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THE ROLE OF FLUID MUD FLOWS IN THE ACCUMULATION OF ORGANIC-RICH SHALES. THE UPPER JURASSIC-LOWER CRETACEOUS VACA MUERTA FORMATION, NEUQUÉN BASIN, ARGENTINA

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RESUMEN

El rol de los flujos fluidos de fango en la acumulación de fangolitas bituminosas. Formación Vaca Muerta (Tithoniano temprano-Valanginiano temprano), Cuenca Neuquina, Argentina.

Durante los últimos años, el avance de técnicas no convencionales de explotación de hidrocarburos puso especial interés en obtener una mejor comprensión de los procesos sedimentarios que controlan la acumulación de materiales finos con abundante contenido orgánico. Bajo este escenario, en Argentina el principal foco de estudio ha sido puesto en la Formación Vaca Muerta, dadas las excelentes propiedades que presenta esta unidad como reservorio no convencional de hidrocarburos. En esta contribución se presenta un estudio integrado de afloramiento y subsuelo orientado al análisis sedimentológico de la Formación Vaca Muerta. El estudio de afloramiento se focalizó en el análisis de procesos de sedimentación de materiales finos en cortes pulidos de concreciones carbonáticas. Por otro lado, el estudio de subsuelo permitió abordar un análisis sedimentológico de alta resolución en testigos corona provenientes de ocho pozos exploratorios de la Formación Vaca Muerta. Las evidencias encontradas en los intervalos analizados permitieron reconocer una gran variedad de depósitos asociados a flujos fluidos de fango. Su origen se relaciona a dos procesos principales: flujos hiperpícnicos fangosos de larga duración (origen extracuencal) y flujos de fango intracuencales asociados a procesos de resedimentación. Los flujos de fango intracuencales serían más frecuentes en sectores próximos al quiebre de la plataforma, generando depósitos con bajo contenido orgánico. Por otro lado, los flujos hiperpícnicos fangosos de origen extracuencal habrían actuado como excelentes medios de transferencia de sedimentos finos y materia orgánica desde áreas emergidas hasta zonas internas de la cuenca, atravesando relieves de muy baja pendiente. En su trayectoria cuenca adentro, habrían incorporado material intracuencal previamente depositado creando depósitos de origen mixto. La rápida transferencia de fango rico en materia orgánica (tipo II y III) hacia sectores internos de la cuenca habría permitido alcanzar un soterramiento rápido y eficiente, evitando su exposición en el fondo marino. Este proceso habría favorecido la preservación de fangos bituminosos en sectores internos de la Cuenca Neuquina.

INTRODUCTION

During the last years, the study of fine-grained sedimentary deposits has received growing attention due to the advance in the development of shale reservoirs, leading to detailed geological surveys on a variety of unconventional resource shales. In addition, recent laboratory research (Schieber *et al.* 2007, Schieber and Southard 2009, Schieber and Yawar 2009, Schieber *et al.* 2013) and oceanographic expeditions in off-shore and deep marine environments (Baudin *et al.* 2010, 2017a, b, Biscara *et al.* 2011, Stetten *et al.* 2015, Mignard *et al.* 2017) have provided novel information about the mechanisms that control mud distribution and accumulation, contributing to a gradual paradigm shift in mudstone sedimentology (Bhattacharya and MacEachern 2009, Macquaker *et al.* 2010, Schieber *et al.* 2010, Abouelresh and Slatt 2011, Bohacs *et al.* 2014, Wilson and Schieber 2014, 2015, Lazar *et al.* 2015a, Schieber 2016, Zavala and Arcuri 2016).

The study of fine-grained sedimentary rocks constitutes a great challenge. First of all, the fine-grained nature (<62.5 µm) and the repeated lithofacies alternations demand the development of high resolution sedimentological analyses. In addition, the common occurrence of high mechanical compaction creates a disruption of the deposit primary fabric, flattening almost every primary feature (Schieber *et al.* 2010). Mechanical compaction is such an effective process in mud deposits because of the large primary pore spaces, exceeding 70 or even 80% at shallow burial depths (Enos and Sawatsky 1981, Goldhammer 1997, Lash and Blood 2004). As burial increases, the gradual expulsion of the water stored in the pore network of the sediment causes an important thickness reduction. For a long time, compaction effect was not considered at the moment of describing sedimentary structures in fine-grained deposits. As a consequence, almost every laminated mudstone used to be described as parallel-laminated, relating its origin to fallout processes in low energy depositional environments. In fact, the described “parallel lamination” is not a diagnostic criteria of hemi-pelagic deposits, since its parallel-laminated aspect can be a product of the flattening caused by compaction. Consequently, careful examinations are essentially required for capturing and describing rock heterogeneities in terms of bedding bounding surfaces, grain size variations and physical sedimentary structures. These primary features constitute key attributes for studying mudstone depositional processes.

In Argentina, the Upper Jurassic – Lower Cretaceous Vaca Muerta Formation is composed of organic-rich mudstones and carbonates dominated by type II kerogen, representing South America’s main unconventional reservoir (Askenazi *et al.* 2013, Stinco and Barredo 2014, Vallejo and González 2016). For a long time, these deposits were described and interpreted as a monotonous mudstone succession accumulated by fallout deposition in quiet and anoxic slope to basinal marine settings (Leanza 1973, Leanza *et al.* 1977, Legarreta *et al.* 1981, Gulisano *et al.* 1984, Mitchum and Uliana 1985, Legarreta and Gulisano 1989, Legarreta and Uliana 1991). However, recent sedimentological analyses and reservoir characterization have revealed that the Vaca Muerta

Formation is a highly heterogeneous stratigraphic unit whose depositional processes are largely more variable(Askenazi *et al.* 2013, Kietzmann *et al.* 2014a, 2016, Galeazzi *et al.* 2014, Zeller *et al.* 2015, González *et al.* 2016). In fact, this formation displays distinct lithofacies alternating at centimeter to millimeter scale having variable contents of carbonate and organic matter, features that influence its reservoir quality and production performance.

This study is focused on providing new sedimentological evidences for a better understanding of Vaca Muerta organic-rich shales occurrence and distribution. For this purpose, high resolution sedimentological analyses were performed on subsurface cores and outcrop cut and polished samples corresponding to relatively uncompacted intervals preserved in early diagenetic calcareous concretions. The evidences found in the studied intervals suggest that the Vaca Muerta Formation was deposited under a more complex scenario than previously assumed, where hemi-pelagic deposition was probably subordinated to intrabasinal and extrabasinal fluid mud flow events. This contribution discusses the importance of mudstone depositional processes for future exploration of unconventional resources in the Vaca Muerta Formation and other shale reservoirs.

GEOLOGICAL BACKGROUND

The Neuquén basin is a triangular-shaped back-arc basin developed during the Mesozoic in the western margin of Gondwana (Mosquera *et al.* 2011). It is located in the eastern side of the Andes in west central Argentina and central Chile, between 32° and 40° S (Fig. 1). The basin boundaries are defined by the Sierra Pintada belt to the northeast and the North Patagonian Massif towards the southeast, whereas the occidental margin is defined by the Andean magmatic arc. It presents a northwest-southeast elongated shape that covers more than 160,000 km^2 (Vergani *et al.* 1995), with a sedimentary infill of at least 7,000 m of continental and marine siliciclastic, carbonate and evaporite deposits. Historically, the Neuquén basin has been widely studied because of its importance as an oil-bearing basin, with vast research developed on conventional clastic reservoirs. Nevertheless, the crescent hydrocarbon production from unconventional reservoirs have promoted the onset of several geological studies on the main unconventional targets.

The origin of the Neuquén basin is related to the convergence of the South American plate with the southern segment of the Nazca-Pacific plate (Hogg 1993). This tectonic scenario caused a flexural subsidence of the continental crust behind a stationary magmatic arc, resulting in the development of different back-arc basins during the Permo-Triassic (Mpodozis and Ramos 1989, Vergani *et al.* 1995). Under such tectonic settings, the basin fill evolution was controlled by repeated sea-level oscillations that conditioned the basin connection with the paleo-Pacific Ocean (Legarreta and Uliana 1991, Mutti *et al.* 1994). As a result, periods of high eustatic sea level resulted in fast marine flooding coming from the paleo-Pacific Ocean, providing anoxic to sub-toxic marine conditionsoptimum for source rock development (Legarreta 2002). On the other hand, lowstand periods caused forced regressions and the consequent development of evaporites and non-marine clastics. These flooding-desiccation events are repeatedly manifested in the stratigraphic record of the Neuquén basin. According to Zavala *et al.* (2006), periods of marine disconnection are usually associated to regional unconformities defined by sharp lithologic contacts between continental and marine deposits. Also, in places some angularity can be detectable, what suggesta tectonic overprint. The basin accommodation space increased progressively above such unconformities, resulting in the accumulation of transgressive successions over the former continental deposits (Fig. 1).

The sedimentary evolution of the Neuquén basin can be divided into three main depositional stages (Zavala and González 2001): The first stage (UpperTriassic-Lower Jurassic) represents the syn-rift phase, characterized by the deposition of volcanic and volcaniclastic materials (Precuyo

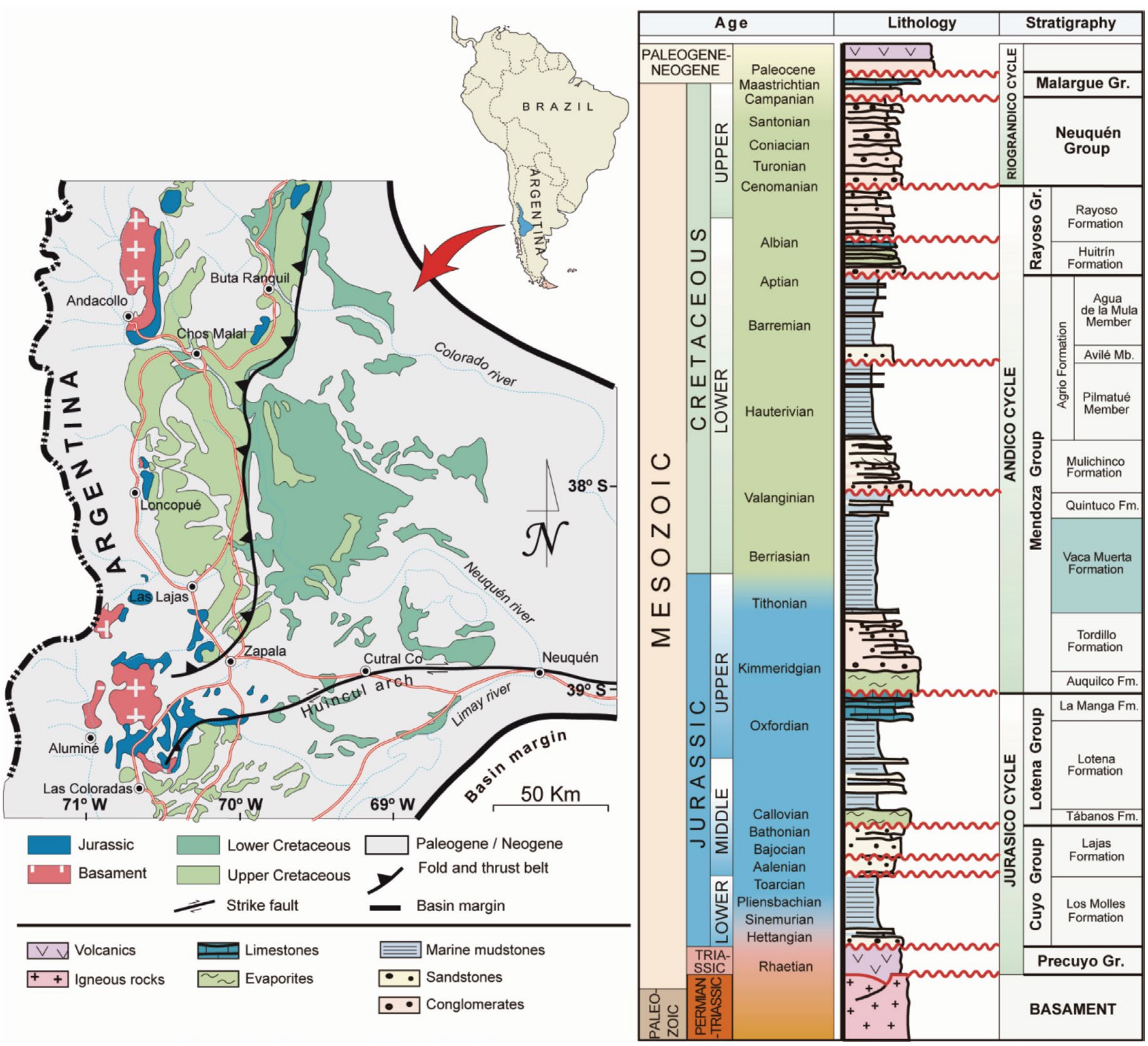

Figure 1. Geological map and main stratigraphic column for the central area of the Neuquén basin (After Zavala *et al*. 2006).

Group) along hemi-graben depocenters (Gulisano 1981). The second stage (Lower-Upper Jurassic) is characterized by a mainly clastic prograding marine to continental succession (Cuyo and Lotena groups) deposited over a tectonically induced irregular relief. The third stage (Upper Jurassic-Upper Cretaceous) is a marine to continental succession up to 6,000 m thick (Mendoza, Rayoso, and Neuquén groups). During this last stage, a global high eustatic sea level stand favored a maximum expansion of marine deposits throughout the basin, with the consequent development of the main source rock unit (Vaca Muerta Formation). The basin was totally disconnected from the paleo-Pacific Ocean in the late early Cretaceous. Finally, the establishment of a compressive tectonic regime during the late Cretaceous and the Cenozoic caused an uplift of the western part of the basin, providing widespread, north-south oriented outcrops that constitute different fold and thrust belts. Therefore, oil bearing deposits are mainly preserved on the eastern margin of the Neuquén basin (Fig. 1).

THE VACA MUERTA FORMATION

The Vaca Muerta Formation (Weaver 1931, enmend. Leanza 1973) constitutes a thick, widely distributed stratigraphic unit developed during the lateJurassic-early Cretaceous in the Neuquén basin. In the Neuquén province domain, this unit is mainly composed of dark, bituminous fine-grained mudstones thinly interbedded with gray siliceous/calcareous fine-to coarse-grained mudstones. These fine-grained deposits are also alternating with limestones and minor sandstone intervals. As mentioned by Stinco and Barredo (2014), the Vaca Muerta Formation constitutes South America's main unconventional reservoir (Askenazi *et al.* 2013, Vallejo and González 2016), with total organic carbon (TOC) contents between 3-8 %, Ro max (%) 0.8-2, hydrogen Index 400-800 mg HC/gtoc, SPI 5 to 20 t HC/m2 and a kerogen type I-II/IIS (Legarreta and Villar 2015). This sedimentary succession comprises the lower part of the Mendoza Group (Stipanicic *et al.* 1968), also referred to as the Lower Mendoza Mesosequence (Legarreta and Gulisano 1989).

The Lower Mendoza Mesosequence is an upper Kimmeridgian-lower Valanginian shallowing-upward sedimentary cycle comprising all the deposits between the Intramalm and the Intravalanginian unconformities. At the base, this cycle starts with non-marine clastics of the Tordillo Formation (Kimmeridgian), which are sharply overlaid by off-shore to basinal marine deposits of the Vaca Muerta Formation (lower Tithonian-lower Valanginian). The origin of these deposits is related to a global sea level rise that took place during the early Tithonian, causing a rapid and catastrophic marine flooding from the paleo-Pacific Ocean (Mutti *et al.* 1994). The initial flooding event was such an important transgression that exceeded all previous paleogeographical boundaries, displaying a typical retrogradational stacking pattern. Subsequently, an important clastic input from the North Patagonian Massif caused the development of a western-northwestern prograding mixed-shelf system during a regional highstand context (Leanza *et al.* 2011).

At the subsurface, towards the eastern margin of the basin, the Vaca Muerta Formation is diachronically covered by shallow marine carbonates and clastics of the Quintuco and Loma Montosa formations (upper Tithonian-lower Valanginian), and the continental deposits of the Puesto Gonzalez Formation (lower Valanginian, Mitchum and Uliana 1985). At the same time, in the southern domain (Picún Leufú sub-basin, Fig. 1), these nearshore clastics and carbonates are grouped into the Carrín Cura and Picún Leufú formations, whereas the continental deposits match into the Bajada Colorada Formation (Leanza *et al.* 2011). These units constitute the proximal facies of the Tithonian-Valanginian system, being totally replaced by off-shore to basinal facies of the Vaca Muerta Formation towards distal basin positions. In basin inner zones, the Vaca Muerta Formation is characterized by organic-rich fine-grained deposits up to 1,200 m thick, also including slope turbidites referred to the Huncal Member (lower Berrasian, Leanza *et al.* 2003).

The former outstanding seismic stratigraphic analyses (Mitchum and Uliana 1985) recognized nine depositional sequences for the lower Tithonian-lower Valanginian system (Sequence A-I, Mitchum and Uliana1985). According to Leanza *et al.* (2011), this system comprises three main evolutionary stages: a lower ramp system developed during the early-middle Tithonian (Sequences A, B and C) followed by a slope configuration extended from the late Tithonian up to the Berrasian (Sequences D, E, and F), and a final stage of shelf-break configuration (Sequences G, H and I) developed during the early Valanginian (Mitchum and Uliana 1985).

Mitchum and Uliana (1985) magnificent work was recently complemented by an integrated regional seismic stratigraphic analysis developed during the IX CONEXPLO (Galeazi *et al.* 2014). It was conducted by professionals from the industry and academic researchers who integrated the latest 3D seismic data with well logs, geochemical and core data from newly drilled wells, including also outcrop studies for a better characterization of the lower Tithonian-lower Valanginian system. The results of this study were later published as a special publication by the IAPG (Vallejo and González 2016), suggesting the presence of 6 seismic units (Fig. 2, Sattler *et al.* 2016). These units are characterized by distinctive seismic stacking patterns separated by regional horizons, having a great correspondence with the previous seismic-stratigraphic framework (Mitchum and Uliana 1985). As mentioned by Desjardins *et al.* (2016), different clinoform types have been recognized within the lower Tithonian-lower Valanginian system (Dominguez *et al.* 2017). In a regional context, an initial mixed-ramp configuration composed of low angle clinoform geometries with a typical agradational pattern (Units 1-2, Fig. 2) is followed by a well-defined progradational arrangement with oblique and sigmoidal clinoform types defining a shelf-break(Units 3-6). Clinoform origin within the Vaca Muerta Formation is currently under increasing debate. Present-day research on this topic are suggesting different sedimentary processes, including: contornites, downwelling-triggered off-shore bottom currents, bottom Ekman transport, muddy hyperpycnal flows and muddy turbidity currents (Desjardins *et al.* 2016).

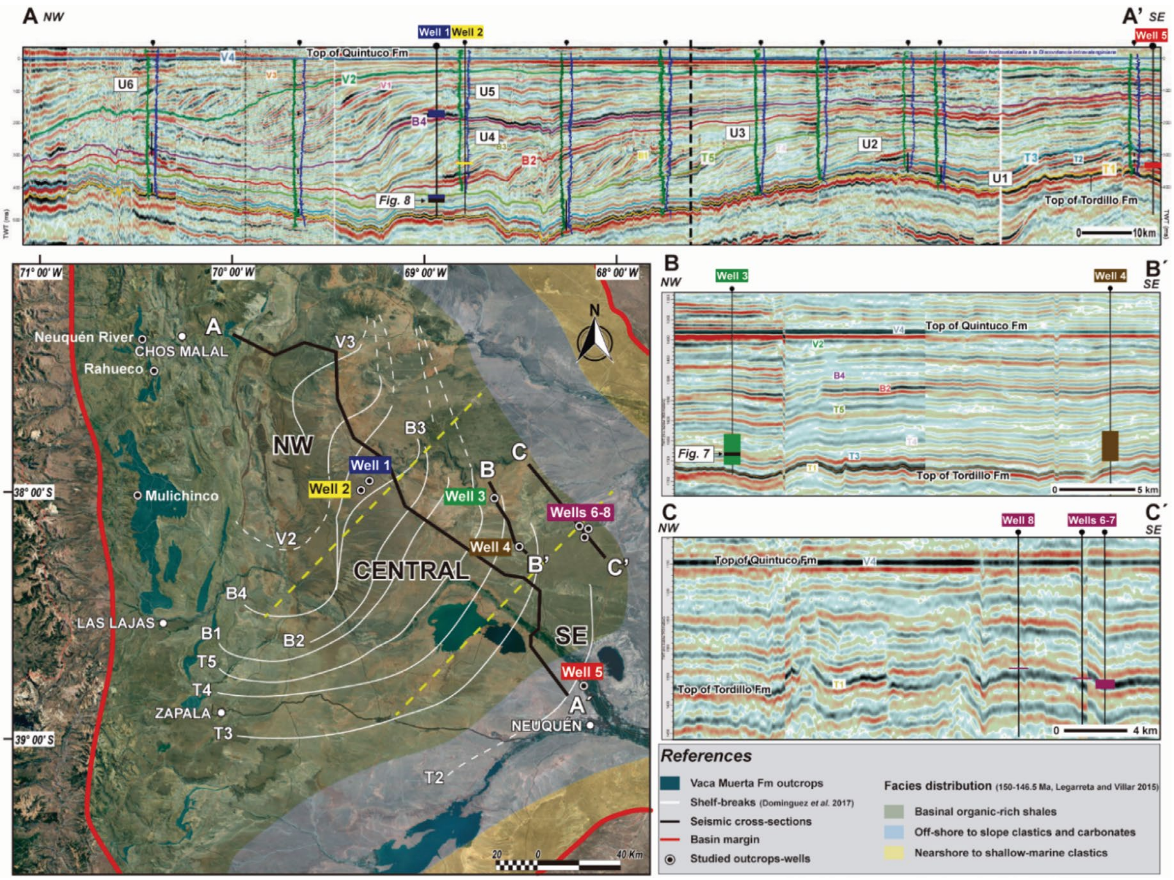

Figure 2. Seismic cross-section from Sattler *et al.* (2016) with projection of wells 1, 2 and 5 core intervals. Additional seismic cross sections for wells from the central (wells 3 and 4) and southern areas (wells 6, 7 and 8) are also presented (B-B', C-C'). The surfaces defined by Sattler *et al.* (2016) are plotted in the satellite image according to Dominguez *et al.* (2017).

METHODS

This study comprises an integrated high-resolution sedimentological analysis of outcrop samples and subsurface cores of 8 different wells (Fig. 2). Rock description was performed following the nomenclature proposed by Lazar *et al.* (2015b).

OUTCROP STUDIES

High resolution sedimentological analyses were performed in early-diagenetic carbonate concretions (Figs. 3a and b) that preserve an exceptional record of mudstone depositional history (Otharán and Zavala 2016, 2018, Otharán *et al.* 2017a). These syn-sedimentary concretionary bodies grow near sediment-water interface at shallow burial depths, providing a compaction-resistant framework capable of preserving a "frozen" record of the deposit primary fabric (Westphal *et al.* 2000, Lash and Blood 2004, Abouelresh and Slatt 2012, Marshall and Pirrie 2013, Kietzmann *et al.* 2014b, McNeill *et al.* 2015). The employed method consists in sampling different carbonate concretions that at first sight exhibit primary sedimentary features (Fig. 3c). Afterwards, the samples are cut using a rock cutting machine and then polished through steel discs using a silicon carbide abrasive. Finally, the polished slabs are digitally scanned and processed for a better characterization (Fig. 3d).

The studied samples were collected from the basal deposits of the Vaca Muerta Formation in inner basin positions, close to Huncal and Rahueco localities (Fig. 2). This basal succession is characterized by dark, bituminous organic-rich mudstones rhythmically intercalated with calcareous concretions up to 1 m thick, with common beef and tuff levels occurrence (Otharán *et al.* 2017a). It represents the initial transgressive deposits of the Vaca Muerta Formation over the continental deposits of the Tordillo Formation, matching within the Unit 1 of Sattler *et al.* (2016), which is equivalent to the Sequence A of Mitchum and Uliana (1985).

CORE STUDIES

In contrast with stratigraphically-isolated outcrop samples, core studies provide a continuous stratigraphic record of fine-grained successions, supporting the performance of high-resolution sedimentological analyses. A total core data of 412 m from 8 wells property of Pampa Energía S.A. and Vista Oil & Gas were carefully examined (Fig. 2).Primary rock attributes (e.g. texture, bedding, composition, physical sedimentary structures, bioturbation degree) were captured using a specific software designed for stratigraphic column description (LithoHero®, Iparraguirre *et al.* 2016). Nevertheless, the purpose of this study was to describe and illustrate different event beds within the Vaca Muerta mixed-system, trying to establish a genetic linkage between outcrop and subsurface fluid mud flow deposits (FMFd). Also, based on the seismic-stratigraphic framework developed by Sattler *et al.* (2016, Fig. 2), the authors have proposed to analyze FMFd occurrence within the Vaca Muerta mixed system, trying to establish their lateral facies changes at different system positions (shelf-slope-basin). For this purpose, when possible, the studied cores were projected into the seismic cross-sectionof Sattler *et al.* (2016). For those wells located distant from this transect, additionalseismic cross-sectionare presented (Fig2).

The studied cores are widely distributed across the lower Tithonian-lower Valangian mixed system, comprising a whole spectrum of facies from mainly shelfal areas (SE, Wells 3-8) towards inner basin positions (NW, Wells 1-2, Fig. 2). It must be clarified that the mention of proximal-distal system positions in this work does not refer to the cores position respect to the ancient coastline. Instead, this concept is employed to illustrate their relative position within the study area, being proximal cores those located towards the SE area (defined by Sattler *et al.* 2016) and distal the ones situated at the NW margin, whereas central ones are those comprised between the SE and NW areas (Fig. 2).

Core studied intervals

Most of the core intervals from the SE and central areas match within the basal transgressive deposits of the Vaca Muerta Formation, presenting a typical aggrading to low-angle prograding seismic stacking pattern. They are mainly comprised within the Unit 1 of Sattler *et al.* (2016), with the exception of Wells 3 and 5 cores, which also go through agradding to low-angle pograding clinoforms of the Unit 2. Particularly, Well 6 core spread to the basal contact of the Vaca Muerta Formation withthe underlying continental deposits of the Tordillo Formation. On the other hand, core intervals from the NW margin did not attempt to sample the basal transgressive sequence (Unit 1). Particularly, in Well 1 two different core intervals have been studied: a lower interval situated within bottomset segments of low angle clinoforms corresponding to the Unit 2 (Sattler *et al.* 2016), and an upper interval matching with an important transgression that defines the onset of the Unit 5, presenting a typical retrogradational seismic stacking pattern (Desjardins *et al.* 2016). Well 2 core is located in high-angle foresets of prograding sigmoidal clinoforms present at the B2-B3 interval of the Unit 4 (Marchal *et al.* 2016).

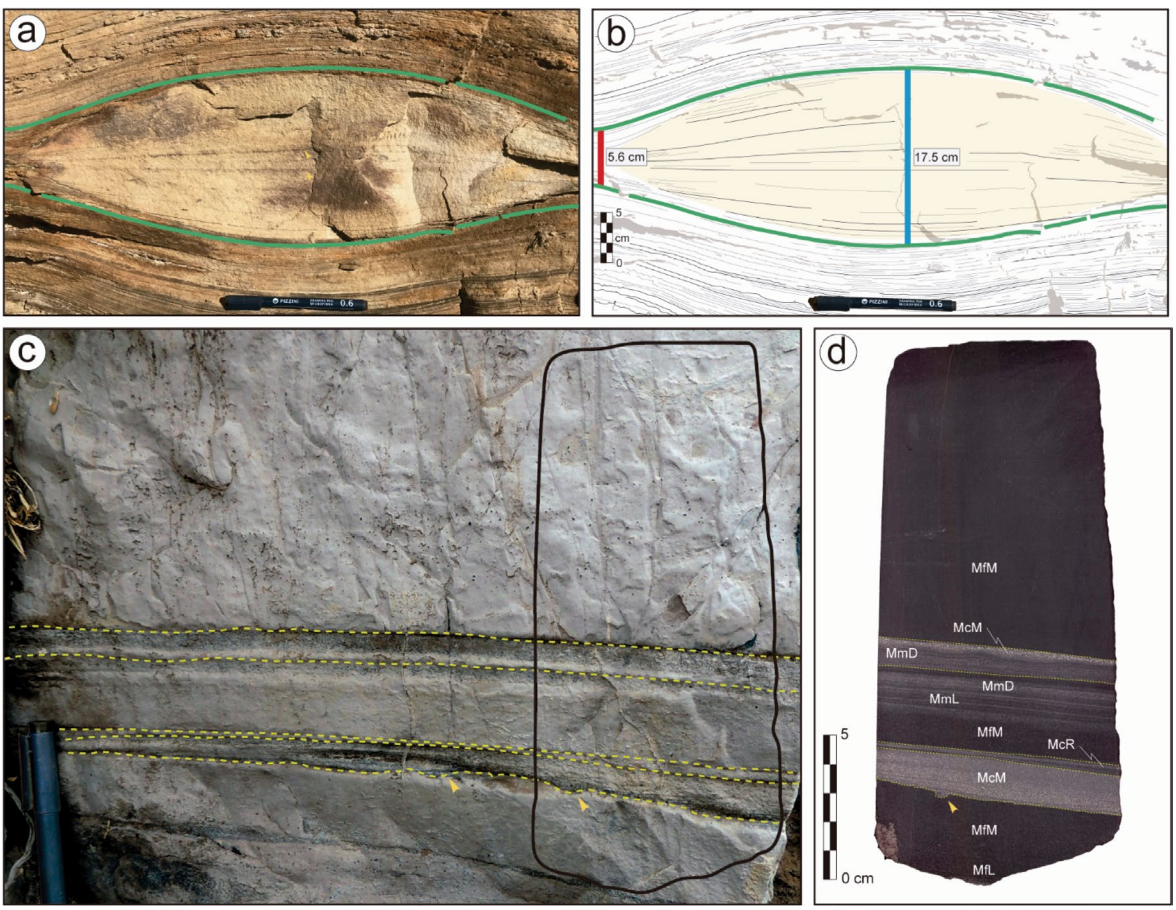

Figure 3. a) Example of an early-diagenetic calcareous concretion in the Vaca Muerta Formation. b) Line drawing of the concretion exhibited in a). Note the differential compaction between the sediments within the concretion and those adjacent to it (highly-compacted fissile mudstones). c)Early-diagenetic carbonate concretion with perfect preservation of the primary lamination. d)Scanned and digitally-processed cut and polished slab of the carbonate concretion exhibited in c.

RESULTS

OUTCROP STUDIES

Description

The sedimentological analysis of the Vaca Muerta Formation carbonate concretions has revealed the common occurrence of micro-erosional surfaces and low-angle lamina truncations within different mudstone beds (Fig. 4). These deposits are mainly composed of carbonate-cemented detrital mud (clay floccules and silt grains) with abundant plant remains and subordinated carbonate skeletal grains. The resulting beds, rarely thicker than 5 cm, are commonly characterized by a basal micro-erosional surface over which mud deposition occurs (Figs. 4a, f and g). At times, bed boundaries are defined by an orange-coloured oxidized pyritic interval (Figs. 4a, b and c). These pyrite concentrations can be helpful to identify bed limits when contacts among beds and internal lamination distinction becomes challenging due to the lack of textural or compositional changes.

A wide range of primary sedimentary structures have been recognized within the studied samples, including: 1) current mud ripples (McR, Figs. 4d, e, f, g and h), 2) planar, continuous to discontinuous parallel lamination with occasional low-angle lamina truncations (MfL, MmL, McL, Figs. 4e, f, g and h), 3) massive beds (MfM, Figs. 4e and f; McM, Figs. 4g and h) and 4) thin massive laminae with repeated transitional grain size variations (normal-inverse grading trends, Figs. 4g, h and 5a). Current mud ripples are similar to those originally described in laboratory flumes (Schieber *et al.* 2007). They are characterized by downlapping foresets that can be either composed of coarse silt grains (Figs. 4d, e and f) or clay floccules that act hydrodynamically as very fine-grained sand (floccule ripples, Figs. 4g and h). The foresets are commonly downlapping onto a sharp, scoured surface (Fig. 4g) and they may overlay parallel-laminated mudstones (McL, Figs. 4d, e and f). Upwards, mud ripples are replaced by massive fine to medium-grained mudstones that towards the top of the bed turn into organic-rich, bituminous mudstones.

Additionally, post-depositional sedimentary structures are common features of the studied mud deposits. These include shallow depth soft-sediment deformation structures developed in soup-like muddy bottoms (flame and convolute lamination, Figs. 2d and f) and flute marks (Figs. 3a and b) related to deeper, cohesive and strength-firm muddy substrates (Dzulynski and Sanders 1962, Allen 1969). No signatures of biological sedimentary structures have been recognized within the concretions (burrows, tracks and trails are absent).

Interpretation

The afore mentioned sedimentary features have an important sedimentary sense in terms of mud depositional processes in inner basin environments. Micro-erosional surfaces within different

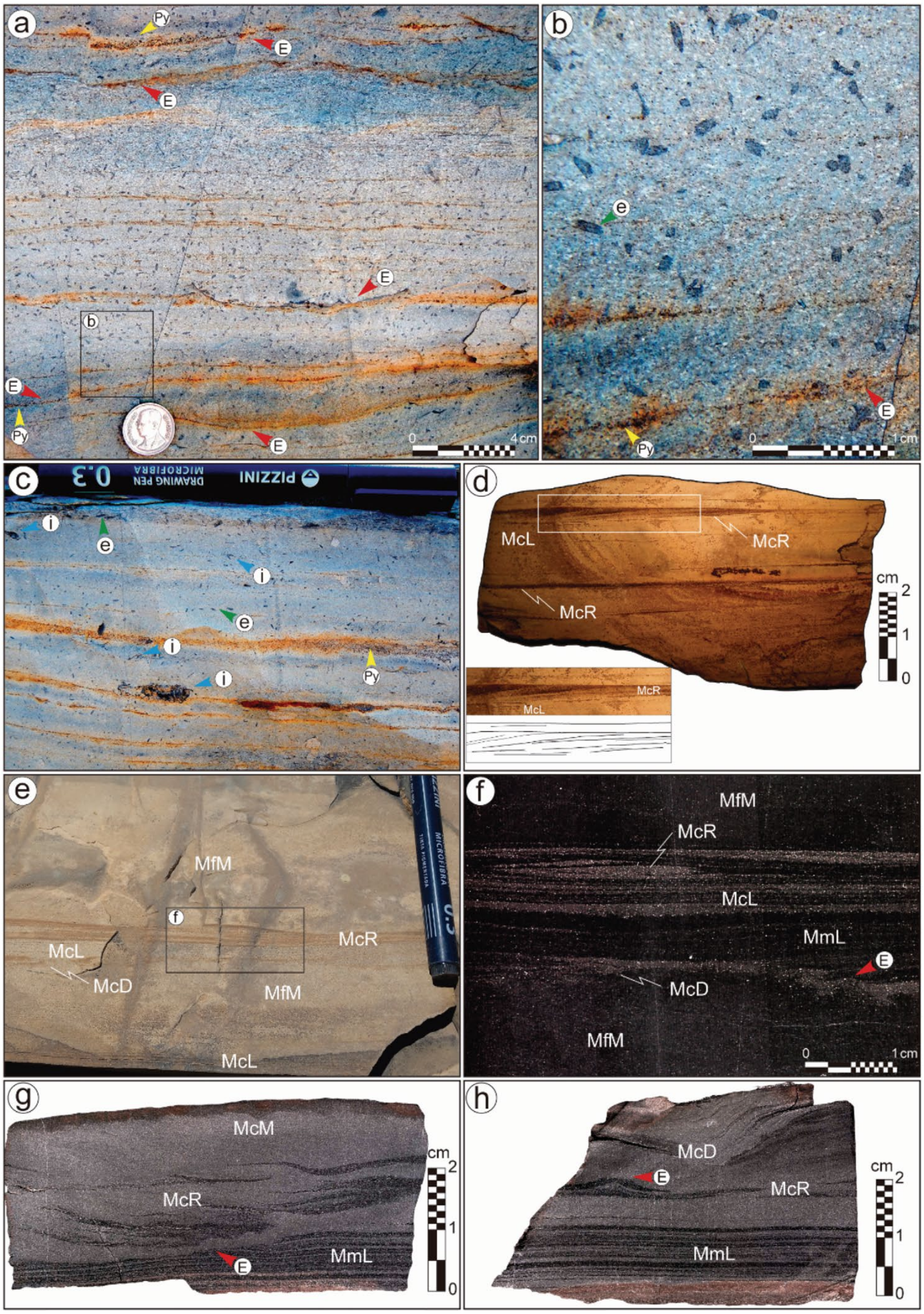

Figure 4. Primary sedimentary features in carbonate concretions. a) Mudstone beds displaying a basal micro-erosional surface (red arrows, E). Boundary between beds are defined by an oxidized pyritic interval (yellow arrows, Py). Internally, beds are massive and parallel-laminated.b) Close up of figure a). Appreciate the abundance of plant debris (e). c) Mudstone beds separated by erosional surfaces with associated pyritic intervals. In this case, plant debris (e, extrabasinal components) are found together with fossiliferous skeletal grains(i, intrabasinal components). d) Mud ripples in coarse mudstones (McR). Ripples are interbedded with laminated coarse mudstones (McL). e, f) Outcrop (e) and cut and polished slab (f) of a carbonate concretion. Note the presence of soft-sediment deformation structures (McD) under erosional surfaces (E). Parallel-laminated facies (MmL, McL) and mud ripples (McR) are developed above the erosional surface. g, h) Samples from a same carbonate-cemented bed. Note how the erosional surface exhibited in g is absent in h, where a sharp contact is present. Also, in figure h, mud ripples crest is truncated (E), what suggest the occurrence of subtle erosion. This erosional episode is not recorded in figure g, where mud ripples (McR) grade upwards to massive coarse mudstones (McM).

mudstone beds suggest the occurrence of high-energy events capable of eroding substantial quantities of mud from the basin floor. These events are interpreted as bottom fluid mud flows transporting fine-grained clastics, minor carbonate skeletal grains and particulate organic matter in fully turbulent conditions.

Fluid mud flows are basically low-density muddy turbidity currents which, according to the flow velocity and the sediment concentration, can have a variable erosion capacity (Fig. 4). The erosion magnitude of each fluid mud flow event can be estimated by the recognition of firm/soupy substrate conditions at bed boundaries (flute marks vs soft-sediment deformation structures). It is generally accepted that mud erodibility is essentially controlled by its water content, being easier to erode soft-soupy muds than firm ones (Potter *et al.* 1980).Particularly, flute marks suggest a flow separation under severe velocity conditions at a place where the seafloor presents geomorphological irregularities, creating powerful eddies capable of eroding the cohesive muddy seafloor (Allen 1969). According to this, the presence of a firm substrate could be related to an erosional event produced by the overpassing of a rapid flow capable of completely removing the topmost soupy mud from the bottom, incorporating the eroded material to its sedimentary load (Fig. 5a,Otharán *et al.* 2017a). Furthermore, pyrite concentrations at bed boundaries (Figs. 4a, b and c) could be associated to the erosion of substantial quantities of mud by bottom fluid mud flows (Schieber 1998, Schieber and Baird 2001).

On the other hand, the preservation of soft-sediment deformation structures underneath an erosional surface (McD, Figs. 4e and f) suggests an overpassing flow with lower erosion capacity, enabling a partial preservation of the uppermost soupy mud. As remarked by Sanders (1965), when the seafloor is cohesive but hydroplastic instead of being firm, the passage of a turbulent flow may cause a deformation of the bed over which the current passes, creating soft-sediment deformation structures. Flume experiments developed by Einsele *et al.* (1974) have demonstrated that plastic muds with 70 % porosity required current velocities of 150 cm/s to produce soft-sediment deformation structures due to current drag on the sediment surface (Schieber 1998).

The primary sedimentary structures recognized in the analyzed fluid mud flow deposits (FMFd) are related to fluctuations in the flow velocity, turbulence and sediment concentration. Depending on the sedimentfallout rate,theresulting mud deposits can exhibit quite different stacking patterns. High fallout rates promote a rapid accumulation of the suspended load, resulting massive mudstone beds. On the other hand, low rates of sediment fallout are going to produce parallel-laminated (medium fallout rate) and rippled (low fallout rate) deposits.Particularly, rippled-mudstone deposits suggest some bedload transport of the coarsest materials that are progressivelyfalling out of the suspension cloud.Otherwise, the common occurrence of massive deposits above the rippled-faciescould represent a rapid accumulation of the suspended load as the flow velocity decreases. The organic-rich finest-grained facies located at the top of each bed could be related to the progressive waning and extinction of the flow. The organic matter perfect

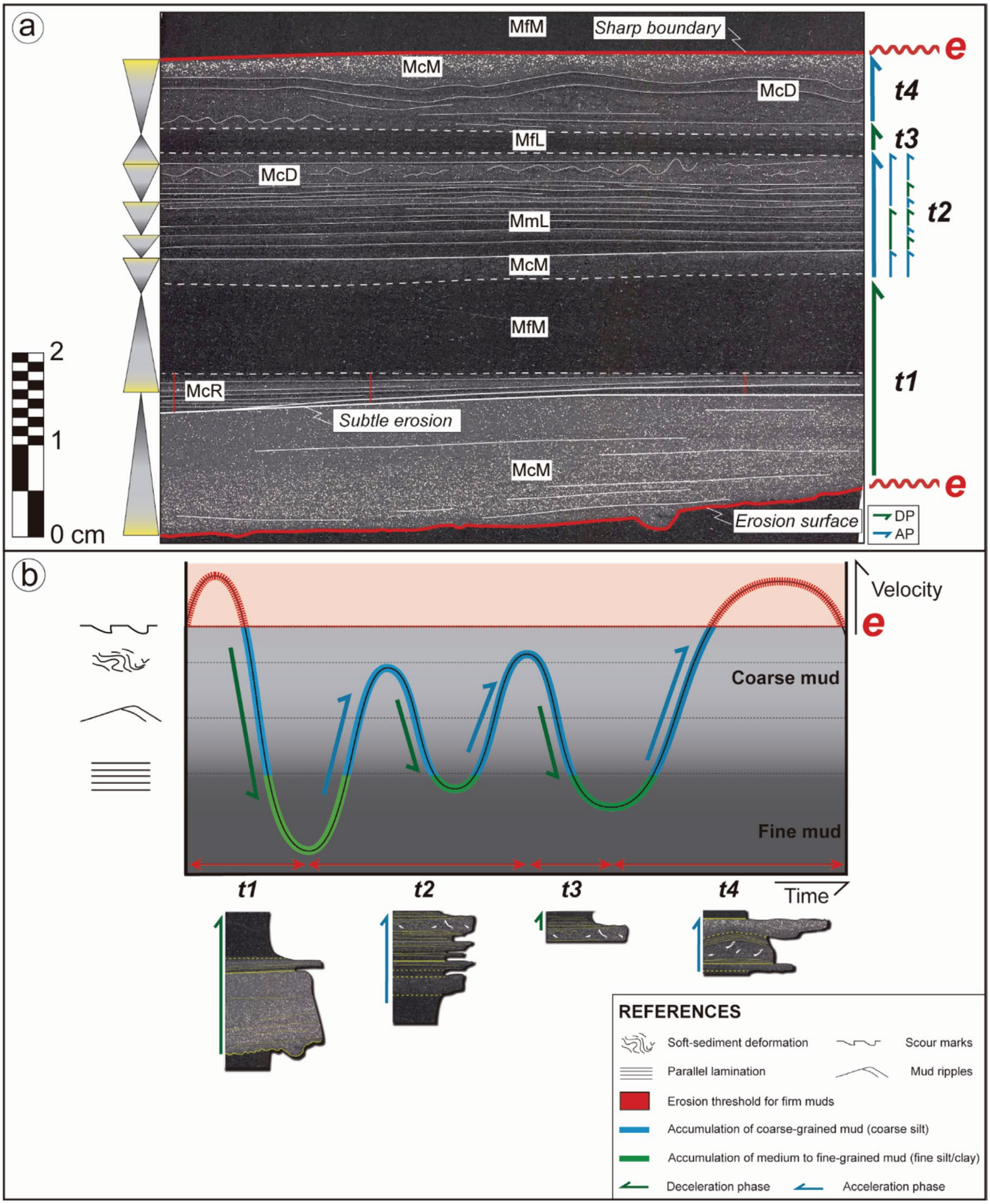

Figure 5. a) Close up of the sample shown in Figure 3d. This sample is characterized by repeated fining-coarsening upwards trends at lamina scale, which represents flow fluctuations (acceleration-deceleration phases) in a long-lasting fluid mud flow event. b) Flow fluctuations can be a possible explanation for the origin of the bed shown in a). The graphic shows the relationship between the flow velocity and the duration time (t1-t4) of a long-lasting fluid mud flow event. The resultant sedimentary structuresand grain-size variations recorded in mudstone strata are believed to occur in response to flow fluctuations.

preservation added to the absence of bioturbation in these deposits suggest either arapid burial or a sub-environment with anoxic to sub-toxic bottom water conditions.

Another distinctive characteristic of the analyzed FMFd is the presence of thin massive laminae with repeated fining-coarsening upward trends (Fig. 5a). These grain size variations are related to quasi-steady fluid mud suspensions with common flow velocity fluctuations (acceleration-deceleration phases). Therefore, during the acceleration phase the coarsest materials would be settling out from suspension (when the flow velocity is under muderosion threshold) whereas the finest grained sediments would remain in transport (Fig. 5b). However, at the flow velocity peak stage the current can exceed the threshold velocity for mud erosion, creating internal lamina truncations and micro-erosional surfaces (Figs. 4f and h). After the peak stage, the decrease of the flow velocity favors a progressive accumulation of fine-grained mud (Fig. 5b).

Origin of fluid mud flows

According to Macquaker *et al.* (2010), the source of energy for the ignition of fluid mud flows in marine basins can be provided by waves, currents, gravity processes or by an interaction of any of these mechanisms. Particularly, sediment gravity flows can be important delivery mechanisms for the basinward transfer of mud. These include muddy hyperpycnal flows (extrabasinal muddy turbidity currents, Zavala and Arcuri 2016) and intrabasinal surge-type muddy turbidity currents similar to the “unifites” described by Blanpied and Stanley (1981) and the turbiditic mud layers of Rupke and Stanley (1974). Likewise, combined flows such as storm events (tempestites) and wave-enhanced sediment gravity flows (WESGFs, Macquaker *et al.* 2010) can be significant mud redistribution mechanisms.

The recognized flow fluctuations (Fig5) are interpreted as the result of direct river discharges during important flood events (Otharán *et al.* 2017a, Fig6). Each flood event would be capable of generating quasi-steady muddy hyperpycnal flows that may be sustained for days, weeks, or even months (Mulder *et al.* 2003, Zavala *et al.* 2006, 2011, 2014, Nakajima 2006, Soyinka and Slatt 2008, Bhattacharya and MacEachern 2009, Chang and Chun 2012, Wilson and Schieber 2014, 2015, Zavala and Arcuri 2016, Azpiroz-Zabala *et al.* 2017). These long-lasting events would be able to transfer significant volumes of plant debris and fine-grained sediments for long distances towards distal basinal settings (Nakajima 2006, Soyinka and Slatt 2008, Bhattacharya and MacEachern 2009, Abouelresh and Slatt 2011, Slatt 2011, Wilson and Schieber 2014, 2015, Li *et al.* 2015, Schieber 2016, Zavala and Arcuri 2016, Poyatos-Moré *et al.* 2016).

As previously discussed, flow fluctuations can produce normal to inverse-graded deposits (Fig. 5a) as well as low-angle lamina truncations, scour marks and subtle erosional surfaces within a single hyperpycnal deposit (Figs. 4e, f, g and h). Such erosional features are the signature of the flood peak stage, where the waxing flow have already exceeded the threshold velocity for mud erosion (Fig. 5b). Occasionally, the flow can completely erode the initial hyperpycnal deposit, leading out to an incomplete record of the hyperpycnal event (Figs. 4g and h). The last could result in a normally-graded bed accumulated over an erosional surface once the flow velocity started to decrease (deceleration phase, Zavala *et al.* 2006). In these situations, the differentiation between muddy hyperpycnites and typical normally-graded deposits such as mud turbidites and tempestites becomes challenging (Mulder and Alexander 2001, Mulder *et al.* 2003, Bhattacharya and MacEachern 2009, Wilson and Schieber 2014, Schieber 2016).

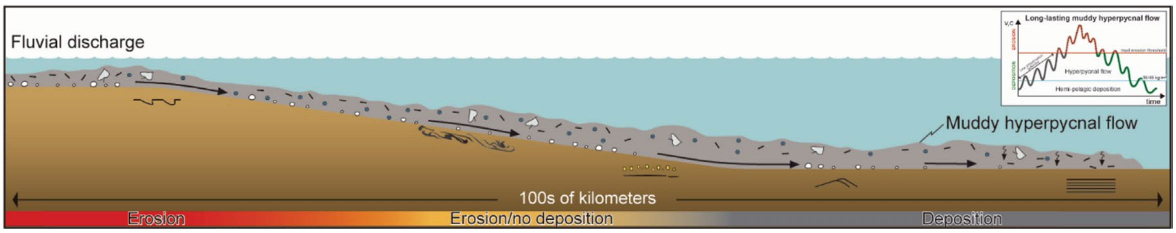

Figure 6. Long-lasting muddy hyperpycnal flows associated to important river flood events. Sustained river discharges allow these flows to travel along very low-gradient reliefs, incorporating intrabasinal materials into their original extrabasinal sedimentary load.

The erosion capacity of muddy hyperpycnal flows enables the incorporation of intrabasinal components (e.g. carbonate mud, microfossils and skeletal grains, type II organic matter) to the primary extrabasinal sedimentary load (e.g. detrital mud, plant debris). For this reason, another diagnostic criterion for a hyperpycnal origin of fluid mud flows is the bed composition, characterized by compositionally mixed (siliciclastic-carbonate) deposits exhibiting both autochthonous (type II) and allochthonous (type III) organic matter content. This was recently proved in organic-rich muddy sediment cores recovered from the distal part of the Ogooue turbidite system (Biscara *et al.* 2011, Mignard *et al.* 2017) as well as in the Congo mud-rich deep-sea turbidite system (Baudin *et al.* 2010, 2017a, b, Stetten *et al.* 2015), where muddy hyperpycnal deposits contain mixtures of marine and terrigenous organic matter. Therefore, the passage of hyperpycnal flows through shelf/ramp environments would have favored the erosion and incorporation of intrabasinal components to the former extrabasinal sedimentary load.

In contrast with intrabasinal fluid mud flows, muddy hyperpycnal flows would be able to go through very low gradient reliefs, since the flow power is provided by sustained river discharges (Fig. 6). This could explainwhy the studiedmuddy hyperpycnitesare associated to the Vaca Muerta Formation basal deposits accumulated in a low gradient mixed-ramp system (Fig. 2).

CORE STUDIES

The studied core intervals display different types of mudstone beds alternating with tuffaceous intervals, bedding parallel fibrous veins (beefs) and carbonate cemented beds (Figs. 7 and 8).

Occasionally, bindstones can be present, displaying a characteristic biogenic lamination. In the NW area, fine-grained organic-richmudstoneswith abundant filament bivalves and ammonite fauna predominate, including also thick beef veinsand early-diagenetic carbonate concretions(Fig. 7). On the other hand, central areas are characterized by fine-to coarse-grained fossiliferous and calcareousmudstones withlesser beef intervals (Fig. 8). Particularly, the SE area isrepresented by highly bioturbated fine-grained carbonates and calcareous mudstones in the Well 5, where as in Wells 6-8 fine-to coarse grained dolomitized mudstones dominate. It must be remarked that tuff levels and beefs are significantly reduced from the NWto the SE area, where they occurrence is really scarce. Bioturbation degree can be significant within tuffaceous deposits, which also exhibit an important diagenetic overprint characterized by sparite cement precipitation.

Subsurface cores commonly exhibit subtle micro-erosional surfaces within distinct mudstone beds (Fig. 8), which is directly linked to fluid mud flow events. These fluid mud flow deposits (FMFd) can be stratigraphically isolated within background sedimentation (e.g. hemi-pelagic mudstones and tuffs, biogenic carbonates) or they may define a full interval dominated by fluid mud flow deposition (Fig. 8).

FMFd description

FMFd in the analyzed cores of the Vaca Muerta Formation are primarily detectable by erosive bed contacts in proximal-central system positions (Figs. 9a, b and c), whereas in distal settings their recognition is more challenging, being only manifested by mm-thick sulfate-rich (pyrite/sphalerite) intervals defining sharp mudstone contacts (Figs. 9d and e). Beds can reach at most 4 cm in thickness. They are commonly characterized by a mixture of extrabasinal and intrabasinal components (Fig. 9f).

FMFd are essentially mixed (siliciclastic-calcareous) mudstones having variable carbonate content according to theirposition within the system. Beds are commonly normally graded, exhibiting medium-to coarse-grained calcareous mud above the basal scoured surface (Figs. 9a, b, c and d).At times, the carbonate fraction is present as skeletal grains (e.g. microfossils, Figs. 9b and c) while in others instances it may be only manifested as coarse-grained calcareous mud (Figs. 7, 8 and 9d). Flute marks and soft-sediment deformation structures can be commonly associated to FMFd bounding surfaces (Figs. 9a, c, d and e). Alternatively, these beds can also exhibit a basal concentration of calcitizied/argillizied tuffaceous coarse-grained mud (Fig. 9a) or a pyritic concentration above beds boundary. Normally, organic-rich fine-grained deposits are displayed towards the top of each FMF bed.

Internally, FMFd can be either massive, parallel-laminated or normal/inverse-graded (Fig. 9). As an exception, Well 2 core interval is characterized by parallel-laminated fine-to coarse-grained mudstones with common low-angle lamina truncations and sin-sedimentary deformational sedimentary structures (micro-slumps, Fig. 10). Bioturbation is generally absent within FMFd.

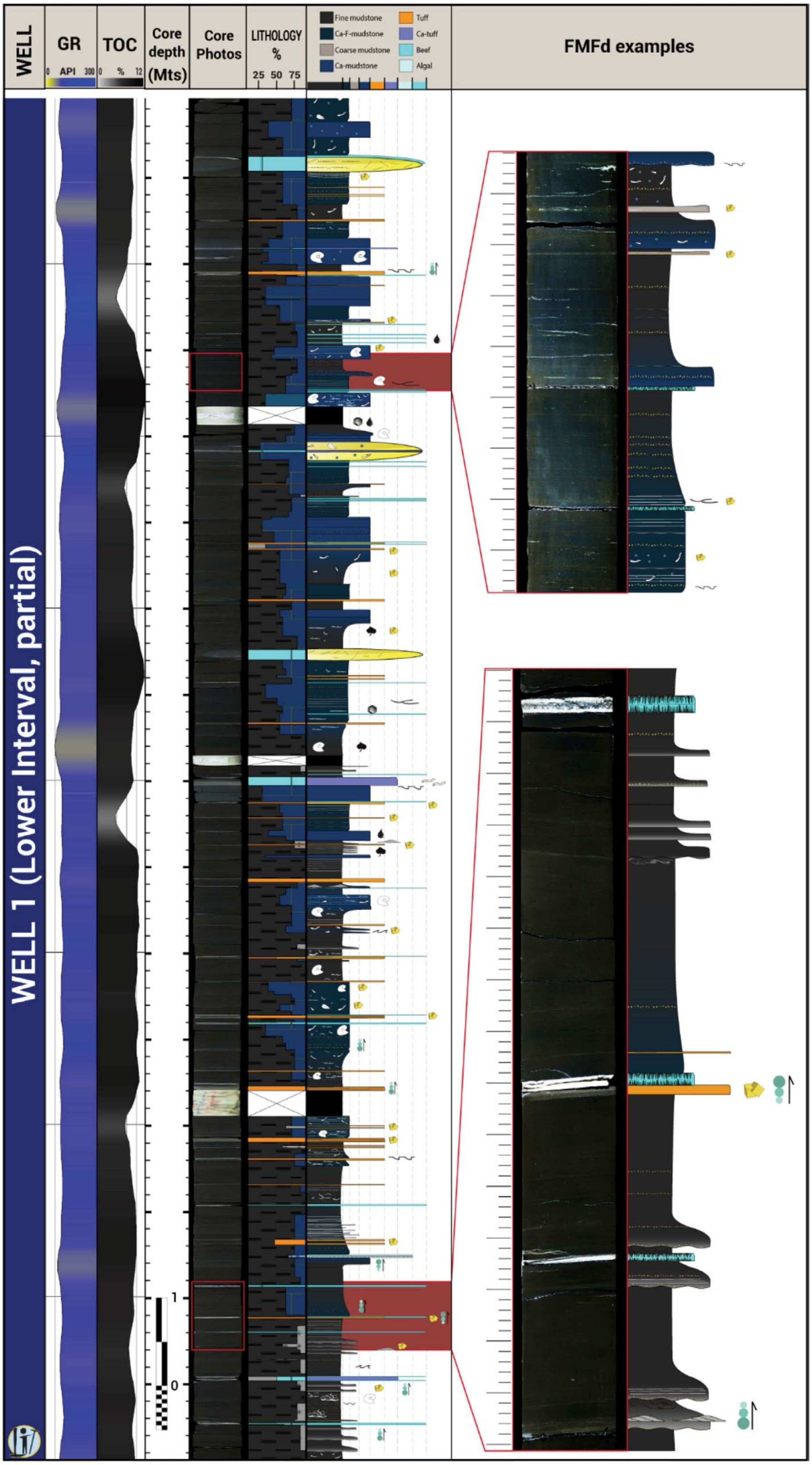

Figure 7. Partial stratigraphic column for the Well 1lower core interval (A-A', Fig. 2; Unit 2).

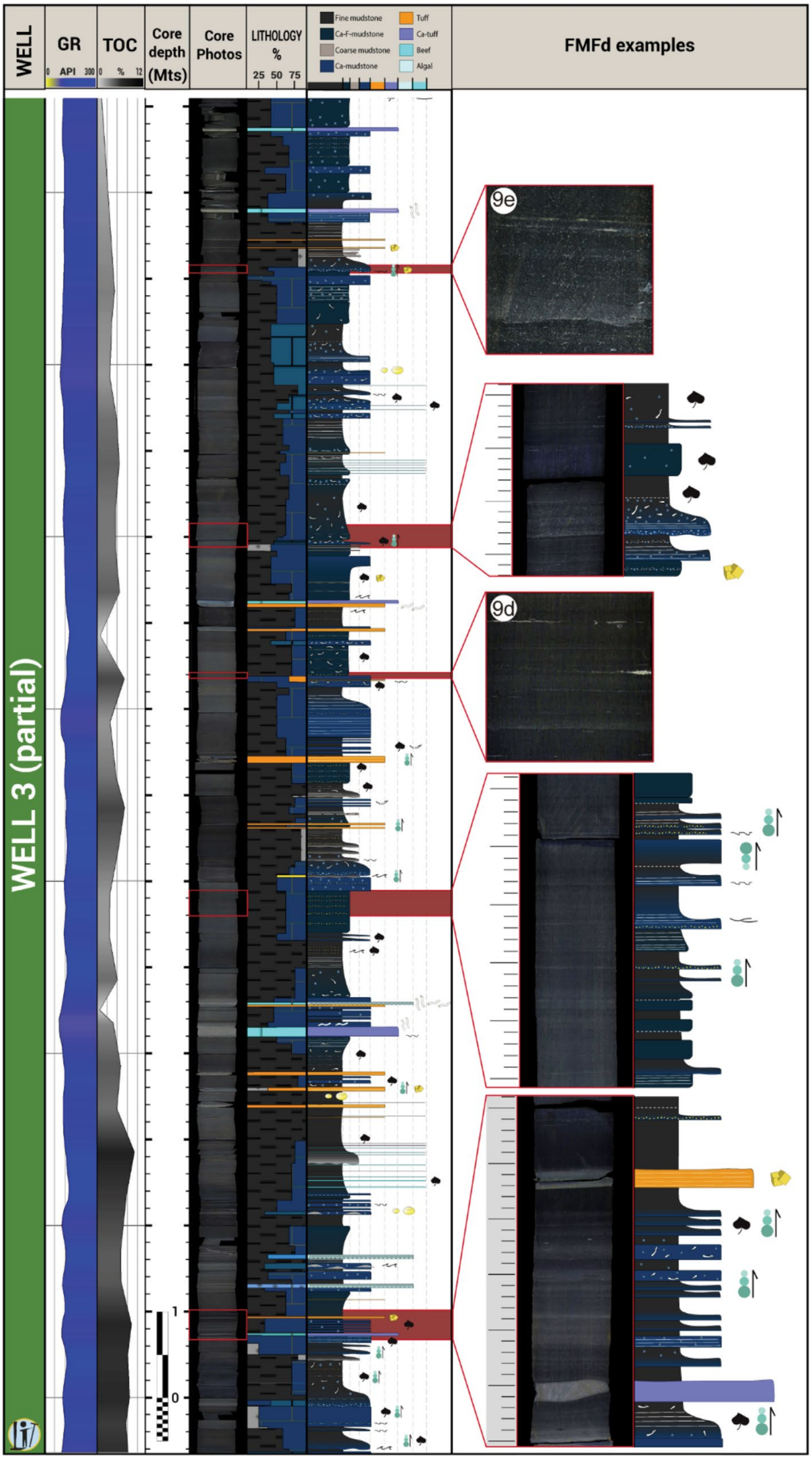

Figure 8. Partial stratigraphic column for the Well 3 core interval (B-B', Fig. 2; Unit 1).

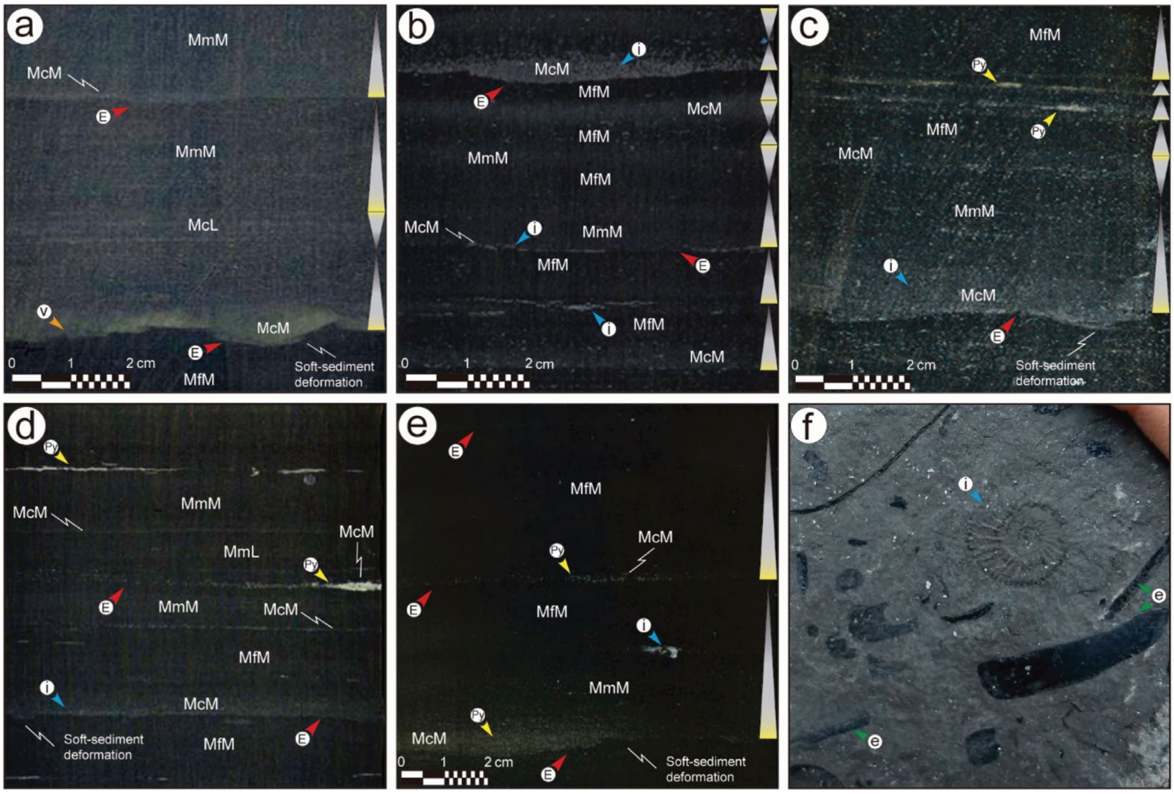

Figure 9. Examples of FMFd from Wells 3 (a-d and f, central area) and 1 (e, NW area). Well 3 examples correspond to the Unit 1 of Sattler *et al.* (2016). a)Massive (McM, MmM) to diffusely laminated (McL) mudstone beds. The lower bed is characterized by a basal tuffaceous mud (V, orange arrows). Soft-sediment deformation structures are associated to bed boundaries (E). b) FMFd with clear flow fluctuations (normal-inverse grading trends). Beds limits (E) are defined by intrabasinal calcareous mud (i) mainly composed of skeletal grains and microfossils (Fig. 7). c) FMFd with high content of intrabasinal materials (carbonate grains, i). Towards the top, pyrite concentrations define beds boundaries (Py, yellow arrows). d) FMFd characterized by normally-graded beds over a basal erosional/sharp contact. Pyrite concentrations are associated to erosional boundaries. e) FMFd from the NW area. Bed boundaries are defined by pyrite intervals and occasionally soft-sediment deformation structures. f)FMFd displaying a mixture of intrabasinal (i) and extrabasinal (e) components.

ORIGIN OF FMFD

Grain size variations within single FMF beds (Figs. 8, 9a, 9b and 9c) are interpreted as the result of flow fluctuations during long lasting muddy hyperpycnal events (Fig. 6). In the FMFd examples exhibited in Figure 8, the interlamination between silt and clay size calcareous mud is interpreted as simultaneous deposition from a unique, long lasting hyperpycnal event. This interpretation is also supported by the mixed composition of these beds, which are integrated by both extrabasinal and intrabasinal elements (Fig. 9e).Regarding the relative light weight of carbonate components, they commonly constitute the coarsest-grained fraction of some muddy hyperpycnites (Figs. 9b, c and d). Recent flume experiments developed with carbonate mud demonstrated that, in spite of the contrasting mineralogy, mud carbonate present a similar hydrodynamic behavior as siliciclastic mud (Schieber *et al.* 2013). Other FMF beds exhibit a basal coarse-grained tuffaceous mud deposit over bed boundaries, which is upwards transitionally replaced by mediumto fine-grained detrital mud (Fig. 9a). The occurrence of both carbonate and tuffaceous materials towards the base of FMFd could be explained by the erosional nature of muddy hyperpycnal flows. During their travel basinward, muddy hyperpycnal flows would be able to erode and incorporate any available type of unconsolidated fine-grained materials laying at the seafloorinto theirprimary extrabasinal sedimentary load. This could be the case of thin levels of volcanic ash materials originally settled out through the water column during the course of volcanic eruptions.

The same assumption can be made for the organic matter content of muddy hyperpycnites, which can be characterized by both intrabasinal (type II) and extrabasinal (type III) organic matter content. TOC in FMFd within the studied wells are generally over 2 %, reaching in some instances more than 10 % TOC in inner basin areas (Fig. 7). The presence of the highest TOC contents in distal system positions is related to the organic matter sequestration from the main production area (shelfal environments) by fluid mud flows, accumulating it far off-shore in terminal turbiditic muddy lobe-complexes (accumulation zone).

However, as mentioned before, when FMFd are characterized by normally-graded beds accumulated over an erosional surface, the distinction between muddy hyperpycnites and other type of fluid mud flows deposits becomes challenging (Mulder and Alexander 2001, Mulder *et al.* 2003, Bhattacharya and MacEachern 2009, Wilson and Schieber 2014, Schieber 2016). In these situations where FMFd internal stacking pattern is not distinctive of any flow type, complementary studies are needed to accurate the deposit origin (e.g. petrography, SEM, palynology, geochemistry).

Besides hyperpycnal flow events, basinward mud transportation could be possible by surge-type muddy turbidity currents developed close to the shelf-break (Fig. 11). Unfortunately, the only studied core interval that match within well-defined foresets of high-angle prograding clinoforms is the Well 2 core (Fig. 2), where syn-depositional deformational structures are clearly recognizable (Fig. 10). Deposits associated to intrabasinal sediment gravity flow processes are well known within high angle slope settings of the Vaca Muerta mixed system (Arregui 2014, Pose *et al.* 2014, Otharán *et al.* 2017b, Reijenstein *et al.* 2017).

Flume experiments performed by Gerber *et al.* (2008) proposed that intrabasinal fluid mud flows could be responsible for the origin and progradation of clinoform morphologies. This autocyclic mechanism for clinoform growth and evolution by slope-flow feedback could give a possible explanation for the origin of the Vaca Muerta Formation prograding clinoforms. If this hypothesis is valid and muddy turbidites are the primary building blocks of Vaca Muerta clinoforms, then distinct stratal patterns should be recognizable in the fine-scale stratigraphic architecture. Future integrated sedimentological and seismic-stratigraphic analyses focused on the foresets segments of the Vaca Muerta Formation clinoforms are going to provide enough evidence to answer these remaining questions aboutclinoform origin.

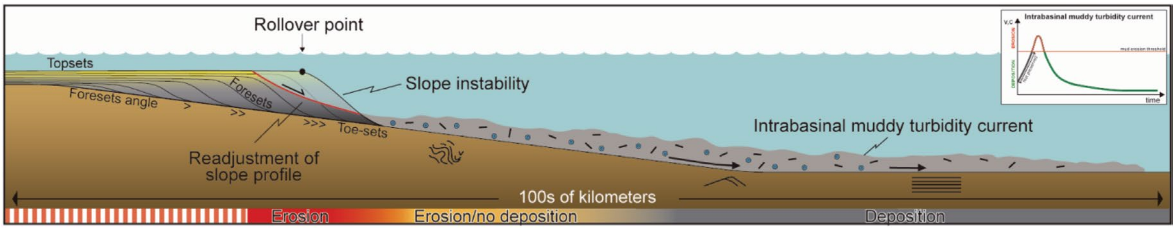

Figure 11. Intrabasinal muddy-turbidity currents associated to slope instabilitiescaused by the progressive clinoform growth and consequent foresets angle increase. In contrast with muddy hyperpycnal flows, intrabasinal muddy turbidity currents need the presence of high-gradient systems with a well-defined shelf-break configuration.

DISCUSSION AND CONCLUSION

The accumulation of organic-rich mudstones was historically associated to low energy depositional environments with anoxic bottom waters, where mudstone deposition was mainly related to gradual and continuous fallout of mud from dilute buoyant plumes (Pettijohn 1975, O´Brein and Slatt 1990, Boggs 2001, Potter *et al.* 2005). Based on this, basin inner zones were considered as unsuitable environments for source rock deposition due to the generally low concentrations of organic matter resulting from both low inputs and production, adding an intense organic matter degradation during its transit time through the large water column (Arthur *et al.* 1984, Stow *et al.* 2001).

This study documents the participation of fluid mud flows in the accumulation of Vaca Muerta organic-rich shales in different system positions. The origin of fluid mud flows can be either related to hyperpycnal river discharges (Fig. 6) or intrabasinal surge-type sediment gravity flows developed close to the shelf-break (Fig. 11). Distinguishing between extrabasinal (hyperpycnal) and intrabasinal (surge-type) muddy turbidites can be important since the organic matter content of these FMFd seem to be different. In agreement with Reijenstein *et al.* (2017) and Notta *et al.* (2017), the studied intrabasinal FMFd within the Vaca Muerta Formation are relativelydepleted in TOC content, at least in the foresets segments of high-angle clinoforms. On the other hand, muddy hyperpycnites are generally associated to high TOC content (Figs. 7 and 8). However, muddy hyperpycnites have been recently documented within different organic-rich mudstones (Abouelresh and Slatt 2011, Wilson and Schieber 2014, 2015) as well as in organic lean mudstones (Soyinka and Slatt 2008, Bhattacharya and MacEachern 2009). These discrepancies in the TOC content of ancient muddy hyperpycnites caused a great confusion about the hydrocarbon potential of hyperpycnal deposits.

Nevertheless, recent oceanographic campaigns in deep-marine turbidite systems have demonstrated that hyperpycnal flows are really efficient in the accumulation and rapid burial of organic-rich sediments (Baudin *et al.* 2010, 2017a, b, Biscara *et al.* 2011, Stetten *et al.* 2015, Mignard *et al.* 2017). Thus, the rapid and direct basinward transfer of organic matter by hyperpycnal flows would have avoided its dilution and degradation in shallow marine environments. Finally, the arrival of extinguishing hyperpycnal flows to the basin inner zones would have provided a fast deposition and burial of high quantities oforganic matter in terminal turbiditic muddy lobe complexes, favoring its preservation (Fig. 12).

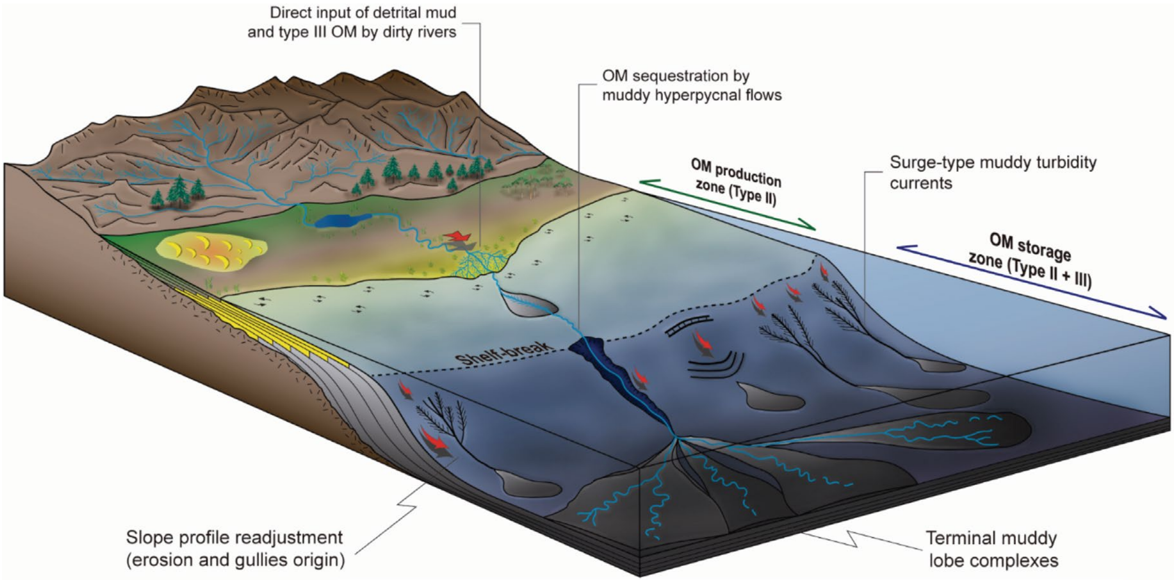

Figure 12. Block diagram illustrating the origin of intrabasinal (surge-type) and extrabasinal (hyperpycnal) fluid mud flows. Particularly, muddy hyperpycnal flows are believed to play an important role in the transference of organic matter from the production zone towards inner basin areas, where it is efficient buried and preserved in organic-rich muddy lobe complexes (storage zone). OM: organic matter.

Muddy hyperpycnal flows should be further considered for the exploration of Vaca Muerta and other unconventional resource shales, since they constitute a major pathway for organic matter transferfrom the main production area (shelf/ramp environments) towards the storage zone (basinal settings). This mud transport mechanism could explain why the highest TOC contents are commonly found in unsuitable environments for organic matter production. The future understanding of the complexity of fluid mud flows internal stacking pattern will be crucial to identify long-term exploitable organic rich levels.

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