Lacustrine carbonate platforms; facies, cycles and tectono-sedimentary models for the pre-salt Lagoa Feia Group (Early Cretaceous), Campos Basin, Brazil

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ABSTRACT

Studies of lacustrine carbonate rocks in continental rifts have received a huge interest in recent years because of their great economic value in the south Atlantic. However, most existing facies and tectono-sedimentary models for carbonate platforms are based on marine carbonate systems, whereas models for non-marine systems are scarce.

The main aim of this paper is the establishment of such models to further our understanding of the late syn-rift Lower Cretaceous carbonate successions of the southern Campos Basin, Brazil. This paper is based on a proximal to distal industrial dataset of 3-D seismic, cores and well logs from the hydrocarbon producing Coqueiros Formation (Coquina), Campos Basin. The dominant carbonate facies in the Coqueiros Formation are mollusk-rich grainstones, rudstones and floatstones, which form the main reservoir facies.

3D seismic interpretations show an oblique extensional rift system, characterized by a series of grabens, half-grabens, accommodation zones and horsts oriented NE-SW to NNW-SSW. Three tectonic domains are recognized based on structural style, stretching

factors, subsidence rates as well as facies and different types of lacustrine carbonate platforms.

Proximal rift margin areas are characterized by a series of half grabens with footwall and hangingwall dip slopes of shallow lacustrine carbonates and fluvio-deltaic mixed carbonate & siliciclastic deposits in marginal, hangingwall basins. Central areas are carbonate-rich with platforms established over horst blocks surrounded by deeper-water carbonate facies. Distal areas have the highest amount of stretching and subsidence and accumulate the thickest carbonate successions over a template of buried horsts and grabens. The entire carbonate succession underlies a thick layer of Aptian salt, which forms the seal to this prolific hydrocarbon system.

Keywords: Pre-salt, lacustrine, carbonate platforms, tectono-stratigraphy, Campos Basin

INTRODUCTION

The lacustrine pre-salt carbonates depositional systems of the Campos and Santos basins are very large, probably unique in the geological record, and have no comprehensive modern analogues. The non-marine, pre-salt stratigraphy of these basins probably accumulated in the largest lacustrine system the world has ever known. The rocks in the Campos Basin host oil and gas reservoirs within mollusk-rich coquinas but also have non-producing microbial or travertine-like carbonate rocks similar to those of the Santos Basin. However, largely because of commercial sensitivities, very little is known on the detail of these rocks. There are very few accessible publications on the thicknesses, stratigraphic geometries, lateral extent, facies, stacking patterns, facies models and environments of deposition. However, there are over 400m (1312ft) of lacustrine carbonate facies encountered in the Coqueiros Formation of the Campos Basin, some of which host large fields (Figure 1) that have been producing oil since the early 1980s (e.g. Badejo and

Pampo fields, Guardado et al., 1989). These hydrocarbons are sourced from the underlying thermally mature shales with high organic content within the Coqueiros and Atafona Formations (*cf.* Jiquiá and Buracica units, Guardado et al., 1989). The reservoirs are within lower Aptian coarse-grained molluscan rudstones, or coquinas of the Coqueiros Formation, and are sealed by upper Aptian evaporites of the Retiro Formation (Figure 2).

This paper describes and interprets successions along a proximal to distal profile through the syn-rift, pre-salt stratigraphy of the southern Campos Basin. This is based on a Petrobras dataset of 3D seismic and a transect of 12 wells with 400m (1312ft) of core, gamma ray logs and one well with BHI log and sidewall cores.

A major result of this study is that carbonate platforms may be formed in large lake systems in continental rift settings. In the Lower Cretaceous of the southern Campos Basin, seismic and well data confirm that the platforms are 100s of meters in thickness and 10s of kms across and that they accumulate over structural highs. These are similar in scale to their marine counterparts and have similar aggrading and prograding geometries. Most of the existing facies and sequence stratigraphic models for carbonate platforms are based on marine carbonate systems, whereas models for non-marine systems are scarce in the current literature. This combined analysis of 3D seismic and well data enables the construction of facies and tectono-stratigraphic models for these lacustrine platforms. These models contribute to the understanding of the Early Cretaceous carbonate successions of the Southern Campos Basin, Brazil, that is needed for further exploration and production but also to assist in the interpretation of the opposing margin offshore southwest Africa where exploration is at an earlier stage (Thompson et al., 2015).

The 3D seismic interpretations reveal an oblique, extensional rifting system, characterized by a series of grabens, half-grabens, accommodation zones and horsts oriented NE-SW to

NNW-SSW. This structural framework is divided into three proximal to distal tectonic domains based on structural style, stretching factors and subsidence rates. This structural template exerts a strong influence on depositional patterns and sedimentary fill of the late syn-rift Coqueiros Formation and the carbonate platforms differ in these three domains.

The sub-surface data analysis indicates 100s of m thick lacustrine carbonate deposits, with fluvio-deltaic mixed carbonate & siliciclastic deposits in marginal areas and pure carbonate platform systems basinward. The dominant carbonate facies in the Barremian and lower Aptian Coqueiros Formation are mollusk-rich rudstones and floatstones that accumulated in open, brackish water, lake system. Ostracods and gastropods occur subordinately. Microbialite-rich facies occur overlying the post-rift unconformity in the middle Aptian Macabu Formation, in more restricted paleoenvironmental conditions. All these carbonate successions are overlain by a thick layer of Aptian evaporite, which concludes the continental sequence of the studied succession.

These pre-salt carbonate successions record the break-up of Gondwana and witness the development of rift evolution, which culminate with the opening of the south Atlantic later in the Early Cretaceous.

METHODS AND DATA

Seismic horizons and the main faults were mapped using a 3D seismic survey and tied to well data, using Landmark software. The 3D seismic data covers an area of some 7500 km^2 (Figure 1) with 23 wells, mostly concentrated in the shallow water sites in the northwest of the study area in the oil-fields of Pampo, Linguado, Badejo and Trilha. The seismic data were merged (“Big Merge”, Figure 1) internally at Petrobras from four prestack processed seismic surveys; Alfa, Beta, Gamma and Delta each of them with different acquisition parameters, grid characteristics and frequencies. The grid is arranged in 1300 in-lines by 2662 cross-lines with the spacing between them of 50 by 50m (164ft) and an average frequency estimated of 15-18 Hz.

Five stratigraphic horizons were mapped throughout the dataset: Top Cabiúnas Fm (basalt, and acoustic basement), base and top Coqueiros Fm (top early and late syn-rift), and base and top Retiro Fm salt (base post-rift) (Figure 3). These picks were based on continuity of the reflectors, seismic facies changes and terminations (onlap, downlap, toplap, etc.). Various seismic attributes were used to assist in the mapping of faults and the best attribute came from dip. 3D views, maps and cross-sections were all used to identify and interpret the tectonic setting, structural patterns, and internal and external geometries of strata in the carbonate-rich units within the late syn-rift Barremian to early post-rift (sag) Aptian succession. Cores and wireline log data through the Coqueiros Fm were studied from 21 wells arranged in a proximal to distal transect (Figure 1) that are tied to the seismic data (Figure 3). The proximal area (Domain I) is sampled in 18 wells from the Pampo, Badejo, Linguado and Trilha oilfields, whilst Domain II is sampled by three wells (19, 20, 21) with BHI logs and sidewall cores together with wireline logs in well 20. The distal area, Domain III, is only known from seismic data. Eight wells were studied in detail with core and electrical logs and a further 13 were used to tie the seismic to electrical logs, 400m (1312ft) of core were logged (1:20 scale), 600m (1968ft) of FMI log were interpreted (1:10 scale) and more than 200 thin sections were studied.

GEOLOGICAL SETTING OF CAMPOS BASIN PLATFORMS

Stratigraphic Setting

The pre-salt carbonates of the Campos Basin are only known from offshore data and form part of the Lagoa Feia Group, which is dated by non-marine ostracod assemblages as early Aptian (Figure 2; Winter et al., 2007). This unit contains reservoirs that have been producing hydrocarbons since the early 1980s and is laterally equivalent to the hydrocarbon-rich Itapena and Barra Velha Fms of the Santos Basin to the south. Both basin-fills contain syn-rift strata laid down during rifting of Gondwana and the early stages of formation of the south Atlantic. The Lagoa Feia Gp is divided into the Itabapoana, Atafona, Coqueiros, Gargau, Macabu and the Retiro formations (Figure 2). The Itabapoana Fm. is characterized of polymict conglomerates, lithic sandstones, siltstones and shales (Rangel et al., 1994) that are associated with the western border faults to the basin in proximal sites. This formation reaches 5km (31,5Mi) thick, rests unconformably on the basalts of Cabiúnas Formation, underlies and is laterally equivalent to the Coqueiros Fm and is interpreted to have accumulated in alluvial fans and deltas near the margins of a syn-rift lacustrine system (Winter et al., 2007).

The Atafona Fm comprises mostly sandstones, siltstones and shales interbedded with thin carbonate layers (Rangel et al., 1994). The siltstones and sandstones are rich in talc and stevensite minerals, formed by chemical precipitation associated with hydrothermal activity in alkaline volcanic lakes (Bertani and Carozzi, 1985a, 1985b). The formation lies unconformably on basalts of the Cabiúnas Fm, and underlies and also grades laterally into the Coqueiros Fm. Palynological and ostracod dating indicate these sediments were deposited during the Barremian (Figure 2; Winter et al., 2007), in the early syn-rift phase of basin evolution.

The Coqueiros Fm (informally referred to as the Coquina) is represented by interbedded units of lacustrine, mollusk-rich carbonates (coquinas) and shales (Rangel et al., 1994) that occur in the central and distal parts of the study area; lateral to the Itabapoana Fm.

The Coquieros Fm comprises hundreds of meter -thick packages of porous molluskan rudstones and floatstones (Thompson et al., 2015). These accumulated in the late syn-rift lacustrine environments of the early Aptian, are the main pre-salt reservoirs of the Campos Basin, and are the major topic of this paper.

The top of the Coqueiros Fm is identified in seismic profiles as a prominent post-rift unconformity (Figures 3 and 4) where extensional faults terminate. This surface is onlapped and overlain by the Macabu Formation; represented by microbial carbonates and some siliciclastic units (Rangel et al., 1994; Muniz and Bosence, 2015). These are interpreted to have been deposited in an arid climate alkali lake, in shallowing-upward, lake margin cycles (Muniz and Bosence, 2015). The Gargau Fm. is a marly unit that is laterally equivalent to the Macabu Fm, occurring in more proximal areas.

The upper contact of the latter two units is unconformable with the Retiro Formation, the main evaporite unit of the post-rift or sag phase of basin evolution. Based on palynological and ostracod dating, these sediments are reported to be of late Aptian age (Figure 2, Winter et al., 2007).

Tectonic Setting

Tectonic setting is a major control on the morphology, depositional geometries and facies distribution of carbonate platforms in rift basins such as the Barremian and Aptian in the Campos Basin (Platt and Wright, 1991; Guardado et al., 2000; Bosence, 2012). To understand the morphology and internal geometries of such carbonate platforms an integrated study of the tectonics and the stratigraphy is essential. Here we illustrate the tectonic setting for the syn and post-rift (sag phase) carbonates of the southern Campos Basin, using 3D seismic reflection and subsurface well data (23 wells with sonic and gamma ray and neutron logs), as indicated in Figures 4 and 5.

The NW to SE dip section through the area (Figure 4) indicates that the basement is cut by extensional faults that continue up through the syn-rift strata with distinctive wedge-shaped infill of half-grabens and grabens. These are filled with the clastic-rich Atafona Fm. The late syn-rift Coqueiros Fm is cut by fewer faults but shows marked thinning over basement highs and thickening into lows.

The map of the top basalt (acoustic basement) illustrates the template for the accumulation of the syn- and post-rift sag strata (Figure 5). Most of the structures are arranged in a NE-SW direction. Secondary structures are aligned NNE-SSW.

The area has been divided into three basinal domains (Figures 4 and 5). Domain I comprises the Badejo High, a horst of volcanic rocks with a steep, fault-bounded margin to the east. This high contains the Pampo, Linguado, Badejo and Trilha oil fields (Figure 1) and wells 1-18 of this study (Figure 6). Domain II is more complex with a series of polygonal shaped half-grabens bisected by a WSW – ENE accommodation zone with a central horst, or interbasinal ridge (Rosendahl et al., 1986) and an interbasinal high on its eastern margin (External High, Figure 4) where wells 19, 20 and 21 are sited. Domain III to the southeast today forms an extensive low, parallel to the rift margin with a number of linked (NE – SW) half grabens and buried (or relict) horsts.

The extensional faults were active for a longer interval distally to the southeast. In proximal areas, Domain DI, they are short lived, and faults appear to terminate in the late syn-rift succession. In Domain DII, the normal faults reach the top of the syn-rift succession. However, in Domain DIII, the normal faults are mostly long-lived and cut the post-rift succession, in some cases reaching to the base salt (Figure 4).

The structural elements in the study area define an extensional rifting system. However, the segmented faults, the curved fault segments together with the NNE-SSW border of the basin that is oblique to the orientations of the rift faults (NE-SW), all indicate an oblique extensional rifting system (McKenzie, 1978). Individual half-graben, graben and horsts form the rift system. Basinward, in the SE of the area, the individual half-grabens appear to have linked due to the advanced evolutionary stage of the rift, where they become more symmetric, forming a large graben, with conjugated border faults (Davison, 1999).

The early syn-rift accommodation is filled with terrigenous sediments of the Itabapoana Fm in the proximal area and Atafona Fm to the offshore (Figures 2 and 6), possibly in response to high extension rates that appear to have reduced by the time of the late syn-rift stage that are dominated by carbonate sediments. A phase of post-rift uplift and erosion is marked by the post-rift unconformity or “breakup unconformity” (Guardado et al., 2000) of Aptian age. The post-rift, or sag, strata infill any remaining inherited rift-related topography and thicken basinward in response to thermal subsidence of the post-rift phase.

SEDIMENTARY FACIES AND FACIES ASSOCIATIONS

Paleontology and Paleoenvironment

Previous authors have noted the absence of typical stenohaline marine organisms within the Lagoa Feia Gp (Schaller, 1973; Bertani, 1984; Carvalho et al*.,* 1984) and have proposed that the unit was deposited in a fluvio-lacustrine complex. Similarly, Abrahão and Warme (1990) based on open-hole logs, cutting and core samples, proposed three depositional environments for the Lagoa Feia Gp; alluvial fans, exposed lake-margin mud flats, and sub-lacustrine deposits. In this work, a suite of non-marine, semi-infaunal, suspension feeding, bivalves have been recognized; *Angelasina cf. A. plenodonta* Riedel, *Arcopagella, longa* n. sp, *Camposella rosea* n. Gen et n. sp, *Desertella acarenata* n. sp, *Kobayashites brasiliensis* n. sp, *Remondia (Mediraon) magna* n. sp, *Sphaerium cf. S. ativum* White, *Trigonodus camposensis* n. sp. With the exception of *Sphaerium*, all are endemic to the Brazilian offshore basins. Pulmonate gastropods (*Limneidae*) are common and typically found in fresh waters (Carvalho et al., 1995). Non-marine ostracods are common to locally abundant and are used as biostratigraphic markers within the Lagoa Feia Gp (Silva-Telles, 1992; Carvalho et al., 1995). Pycnodontid fish of the genus *Pycnodus* (Gallo, oral communication in Carvalho et al., 1995) are also present and considered to be a potential predator of the benthic mollusks and some crustaceans (Carvalho et al., 1995). A vertebrate bone fragment was discovered in Well 2 during this study. From its internal structure it is interpreted to be either from a crocodilomorphous reptile or a dinosaur (Dr. A. Kellner, Brazilian National Museum, pers. comm.). However fresh water algae (e.g. charophytes) have not been observed so it is considered that the aqueous environments of the Lagoa Feia were brackish water lakes. The Mg- silicate Stevensite is present in lower levels of the Group indicating an Mg-rich alkali lake environment (Wright and Barnett, 2015) for the earlier stages of the Campos Basin rift. Although there are some records of possible marine organisms or biochemical indicators within this succession (Hessel and Mello, 1987; Silva Telles, 1996) no unequivocal marine fossils have been seen in the 400m (1312ft) of core or 200 thin sections studied within this project.

Facies descriptions and interpretation

The cores and matching thin sections were used to establish 19 facies based on their lithologies and fossils. The majority of the cores come from proximal sites of Domain I and the bed-by-bed logging of cores (Muniz, 2013) provides the basis for the facies in this paper. These core-based facies, backed up with thin sections, are described and depositional processes interpreted in Table 1 and the carbonate facies are illustrated in Figure 7. The interpreted depositional settings of the facies is illustrated in a facies model based on a proximal-distal lake margin profile in Figure 8.

The more distal sites of the study area have not been cored but are imaged in well 20 with a continuous borehole image log and sampled by some sidewall cores (Figure 9). Together these records enable the identification of borehole image (BHI) facies, and the image log for 400m (1312ft) of the Coqueiros Fm from well 20 are used to extend the data from the cored wells to a more distal area. From the BHI log and sidewall cores from the Macabu Fm in well 20, Muniz and Bosence (2015) described and interpreted 9 BHI based facies (BH1-BH-9); Breccia, Laminated Shale, Marl, Conglomerate, Mudstone, Grain-rudstone, Microbial Laminite, Stromatolite and Thrombolite. Of these, the last three microbial facies do not occur in the Coqueiros Fm. One facies, the Rudstone/coquina (FMI-7 in Muniz, 2013) is in addition to those in the above list, and occurs in abundance in the Coqueiros Fm in well 20. This BHI facies is relatively conductive with a coarse, grainy appearance, visible bivalve shells and pores represented by dark brown patches (Figure 9). This lithology occurs in plane or cross-bedded units that are up to 10s of meters in thickness and is very similar to the Rudstone facies (Rc, Rt, and Rm) of the cored material, and is similarly interpreted to have formed in high energy, shallow lacustrine environments (Table 1).

The facies are grouped into 4 facies associations (FA) based on their environment of deposition. Two of these associations (Alluvial Fan & Plain FA and Delta & Delta Margin FA) are dominated by siliciclastic sediments from the proximal Itabapoana Fm. Two, from the Coqueiros Fm, are carbonate or mixed carbonate-siliciclastic sediments of the Deep Lacustrine FA and the Lacustrine Carbonate Platform FA and are the focus of this paper. The occurrence of the facies of the latter two associations on a proximal to distal lake profile is illustrated in (Figure 10) and the occurrence of the facies associations is discussed below.

Alluvial Fan and Plain Facies Association (AF&P-FA)

This association comprises the clast-supported conglomerate (CB) and coarse sand (Sc) facies that are represented in wells 1 and 2 in the proximal part of the basin (Figures 6 and 10). These sedimentary deposits are interpreted to be associated with braided fluvial systems and alluvial fans that act as a conduit for the transport of polymictic terrigenous sediments into the basin. The alluvial fans and plains occur westwards and proximal to the main lacustrine environments in the hanging wall sub-basin, close to the border fault.

Deltaic and Delta Margin Facies Association (D&DM-FA)

This association is interpreted to occur on the western border of the lacustrine system (Wells 1 and 2), where distal alluvial systems enter the aqueous environment. It comprises siliciclastic deltas at the mouths of rivers together with the delta slope, and mixed carbonate-siliciclastic shoreface deposits marginal to the delta. The siliciclastic facies are represented by medium to fine grained sands (Sf, Sm) interpreted to have formed in the distributary channels of the deltaic system. The finer grained facies of this association are considered to be channel-levee and delta plain deposits, and are predominantly represented by siltstone and shale (ST, SH) facies. Similarly, this association also comprises the more distal portions of prodelta and delta front, with deformed and slumped deposits of matrix supported conglomerates (CM), and also thin and very thin units of sand (Sm, Sc) and rudstone facies that are interpreted to have formed in a deep lake environment as turbidites. This is based on characteristic sharp erosional bases with load and flame structures in the base of the beds. In the lateral marginal portion of the deltas, sandy shoreface deposits may be reworked and pass laterally into mixed carbonate-siliciclastic deposits such as bioclastic-rich sandstones (Sf, Sm, Sc) or grainstones (G), packstones (P) and rudstones (Rt) with terrigenous grains. These shelly shoreface deposits also occur on the delta top (e.g. Well 1, Figure 10) and may be reworked as turbidites on the delta slope.

Deep Lacustrine Facies Association (DL-FA)

This association comprises interbedded siltstones, mudstones and shales, and in distal sites by fine grained carbonate facies such as mudstone (MD), Marl (ML) and wackestone (WK). These facies are interpreted as having formed in the deepest subaqueous sedimentary environment of the continental rift system (Figure 10). Most of it occurs below storm wave base, in the hypoliminium zone, where there is evidence of low-oxygen conditions such as preservation of organic matter and laminated muddy mudstones (MD) and marls (ML). Commonly these deposits are characterised by the abundance of ostracods. Close to the toe of the slope of the delta front, turbidite deposits may also occur (Wells 1 and 2, Figures 6 and 10).

Lacustrine Carbonate Platform Facies Association (LCP-FA)

Shallow lake environments isolated from siliciclastic supply commonly accumulate thick successions (hundreds of meters) of bioclastic carbonates (Figure 10). These are referred to as high energy ramp margin type by Platt and Wright (1991), but because of the thickness (100s m) and lateral extent (10s km), the range of facies and different structural settings developed in the Campos Basin (Domains I – III), these accumulations are regarded as carbonate platforms in their own right (*cf*. Buckley et al., 2015). Rudstones, grainstones and floatstones of bivalves (Rm, Rt, Rc, G, F) dominate and, less commonly, gastropod or oncoid rudstones occur. The rudstones are plane or cross-bedded and commonly stacked in packages up to many tens of meters in thickness and are interpreted to form shallow high-energy bank and bar facies within these platforms. Also included in this facies association are the thick successions of Rudstone/coquina interpreted from the BHI logs and sidewall cores in well 20. Facies with *in situ* bivalves preserved in a muddy matrix (Rm, Figure 7J) are considered to have accumulated in deeper, quieter water settings. These shallow-water facies pass laterally into the deeper lake deposits with lower energy facies such as thinner beds of bioclastic packstones (P), wackestones (WK) and mudstones (MD) or floatstones (F), which are commonly ostracod-rich (Figures 8 and 9).

METER-SCALE SEDIMENTARY CYCLES

In cored successions of the Lacustrine Carbonate Platform FA from wells 7, 8 and 12 (Figure 6) in the central part of the study area, carbonate facies are arranged in meter-scale cycles. Logged intervals show repeated arrangements of facies, typically in shallowing-upward successions, consistent with the proposed facies model (Figures 8 and 11). Cycles comprise subaqueous carbonate facies bounded by brecciated, Fe stained surfaces (Facies Bk, Figure 7A) that are interpreted as forming in emergent conditions (Table 1, Figure 8). These surfaces are overlain by thin beds (with or without ostracods) of interbedded green/grey siltstone (ST), shale (SH), wackestone (Wk), packstone (P), grainstone (G) and molluscan rudstones comprising about 1 meter (3,2ft) in total thickness. The major part of the cycles comprises 2-10m (6,6-32,8ft) of grainstone (G) and rudstone facies (Rm, Rc) (Figure 11) that are capped by emergent surfaces.

The fine-grained clastic intervals, that commonly show a positive spike on the gamma log, are interpreted as lowstand and transgressive deposits whilst the higher energy rudstone intervals, some with cleaning-up gamma trends, represent highstand deposits reflecting higher energy, shallow-water molluskan production. The cycles are interpreted as accumulating from progradation of high-energy lake margins, or bars during repeated periods of lake flooding.

The variation in cycle thicknesses and lithologies preserved, together with observations of desiccation cracks and brecciation developed in low energy, subaqueous facies indicate irregular and rapid changes of lake level. In this setting lake level might be controlled by structural or hydrological/climatic changes and no attempt is made to resolve these controls or to correlate these meter-scale cycles between wells.

TECTONO – SEDIMENTARY MODELS

As discussed above, the study area in the southern Campos Basin, has been divided into three different tectonic domains: DI, DII and DIII (Figure 12). In this section the structural settings are integrated with the sedimentological data to generate tectono-sedimentary models for each of the three Domains.

Tectono-stratigraphic model- Tectonic Domain I

Domain I includes the Pampo, Badejo, Linguado and Trilha oil fields and a proximal half-graben landward of the Badejo High (Figure 5). Here, a series of half-grabens occur with a syn-rift stratigraphy that thickens westwards to the basin border fault and thins to the east onto the Badejo High. Accommodation is provided by both synthetic and antithetic extensional faults. The lateral displacement of the normal faults suggests a crustal stretching β value, of 1.24 (β = a'/a – where a'=deformed length a= original length). Within the late syn-rift Coqueiros Fm in proximal areas both siliciclastic and carbonate sediments occur indicating it is close to the siliciclastic source area. Siliciclastic sediments may predominate in the hangingwall depocentres (e.g. well 2) whereas carbonates occupy the two main horsts (wells 5 and 6) as examples of fault-block carbonate platforms (Figure 13). However, it should be recognized that the Lacustrine Carbonate Platform - Facies Association (LCP-FA) extends into the more distal half-graben sub-basins (wells 1, 7, 8, Figure 6) indicating that rift related topography was filled at these times and also that clastic supply did not reach the more distal areas. Conversely, stratigraphically thinned horst sites may accumulate Deep Lacustrine - Facies Association (DL-FA) indicating flooding of these basement highs by lacustrine waters. During the Barremian the proximal half-graben was partially filled with sediment from the Delta and Delta Margin- FA (wells 1 and 2, Figures 6 and 10) that are locally redeposited as sub-lacustrine fans. Later, during the Aptian, Alluvial Fan and Plain - FA of conglomerates and sandstones occur in both half-graben and footwall sites. The facies successions suggest proximal alluvial fan systems evolve basinward to braided fluvial systems and Gilbert-type deltas in lacustrine environments (Figure 13). Within this proximal dominantly clastic system this bench-type carbonates accumulated (*cf.* Wright, 1992). These comprise bioclastic carbonate sediments accumulating in mixed carbonate-siliciclastic beaches, beach ridges, and also mollusk-rich subaqueous bioclastic bars and shore face deposits (Figure 13). The more distal horsts of the Badejo High are relatively clastic-free and extensive and thick amalgamated packages of bioclastic carbonates of the LCP –FA accumulated mainly in shallow, high-energy sites. Ramp-like profiles to these platforms are interpreted to have accumulated on hangingwall dip slopes whilst steeper slopes, with reworked facies are interpreted for footwall sites.

The distribution of the facies associations between hanging wall and footwall sites for this half-graben attached to the rift border fault has many similarities to a terrestrial to shallow marine analogue in the Miocene of the Gulf of Suez (Cross and Bosence, 2008)

Tectono-sedimentary model- Tectonic Domain II

The second platform type occurs in the intermediate area of the Campos Basin in the region of Espadarte oil field (Figure 1), where synthetic and antithetic half-grabens are divided by an accommodation or transfer zone (Figures 4 and 13), with an associated horst, or interbasinal ridge (Rosendahl et al., 1986). Stretching values (β) are estimated at 1.40 (Figure 12). This domain has a complex geometric arrangement of acoustic basement (Figures 4 and 5). The geometries of the carbonate platforms are aggradational on interbasinal highs and clinoforms are seen prograding outward from these highs into half-graben depocentres, with a polygonal or rhombic style in plan view (Figure 14). On the interbasinal ridge, thick packages of high energy, bioclastic carbonate banks and bars are interpreted based on a similar gamma response to the cored and imaged Lacustrine Carbonate Platform FA in adjacent wells 19 and 20 (Figure 14). These strata are seismically chaotic (Figure 12a, well 19) but appear to have accumulated in an aggradational style. Laterally to this high shallow lacustrine sediments are seen to prograde southeast and northwest into surrounding lows. The progradational geometries are evident at two levels; they are imaged as large seismic scale geometries but also interpreted from coarsening-upward profiles in wireline logs from well 19 and also in core from well 12 (from Deep Lacustrine to Lacustrine Carbonate Platform FA) and BHI logs

(Muniz 2013). In the interior of the banks, beside the horst block, the seismic sections show aggradational parallel and divergent seismic geometries. This seismic facies is interpreted to reflect low energy mud-rich carbonate sediments such as marls, mudstones or even shales (between wells 12 and 19, Figure 14).

Domain II is limited to the west by the prominent Badejo High and to the east by the External High, which is a regional hinge zone (Figures 4, 5 and 13). The depositional system appears to be isolated from clastic supply and accumulates autochthonous and parautochthonous bioclastic carbonates. These are transported and locally reworked mainly by storm and wave processes as evidenced by the commonly occurring, high energy, Lacustrine Carbonate Platform FA. Hundreds of meters of Aptian bioclastic carbonates accumulated in sub-basins with large amounts of accommodation space (Figure 14). In this context, bioclastic sediments commonly accumulated in progradational sets in the area of well 20 indicating that even stratigraphically thickened sections all accumulated in relatively shallow water, but with episodes of flooding resulting in accumulation of sections of Deep Lacustrine FA with their higher Gamma values. Therefore the productivity of these molluskan carbonate communities appears to have exceeded the accommodation space maintaining keep-up and progradational, shallow facies, locally exhibiting subaerial exposure surfaces in cores.

Tectono-sedimentary model- Tectonic Domain III

The third region, in the most distal part of the study area, has the highest degree of stretching (estimated β factor of 1.59) and asymmetric half-grabens are linked to form a large symmetrical graben with some relict horsts. These form highs and the template for what are interpreted from seismic data only as unattached carbonate platforms (Figures 5, 12 and 15).

There is considerable thickening of the Early Cretaceous strata in this distal area in response to a higher rate of stretching and subsidence. Relict horsts formed morphological highs that acted as the basement for what are interpreted as unattached, or isolated, carbonate platforms that are kms across and 100s of meters in thickness (Figures 12 and 15). There are no wells in this area and the interpretation is based solely on the progradational seismic geometries radiating from the highs. These are unlikely to be clastic progradational features as there is no source area for clastic supply and progradation is interpreted radially out from the structure. Seismic lines show progradation of interpreted platform carbonates (LCP-FA?) with lenticular / sigmoidal geometries into deeper basinal areas and these are onlapped by interpreted deep basinal sediments (DL-FA?) with aggradational parallel reflectors (Figure 12). On the platform top aggradational and also chaotic seismic facies are seen (Figure 12). If these horizons are traced to the nearest and more proximal wells (wells 12 and 20) then the lower portion of aggradational and progradational seismic geometries are interpreted to be molluskan rudstones and grainstones (LCP-FA) and upper portion as microbialite facies as described from well 20 by Muniz and Bosence (2015).

DISCUSSION

Hydrological controls

Whilst the morphology of this lake or lake system is still unknown there are some indicators of its extent and likely connectivity. Despite the unavailability of a detailed biostratigraphy for the wells in this study, there are lithological similarities between the sub-basins studied along this NW – SE transect (Figure 6). Cored lithologies and gamma and

BHI log responses indicate that correlations at the facies association level can be made between the sub-basins indicating a common sedimentological history and likely connection during the late syn-rift and post-rift (sag) phases. There is no evidence in the form of evaporitic intervals to suggest isolation or closure of parts of the lake system. The conclusion is that this transect represents a section through a connected through-flowing lacustrine system of at least 150 km (93.2Mi) across.

The core logging, thin section and facies analysis indicates paragenesis of a progressive change through time in the Lagoa Feia lake hydrology, from alkaline in the lower sequences, to fresh water, to brackish waters and finally hypersaline in the upper successions with the Aptian salts (Figure 9). The lower coquina succession comprises rudstones rich in bivalves but also with ostracods and grains of stevensite, a tri-octahedral Mg silicate. Stevensite is characteristic of alkaline lake waters, commonly derived from volcanic source areas (Cerling, 1994; Wright, 2012). A flooding event depositing widespread shales, the main source unit for the Campos Basin, separates these lower coquinas from the thick overlying bivalve rudstones and grainstones of the lacustrine Carbonate Platform Facies association. These deposits have a higher diversity of bivalves but charophytes appear to be absent. The bivalves are various taxa of the family Unionidea, many are new species, some new genera, which appear to be endemic to the south Atlantic so their specific environmental tolerances are, as yet, not fully understood. However, we have found no equivocal marine taxa in the cores or thin sections we have studied. Similarly, we have found no horizons with evaporite minerals indicating isolation and hypersalinity. Taken together, these palaeoenvironmental indicators imply brackish water conditions for the accumulation of this unit.

Towards the top of the Lagoa Feia Gp., Hessel (1993) records a decrease in diversity of bivalves, but an increase in the abundance of gastropods and this is also found in this study (Figure 9). A shift to more closed lake conditions in this late syn-rift succession in a well 2km (1.24Mi) to the west of well 5 is proposed by Silva Telles (1996) based on the Talbot (1990) model of a positive correlation of $\delta^{13}C$ and δ^{18} O isotopes (see discussion in Muniz and Bosence, 2015). A radical environmental change is indicated at the post-rift unconformity as the molluskan communities of the Coqueiros Fm disappear to be replaced by microbial carbonates of the Macabu Fm. These are associated with coarse carbonate grainstones, comprising ooids, spherulites, stevensite grains, quartz and feldspar suggesting a return to alkali Mg-rich lake waters (Muniz and Bosence, 2015). A 2 per mil positive shift to heavier oxygen isotopes over the post-rift unconformity followed by a continuing positive trend up to the base of the evaporites indicates increasing salinity and desiccation of the lake system. This succession underlies a thick layer of Aptian age salt that records evaporation of the lake system and closure of the continental record in the Campos Basin.

The Coquina Facies (LCP Facies Association)

A facies model for the carbonate facies of the Coqueiros Fm. is presented which integrates shallow and deep lacustrine facies associations. This has similarities to the wave-influenced ramp-type margin of Wright (1990). However, in the Campos Basin, the high energy shallow facies are dominated by molluskan (in particular bivalve) grainstones and rudstones. These pass through deeper waters below storm wave-base into wackstones, marls and shales with abundant ostracods (Figure 9). The dominance of endemic, non-marine bivalve taxa within this eponymous formation has been documented by many authors (e.g. Guardado et al., 1989; Abrahão and Warme, 1990; Carvalho et al., 2000 and Thompson et al., 2015). All authors are agreed that the bivalve accumulations represent high energy, shallow lacustrine sites and that there is variability in size, sorting and matrix within the coquinas. In this study we found the Dunham (1962) classification modified by

Embry and Klovan (1971) enables the broad range of facies in these unusual rocks to be classified. Quieter water, deeper or shallow protected sites accumulate molluskan wackestones and floatstones whilst higher energy sites, grainstones and rudstones. The rudstones are diverse and range from clean-washed rudstones with variable amounts of cement and pore types to rudstones with a coarse terrigenous matrix. Others rudstones have a muddy matrix and a higher proportion of articulated bivalves, some preserved in original life position suggesting a more autochthonous facies (Muniz, 2013). The reworked grainstones and clean rudstones preserve the best porosity comprising interparticle, mouldic, vuggy and some fracture porosity. When stacked in meter to tens of meter-thick successions, these form the best quality reservoir facies.

This combined study of seismic data and core indicate that the grainstone and rudstone facies in the Lacustrine Carbonate Platform facies association reach hundreds of meters in thickness and that these accumulate on basement highs but also build out into structural lows within the late syn-rift phase. These molluscan communities formed shallow carbonate platforms on a scale that is unknown elsewhere in the geological record. It is therefore instructive to consider what conditions gave rise to these unique stratigraphic thicknesses of molluscan lacustrine limestones. The late syn-rift stratigraphy is about 200m (656ft) in thickness in the proximal area (Domain I) with marginal interbedded clastics and localized thinning over basement highs which accumulate LCP and DL facies associations. However, the late syn-rift succession reaches about 400m (1312ft) in more offshore areas (Domain II), of which about 300m (984ft) is interpreted from a BHI log in well 20 to be shallow-water LCP facies association and 100m (328ft) of DL facies association. The Coqueiros Fm is considered to have accumulated over 8.0 myr from 125 to 117 Ma (Winter et al., 2007 – Figure 2) which gives accumulation rates in the southern Campos Basin in the range of 32-50m / myr (32-50m / myr 105-164ft / myr). When compared to accumulation rates of shallow- marine tropical carbonates both Sadler (1999) and Schlager (2005) give an upper limit of approximately 100m / myr (328ft / myr) and an average of about 10m / myr (32,8 ft /myr) , when measured at a similar million-year scale. Accumulation rates are a function of carbonate production, subsidence, transport and compaction as well as the time-scale of measurement. Subsidence rates for the southern Campos Basin may be taken from the thickness of these high-energy, shallow water carbonates (ie 32-50m / myr 105-164ft / myr) which are within the range for other passive margin basins (cf. Einsele, 1992), transport rates are not considered significant as the stratigraphy comprises both shallow and deep water facies and thin-section observations suggest compaction is minimal, however stylolites and solution seams are locally present in some of the cores (Figure 7D). These figures therefore suggest that the production rates from these lacustrine bivalve communities were exceptionally high and similar to marine, shallow-water, tropical carbonate production. Such high rates can only be confirmed with detailed analysis of abundance and growth rates of the preserved *in situ* bivalve communities that would require exceptional preservation conditions.

Tectono-stratigraphic models

Three tectono-stratigraphic models are presented for the three tectonic domains interpreted for the southern Campos Basin. These build on the earlier depositional models of Guardado et al. (1989) and Carvalho et al. (2000) that showed rift margin interfingering of carbonate and clastic facies and more distal bioclastic bars and banks related to horst blocks.

The lacustrine carbonate platforms in the proximal Domain I in the Campos Basin are kms in length and width and up to 150m (492ft) thick (Figures 6 and 14). These are interpreted to show many similarities with their counterparts in marine rift basins such as the Miocene of the Gulf of Suez (Cross and Bosence, 2008). Here, shallow-water carbonates accumulate on horsts and footwall highs and, where clastics dominate along the rift border fault and adjacent hangingwall basin in this “margin-attached” (*sensu* Cross and Bosence, 2008) setting. Comparison with carbonate sediments generated by a photozoan marine factory seem justified in that the molluskan facies forming the bulk of the coquinas have evidence of being the shallowest, and the highest producing, carbonate facies. Comparison with examples from modern lacustrine environments seem less instructive because whilst some similar mollusk-rich facies may be documented as in Lake Tanganyika (Cohen and Thouin, 1987) and Lake Turkana (Soreghan and Cohen, 1996) from the East African rift, they appear to be thin accumulations and the occurrence and stratigraphic geometries of the carbonate facies association are not known. The East African lake waters are not carbonate-rich and this may be a major limitation to the accumulation of thick packages of carbonate sediments (Cohen, 1989).

In Domain II platforms develop around basement highs associated with transfer zones. We have found no similar configurations of tectonic setting and thick lacustrine carbonate deposits in the literature and this appears to be a new type of lacustrine carbonate platform for the continental rift environment. Marine Miocene carbonate platforms in the Gulf of Suez rift, however, show the aggradational and progradational accumulation of carbonates in the transfer zone in the Wadi Kharaza area of Abu Shaar (Cross and Bosence, 2008). In the southern tip to Abu Shaar the accommodation zone accumulates up to 200m (656ft) of shallow marine and slope facies carbonates that prograde to the south into the accommodation zone.

In Domain III an isolated platform is interpreted surrounded by deeper lacustrine facies. Isolated microbialite buildups are found in modern lake systems such as Pyramid Lake, USA and in the tufa pinnacles in Mona Lake, USA (Della Porta, 2015) but these are of a much smaller in scale than the platforms described here. Similar scaled lacustrine platforms are described from the pre-salt of the adjacent Santos Basin to the south on the Terminal Horst and the Peroba and Lula (or Tupi) highs (Buckley et al., 2015). These are also sited on basement horsts that are unattached from the rift basin margin. It should also be noted that similar platform morphologies are seen in marine isolated platforms sited on fault blocks not attached to the basin margin in extensional basins such as the Red Sea (Purser et al. 1998) and southeast Asia (Wilson, 2002). The geometries of the two platform systems are rather similar despite the major differences in facies and environments. This is taken to reflect the similar tectonic setting of offshore fault-bounded highs but also the similarities in the Lagoa Feia molluskan carbonate factory with marine photozoan carbonate production. Both carbonate factories have high rates of production in shallow-waters producing either coarse carbonate grains or in-situ buildups, both of which result in semi-autochthonous or autochthonous accumulations that are not transported far from their site of production.

A recent paper by Goldberg et al. (2017) proposes a different sedimentary model for the Lagoa Feia Gp of the Campos basin based on more localised 2-D seismics and cored wells from the proximal part of the basin (our Domian I). Their findings support a model of predominantly re-sedimented carbonate and mixed carbonate-siliciclastic sediments as deeper-water deposits that they extend to the broader Campos Basin. Whilst this work is in agreement with our interpretations of facies for these proximal areas our seismic and core data comes from a larger area including rift margin attached and detached half graben basins and includes large areas and thicknesses of shallow lacustrine carbonate facies. These being the source areas for the shallow lake margin carbonate factory. Our sedimentological models are supported by the abundance of tractive structures within the rudstones and grainstones (Table 1), evidence of extensive reworking (abrading and rounding of bioclasts, Figure 7), and the commonly observed and logged arrangement of facies in meter-scale, shallowing-upward cycles capped by emergent surfaces (Figure 11, Muniz, 2013).

The integration of data in this study from seismic scale through to wireline log to core-based observations and logging provides relatively robust models for the Campos Basin that can be used in future exploration of the lacustrine successions.

CONCLUSIONS

1) The Coqueiros Formation of the Lagoa Feia Group of the southern Campos Basin, Brazil comprises up to 400m (1312ft) of mollusk-rich limestones, coquinas, extending for at least 100km (62Mi) through a proximal to distal transect.

2) This dominantly carbonate formation accumulated in the late syn-rift phase of Early Cretaceous rifting of the southwest Atlantic margin in an oblique extensional rift system with faults trending northeast – southwest with a NNE-SSW rift border.

3) There are three main structural domains within the rifted margin; a proximal Badejo High is a horst block bounded by half graben and hosts producing oil fields, a central domain, characterized by a mosaic of polygonal half-grabens bisected by a WSW-ENE accommodation zone with a central horst and an offshore domain of linked half-graben and buried horsts, which is in deep water today.

4) A similar stratigraphy can be traced throughout the syn- to post-rift (sag) from proximal to distal areas despite this structural complexity suggesting that they formed linked lacustrine basins.

5) The bivalve, gastropod and ostracod communities, together with an absence of charophytes, and also evaporites, all suggest an overall brackish water lacustrine environment for the accumulation of these rocks.

6) Over 400m (1312ft) of cored wells together with one BHI log and sidewall cores from the proximal to distal transect penetrate a large number of lithologies and 9 carbonate, 7 siliciclastic and 3 diagenetically and tectonically modified facies are described from four facies associations; Alluvial Fan and Plain, Deltaic and Delta Margin, Deep Lacustrine and the Lacustrine Platform Facies Associations.

7) Proximal areas show interbedding of siliciclastic and carbonate facies whilst distal sites are purer carbonate. Lacustrine Platform FA characterize structural highs and Deep Lacustrine FA the lows. However the platform facies may prograde into and infill some structural lows.

8) The facies within the Lacustrine Platform Facies Association are commonly arranged in meter-scale cycles that show both deepening and shallowing phases and are capped by emergent surfaces. In this syn-rift setting lake level can be controlled by a complex of factors such as structural history, climate and fluvial dynamics but these cannot be resolved with our widely spaced wells and with no detailed biostratigraphy.

9) Different types of carbonate platforms are found in the different structural domains with a strong tectonic control on facies and geometries; proximal areas are attached to the rift margin and have platforms developed as rectilinear structures on footwall highs to fault blocks with steeper footwall slopes and gentle hangingwall dip slope ramps into clastic-filled half graben, the central zone has a transfer zone with an interbasinal ridge/horst which forms the core for an associated rectilinear platform that progrades into surrounding structural lows, and the offshore domain, with the highest stretching factors and subsidence rates has a buried horst that acts as a template for a large unattached carbonate platform or bank.

10) The lake chemistry is considered to change through time from a lower interval of Mg rich alkali lake (with stevensite) to the main part of the late syn-rift with through-flowing

brackish lake waters dominated by non-marine molluskan and ostracod taxa but with no charophytes and no evaporite minerals. The post-rift sag succession, following a regional unconformity, is dominated by microbial carbonates of the Macabu Formation with associated spherulites and stevensite and is interpreted to return to Mg- rich alkali waters prior to evaporation and accumulation of late Aptian salts.

11) The Coqueiros Fm has carbonate platforms of various types, but with a strong tectonic control on their siting, morphology and facies associations. They are similar in scale to their marine counterparts and surprisingly the accumulation rates are similar to those recorded for marine tropical carbonate platforms.

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FIGURE HEADINGS

Figure 1. Location map with the main oil fields (in yellow) in the Campos Basin – Red rectangle delineates the area of this study. Orange colors are carbonate hosted oil fields (Courtesy Petrobras).

Figure 2. Summary of the chrono- and lithostratigraphic divisions of the Lower Cretaceous of the Campos Basin together with tectono-stratigraphic phases of basin evolution. The carbonate rocks of the Coqueiros Formation are the subject of this study (After Winter *et al.,* 2007).

Figure 3 - Seismic horizons mapped in this study exemplified by profile from well 20. Lithologies and phases of basin evolution also indicated.

Figure 4. NW to SE seismic section in time indicating units mapped within the southern Campos Basin (red-acoustic basement and volcanics, dark blue-top Atafona and base Coqueiros, light blue- top Coqueiros, dark pink-base salt, purple-top salt). Inset shows top basement surface within study area and approximate location of seismic line.

Figure 5. 3D view of study area (see Figure 1) in Geoprobe of top acoustic basement surface in TWT illustrating 3 main structural domains described in text and location of wells.

Figure 6. Stratigraphic cross section: proximal to distal well ties through the study area indicating electrical logs, core coverage, phases of basin evolution and unconformities mapped. Section flattened to base salt.

Figure 7. Core slabs (with 1 cm scales) and photomicrographs (1mm scales) of rocks described in Table I. A, E) Brecciated Mudstone (Bk) interpreted as exposure surface. Younger material fills the interstitial clast space.. In core slab A breccia is overlain by a thin bed of laminated siltstone (ST). B, F) Bivalve Rudstone (Rt) with interbedded coarse terrigenous sand. C, G) Bivalve rudstone (Rc) articulated and disarticulated (whole and broken) shells with interparticle porosity and clean grainstone matrix. D,H) Bivalve Rudstone (Rm) with muddy matrix and disarticulated bivalves. I) Core slab of oncoid rudstone (Rm). J) Core slab of muddy rudstone with articulated bivalves, some in upright in situ position. K) Marl erosively overlain by a 10 cm thick bed of rudstone, interpreted as a tempestite. L) Mudstone (MD) with irregular bedding, dark and organic rich.

Figure 8. Facies model. Proximal to distal lake margin illustrating interpreted facies distribution in relation to lake level and fair weather (FWWB) and storm (SWB) wave base.

Figure 9 Gamma log, thin-sections from sidewall cores and BHI logs from Coqueiros and Macabu Fm in well 20 (located in Figure 1). BHI log indicates plane bedding, coarse grainy texture and curved conductive shapes (interpreted as bivalve shells). Side wall core thin-sections 1) ostracod –rich grainstone with stevensite (brown), (2-3) show clean bivalve and gastropod rudstones with disarticulated, neomorphosed, thick-shelled molluscan shells with good interparticle porosity, 4) digitate stromatolite (microbialite) from Macabu Fm.

Figure 10. Schematic 3-D diagram of the Barremian Lagoa Feia lake indicating depositional environments and occurrences of the 4 facies associations identified based on cores and logs (mod. from Platt & Wright 1991).

Figure 11. Graphic log and Gamma log from cored interval in well 7 (for location see Figure 6) illustrating five meter-scale cycles within the Lacustrine Carbonate Platform Facies Association. Each cycle is bounded by a brecciated and /or Fe-stained surface (facies Bk), or with associated clastics and gamma peaks. The two thicker cycles show cleaning up gamma trends tied to coarsening facies trends from packstones and grainstones to thick rudstone units.

Figure 12. Tectono stratigraphic model. a) Seismic section and flattened on base salt showing the main structural features and the key surfaces mapped. For location see Figure 5b) Interpreted section showing the 3 identified domains and the stratigraphic geometries of each sub-basin fill for each domain. c) Sketches to indicate structural template, stratigraphic geometries and carbonate platform morphologies interpreted from 3D seismic.

Figure 13. Block diagram showing the structural setting, facies associations and depositional environments for mixed siliciclastic – carbonate sediments of Domain I. Based on wells 1-12 and seismic data.

Figure 14. Block diagram of Domain II tectono-stratigraphic model. Carbonate platform forming on an accommodation zone (horst block) with an aggradational build-up and basinward progradation. Model based on 3D seismic interpretation, sidewall core analysis and BHI interpretation in the well 20. The green colored facies on the eastern margin of the model is a deep lake facies and it is thought this fault bound area area

may have undergone inversion from originally deeper water areas.

Figure 15. Block diagram showing a Domain III isolated carbonate platform. In this tectonic context, a carbonate platform is formed over the relict horst, showing progradation of the platform margins that are subsequently onlapped by deeper water sediments. This model is based purely on seismic interpretations with ties to nearby cored horizons within the southern Campos Basin.

Table 1 Description and interpretation of core-based facies from the Lagaoa Feia Gp.

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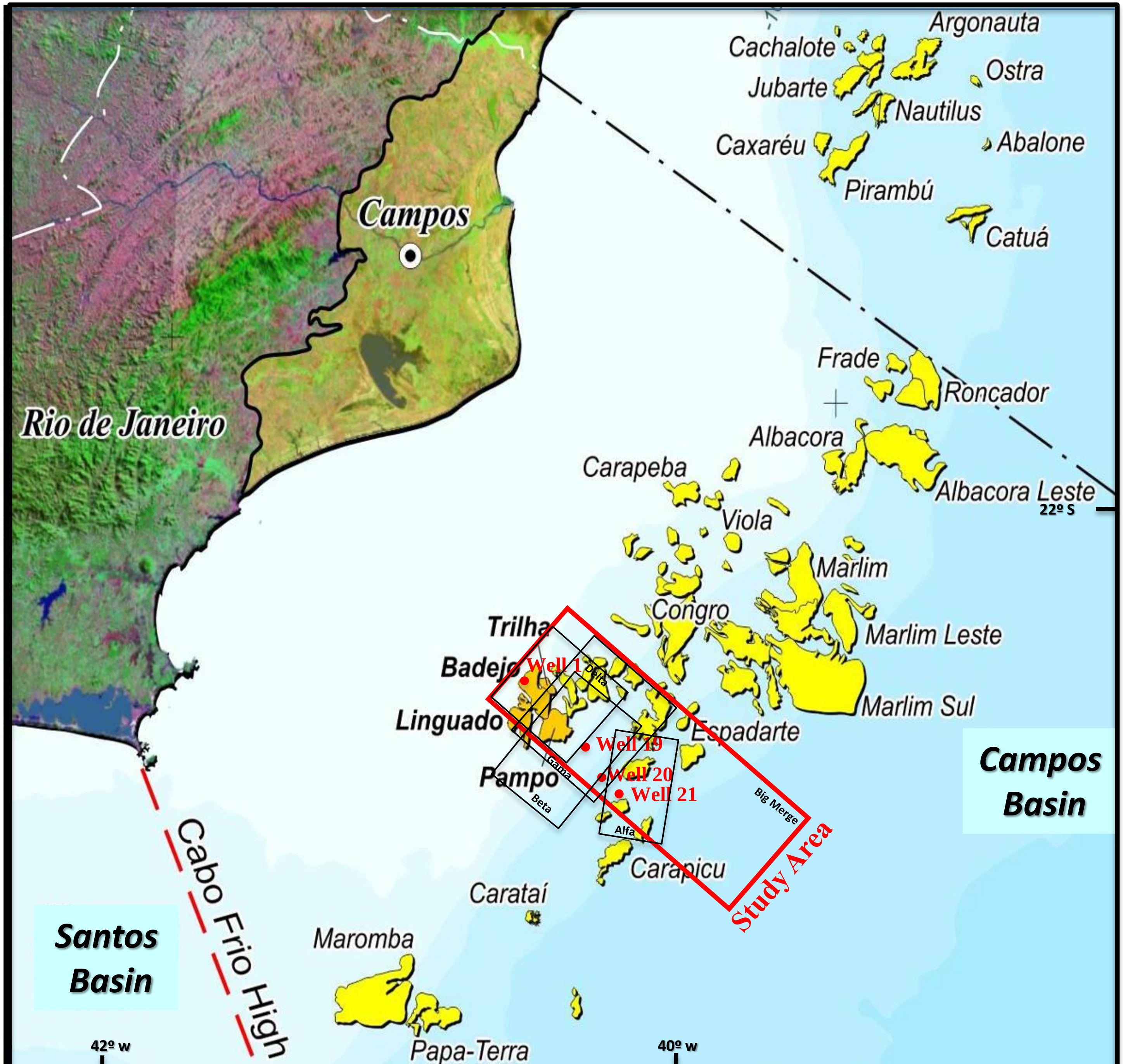


Argonauta
Cachalote
Ostra
Jubarte
Nautilus
Caxaréu
Abalone
Pirambú
Catuá
Campos
Rio de Janeiro
Frade
Roncador
Albacora
Carapeba
Albacora Leste
22º S
Viola
Marlim
Congro
Trilha
Marlim Leste
Badejo
Well 1
Delta
Linguado
Marlim Sul
Espadarte
Well 19
Gama
Pampo
Well 20
Well 21
Beta
Big Merge
Alfa
Campos Basin
Carapicu
Study Area
Carataí
Cabo Frio High
Maromba
Santos Basin
42º w
40º w
Papa-Terra

Figure 1

Figure 2

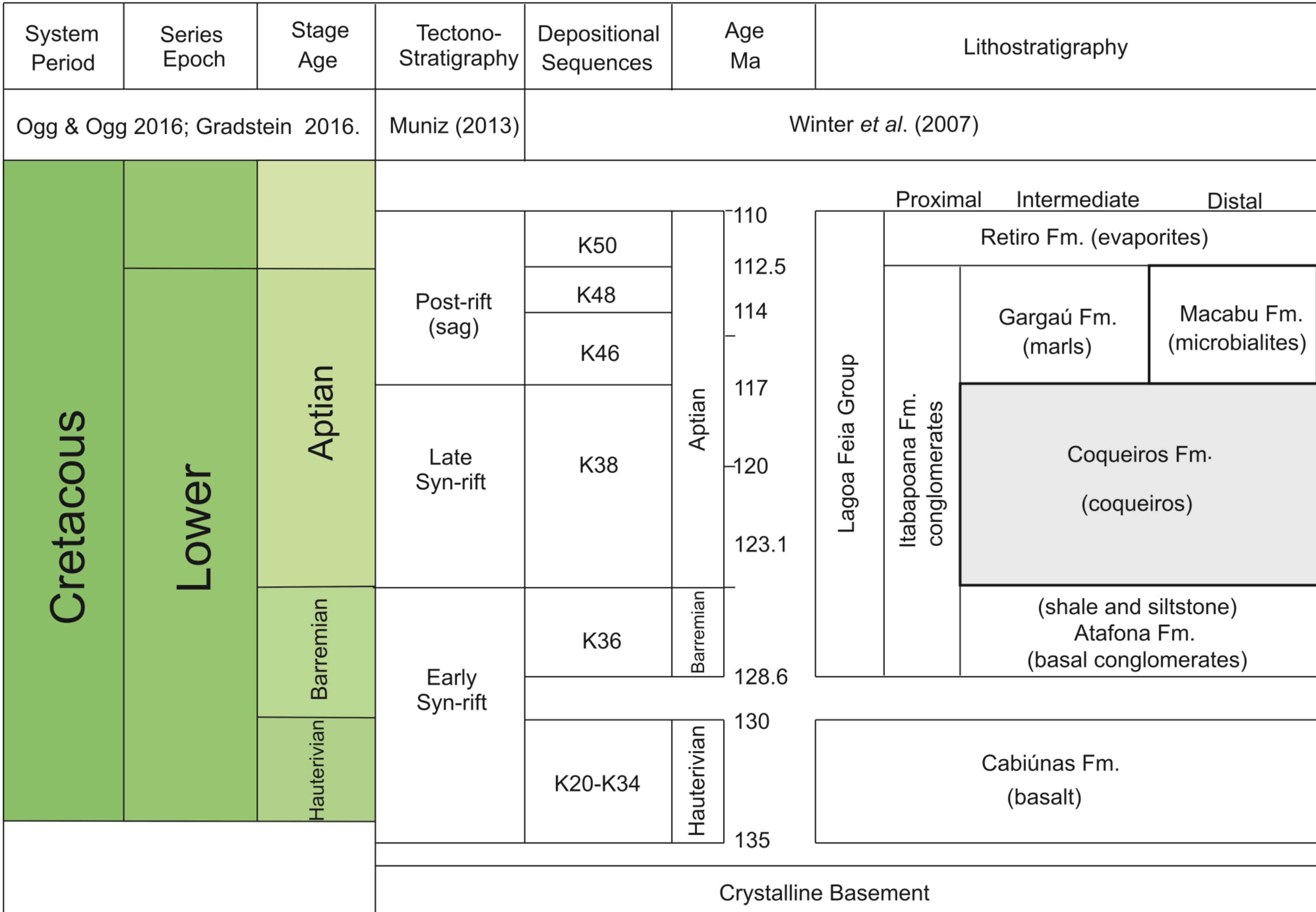
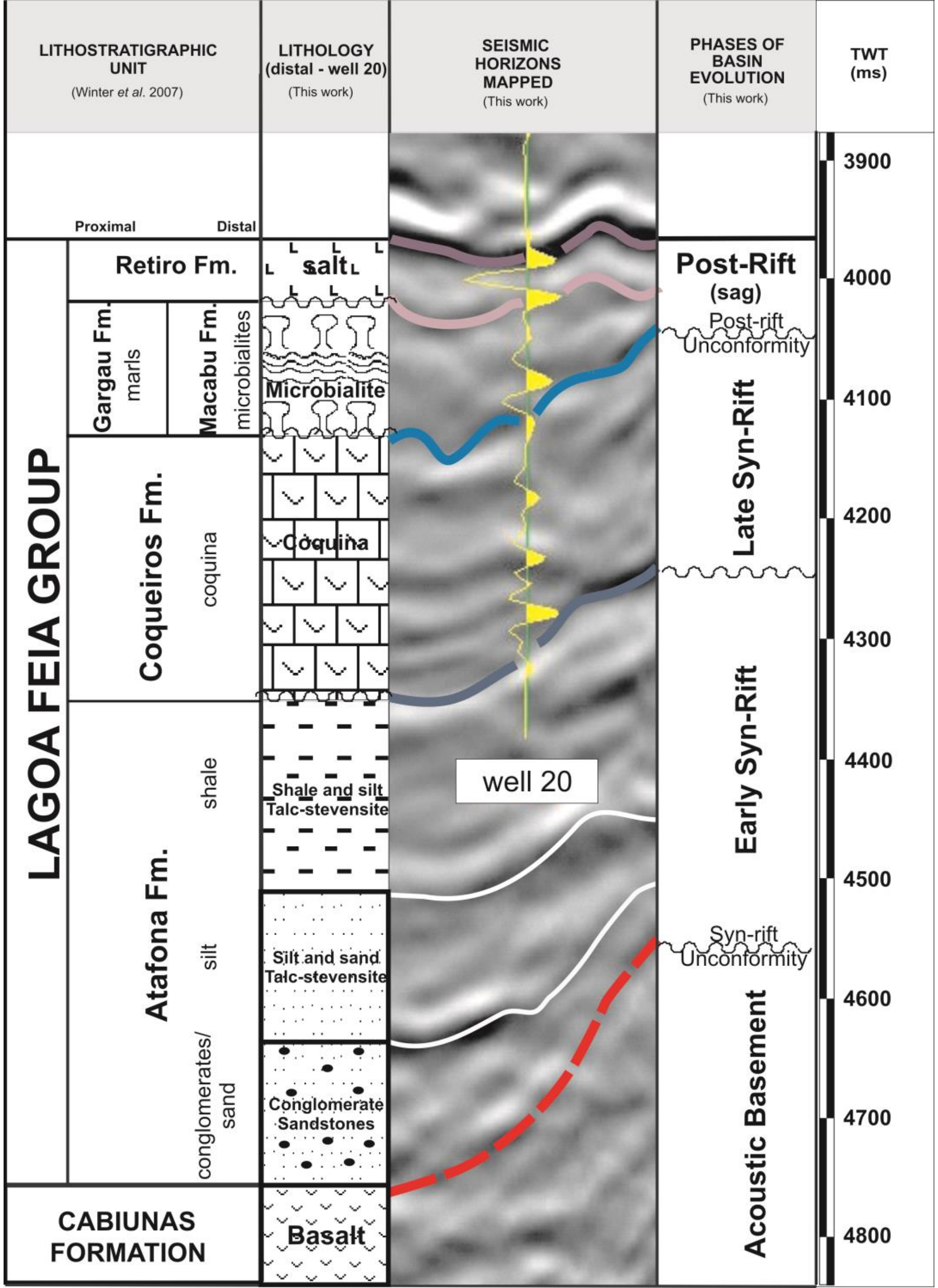
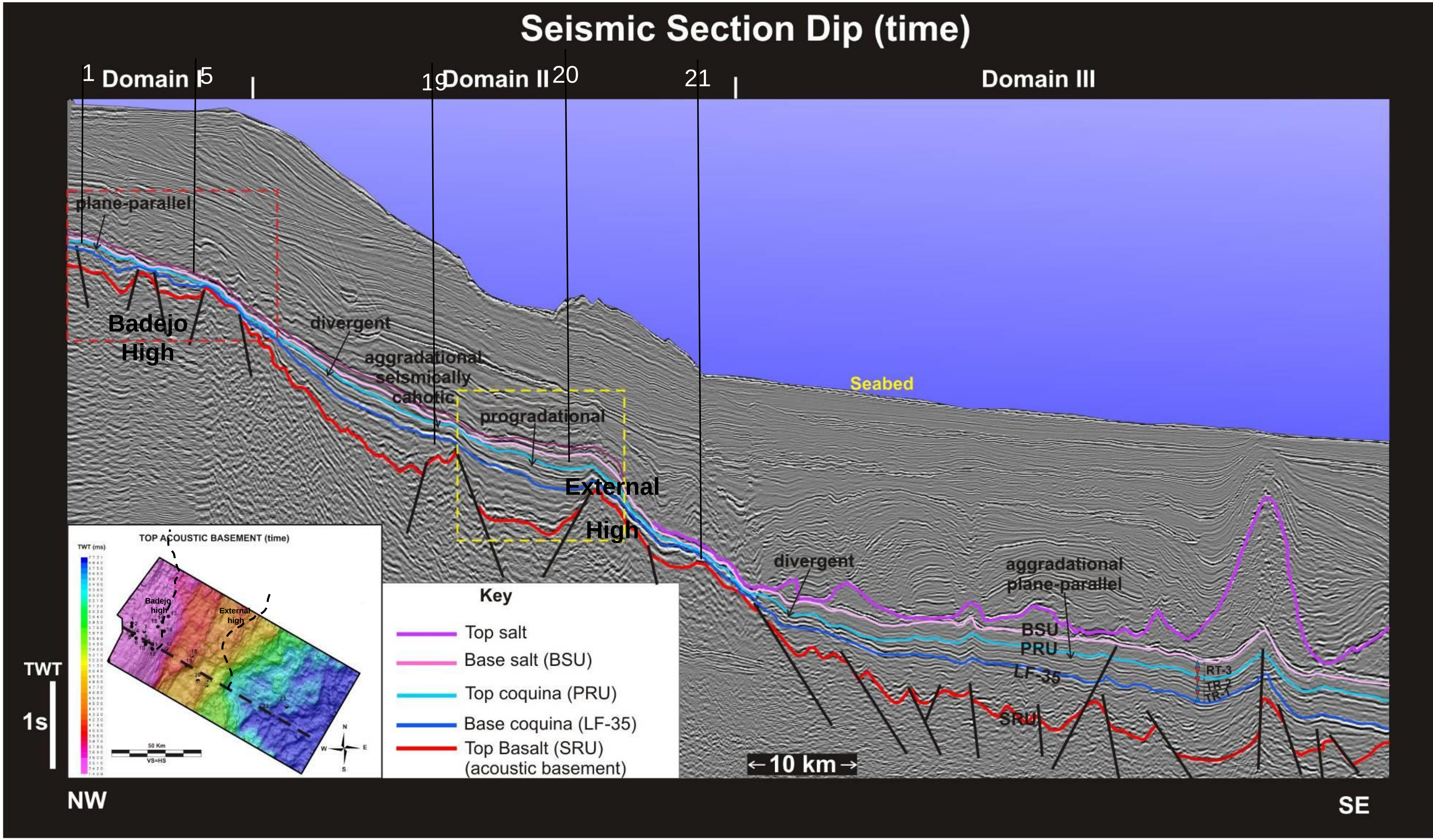

System Period
Series Epoch
Stage Age
Tectono-Stratigraphy
Depositional Sequences
Age Ma
Lithostratigraphy
Ogg & Ogg 2016; Gradstein 2016.
Muniz (2013)
Winter *et al.* (2007)
Cretacous
Lower
Aptian
Barremian
Hauterivian
Proximal
Intermediate
Distal
Post-rift (sag)
Late Syn-rift
Early Syn-rift
K50
K48
K46
K38
K36
K20-K34
Aptian
Barremian
Hauterivian
110
112.5
114
117
120
123.1
128.6
130
135
Lagoa Feia Group
Itabapoana Fm. conglomerates
Retiro Fm. (evaporites)
Gargaú Fm. (marls)
Macabu Fm. (microbialites)
Coqueiros Fm.
(coqueiros)
(shale and siltstone)
Atafona Fm.
(basal conglomerates)
Cabiúnas Fm.
(basalt)
Crystalline Basement

Figure 3



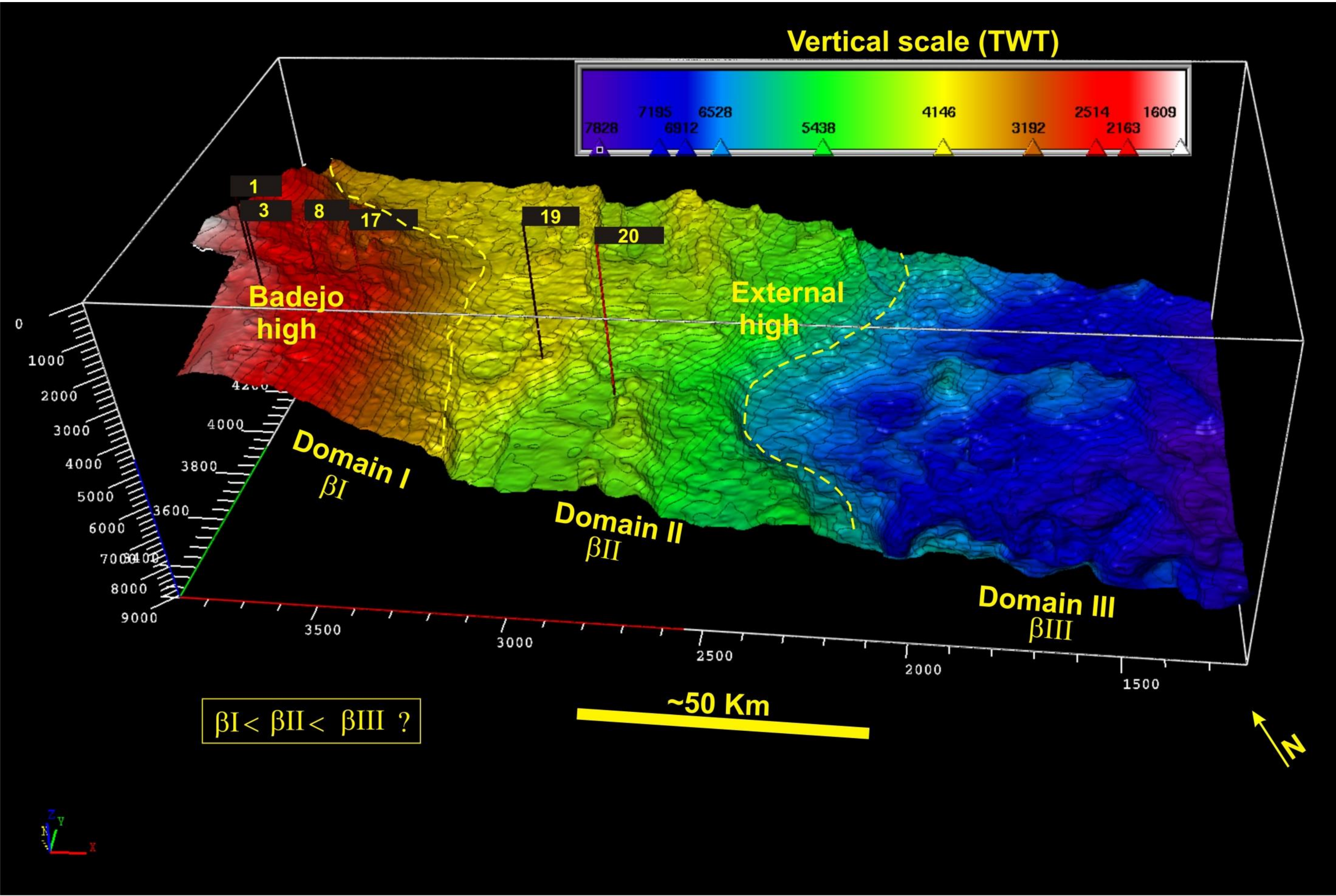
LITHOSTRATIGRAPHIC UNIT
(Winter et al. 2007)
LITHOLOGY (distal - well 20)
(This work)
SEISMIC HORIZONS MAPPED
(This work)
PHASES OF BASIN EVOLUTION
(This work)
TWT (ms)
Proximal
Distal
LAGOA FEIA GROUP
Retiro Fm.
Gargau Fm.
marls
Macabu Fm.
microbialites
Coqueiros Fm.
coquina
Atafona Fm.
shale
silt
conglomerates/ sand
CABIUNAS FORMATION
salt
Microbialite
Coquina
Shale and silt
Talc-stevensite
Silt and sand
Talc-stevensite
Conglomerate
Sandstones
Basalt
well 20
Post-Rift
(sag)
Post-rift
Unconformity
Late Syn-Rift
Early Syn-Rift
Syn-rift
Unconformity
Acoustic Basement
3900
4000
4100
4200
4300
4400
4500
4600
4700
4800

Figure 4



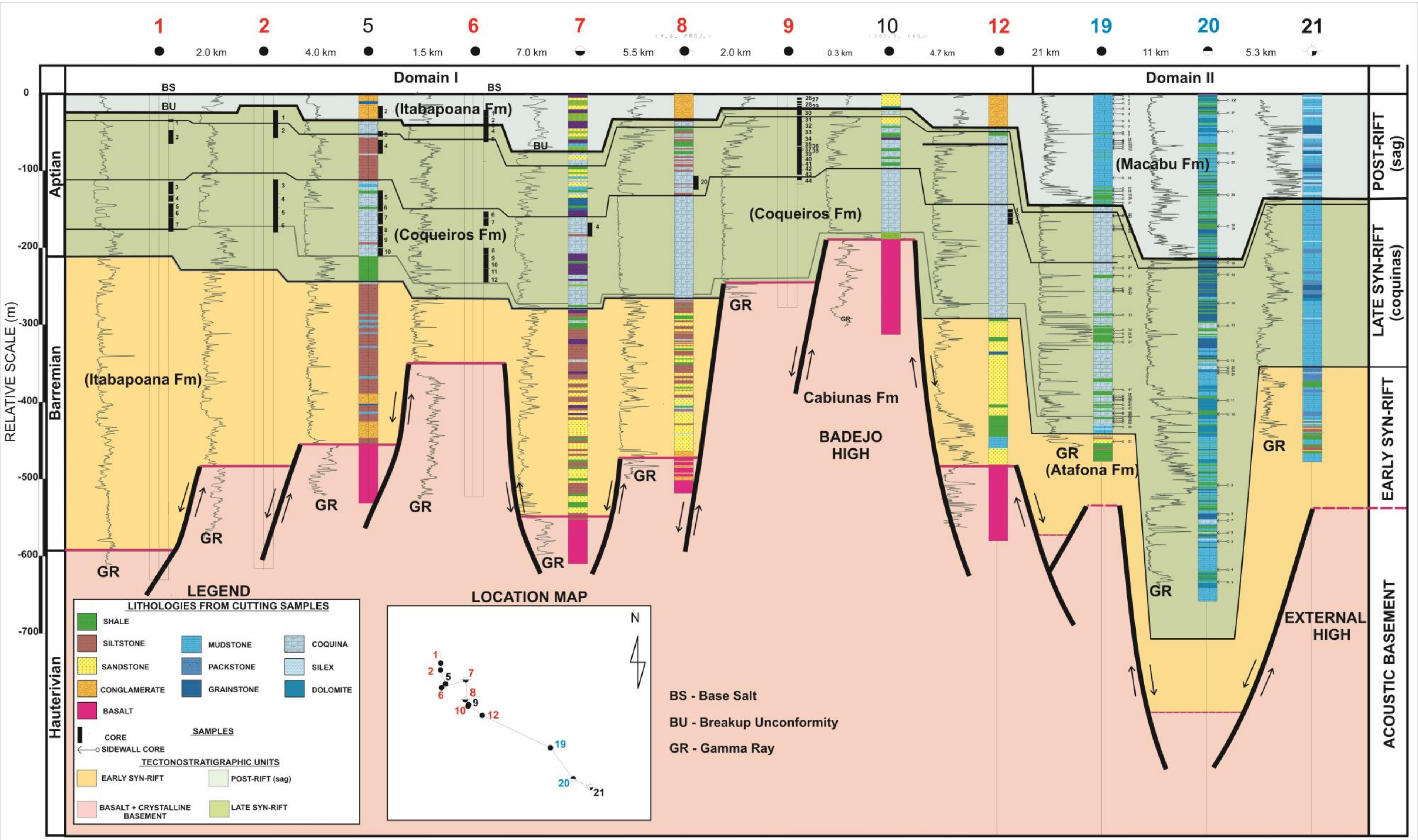
Seismic Section Dip (time)
Domain I
Domain II
Domain III
1
5
19
20
21
plane-parallel
Badejo High
divergent
aggradational seismically cahotic
progradational
External High
Seabed
divergent
aggradational plane-parallel
BSU
PRU
LF-35
SRU
RT-3
TR-2
TR-1
TOP ACOUSTIC BASEMENT (time)
TWT (ms)
Badejo high
External high
50 Km
VS=HS
N
S
E
W
Key
Top salt
Base salt (BSU)
Top coquina (PRU)
Base coquina (LF-35)
Top Basalt (SRU)
(acoustic basement)
←10 km→
TWT
1s
NW
SE

Figure 5



Vertical scale (TWT)
7828
7195
6912
6528
5438
4146
3192
2514
2163
1609
1
3
8
17
19
20
Badejo high
External high
Domain I
βI
Domain II
βII
Domain III
βIII
βI < βII < βIII ?
~50 Km
N
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
4000
3800
3600
3500
3000
2500
2000
1500

Figure 6



1 2 5 6 7 8 9 10 12 19 20 21
2.0 km 4.0 km 1.5 km 7.0 km 5.5 km 2.0 km 0.3 km 4.7 km 21 km 11 km 5.3 km
Domain I
Domain II
RELATIVE SCALE (m)
Aptian
Barremian
Hauterivian
POST-RIFT (sag)
LATE SYN-RIFT (coquinas)
EARLY SYN-RIFT
ACOUSTIC BASEMENT
BS
BU
(Itabapoana Fm)
(Coqueiros Fm)
(Macabu Fm)
Cabiunas Fm
BADEJO HIGH
GR (Atafona Fm)
EXTERNAL HIGH
GR
LEGEND
LITHOLOGIES FROM CUTTING SAMPLES
SHALE
SILTSTONE
SANDSTONE
CONGLAMERATE
BASALT
MUDSTONE
PACKSTONE
GRAINSTONE
COQUINA
SILEX
DOLOMITE
SAMPLES
CORE
SIDEWALL CORE
TECTONOSTRATIGRAPHIC UNITS
EARLY SYN-RIFT
POST-RIFT (sag)
BASALT + CRYSTALLINE BASEMENT
LATE SYN-RIFT
LOCATION MAP
N
BS - Base Salt
BU - Breakup Unconformity
GR - Gamma Ray

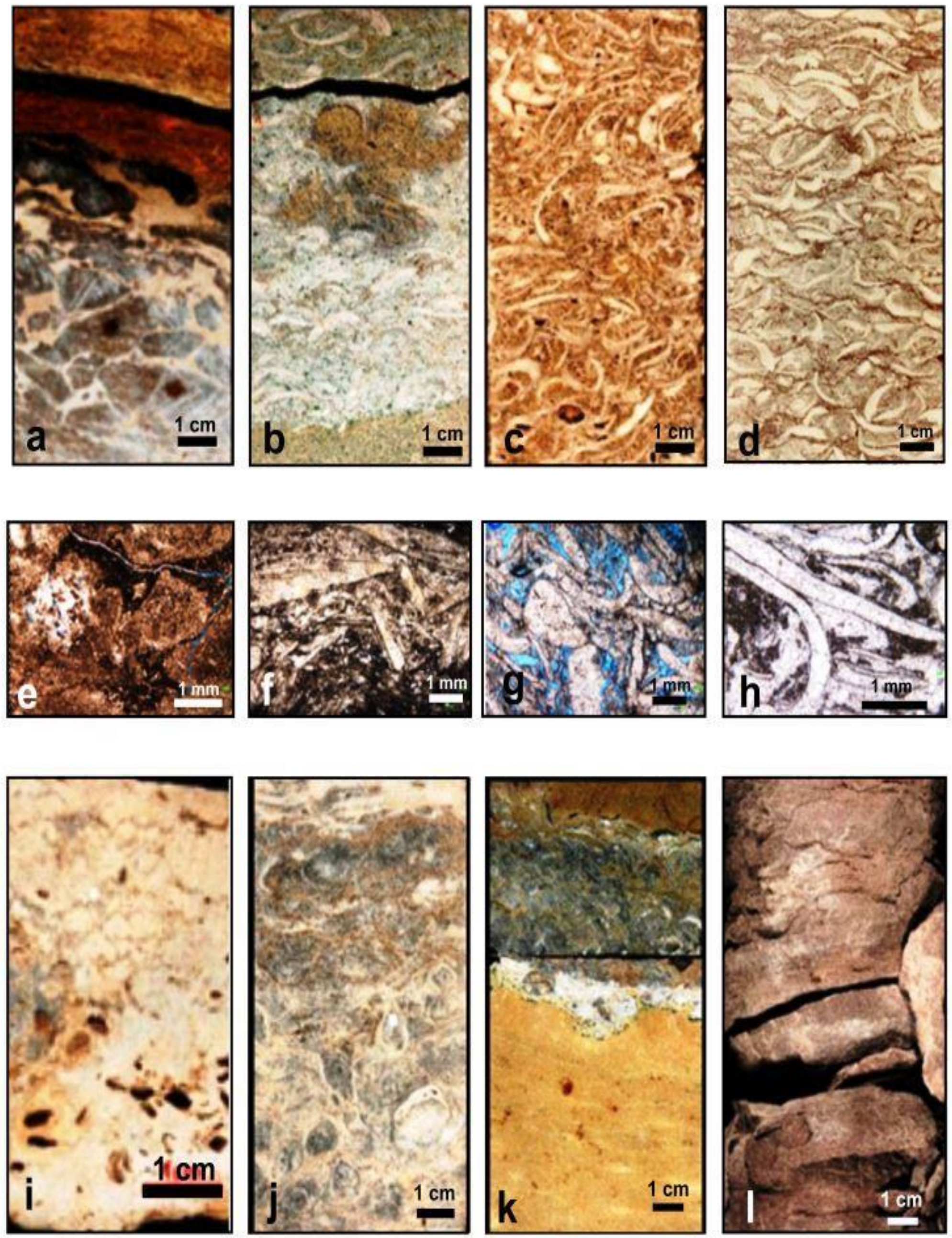
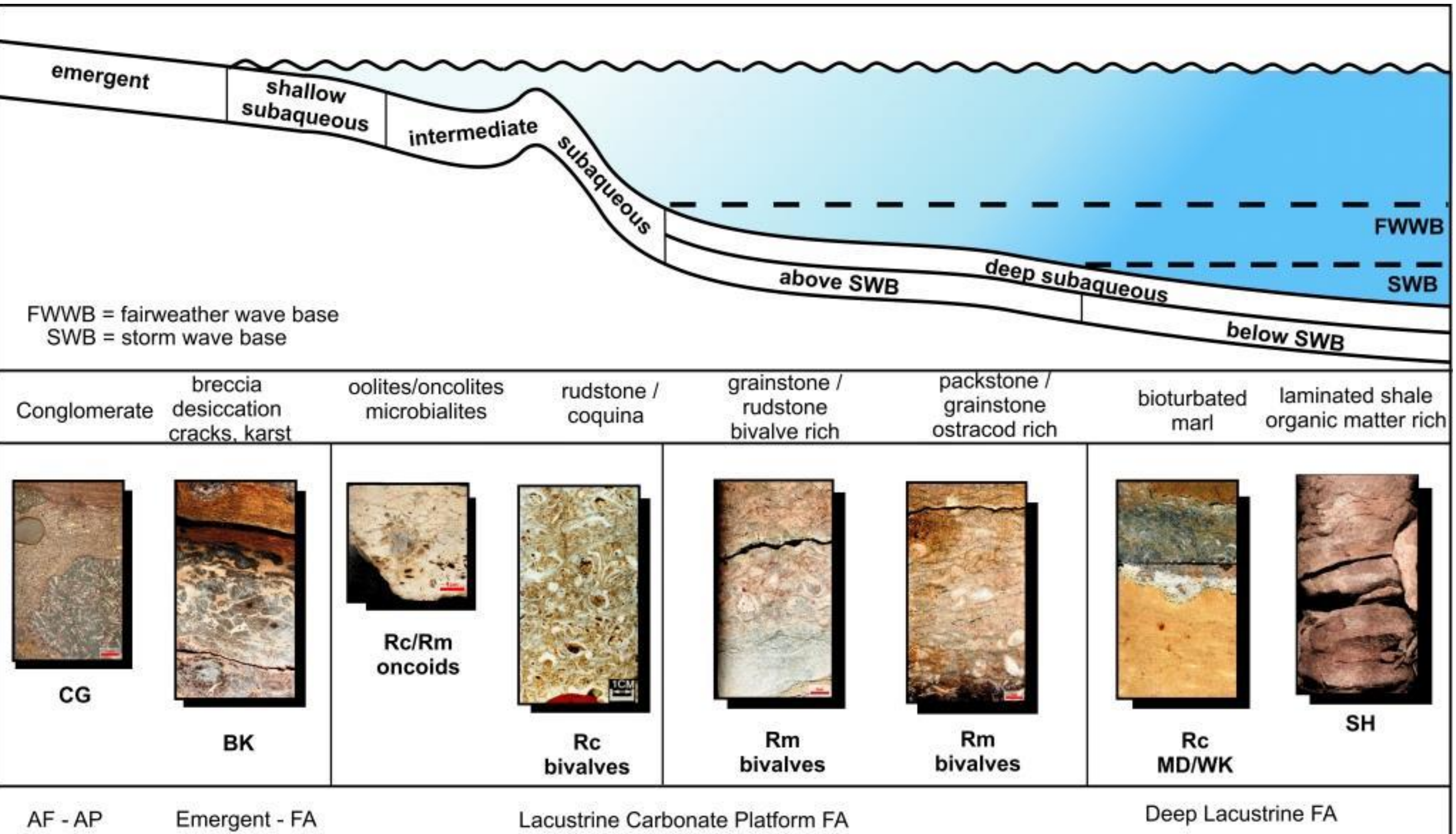
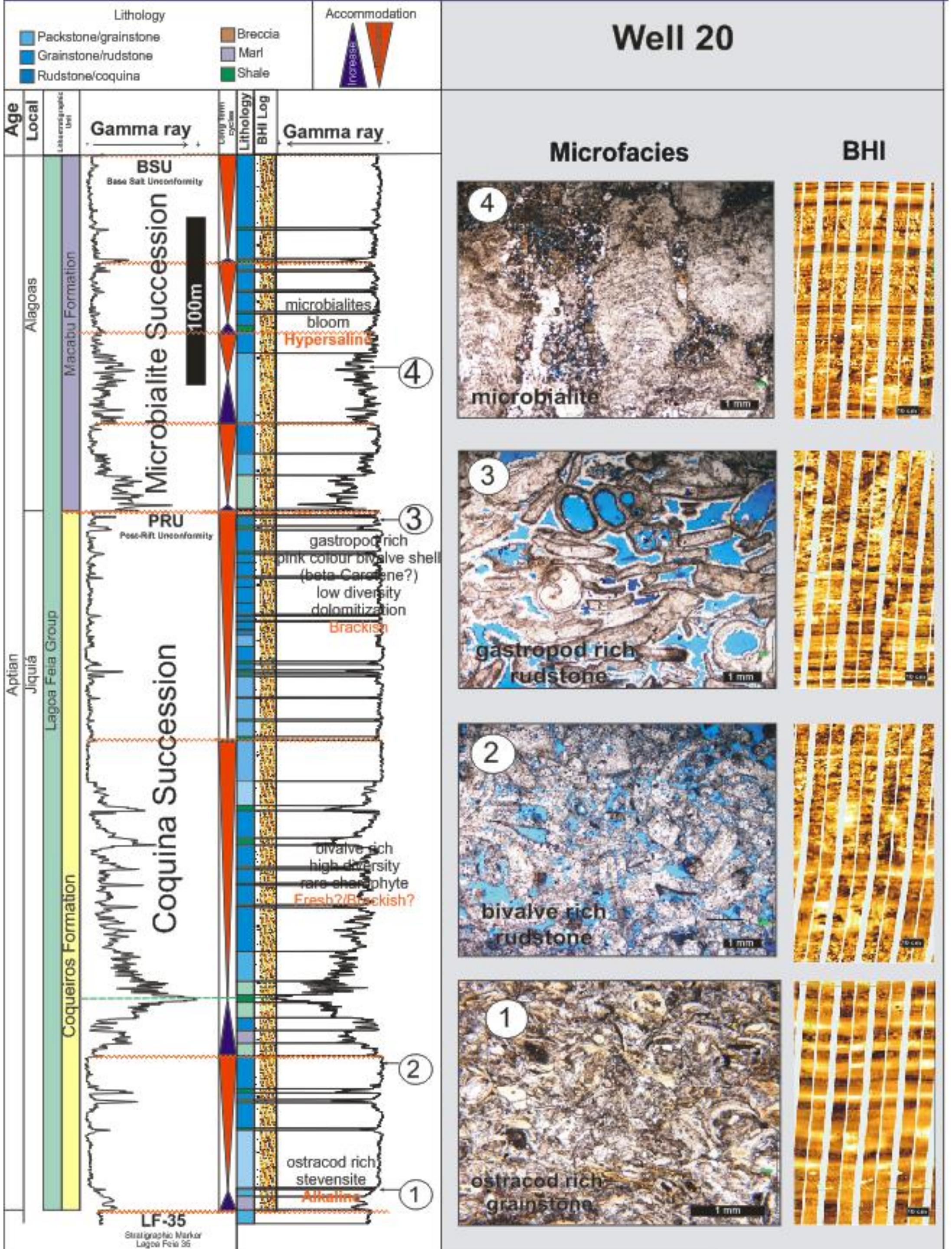


Figure 7

Figure 8



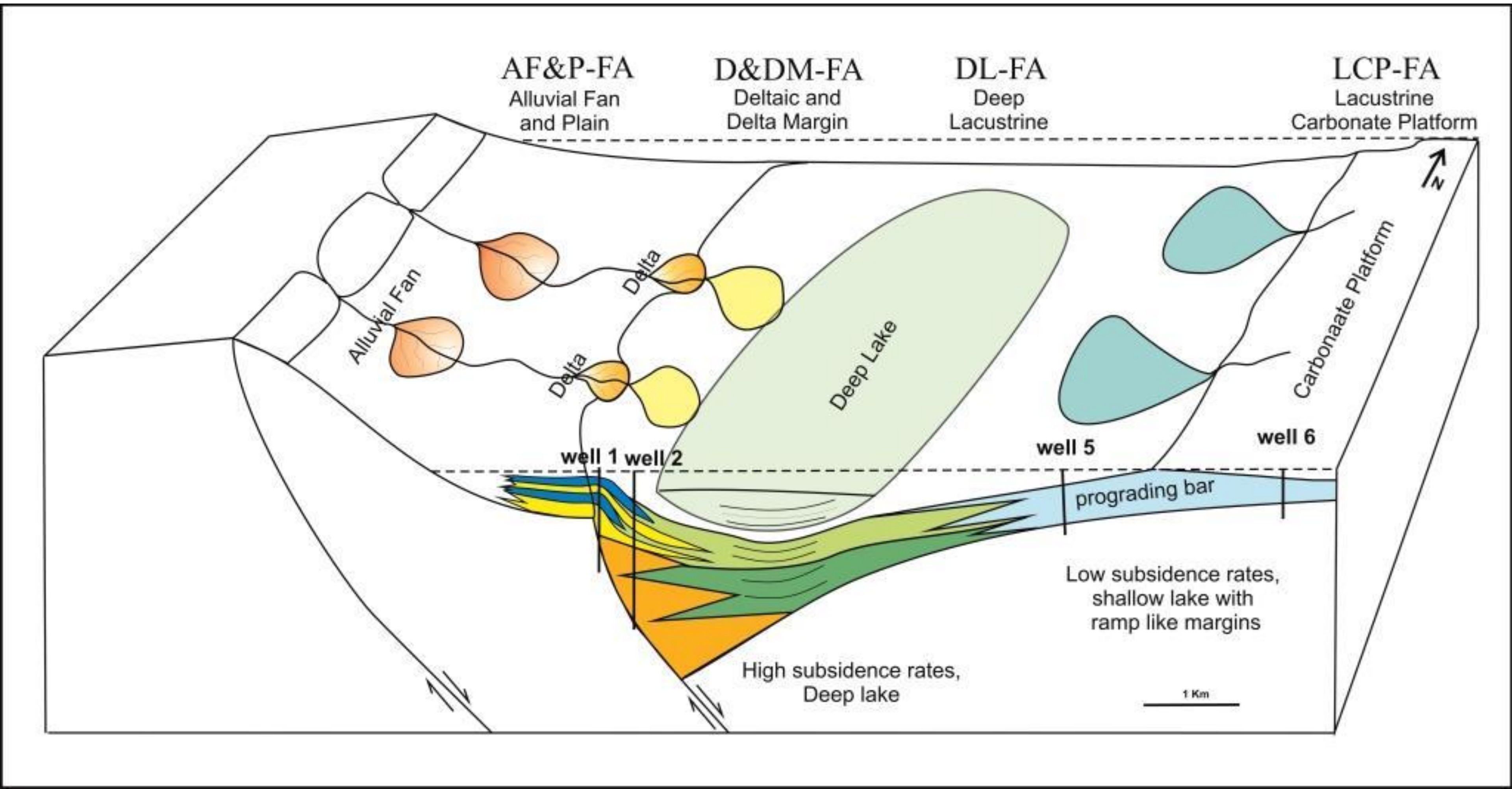
emergent
shallow subaqueous
intermediate
subaqueous
FWWB
SWB
above SWB
deep subaqueous
below SWB
FWWB = fairweather wave base
SWB = storm wave base
Conglomerate
breccia desiccation cracks, karst
oolites/oncolites microbialites
rudstone / coquina
grainstone / rudstone bivalve rich
packstone / grainstone ostracod rich
bioturbated marl
laminated shale organic matter rich
CG
BK
Rc/Rm oncoids
1CM
Rc bivalves
Rm bivalves
Rm bivalves
Rc MD/WK
SH
AF - AP
Emergent - FA
Lacustrine Carbonate Platform FA
Deep Lacustrine FA



Lithology
Packstone/grainstone
Grainstone/rudstone
Rudstone/coquina
Breccia
Marl
Shale
Accommodation
Increase
Well 20
Age
Local
Gamma ray
Lithology
BHI Log
Gamma ray
Microfacies
BHI
BSU
Base Salt Unconformity
Microbialite Succession
100m
Alagoas
Macabu Formation
microbialites
bloom
Hypersaline
4
microbialite
1 mm
PRU
Post-Rift Unconformity
3
gastropod rich
pink colour bivalve shell
(beta-Carotene?)
low diversity
dolomitization
Brackish
gastropod rich
rudstone
Aptian
Jiquiá
Lagoa Feia Group
Coqueiros Formation
Coquina Succession
bivalve rich
high diversity
rare charophyte
Fresh?/Brackish?
2
bivalve rich
rudstone
ostracod rich
stevensite
Alkaline
1
ostracod rich
grainstone
LF-35
Stratigraphic Marker
Lagoa Feia 35

Figure 9

Figure 10


AF&P-FA
Alluvial Fan
and Plain
D&DM-FA
Deltaic and
Delta Margin
DL-FA
Deep
Lacustrine
LCP-FA
Lacustrine
Carbonate Platform
N
Alluvial Fan
Delta
Delta
Deep Lake
Carbonaate Platform
well 1
well 2
well 5
well 6
prograding bar
Low subsidence rates,
shallow lake with
ramp like margins
High subsidence rates,
Deep lake
1 Km

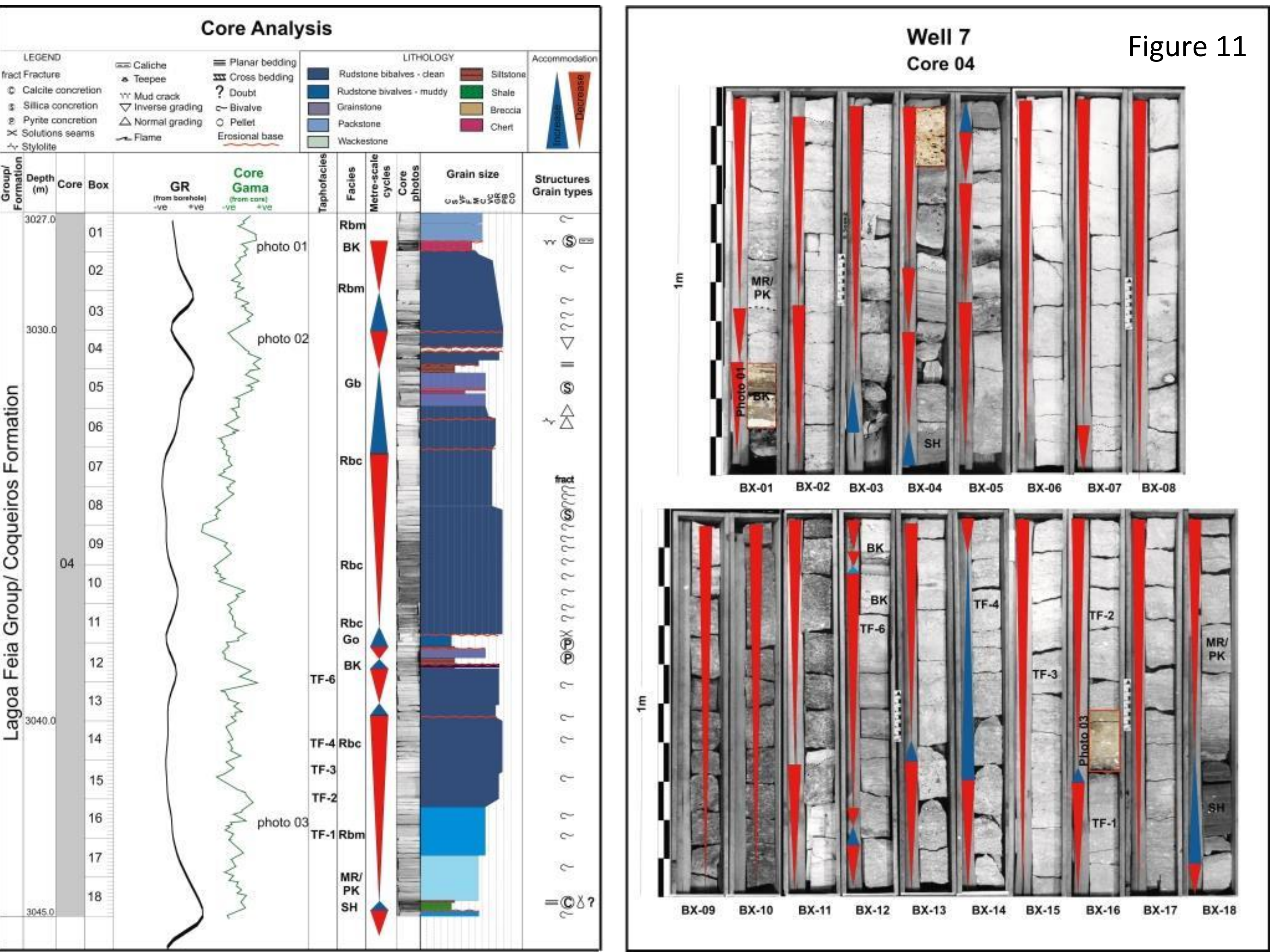
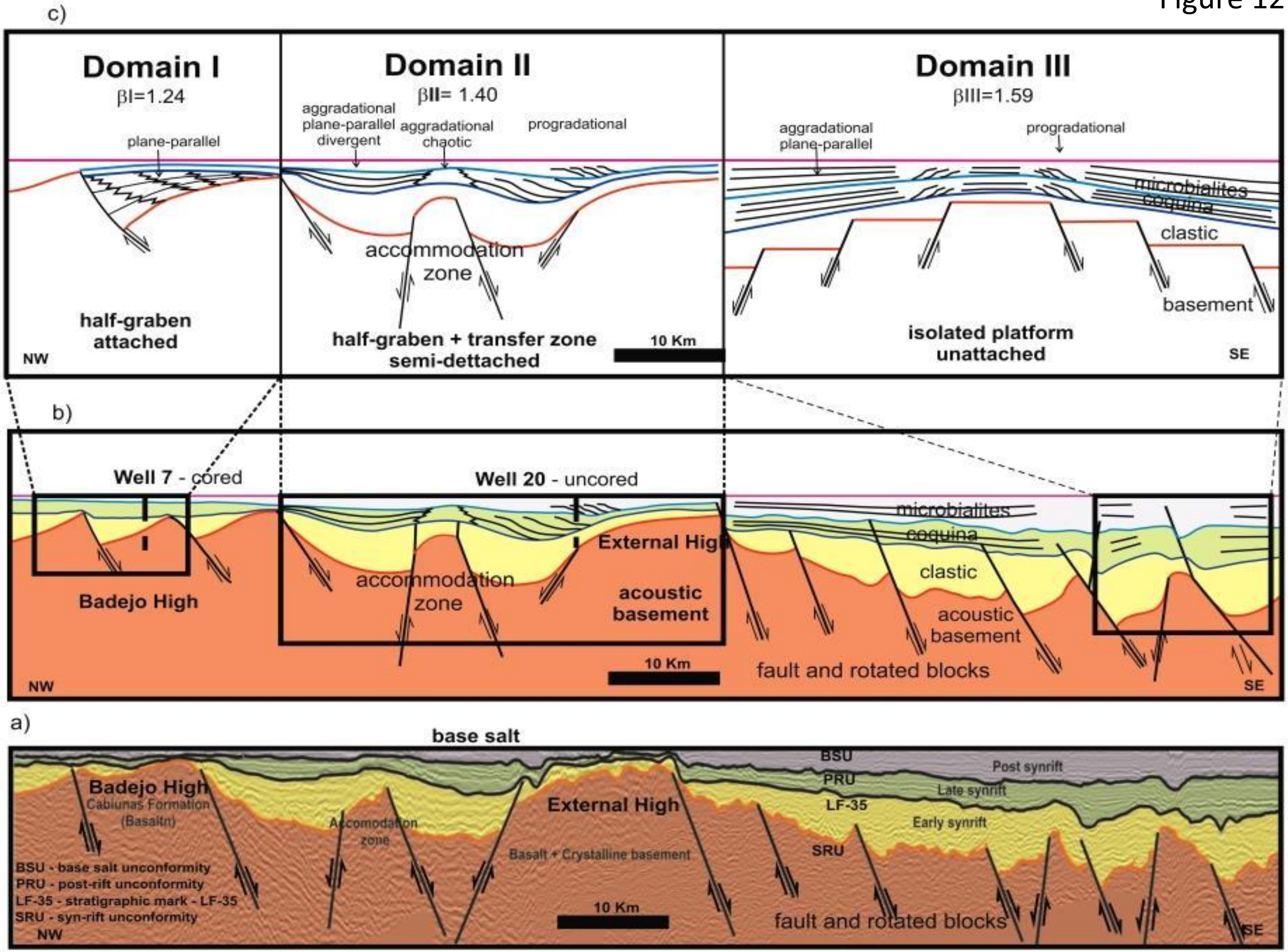
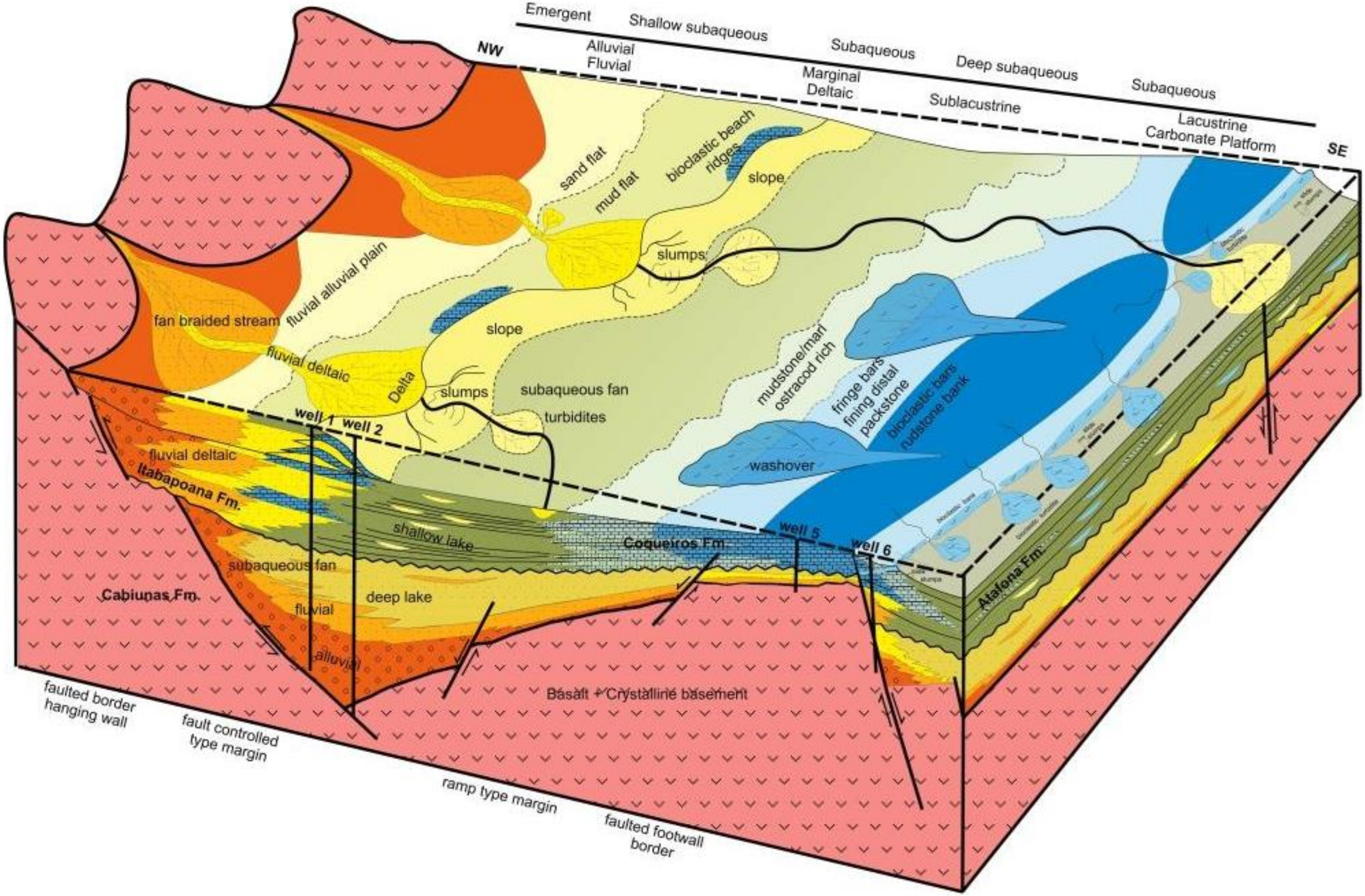

Core Analysis
LEGEND
fract Fracture
Calcite concretion
Silica concretion
Pyrite concretion
Solutions seams
Stylolite
Caliche
Teepee
Mud crack
Inverse grading
Normal grading
Flame
Planar bedding
Cross bedding
? Doubt
Bivalve
Pellet
Erosional base
LITHOLOGY
Rudstone bibalves - clean
Rudstone bivalves - muddy
Grainstone
Packstone
Wackestone
Siltstone
Shale
Breccia
Chert
Accommodation
Increase
Decrease
Group/ Formation
Depth (m)
Core
Box
GR (from borehole)
Core Gama (from core)
Taphofacies
Facies
Metre-scale cycles
Core photos
Grain size
Structures Grain types
Lagoa Feia Group/ Coqueiros Formation
3027.0
3030.0
3040.0
3045.0
photo 01
photo 02
photo 03
TF-6
TF-4
TF-3
TF-2
TF-1
Rbm
BK
Gb
Rbc
Go
MR/ PK
SH
Well 7
Core 04
Figure 11
1m
BX-01
BX-02
BX-03
BX-04
BX-05
BX-06
BX-07
BX-08
BX-09
BX-10
BX-11
BX-12
BX-13
BX-14
BX-15
BX-16
BX-17
BX-18
Photo 01
Photo 03

Figure 12



c)
Domain I
βI=1.24
plane-parallel
half-graben
attached
NW
Domain II
βII= 1.40
aggradational
plane-parallel
divergent
aggradational
chaotic
progradational
accommodation
zone
half-graben + transfer zone
semi-dettached
10 Km
Domain III
βIII=1.59
aggradational
plane-parallel
progradational
microbialites
coquina
clastic
basement
isolated platform
unattached
SE
b)
Well 7 - cored
Well 20 - uncored
External High
Badejo High
accommodation
zone
acoustic
basement
microbialites
coquina
clastic
acoustic
basement
fault and rotated blocks
10 Km
NW
SE
a)
base salt
BSU
PRU
LF-35
SRU
Post synrift
Late synrift
Early synrift
Badejo High
Cabiunas Formation
(Basaltn)
Accomodation
zone
External High
Basalt + Crystalline basement
BSU - base salt unconformity
PRU - post-rift unconformity
LF-35 - stratigraphic mark - LF-35
SRU - syn-rift unconformity
10 Km
fault and rotated blocks
NW
SE

Figure 13



Emergent
Shallow subaqueous
Subaqueous
Deep subaqueous
Subaqueous
NW
Alluvial
Fluvial
Marginal
Deltaic
Sublacustrine
Lacustrine
Carbonate Platform
SE
sand flat
mud flat
bioclastic beach ridges
slope
slumps
fan braided stream
fluvial alluvial plain
fluvial deltaic
Delta
slope
slumps
subaqueous fan
turbidites
mudstone/marl ostracod rich
fringe bars fining distal packstone
bioclastic bars rudstone bank
washover
well 1
well 2
fluvial deltaic
Itabapoana Fm.
shallow lake
Coqueiros Fm.
well 5
well 6
Atafona Fm.
subaqueous fan
Cabiunas Fm.
deep lake
fluvial
alluvial
Basalt + Crystalline basement
faulted border hanging wall
fault controlled type margin
ramp type margin
faulted footwall border

Figure 14

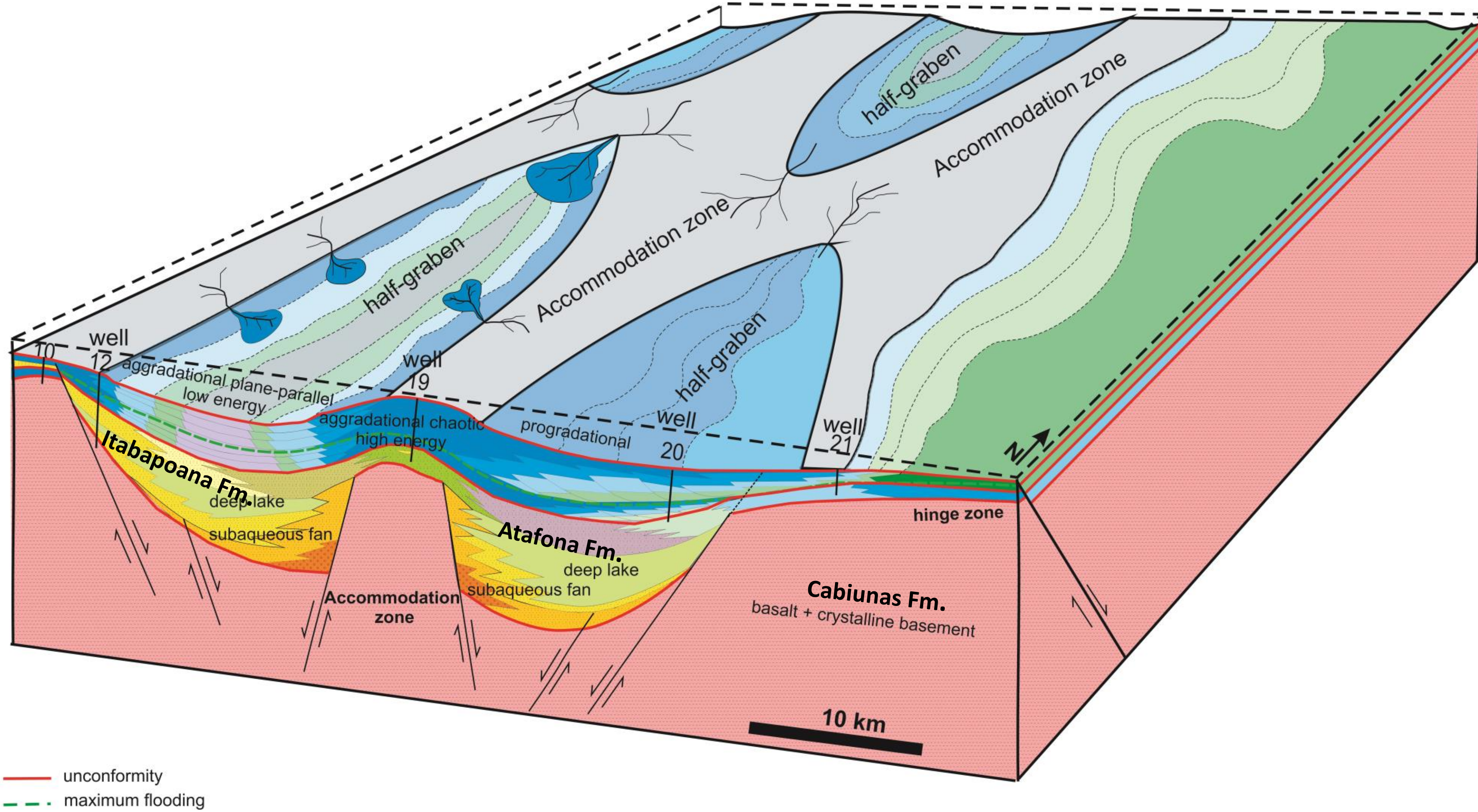
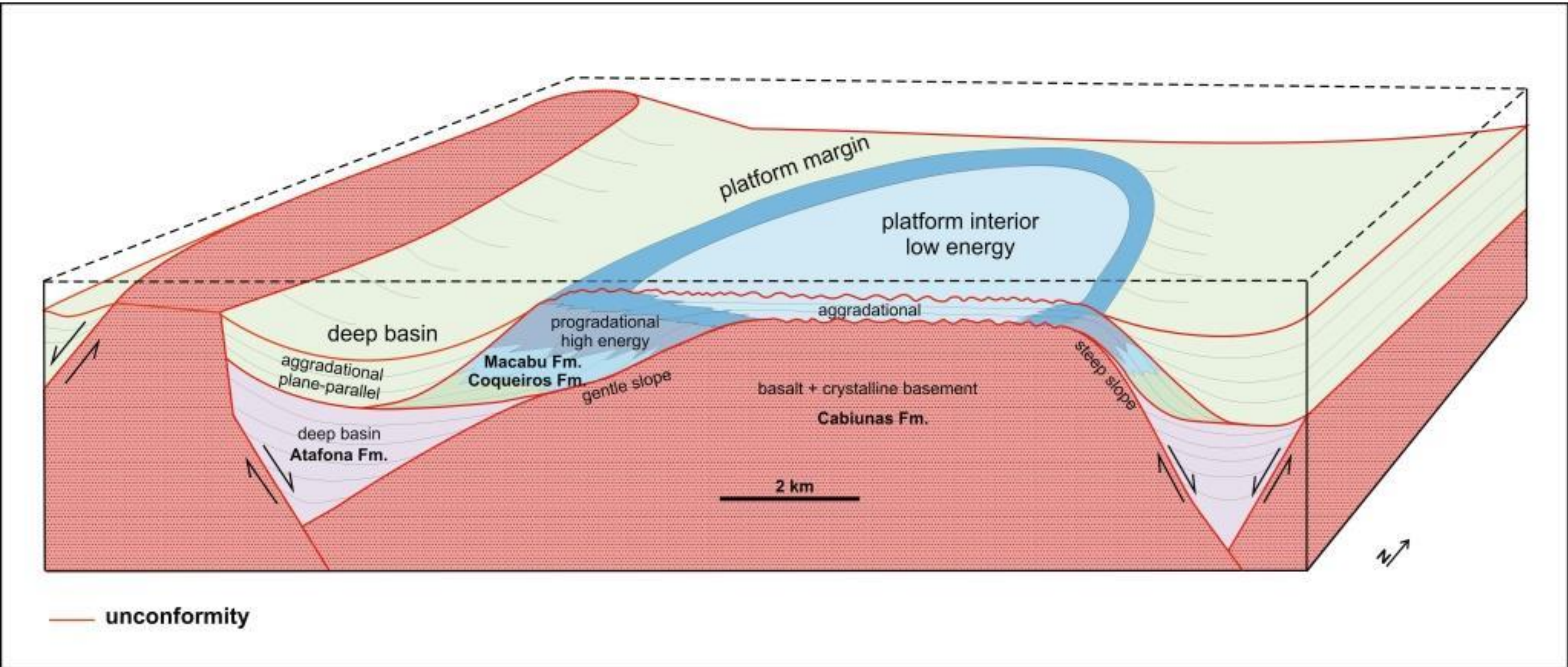

half-graben
Accommodation zone
half-graben
Accommodation zone
half-graben
well 10
well 12
well 19
well 20
well 21
aggradational plane-parallel
low energy
aggradational chaotic
high energy
progradational
Itabapoana Fm.
deep lake
subaqueous fan
Atafona Fm.
deep lake
subaqueous fan
Accommodation zone
hinge zone
Cabiunas Fm.
basalt + crystalline basement
N
10 km
unconformity
maximum flooding

Figure 15



platform margin
platform interior
low energy
deep basin
aggradational
plane-parallel
progradational
high energy
Macabu Fm.
Coqueiros Fm.
gentle slope
aggradational
basalt + crystalline basement
Cabiunas Fm.
steep slope
deep basin
Atafona Fm.
2 km
N
unconformity

Carbonate facies	Structures	Textures	Composition	Diagenetic Features	Porosity Types	Depositional Processes
Mudstone MD	10-30 cm beds	mudstone	Peloids <10% bivalve and ostracod frags. Locally argillaceous	Localised pyrite, phosphate & calcite concretions Microspar	Fracture	Abiotic precipitation/ abrasion/disintegration of skeletal material Quiet water Deep subaqueous, dysoxic
Marl ML	Lamination	Bioturbation	Mixed carbonate and terrigenous mud Ostracod fragments			Quiet water, deep subaqueous, dysoxic-oxic
Wackestone WK	Centimetric to m-thick massive beds Local erosive contacts	Matrix support Bioturbation	Bivalves, ostracods rare gastropods Peloids, Stevensite, volcanic lithoclasts	Local silica nodules and brecciation	Fracture	Quiet water Deep or protected subaqueous
Packstone P	Centimetric to m-thick massive beds w. erosive contacts. Rare low L x-stratification	Aligned shells Normal grading Local bioturbation	Bivalves, ostracods gastropods Peloids, Stevensite, volcanic lithoclasts	Solution seams, stylolite Replaced & recrystallised shells Spar cement Microspar matrix	Vuggy Mouldic Fracture	Erosively based graded beds- storm events and density currents. Matrix infiltrated grainstones
Grainstone G	Thin – thick beds stacked up to 3 m X-stratification	Fine-coarse grain supported Moderate-well sorted Subrounded	Bivalves (whole or broken), gastropods, ostracods Peloids, ooids Quartz, volcanic lithoclasts	Replaced & recrystallised shells Spar cement Locally silicified Dissolution seams stylolites	Interparticle mouldic vuggy Micro-fractures	Subaqueous high-energy, mud free waters Above fair weather wave base
Floatstone	Up to 1 m thick	Skeletal frags floating in silt to	Bivalves (articulated or disarticulated),	Replaced & recrystallised shells	Fracture	Quiet water Deep or protected

F		sand size matrix	gastropods, ostracods Rare oncoids	Microspar matrix Stylolites		subaqueous Bivalve colonization and local reworking
Rudstone muddy Rm	Cm to m-thick beds Bioturbation	Inverse graded beds Skeletal frags with peloidal muddy matrix	Bivalves (disarticulated or articulated) <3 cm *Trigonodus, Kobayashites, Camposella,* Stevensite Oncoids	Replaced & recrystallised shells Microspar and spar cement Local silicification,stylolites		Subaqueous moderate-energy waters Above fair weather wave base Intermediate subaqueous lake
Rudstone sandy Rt	Cm to m-thick beds	Skeletal frags in matrix in coarse terrigenous sand	Disarticulated and fragmented *Camposella* Lithoclasts (volcanic) feldspar quartz	Recrystallised/replaced & silicified shells Spar cement Local stylolites	Interparticle	Proximal environments Subaqueous high-energy, Above fair weather wave base Intermediate subaqueous lake
Rudstone clean Rc	Cm to m-thick shell beds & X beds Bed parallel alignment, concave-down or -down	Well rounded bivalve frags (<5 cm) in grainstone	Unionid bivalves *Trigonodus, Camposella, Desertella* and fragments Oncoids	Replaced & recrystallised shells Spar cement Local silicification,stylolites	Interparticle mouldic vuggy	Subaqueous high-energy, mud free waters Above fair weather wave base Intermediate subaqueous lake
Siliciclastic Facies	**Structures**	**Textures**	**Composition**	**Diagenetic Features**	**Porosity Types**	**Depositional Processes**

Shale SH	Laminated, syn-sedimentary folds. Locally brecciated Microbial laminite	Clay and silt size	Quartz and mica. Locally bioclast rich (bivalves, ostracods & fish)	Calcite nodules Pyrite	None visible	Deep subaqueous lake or delta plain. Lack of bioturbation and reduced biota implies low oxygen
Siltstone ST	to 0.3 m thick beds Up to 7 m thick when stacked Weak laminae	Bioturbation and mottling	Clay minerals, mica, quartz, volc rock frags, mud pebbles Abraded mollusc bioclasts, fish bones	Calcite and pyrite nodules Spar cement Fractures	None visible	Quiet water deposition Burrowing indicates oxic zone Deep subaqueous or protected shallow lacustrine waters
Sandstone fine Sf	0.1 to 1m thick beds stacked to 6 m units Low angle X beds Ripple lamination Erosive bases	Very fine to fine sand Locally argillaceous Fluidisation	Quartz, feldspar, mica, volc rock frags, Clay minerals, Abraded mollusc bioclasts, fish bones	Calcite and pyrite nodules Replaced & recrystallised shells Spar cement Fractures	None visible	Fluvio-deltaic settings with moderate energy Proximal lacustrine margins
Sandstone medium Sm	Centri-metric beds plane laminated X- bedded Fluidisation structures	Medium sand Bioturbation	Quartz, feldspar, mica, volc rock frags, garnet, , Abraded mollusc bioclasts,	Replaced & recrystallised shells Spar cement Local silicification	Interparticle	Fluvio-deltaic settings with moderate energy Proximal lacustrine margins Lacustrine fans
Sandstone coarse Sc	Centri-metric thick beds Plane laminated X- bedded Graded beds	Coarse sand	Quartz, feldspar, mica, volc rock frags Bivalve frags <4 cm	Replaced & recrystallised shells Spar cement Local silicification	Interparticle	Fluvio-deltaic settings with moderate-high energy Proximal lacustrine margins Lacustrine turbidite fans
Conglomerate matrix support CM	Massive, m-thick bedded Syn-sedimentary	Poorly sorted pebbles supported in	Lithoclasts incl. shale clasts plus sand		None visible	Mass flow deposit. Associated with shale and turbidite sands in deep

	deformation structures	muddy matrix				subaqueous lacustrine setting
Conglomerate clast support CB	0.1 to 1m thick beds stacked up to 3 m units Erosive base, fining up	Well rounded pebbles in coarse sand-granule Clast support	Polymictic; Igneous, metamorphic and sedimentary rock pebbles in quartz, feldspar, lithoclast and mica coarse sand	Spar cement Locally with replaced & recrystallised shells	Interparticle	High energy event deposit Occurs adjacent to basin margin faults Alluvial fan or fan delta, where subaqueous
Modified Facies						
Chert CH	cm-0.2 m thick beds and as nodules Shrinkage cracks and fractured		Brown cryptocrystalline silica	Replacement of host sediments	None visible	Diagenetic replacement of marginal siliciclastic sands Possible palustrine silcretes
Breccia tectonic Bt	Fractured rocks With clay and sand filled fractures		Fractured host rocks	Spar cement in fractures	Fracture	Encountered in wells adjacent to basin bounding faults (e.g. Well 6)
Breccia karst Bk	Brecciated tops to beds	Clasts of host rock, reworked and set in fine sediment	Variable dependant on siliciclastic or carbonate host rock Iron oxides, calcite and silica nodules	Angular and coated grains Brecciation	Breccia	Brecciated tops of beds and associated mineralisation indicate emergent conditions