit of the Cardonal Formation most likely represents the incision of a sharp–based, forced regressive shoreface, which is included in the falling stage systems tract. The base of this formation is, therefore, a regressive surface of marine erosion and the sequence boundary is placed at the top of the lower shoreface interval. Lowstand deposits have not been identified and the sequence boundary is regarded as a co–planar surface or amalgamated flooding surface/sequence boundary. A subsequent transgressive–regressive cycle is detected within the middle and upper interval of the Cardonal Formation (ARE1 and ARE2 *sensu* Moya *et al.*, 2003). This cycle culminates with the progradation of the upper shoreface unit during a "normal" regression.

Saladillo Formation. The Cardonal Formation is abruptly overlain by fine–grained deposits of the Saladillo Formation (Figure 19, 20). The contact between both units is a sequence boundary represented by a co–planar surface. In the analyzed section, the Saladillo Formation is approximately 200 m thick. The lower interval of the Saladillo Formation at Angosto del Moreno consists of parallel laminated mudstone with occasional intercalations of very thin, very fine–grained, silty sandstone beds with combined–flow ripple cross–lamination and microhummocky cross–stratification that become more common towards the top of this lower interval. Trilobites and graptolites are abundant in these fine–grained deposits (Moya *et al.*, 2003). The first record of *Anisograptus matanensis* Ruedemann is placed about 7 m above the base of the formation, associated with scarce *Rhabdinopora* sp. *Anisograptus matanensis* is abundant through the succeeding 10 m, being the only graptolite found in these levels. It represents the *A. matanensis* Zone, the third graptolite zone of the Lower Tremadocian, according to the scheme proposed by Cooper *et al.* (1998). Interestingly, a new species of *Saltaspis* is recorded in the lowermost strata of the formation, ranging up to 20 m from the base, in association with the graptolites mentioned. A transitional trilobite association between the *P. (N.) frequens argentina* and *Kainella meridionalis* zones was recognized in the basal part of the Saladillo Formation (Moya *et al.*, 2003). It includes *Parabolinella coelatifrons* Harrington & Leanza, *Pseudokainella conic* (Kobayashi), *Apatokephalus exiguus* Harrington & Leanza, *Geragnostus nesossi*, and *Micragnostus* sp., among others.

The middle interval consists of interbedded parallel laminated mudstone and thin, very fine– to fine–grained sandstone beds with combined–flow ripple cross–lamination, microhummocky cross–lamination and, more rarely, hummocky cross–stratification. Trilobite traces, such as *Cruziana* and *Diplichnites*, are extremelly abundant, but *Skolithos* is rare. Physical sedimentary structures indicate alternation of sediment fallout and storm deposition. The presence of synsedimentary deformational structures indicates high sedimentation rates in a relatively steep slope and a deltaic influence is inferred. Absence of dwelling traces of suspension feeders probably reflects high suspended, fine–grained sediment load due to deltaic discharge. The lower and middle intervals of the Saladillo Formation record a transgressive–regressive cycle. Transgressive deposits are present at the lowermost interval of the Saladillo Formation. The maximum flooding surface occurs within the shelf deposits and is overlain by a progradational parasequence set that records deposition in prodelta to distal delta front environments of a wave–dominated deltaic system (highstand systems tract). The parallel laminated mudstones and thin shell beds of the upper interval represent the drowning of the deltaic system during a subsequent transgressive event. Despite particular efforts were addressed in search of conodonts (ca. 15 kg of calcarenites and calcareous coquinas completely digested by conventional acid etching techniques) no findings are registered at the moment.

Paleontologic information suggests that the Cambrian–Ordovician boundary may be located within the depositional sequence that comprises the middle and upper interval of the Cardonal Formation. In particular, the sequence boundary at the top of the Cardonal Formation may represent a significant hiatus. Therefore, the Cambrian–Ordovician boundary may be coincident with the contact between the Cardonal and Saladillo Formations. The lowermost Tremadocian graptolite zones may be absent in the basal interval of the Saladillo Formation at the studied section, reflecting a hiatus due to amalgamation between lowstand erosion and subsequent transgression. Further paleontologic sampling in this depositional sequence is essential for a more accurate delineation of the Cambrian–Ordovician transition.

Stop 6. Upper Saladillo Formation – Acoite Formation.

Another outcrop of the Saladillo Formation occurs further south in the same area and has been analyzed by Gómez Martínez et al. (2002). This 120 m–thick interval corresponds to the uppermost part of the Saladillo Formation in the El Moreno area and occurs stratigraphically above the succession previously discussed (Figure 21). These authors recognized a mainly sandy bioturbated interval in the lower part of the outcrops, representing subtidal and intertidal environments, and offshore to shoreface storm–dominated deposits in the upper part of the formation. According to Moya *et al.* (2003) the surface separating the Saladillo and Acoite formations (Tumbaya unconformity) corresponds to the Black Mountain Regresive Event (BMEE), also recorded in other areas of the Western Cordillera (Moya *et al.*, 2003 b).

The trilobite *Kainella meridionalis* Kobayashi and *Pseudokainella lata* (Kobayashi) are present in these beds (Moya and Albanesi, 2000). Additionally, conodonts from the *Cordylodus angulatus* Zone (Moya and Albanesi, 2000), which indicate a late Early Tremadocian age for this outcrop, were recovered.*Rhabdinopora flabelliformis* and *Anisograptus matanensis* remains were collected in these layers (Figure 22, 24, 25, 26).

The Tumbaya unconformity separates the Lower Tremadocian Saladillo Formation from Lower Arenig deposits of the Acoite Formation. The latter is a shaly unit that reaches 450 m thick in the Mojotoro range (Moya, 1998) and 1440 m thick at Santa Victoria range (Harrington & Leanza, 1957). The succession is dominated by green and black shales with subordinate sandstone and calcareous sandstone levels, mostly present in the lower part of the unit. Trilobites, conodonts and graptolites are most frequent fossils in the Acoite Formation, although ostracods, phyllocarids, brachiopods, nautiloids, and gastropods were also mentioned (*e.g.,* Harrington & Leanza, 1957; Moya *et al.*, 2003). An early Arenig graptolite assemblage was recorded from the basal part of the Acoite Formation (Moya *et al.*, 1998). *Tetragraptus* sp. cf. *T. phyllograptoides* Strandmark occurs in the lowermost strata, and ranges up *ca.* 5 m above the base of the formation, where it is associated to *Tetragraptus approximatus* Nicholson, *Didymograptus* (s.l.) sp. cf. *D. demissus* Törnquist, and *D.* (*s.l.*) *D. rigoletto* Maletz, Rushton & Lindholm. The occurrence of *Baltograptus geometricus* (Törnquist), *T. approximatus*, *D.* (s.l.) sp. cf. *D. demissus*, and *D.* (*s.l.*)*D. rigoletto* is recorded *ca.* 12 m above the base of the unit (Figure 23).

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