The storm-influenced deposits of the Portezuelo del Tontal Formation, western Gondwana margin, middle-upper Ordovician, Argentine Precordillera

A. Henrique, P.A. Moretti Jr. & G. Basilici

University of Campinas – Institute of Geosciences – Department of Geology and Natural Resources, PO 6152, Campinas-SP, Brazil, andre.henrique@ige.unicamp.br

Abstract The Portezuelo del Tontal Formation (Middle-Upper Ordovician) is a thick succession of siliciclastics deposits influenced by storm waves. This formation can be observed in the entire Sierra del Tontal, located in the western central portion of the Argentine Precordillera. A detailed sedimentological analysis allowed us the identification of deposits by concentrated density flow. These deposits are associated with turbidity current deposits and interbedded with pelite sediments. These flows were induced by storm waves in a distal shelf setting. The concentrated density flow deposits are represented by massive medium grain-size sandstones, compositionally and texturally immature. In addition, they show traction carpet structures. It is also possible to identify deposits caused by turbidity currents modified by storm waves (wave-modified turbidity currents). These deposits are consisted of very fine grained sandstone, from 2 cm to 50 cm thick, characterized by planar-parallel laminations, anisotropic hummocky cross stratifications, and sole marks (flute cast, groove cast and prod cast). Furthermore, pelite layers observed are interpreted as deposited during fair-weather periods.

Keywords: Tempestites, Combined flows, Portezuelo del Tontal Formation, Precordillera

INTRODUCTION Detailed studies have demonstrated the importance of storms in sediment deposition through turbidity currents transportation onto shelf (Hayes 1967, Cheel & Leckie 1993, Myrow *et al.* 2002, Higgs 2004). In attempt to understand this kind of deposits, a wide variety of hummocky cross stratification (HCS) have been related to high energy oscillatory events associated with a unidirectional component (Campbell 1966, Brenchley *et al.* 1979, Cheel & Leckie 1993, Myrow & Southard 1991, Myrow & Southard 1996, Dumas *et al.* 2005).

This work aims the study of depositional mechanisms in a storm-influenced setting. We investigated the vertical distribution of beds in the upper part of Portezuelo del Tontal Formation (PTF), Middle-Upper Ordovician of Argentine Precordillera. As a result, we present a facies description and interpretation that played an important role in the proposal of a flow model and depositional history of siliciclastic shelf deposits.

The previous studies of the PTF sedimentation (Cuerda *et al.* 1985, Cingolani *et al.* 1989, Spalletti *et al.* 1989) interpreted the sandstone beds and shale as turbidites associated to deep fan system. However, in the measuring and description of seven stratigraphic sections we have observed a constant presence of anisotropic HCS. These HCS structures indicate the influence of an oscillatory flow associated with a unidirectional component.

GEOLOGICAL SETTING The Precordillera is a tectono-stratigraphic province extending for 45 km in N-S direction as part of Andean mountain chain. It is considered as part of a larger exotic terrane accreted to western margin of Paleozoic Gondwana during the early Paleozoic Famatinian orogeny (Keller 1999, Thomas & Astini 2003).

The unit in study is located in the central-western Precordillera and it is characterized by a thick succession (more than 2000 m) of sandstones and shale interlayered with rare conglomerate lenses. The paleontological contents are represented by Llanvirnian-Llandeilian graptolite assemblages (Cingolani *et al.* 1989).

According Cuerda *et al.* (1985), the elementary ritmic units could be interpreted as a typical proximal turbidites. Spalletti *et al.* (1989) proposed a deep water fan system which formed on a passive continental margin. These deposits would be intermediary between a pelite-rich and sand-rich fan system.

SEDIMENTARY FACIES The interpretation of depositional mechanisms was based in the subdivision of succession in facies. Each facies contain a variety of different bed types; these are characterized by the variation in the sequence of the structure layers (Fig.1A, B and C).

Three facies were described and interpreted during this research: medium to very-fine sandstone facies, fine to very-fine sandstone facies, and shale facies.

Medium to very fine sandstone facies This facies is vertically distributed for about 80% of the succession. It consists of tabular bipartite beds: a lower massive medium sandstone portion and an upper fine to very-fine sandstone portion (Fig. 1A). The thickness is widely variable (few centimeters to ten meters).

The base of massive lower part is abrupt with erosive contact. Large and abundant sole markings are found; they include flute and groove casts. The medium to coarse sand grain size is predominant. The grain selection is very incipient and sometimes there are buoyancy clasts, such as granules and pebbles. Some beds show basal coarse grained concentration with variable thickness (5 – 40 cm) (Fig. 2A). Besides, layers inversely graded (3 – 5 cm) can be found; they are interpreted as traction carpet.

The contact between the lower and upper portion is abrupt. The upper portion of beds is thinner than lower portion. It is characterized by fine to very-fine sandstone. At these beds portions, it is observed a sequence of similar sedimentary structures to those found in typical tempestites. The base normally has a few centimeters thick of parallel lamination which passes upwards to anisotropic HCS. Parting lineation occurs on some bedding planes of parallel lamination and in the hummocks & swales bedforms. The wave length is about 20 - 40 cm.

To interpret this facies we have to provide a special attention for the two different portions which are the product of different depositional mechanisms. However, these mechanisms are genetically related since both portions are always seen associated (physically together). The massive lower portion presents typical features of gravitational flows. On the other hand the HCS level is a typical tempestite with a unidirectional component. Both facies portions seem linked to storm events.

Mulder & Alexander (2001) suggested a unification of the termed “density flows” or “gravity-driven flows”. According to this classification and based on the textural features identified at the lower portion, it is interpreted as a non-cohesive concentrated density flow. Grain-to-grain interaction supports the sedimentary particles during the flow movement. At the top boundary, the flow may interact with the external fluid and become fully turbulent.

The turbidity current produces the upper fine grained portion of this facies. It can be originated because of the fluid entrance in the top of concentrated flow. However, we also believe that this kind of flow can be directly generated by storm activity, once it produces a concentrated bottom current by gravitational segregation of sedimentary load. In both cases the turbidity current is influenced by oscillatory movement of storms waves. At first moment, the unidirectional component prevails and a thin parallel laminated portion is generated. Then this portion passes upward to an oscillatory dominant flow characterized by HCS presence. This sequence of parallel lamination and then HCS structures is observed in almost all beds. Nevertheless, sometimes, only HCS portion can be found. In this case, the unidirectional component of turbulent flow is overlapped by the oscillatory component.

Fine to very fine sandstone facies The fine to very fine sandstone facies shows high similarity with the upper portion of the medium to very fine sandstone facies. They are thin beds (10–50 cm) with tabular geometry and sharp contact at the bottom (Fig. 1B). Sole marks, such as flute and groove casts, are very abundant.

This facies, which are found in 13 % of the measured section, are often intercalated with shale facies (Fig. 2B). Generally the beds show a fine to very fine sand grain size with a structureless portion in the base. Occasionally this portion shows small asymmetrical folds with uniform vergence direction (from south to north). Another variation of bed type presents a parallel laminated lower portion which passes upwards to anisotropic HCS. The structure variations and soft grain size variations are concomitant.

The beds of this facies have been termed “wave modified turbidites” (Myrow *et al.* 2002). As well as the earlier facies description, the anisotropic character of HCS indicates the unidirectional component incidence. This is likely related to gravitational action (density induced). The parallel lamination at the base also supports this interpretation (Walker *et al.* 1983). Furthermore, the HCS presence indicates storm induced high energy oscillatory flow.

The asymmetrical folds identified are related to syn-depositional deformation. According Myrow *et al.* (2002), the susceptibility of fine grain sized sediments for liquefaction is well established. The liquefaction is the result of gravitational instability on the saturated sediments. In fact, the vergence of folds reveals the offshore direction. It is a consequence of the gravitational component of these syn-depositional deformations.

Shale facies This facies is constituted by massive black shale sometimes rich in graptolite remains. It was described in about 7% of the measured section and assumes varied thicknesses (few centimeters to 1.3 meters). Lenticular beds of very-fine sand sized are usually found within shale; sometimes it shows small sets of cross lamination (Fig. 1C).

The shale is alternated with the two previously described facies. It is interpreted as the background sedimentation produced by settling in a fair-weather stage. The lenses of very-fine sandstone beds are deposited by low density gravitational flows associated with lower intensity storms.

This work did not make any detailed study in the graptolite remains, but Peralta *et al.* (2003) described several species found at La Antena region. These species (Llanvirnian-Llandeilian aged) have strong similarity with that from the Appalachian margin of Laurentia.

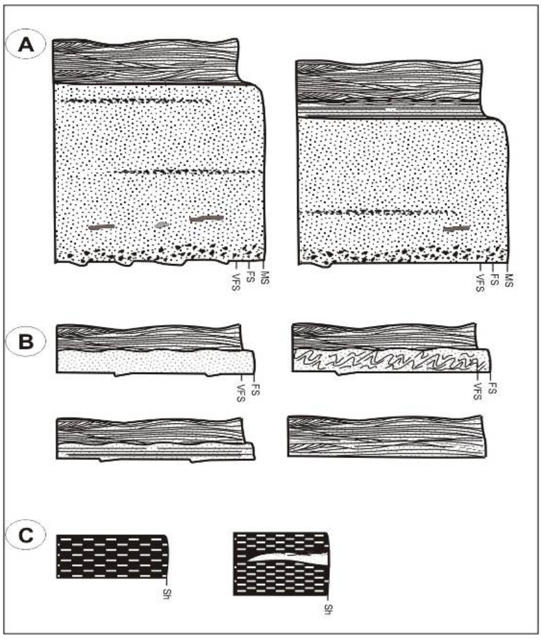

Figure 1. Three facies described: A) Medium to very fine sandstone facies - two types of beds; B) Fine to very-fine sandstone facies - four types of beds; and C) Shale facies sometimes with lenticular sandstone beds

DEPOSITIONAL SYSTEM The HCS is the key structure in the facies interpretation. Consequently, any model for the PTF deposition must account for its presence. The model here proposed does not correspond to the Cuerda *et al.* (1985) and Spalletti *et al.* (1989). In fact, it does not seem probable that the PTF was generated in a deep water fan system. In this unit the main architectonic elements of a subaquatic fan are absent: channel and lobes, interchannel or overbank deposits and slope deposits.

Moreover, the HCS indicates an oscillatory component that acts above the storm wave base. As a consequence, this succession is interpreted as wave-influenced gravitational deposits in a shelf depositional system. The shale facies is deposited in a fair-weather condition. This facies and the absence of bioturbation point out the deposition in an outer shelf. Furthermore, the lack of nearshore facies suggests that the entire succession was deposited below of the fair-weather wave base but above storm wave base (evidenced by HCS). Finally, we can suppose that these conditions of accommodation space were almost constant during the succession deposition.

FLOW ORIGIN AND SEDIMENT TRANSPORTATION Several researches have contributed to the best knowledge about the depositional mechanism that acts in the HCS generation and the vertical sequences of tempestites (Campbell 1966, Brenchley *et al.* 1979, Kreisa 1981, Dott Jr. & Bourgeois 1982, Duke *et al*. 1991, Myrow & Southard 1991, Cheel & Leckie 1993).

There is a consensus that HCS is related to high energy oscillatory events: storms. However, it is difficult a detailed interpretation on internal stratification of beds. Similarly, it is difficult to establish the characteristics and controlling mechanism of the flows that transport the sedimentary load (Myrow & Southard 1996).

Hayes (1967) was one of the first authors who proposed that catastrophic storms have an important role in sedimentary process near to coastal setting. He argued that the storm associated flows could generate gravitational flows on the shelf. Reineck & Singh (1972) suggested that the gravitational flows can not be the transport driving force of sediments to the outer shelf. In this case, the simple storm wave activity was sufficient to produce the necessary turbulence for sustain a large sedimentary cloud. This cloud would deposit the sedimentary load by settling after the reduction of wave energy.

However, this interpretation neither explains the wide variety of structures formed in vertical sequences of tempestites, nor the typical basal facies associated with a gravitational component of flows.

The main unanswered question about the sediment transport on the shelf is the nonactualistic aspect. The gravitational flows observed in the geologic record of shelves have downward direction (perpendicular to shore), while the oceanographic studies show the sediment transport by geostrophic currents nearly parallel to shoreline (Myrow & Southard 1996, Myrow *et al.* 2002).

The most accept model for ancient deposits is based in the Hayes (1967) ideas. The sand transport would be result of powerful downward direction gravitational currents that are related to excess-weight force. Once the gravitational component ceases, the suspended load is deposited under wave storm influence. Differences in storm intensity are reflected in the bed thickness variation within the facies.

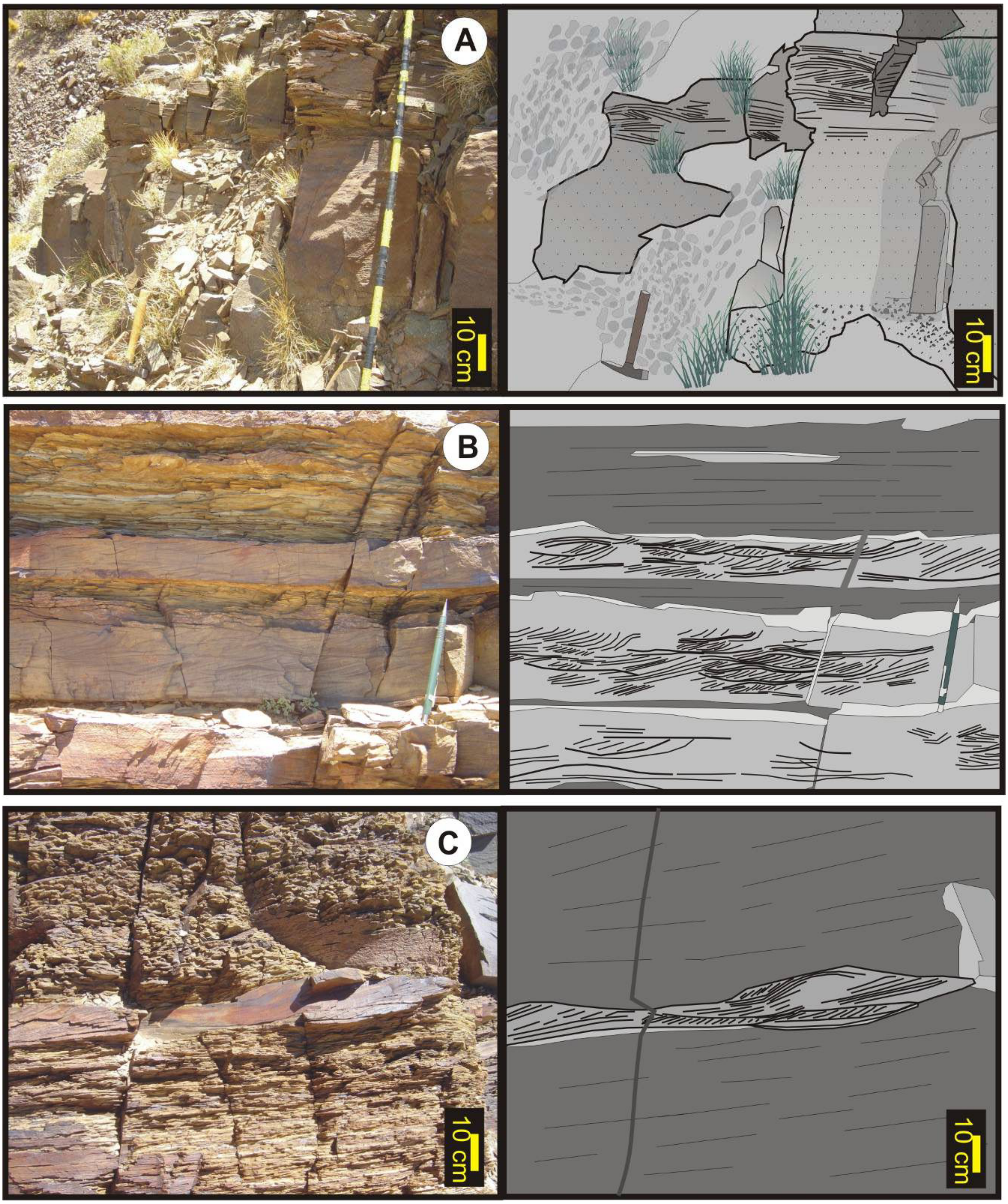

Figure 2. A) Medium to very fine sandstone facies. Bipartite beds with a medium massive sandstone in the lower portion and a very-fine sandstone upper portion. B) Fine to very fine sandstone portion interbedded with shale facies. C) Shale facies with lenticular sandstone beds

In PTF deposits some evidences indicate a gravitational (unidirectional) component for the flows: erosive bottom of beds with flute cast; anisotropic characteristics of HCS; strong parallelism among the sole marks paleocurrents and the anisotropic planes of HCS; and the asymmetrical sin-sedimentary folds.

It is important to emphasize that the lower portion of the medium to very fine sandstone facies is a typical gravitational generated facies (the concentrated density flows *sensu)* (Mulder & Alexander 2001). This facies mineralogy is immature, as well as its grain size. This way, the carrier flow does not rework the coastal sediments (shoreface) which have normally high maturity. It is necessary a large sediment supply, probably from a continental source. Myrow *et al.* (2002) considered the high concentrated flows can be related with catastrophic events of sediment influx such as hyperpicnal flows induced by oceanic flood (*sensu* Wheatcroft 2000). They are short duration flows originated of the river-ocean system response to a storm.

Myrow & Southard (1996) presents the main components of transport in a storm conditions: wave oscillation, density induced flow and geostrophic currents. The interaction of these components allow for the generation of tempestite beds found in the geological record. In PTF, the concentrated density flow moves like a purely density induced flow. However the wave-modified turbidites represents a combined flow between density induced and the wave oscillation component.

In summary, we proposed the followed model of flow evolution for the PTF deposits.

The medium to very fine sandstone facies was generated by a storm that reworked the shelf sediments. Furthermore, it promoted a high influx of continental source immature sediments producing the concentrated density flows. With the decrease of concentration, the upper part of flow moves as a turbidity current. The consequent increasing of oscillatory component creates a typical sequence of tempestites: parallel lamination and anisotropic HCS.

The fine to very fine sandstone facies was generated with lower intensity storms that can not promote the high concentration influx necessary to the massive portion of former facies. However, this facies may be the distal portion of the same flow which produced the medium to very fine sandstone in a proximal setting. It is consequence of the fact that the flow loses its sediment concentration.

The shale facies is the fair-weather deposits. Thus it represents the normal sedimentation in the basin. The other facies are extreme events or termed episodic events that represent cyclic or acyclic pulses of rapid deposition.

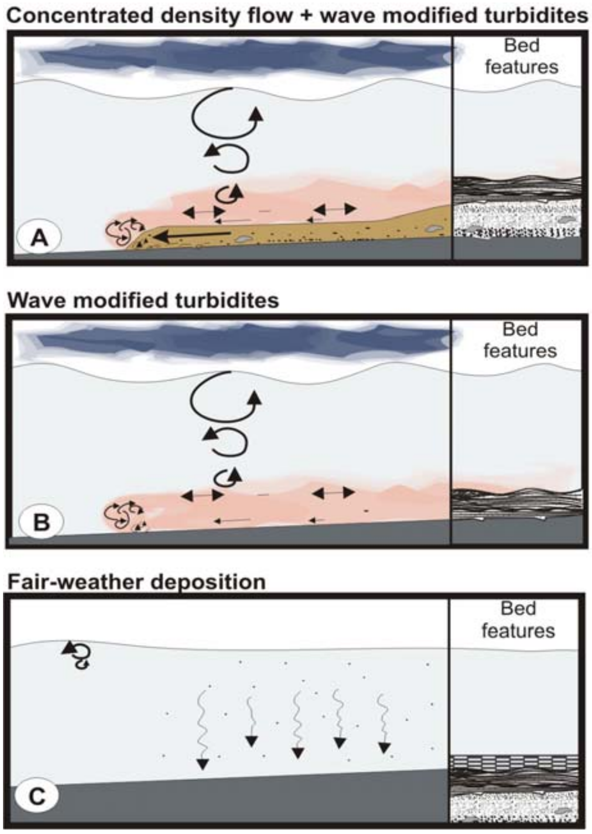

Figure 3. Models for the transport and deposition of sediments in each facie: A) Medium to very fine sandstone facies, B) Fine to very fine sandstone facies and C) Shale facies

Acknowledgments This research was supported by FAPESP (São Paulo State Research Support Foundation) and CNPq (National Research Council), Brazil.

References

BRENCHLEY P.J., NEWALL G., STANISTREET I.G. 1979. A storm surge origin for sandstone beds in an epicontinental plataform sequence, Ordovician, Norway. *Sedimentary Geology*, **22**:185-217.

CAMPBELL C.V. 1966. Truncated wave-ripple laminae. *Journal of Sedimentary Petrology*, **36**:825-828.

CHEEL R.J. & LECKIE D.A. 1993. Hummocky cross-stratification. *Sedimentology Reviews*, 1:103-121.

CINGOLANI C., CUERDA RA., VARELA R., SCHAUER O. 1989. Geología de la Precordillera Occidental en la comarca de la Sierra del Tontal, Provincia de San Juan, Republica Argentina. *In*: V Congreso Geológico Chileno, *Serie Comunicaciones*, Santiago, 40, p. 39-56.

CUERDA A., CINGOLANI C., SCHAUER O., VARELA R. 1985. El Ordovícico de la Sierra del Tontal, Precordillera de San Juan, República Argentina. *In*: IV Congresso Geológico Chileno, *Serie Comunicaciones*, Santiago, p.109-131.

DOTT Jr. R.H. & BOURGEOIS J. 1982. Hummocky stratification: Significance of its variable bedding sequences. *Geol. Soc. Am. Bulletin*, **93**:663-680.

DUKE W.L., ARNOTT R.W.C., CHEEL R.J. 1991. Shelf sandstones and hummocky cross-stratification: New insights on a stormy debate. *Geology*, **19**:625-628.

DUMAS S., ARNOTT R.W., SOUTHARD J.B. 2005. Experiments on oscillatory-flow and combined-flow bed forms: implications for interpreting parts of the shallow-marine sedimentary record. *Journal of Sedimentary Research*, **75**(3):501-513.

HAYES M.O. 1967. Hurricanes as geological agents, South Texas Coast. *The Americam Ass. Petrol. Geol. Bullletin*, **51**(6):937-956.

HIGGS R. 2004. Ross and Bude Formations (Carboniferous, Ireland and England): Reinterpreted as lake-shelf turbidites. *Journal of Petroleum Geology*, **27**(1):47-66.

KELLER M. 1999. Argentine Precordillera: sedimentary and plate tectonic history of a Laurentian crustal fragment in South America. *Geol. Soc. Am. Special Paper*, **341**:1-131.

KREISA R.D. 1981. Storm-generated sedimentary structures in subtidal marine facies with examples from the Middle and Upper Ordovician of Southwestern Virginia. *Journal of Sedimentary Petrology*, **51**(3):823-848.

MULDER T. & ALEXANDER J. 2001. The physical character of subaqueous sedimentary density flows and their deposits. *Sedimentology*, **48**(2):269 – 299.

MYROW P.M. & SOUTHARD J.B. 1991. Combined-flow model for vertical stratification sequences in shallow marine storm-dominated beds. J*ournal of Sedimentary Petrology*, **61**:202-210.

MYROW P.M. & SOUTHARD J.B. 1996. Tempestite deposition. *Journal of Sedimentary Research*, **66**:875-887.

MYROW P.M., FISCHER W., GOODGE J.W. 2002. Wave-modified turbidites: combined-flow shoreline and shelf deposits, Cambrian, Antarctica. *Journal of Sedimentary Research*, **72**(5):641-656.

PERALTA S.H., FINNEY S.C., BASILICI G. 2003. Portezuelo del Tontal Formation (Lower Caradoc), Western Precordillera, San Juan Province: its biostratigraphic and paleogeographic significance. *In*: ALBANESI G.L., BERESI M.S., PERALTA S.H. (eds.) Ordovician from the Andes. INSUGEO, *Serie Correlación Geológica*, 17, pp.:119-123.

REINECK H.E. & SINGH I.B. 1972. Genesis of laminated sand and graded rhythmites in storm-sand layers of shelf mud. *Sedimentology*, **18**: 123-128.

SPALLETTI L.A., CINGOLANI C.A., VARELA R., CUERDA A.J. 1989. Sedimentary gravity flow deposits of an Ordovician deep-sea fan system (western Precordillera, Argentina). *Sedimentary Geology*, **61**:287-301.

THOMAS W.A. & ASTINI R.A. 2003. Ordovician accretion of the Argentine Precordillera terrane to Gondwana: a review. *Journal of South American Earth Sciences*, **16**:67–79.

WALKER R.G., DUKE L.W., LECKIE D.A. 1983. Hummocky stratification: significance of its variable bedding sequences: Discussion and reply. *Geol. Scam. Bulletin*, **94**:1245-1251.

WHEATCROFT R.A. 2000. Oceanic flood sedimentation: a new perspective. *Continental Shelf Research*, **20**:2059-2066.