AAPG Search and Discovery Article #90007©2002 AAPG Annual Meeting, Houston, Texas, March 1-13, 2002

GIORGIO BASILICI, Instituto de Geociências, Universidade Estadual de Campinas, Campinas, SP, BR.
E-mail: basilici@ige.unicamp.br

From Sand to Sand-Mud Deep-Water Ramp: The Apiúna Unit (Early Cambrian, South Brazil)

Abstract

Analogous outcrops allow to investigate on type, genesis and development of reservoirs. That is of primary importance for the petrophysical characteristics and to investigate on the general architecture of the reservoirs. Outcrop data come from an early Cambrian siliciclastic succession of deep-water deposits, (Apiúna, Santa Catarina, Brazil), about 200 m thick and 300 m wide.

From the bottom to the top, four informal depositional units (A-D) have been recognized. The unit A is made up by muddy fall-out and slumping sediments. The unit B is formed by sheet-like, sandstone bodies, alternated with muddy deposits, deposited by concentrated density flow and surge-like turbidity flow. Amalgamated sandstone strata, deposited by hyperconcentrated and concentrated density flows (analogous of debris flow *s.l.* of other authors), make up the unit C. The unit D is characterized by gravelly sandstone or gravelly muddy, produced by hyperconcentrated density flows and debris flows respectively. These are covered by lenticular sandstone strata, produced by concentrated or surge-like density flows, alternated with muddy strata.

The succession records a system evolution from low inclined slope conditions (unit A), to a prograding distal to proximal ramp system (unit B and C, respectively), characterized by non-channelized sandy sheet bodies, multisource and intermittent sandy input. The last phase (unit D) represents a radical variation of the depositional system; it is interpreted as progressive filling of a channellized structure, laterally migrating and vertically replaced by levee deposits. This transformation could be caused by grain size decreasing of the clastic input, modifying the ramp system from sand-rich to sand-mud mixed.

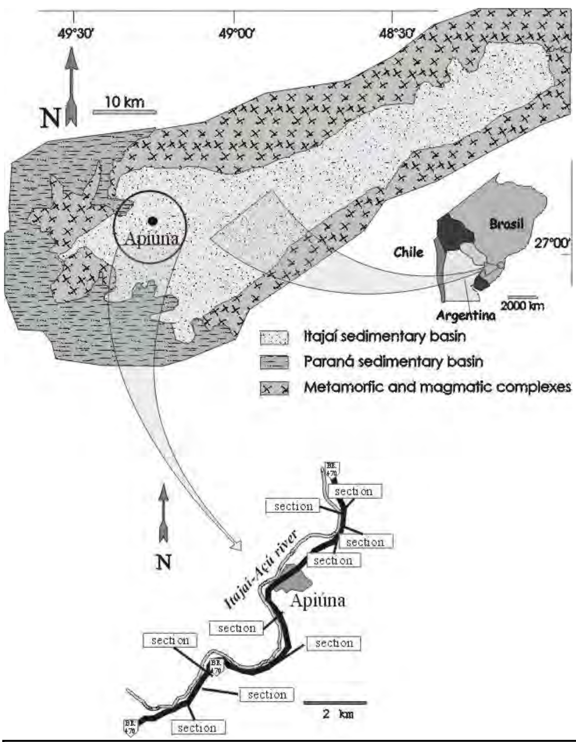

Fig. 1. Map and geological sketch of the study area.

Introduction

Although to study outcrops to reconstruct the geometrical characteristics of the reservoirs is not an exhaustive process (Paola et al., 2001), undoubtedly the outcrop analyses permit to have a direct idea of petrophysical features, internal and external geometry, and architecture of reservoirs. Obviously the outcrop conditions and the reduced scale respect an oil field restrict much the direct relation with the petroleum industry, but it has to

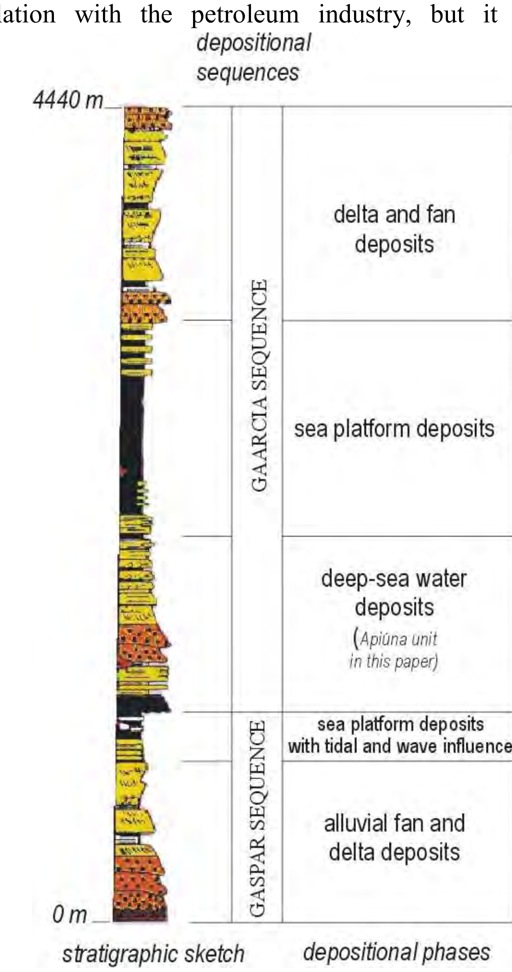

Fig. 2. Stratigraphic sketch of the Itajaí basin succession. Modified from Rostirolla and Figueira (1995).

remember that the main reservoir models, used in hydrocarbon research, came from the outcrop studies and, as Shanmugam (2000) sustains, the study of depositional mechanisms from outcrops is an fundamental premise to build a reasonable stratigraphic model and it is determinant to define the distribution of reservoir and non-reservoir bodies. The cited author considers an unhealthy trend of the petroleum industry and of the some academic structures whose pay attention to the great scale structure without examine the depositional processes.

The main objective of this work is to describe the geometrical and architectural characteristics of reservoirs in a deep-water ramp depositional system from outcrop data.

The Apiúna unit is part of the Itajaí basin, near Blumenau City (Santa Catarina State, Southern Brazil; Fig. 1). This basin is 90 km long in NE-SW direction and 20 km wide in perpendicular direction (Fig. 1). The sedimentary succession is about 4440 m thick; recent works (Rostirolla et al., 1992; Rostirolla et al., 1995) interpret this basin as foreland and recognize two principal depositional sequences (Gaspar and Garcia sequences, Fig. 2). The Gaspar sequence is divided into two sedimentary phases, corresponding to alluvial fan-delta and sea platform deposits. The transition to the Garcia sequence is abruptly indicated by sandstone deep-water deposits; this third sedimentary phase, known as Apiuna unit, is the object of this work. The deep-water deposits are covered by argillite, that have been interpreted as sea platform deposits. The last sedimentary phase is represented by delta and fan systems. Radiometric data and paleontological considerations attribute all the sedimentary succession to the early Cambrian (Macedo et al., 1984).

The Apiuna unit is almost 1000 m thick with sandstone, argillite and conglomerate siliciclastic deposits. Rostirolla et al. (1995) interpret the Apiuna unit as a system of deep-water canyon-fed fan, recognizing channel, lobe, channel-lobe transition, margin of lobe, pelite of basin and slumping deposits. It will try to demonstrate that this model is too simple and it leads to an uncorrected vision of the reservoir distribution.

Depositional mechanism and process reconstruction

A stratigraphic interval of 209 m, on an estimated total thickness of the Apiúna unit of 1000 m, has been studied with very detail (the facies analysis has interested strata with a thickness of less than 3 cm). The stratigraphic sections are made up of sandstone and argillite, and minor quantities of sandy and muddy conglomerate. Due to the lack of detailed chronostratigraphic data the correlation among the sections were based on the evidences of depositional continuity and/or stratimetric and structural calculations. Four informal stratigraphical units (called "depositional units" and labelled, from the base to the top, A-D) are described (Fig. 3). They have been distinguished according to the lithological aspects and the organization of the strata as established for the lithostratigraphic units, but an important genetic connotation was attributed to them.

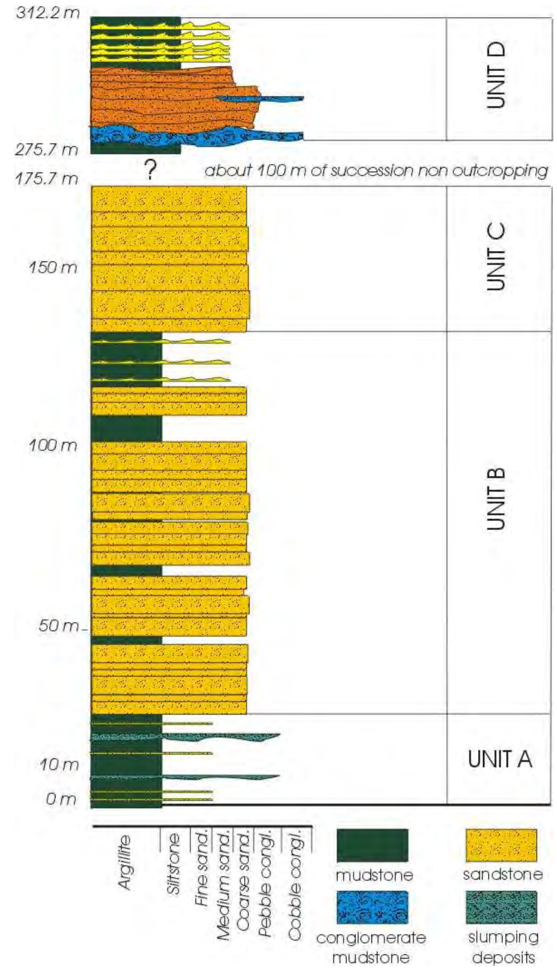

Fig. 3. Mono-dimensional stratigraphic synthesis of the study Apiúna unit. The strata thickness is not in scale, but they are approximately proportional.

Unit A.

The **unit A** (Fig. 3) has a total thickness of 25 m and a lateral exposition of more than 200 m. Almost 90% of the lithofacies is constituted by greenish gray argillite, showing thin laminae of siltstone or very fine sandstone (<1 - 5 mm thick), graded, planar, parallel and very continuous, in few cases characterized by very small current ripples. Contorted and folded argillite, filling concave depressions, have been observed; the greatest is 20 m width and 1.8 m high.

Interpretation. The argillite was accumulated by suspension fall-out depositional mechanisms on a surface with a light gradient, as testified by the contorted argillite strata interpreted as slumping deposits. The slope was tilted toward S-SW, as the ripple foresets and the axis of slumping deposits indicate. Sandstone strata and laminae were deposited by turbidity currents, but these depositional mechanisms were very unusual and they did not build regular sandstone depositional structures; the area was probably starving or it was bypassed by the sandy input. The predominance of fine deposits, the unstable conditions of the depositional surface, the starvation and/or bypassing of coarse sedimentary input, and the absence of sequential organization of the strata are features already described for slope environment deposits (Pickering, 1983; Nilsen, 1984).

Unit B and C.

The **unit B** overlies the unit A (Fig. 3), representing the first significant input of sandy deposits in the sedimentary environment. The unit B is about 110 m thick with maximum lateral exposure of each strata of 50 m. The unit B is dominated by three main lithofacies: a) sandstone strata packages, b) fine - very fine sandstone strata alternated with sandy argillite siltstone, c) argillite. More than 60% of the volume is constituted of ***packages of fine or medium sandstone strata***, lying on each other, 3-100 cm thick, generally ungraded and showing a sharp decease of granulometry only in the last upper few centimetres. Their bottom is planar, while their top commonly shows undulated bed forms, corresponding to current ripples; mud clasts up to 1 m of *a* axis are frequently dispersed within the sandstone. Laminae of grain dimensional segregation, attributable to traction carpet, according to Lowe (1982) and Mutti (1992), have

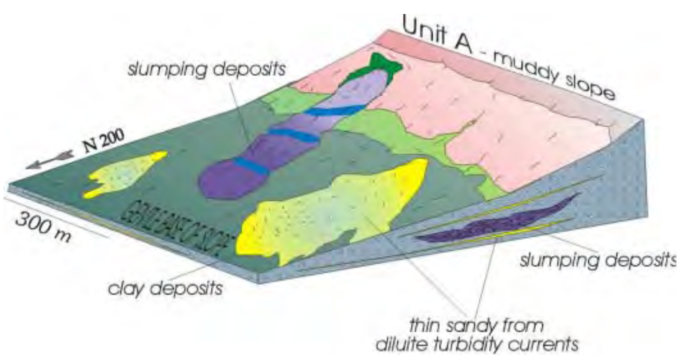

Fig. 4. Conceptual model of the muddy slope (unit A).

been observed. The 2D view of the strata is rectangular; strata with lenticular shape are very rare. Nearly 20% of the lithofacies is represented by ***fine - very fine sandstone strata alternated with sandy argillite siltstone***. The sandstone strata (1-28 cm thick) are frequently characterized by planar laminations overlain by current ripple laminations. The sandy argillite siltstone strata are generally massive. Four ***greenish grey argillite*** intervals break the sandstone succession; they display the same sedimentological aspects of the argillite of unit A, i.e., massivity, siltstone or very fine sandstone coarser laminae and up 5 cm thick very fine rippled sandstone strata. The thickness of the argillite intervals varies from 1.5 m to 15 m.

The **unit C** is 41 m thick, the outcrop conditions allow lateral observation of the bodies up to 40 m. This unit is completely constituted of sandstone strata without finer interstrata. The lower contact with the unit B is covered, but small outcrops and morphological aspects suggest that the contact is stratigraphic and characterized by an abrupt transition to sandy sedimentation (Fig. 3). The dominant facies (70% of the volume) is made up of ***massive strata of medium and coarse - medium sandstone***, rectangular in shape, more than 50 m wide in a perpendicular direction in respect to the paleocurrents; the bottom of the strata is plain and smooth, floating mud clasts in medium or lower part of the bed are frequent; uncommonly planar laminae, similar to traction carpet, can be observed in the lower part of the bed, and rare cross laminations cover the bed. The upper part of the unit C shows ***massive conglomeratic sandstone*** with local scoured bottom. Above stratigraphic quote 150 m (Fig. 3) the unit C displays an interval, 2 m thick (Fig. 3), characterized by lenticular sandstone strata with erosive concave bottom in the lower part and low inclined surfaces in the upper part. These surfaces are separated by a thin bed of argillite siltstone and they show small ripple bed forms on the top, with foresets at high angle in respect to their dipping direction. These surfaces could be similar to the Inclinated Heterolitic Stratifications (IHS) described by Thomas et al. (1987), pointing out lateral depositional accretions.

Interpretation. The medium or coarse sandstone strata of the unit B and C have analogous features: rectangular shape, linear and smooth bottom, massivity, floating mud clasts, top covered by current ripple bed forms. On the other hand, these strata have the following differences: the sandy bodies of the unit C are in average thicker, coarser (medium or medium - coarse sandstone), and not alternated with argillite siltstone.

Massive sandstone strata mean lack of turbulence during the last depositional processes, therefore lack of turbidity currents. Floating mud clasts up to 1 m means that other forces (such as buoyancy, dispersive pressure, attrictional and matrix strength) sustain the grain instead of the turbulence, being the mentioned forces typical of debris flows *s.l.* (Lowe, 1982).

The sandstone strata bottom lacks erosive sole marks (like flute, gutter, groove, obstacle scour) produced by turbulent currents. Traction carpets are produced by laminar flows, therefore are not present in turbulent flows (Shanmugam, 2000). Therefore it sustains the massive sandstone as characteristics of debris flows *s.l* deposits. In spite of the fact that in the few centimetres of the upper part of the sandstone strata, mainly in the unit B, it observed cross laminations produced by turbulent flows as turbidity currents. In this way, a sandstone bed was formed for the most part by debris flows and only in the upper part the ripple bed forms were deposited or re-elaborated by turbidity currents. By the massive sandy bodies, it proposed a bipartite density-stratified flow, based on the experiment of Postma et al.(1988). This model of deposition is constituted by a transport mechanism divided in two parts: a lower part with laminar and pseudo-plastic flow (debris flow *s.l.*) and an upper part with speedier turbulent flow (turbidity current). Sedimentary processes caused a thick ungraded sandy strata from the debris flow, whereas the turbidity current deposited and/or re-elaborated few centimetres of fine sand at the top of the previous debris flow sandy deposit.

Towards the current direction, as the power and competence of the flow decreased, it expected: i) a decreasing of the granulometry and of the quantity of the sand transported by debris flow and ii) a contemporary increase in the depositional influence of the turbidity current. Therefore in the more proximal part of the depositional area it deduced coarser, thicker, massive sandy strata with rare rippled top (unit C), whereas in the distal part it inferred thinner, finer sandy strata with rippled top (unit B). Following this depositional hypothesis the unit C and B should represent the proximal and the distal part of the same depositional system, respectively. Moreover in this context it may interpret the rippled thin beds of fine sandstone alternated with argillite siltstone as produced by the more distal part of the above described bipartite depositional processes. In fact in the more distal part the small quantity of transported sand and the dominance of turbulent flows can deposit thin rippled sandy strata.

The depositional mechanism, above described, produced sheet sand strata >50 m wide, up to 1.8 m thick, with unknown length. The succession of several depositional events created superposed sandy bodies, from 3 to 20 m thick, which fining and thinning toward the paleocurrent direction.

In the unit C the lenticular sandstone with accretion surface (IHS) can be interpreted as the filling up of an erosive depression (probably a channel) not deeper than 2 m. The rarity of these depositional forms (5% of the unit succession), their small dimensions and the absence of interchannel (or overbank) deposits make the presence of the channelled forms meaningless in this depositional environment; so, it is irrelevant in the conceptual interpretation of the depositional system.

The four argillite intervals in the unit B interlayered with the sandstone packages represent an interruption of the coarse sedimentation. Two of these have minor thickness (up to 2.6 m), show lenticular shape and they could mean a local interruption of sandy deposits because of the lateral shift of the sedimentary entry point. The other two have a major thickness (up to 15 m) and a lateral continuity of more than 100 m; they represent a general interruption of the sandy input. In the unit C the coarser input starvation is not apparently recorded.

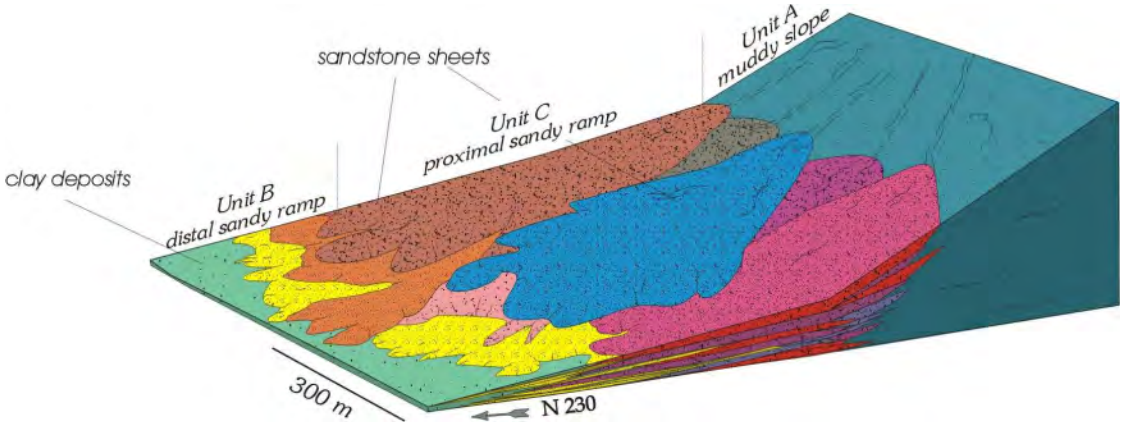

Fig. 5. Conceptual model of the distal and proximal sand-rich ramp (unit B and C respectively).

Unit D.

The unit D remains about 100 m above the unit C; between unit C and unit D significant outcrops does not exist. The unit D (Fig. 3) is 35 m thick, it can be divided into two portions: a lower portion, 19 m thick, made up of coarser deposits, and an upper portion, 16 m thick, made up of finer deposits. The ***lower portion*** covers erosively argillite strata; just above the erosive base, it shows a muddy conglomerate. Conglomerate and medium to very coarse sandstone form bodies 1.5 m to 2.5 m thick; erosive surfaces divided the bottom and the top of the strata and give a lenticular shape to the beds, which are larger than 60 m. Sole casts record paleocurrents toward S-SW. In the higher part of the lower portion, lenticular sandstone strata are replaced from rectangular bodies, with flat top, and slightly erosive bottom. In the ***upper portion*** the unit D changes radically the facies association: lenticular rippled sandstone strata, 2-22 cm thick, with flat bottom and undulated top are alternated with silty sandy argillite. The sandstone strata show current ripples directed toward W, that is at high angle in respect to the recorded paleocurrents in the lower portion. The sandstone strata commonly show pinch out terminations at 30 m of distance. The percentage distribution of the sandstone varies from 80% to <30%, showing an upward decrease. Rectangular sandstone beds, up to 135 cm thick, are interlayered in the upper portion with the facies described above. These strata are laterally continuous for more than 50 m, they are massive, locally characterized by erosive depressions.

Interpretation. The base of the unit D is an erosion surface. High-concentrated mass flows are responsible for the sedimentation of the lenticular coarse deposits: cohesive debris flows deposited muddy conglomerate and grain flows *s.l.* produced the conglomerate sandstone. The geometry of the bodies and the interpreted sedimentary processes allow to deduce that the high-concentrated mass flows were driven and deposited in a confined and erosive depression: a channel. The upward decreasing of granulometry and thickness of the beds testify, during the filling, a local decreasing of competence and capacity of transport in the channel. The facies association of the upper portion records a decrease of sandy input, decrease of the energy of the depositional flows and paleocurrents perpendicular to the channel flow direction. The depositional mechanisms of the lenticular sandy strata are attributed to turbidity currents. As the facies association of the upper portion overlies in continuity the channel deposits and as the sandstone strata show perpendicular paleocurrents, it interprets these as overbank or levee deposits. The upper portion shows similarity with the successions described in the Echo Group (Mutti, 1977) of the Pyrenees as deposits of channel margins. In this context, the lenticular thin sandstone strata are interpreted as turbidity currents which went out of the channel. The channel paleocurrents are directed toward S-SW whereas overlying levee facies have paleocurrents directed toward the W. That makes to suppose that the channel underwent, contemporary to the local filling, a lateral migration toward E. Actually 500 m to E from the unit D and at upper stratigraphic position a sandy conglomerate, that could testify the channel migration, outcrops.

Architecture conceptual model

The conceptual model is very useful to create a platform work where more detailed and quantitative analyses could be built. In this work the conceptual model is founded on facies analysis of outcrop data, and on the qualitative interpretation of the data based on recent or ancient depositional systems taken from the scientific literature.

The earliest study deposits (unit A) indicate that the depositional area was faintly inclined and devoid of sand deposition due to starvation of sand input and/or bypassing of sandy driving flows (Fig. 4). The great abundance of fine deposits (more than 95%), the recording of depositional surface instability (slumping deposits), the bypassing of coarser clastic input and the lack of the sedimentary sequential organization are elements already recognized in ancient or actual slope deposits (Pickering, 1983; Nilsen, 1984; Galloway, 1998). The sedimentary structures indicate a slope dipping towards S-SW.

The transition to the unit B is marked by a sudden input of sand. With the start of the unit B the area became a site of sandy deposition, although the general morphological conditions did not vary; in fact, paleocurrent directions of the gravitative flow still indicate a S-SW dipping slope. The unit B and C are dominated by extensive sheet sandstone. The two units take part of the same depositional system, considering the unit C as the proximal part and the unit B as the distal part. In the proximal part, the sheet sandstone is coarser and thicker; and it is lacking finer interlayering and, in some cases, the beds are amalgamated. In the distal part, the sandy strata are finer and thinner, and silty argillite interlayering is very common. Visual consideration and simple statistical tests, based on the sandstone thickness, does not show a clear vertical organization of the strata; particularly coarsening and thickening upward sedimentary sequences are not observed in the unit B or C. For these reasons these bodies are not interpreted as lobes *s.s.*, which, in the literature, are described as produced by turbidity current deposits and showing a vertical sedimentary sequence (Ricci Lucchi, 1975; Pickering, 1983; Mutti, 1992;). It presumes that the non organization of the sandstone strata could be linked to: a) different origin of sandy input, and b) arrhythmic variations of the sandy input and/or energy of the driven sediment mechanisms.

Analogous non organized vertical succession of deep-water sandstone bodies have been described by Surlyk (1987); he interprets these sandstone strata as deposited on a terminal part of a slope surface from multiple entry points. The sedimentary succession of the unit B and C is also very similar to those described by Heller and Dickinson (1985). Observing the sedimentary succession of the Tyee Formation and Matilija Formation (Heller and Dickinson, 1985) (fig. 2 and 9 of this work), very strong analogies with the Apiuna unit are recognized: i) the sandy deposits are predominantly massive and show similar sedimentological characteristics, ii) the vertical distribution of the sandstone thickness appears to be random, for example no clear asymmetric cycles of thickening or thinning sequences are found, iii) no evidence for facies segregation into channel or interchannel deposits is found, iv) the fine deposits of the unit A do not represent a muddy basin, but a muddy slope. Heller and Dickinson (1985) described the Tyee Formation and Atilija Formation as ramp, a system different from the classical canyon-fed fan. In the last decade, some papers (Richards, Bowman and Reading, 1998) suggested twelve different depositional models for deep-water systems, based on the granulometry and the source of the clastic input. Based on these models, unit B and C could be interpreted as sand-rich and multiple source input, and identified as a sand-rich ramp depositional systems (Fig. 5).

Unit D has been interpreted as a channel-levee complex; facies analysis inferred that the channel migrated towards

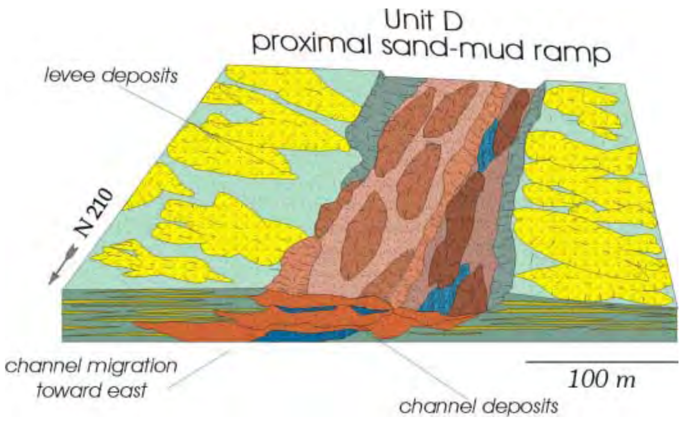

Fig. 6. Conceptual model of the sand-mud channel ramp (unit D).

east at the same time as the channel filling, producing a oblique channel body (Fig. 6). The channel filling thickness is 19 m, it is filled with conglomerate sandstone, but in the lower part muddy conglomerate can be observed. Upwardly the coarse channel filling passes to overbank or levee deposits, made up of lenticular sandstone strata alternated with silty sandy argillite. The deposition of unit D probably occurred in the same generic morphological conditions as the other units, as testified by the channel paleocurrent (S-SW), but probably the unit D represents a radical change in the depositional system. Particularly, accepting the ramp model, the unit D is not a lateral expression of the sand-rich ramp (units B and C). Therefore it thinks that an increase of clay in the clastic input transformed a sand-rich ramp into a mixed sand-mud ramp (unit D). According to Richards et al.(1998), the mixed sand-mud system is constituted by proximal channel-levee complexes, similar to unit D, and by distal lobes, not outcropping.

The entire measured succession records the rapid evolution of a deep-water depositional environment. The bottom of the succession (unit A) represents a faintly inclined slope, probably a deeper and gentle part of the slope. The transition to unit B is very rapid; it points out the beginning of the sandy deposition in an area of terminal slope. For this reason it thinks the transition from unit A (slope) to unit B (ramp) represents a progradation of a sandy depositional system (delta?) located towards land. For the present, there are insufficient information about the presence of erosive channels in unit A, constituting route passing of coarser sediments towards the lowest part of the basin. Units B and C constitute a ramp system and their evolution is interpreted as a progradation of the ramp. Four main silty argillite strata, constituting interruptions of the sandy input, are measured. The two thinnest strata have a limited lateral continuity, so they could represent only a local interruption of the sandy input, for example, for migration of shifting of the source point. The other two strata are thicker (7 and 15 m) and they could be caused by general interruption of the coarser input. Unfortunately, there are not data to suppose if these interruptions were caused by the water level standing or by climatic or tectonic factors. The change from sand-rich ramp (units B and C) to mixed sand-mud ramp (unit D) is linked to an increase into the muddy input. The mud increase triggered the complete reorganization of the depositional system and consequently of the architecture in a mixed sand-mud ramp. Nelson and Maldonado (1988), Richards and Bowman (1998) and Richards et al (1998) described this system as characterized by channel-levee complexes in the proximal part and by sand sheet (named lobes) in the distal part.

As mentioned in the Introduction, the sedimentary history of the Itajaí basin is very articulated and probably rapid, mainly controlled by tectonic changes (Rostirolla et al., 1992). Morphological variations of the basin as well as the sediment source areas could be responsible for the change of the slope, through a sand-rich ramp, dominated by sheet sand strata, to a mixed sand-mud ramp, dominated by proximal channel-levee complex and distal lobes. Eustatic variations could be superimposed and partially could have controlled this architecture, but the known geological history of the Itajaí basin would be more in agreement with the tectonic control. The eustatic aspects could be responsible for minor dimension architectural elements, such as the silty argillite intervals in the unit B.

Discussion

As the deep-water depositional systems make up one of the most important hydrocarbon reservoirs of the world (Stow and Johansson, 2000), this work could contribute to petroleum geology. Discriminating, in a potential oil field of deep-water deposits, a depositional architecture of sand-rich ramp or mixed sand-mud ramp from a classical canyon-fed fan is crucial, because the architectural construction of the quoted systems is very different, as is the distribution of reservoir and non-reservoir rocks.

The main reservoir in a *sand-rich ramp* is extensive architectural elements, named sheet sandstone. In this conceptual model, the sand-rich ramp shows thick and coarse sandstone strata, forming in the proximal part (unit C) continuous sedimentary sequences up to 40 m thick and more than 300 m wide. Whereas in the distal part (unit B) the sheet sandstone are finer and thinner, they constitute sequences up to 15 m thick and more than 300 m wide, frequently interlayered with finer sealing rocks (silty argillite). Consequently in the sand-rich ramp the best reservoirs are located in the proximal part of the system. Moreover the sand-rich system does not possess developed channel deposits, therefore, when this model is applied to an oil field, it is useless to search for channel deposit reservoirs towards the proximal part of the system.

Reservoir rocks in *mixed sand-mud ramp* have other shapes, sizes and distribution. In this outcrop model only the channel is exposed. This is a conglomerate sandstone or coarse sandstone body, 19 m thick, more than 50 m wide, with concave erosive bottom and flat top; in this example it was affected by lateral migration, that produced a low angle inclined body of amalgamated channel fills. Channel reservoirs are completely surrounded by finer levee or overbank deposits, that make up sealing rocks. The shape of the channel reservoir is more irregular and the size smaller than the sheet sandstone reservoir in sand-rich ramps. Moreover channel deposits are characterized by strong inner variations of porosity and permeability; for example a muddy conglomerate, deposited by cohesive debris flow, constitutes barriers to the fluid and isolates the reservoirs.

Acknowledgements

This work was permitted by financial support of Fapesp (proc. no. 98/04461-0) and Cepetro/Unicamp.

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