Tectonic controls on deposition in the late Cambrian - Early Ordovician Central Andean Basin (Cordillera Oriental; northwest Argentina) – the first step towards an integrative reconstruction

[1,2*] Romain Vaucher | [1,2] N.Emilio Vaccari | [1,2] Diego Balseiro | [1,2] Diego F. Muñoz | [1,2] Beatriz G. Waisfeld | [3] Luis A. Buatois

[1] *Universidad Nacional de Córdoba. Facultad de Ciencias Exactas, Físicas y Naturales. Av. Vélez Sársfield 299, X5000JJC, Córdoba, Argentina*

[2] *Consejo Nacional de Investigaciones Científicas y Tecnológicas (CONICET), Centro de investigaciones en Ciencias de la Tierra, (CICTERRA). Av. Vélez Sársfield 1611, Edificio CICTERRA, X5016CGA, Ciudad Universitaria, Córdoba, Argentina*

[3] *Department of Geological Sciences, University of Saskatchewan, 114 Science Place, Saskatoon, SK S7N 5E2, Canada*

**corresponding author:* romain.vaucher88@gmail.com

ABSTRACT

At least since the early Paleozoic, the western Gondwanaland is an active margin. Although several studies have tried to tackle its complex geodynamics, there are still major uncertainties regarding the role of tectonism in sedimentary dynamics. This study provides new data to delineate a tectonic pulse recorded at the south of the Central Andean Basin during the Cambrian-Ordovician transition. Sedimentary rocks of this time interval crop out extensively in northwest Argentina. However, these fluvio-marine sedimentary successions lack detailed reconstructions that are crucial to constrain the evolution of the basin. This study focuses on upper Cambrian – Lower Ordovician strata containing the lowermost fossil-bearing levels of the basin (Santa Rosita Formation and Guayoc Chico Group). Bounded by two major regional unconformities, this stratigraphic interval was previously considered as a retro-arc foreland basin displaying evidence of westward progradation without tectonic activity during its deposition. Throughout the sedimentary successions, four main facies zones are described, namely fluvial-estuarine, shoreface-foreshore, delta-front, and offshore-shelf environments. Biostratigraphic constrain is provided by trilobite biozones (*Neoparabolina frequens argentina, Jujuyaspis keideli, Kainella andina, Kainella meridionalis* and *Kainella teiichii*). Integrating sedimentary facies analysis, biostratigraphy, and sequence stratigraphy information from four selected areas across the Cordillera Oriental (Sierra de Cajas, Angosto del Moreno, Quebrada de Trancas and Quebrada de Moya; Province of Jujuy), a more complex evolution of the basin is proposed. Newly acquired data attest for a northward progradation of the system associated with a partially diachronic basin closure related to a first tectonic pulse induced by the Oclóyic phase. This southernmost tectonic pulse is recorded in various areas at the Cambrian-Ordovician boundary. It is highlighted by large highly erosive wave-ravinement surfaces and depositional geometries suggesting a major change in the basin physiography during the Cambrian-Ordovician transition. This study provides new results helping to constrain the evolution of the western Gondwana margin during the early Palaeozoic.

Keywords

Basin reconstruction; Cambrian-Ordovician; Shallow-marine; Biostratigraphy; Tectonism; Argentina

1 | INTRODUCTION

Sedimentary basin evolution provides crucial information to decipher past geodynamic constraints. Located on an active margin since at least the early Palaeozoic, the Central Andean Basin has been affected by various compressive, extensive and transpressive phases through time (e.g., Forsythe et al., 1993; Bahlburg et al., 1994; Bahlburg and Hervé, 1997; Dalziel, 1997; Coira et al., 1999; Rapalini, 2005; Ramos, 2008; 2018; Casquet et al., 2012; 2018; Weinberg et al., 2018). The Cambrian (Furongian – Stage 10) to Ordovician (Tremadocian – Tr1) interval of the basin consists of shallow-marine to fluvial sedimentary successions cropping out extensively in northwest Argentina (Provinces of Salta and Jujuy; Figures 1 and 2). These stratigraphic units were subject to intense paleontological (e.g., Harrington and Leanza, 1957; Franco Tortello et al., 1999; Benedetto and Carrasco, 2002; Tortello and Esteban, 2003; Vaccari et al., 2004; Balseiro et al., 2011; Balseiro and Waisfeld, 2013; Albanesi et al., 2015; Muñoz and Benedetto, 2016; Waisfeld and Balseiro, 2016; Aris et al., 2017; Salas et al., 2018 among others) and paleoenvironmental (Moya, 1988; 1998; Astini et al., 2003; Buatois and Mángano, 2003; Tortello and Esteban, 2003; Buatois et al., 2006) studies during the last decades. In addition, some studies focused on regional tectonostratigraphic reconstructions (e.g., Gohrbandt, 1992; Forsythe et al., 1993; Bahlburg et al., 1994; Bahlburg and Hervé, 1997; Ramos, 2008; 2018). However, there is a marked paucity of studies attempting to frame detailed facies characterization within the perspective of basin evolution (Astini, 2003; 2008; Egenhoff, 2007).

Since the basin settled on an active margin (e.g., Ramos, 1988; Dalziel, 1997; Aceñolaza et al., 2002; Casquet et al., 2012; 2018), various unconformities were formed (Moya, 1988; 1997; Astini, 2003). Therefore, performing basin reconstruction is not straightforward. Relative sea-level fluctuations driven by tectonic or eustacy have resulted in the deposition of siltstone and sandstone packages which are almost impossible to differentiate without the evaluation of fossil content and detailed facies analysis (e.g., Astini, 2003; Buatois and Mángano, 2003; Buatois et al., 2003; 2006). This study aims to provide the first step towards an integrative and detailed basin reconstruction of the southern part of Central Andean Basin based on outcrops from Cordillera Oriental in Jujuy Province (Argentina). It represents an example of a multi-scale approach combing facies analysis, biostratigraphy and sequence stratigraphy in order to provide a model of basin reconstruction in an active margin. This contribution highlights an unsuspected

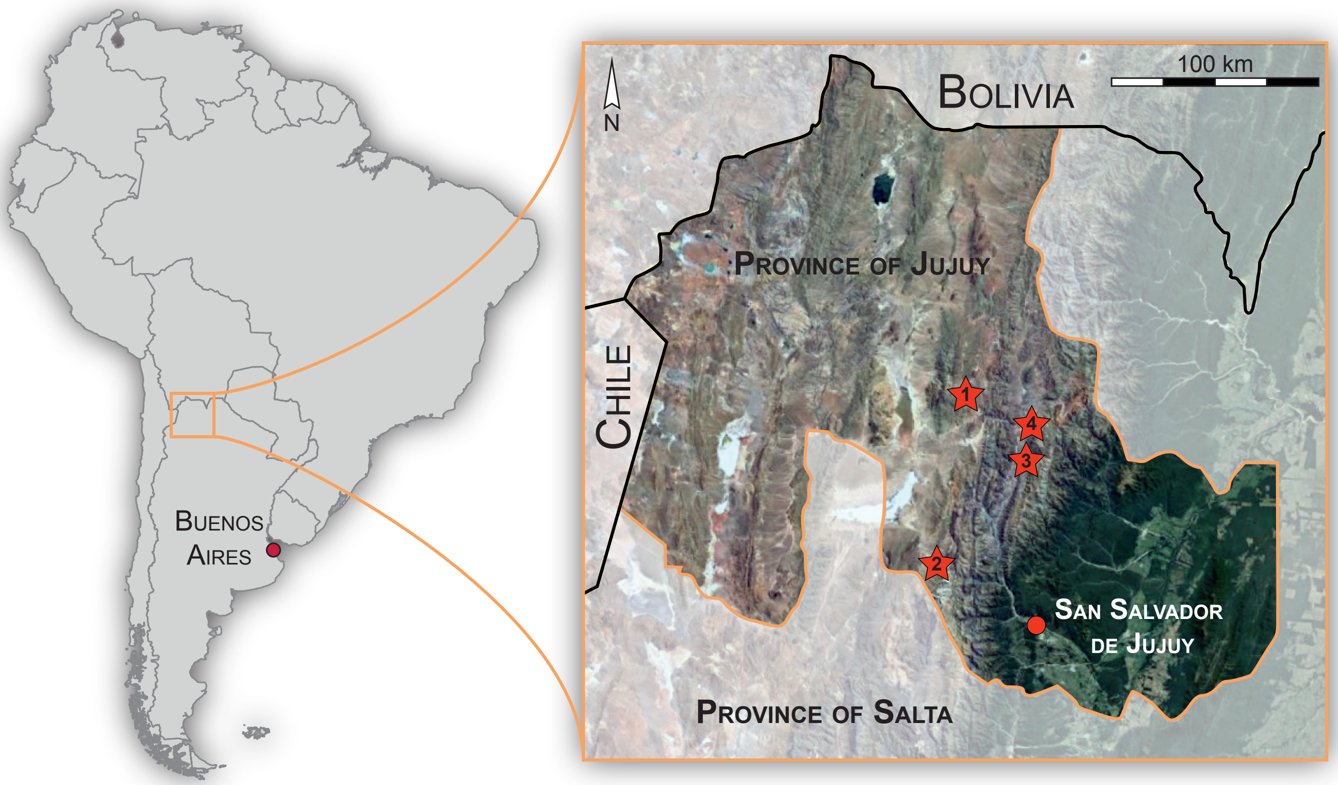

Fig. 1. Map of the studied area in the northwest of Argentina (Province of Jujuy). Satellite picture from Google Earth©. 1: Sierra de Cajas; 2: Angosto del Moreno; 3: Quebrada de Trancas; 4: Quebrada de Moya.

tectonic pulse related to the Oclóyic phase during the Cambrian-Ordovician transition modifying the basin physiography. Therefore, these data are not only important for the reconstruction of the studied basin, but also provide new evidences helping to refine geodynamic evolution of the western margin of Gondwana, while suggesting future research areas.

2 | STRATIGRAPHIC NOMENCLATURE UPDATE

Cambrian (Stage 10) – Ordovician (Tr1) sedimentary successions exhibit a complex nomenclature including formal and informal names that have been employed among different localities across the basin (Astini, 2003 and references therein). Buatois et al. (2006) proposed a stratigraphic framework for the Quebrada de Humahuaca area (east of Cordillera Oriental; Figure 2a) based on an integrated sedimentologic, sequence-stratigraphic and biostratigraphic study. In contrast, for the western border of the Cordillera Oriental and Salinas Grandes area (i.e., Sierra de Cajas and Angosto del Moreno; Figure 3), formational names largely derive from uncertain correlations. Ramos (1973) proposed the Guayoc Chico Group (GCG) to include the Lampazar, Cardonal, and Saladillo formations in this area. These names were previously used by Harrington (1957), partially based on Keidel (in Harrington, 1937), for the successions exposed in the Incamayo region (SE from Angosto del Moreno; Figures 1 and 2a). However, subsequent authors (e.g., Malanca and Brandán, 2000; Moya and Monteros, 2000) did not use the name GCG, but referred the successions to their three component formations. Astini (2003; 2005) indicated that these formations should not be extended from the Incamayo to the Salinas Grandes due to substantial stratigraphic differences between these regions. Astini (2003; 2008), therefore, restricted the use of the GCG for the Angosto del Moreno area, excluded from this group the Lampazar Formation, and proposed five informal members for the interval that Ramos (1973) and subsequent authors referred to the Cardonal and Saladillo formations. Following the idea of not using previously defined formational names for the Angosto del Moreno area, Buatois et al. (2003) and Moya et al. (2003) proposed an informal stratigraphic framework that included four units (I, II, II, IV; Figure 3). Based on a biostratigraphically well-constrained, sedimentologic and stratigraphic study, it is here suggested to retain the GCG for the succession bracketed between the Mesón Group and the Tumbaya Unconformity that separates this stratigraphic interval from the Acoite Formation

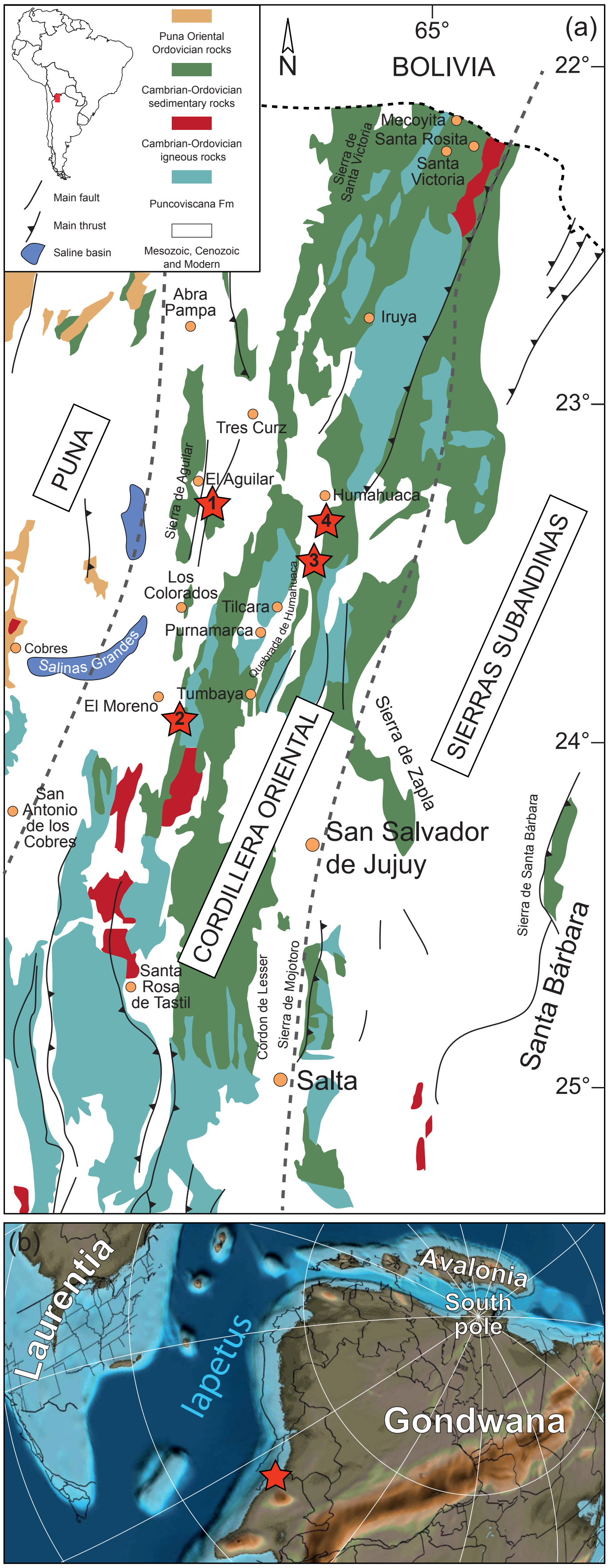

Fig. 2. Geological context of the study zone. (a) Simplified geological map showing the main lower Paleozoic units cropping out in the northwest of Argentina, modified after Astini (2003). 1: Sierra de Cajas; 2: Angosto del Moreno; 3: Quebrada de Trancas; 4: Quebrada de Moya. (b) Palaeogeographic map of west Gondwana at ca. 485 Ma, modified after Scotese (2016). Red star shows the Central Andean Basin location.

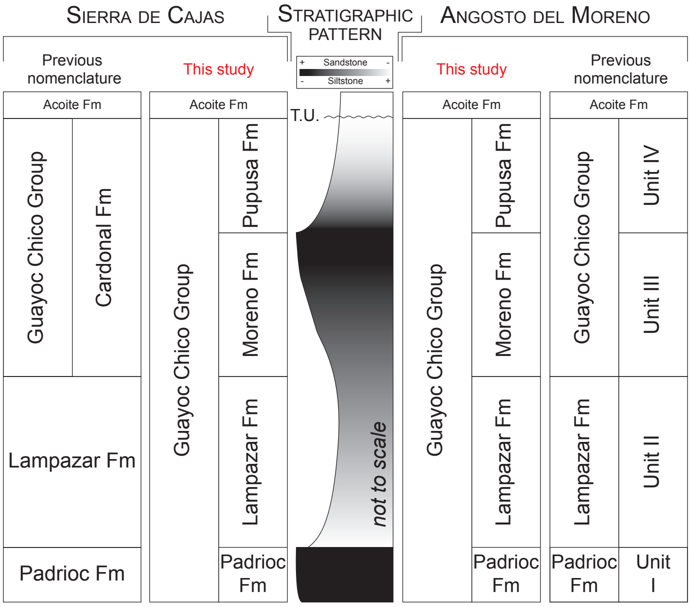

Fig. 3. Stratigraphic nomenclature update for the localities of Sierra de Cajas and Angosto del Moreno. The previously used nomenclature (see main text for details) is now updated providing easiest correlation between the western and the eastern part the Cordillera Oriental (Figure 4). The Guayoc Chico Group encompasses the Padrioc, the Lampazar, the Moreno and the Pupusa formations. T.U.: Tumbaya Uncomformity.

(Floian). Thus, the GCG encompasses the Padrioc, Lampazar, Moreno, and Pupusa formations (Figure 3). The last two names are proposed herein to replace the informal members/units of previous authors and are formally defined in the Appendix. No trilobites have been ever found in the Padrioc Formation, whereas the Lampazar and Moreno formations yield the Furongian *Neoparabolina frequens argentina* Biozone and the Pupusa Formation encompasses the *Jujuyaspis keideli* and *Kainella andina* biozones of the scheme put forward by Vaccari et al. (2010). The same stratigraphic pattern is recognized for the Furongian to lower Tremadocian deposits of Sierra de Cajas (Figure 3).

3 | GEOLOGIC AND GEODYNAMIC FRAMEWORK

The Cordillera Oriental (Figure 2a) represents one of the three sub-basins included in the Cambrian-Ordovician Central Andean Basin located in northwest Argentina, which extends into Peru, Bolivia and Chile (e.g., Astini, 2003 and references therein). Cambrian – Ordovician sedimentary rocks are well exposed in the Province of Jujuy and four stratigraphic sections have been selected to conduct this study: (1) Sierra de Cajas; (2) Angosto del Moreno; (3) Quebrada de Trancas; and (4) Quebrada de Moya (Figures 1 and 2a). These localities were chosen due to their high biostratigraphic resolution and good quality exposures. Cambrian-Ordovician sedimentary rocks reflect deposition in shallow-marine environments (Astini, 2003; Buatois and Mángano, 2003; Buatois et al., 2006) in the southern part of Central Andean Basin at the periphery of Gondwana at ~40°S of paleolatitude (e.g., Torsvik and Cocks, 2013a; b; Figure 2b). The sedimentary successions studied belong to the GCG (Padrioc, Lampazar, Moreno and Pupusa formations) in the localities of Sierra de Cajas and Angosto del Moreno (Figures 3 and 4). Regarding the two other sections, Quebrada de Trancas and Quebrada de Moya, the stratigraphic successions are part of the Santa Rosita Formation (SRF; Tilcara, Casa Colorada, Alfarcito and Ruspaca members; Figure 4). The Santa Victoria Group encompasses the SRF (late Cambrian; Stage 10 – Early Ordovician; Tr1 – Tr3) and the Acoite Formation (Early Ordovician – Floian) (Turner, 1960). In all places, the Tilcara Member and the Padrioc Formation overlain the lower-middle Cambrian Mesón Group (e.g., Turner, 1960; Moya, 1988).

The basement in Cordillera Oriental is the metasedimentary Puncoviscana Formation deposited between ca. 570 Ma and ca. 537 Ma (e.g., Aparicio González et al., 2014). This unit was subsequently metamorphosed during the early Cambrian Pampean Orogeny (e.g., Mon and Hongn, 1996; Escayola et al., 2011; Casquet et al., 2018) induced by the oblique transpressive collision of the MARA block *sensu* Casquet et al. (2012) which accreted the Maz, Arequipa, and Rio Apa terranes. Further, the Mesón Group uncomformably overlains the Puncoviscana Formation (Sánchez and Salfity, 1999). This unconformity is related to the previously mentioned collision of the MARA block (Forsythe et al., 1993; Bahlburg and Hervé, 1997; Egenhoff, 2007). The Santa Victoria Group is on top of the Mesón Group (Moya, 1988; Sánchez and Salfity, 1999). On one hand, the contact between the Santa Victoria Group and the Mesón Group is considered as an unconformity related to the rifting phase (Irúyica Event; Turner and Méndez, 1975) moving eastward the Arequipa-Antofalla terrane (AAt) opening a V-shaped marine basin wider northwards in Bolivia (Gohrbandt, 1992; Forsythe et al., 1993; Bahlburg and Hervé, 1997; Egenhoff, 2007). Alternatively, this contact has been considered as an unconformity due to a relative sea level fall (e.g., Moya, 1998; Buatois et al., 2000; Buatois and Mángano, 2003; Mángano and Buatois, 2004) or as a conformable depositional transition (e.g., Ruiz Huidobro, 1975; Fernández et al., 1982). The V-shaped basin is inherited from

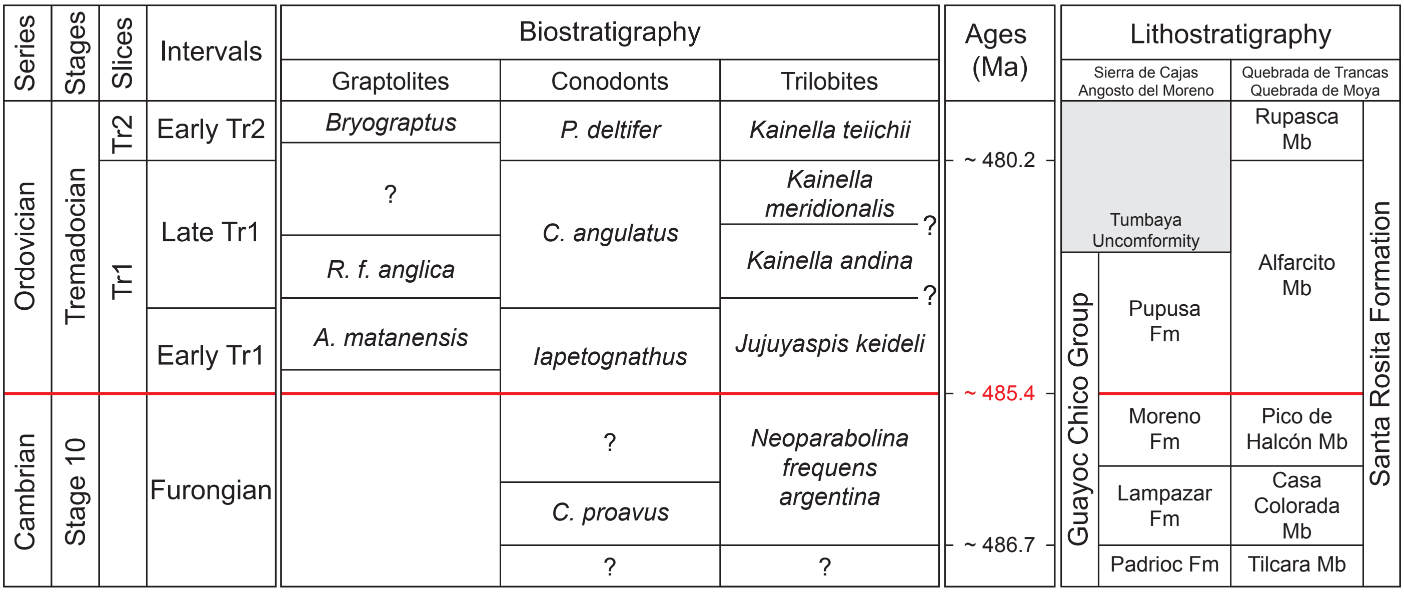

Fig. 4. Regional biostratigraphy and lithostratigraphy, correlated to the chat intervals used. Modified and updated form Balseiro and Waisfeld (2013), absolute ages extracted from Ogg et al. (2016). Note that the Humacha Member (the sixtieth official member of the SRF), which come above the Rupasca Member is not represented since it is not part of this study.

the counterclockwise rotation of AAt with a Euler pole located in NW Argentina as evidenced by paleomagnetic data by Forsythe et al. (1993). After this opening phase, it has been proposed that the SRF and the GCG were deposited in a back-arc foreland context without major tectonic events and recording mostly long-term sea-level fluctuations (Moya, 1988; Astini, 2003; Buatois and Mángano, 2003; Buatois et al., 2006).

4 | METHODOLOGY

4.1 | Sedimentology & Stratigraphy

Sedimentological field-based studies were undertaken in order to reconstruct the evolution of the basin across the Cambrian-Ordovician transition in the northwest of Argentina. The first step involved logging at a decimeter-scale approximately 1700 m of cumulative thickness from four different sedimentary successions (Sierra de Cajas, Angosto del Moreno, Quebrada de Trancas, and Quebrada de Moya; see Figure 5). The studied sedimentary successions range from the Stage 10 (late Cambrian – Furongian) to Tr2 (Early Ordovician – Tremadocian). Stratigraphic sections display a repeated alternation of siltstone and sandstone packages, which belong to the SRF and its stratigraphic equivalent (i.e., GCG; see Figure 4). Lithology, grain size, sedimentary structures, beds thickness, bed contacts, and overall geometries were described, allowing the distinction of sedimentary facies that were grouped into four facies zones. Due to the large extent of the studied area and the thickness of the deposits, the classic continental to shallow-marine subdivisions (e.g., Walker and James, 1992; Clifton, 2006; Buatois and Mángano, 2011; Vaucher et al., 2017) have been simplified in order to allow for reconstruction of basin evolution. Accordingly, fluvial and inner to outer estuarine systems are here grouped as fluvial-estuarine facies zone; foreshore, upper, middle and lower shoreface environments are gathered into foreshore-shoreface facies zone (i.e., between mean sea level and the fair-weather wave base; FWWB); distal and proximal delta-front are clustered into delta-front; and offshore transition, upper and lower offshore, and shelf environments are referred to as offshore–shelf zone (i.e., from the fair-weather wave base to the shelf break). An integrative, multi-scale based approach basin reconstruction is then proposed for the southern part of the Central Andean Basin across the Cambrian-Ordovician boundary, covering an area of ca. 3000 km2 lasting ca. 6.5 Myr (Ogg et al., 2016).

4.2 | Biostratigraphy

Difficulties for lithostratigraphic correlation among the different localities of the Cordillera Oriental have been pointed out for the upper Cambrian to Lower Ordovician sedimentary rocks due to the repeated alternation of homogenous siltstone and sandstone packages (Astini, 2003; Buatois and Mángano, 2003; Buatois et al., 2006). Therefore, in order to provide the more accurate correlation while doing basin reconstruction for this studied stratigraphic interval, age control is required. Due to the highly fossiliferous nature of the studied strata,

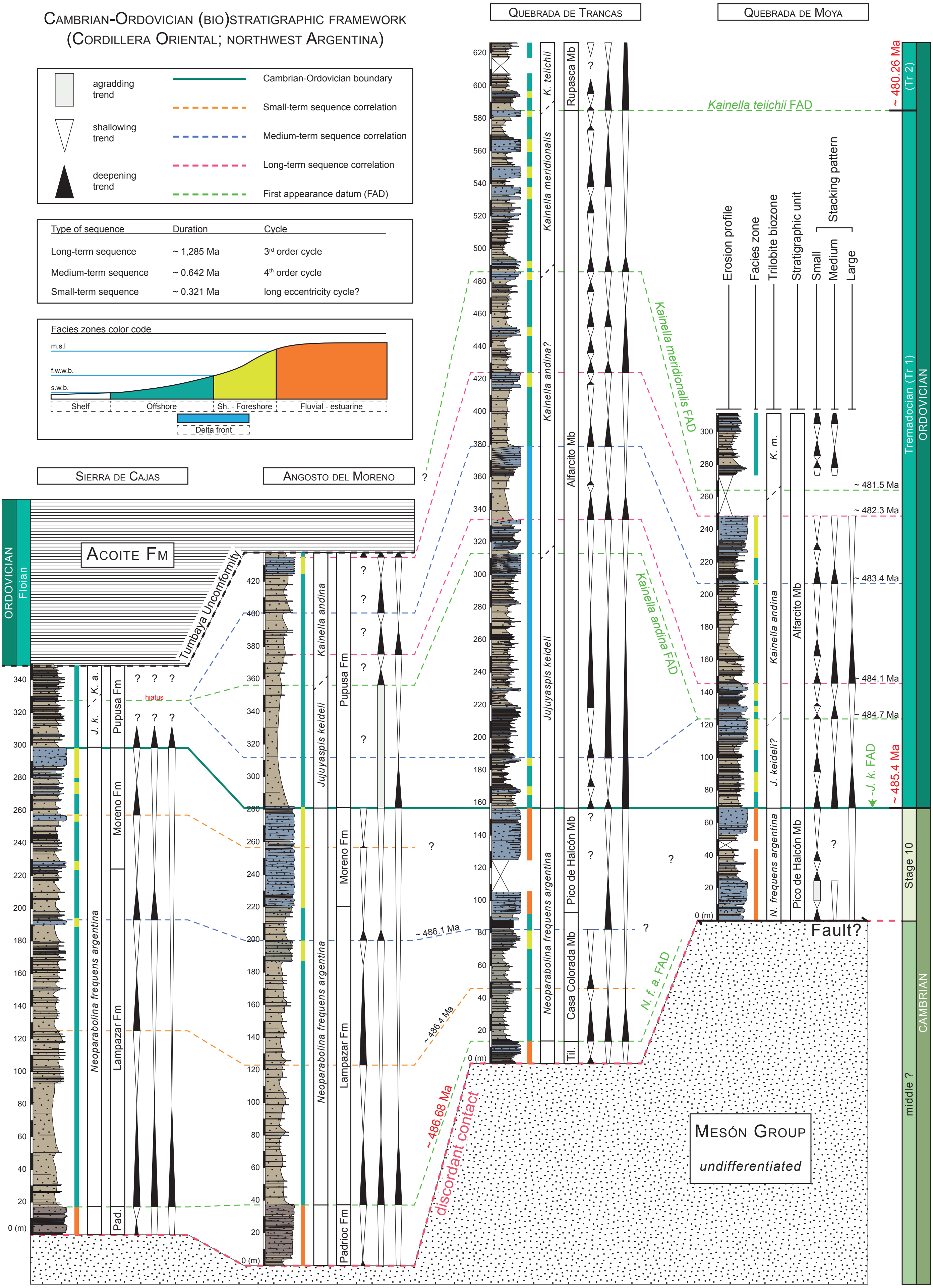

Fig. 5. Detailed stratigraphic sections encompassing the Cambrian-Ordovician boundary. Sequence stratigraphic and biostratigraphic correlations between localities are shown. Ages in red are from Ogg et al. (2016) while ones in black are calculated based on sequence stratigraphic cycles. m.s.l.: mean sea level; f.w.w.b.: fair weather wave base; s.w.b.: storm wave base; Sh.: shoreface; Pad.: Padrioc Formation; N.f.a.: *Neoparabolina frequens argentina*; J.k.: *Jujuyaspis keideli*; K.: *Kainella*; K.m.: *Kainella meridionalis*.

the fossil record represents the most reliable tool for correlation in this basin. Trilobites are used since they have well-defined biozones (e.g., Vaccari et al., 2010 and references therein) for the studied time interval (Furongian – Tr2). Ranging from the Stage 10 (upper Cambrian) to the base of the Tr2 (Lower Ordovician), the trilobite assemblages belong, from base to top, to the Cambrian *Neoparabolina frequens argentina,* and the Ordovician *Jujuyaspis keideli*, *Kainella andina, Kainella meridionalis* and *Kainella teiichii* biozones (Figure 4; e.g., Vaccari et al., 2010).

5 | DEPOSITIONAL SETTINGS

The SRF displaying muddy siltstone alternating with medium- to very fine-grained sandstone were subjected to previous publications describing paleoenvironmental conditions (e.g., Buatois and Mángano, 2003; Buatois et al., 2006). In contrast, the GCG has received less attention regarding to paleoenvironmental reconstructions. Four-facies assemblages, representing four main paleoenvironmental belts (i.e., Fluvial-Estuarine, Foreshore to Shoreface, Delta-front, and Offshore to Shelf), have been identified throughout the studied sedimentary successions. The delta-front reflects a new facies zone that was not previously described in these localities.

5.1 | Fluvial-estuarine

This facies assemblage occurs in the Tilcara and the Pico de Halcón members of the Santa Rosita Formation and in the Padrioc Formation. Massive to planar cross-bedded, fine- to medium-grained sandstone units (individual beds >1m) with irregular bases occur in the Tilcara Member in Quebrada de Trancas. Mudstone intraclasts (Figure 6a) are present in the sandstone, and millimetric mudstone layers are intercalated. This facies assemblage records deposition in a sandy braided fluvial system which prograded northward. Rip-up clasts may have formed by avulsion of the fluvial system over the floodplain (e.g., Dalrymple and Choi, 2007) or due to the interplay of fluvial and tide processes along the fluvial to marine transition zone (e.g., Gugliotta et al., 2018).

Massive to trough and tangential cross-bedded, erosively based, fine- to medium-grained sandstone (Figure 6b, c) are present in the Pico de Halcón Member in Quebrada de Trancas and Quebrada de

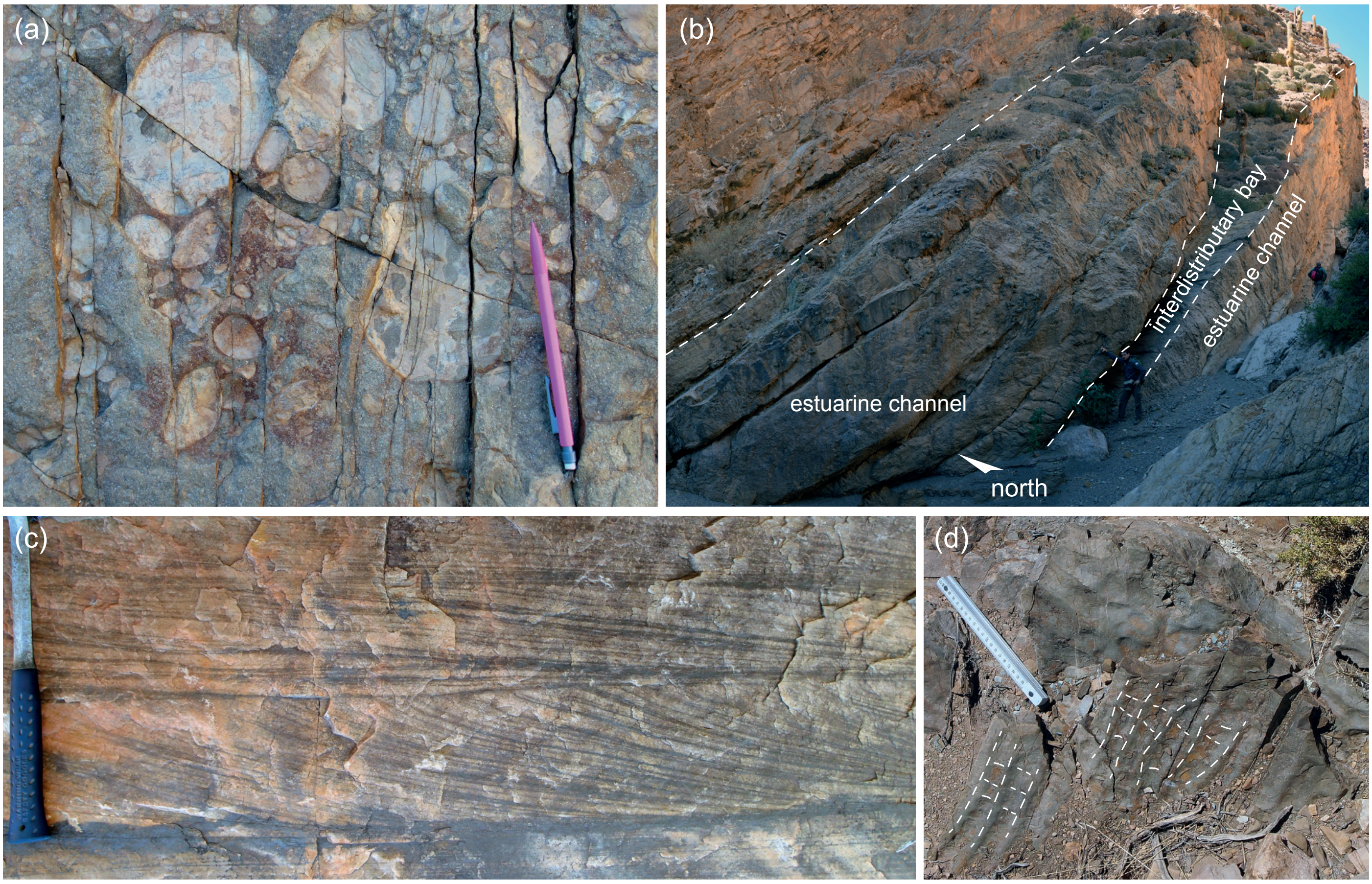

Fig. 6. Fluvial-estuarine facies zone. (a) Rip-up clasts in sandstone bed; Tilcara Member; Quebrada de Trancas. (b) Massive amalgamated sandstone beds reflecting estuarine channels; Pico de Halcón Member; Quebrada de Moya. Person for scale is 1.75m. (c) Cross-stratified sandstone and associated mudstone drapes; Pico de Halcón Member; Quebrada de Trancas. (d) Ladder-back ripples; Padrioc Fm; Sierra de Cajas.

Moya. Single and double mudstone drapes occur on the foreset of the tangential cross-stratified sandstone. The axes of erosion are orientated south/north (Figure 6b). These deposits are interpreted as subtidal sandbodies in middle-to-outer estuarine environments (Dalrymple and Choi, 2007). Heterolithic packages exhibit wavy, flaser and lenticular-bedded sandstone layers alternating with muddy-siltstone. In some localities, ladderback ripples (Figure 6d) on bed tops were also observed, as well as synaeresis cracks. Heterolithic intervals in this unit reflect mixed intertidal flats (Buatois and Mángano, 2003; Buatois et al., 2006), resembling similar deposits elsewhere (e.g., Collinson et al., 2006; Dalrymple and Choi, 2007).

5.2 | Foreshore-Shoreface

This facies assemblage is represented in the Moreno Formation and the lower interval of the Alfarcito Member in the localities of Sierra de Cajas, Angosto del Moreno, and Quebrada de Moya, respectively. Medium-grained sandstone of ca. 1 m thick commonly occurs throughout the studied sedimentary succession. Low-angle planar stratified sandstone intercalated with sandstone having

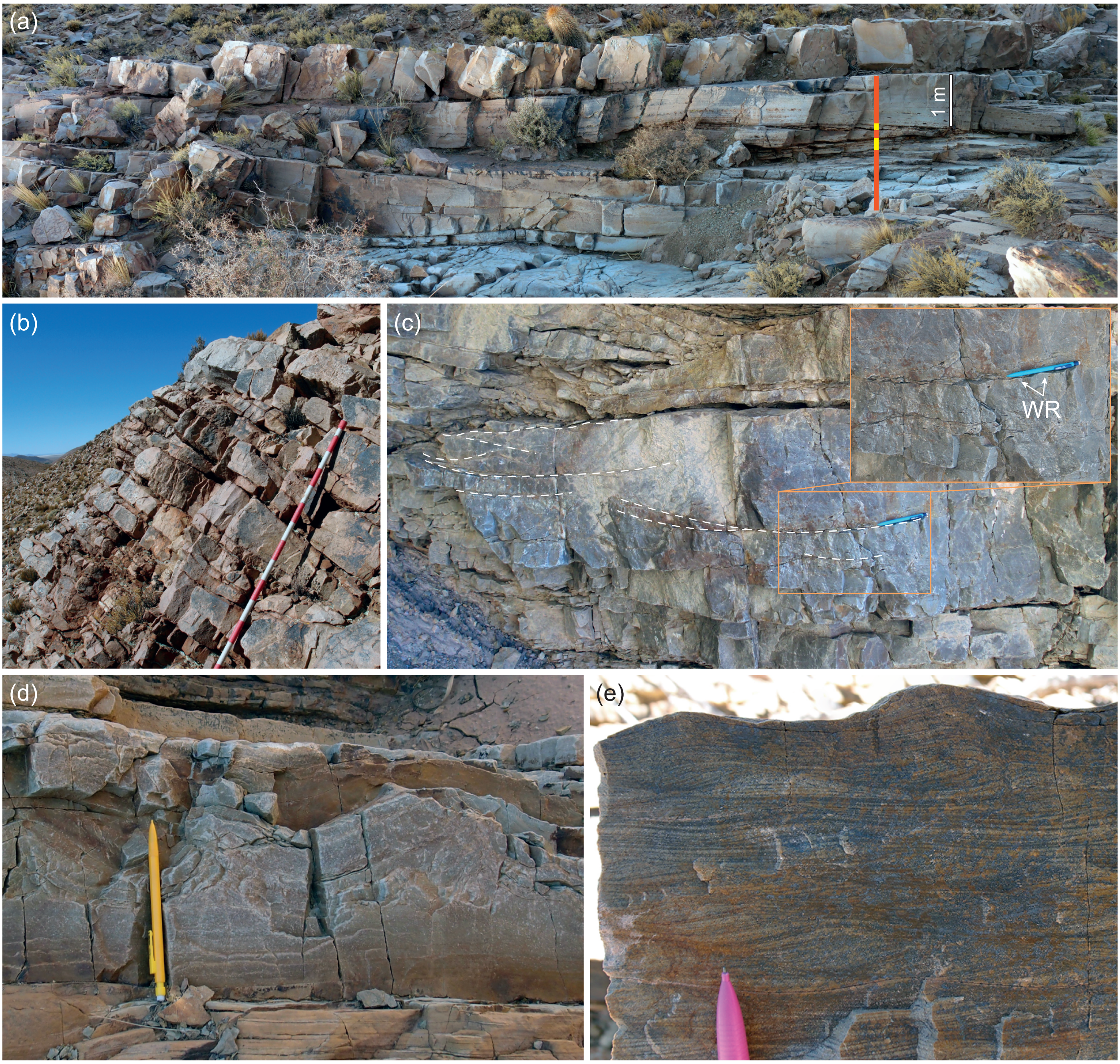

Fig. 7. Foreshore to shoreface facies zone. (a) Massive sandstone bed displaying low-angle planar stratification associated to keystone vugs (in orange) alternated with thinner sandstone levels exhibiting small-scale symmetrical and asymmetrical ripples (in yellow); Sierra de Cajas, Moreno Fm. Note that rippled intervals have a very limited lateral extension. (b) Amalgamated trough cross-bedded sandstone; Angosto del Moreno; Moreno Fm. (c) Trough cross-stratified sandstone with superimposed wave ripples (WR); Alfarcito Member; Quebrada de Moya. (d) sandstone with symmetric ripples suggesting high aggradation rate; Sierra de Cajas, Moreno Formation. (e) Sandstone with wave and combined-flow cross-lamination; Quebrada de Trancas; Alfarcito Member.

symmetrical to asymmetrical ripples (Figure 7a) occurs locally in Sierra de Cajas. These beds exhibit normal contacts but have lateral thickness variations, reaching up to ca. 12 m thick. This interval reflects deposition in a wave-dominated, tide-modulated foreshore-shoreface, where surf-swash process (at low tide) alternated periodically with oscillatory processes (at high tide) (e.g., Dashtgard et al., 2012; Vaucher et al., 2017; 2018).

Up to 1 m thick, trough cross-stratified very fine- to fine-grained sandstone (Figure 7b, c) and symmetrical (Figure 7d) to asymmetrical ripples (Figure 7e) occurs in all localities. Individual beds are stacked forming up to 10 m thick stratigraphic packages (Figure 7b). Sedimentologic features point out to deposition from permanent, nearshore oscillatory, unidirectional and combined-flow currents acting at the water-sediment interface punctuated by storm events in shoreface environments as discussed in previous studies in these strata (Buatois and Mángano, 2003; Buatois et al., 2006) and elsewhere (e.g., Hampson and Storms, 2003; Clifton, 2006).

5.3 | Delta-front

This facies assemblage is only present in the Quebrada de Trancas outcrops of the Alfarcito Member (Figure 5). Thick homogeneous siltstone intervals (Figure 8a) intercalated with sandstone having symmetrical ripples (Figure 8b) and planar-cross bedding (Figure 8c) are dominant in this facies assemblage. Amalgamated, trough cross-stratified, fine-grained sandstone forming packages of ca. 2-10 m thick are present within siltstone intervals (Figure 8d, e). Lobate geometries are characteristic of these sandstone packages, pinching out westwards and eastwards into siltstone intervals at the scale of hundred of meters displaying evidence of northward progradation (Figure 8a, e). Trace and body fossils are scarce and poorly diverse. This facies association points to a river-dominated, wave-affected distal to proximal delta-front (e.g., Orton and Reading, 1993; Olariu and Bhattacharya, 2006; Coates and MacEachern, 2007). Lobate morphologies suggest the dominance of river processes during fluvial discharge under unidirectional flow combined to a high rate of sedimentation without substantial reworking of material by strong wave process (e.g., Bhattacharya and Walker, 1992; Reading, 1996; Bhattacharya and Giosan, 2003). Only a few oscillatory structures were observed, suggesting limited wave/storm influence. The sandstone interval would reflect more proximal settings while siltstone suggests more distal emplacement. However, due to the lobe shape, siltstone packages could also be interpreted as a lateral shift of deposition due to autogenic processes (Catuneanu, 2018), away from terrestrial input. Furthermore, the combined reduced bioturbation and body fossil content could reflect stressed environments related to freshwater input and high sediment concentration in the water column (e.g., MacEachern et al., 2005).

5.4 | Offshore to shelf

This facies assemblage occurs in the four studied localities corresponding to the Lampazar, and Pupusa formations, and the Casa Colorada and Alfarcito members (Figure 5). Laterally persistent, meter-thick siltstone packages represent the most common lithology throughout the different localities (Figure 9a). Only at the base of the Lampazar Formation in Sierra de Cajas, up to 2 m thick, isolated layers of fossil-rich limestone were observed. Structureless, mm-thick mudstone intercalations may also occur. Up to 10 cm thick sandstone layers displaying parallel stratification, combined-flow cross-lamination, as well as symmetrical ripples (Figure 9b, c), are intercalated within siltstone intervals. Ranging from cm- to pluri-dm of thickness, fine-grained sandstone layers with a sharp basal contact associated to flute and gutter casts, flame structures, as well as scour-and-drape hummocky cross-stratification (with associated wavelengths of a cm- to pluri-dm scale), have been observed (Figure 9d, e, f). Gutter casts are all oriented north-south (Figure 9d) and flute casts indicate a northward direction of the paleoflow (Figure 9f). This facies assemblage records deposition below the FWWB in wave-dominated open marine offshore to shelf environments reflecting alternation of low energy suspension fall-out conditions interrupted by storm events at various depths (e.g., Heward, 1981; Buatois et al., 2006; Clifton, 2006; Vaucher et al., 2017). According to the previously described facies-zone (i.e., Delta-front), a prodeltaic paleoenvironmental setting for the siltstone intervals displaying thin fine-grained sandstone layer cannot be excluded (e.g., Coates and MacEachern, 2007; Bhattacharya and MacEachern, 2009). The only limestone layers found in Sierra de Cajas, exclusively composed of shelly remains (mostly trilobite) seem to reflect low

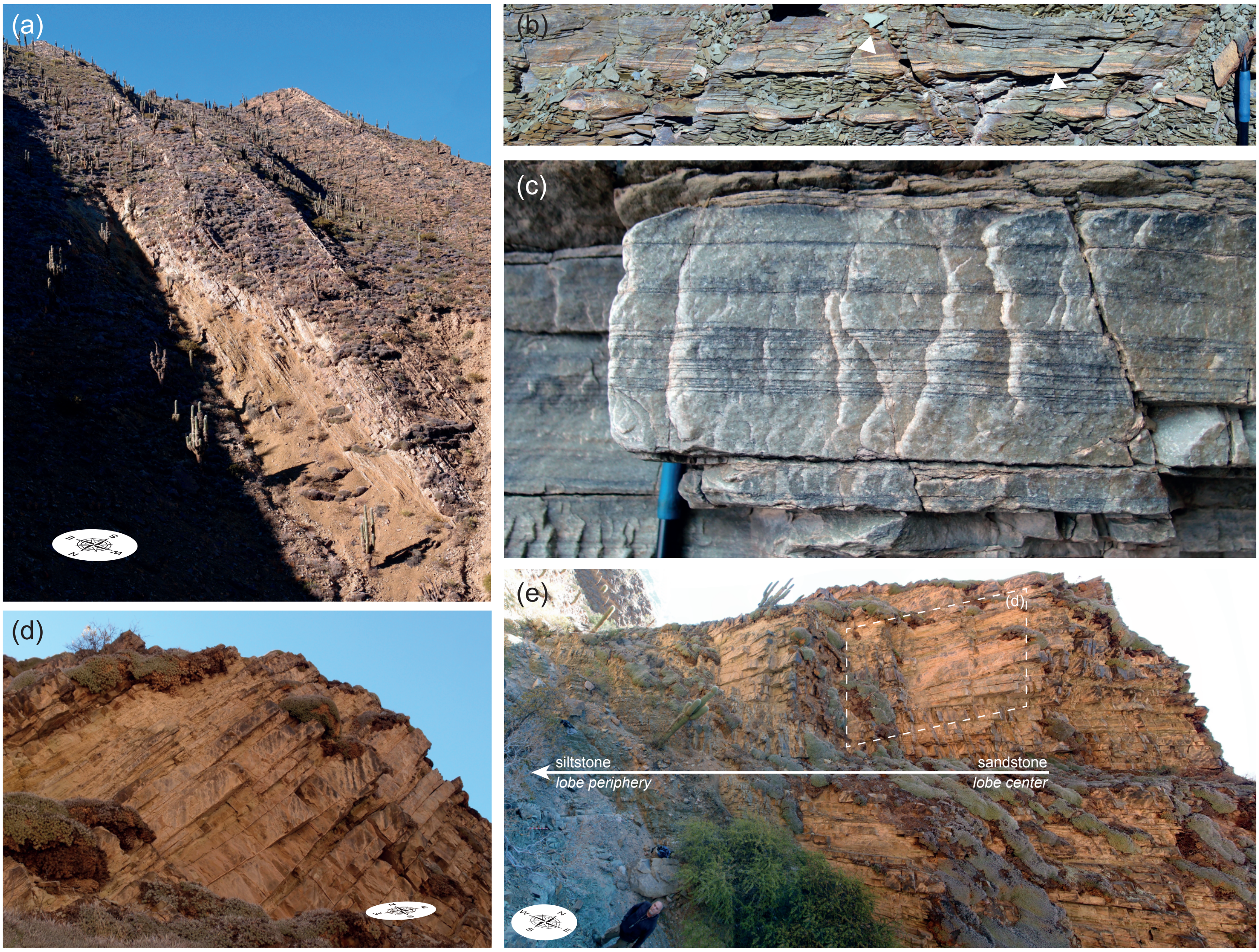

Fig. 8. Delta-front facies zone in Quebrada de Trancas; Alfarcito Member. (a) Channel-lobe sandstone complex with the axis toward the north laterally pinching out into a siltstone interval. (b) Siltstone interval displaying fine-grained wavy shaped sandstone layers (pointed out by the white triangle). (c) Sandstone beds occurring within the sandstone lobe complex displaying planar bedding. (d) Central view of a lobate sandstone package showing the lateral relationship with the adjacent siltstone interval. (d) Zoom of (e) showing the internal stratal architecture of the sandstone lobe complex exhibiting small-scale lobe sandstone units.

sedimentation rates during transgressive phase (e.g., Beckvar and Kidwell, 1988; Botquelen et al., 2004).

6 | CAMBRIAN - ORDOVICIAN UNCONFORMITY

In Quebrada de Trancas and Angosto del Moreno, the stratigraphic contact between Cambrian and Ordovician deposits is erosional and unconformable (Figure 10). In Quebrada de Trancas, the very base of the Ordovician consists of shallow-marine deposits (base of Alfarcito Member; Figures 5, 10a and 10b) truncating the underlying fluvial-estuarine Cambrian deposits (Pico de Halcón Member). Lower Ordovician deposits onlap against the underlying Cambrian (Figure 10a). Measured dipping of the layers below the erosional surface is ~60° while above is ~50°. At the very base of the Ordovician deposits, sandy matrix supported breccia levels were observed on top of the underlying Pico de Halcón Member (Figure 10c). On the southern flank of the Angosto del Moreno (red dot; Figure 10d), three massive sandstone units (foreshore-shoreface deposits containing *Neoparabolina frequens argentina*; late Cambrian) pinch-out laterally (i.e., northward) within a siltstone unit (offshore to shelf deposits of the Pupusa Formation that contains *Saltaspis* sp., a trilobite belonging to the *Jujuyaspis keideli* biozone; Early Ordovician). From south to north, the erosional surface of Angosto del Moreno only goes down. Northward (purple dot; Figure 10d) and further, the contact between the Moreno and Pupusa formations appears as "normal". Contrarily to Quebrada de Trancas, no breccia level has been found at the contact. In both localities, such observations point out to a wave ravinement surface (Zecchin et al., 2018), but in the case of the Angosto del Moreno no evidence of associated transgressive deposits (i.e., breccia) have been identified. In a high-energy context, erosion due to wave ravinement is commonly able to remove up to 10 – 20 m of sediment (e.g.,

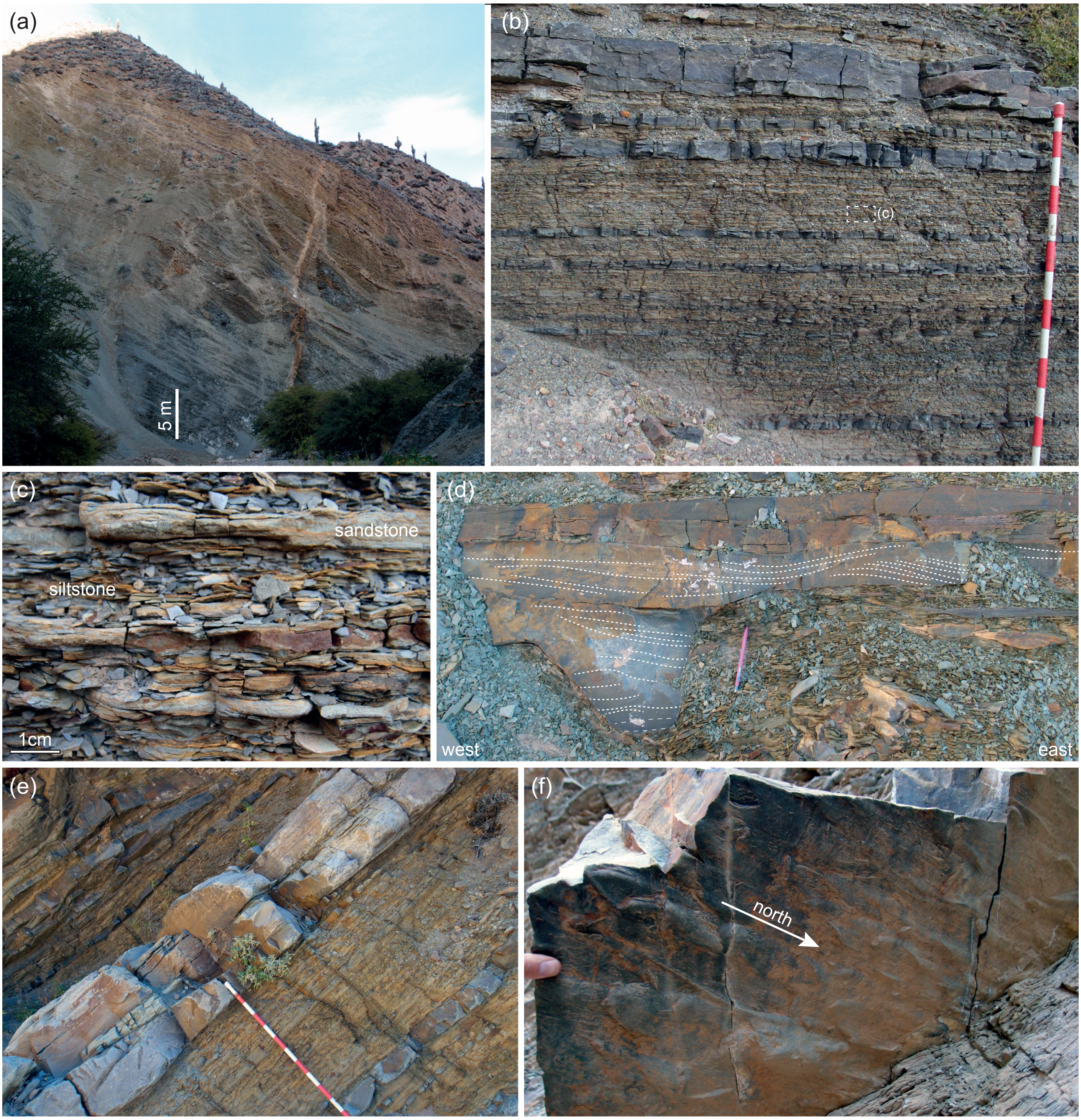

Fig. 9. Offshore to shelf facies zone. (a) Overview of the siltstone-dominated intervals; Quebrada de Moya; Alfarcito Member. (b) Hummocky cross-stratified sandstone interbedded with siltstone-dominated levels; Quebrada de Moya; Alfarcito Member. (c) Zoom from (b) on millimetric sandstone layer intercalated within siltstone packages. (d) Hummocky cross-stratified sandstone displaying a steep-sided gutter cast, Quebrada de Trancas, Alfarcito Member. (e) Hummocky cross-stratified sandstone intercalated within sandy siltstone, Quebrada de Trancas, Alfarcito Member. (e) North-directed flute casts at the base of a sandstone bed, Quebrada de Moya; Alfarcito Member.

Zecchin et al., 2011; 2018). However, in Quebrada de Trancas ~25 m of substrate has been removed while in Angosto del Moreno ~ 60 m (Figures 10 a and 10d). This suggests a slow landward retreat of the shoreline allowing longer time to the wave energy to remove the underlying sediment (Zecchin et al., 2018). In addition, the angular relationship observed in Quebrada de Trancas (Alfarcito Member) suggests that the wave ravinement surface was formed on a steep profile implying an uplift (Pico de Halcón Member and Moreno Formation). In the two other studied localities, Sierra de Cajas and Quebrada de Moya, absence of outcrop continuity prevents closer examination of the stratal geometries associated with the Cambrian-Ordovician boundary.

7 | SEQUENCE STRATIGRAPHY

Time control is provided by trilobite occurrences and the ages are extracted form Ogg et al. (2016 and references herein). The earliest fossil-bearing strata correspond to the base of the Lampazar Formation and the Casa Colorada Member (Figures 4 and 5). No fossils have been ever found in the Padrioc Formation and the Tilcara Member. The base of the Lampazar Formation and the Casa Colorada Member record the first appearance datum (FAD) of *Neoparabolina frequens argentina*, which corresponds to the FAD of *C. proavus* (conodont biozone; Shergold, 1988; Waisfeld and Vaccari, 2008 and references therein) aged at ~486.7 Ma (Figures 4 and 5). The Cambrian-Ordovician boundary is indicated in our studied area by the FAD of *Jujuyasis keideli*, suggesting an age of ~485.4 Ma (Figures 4 and 5). Further, the last absolute available age corresponds to the transition of between the *Kainella meridionalis* and *Kaninella teiichii* biozones. This biozone limit corresponds to the Tr1 – Tr2 boundary aged at ~480.2 Ma (Figures 4 and 5).

Interpretation in term of stratigraphic sequences is proposed for the four stratigraphic sections. Identification of large, medium and small-scale sequences is possible by the facies-zone description proposed previously (Figure 5). Although elementary sequences (*sensu* Strasser et al., 1999) were observed in this study, they fall beyond the scale of resolution for correlation due to the dimension (temporal and geographical extension) of the studied basin. Therefore, small-scale sequences are the smallest sequences described in this study (Figure 5). They varied between ~100 to 10 m thick, reflecting the lithological change from siltstone- to sandstone-dominated intervals. Medium-scale sequences of ~160 to 30 m thick, are composed of 2 small-scale sequences defined by siltstone-dominated small-scale sequence passing to sandstone-dominated small-scale sequence (Figure 5). Large-scale sequences consist of 2 medium-scale sequences and show a thickness of ~180 to ~80 m. They reflect the transition from siltstone- to sandstone-dominated medium-scale sequences (Figure 5). The *Neoparabolina frequens argentina* biozone corresponds to a duration of ~1.28 myr. Considered together the *Jujuyasis keideli, Kainella andina* and *Kainella meridionalis* biozones represent the entire duration of the Tr1 (early early Tremadocian; Figures 4 and 5), which correspond to a duration of ~5.15 myr. While the *Neoparabolina frequens argentina* biozone consists of one large-scale sequence and the Tr1 time interval of 4 large-scale sequences, the proposed duration for a large-scale sequence is then of ~1.28 myr. According to the large-scale sequence duration, this can be considered as a third-order cycle (e.g., Strasser et al., 2006). Thus, medium-scale and small-scale sequences have a respective duration of ~642 kyr and ~301 kyr, respectively. Medium-scale sequences would correspond to fourth-order cycle and small-scale sequence can reflect long-term of eccentricity cycle (Strasser et al., 2006).

8 | DEPOSITIONAL HISTORY

8.1 | late Cambrian (Furongian)

The oldest record of deposition (Furongian) of the studied interval corresponds to the lower part of the SRF and GCG, respectively, and the Tilcara Member and the Padrioc Formation, overlying the Mesón Group. Both units reflect proximal (Tilcara Member) to distal (Padrioc Formation) fluvio-estuarine environments corresponding to a lowstand systems tract (LST) to an early transgressive systems tract (TST). The fluvial system prograded northwards. Further, the onset of the TST took place place at ~486.8 myr. This third order transgression is recorded by the offshore to shelf environments of the Lampazar Formation and its lateral equivalent, the Casa Colorada Member. The long-term retrogradation trend characterizing the Cambrian interval is punctuated by a first fourth-order regressive pulse (~486.1 myr; Figure 5) that delimitates the top of the Lampazar Formation and the Casa Colorada Member. Since the underlying fluvio-estuarine deposits were accumulated at mean sea level, the thickness variations between the Lampazar Formation (~ 165 m) and the Casa Colorado Member (~ 70 m) can either reflects different clastic input into the basin, the action of currents winnowing fine-grained sediments, or different accommodation (e.g., Viana et al., 1998; Catuneanu, 2018 and references therein). From ~486.1 to 485.4 Ma, a third-order regressive phase took place as reflected by deposition of the late highstand systems track (HST) sandstone-dominated Moreno Formation in Sierra de Cajas and Angosto del Moreno. Otherwise, in Quebrada de Trancas and Quebrada de Moya, the fluvial-estuarine Pico de Halcón Member would represent the subsequent LST and TST implying that underlying deposits (i.e., Moreno Formation) have been eroded in these areas. In Sierra de Cajas, sharp-based shoreface to foreshore parasequence sets are observed. Furthermore, in this locality, the Moreno Formation commonly displays mostly lower shoreface environments that abruptly pass to a foreshore environment (Figure 5;

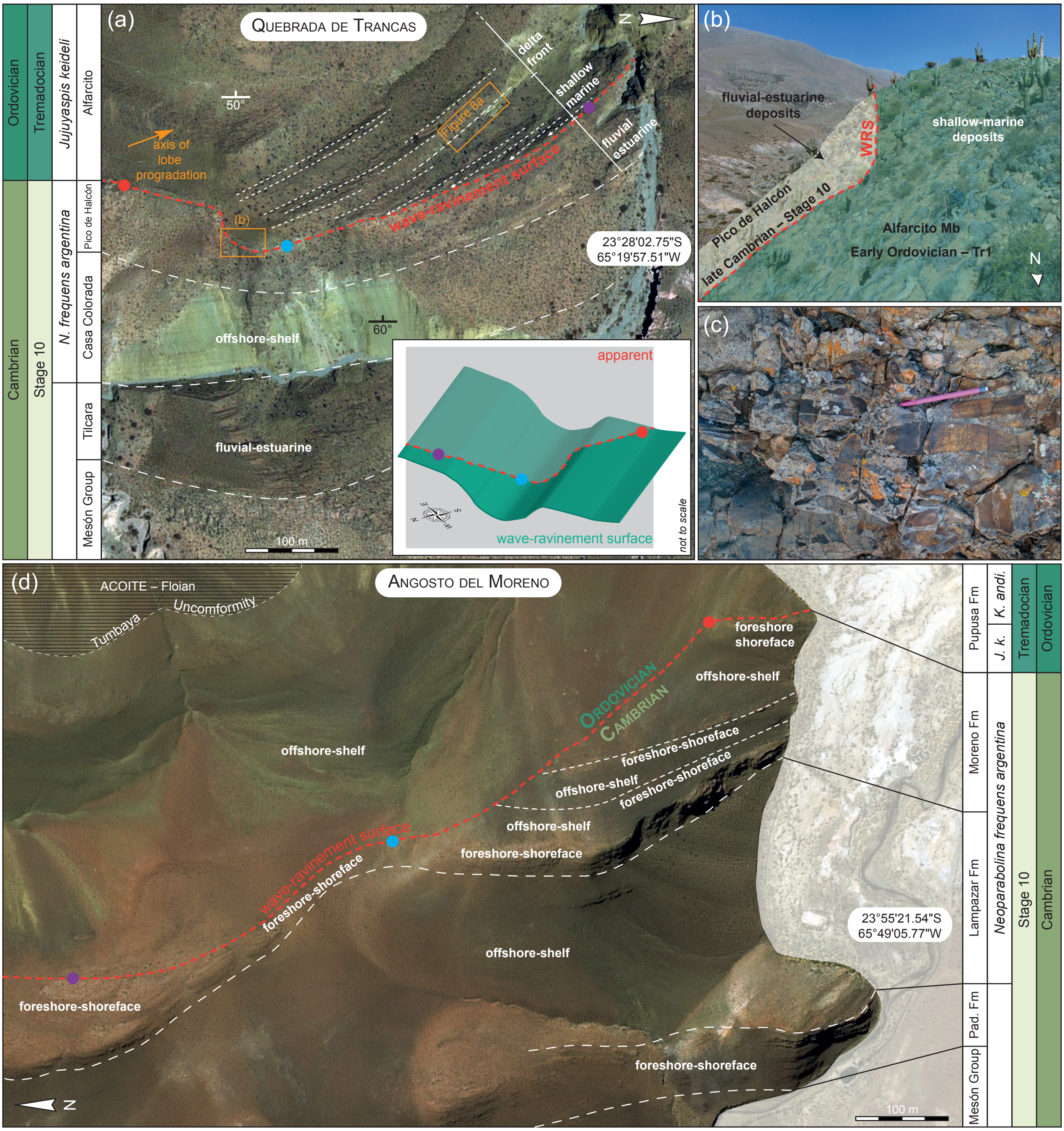

Fig. 10. Unconformity at the Cambrian-Ordovician boundary. (a) Satellite view from Quebrada de Trancas highlighting the discordant and erosional contact between the upper Cambrian Pico de Halcón Member with the overlying lower Tremadocian Alfarcito Member. Red, blue and purple dots on the apparent wave ravinement are reported on the schematic view. (b) Field observation of the wave ravinement surface between Pico de Halcón and Alfarcito members. (c) Sandy matrix supported breccia corresponding to the basal levels of Aflarcito Member above the wave ravinement surface. (d) Satellite view from Angosto del Moreno showing the wave ravinement surface. Satellite images are from Bing Maps ©.

between 285 and 300 m). Such stratigraphic pattern seems to point out to a forced regression (FSST) in Sierra de Cajas (Clifton, 2006). In the Angosto del Moreno, the Moreno Formation exclusively displays shoreface environments suggesting slightly deeper settings of deposition in comparison with Sierra de Cajas. In Quebrada de Trancas and Moya, fluvial-estuarine deposits display a northward orientation of the system as exhibited by axes of incision of the estuarine channels and tidal currents.

8.2 | Early Ordovician (Tr1)

The Cambrian-Ordovician transition is marked by the start of a third-order trangressive phase displayed by the TST of the Pupusa Formation and the Alfarcito Member (Figure 5) over wave ravinement surfaces observed in Quebrada de Trancas (discordance) and Angosto del Moreno (Figure 10a, b). According to the facies zone at the very beginning of the Tr1 (~ 485 myr; Figure 5), wave-dominated conditions

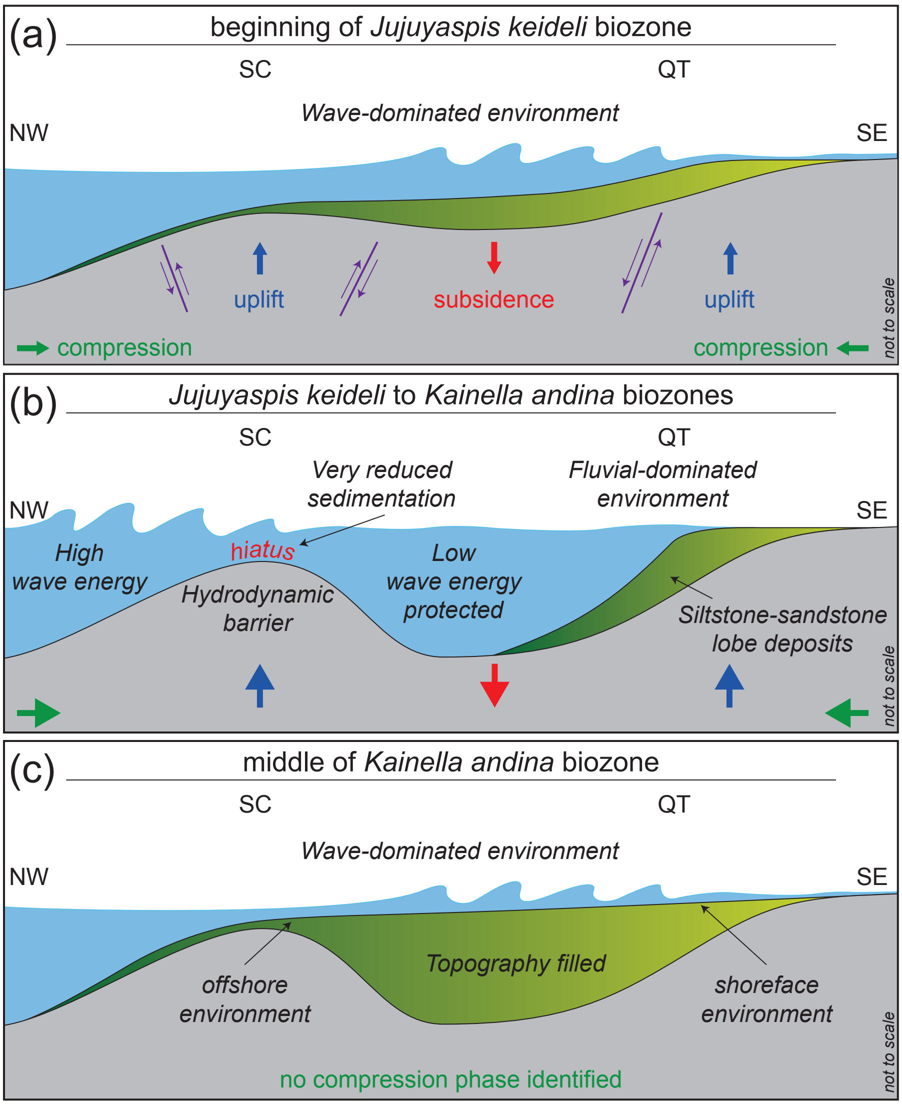

Fig. 11. Southeast-northwest cross-sections showing the basin evolution at different time frame during the early Tremadocian. (a) Initiation of the compression regime during the Cambrian-Ordovician transition. The compression starts reactivating the normal faults of the Mesón Group associated to the extensive phase and now acted as inverse faults. This mechanism induced local uplift (blue arrow) and subsidence (red arrow). Physiographical changes are still weak, allowing establishment of open wave-dominated environments during the transgressive phase at the beginning of the Jujuyaspis keideli biozones. SC: Sierra de Cajas; QT: Quebrada de Trancas. (b) A tectonic pulse inducing the stronger compression constraints accentuated local uplift and subsidence forming a high relief in SC acting as hydrodynamic barrier dissipating incoming wave energy that winnowed sediment in this locality. Thus, SC created protected environments southward, allowing the development of the lobe-shaped deltaic deposits in QT from Jujuyaspis keideli to Kainella andina biozones. (c) Absence of tectonic pulse maintained the physiography as it was in (b) and the distal to proximal delta-front progressively fill the inherited topography up to SC. Once the topography filled, open wave-dominated environments set up from the middle of Kainella andina biozone. Yellowish colour corresponds to sandstone-dominated deposits, while greenish one to mudstone-dominated deposits. Purple arrows represent normal faults that might occur in the Mesón Group associated to the extensive phase that acted as inversed faults generating topography during the compression phase.

prevailed displaying foreshore-shoreface to offshore (Quebrada de Trancas and Moya; Figures 5 and 11a), and offshore to shelf environments (Sierra de Cajas and Angosto del Moreno; Figures 5 and 11a). A rapid change from wave-dominated offshore to shoreface conditions (TST) to river-dominated distal to proximal delta-front environments (HST) is revealed by the presence of the siltstone-to-sandstone lobate interval in Quebrada de Trancas. This change is apparent several meters above the base of the *Jujuyaspis keideli* Biozone, continuing up to the middle of *Kainella andina* Biozone (Figure 5). In order to preserve this overall lobate geometry that characterized the interval of the Alfaricto Member between 185 to 380 m (in Quebrada de Trancas; Figure 5), a reduced incoming wave energy is necessary (e.g., Bhattacharya and Walker, 1992; Reading, 1996; Bhattacharya and Giosan, 2003). Even if continental input into the basin previously existed during the late Cambrian (i.e., Pico de Halcón Member, Tilcara Member, Padrioc Formation), no similar lobate geometries were observed elsewhere. Therefore, if the river processes were present during the early Tr1, reduced incoming wave energy may need to be invoked. The Sierra de Cajas lower Tremadocian interval consists of two biozones (*Jujuyaspis keideli* and *Kainella andina*) exhibited in the much thinner Pupusa Formation (25 m in Sierra de Cajas for 165 m in Quebrada de Trancas; Figure 5). Therefore, Sierra de Cajas is considered as a high relief acting as natural hydrodynamic barrier dissipating the incoming wave energy (Beji and Battjes, 1993), allowing lobe deposition in a protected southern area (Figure 11b). In this scenario, strong currents may have been present in Sierra de Cajas, winnowing sediments and therefore explaining the reduced thickness of these deposits. It is considered that a sedimentary hiatus between the two identified biozones in Sierra de Cajas is present (Figure 11b). In Quebrada de Moya, during the emplacement of the lobe deltaic complex in Quebrada de Truncas, foreshore-shoreface settings prevailed. Quebrada de Moya is located slightly at the northeast of Quebrada de Trancas, but was under the influence of more energetic processes (i.e., fair-weather and storm waves). Therefore, Quebrada de Moya is considered as high-relief partially emerged that probably helped to produce a protected environment in Quebrada de Trancas and in Sierra de Cajas. Such conditions very likely happened during deposition of the deltaic lobes (i.e. up to the middle of *Kainella andina* biozone; Figure 5) until the topography was filled (Figure 11c). Once filled, wave-dominated settings returned (Figure 11c).

Previously, it was proposed that this sedimentary basin had an east-to-west prograding trend (Astini, 2003 among others). However, this progradational trend it is not consistent with the sandy deltaic lobes progradation (Figures 10a, b, d), the geometrical organization of the stratigraphic units (Figure 11) or the paleocurrent indicators (i.e., flute casts, gutter casts; see Figure 9d, f), which all point to a south-to-north trend of deposition. Therefore, it is more consistent with the northward orientations proposed by Buatois and Mángano (2003) and Buatois et al. (2006). In order to propose the more parsimonious reconstructions of the basin, taking into account the geometries of deposition, the paleoflow orientations, as well as the thickness variations, a change of physiography is proposed during the Cambrian-Ordovician transition (Figures 11 and 12).

9 | GEODYNAMIC IMPLICATIONS

The rotational opening phase moving the AAt away from Gondwana (Forsythe et al., 1993; Bahlburg and Hervé, 1997; Ramos, 2008) has led to thickest and more extended deposits in northward part of the Central Andean Basin in Bolivia (Gohrbandt, 1992; Egenhoff, 2007). In this context, the SRF and the GCG were previously considered as sedimentary successions only recording various magnitudes of sea-level fluctuation devoid of tectonic activity (Moya, 1988; Astini, 2003; Buatois and Mángano, 2003; Buatois et al., 2006), despite that Bahlburg and Hervé (1997) expected significant tectonic disturbance related to the active geodynamic context. As evidenced previously by sedimentological and stratigraphical data, a physiographic change of the basin is revealed by a major change in stratigraphic architecture during the Cambrian-Ordovician transition (Figures 5 and 12). Previously considered as a single block (Ramos, 1988), the Arequipa and Antofalla are now considered as two separates terranes (Bahlburg and Hervé, 1997; Rapalini, 2005; Ramos, 2008). However, in order to be consistent with previous work (Egenhoff, 2007) and to tackle if the AAt is responsible for what happened in the basin, the Arequipa and Antofalla blocks are grouped here. In the northern part of the Central Andean Basin in Bolivia, Egenhoff (2007) has described a similar extension-to-compression evolution of the basin with a reversal geodynamic regime occurring into the Expansograptus holmi biozone (Fl2 - Floian - Early Ordovician; e.g., Gutiérrez-Marco and Martin, 2016). Egenhoff (2007) interpreted this first deformation related to the counterclockwise motion of the AAt. This tectonic pulse occurring during the Cambrian-Ordovician transition is contemporaneous with the emplacement of the Vicuñas Formation towards the west that records the first volcanic deposits corresponding to the emplacement of the Famatinian magmatic arc (Moya et al., 1993; Coira et al., 1999). The initiation of this magmatic episode was first assigned to the accretion of AAt during the Early Ordovician (Ramos, 1988; Bahlburg and Hervé, 1997). Further, new drawn conclusions explain the evolution of the western Gondwana in the Central Andes region without the necessity of terrane accretion and solely related to the northeast-directed subduction (Coira et al., 1982) that developed the magmatic arc (Zimmermann et al., 2010; Zimmermann, 2011; Niemeyer et al., 2018). This study cannot discriminate between these two explanations since both scenarios could have led to basin deformation inducing a change of physiography (Figure 12). According to the inherited V-shaped basin formed during the extension phase (Figure 12a), the change of the Euler pole of rotation of the AAt responsible of its re-accretion (Ramos, 1988; Forsythe et al., 1993; Bahlburg and Hervé, 1997) or the emplacement of the magmatic arc (Coira et al., 1982; Coira et al., 1999; Zimmermann et al., 2010; Zimmermann, 2011; Niemeyer et al., 2018), both could have led to a deformation coming from the southwest towards the northeast (Figure 12a). In this scenario, the deformation should occur first in the south (present-day northwest Argentina) and further toward the north (in Bolivia). It is very likely that the tectonically induced change of physiography might occur earlier in Argentina rather than in Bolivia. Since the basin remained open during the Early Ordovician, this architectural reorganisation of the basin may have been related to a first tectonic pulse initiated from the southwest toward the northeast. This event partially and progressively closed the

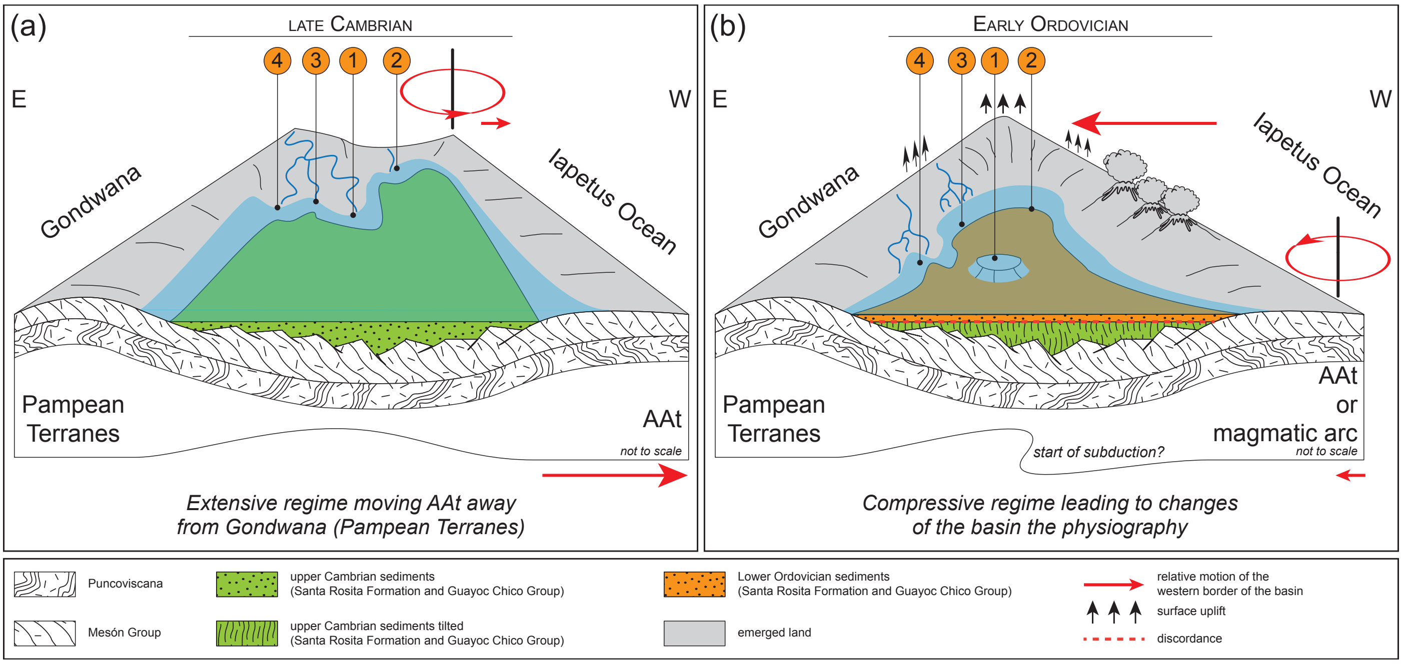

Fig. 12. Simplified reconstruction of physiographical changes occurring at the southern border of the Central Andean Basin. (a) Extensive regime moving AAt away from Gondwana (Pampean Terranes) associated with the counterclockwise rotation of the AAt with a Euler pole of rotation located the north of actual Argentina (b) Compressive regime leading to changes of the basin the physiography associated to tectonic pulse of the Oclóyic phase. Numbers represent the relative location of each locality. 1: Sierra de Cajas; 2: Angosto del Moreno; 3: Quebrada de Trancas; 4: Quebrada de Moya.

basin, triggering an uplift at the south (i.e., Salta area), at the east margin (i.e., Pampean terranes) and at the west (i.e., western Puna) of the basin (Figure 12b). It can be assumed that the rifting phase of AAt during the middle-late Cambrian opening the V-shaped basin has led to a normal faulting of the Mesón Group creating grabens (Figures 11a and 12a). Once the basin inversion phase took place, either due the accretion of AAt or to the emplacement of the magmatic arc, reactivation of these normal faults would have led to an uplift of the graben converting the topographic low in a topographic high (Bonini et al., 2012). This mechanism very likely explains the forced regression in Sierra de Cajas, as well as its interpretation as a topographic barrier protecting the southern part of the studied area (Figure 11b). In the same axis, northward in Bolivia in the locality of Taraya, a pre-Ordovician high relief was also described by Egenhoff (2007).

Southward of the studied zone, in the city of Salta (i.e., Sierra de Mojotoro; Figure 2), no upper Cambrian sedimentary rocks occur (Harrington and Leanza, 1957; Balseiro and Waisfeld, 2013; Barrientos Ginés et al., 2018). Indeed, Lower Ordovician sedimentary rocks rest directly on top of the Mesón Group. The absence of upper Cambrian deposits may either reflect non-deposition or erosion. In the case of a non-deposition, it could be suggested that the tectonic pulse has uplifted and emerged surfaces southward. Regarding an erosional event, this could fit with the change of physiography occurring at the Cambrian-Ordovician transition uplifting surfaces southward of the studied area and exposing late Cambrian sedimentary rocks eroded during the Early Ordovician. The stratigraphic succession in the Salta area starts with the conglomeratic Pedrera Formation (Moya, 1998). Strong vegetation cover in this zone makes exploration and correlation complex there, but further investigation should be undertaken to tackle the provenance issue of this conglomeratic unit. In a more regional perspective, refinement and restudy of the Lower Ordovician stratigraphic units and their paleoenvironmental interpretations are underscored. Indeed, the Sierra de Mojotoro contains the southernmost Lower Ordovician sedimentary rocks and should bring data having geodynamical issue able to constrain more widely the evolution of the Central Andean Basin.

10 | CONCLUSIONS

The studied stratigraphic interval of the upper Cambrian-Lower Ordovician Central Andean Basin outcropping in the northwest of Argentina was previously interpreted as sedimentary succession recording several magnitudes of sea-level fluctuations with an east-to-west depositional trend lacking any record of tectonic activity. This first basin-scale integrated study, based on outcrops from the Cordillera Oriental (Province of Jujuy), highlights a more complex story. Main points are summarized hereafter:

• Ranging from late Cambrian (Stage 10; N. frequens argentina Biozone) to Early Ordovician (Tr1; J. keideli, K. andina, K. meridionalis), four mains facies zones were described: fluvio-estuarine, foreshore to shoreface, distal to proximal delta-front, and offshore to shelf. Correlation was possible due to the highly fossiliferous trilobite assemblages. Throughout the vertical stacking patterns based on facies zone description, five third-order sequences of ~1.28 myr are recognized.

• Basin physiographical changes are highlighted by (1) large wave ravinement surfaces at the Cambrian-Ordovician transition (at Quebrada de Trancas and Angosto del Moreno), (2) an unconformity between the Pico de Halcón (Cambrian) and Alfarcito (Ordovician) members, and (3) a change of coastal processes evolving from river-dominated to wave-dominated across the *Jujuyaspis keideli* to *Kainella andina* Biozones. The latter depositional change was allowed by the uplift of Sierra de Cajas and Quebrada de Moya, which created protected settings southwards at Quebrada de Trancas.

• Even if the current study cannot argue in favour of the accretion of the Arequipa-Antofalla terranes or the Famatinian magmatic arc as a driver for the physiographical changes of the basin, it suggests that a tectonic pulse associated to the Oclóyic phase occurred during deposition of the Santa Rosita Formation and the Guayoc Chico Group. Therefore, this study confirms the expectation of Bahlburg and Hervé (1997) regarding tectonic disturbance present throughout the stratigraphic successions.

• This study corroborates the south-to-north trend of deposition proposed by Buatois and Mángano (2003) and Buatois et al. (2006), and is in agreement with the results of Egenhoff (2007), supplementing additional data on the Central Andean Basin further south in Argentina.

• In addition, a revised lithostratigraphic framework is proposed, with newly formally defined formational names, assisting in the correlation between eastern (Quebrada de Trancas and Quebrada de Moya) and western (Sierra de Cajas and Angosto del Moreno) areas of the Cordillera Oriental.

ACKNOWLEDGMENTS

We are grateful to Compañia Minera Aguilar S.A, Florencia Califano, Fernando Hongn and Marissa Fabrezi for hosting us during fieldwork. Grateful considerations are given to the owners of the fields providing access to the studied localities. M. Gabriela Mángano, Brian Pratt, Sebastián O. Verdecchia and Blanca A. Toro are thanked for fruitful discussion. Romain Vaucher gives special thanks to Juan A. Moreno and Nicolás J. Cosentino for their buena onda during these years providing a good working atmosphere as well to Samantha Blandin, who followed him through this postdoctoral journey far away from our home. The manuscript has been improved due to insight comments made by the reviewers _________ and _________ as well as the associate editor _________. Financial support for this study was provided by Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) Grant PIP 112-201201-00581, Agencia Nacional de Promoción Científica y Tecnológica (ANPCyT-FONCyT) PICT 2016-0588 and Global Ambassador Incoming Program of the University of Saskatchewan. Field trips and fossil collections were made under permission of the Secretaría de Cultura de la Provincia de Jujuy (Res. 01390_ SC/2015) and the Secretaría de Cultura, Ministerio de Cultura y Turismo de la Provincia de Salta (Disp. int. 010/2010 and 007/2014). This is a contribution to PUE 2016 (CICTERRA – CONICET).

REFERENCES

Aceñolaza, F.G., Miller, H., Toselli, A.J., 2002. Proterozoic–Early Paleozoic evolution in western South America—a discussion. Tectonophysics, 354(1): 121-137.

Albanesi, G.L., Giuliano, M.E., Pacheco, F., Ortega, G., Monaldi, C.R., 2015. Conodonts from the Cambrian-Ordovician boundary in the Cordillera Oriental, NW Argentina. Stratigraphy, 12(3-4): 237-256.

Aparicio González, P.A., Pimentel, M.M., Hauser, N., Moya, M.C., 2014. U-Pb LA-ICP-MS geochronology of detrital zircon grains from low-grade metasedimentary rocks (Neoproterozoic - Cambrian) of the Mojotoro Range, northwest Argentina. Journal of South American Earth Sciences, 49: 39-50.

Aris, M.J., Corronca, J.A., Quinteros, S., Pardo, P.L., 2017. A new marrellomorph euarthropod from the Early Ordovician of Argentina. Acta Palaeontologica Polonica, 62(1): 1-8.

Astini, R., 2003. The Ordovician Proto-Andean basins. In: J.L. Benedetto (Ed.), Ordovician fossils of Argentina. Universidad Nacional de Córdoba, Secretaría de Ciencia y Tecnología, pp. 1-74.

Astini, R., 2008. Sedimentación, facies, discordancias y evolución paleoambiental durante el Cambro-Ordovícico, Geología y recursos naturales de la provincia de Jujuy, Relatorio del XVII

Congreso Geológico Argentino, Jujuy, pp. 50-73.

Astini, R., Marengo, L., Rubinstein, C., Albanesi, G., Beresi, M., Peralta, S., 2003. The Ordovician Stratigraphy of the Sierras Subandinas (Subandean Ranges) in northwest Argentina and its bearing on an integrated foreland basin model for the Ordovician of the Central Andean region, 9 th International Symposium on the Ordovician System. In : Albanesi, GL; Beresi, MS; and Peralta, S.H (eds.), pp. 381-386.

Astini, R.A., 2005. Las sedimentitas que apoyan en no concordancia sobre el» granito rojo» en el angosto de la Quesera (Cordillera Oriental, Salta): una revisión crítica a más de 60 años de los trabajos pioneros de J. Keidel. Revista de la Asociación Geológica Argentina, 60(3): 513-523.

Bahlburg, H., Hervé, F., 1997. Geodynamic evolution and tectonostratigraphic terranes of northwestern Argentina and northern Chile. GSA Bulletin, 109(7): 869-884.

Bahlburg, H., Moya, M.C., Zeil, W., 1994. Geodynamic Evolution of the Early Palaeozoic Continental Margin of Gondwana in the Southern Central Andes of Northwestern Argentina and Northern Chile. In: K.-J. Reutter, E. Scheuber, P.J. Wigger (Eds.), Tectonics of the Southern Central Andes: Structure and Evolution of an Active Continental Margin. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 293-302.

Balseiro, D., Waisfeld, B., Vaccari, E., 2011. Paleoecological dynamics of Furongian (Late Cambrian) trilobite-dominated communities from northwestern Argentina. Palaios, 26(8): 484-499.

Balseiro, D., Waisfeld, B.G., 2013. Ecological instability in Upper Cambrian–Lower Ordovician trilobite communities from Northwestern Argentina. Palaeogeography, Palaeoclimatology, Palaeoecology, 370: 64-76.

Barrientos Ginés, A.V., Aparicio González, P., Bercheñi, V.A., Moya, M.C., 2018. Geología y sedimentología de los cerros San Bernardo, 20 de Febrero y Vélez, Cordillera Oriental, Noroeste Argentino. Revista de la Asociación Geológica Argentina, 75(4).

Beckvar, N., Kidwell, S.M., 1988. Hiatal shell concentrations, sequence analysis, and sealevel history of a Pleistocene coastal alluvial fan, Punta Chueca, Sonora. Lethaia, 21(3): 257-270.

Beji, S., Battjes, J.A., 1993. Experimental investigation of wave propagation over a bar. Coastal Engineering, 19(1): 151-162.

Benedetto, J.L., Carrasco, P.A., 2002. Tremadoc (earliest Ordovician) brachiopods from Purmamarca and the Sierra de Mojotoro, Cordillera Oriental of northwestern Argentina. Geobios, 35(6): 647-661.

Bhattacharya, J.P., Giosan, L., 2003. Wave-influenced deltas: geomorphological implications for facies reconstruction. Sedimentology, 50(1): 187-210.

Bhattacharya, J.P., MacEachern, J.A., 2009. Hyperpycnal Rivers and Prodeltaic Shelves in the Cretaceous Seaway of North America. Journal of Sedimentary Research, 79(4): 184-209.

Bhattacharya, J.P., Walker, R.G., 1992. Deltas. In: R.G. Walker, N.P. James (Eds.), FaciesModels: Response to Sea-Level Change, Geological Association of Canada, St Johns., pp. 157–177

Bonini, M., Sani, F., Antonielli, B., 2012. Basin inversion and contractional reactivation of inherited normal faults: A review based on previous and new experimental models. Tectonophysics, 522-523: 55-88.

Botquelen, A., Loi, A., Gourvennec, R.m., Leone, F., Dabard, M.-P., 2004. Formation et signification paléo-environnementale des concentrations coquillières : exemples de l'Ordovicien de Sardaigne et du Dévonien du Massif armoricain. Comptes Rendus Palevol, 3(5): 353-360.

Buatois, L., Moya, M., Mángano, M., Malanca, S., 2003. Paleoenvironmental and sequence stratigraphic framework of the Cambrian-Ordovician transition in the Angosto del Moreno area, northwest Argentina, IInternational Symposium on the Ordovician System, pp. 397-401.

Buatois, L.A., M.G., M., Moya, M.C., 2000. Incisión de valles estuarinos en el Cámbrico Tardío del noroeste argentino y la problemática del límite entre los grupos Mesón y Santa Victoria. Segundo Congreso Latinoamericano de Sedimentología, Resúmenes, Mar del Plata: 55.

Buatois, L.A., Mángano, M.G., 2003. Sedimentary facies, depositional evolution of the Upper Cambrian–Lower Ordovician Santa Rosita formation in northwest Argentina. Journal of South American Earth Sciences, 16(5): 343-363.

Buatois, L.A., Mángano, M.G., 2011. Ichnology: Organism-substrate interactions in space and time. Cambridge University Press.

Buatois, L.A., Zeballo, F.J., Albanesi, G.L., Ortega, G., Vaccari, E., Mángano, M.G., 2006. Depositional Environments and Stratigraphy of the Upper Cambrian-Lower Ordovician Santa Rosita Formation at the Alfarcito area, Cordillera Oriental, Argentina: Integration of biostratigraphic data within a sequence stratigraphic framework. Latin American Journal of Sedimentology and Basin Analysis, 13: 65 - 95.

Casquet, C., Dahlquist, J.A., Verdecchia, S.O., Baldo, E.G., Galindo, C., Rapela, C.W., Pankhurst, R.J., Morales, M.M., Murra, J.A., Mark Fanning, C., 2018. Review of the Cambrian Pampean orogeny of Argentina; a displaced orogen formerly attached to the Saldania Belt of South Africa? Earth-Science Reviews, 177: 209-225.

Casquet, C., Rapela, C.W., Pankhurst, R.J., Baldo, E.G., Galindo, C., Fanning, C.M., Dahlquist, J.A., Saavedra, J., 2012. A history of Proterozoic terranes in southern South America: From Rodinia to Gondwana. Geoscience Frontiers, 3(2): 137-145.

Catuneanu, O., 2018. Model-independent Sequence Stratigraphy. Earth-Science Reviews.

Clifton, H.E., 2006. A re-examination of facies models for clastic shorelines. In: H.W. Posamentier, R.G. Walker (Eds.), Facies

Model Revisited. SEPM, Special Publication, vol. 84, pp. 293-337.

Coates, L., MacEachern, J.A., 2007. The ichnological signatures of river- and wave-dominated delta complexes: differentiating deltaic from non-deltaic shallow marine successions, Lower Cretaceous Viking Formation and Upper Cretaceous Dunvegan Formation, west-central Alberta. In: J.A. MacEachern, K.L. Bann, M.K. Gingras, S.G. Pemberton (Eds.), Applied Ichnology: SEPM, Short Course Notes 52, pp. 227–254.

Coira, B., Davidson, J., Mpodozis, C., Ramos, V., 1982. Tectonic and magmatic evolution of the Andes of northern Argentina and Chile. Earth-Science Reviews, 18(3): 303-332.

Coira, B., Peréz, B.n., Flores, P., Kay, S.M., Woll, B., Hanning, M., 1999. Magmatic sources and tectonic setting of Gondwana margin Ordovician magmas, northern Puna of Argentina and Chile. In: V.A. Ramos, J.D. Keppie (Eds.), Laurentia-Gondwana connections before Pangea. Geological Society of America.

Collinson, J.D., Mountney, N., Thompson, D.B., 2006. Sedimentary structures (3rd ed). Terra, Harpenden, Hert, England.

Dalrymple, R.W., Choi, K., 2007. Morphologic and facies trends through the fluvial-marine transition in tide-dominated depositional systems: a schematic framework for environmental and sequence-stratigraphic interpretation. Earth-Science Reviews, 81(3): 135-174.

Dalziel, I.W.D., 1997. OVERVIEW: Neoproterozoic-Paleozoic geography and tectonics: Review, hypothesis, environmental speculation. Geological Society of America Bulletin, 109(1): 16-42.

Dashtgard, S.E., MacEachern, J.A., Frey, S.E., Gingras, M.K., 2012. Tidal effects on the shoreface: Towards a conceptual framework. Sedimentary Geology, 279: 42-61.

Egenhoff, S.O., 2007. Life and death of a Cambrian–Ordovician basin: An Andean three-act play featuring Gondwana and the Arequipa-Antofalla terrane. Geological Society of America Special Papers, 423: 511-524.

Escayola, M.P., van Staal, C.R., Davis, W.J., 2011. The age and tectonic setting of the Puncoviscana Formation in northwestern Argentina: An accretionary complex related to Early Cambrian closure of the Puncoviscana Ocean and accretion of the Arequipa-Antofalla block. Journal of South American Earth Sciences, 32(4): 438-459.

Fernández, R., Guerrero, C., Manca, N., 1982. El límite Cámbro-Ordovícico en el tramo medio y superior de la quebrada de Humahuaca, Provincia de Jujuy, Argentina. 5to Congreso Latinoamericano de Geología, Actas, Buenos Aires, 1: 3-22.

Forsythe, R.D., Davidson, J., Mpodozis, C., Jesinkey, C., 1993. Lower Paleozoic relative motion of the Arequipa Block and Gondwana; Paleomagnetic evidence from Sierra de Almeida of northern Chile. Tectonics, 12(1): 219-236.

Franco Tortello, M., Rábano, I., Rao, R., Aceñolaza, F., 1999. Los trilobites de la transición Cámbrico-Ordovicico en la quebrada Amarilla (Sierra de Cajas, Jujuy, Argentina). Boletín Geológico y Minero, 110(5): 555-572.

Gohrbandt, K.H.A., 1992. Paleozoic paleogeographic and depositional developments on the central proto-Pacific margin of Gondwana: Their importance to hydrocarbon accumulation. Journal of South American Earth Sciences, 6(4): 267-287.

Gugliotta, M., Saito, Y., Nguyen, V.L., Ta, T.K.O., Tamura, T., Fukuda, S., 2018. Tide- and River-Generated Mud Pebbles from the Fluvial To Marine Transition Zone of the Mekong River Delta, Vietnam. Journal of Sedimentary Research, 88(9): 981-990.

Gutiérrez-Marco, J.C., Martin, E.L.O., 2016. Biostratigraphy and palaeoecology of Lower Ordovician graptolites from the Fezouata Shale (Moroccan Anti-Atlas). Palaeogeography, Palaeoclimatology, Palaeoecology, 460: 35-49.

Hampson, G.J., Storms, J.E.A., 2003. Geomorphological and sequence stratigraphic variability in wave-dominated, shoreface-shelf parasequences. Sedimentology, 50(4): 667-701.

Harrington, H.J., 1937. On some Ordovician Fossils from Northern Argentina. Geological Magazine, 74(3): 97-124.

Harrington, H.J., 1957. Ordovician Formations of Argentina. In: H.J. Harrington, A.F. Leanza (Eds.), Ordovician trilobites of Argentina. University of Kansas Special Publication, pp. 1-59.

Harrington, H.J., Leanza, A.F., 1957. Ordovician fossils of Argentina. University of Kansas Press, 276 pp.

Heward, A.P., 1981. A review of wave-dominated clastic shoreline deposits. Earth-Science Reviews, 17(3): 223-276.

MacEachern, J.A., Bann, K.L., Bhattacharya, J.P., Howell, C.D., Jr, 2005. Ichnology of deltas: organism responses to the dynamic interplay of rivers, waves, storms, and tides. In: J.P. Bhattacharya, L. Giosan (Eds.), River Deltas — Concepts, Models, and Examples: SEPM, Special Publication pp. 49–85.

Malanca, S., Brandán, E.M., 2000. Nuevos Orometopidae (Asaphida, Trilobita) de la Formación Saladillo, Tremadoc Temprano de la Cordillera Oriental argentina, XIV Congreso Geológico Boliviano, La Paz. Memorias, pp. 131-135.

Mángano, M.G., Buatois, L.A., 2004. Integración de estratigrafía secuencial, sedimentología e icnología para un análisis cronoestratigráfico del Paleozoico inferior del noroeste argentino. Revista de la Asociación Geológica Argentina, 59(2): 273-280.

Mon, R., Hongn, F., 1996. Estructura del basamento proterozoico y paleozoico inferior del norte argentino. Revista de la Asociación Geológica Argentina, 51(1): 3-14.

Moya, M., 1998. El Paleozoico inferior en la sierra de Mojotoro, Salta-Jujuy. Revista de la Asociación Geológica Argentina, 53(2): 219-238.

Moya, M.C., 1988. Lower ordovician in the southern part of the argentine eastern cordillera. In: H. Bahlburg, C. Breitkreuz, P. Giese (Eds.), The Southern Central Andes: Contributions to Structure and Evolution of an Active Continental Margin. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 55-69.

Moya, M.C., 1997. La fase Tumbaya (Ordovícico Inferior) en los Andes del norte argentino, VIII Congreso Geológico Chileno, pp. 185-189.

Moya, M.C., Malanca, S., Hongn, F.D., Bahlburg, H., 1993. El Tremadoc temprano en la Puna occidental argentina, XII Congreso Geológico Argentino y II Congreso de Exploración de Hidrocarburos Actas, pp. 20–30.

Moya, M.C., Malanca, S., Monteros, J.A., Albanesi, G.L., Ortega, G., Buatois, L.A., 2003. Late Cambrian – Tremadocian faunas and events from the Angosto del Moreno section, Eastern Cordillera, Argentina. In: G.L. Albanesi, M.S. Beresi, S.H. Peralta (Eds.), Ordovician from the Andes, Serie de Correlación Geológica, pp. 439-444.

Moya, M.C., Monteros, J.A., 2000. El Angosto del Moreno (Cordillera Oriental argentina), un área clave para analizar el límite Cámbrico–Ordovícico y la Discordancia Iruya, XIV Congreso Geológico Boliviano, La Paz. Memorias, pp. 142-147.

Muñoz, D.F., Benedetto, J.L., 2016. The eoorthid brachiopod Apheoorthina in the Lower Ordovician of NW Argentina and the dispersal pathways along western Gondwana. Acta Palaeontologica Polonica, 61(3): 633-644.

Niemeyer, H., Götze, J., Sanhueza, M., Portilla, C., 2018. The Ordovician magmatic arc in the northern Chile-Argentina Andes between 21° and 26° south latitude. Journal of South American Earth Sciences, 81: 204-214.

Ogg, J.G., Ogg, G.M., Gradstein, F.M., 2016. A concise geologic time scale. Elsevier, 235 pp pp.

Olariu, C., Bhattacharya, J.P., 2006. Terminal Distributary Channels and Delta Front Architecture of River-Dominated Delta Systems. Journal of Sedimentary Research, 76(2): 212-233.

Orton, G.J., Reading, H.G., 1993. Variability of deltaic processes in terms of sediment supply, with particular emphasis on grain size. Sedimentology, 40(3): 475-512.

Ramos, V.A., 1973. Estructura de los primeros contrafuertes de la Puna salto-jujeña y sus manifestaciones volcánicas asociadas. 5º Congreso Geológico Argentino, Actas 4: 159-202, Carlos Paz, 27.

Ramos, V.A., 1988. Late Proterozoic-early Paleozoic of South America-a collisional history. Episodes, 11: 168-174.

Ramos, V.A., 2008. The Basement of the Central Andes: The Arequipa and Related Terranes. Annual Review of Earth and Planetary Sciences, 36(1): 289-324.

Ramos, V.A., 2018. Tectonic Evolution of the Central Andes: From Terrane Accretion to Crustal Delamination. In: G. Zamora, K.M. McClay, V.A. Ramos (Eds.), Petroleum basins and hydrocarbon potential of the Andes of Peru and Bolivia. AAPG Memoir 117, pp. 1-34.

Rapalini, A.E., 2005. The accretionary history of southern South America from the latest Proterozoic to the Late Palaeozoic: some palaeomagnetic constraints. Geological Society, London, Special Publications, 246(1): 305-328.

Reading, H.G., 1996. Sedimentary Environments, Processes, Facies and Stratigraphy. Blackwell Science Ltd., Oxford, 688 pp.

Ruiz Huidobro, O.J., 1975. El Paleozoico Inferior del centro y sur de Salta y su correlación con el Grupo Mesón. 1er Congreso Argentino de Paleontología y Bioestratigrafía, Actas, San Miguel de Tucumán, 1: 91-107.

Salas, M.J., Waisfeld, B.G., Muñoz, D.F., 2018. Radiation, diversity and environmental expansion of Early Ordovician ostracods: a view from the Southern Hemisphere. Lethaia, 0(0).

Sánchez, M.C., Salfity, J.A., 1999. The cambrian mesón group basin (NW Argentina): Stratigraphic and paleogeographic development. Acta Geologica Hispanica, 34(2-3): 123-139.

Scotese, C.R., 2016. Tutorial: PALEOMAP PaleoAtlas for GPlates and the PaleoData Plotter Program, http://www.earthbyte.org/paleomap-paleoatlas-for-gplates/. PALEOMAP Project, Evanston, IL.

Shergold, J.H., 1988. Review of trilobite biofacies distributions at the Cambrian–Ordovician Boundary. Geological Magazine, 125(4): 363-380.

Strasser, A., Hilgen, F.J., Heckel, P.H., 2006. Cyclostratigraphy – concepts, definitions, and applications. Newsletters on Stratigraphy, 42(2): 75-114.

Strasser, A., Pittet, B., Hillgärtner, H., Pasquier, J.-B., 1999. Depositional sequences in shallow carbonate-dominated sedimentary systems: concepts for a high-resolution analysis. Sedimentary Geology, 128(3–4): 201-221.

Torsvik, T.H., Cocks, L.R.M., 2013a. Chapter 2 New global palaeogeographical reconstructions for the Early Palaeozoic and their generation. Geological Society, London, Memoirs, 38(1): 5-24.

Torsvik, T.H., Cocks, L.R.M., 2013b. Gondwana from top to base in space and time. Gondwana Research, 24(3): 999-1030.

Tortello, M.F., Esteban, S.B., 2003. Trilobites del Cámbrico tardío de la Formación Lampazar (sierra de Cajas, Jujuy, Argentina). Implicancias bioestratigráficas y paleoambientales. Ameghiniana, 40(3): 323-344.

Turner, J.C.M., 1960. Estratigrafía de la Sierra de Santa Victoria y adyacencias. Boletín de la Academia Nacional de Ciencias de Córdoba, 41(2): 163-196.

Turner, J.C.M., Méndez, V., 1975. Geología del sector oriental de los departamentos de Santa Victoria e Iruya, Provincia de Salta, República Argentina. Boletín de la Academia Nacional de Ciencias de Córdoba, 51(1-2): 11-24.

Vaccari, N.E., Edgecombe, G.D., Escudero, C., 2004. Cambrian origins and affinities of an enigmatic fossil group of arthropods. Nature, 430(6999): 554-557.

Vaccari, N.E., Waisfeld, B.G., Marengo, L.F., Smith, L., 2010. Kainella Walcott, 1925 (Trilobita, Ordovícico Temprano) en el noroeste de Argentina y sur de Bolivia. Importancia bioestratigráfica. Ameghiniana, 47(3): 293-305.

Vaucher, R., Pittet, B., Hormière, H., Martin, E.L.O., Lefebvre, B., 2017. A wave-dominated, tide-modulated model for the Lower Ordovician of the Anti-Atlas, Morocco. Sedimentology, 64(3): 777-807.

Vaucher, R., Pittet, B., Passot, S., Grandjean, P., Humbert, T., Allemand, P., 2018. Bedforms in a tidally modulated ridge and runnel shoreface (Berck-Plage; North France): implications for the geological record. BSGF - Earth Sci. Bull., 189(1): 5.

Viana, A.R., Faugères, J.C., Stow, D.A.V., 1998. Bottom-current-controlled sand deposits — a review of modern shallow- to deep-water environments. Sedimentary Geology, 115(1): 53-80.

Waisfeld, B., Vaccari, E., 2008. Bioestratigrafía de trilobites del Paleozoico inferior de la Cordillera Oriental. In: B. Coira, E.O. Zappettini (Eds.), Geologia y Recursos Naturales de Jujuy Relatorio Del XVII Congreso Geológico Argentino. Asociación Geológica Argentina, Buenos Aires, Argentina, pp. 119–127.

Waisfeld, B.G., Balseiro, D., 2016. Decoupling of local and regional dominance in trilobite assemblages from northwestern Argentina: new insights into Cambro-Ordovician ecological changes. Lethaia, 49(3): 379-392.

Walker, R.G., James, N.P., 1992. Facies models: response to sea level change. St. John's, Nfld. Geological Association of Canada.

Weinberg, R.F., Becchio, R., Farias, P., Suzaño, N., Sola, A., 2018. Early paleozoic accretionary orogenies in NW Argentina: Growth of West Gondwana. Earth-Science Reviews.

Zecchin, M., Catuneanu, O., Caffau, M., 2018. Wave-ravinement surfaces: Classification and key characteristics. Earth-Science Reviews.

Zecchin, M., Ceramicola, S., Gordini, E., Deponte, M., Critelli, S., 2011. Cliff overstep model and variability in the geometry of transgressive erosional surfaces in high-gradient shelves: The case of the Ionian Calabrian margin (southern Italy). Marine Geology, 281(1): 43-58.

Zimmermann, U., 2011. From fore-arc to foreland: a cross-section of the Ordovician in the Central Andes. In: J.-C. Gutiérrez-Marco, I. Rábano, D. García-Bellido (Eds.), Ordovician of the World. Cuadernos del Museo Geominero, Madrid, pp. 667-674.

Zimmermann, U., Niemeyer, H., Meffre, S., 2010. Revealing the continental margin of Gondwana: the Ordovician arc of the Cordón de Lila (northern Chile). International Journal of Earth Sciences, 99(1): 39-56.

APPENDIX

PROPOSED STRATIGRAPHIC SUBDIVISION

The Guayoc Chico Group is redefined in this study and subdivided into four stratigraphic formations (see main text for details and Figures 4 and 5 for correlation with other formational names). From base to top, these are: the Pardioc, Lampazar, Moreno, and Pupusa formations. The Padrioc and the Lampazar formations were previously defined in the literature; however, the Moreno and the Pupusa formations are newly introduced names in this study and are defined hereafter.

MORENO FORMATION

Name origin: *Moreno* is the name of the native community living in this area.
Type area: Southeast of Salinas Grandes area, Province of Jujuy, Argentina
Type section: Angosto del Moreno
GPS points: base 23°55'18.17"S 65°48'52.49"W
top 23°55'19.18"S 65°48'47.05"W
Facies: Greyish sandstone-dominated interval mostly displaying trough cross-stratification. Siltstone-dominated intervals are interbedded with hummocky cross-stratified sandstone.
Thickness: maximum 120 m; minimum 60 m
Boundaries: The base is placed where trough cross-stratified, medium-grained sandstone replaces a muddy siltstone-dominated interval of the Lampazar Formation. The upper boundary corresponds to a return of muddy siltstone-dominated interval of the Pupusa Formation.
Fossils: *Neoparabolina frequens argentina* (Kayser 1876); *Beltella ulrichi* (Kayser, 1897).
Age: late Cambrian; Furongian; late Stage 10
Note: The wave ravinement surface eroding the Moreno Formation occurring in the Angosto del Moreno is responsible for the thickness variation (see Figure 10d).

PUPUSA FORMATION

Name origin: *Pupusa* is the vernacular name of a plant growing in the Andes used by native people as an infusion for helping with the altitude sickness.
Type area: Southeast of Salinas Grandes area, Province of Jujuy, Argentina
Type section: Angosto del Moreno

GPS points: base 23°54'51.96"S 65°49'00.46"W
top 23°54'51.49"S 65°48'48.77"W

Facies: Greenish siltstone-dominated package with interbedded trough cross-stratified sandstone, hummocky cross-stratified sandstone and mudstone. In the upper part of this interval, interbedded trough cross-stratified sandstone and shell beds become increasingly common.

Thickness: maximum 160 m; minimum 100 m

Boundaries: The base corresponds to the transition from a trough cross-stratified sandstone-dominated interval of the Moreno Formation to a siltstone-dominated interval. The Pupusa Formation ends with the Tumbaya Unconformity mantled by the siltstone-dominated package of the Acoite Formation (Early Ordovician; Floian)

Fossils: *Leiostegium douglasi* (Harrigton 1937); *Jujuyaspis keideli* (Kobayashi, 1936); *Saltaspis steinmanni* (Koabayashi, 1936); *Hapalopleura* acantha (Malanca & Brandán 2000); *Parabollinella argentinensis* (Kobayashi 1936); *Onychopyge* sp, *Kainella morena* (Vaccari & Waisfeld, 2010); *Kwania azulpanpensis azulpampensis* (Benedetto 2007); *K. azulpampensis dichotoma* (Benedetto 2007); *Nanorthis calderensis alternata* (Benedetto 2007); *Chaniella pascuali* (Benedetto 2009).

Age: Early Ordovician; Tremadocian; early Tr1

Note: The wave-ravinement surface eroding the Moreno Formation in the Angosto del Moreno is responsible for the thickness variation since the Pupusa Formation fills the created depression (see Figure 10d).