Sedimentology and depositional system of the shelf deposits of the Sierra de la Invernada Formation (middle-upper Ordovician)

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Abstract This study consists in a detailed lithofacies analysis of the Sierra de La Invernada Formation (middle-late Ordovician), located in Argentine Precordillera. This analysis is based on three stratigraphic sections that point out a storm-dominated monotonous sedimentary succession. Most of the succession is formed by very fine grained sandstone, few centimetres to 20 cm thick, deposited by wave-modified turbidity currents, interbedded with laminated sandy siltstone. This succession is characterized by *Skolithos-Cruziana* ichnofacies association. The upper part of the succession shows sandstone and conglomerate bodies generated by concentrated density flows and wave-modified turbidity current. There are also in this portion rare interbed with muddy-siltstones beds. From the base to the top of the succession can be noted changes in the predominant type flows: from wave-modified turbidity currents to concentrated density flows / wave-modified turbidity currents. This work proposes that the sedimentary succession of Sierra de La Invernada Formation was deposited in a siliciclastic shelf (lower shoreface or inner shelf).

Keywords: Sierra de La Invernada Formation, Argentine Precordillera, depositional mechanisms, ichnofacies, shelf deposits

INTRODUCTION Detailed interpretation of the deposition of storm influenced beds is still difficult, and some questions remain unanswered. These questions bear heavily on the mechanisms responsible for the sediment transport and deposition across shelves (Arnott & Southard 1991, Cheel & Leckie 1993, Myrow & Southard 1996).

The main objectives of this study are as follows: (i) to describe and interpret the sedimentology and (ii) the depositional mechanisms of Sierra de La Invernada Formation (middle-late Ordovician); (iii) document the trace-fossil assemblage of this deposit and (iv) to propose a depositional system for the unit.

Early studies for the Sierra the la Invernada Formation suggest that the unit was deposited in deep-water fan systems (Furque *et al.* 1990, Brussa 1997). At the now presented research there was a re-interpretation of the deposition system. The unit is here understood as storm-influenced deposits associated with a siliciclastic inner shelf.

Lithofacies model for storm deposition have historically involved sandy or coarser-grained foreshore and shoreface zones (Myrow 1991). There are few examples of well-described form in storm-influenced inner shelf. The results should broaden our understanding of shallow water siliclastic system. Moreover, new light on the evolution of the Argentine Precordillera during the Ordovician Period can be supported by this work.

GEOLOGICAL SETTING The Sierra de La Invernada Formation (middle-upper Ordovician) is part of siliciclastic sedimentary succession located at the western Argentine Precordillera (San Juan Province, Argentine). The Argentine Precordillera is a part of a larger terrane exotic to the western margin of Gondwana (Thomas *et al.* 2002). This terrane is characterized by the presence of carbonate and siliciclastic rocks of Cambrian-Ordovician age. Keller (1999) interpreted the depositional history of the Argentine Precordillera during de middle and late Ordovician like a reflect of rifting that led to the final separation of the Precordillera from mainland Laurentia. Thomas & Astini (2002) argued that the Ordovician sedimentation in the Precordillera terrane could have been occurred in a foreland basin or passive margin adjacent to the colision.

The Sierra de La Invernada Formation was dated from upper Arenig to lower Llanvirn age through graptolites assemblage (Brussa 1997). These rocks are characterized by very fine sandstone, from few centimeters to 10 cm of thickness, showing anisotropic hummocky cross stratifications, alternated with sandy pelite. The sandstone strata frequency is variable, from 10 to 70%. The Sierra the La Invernada Formation is rich in trace-fossils, testifying a high biological benthonic activity. The lower and medium parts of succession show thin calcarenitic beds with small anisotropic hummocky cross stratifications. The data basis for this study comprises 3 measurments of outcrop sections. The outcrop sections vary between 500 m to 1.300 m of thickness. The succession is ~2000 m thick and the crops out for more than 80 km in a roughly north-south trend. Furque & Caballé (1985) and Brussa (1997) interpreted the unit as deposited in a deep-fan system of passive margin.

LITHOFACIES This study focuses on the analysis of specific features of beds and its relationship with depositional mechanisms. The main features of the lithofacies are demonstrated in figure 1.

Lithofacies 1: silty mudstone This lithofacies consists in mudstones and muddy siltstones usually structureless or parallel laminated. These deposits are generally interbedded with very fine sandstone beds (Lithofacies 2) on the scale of few meters. Bioturbation is very rare and consists mainly of *Planolites*. They were founded just on the top of the succession measured (last 100 m).

The sandstones are interpreted as deposits of storm events (tempestite deposits) (Myrow & Southard 1991, Myrrow & Southard 1996, Cheel & Leckie 1993). The shale was deposited by settling during fair-weather.

The presence of shale and the thinner nature of the interbedded sandstones indicate that this lithofacies should have been deposited in more distal areas than the sandstones lithofacies.

Lithofacies 2: thin sandstones with anisotropic hummocky cross lamination This lithofacies consists of interbedded centimeter thick (25 cm maximum) alternations of very fine sandstone and siltstone. The alternation form sequences up to 60 m thick. This lithofacies are the most frequent in the succession measured. The siltstone is parallel laminated and contains thin sandstone laminae showing starved ripple cross lamination.

The sandstones beds are characterized by the presence of anisotropic hummocky cross lamination (Myrow *et al.* 2002). Sole marks and convolute beds also are common. Both sandstone and siltstone beds have tabular shape. The main trace fossils found are *Planolites*, *Skolithos*, *Diplocratiorion*, *Arenicolites* and *Helminthopsis*.

The hummocky cross lamination indicates that the sediments were deposited above the storm-wave base. The sandstone beds were transported by wave-modified turbidity currents related to storm events. These flows are formed by superimposition of wave-generated oscillatory flow on a turbidity current (Myrow & Southard 1996) The presence of sole marks and the anisotropic hummocky cross lamination are associated with the unidirectional component of the flows. Paleocurrents measurements in these sedimentary structures indicate a sediment transport from north to south. The siltstone layers were deposited during fair-weather by traction-plus-fallout interlayered with low-density turbidity currents (Mulder & Alexander 2001).

Sandstones and siltstones alternation packages (from 20 m to 60 m thick) show fining and thinning upward trend. Just an interval ~100 m thick shows a set of coarsening and thickening upward package.

Lithofacies 3: thick sandstone beds and conglomerate This lithofacies consists of immature massive sandstones that range from 20 cm to 2 m in thickness and granules to pebble conglomerate. The beds have sharp to erosive base. Internally, the sandstone beds can exhibit localized sole marks and diffuse parallel lamination. Thickness between laminae is 2-4 cm. Granules are common at the base of beds. Sand grade varies between very fine to medium sand. At the top of some beds can be found anisotropic hummocky cross laminations, forming bipartide beds. The upper part is composed by very fine sandstones.

The conglomerate beds consist in clast-supported mixtures of granules to cobbles with poorly sorted sandy matrix. The conglomerate contains a wide variety of rounded siliciclastic and carbonate clasts. These lithofacies were found only at the top of the measured successions. Trace fossils, mainly *Helminthopsis* and *Gordia* are primarily associated with the siltstone interbeds.

The deposition of sandstone beds is associated with concentrated density flows (Mulder & Alexander 2001). The presence of hummocky cross lamination at the upper part the beds formed by the concentrated flows reflects the influence of an oscillatory component. The abundant presence of rounded pebbles and cobbles and the clast-supported texture indicate that the conglomerate beds were deposited by powerful traction currents (hyperconcetrated density flows).

Lithofacies 4: calcarenites Calcarenite beds are impure, usually 5 to 15 cm thick and display tabular shape. This lithofacies occur at the base of the succession interbedded with the lithofacies 2. The structures are massive or present parallel lamination rare portions of pellets and bioclasts can be observed in these beds.

These beds are associated with low density turbidity currents. The possible source for the calcarenites is an active carbonate platform.

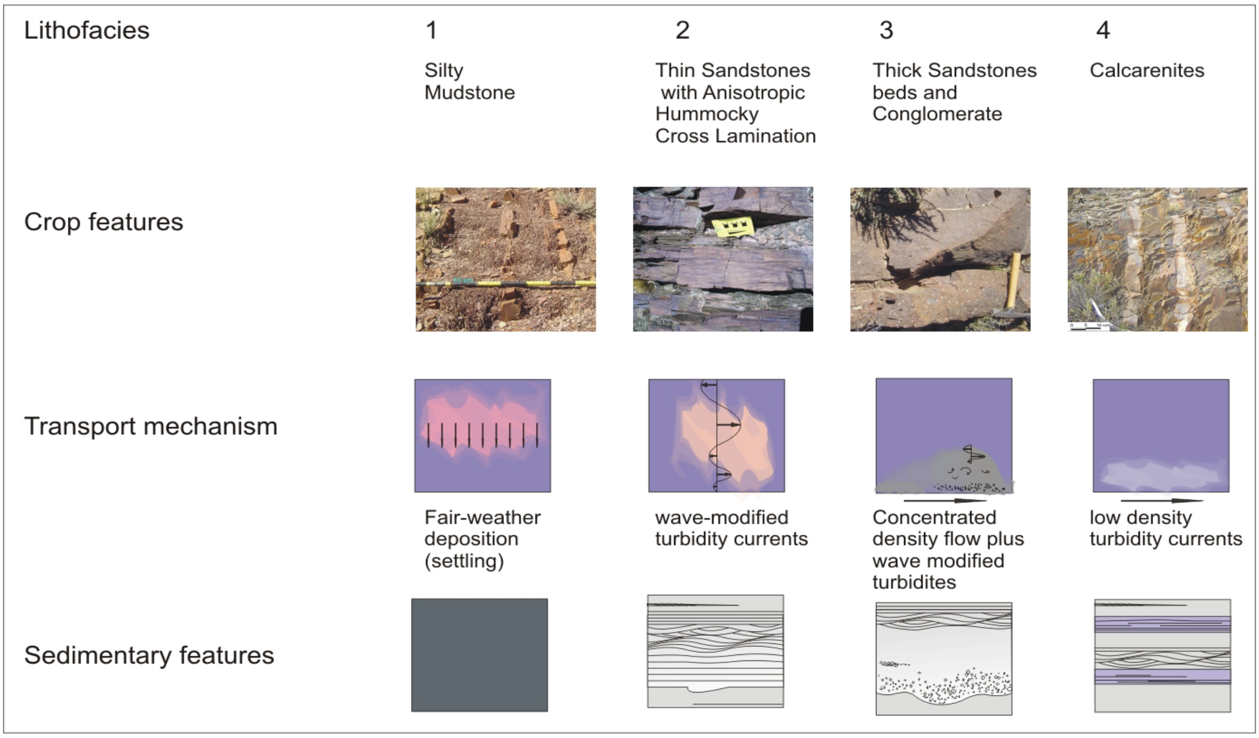

Figure 1: Main features and of the lithofacies

ICHNOLOGY The trace fossils in very fine sandstone beds are represented by *Arenicolites*, *Chondrites*, *Diplocraterion*, *Paleophycus*, *Skolithos* and rarely *Zoophycos*. The association of these assemblages appears to belong to *Skolithos* and *Cruziana* ichnofacies (Seilacher 1967).The structures are related to a colonization of opportunistic organisms in a substrate which has been rapidly deposited (Pemberton *et al.* 1992).

The trace fossils *Helminthorhaphe*, *Planolites*, *Paleophycus* and rare *Zoophycus* are associated with siltstone layers. They represent a stable benthic community colonizing the substrate during fairwether. They are found at the base or top of the beds. These trace fossils are related mainly to *Cruziana*, ichnofacies (Seilacher 1967). Rare trace fossils of *Zoophycus* and *Nereites* ichnofacies were described at the upper part of the succession.

This ichnofacies are typical in shelf settings, above or at storm wave base (Seilacher 1967). The duality represented by the presence of opportunistic and fair-weather assemblages is typical of storm deposits (Pemberton *et al.* 1992, Cheel & Leckie 1993).

LITHOFACIES MODEL AND DEPOSITIONAL SYSTEM The majority of the sedimentary rocks is a monotonous deposit dominated by lithofacies 2. The lithofacies 4 occurs (interbedded with lithofacies 2) more frequently in the interval that begins at the base to 750 m of measured deposits. An active carbonate platform occasionally provided the sediments for the calcarenites.

The interbedding of the lithofacies 2, formed by wave-modified turbidity currents and siltstones, indicates that the deposition occurred above the storm wave base. This interpretation is also supported on the predominance of *Skolithos*-*Cruziana* ichnofacies.

An interval c.100 m thick (distant 500 m from the base of the succesion) shows a set of coarsening and thickening upward sequences. The sequences are formed by the variation on the grain size of lithofacies 2. The sequences can reflect the sea-level variations. The predominance of *Skolithos and Cruziana* ichnofacies testifies that the deposition occurred bellow the fair-weather wave base.

The next interval (~100 m thick) consists of deposits dominated by the lithofacies 1, indicating a deeper-water deposition. The presence of trace fossils is less abundant.

Conglomerates and thick sandstones beds (lithofacies 3) are present at the top of the succession (last 150 m). They were formed by concentrated (and hiperconcentrated) density flows with minor influence of oscillatory flows. These deposits could indicate a more distal deposition trend. These processes are related to sediment bypass (Myrow 1992) in proximal areas.

The presence of rare trace fossils associated with *Zoophycus* and *Nereites* ichnofacies at the upper part of the succession could indicate a minute deepening of the shelf depositional system.

CONCLUSIONS The wave-modified turbidity currents are the most important transport mechanism occurred during the deposition of the Sierra the La Invernada Formation. The upper part of the succession shows sandstone and conglomerate bodies generated by concentrated density flows and wave-modified turbidity current.

The presence of silty mudstone at the upper part of the succession indicates a gradual deepening of the basin.

The ichnofacies suggests a deepening of the shelf across the succession measured.

The Sierra the La Invernada Formation was deposited in a siliciclastic shallow marine system above or at the storm wave base. The *Cruziana-Skolithos* ichnofacies and the deposits marked by wave-modified turbidity currents indicate that interpretation of deep-water deposition is not adequate.

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