DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2009/8

Burial anomalies and magnitude of exhumation estimated from sonic data for 19 wells, onshore and offshore NE Brazil; Almada, Camamu, Recôncavo, Sanfranciscana and Tucano Basins

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MINISTRY OF CLIMATE AND ENERGY

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Contribution to the project "Burial and exhumation history of NE Brazil focussing on the Camamu Basin: a multidisciplinary study based on thermal, sonic and stratigraphic data and landform analysis"

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1. Summary

This report documents the estimation of magnitude of exhumation based on burial anomalies evaluated from sonic data for the Mesozoic succession in 18 onshore and offshore wells and for the Proterozoic succession in 1 onshore well, NE Brazil. The burial anomaly is the difference between the present-day burial depth of a rock and its maximum burial estimated as the depth corresponding to normal compaction for the measured velocity predicted by a normal velocity-depth trend for the lithology in question; in this study we will only refer to the absolute value of the burial anomaly. The amount of section removed since maximum burial is the sum of the burial anomaly and the post-exhumational burial.

Burial anomalies are estimated for the drilled succession in each well and they are primarily based on a comparison between (1) the sonic data for high-velocity sandstones and a slightly revised baseline for pure sandstone (relative to those of Japsen et al. 2007) and (2) by a comparison between the sonic data for low-velocity shales and a new baseline for organic-rich shales defined for the Morro do Barro and Rio de Contas Formations. Furthermore, the interpretation may be supported by a comparison between the sonic data and the baseline for pure shale (Japsen 2000).

The estimation of the burial anomaly is based on depth-shifting all three baselines by the same amount until a match is obtained between the baselines and velocity-depth datapoints for the corresponding lithologies. The benefit of this qualitative approach is that whereas the velocity-depth trend for one of the lithologies may be difficult to identify from the sonic data, the comparison of the sonic data for two or more lithologies with the respective baseline effectively limits the range of the possible burial anomalies. The interpretation of the data for the sandstone units relies on identification of high-velocity units with pure sand and the estimated burial anomaly may thus in some cases only be considered as a lower limit.

Estimates of the section removed relative to the Mesozoic sediments in the Early Cretaceous rift basins are (see Table *i;* Figure *i*):

- Tucano Basin, 2.5 ± 0.6 km for one well (FPO-1) with two other wells only yielding lower limits of 1.5 and 1.8 km, respectively (BRN-1, FVM-1).
- Recôncavo Basin, 2.5 ± 0.8 km for one well (MGP-34).
- Camamu Basin
  Inshore, north-west: about 2.0 km for two wells (BAS-84, -113).
  Inshore, south-west: about 1.4 to 1.7 km with estimates ranging from 1.1 ± 0.9 to 1.9 ± 0.5 km for five wells (BAS-21, -64, -74, -97, -107).
  Deep-water: The drilled section is at maximum burial today in one well (BAS-129).
- Almada Basin
  Inshore, exhumed: variations between 1.1 ± 0.7 to 2.9 ± 0.9 km (BAS-71, -77 ,-79).
  Inshore, maximum burial: the drilled sections in two wells are found to be at maximum burial today (BAS-88, -118).
  Deep-water: The drilled section is at maximum burial today in one well (BAS-102)

A tentative estimate of the section removed relative to Proterozoic shale drilled in western Bahia:

- Sanfranciscana Basin: about 5 km for one well (FLU-1).

In the inshore parts of the south-western Camamu Basin, a section of up to 2 km was removed at an unconformity above the Albian–Cenomanian Algodões Fm (c. 400 m preserved) and below the preserved parts of the Urucutuca Fm which are not older than Campanian in this area. This suggests that the exhumation (and hence maximum burial) occurred at the mid-Campanian unconformity which is recognized across the Almada and Camamu Basins (Gontijo et al. 2007; Caixeta et al. 2007). This interpretation is furthermore, in agreement with the Campanian cooling event identified from AFTA data along eastern Bahia and in offshore well BAS-113 (cf. Geotrack onshore and offshore reports 990 & 1013 prepared as part of this study). The section removed at the mid-Campanian unconformity in this part of the Camamu Basin was thus partly a Turonian–mid-Campanian sequence in the lower part of the Urucutuca Fm (probably >1 km prior to exhumation) and partly an upper part of the Algodões Fm.

In the onshore Recôncavo and Tucano Basins, the youngest Mesozoic sediments belong to the Aptian Marizal Fm that rests on rift sediments above a major Aptian unconformity. The section removed above the Marizal Fm is estimated to c 2.5 km with an upper limit around 3 km based on the sonic data in two wells. This magnitude of exhumation onshore is comparable to the exhumation offshore that reaches 2.0 to 2.5 km. The section removed thus corresponds to the accumulated thicknesses of an upper part of the Aptian Marizal Fm (equivalent to the uppermost parts of the Taipus-Mirim Fm), an Albian–Cenomanian sequence (equivalent to the Algodões Fm) and a Turonian–mid-Campanian sequence (equivalent to the Urucutuca Fm below the mid-Campanian unconformity).

In the inshore parts of the Almada and SW Camamu Basins, Paleocene–Oligocene and possibly Campanian strata are preserved above the main unconformity and the Palaeogene section is almost at seabed (wells BAS-77, -79 and -107). The Mesozoic sediments are not at maximum burial whereas the sonic data do not allow us to discriminate whether this is the case for the Palaeogene sediments, but their shallow burial suggests that they could have been buried below a section that is now removed. If this is the case, the burial probably continued into the Neogene when both onshore and inshore areas were affected by Miocene exhumation starting between 18 and 15 Ma as documented by the AFTA data (e.g. BAS-113; Geotrack onshore and offshore reports 990, 1013). The magnitude of any Eocene exhumation at c. 45 Ma (as identified in AFTA data in samples from deep wells in the Recôncavo-Tucano Basins) was not sufficient to remove the Paleocene strata in these wells. Likely implications of these observations are

- that the exhumation following the main Cenomanian event was completed during the Late Cretaceous in the western parts of the Almada and Camamu Basins, both onshore and offshore;
- that Paleogene burial took place in the Almada and Camamu Basins, both onshore and offshore and that the Miocene palaeothermal peak identified in AFTA data in outcrop samples along the coast represents maximum Cenozoic burial prior to Miocene exhumation.

However, in the Recôncavo Basin any Palaeogene deposits were removed prior to the Neogene (probably by Eocene exhumation) because the Lower Miocene Sabiá Fm rests on Early Cretaceous rift sediments in this area (Petri 1972).

In the inshore parts of the Almada Basin, the section drilled (including the Palaeogene sediments) are however, now at maximum burial in the well BAS-88 (supported by AFTA data; Geotrack onshore report 1013). This indicates that the well is located on a block that has experienced a different tectonic history than most of the coastal zone. The sediments in well BAS-118 are also at maximum burial, but this well is located further offshore where it penetrated a 900 m thick section above Paleocene strata.

Table i. *Estimates of burial anomaly for the pre-Campanian section in individual wells and the corresponding amount of removed section. The estimate is based on comparison between the normal velocity-depth trends for pure sandstone, shale and organic-rich shale and sonic log data for the relevant intervals. Depths below sea bed / ground level.*

Basin	Well	Formation below unconformity		Burial anomaly*	Post-exhumational burial	Section removed **	
		Name	Thick (km)	(km)	(km)	Thick (km)	Formations
Tuc	1-BRN-1	Mrz	0.1	1.5 – 3.5	0	1.5 – 3.5	Mrz-younger
WB	1-FLU-1	Prot	1.0	5.0 ± 0.5	0	5.0 ± 0.8	Cmb-Cret
Tuc	1-FPO-1	Mrz	0.3	2.5 ± 0.3	0	2.5 ± 0.6	Mrz-younger
Tuc	1-FVM-1	Mrz	0.1	1.8 ± 0.6	0	min 1.8	Mrz-younger
Rec	6-MGP-34	SSb	0.6	2.5 ± 0.5	0	2.5 ± 0.8	SSb-younger
Cam	BAS-021	Alg	0.4	1.9 ± 0.2	0	1.9 ± 0.5	Alg-Uruc
Cam	BAS-064	Alg	0.4	1.4 ± 0.4	0	1.4 ± 0.7	Alg-Uruc
Alm	BAS-071	RdC	1.4	2.5 ± 0.6	0.4	2.9 ± 0.9	(RdC) Tm-Uruc
Cam	BAS-074	Alg	0.4	1.4 ± 0.4	0	1.4 ± 0.7	Alg-Uruc
Alm	BAS-077	Alg	0.0	0.7 ± 0.4	0.8	1.5 ± 0.7	Alg-Uruc
Alm	BAS-079	Alg	0.0	0.7 ± 0.4	0.4	1.1 ± 0.7	Alg-Uruc
Cam	BAS-084	RdC	2.0	2.0 ± 0.4	0.4	2.4 ± 0.7	(RdC) TM-Uruc
Alm	BAS-088	TM	0.0	0 ± 0.2	1.6	(<1.6)***	(TM-Uruc)
Cam	BAS-097	Alg	0.4	1.6 ± 0.2	0.1	1.7 ± 0.5	Alg-Uruc
Alm	BAS-102	-	-	0 ± 0.2	-	0	-
Cam	BAS-107	Alg	0.3	0.8 ± 0.6	0.3	1.1 ± 0.9	Alg-Uruc
Cam	BAS-113	RdC	0.1	2.2 ± 0.2	0.1	2.3 ± 0.5	RdC-Uruc
Alm	BAS-118	TM	0.8	0 ± 0.4	(1.3)	(<1.3)***	(TM-Uruc)
Cam	BAS-129	Alg	0.1	0 ± 0.2	(1.2)	(<1.2)***	(Alg-Uruc)

*) Magnitude of the burial anomaly (positive numbers). Uncertainty given for the match between the datapoints and the baselines.

**) Allowing for the uncertainty of the baselines.

***) Since the Mesozoic sediments are at maximum burial today, any exhumation on the Late Cretaceous unconformity must have a smaller magnitude than the depth to the unconformity (see Fig. 4-2). min: minimum.

Alg: Algodões Fm; Alm: Almada; Cam: Camamu; Cmb: Cambrian; Cret: Cretaceous; Mrz: Marizal Fm; Prot: Proterozoic; RdC: Rec: Recôncavo; Rio de Contas Fm; TM: Taipus-Mirim Fm; Tuc: Tucano; SSb: São Sebastião Fm; Uruc: Urucutuca Fm; WB: West Bahia.

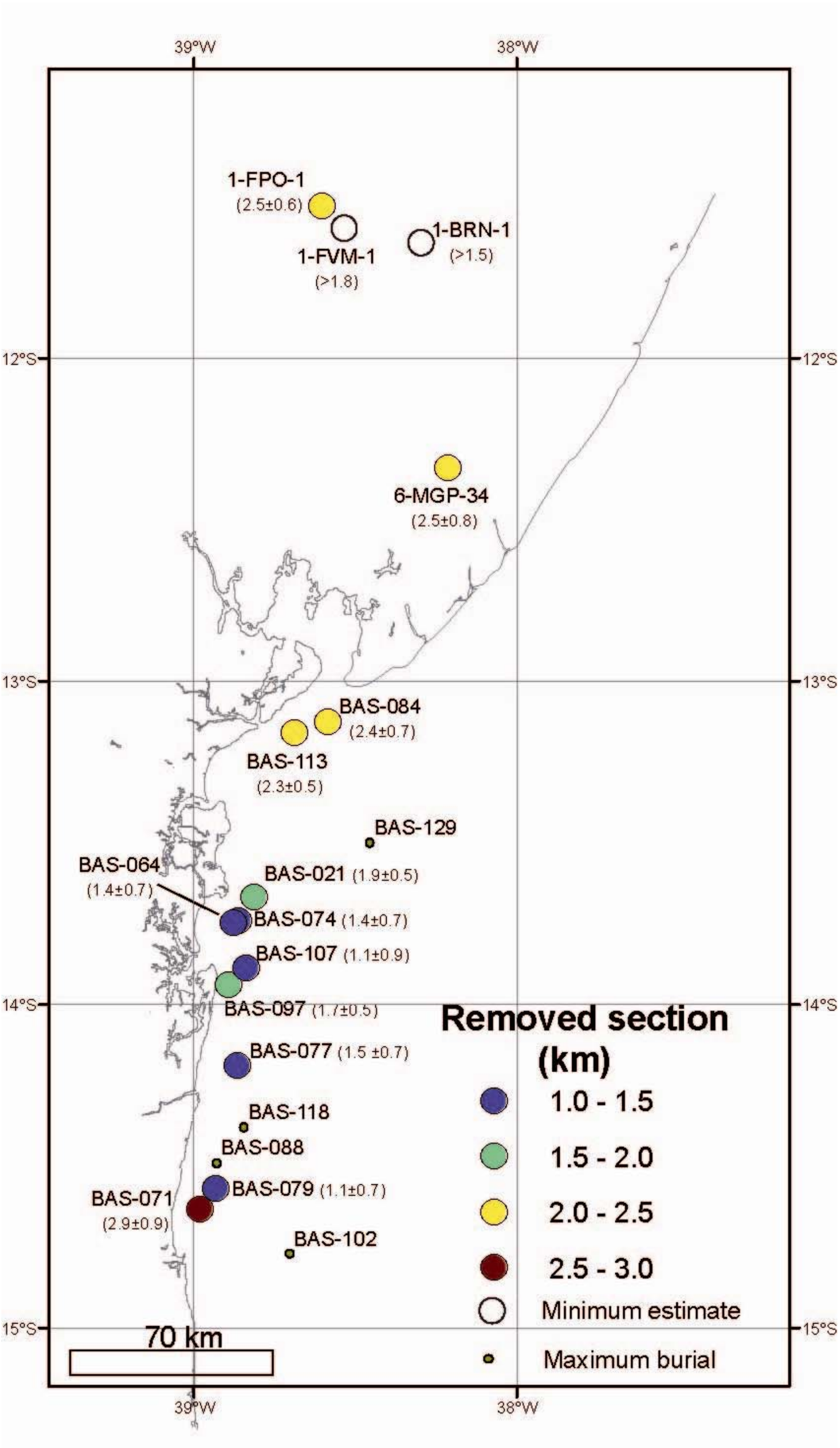


Figure i. *Map of the estimated magnitude of exhumation since maximum burial in the Late Cretaceous based on sonic data in onshore and offshore wells, NE Brazil.*

2. Introduction

This report is a contribution to the research project ‘Burial and exhumation history of NE Brazil focussing on the Camamu Basin: A multidisciplinary study based on thermal, sonic and stratigraphic data and landform analysis’. The project is carried out by GEUS in close cooperation with Geotrack International for StatoilHydro do Brasil Ltda and Petrobras as a multi-disciplinary research project aimed at understanding the regional burial and exhumation history of NE Brazil and the Camamu Basin. The project started in 2007 and will be finished in 2009.

The burial and exhumation history of the study area are also analyzed in reports (that are part of thus study) of apatite fission-track analysis (AFTA) data in samples from offshore wells (Geotrack report 1013) and in samples from onshore wells and outcrops (Geotrack report 990). These reports form part of the present project. These AFTA studies have identified three episodes of post-rift cooling:

- Late Cretaceous (Campanian) cooling starting in the interval between c. 80 and 75 Ma,
- Eocene cooling starting in the interval between c. 48 and 45 Ma
- Miocene cooling starting in the interval between c. 18 and 15 Ma

Whereas the Campanian and the Miocene event affected the entire onshore study area in eastern Bahia and inshore Camamu well BAS-113, the Eocene event has only been detected in deep wells in the Recôncavo-Tucano Basins.

3. Data

The study is based on log data for 19 boreholes, 5 onshore and 14 offshore (Table A-1 in Appendix A). Three wells are from the southern part of the Tucano Basin (BRN-1, FPO-1, FVM-1), 1 from Recôncavo (6-MGP-34) and one from the margin of the Sanfranciscana Basin in the western part of the state of Bahia (FLU-1). Eight offshore wells are from the Camamu Basin (BAS-21, -64, -74, -84, 97, -107, 113, -129) and 6 from the Almada Basin (BAS-71, -77, -79, -88, -102, -118). All wells drill into the Lower Cretaceous rift sequence, apart from the FLU-1 well that was drilled into Proterozoic sediments. The thickness of the drilled sequences onshore range between 1.0 km (FLU-1) and 5.6 km (FVM-1), and offshore this range is between 2.3 km (BAS-107) and 3.9 km (BAS-84).

Stratigraphic charts for the Almada, Camamu and Recôncavo Basins are shown in figures A-1 to A-3 (*Gontijo et al. 2007; Caixeta et al. 2007; Silva et al. 2007*). Composites logs and interpretations of the lithology (digital LithoLogs) were supplied for most of the wells as listed in Table A-1. A lithostratigraphic subdivision of the wells was supplied by the costumer and is listed in Table A-2. Well log data were supplied in LAS format, in most cases containing tracks with caliper, sonic transit time, density, gamma and in some cases neutron porosity (log plots in Appendix B).

3.1 Deletion of bad-hole data

Figure 3-1 shows an example of how caving may cause recording of atypical low sonic velocities; in the left panel, data points for which the caliper exceeds 13'' are marked by red dots and in the right panel, it seen that the corresponding Vp-values plot below the general trend. Consequently, log data from borehole intervals with caving have been deleted in the most extreme cases (see plots in Appendix B).

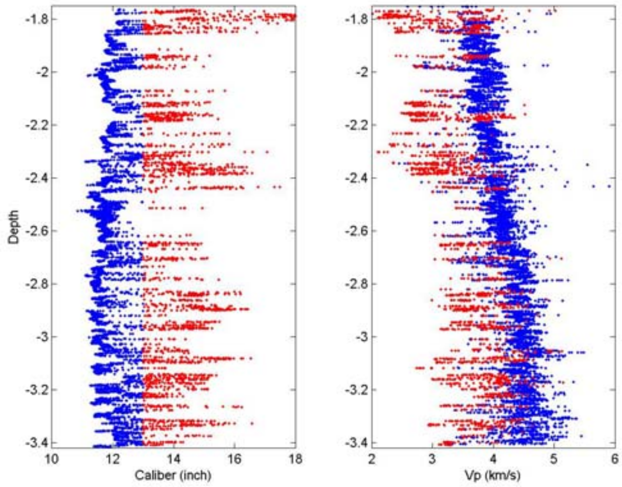


Figure 3-1. *Plots of caliper (left) and Vp (right) versus depth for well FPO-1. The size of the regular hole in this depth interval is about 12 inches, but locally the hole is more than 16'' wide. Data points for which the caliper exceeds 13'' are marked by red dots and it is seen that these bad-holed data have Vp-values below the general trend.*

3.2 Displays of sonic data

The log data for each well are displayed on double pages in Appendix B:

- Composite plots of the caliper, raw sonic, density, neutron porosity (where available) and gamma logs (upper left plots).
- Plots of caliper and sonic logs for detection of bad-hole data and a plot of the edited sonic data (lower left plots).
- Plots of the bad-hole corrected sonic log colour-coded according to the lithology as interpreted from the LithoLog (upper right plot).
- Plots with interpretation of burial anomaly based on a comparison of the edited sonic (averaged over 10-m intervals) log and the baselines for pure sandstone (BR00, BR05), pure shale (Vsh) and organic-rich shale (Vsh-o). In these plots the sonic log is colour-coded according to the main lithostratigraphic units. The full range of the sonic velocities is thus not shown in these plots and thus both data scatter and sonic variations related to lithology are suppressed (lower right plot).

The interpreted datapoints for high-velocity sandstone and low-velocity shale units in each well are displayed on both the upper and lower right plots

Details of the sonic logs as plotted in the composite logs (not included in this report) show that the quality of the sonic logs may not always allow for reliable estimates of the mean velocity of a unit; e.g. in well FVM-1 where the likely velocity around 5 km/s of a sand (?) unit at c. 4.4 km is only reached in a few data points due to considerable scatter (cf. the sonic log for the near-by FPO-1 well).

4. Velocity anomalies and burial anomalies

4.1 Estimation of maximum palaeoburial using sonic data

The technique for estimating maximum palaeoburial of a sedimentary unit – and thus the amount of erosion of its overburden – from sonic data has been known for decades (e.g. Marie 1975; Magara 1976; Scherbaum 1982; Chapman 1983; Bulat & Stoker 1986; Japsen 1993, 1998, 2000; Hillis 1995; Heasler & Kharitonova 1996; Al-Chalabi & Rosenkranz 2002). There is, however, no generally accepted methodology of how such estimates are best derived; see Corcoran & Doré (2005) for a review. The technique is based on the general observation that the sonic velocity of most sedimentary rocks increases as the porosity of the sediment is reduced through deeper burial. Porosity is reduced due to increased effective stress that causes mechanical compaction and pressure solution. Sonic velocity is increased due to porosity-reduction and stiffer grain contacts, and as these processes are considered largely irreversible, measured velocity will depend on the maximum effective stress experienced by the sedimentary rock – and hence on its maximum burial if the burial depth has been reduced by erosion. The timing of the erosion of the overburden is represented by any of the unconformities in the overburden.

A normal velocity-depth trend is thus a function that describes how sonic velocity increases with depth in a relatively homogenous, brine-saturated sedimentary formation when porosity is reduced during normal compaction (mechanical or chemical). Compaction is 'normal' when the fluid pressure of the formation is hydrostatic, and the formation is at maximum burial depth. Simple boundary conditions for such trends are that the velocity at the surface equals the velocity of the sediment when it was first deposited (Nur *et al.* 1998), and that velocity approaches the matrix velocity of the rock while the velocity-depth gradient approaches zero with increasing depth (see Japsen *et al.* 2007).

The derivation of a normal velocity-depth trend involves three steps of generalisation: 1) Identification of a relatively, laterally homogenous lithological unit, 2) selection of data points that represent normal compaction and 3) assignment of a function that expresses the velocity-depth trend (see Japsen *et al.* 2007). Few attempts have been made to constrain normal velocity-depth trends for different lithologies rather than just considering velocity-depth trends as fits of arbitrary functions to local data sets. The increase of velocity with depth for a uniform sedimentary formation (and thus the shape of the baseline) has been shown to depend on the mineralogical composition of the formation (Japsen *et al*. 2007).

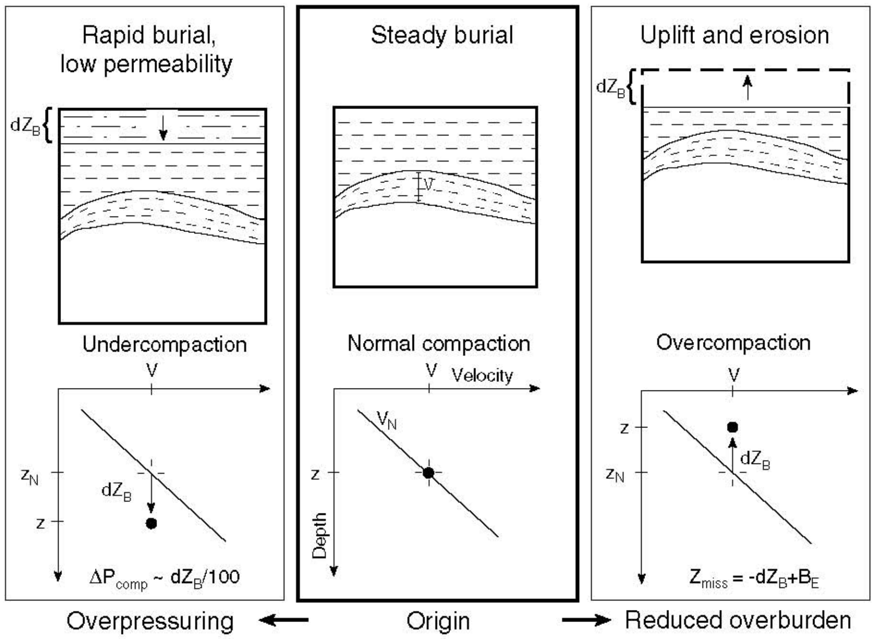


Figure 4-1. *Burial anomaly, dZ_B [m], relative to a normal velocity-depth trend, V_N, for a sedimentary formation (Eq. 4-1). In the North Sea Basin, burial anomalies of ±1 km for pre-Miocene formations result from late Cenozoic exhumation along basin margins and over-pressuring due to rapid, late Cenozoic burial in the basin centre. Rapid burial and low permeability cause undercompaction and overpressure, ΔP_{comp} [MPa], and velocities low relative to depth (positive dZ_B) (cf. Eq. 4-3). Exhumation due to uplift reduce the overburden thickness, and causes overcompaction expressed as velocities high relative to depth (negative dZ_B); however, post-exhumational burial, B_E, will mask the magnitude of the missing section, Δz_{miss} (Eq. 4-2). The normalized depth, z_N, is the depth corresponding to normal compaction for the measured velocity (cf. Terzaghi's principle). Modified after Japsen (1998).*

Normal velocity-depth trends for chalk (V_N^{ch}), marine shale dominated by smectite/illite (V_N^{sh}) and quartz-dominated Triassic deposits (V_N^{B}) were defined by Japsen (1998, 1999, 2000) in such a way that the velocity at the surface agreed with those of recently deposited sediments, and that velocity did not approach infinity at depth. Velocity-depth anomalies relative to these trends were found to be in agreement with estimates of erosion along the margins of the North Sea Basin as well as with measurements of overpressure in the centre of this basin. Furthermore, these baselines are in agreement with those of previous workers even though such analytical expressions have often not fulfilled simple boundary conditions (e.g. Marie 1975; Scherbaum 1982; Bulat & Stoker 1987; Hillis 1995; Hansen 1996). Baselines for sandstone was established by Japsen *et al*. (2007) by eliminating porosity from an exponential porosity-depth relation by assuming a modified Voigt relation between sonic velocity and porosity for sandstone with different clay content.

The burial anomaly, dZ_B, is the difference between the present-day burial depth of a rock, z, and the depth, $z_N(V)$, corresponding to normal compaction for the measured velocity, V (Japsen 1998):

$$dZ_B = z - z_N(V) \tag{4-1}$$

The burial anomaly is zero for normally compacted sediments, whereas high velocities relative to depth give negative burial anomalies which may be caused by a reduction in overburden thickness when lithology is relatively homogenous over the study area, and if lateral variations of horizontal stress are minor. A positive burial anomaly may indicate undercompaction due to overpressure. To assess whether the burial anomaly for a stratigraphic unit is a measure of exhumation requires an integrated evaluation: The burial anomalies should thus agree with other estimates of erosion and should correspond geographically to where there is a missing section in the stratigraphic record. Any post-exhumational burial, B_E, will mask the magnitude of the missing (removed) overburden section, Δz_{miss}:

$$\Delta z_{miss} = -dZ_B + B_E \tag{4-2}$$

where the minus indicates that erosion reduces depth (Hillis 1995; Japsen 1998). The timing of the exhumation events is thus important for understanding the succession of events, their true magnitude and for identifying the age of the eroded succession.

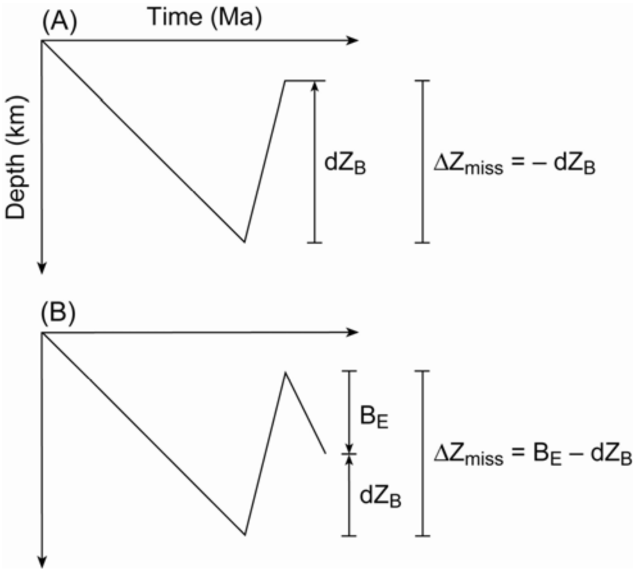


Figure 4-2. *Burial diagrams illustrating that the magnitude of the missing (or removed) section (Δz_{miss}) will be less than the magnitude of the measured burial anomaly (dZ_B) in the case of post-exhumational burial (B_E) (Eq. 4-2). (A) Exhumation followed by no deposition; (B) exhumation followed by burial.*

4.2 Overpressure-prediction from sonic data

Overpressure in the central North Sea was successfully predicted from velocity-depth anomalies for the Cenozoic succession relative to a normal velocity-depth trend for shale close to that given by Eq. (5-1) (Japsen 1999; Fig. 4-1). The overpressure results from a balance between the load of the upper Cenozoic deposits, and the draining determined by the thickness and sealing quality of the lower Cenozoic sediments. The overpressure of an undercompacted rock, ΔP_{comp}, is proportional to the burial anomaly, dZ_B, if the effective stress is increasing with time (cf. Magara 1978; Japsen 1998). We get $\Delta P_{comp} = \Delta\rho_{up} \cdot g \cdot dZ_B$ where $\Delta\rho_{up}$ is the density contrast (wet bulk density minus pore fluid density) of the upper Cenozoic and *g* is the gravitational acceleration (9.807 m/s2). The equation is based on Terzaghi's principle and states that if a rock is buried at a greater depth by dZ_B without change in the effective stress (indicated by unchanged velocity), the effective stress of the added load is carried by an increase in pore pressure. If we substitute $\Delta\rho_{up} \approx 1.02 * 10^3$ kg/m^3, and dZ_B is in meters, we find that the overpressure of an undercompacted rock, ΔP_{comp} [MPa], is proportional to the burial anomaly, dZ_B [m] (Fig. 4-1):

$$\Delta P_{comp} \approx dZ_B/100 \text{ [MPa]}, \tag{4-3}$$

'which means that a burial anomaly of 1000 m may reflect overpressure due to undercompaction of 10 MPa (Japsen 1998). From the above expression we can define the effective depth, Z_{eff}, for a unit at measured depth, Z, as the depth where the same effective stress would occur during normal compaction. In the case of overpressure (ΔP) we get

$$Z_{eff} = Z - \Delta P \cdot 100 \tag{4-4}$$

where ΔP is measured in MPa and depths are in metres (cf. Japsen 1998).

In Figure 4-3 we compare the degree of undercompaction of the lower Cenozoic succession in the North Sea expressed by its burial anomaly, dZ_B^{low}, with pressure data from the underlying Chalk, ΔP_{Ch}, because pressure measurements from the lower Cenozoic shales are rare in the central North Sea. We observe that ΔP_{Ch} is proportional to dZ_B^{low}, and in the order of the overpressure predicted by Eq. (4-3). This indicates that the burial anomaly for the lower Cenozoic succession relative to the shale trend given by Eq. (5-1) is a measure of overpressure due to undercompaction. Investigation of interval velocities from almost a thousand wells revealed basin-wide differences in the physical properties of the Cenozoic deposits related to disequilibrium compaction below the mid-Miocene unconformity in the central North Sea (cf. Osborne and Swarbrick 1997).

Japsen (1998) demonstrated that positive burial anomalies for the chalk in the central North Sea were proportional to measured values of overpressure in the chalk and that the overpressure was in the order of magnitude given by Eq. (4-3).

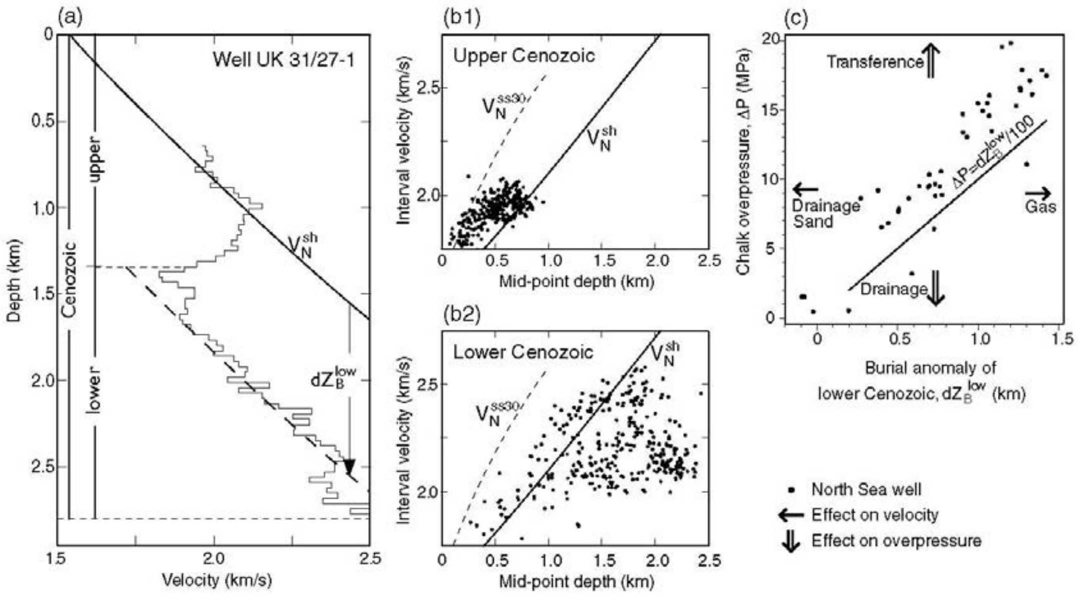


Figure 4-3. *Prediction of overpressure in the North Sea from interval velocities of the Cenozoic deposits (excluding the Danian) (cf. Figure 4-1).*
(a) Sonic log where low velocities reveal undercompaction of the lower Cenozoic sediments corresponding to measured overpressure in the underlying chalk.
(b1) and (b2) Interval velocity versus depth to the midpoint of the upper and lower Cenozoic deposits, respectively, for 322 North Sea wells.
(c) Burial anomalies for the lower Cenozoic sediments (dZ_B^{low} *) versus Chalk formation overpressure (* ΔP *) in North Sea wells.*
The upper Cenozoic deposits are close to normal compaction whereas velocity-depth anomalies for the lower Cenozoic sediments outline a zone of undercompaction in the central North Sea. The deviations from the trend line in figure (c) is due to the non-compactional sources that add to the Chalk overpressure from below (transference; cf. Osborne and Swarbrick 1997), the easier drainage from the more shallow Cenozoic section and sandy lithology; $\Delta P=dZ_B/100$ *(see equation 4-3). The burial anomalies are calculated relative to the shale trend given by equation (5-1). Depths below top of sediments.* V_N^{ss30} *: modified Voigt model for sandstone, 30% clay content.* V_N^{sh} *: marine shale (Eq. 5-1). Modified after Japsen et al. (2007).*

5. Normal velocity-depth trends for different lithologies

5.1 A baseline for smectite/illite-dominated shale

Japsen (2000) formulated a constrained baseline, V_N^{LJur} , for marine shale dominated by smectite/illite based on velocity-depth data for the Lower Jurassic F-1 Member of the Fjerritslev Formation from 31 Danish wells of which 28 have sonic data for the Chalk:

$$tt = 460 \cdot e^{-z/2175} + 185 \qquad (5\text{-}1)$$

where transit time, *tt*, is the inverse of velocity. The baseline was reconstructed by correcting present formation depths for the effect of late Cenozoic erosion as estimated from the velocity of the overlying Chalk in these wells relative to the Chalk baseline of Japsen (2000). The corrected depths correspond to the burial of the formation prior to erosion when the sediments were at maximum burial at more locations than today. The baseline can thus be traced more easily in a plot of velocity versus the corrected depths, and is well defined at great depth where velocity-depth data for normally compacted shale at maximum burial can be difficult to identify (2.1<z<3.8 km). This formulation is a constrained, exponential transit time-depth model that fulfils reasonable boundary conditions at the surface (1550 m/s) and at infinite depth (5405 m/s); maximum velocity-depth gradient 0.6 1/s for z=2.0 km. The shale trend corresponds closely to baselines for marine shale found by other workers (Scherbaum 1982, Hansen 1996; see discussion in Japsen 1999 and in Japsen *et al*. 2007.

5.2 A baseline for the Lower Triassic Bunter 'Shale'

Japsen (2000) formulated a segmented, linear baseline, V_N^{BSh} , for the Lower Triassic Bunter Shale based on velocity-depth data from 142 British and Danish wells of which 91 have velocity-depth data for the Chalk:

$$\begin{aligned} V_N^{BSh} &= 1550 + z \cdot 0.6, & 0 < z < 1393\,\text{m} \\ V_N^{BSh} &= -400 + z \cdot 2, & 1393 < z < 2000\,\text{m} \\ V_N^{BSh} &= 2600 + z \cdot 0.5, & 2000 < z < 3500\,\text{m} \\ V_N^{BSh} &= 3475 + z \cdot 0.25, & 3500 < z < 5300\,\text{m} \end{aligned} \qquad (5\text{-}2)$$

The trend indicates a pronounced variation of the velocity gradient with depth. The gradient is only 0.5 1/sin the upper part, and increases to 1.5 1/s for depths around 2 km, from where it decreases gradually with depth to 0.5 and then 0.25 1/s. The decline of the gradient with depth reflects that velocity approaches an upper limit.

The Bunter Shale baseline was reconstructed by applying the same procedure as for the Lower Jurassic shale by correcting present formation depths for the effect of late Cenozoic erosion as estimated from Chalk velocities. The trend was constructed to predict likely values near the surface (1550 m/s), and is based on reference data with corrected depths from 1600 to 5600 m (Japsen 2000). Rather than proposing a specific baseline for the Lower Triassic Bunter Sandstone, Japsen (2000) found that the trend derived for the Bunter Shale was a reasonable approximation for a data set from 133 British and Danish wells of which 87 have velocity-depth data for the Chalk. Burial anomalies for the Bunter Sandstone can thus be used to place an upper limit on estimates of erosion based on Bunter Shale data.

The dominance of smectite/illite in the distal parts of the Fjerritslev Formation, and of kaolin in the continental Bunter Shale was suggested by Japsen (2000) to be a possible explanation why baselines for these formations diverge, and why those for Bunter Shale and Bunter Sandstone converge at depth. Alternatively, the similarity of the baselines for the Bunter Shale and the Bunter Sandstone may be due to the dominance of quartz in both formations.

5.3 A revised baseline for sandstone

Japsen *et al*. (2007) found *V-z* trends for sandstone by eliminating porosity from an exponential porosity-depth relation by assuming a so-called modified Voigt relation between sonic velocity and porosity for sandstone with different clay content. The model was based on the properties of sandstone at an assumed maximum depth for practical purposes of 4 km. The resulting modified Voigt velocity-depth model for sandstone has a *V-z* gradient that decreases monotonously from values greater than 1 s^{-1} for z<0.4 km and 30% clay content; the resulting SS00 and SS05 trends thus corresponds to sandstone with a clay content of 0% and 5%. Reduction of the clay content leads to higher velocity and velocity gradient.

If we compare the modified Voigt model with the normal trend for the Bunter Shale and Sandstone, we find that the Bunter trend plot between the sandstone models for 0% and 5% clay content for depths below *c*. 2 km. The match between the modified Voigt model and the Bunter Sandstone trend supports the application of the modified Voigt model for sandstone as well as the estimation of the amount of exhumation by means of chalk velocities (because burial anomalies based on chalk velocities were used to derive the Bunter baseline). The match between the modified Voigt model and the data points for the Bunter Shale suggests that the lithology of the Bunter Shale is dominated by quartz in the wide area covered by the data set (southern and eastern North Sea Basin). Consequently, the term ‘Shale’ seems to be an indication of grain size rather than of mineralogy.

The modified Voigt model can be approximated by a modified velocity-average equation:

$$V = V_m - (V_m - V_c)e^{-z/b} \qquad (5\text{-}3)$$

where V_m is the matrix velocity of the sediment, V_c is the sonic velocity of the sediment at critical porosity (the porosity limit above which a particular sediment exists only as a suspension) and *b* is a decay parameter (Nur *et al*. 1998). Japsen *et al*. (2007) estimated the parameters in equation (5-3) for sandstone with varying clay content as an approximation to the modified Voigt trend for z<4 km taking V_c=1600 m/s. For 0% and 5% clay content the parameters to the modified velocity-average equation (Eq. 5-3) were found to be:

$$\begin{aligned}&\text{SS00, 0\% clay: } V_m = 5065 \text{ m/s, } b_3 = 1923 \text{ m.}\\&\text{SS05, 5\% clay: } V_m = 4796 \text{ m/s, } b_3 = 1963 \text{ m.}\end{aligned} \tag{5-4}$$

The baselines for pure sandstone of Japsen *et al*. (2007) predict velocities around 4.5 km/s at the assumed maximum depth of 4 km (0%-%5 clay). However, the sonic data for many wells in this study show sandstone velocities that reach 5 km/s; e.g. BAS-21, -113 and FPO-1 (see Fig. 5-1 and Appendix B). Sonic velocities well above 5 km/s are characteristic of conglomerates; e.g. in well BRN-1 below 3 km.

Consequently, the pure sandstone baselines have been calibrated to match the data presented in this report, in particular well BAS-21 and -88 (Fig. 5-1).

- The sonic log for well BAS-88 displays data for a c. 1 km thick sandstone unit with a velocity-depth trend increasing from c. 3.5 to 4.25 km/s (Rio de Contas Fm). The higher velocities over this unit plot within the range given by the SS00 and SS05 trends, and the drilled sequence is thus interpreted to be at maximum burial at present.
- The sonic log for well BAS-21 displays data for a c. 2 km thick sandstone unit with a velocity-depth trend increasing from c. 4 to almost 5 km/s (Morro do Barro Fm). These velocities are much higher than predicted for the SS00 and SS05 trends for this depth interval, and the section is thus interpreted to have been deeper buried in the past. Furthermore, the data show a gradual increase of velocity with depth over the entire interval, whereas the SS00 and SS05 trends predict almost no increase in velocity. The velocity-depth gradient over this sandstone unit is about 0.5 1/s and this corresponds closely to the gradient predicted by the Bunter Shale trend for velocities around 4.5 km/s whereas the gradients of the SS00 and SS05 trends are much smaller.

To account for these observations, slightly modified baselines for pure sandstone, BR00 and BR05, are formulated by with the following parameters to the modified velocity-average equation (Eq. 5-3):

$$\begin{aligned}&\text{BR00, 0\% clay: } V_m = 5400 \text{ m/s, } b_3 = 2500 \text{ m.}\\&\text{BR05, 5\% clay: } V_m = 5400 \text{ m/s, } b_3 = 2800 \text{ m.}\end{aligned} \tag{5-5}$$

These parameters represent only a slight modification of the parameters for SS00 and SS05 (Fig. 5-2). The modified trends plot at slightly greater depths for velocities less than c. 4.5 and 4 km/s, for BR00 and BR05, respectively, and at slightly more shallow depths for higher velocities (and thus predict smaller amounts of exhumation for high velocities). This change in curvature was made to account for the trends observed in the data and in particular to reach a velocity of 5 km/s at a more shallow depth than predicted by SS00 and

SS05 (e.g. at 8 km for SS00). The revised baselines predict velocities near 5 km/s at 6 km depth, and these values match the input data used for the original modified Voigt model. The use of 4 km as maximum depth (anchor point) in the calculations of Japsen *et al*. (2007) caused the velocity predictions for greater depths to be too small.

If we compare this model with the normal trend for the Bunter Shale and Sandstone, we find that the BR05 trend corresponds closely to the Bunter trend. Pure sandstone units are thus likely to plot in the interval defined by the BR00 and BR05 trends.

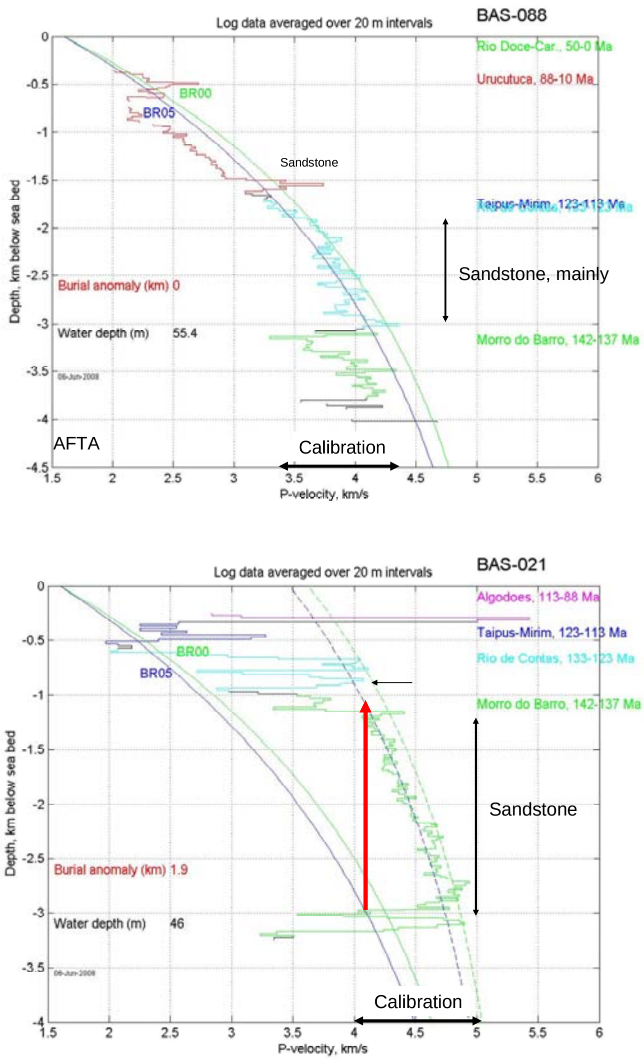


Figure 5-1. *Plots of sonic logs used for calibration of the sandstone baselines used in this study, BR00 and BR05 for 0% and 5% clay, respectively. Sandstone sonic data between c. 3.5 and 4.25 km/s in BAS-88 and between c. 4 and 5 km/s in BAS-21 are used for calibration. Whereas the drilled sequence in BAS-88 is found to be at maximum burial, the sequence drilled in BAS-21 is found to have been more 1.9 km deeply buried as indicated by the red arrow and the dashed baselines that are shifted upwards by that amount. Full plots and legend: See Appendix B.*

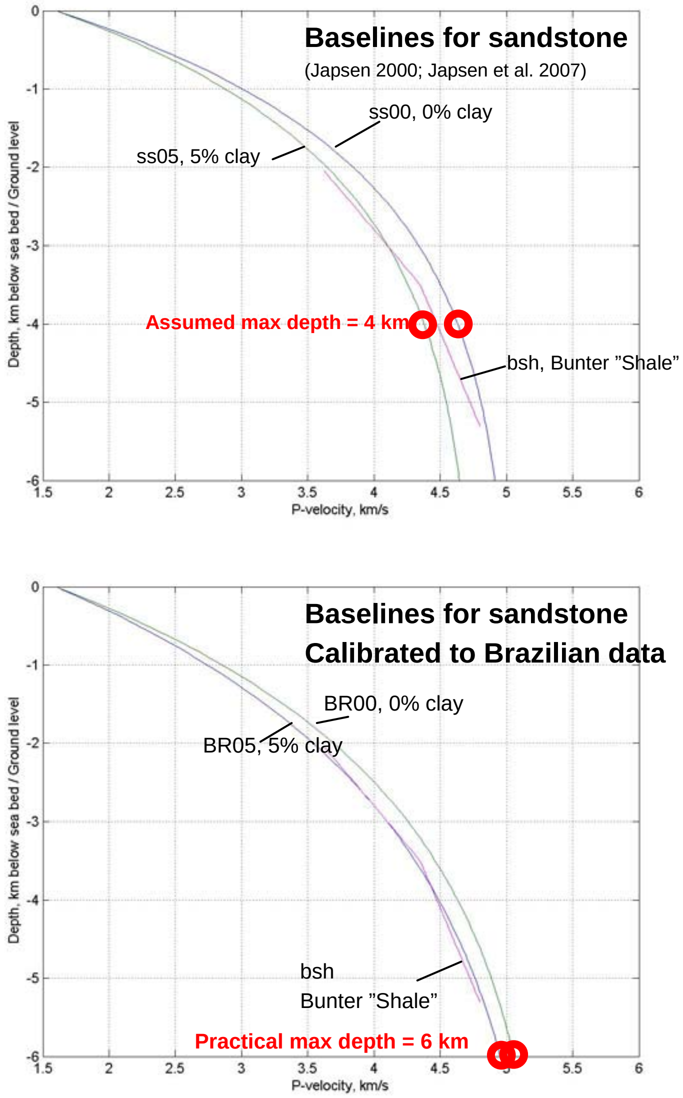


Figure 5-2. *Baselines for sandstone. Upper panel: Baseline models for 0% and 5% clay content based on a prediction of porosity and sonic velocity of consolidated sandstone with data at 4 km depth as anchor point (Eq. 5-4; Japsen et al. 2007). Lower panel: Baselines calibrated to data from wells BAS-21 and -88 (BR00 and BR05: Eq. 5-5). 'bsh': Baseline for the quartz-dominated Lower Triassic Bunter Shale, North Sea (Eq. 5-2).*

5.4 A new baseline for organic-rich shales

Ongoing studies in the Norwegian sector of the North Sea indicate that the sonic velocity of the organic-rich, Upper Jurassic Tau Formation is much lower than for pure shale at similar burial depth. The normal velocity for the Tau Formation is found to be c. 2750 m/s at 3 km depth (corrected for possible reduction of the overburden thickness due to exhumation), whereas the normal velocity for marine shale at that depth is c. 3300 m/s. Conversely stated, a sonic velocity of 2750 m/s for organic-rich shale corresponds to a c. 1 km deeper burial than for marine shale.

A new velocity-depth trend for organic-rich shales has been identified based on well data for minimum-velocity shale units of the rift sediments in the study area; primarily based on sonic data for the Morro do Barro and Rio de Contas Formations. The shale data are picked from well-defined data points based on the lithological interpretation of the LithoLogs (or the composite logs) and furthermore chosen from the data that plot along a lower bound in velocity-depth plot (indicating minimum velocities a given depth). Such minimum-velocity shale data points can be identified for wells BAS-64, 71 and 74 and the velocity range for these data points between 2.3 and 3.7 km/s make them well-suited to define such a baseline (Fig. 5.3).

The maximum burial depth for these shale units in these wells is estimated by correcting present burial depth by the magnitude of the burial anomaly for the drilled section as estimated from velocity-depth data for sandstone units in the well. The datapoints for these shale units show a considerable scatter when their sonic velocity if plotted against present depth, but they plot along a fairly well-defined trend when plotted against their maximum burial depth because the sonic velocity is controlled by the corresponding effective stress (Fig. 5-4, upper panel). Note that that the identified shale datapoints indicated by red circles in Figure 5.3 are identical to those plotted in Fig. 5.4. Moreover, the baseline for these shale units predicts a velocity of c. 2750 m/s for a depth of 3 km which corresponds to the velocity-depth relation for the organic-rich Tau Fm and thus supports an interpretation of these minimum-velocity shale units as also being rich in organic material. The velocity-depth trend for these organic-rich shales can be defined by an equation of the same form as that for pure shale (Eq. 5-1):

$$tt = 645 \cdot e^{-z/3800} + 145 \qquad (5\text{-}6)$$

This formulation is a constrained, exponential transit time-depth model that fulfils reasonable boundary conditions at the surface (1550 m/s) and at infinite depth (6900 m/s) – although the indicated high latter value should be considered as a mathematical parameter rather than as a matrix velocity that is higher than that of pure shale (Eq. 5-1). The velocity-depth gradient is increasing from 0.32 1/s to a maximum value of 0.45 1/s at a depth of 4.7 km. The trend line plots below that for pure shale and thus predicts deeper burial for organic-rich shale than for pure shale for the same velocity; for velocities above 2.6 km/s, the difference is greater than 1 km and reaches a maximum difference of 1.7 km for a velocity of 4.2 km/s.

The lower panel in Fig. 5-4 displays minimum velocity-depth data for all wells plotted at present and maximum burial depth; additional wells are BAS-77, -84, -88, -97, -107, -113, -118, FPO-1 and 6-MGP-34 (the lithological interpretation of the onshore wells is based on the composite logs). The figure shows a great consistency between these datapoints and the trend defined by the reference wells (and the corresponding baseline given by Eq. 5-6).

The only major deviations relative to the baseline are seen for the data for wells BAS-88 and -118 where organic-rich shales apparently are absent (both wells are found to be at maximum depth at present). These wells are localized near each other and to well BAS-79 where such shales also appear to be absent. Another deviation relative to the trend is deepest datapoint for the MGP well which corresponds to a low-velocity unit within the Candeias Fm. As the Candeias Fm is known to be the main source rock in the Recôncavo Basin, this may indicate that shales that are very rich in organic matter may have even lower velocities than predicted by the baseline. However, for datapoints from the Rio da Contas and Morro do Barro Fms, the baseline appear to be a good approximation.

No LithoLog interpretation was available for wells BAS-64 and -88; according to the LithoLogs there is no shale within the rift sequence in wells BAS-79 and -102; well BAS-129 did no reach the rift sequence.

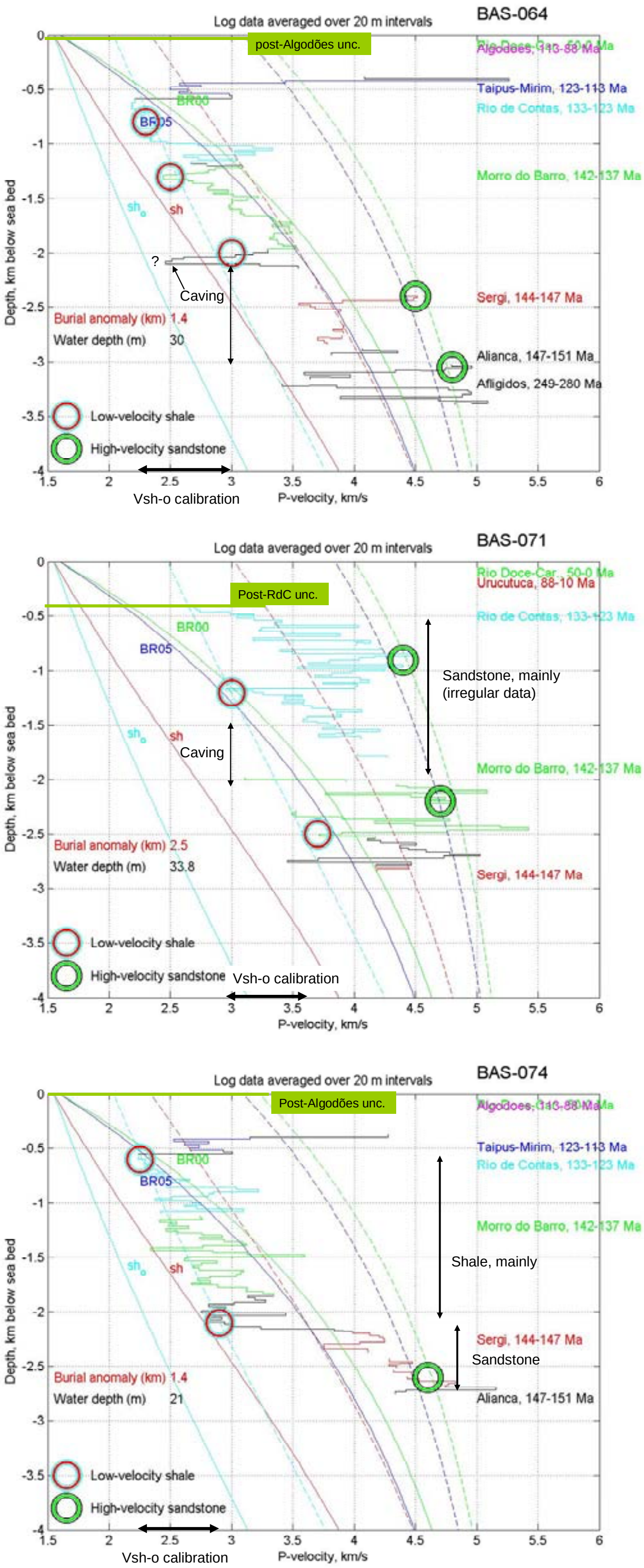


Figure 5-3. *Sonic log data for wells BAS-64, -71 and -74 used for establishing a baseline for organic-rich shale. Datapoints for low-velocity shale (red circles) plot along a consistent trend when depths are corrected to the maximum burial depth; here shown by shifting the baselines by magnitude of the burial anomaly. Legend in Appendix B.*

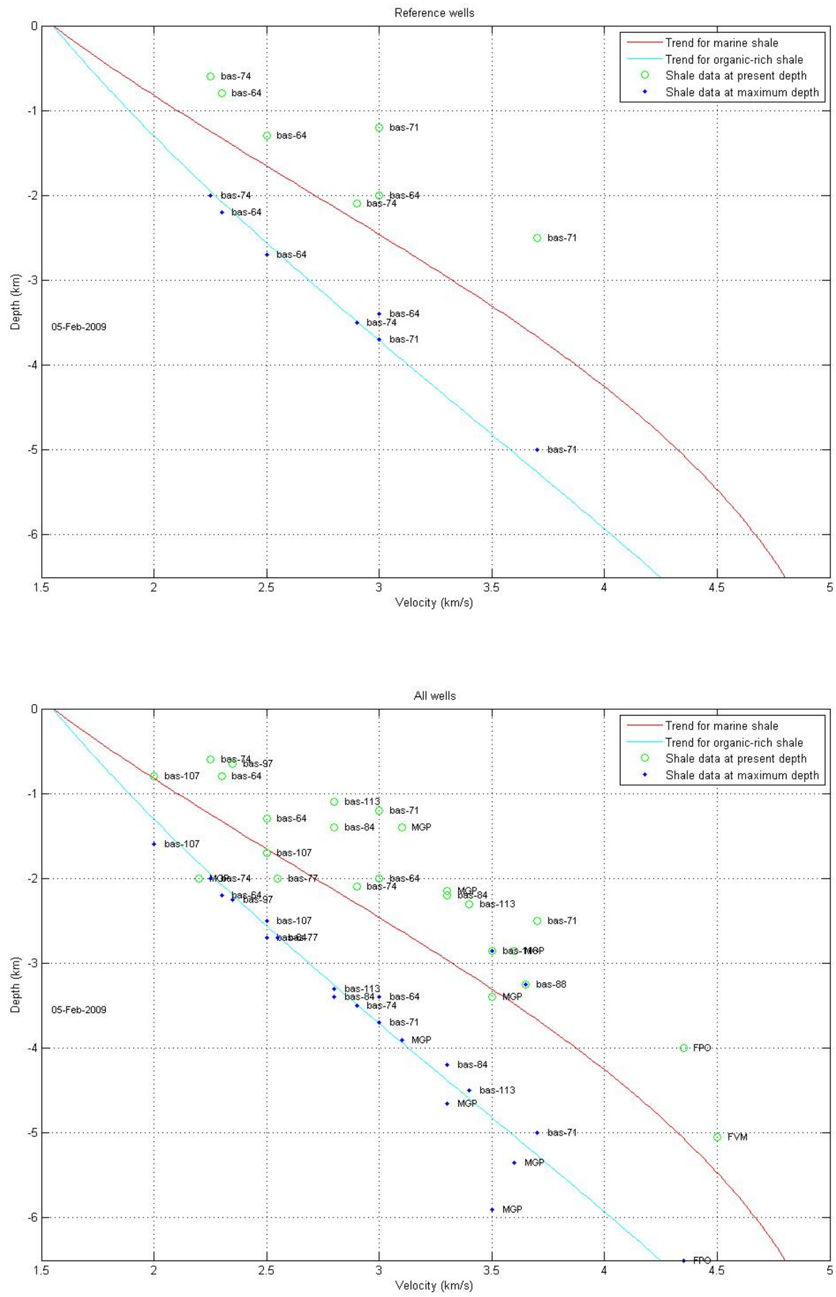


Figure 5-4. *Identification of a normal velocity-depth trend for organic-rich shales based on well data for minimum-velocity shale units from the rift sediments. Maximum burial depth for a shale unit is estimated by correcting present depth by the magnitude of the burial anomaly for the drilled section as estimated from velocity-depth data for sandstone units in the well. Upper panel: Plot of data points plotted at present and maximum burial depth for the reference wells (BAS-64, -71 and -74; see Fig. 5-3). The data points define a trend when they are plotted against maximum burial depth because the sonic velocity is controlled by the corresponding effective stress. The velocity-depth trend for these organic-rich shales are defined by Equation 5-6. Lower panel: Plot of data points plotted at present and maximum burial depth for all wells. Depths below sea bed/ground level. Shale datapoints are indicated in the plots for the individual wells in Appendix B.*

6. Estimation of amounts of removed sections based on burial anomalies evaluated from sonic data

6.1 Estimation procedure

The burial anomalies are estimated for the drilled succession in each well and they are primarily based on a comparison between (1) the sonic data for high-velocity sandstones and the baselines for pure sandstone, BR00 and BR05 (Eq. 5-5) and (2) by a comparison between the sonic data for low-velocity shales and the baseline for organic-rich shales defined for the Morro do Barro and Rio de Contas Formations, Vsh-o (Eq. 5-6; see Fig. 6-1). Furthermore, the interpretation may be supported by a comparison between the sonic data and the baseline for pure shale, Vsh. The amount of section removed is found by adding (the magnitude of) the burial anomaly and the post-exhumational reburial (Fig. 4-2).

The data and the interpretation are discussed in detail in Appendix B where plots of the log data for each well are displayed.

6.2 Results

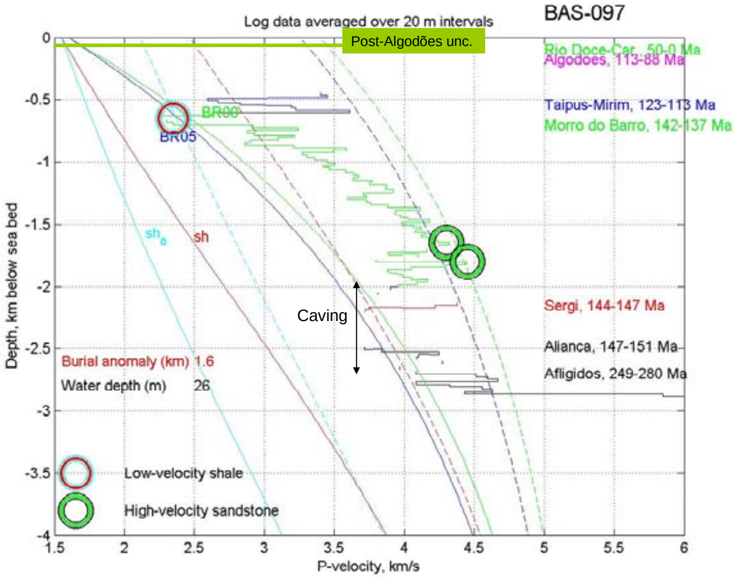
The estimated burial anomalies and their range of uncertainty for each well together with amounts of removed section are discussed in Appendix B (cf. Fig. 4-2 and Table 6-1). The results show a very consistent pattern of exhumation of the Early Cretaceous rift basins along the Atlantic margin of Bahia (Fig. 6-2). Maximum burial clearly took place sometime after the deposition of the Albian–Cenomanian Algodões Formation, but this is discussed in the following chapter.

Estimates of the section removed relative to Mesozoic sediments in Early Cretaceous rift basins:

- Tucano Basin, 2.5 ± 0.6 km for one well (FPO-1) with two other wells only yielding lower limits of 1.5 and 1.8 km, respectively (BRN-1, FVM-1).
- Recôncavo Basin, 2.5 ± 0.8 km for one well (MGP-34).
- Camamu Basin
  Inshore, north-west: about 2.0 km for two wells (BAS-84, -113).
  Inshore, south-west: about 1.4 to 1.7 km with estimates ranging from 1.1 ± 0.9 to 1.9 ± 0.5 km for five wells (BAS-21, -64, -74, -97, -107).
  Deep-water: The drilled section is at maximum burial today in one well (BAS-129).
- Almada Basin
  Inshore, exhumed: variations between 1.1 ± 0.7 to 2.9 ± 0.9 km (BAS-71, -77 ,-79).
  Inshore, maximum burial: the drilled sections in two wells are found to be at maximum burial today (BAS-88, -118).
  Deep-water: The drilled section is at maximum burial today in one well (BAS-102)

Tentative estimate of the section removed relative to Proterozoic shale drilled in western Bahia:

- Sanfranciscana Basin: about 5 km for one well (FLU-1).



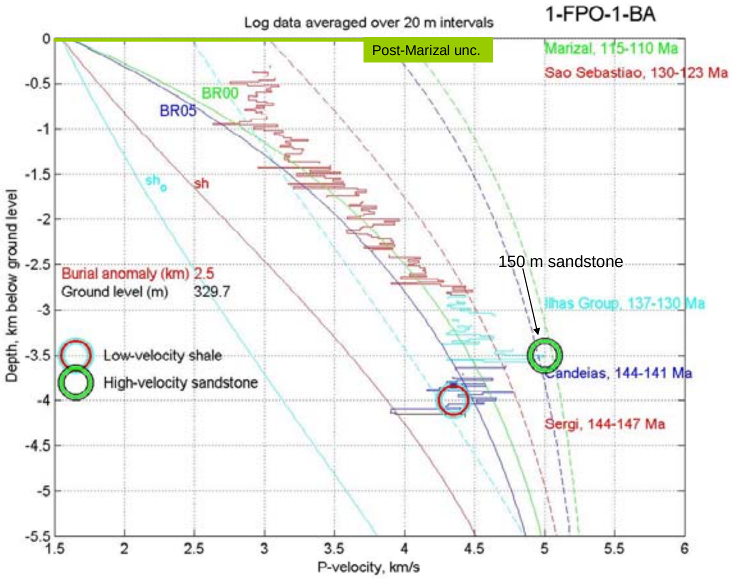


Figure 6-1. *Plots of the sonic log for wells BAS-97 and FPO-1 compared to baselines for three lithologies and to the baselines shifted by burial anomalies (absolute value) of 1.6 and 2.5 km, respectively. For both wells the chosen value of the burial anomaly is primarily based on the good agreement between the sonic data for the high-velocity sandstone and the baselines for pure sandstone (BR00, BR05). The interpretation is supported by the data for the low-velocity shale units relative to the baseline for organic-rich shales, Vsh-o. The interpretation of the data for the sandstone units relies on identification of high-velocity units with pure sand and the estimated burial anomaly may thus in some cases only be considered as a lower limit on the amount of exhumation. Legend in Appendix B*

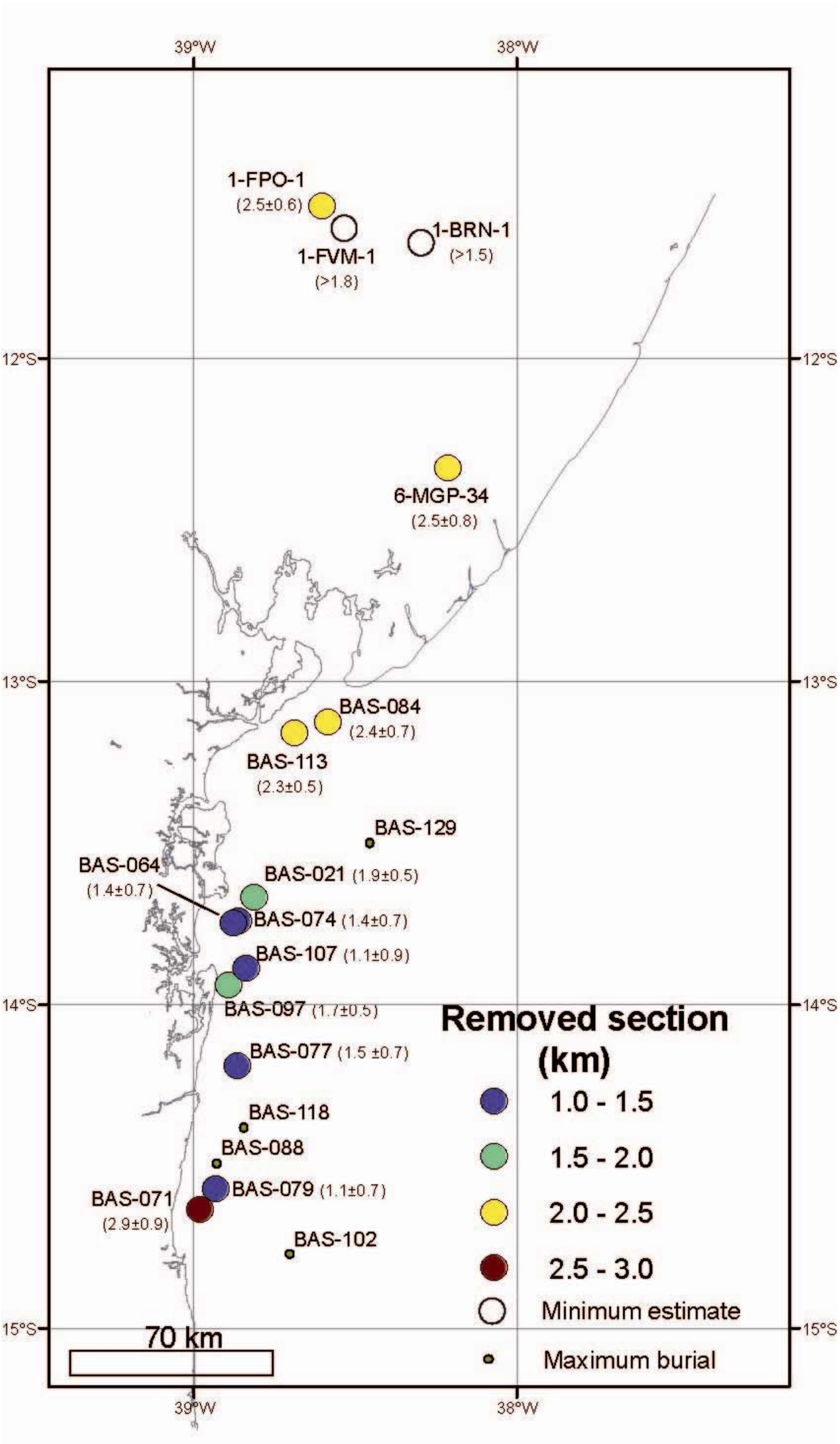


Figure 6-2. *Map of the estimated amount of section removed since maximum burial in the Late Cretaceous based on sonic data in onshore and offshore wells, NE Brazil.*

Table 6-1. *Estimates of burial anomaly for the pre-Campanian section in individual wells and the corresponding amount of removed section. The estimate is based on comparison between the normal velocity-depth trends for pure sandstone, shale and organic-rich shale and sonic log data for the relevant intervals. Depths below sea bed / ground level.*

Basin	Well	Formation below unconformity		Burial anomaly*	Post-exhumational burial	Section removed **	
		Name	Thick (km)	(km)	(km)	Thick (km)	Formations
Tuc	1-BRN-1	Mrz	0.1	1.5 – 3.5	0	1.5 – 3.5	Mrz-younger
WB	1-FLU-1	Prot	1.0	5.0 ± 0.5	0	5.0 ± 0.8	Cmb-Cret
Tuc	1-FPO-1	Mrz	0.3	2.5 ± 0.3	0	2.5 ± 0.6	Mrz-younger
Tuc	1-FVM-1	Mrz	0.1	1.8 ± 0.6	0	min 1.8	Mrz-younger
Rec	6-MGP-34	SSb	0.6	2.5 ± 0.5	0	2.5 ± 0.8	SSb-younger
Cam	BAS-021	Alg	0.4	1.9 ± 0.2	0	1.9 ± 0.5	Alg-Uruc
Cam	BAS-064	Alg	0.4	1.4 ± 0.4	0	1.4 ± 0.7	Alg-Uruc
Alm	BAS-071	RdC	1.4	2.5 ± 0.6	0.4	2.9 ± 0.9	(RdC) Tm-Uruc
Cam	BAS-074	Alg	0.4	1.4 ± 0.4	0	1.4 ± 0.7	Alg-Uruc
Alm	BAS-077	Alg	0.0	0.7 ± 0.4	0.8	1.5 ± 0.7	Alg-Uruc
Alm	BAS-079	Alg	0.0	0.7 ± 0.4	0.4	1.1 ± 0.7	Alg-Uruc
Cam	BAS-084	RdC	2.0	2.0 ± 0.4	0.4	2.4 ± 0.7	(RdC) TM-Uruc
Alm	BAS-088	TM	0.0	0 ± 0.2	1.6	(<1.6)***	TM-Uruc
Cam	BAS-097	Alg	0.4	1.6 ± 0.2	0.1	1.7 ± 0.5	Alg-Uruc
Alm	BAS-102	-	-	0 ± 0.2	-	0	-
Cam	BAS-107	Alg	0.3	0.8 ± 0.6	0.3	1.1 ± 0.9	Alg-Uruc
Cam	BAS-113	RdC	0.1	2.2 ± 0.2	0.1	2.3 ± 0.5	RdC-Uruc
Alm	BAS-118	TM	0.8	0 ± 0.4	(1.3)	(<1.3)***	(TM-Uruc)
Cam	BAS-129	Alg	0.1	0 ± 0.2	(1.2)	(<1.2)***	(Alg-Uruc)

*) Magnitude of the burial anomaly (positive numbers). Uncertainty given for the match between the datapoints and the baselines.

**) Allowing for the uncertainty of the baselines.

***) Since the Mesozoic sediments are at maximum burial today, any exhumation on the Late Cretaceous unconformity must have a smaller magnitude than the depth to the unconformity (see Fig. 4-2). min: minimum.

Alg: Algodões Fm; Alm: Almada; Cam: Camamu; Cmb: Cambrian; Cret: Cretaceous; Mrz: Marizal Fm; Prot: Proterozoic; RdC: Rec: Recôncavo; Rio de Contas Fm; TM: Taipus-Mirim Fm; Tuc: Tucano; SSb: São Sebastião Fm; Uruc: Urucutuca Fm; WB: West Bahia.

7. Discussion

7.1 Constraints on the age and thickness of the section removed at the post-Algodões unconformity

A minimum stratigraphic range for the main post-rift unconformity can be defined in a number of offshore wells for which the rift section has been more deeply buried. In these wells, the Albian–Cenomanian (100–93 Ma) Algodões Fm is buried below the post-Cenomanian Urucutuca and Rio Doce-Caravelas Fms. The unconformity at which the exhumation took place can thus loosely be referred to as a post-Algodões unconformity. However, stratigraphic data together with the estimated amounts of removed sections for these wells can give us further insight into the age of the section that has removed at that unconformity and thus a more precise timing for when the exhumation took place.

The results are very consistent in a cluster of 5 inshore wells in the southern Camamu Basin (BAS-21, -64, -74, -97, -107). If we focus on two key wells with narrowest limits on the burial anomaly (BAS-21, 97) we find that the section removed was 1.7–1.9 km and that the preserved part of the Algodões Fm is 0.3–0.4 km. If the section was removed at the Cenomanian unconformity (Fig. A-2 in Appendix A; Caixeta et al. 2007) prior to the deposition of the Urucutuca Fm, the complete thickness of the Algodões Fm would have been c. 2 km prior to exhumation; a result which is in contrast to the known maximum thickness of 0.5 km for this formation in the Camamu Basin (Caixeta et al. 2007).

It seems more likely that the exhumation occurred at the intra-Campanian unconformity (Caixeta et al. 2007) after deposition of the lower part of the Urucutuca Fm and thus that maximum burial occurred at that time. In this case the section removed included an upper part of the Algodões Fm and the part of the Urucutuca Fm below the intra-Campanian unconformity. This interpretation is in perfect agreement with the identification of a regional Campanian cooling event based on the AFTA data (Geotrack reports 990 & 1013).

The total thickness of the Algodões Fm and the Turonian–mid-Campanian part of the Urucutuca Fm was thus c. 2 km prior to exhumation that removed all but the remaining c. 0.4 km thick Algodões Fm in the key wells. This interpretation is supported by the available biostratigraphy that shows that no Turonian to Campanian strata are preserved above the Algodões Fm in this area. In BAS-107 Campanian nannofossils are recorded 0.1 km above the base of the Urucutuca Fm and from BAS-97 where the Algodões Fm is overlain by the post-30 Ma Rio Doce-Caravelas Fms. Further south, in the Almada Basin the unconformity in wells BAS-77 and -79 is overlain by Paleocene and younger strata.

In contrast to this stratigraphy, most of the Late Cretaceous interval is represented within the Urucutuca Fm in BAS-102 which is found to be at maximum burial based on both sonic and AFTA data. This result agrees well with the 1.5 km thick section of the Algodões Fm and the Urucutuca Fm below Maastrichtian deposits in this well. The sections drilled in BAS-88 and -118 are also found to be at maximum burial and hence the sections removed at the post-Taipus-Mirim unconformity in these wells must be smaller than the present depth to the unconformity of 1.6 and 1.3 km, respectively.

Out of the c. 2 km Albian–mid-Campanian section that was deposited in the two key wells prior to exhumation, only 0.4 km thick Algodões Fm is preserved, so the Turonian–mid-Campanian section was probably thicker than 1 km prior to exhumation. In the wells available for this study, the comparable sequence below Maastrichtian deposits in the Urucutuca Fm is 348 m thick in BAS-102.

7.2 Constraints on the age and thickness of the section removed in the Recôncavo-Tucano Basin

In the onshore Recôncavo and Tucano rift basins, the youngest Mesozoic sediments belong to the Aptian Marizal Fm (<240 m) that rests on the rift sediments above a major Aptian unconformity (Fig. A-3; Silva et al. 2007). AFTA data from deep wells in the area show that maximum burial occurred during the Campanian as it did in the inshore parts of the Almada and Camamu Basins. For two wells in the Recôncavo-Tucano Basin, the removed section is estimated to 2.5 km with an upper limit of 3 km based on the sonic data (FPO-1, MGP-34). We can compare this thickness with the estimated thickness of the Albian–mid-Campanian sequence in two offshore wells of c. 2 km prior to exhumation (with a minimum thickness of 400 m Aptian Algodões Fm). This magnitude of exhumation onshore is comparable to the exhumation offshore that reaches 2.0 to 2.5 km. The section removed thus corresponds to the accumulated thicknesses of an upper part of the Aptian Marizal Fm (equivalent to the uppermost parts of the Taipus-Mirim Fm), an Albian–Cenomanian sequence (equivalent to the Algodões Fm) and a Turonian–mid-Campanian sequence (equivalent to the Urucutuca Fm below the mid-Campanian unconformity). The presence of the Lower Miocene the Sabiá Fm (Viana et al. 1971; Petri 1972) c. 14 km from well MGP-34 implies that the post-Marizal Cretaceous section was removed prior to the Neogene.

7.3 Constraints on the burial and exhumation history after maximum burial

The burial and exhumation history after maximum burial during the Late Cretaceous is constrained by the presence of a Paleogene sequence in three inshore wells drilled in the Camamu and Almada Basins (BAS-77, -79 and -107; see Table 7-1). The analysis of the sonic data for these wells shows that the rift sediments in these wells were more deeply buried prior to the regional Campanian exhumation event, this implies that

- The Campanian exhumation event was completed during the Late Cretaceous (Paleocene and possibly Campanian strata preserved above the unconformity).
- A Palaeogene section up to 600 m thick was deposited after exhumation.
- The Palaeogene section is almost at seabed today as the undated sequence above the known stratigraphy is only 100-200 m thick.
- The magnitude of any Eocene exhumation (as identified in AFTA data in samples from deep wells in the Recôncavo-Tucano Basins) was not sufficient to remove the Paleocene strata in these wells. An Eocene event did however, also affect the off-

shore areas as a mid-Eocene unconformity is marked on the stratigraphic charts for the Camamu and Almada Basins (See Figures A-1, A-2 in Appendix A; Gontijo et al. 2007; Caixeta et al. 2007).

Figure 7-1 illustrates these observations and also two possible scenarios for the Neogene burial and exhumation history:

- Case A: No sedimentation during the Neogene.
- Case B: Neogene deposition followed by removal of these sediments after the regional Miocene exhumation event.

Case B is considered as the most likely scenario because Miocene exhumation affected the entire onshore part of the study area as well as inshore areas as documented by the AFTA data in BAS-113. AFTA data from four outcrop samples along the coast at distances from 30 to 50 km from the three wells, all show evidence for Miocene cooling with minimum palaeotemperatures above 35 to 50°C during that event (Geotrack onshore report 990). This corresponds to a cover at that time in the order of 1 km. The thickness of the cover removed above the Palaeogene sections in the wells cannot be estimated from the sonic data, but the sonic data in BAS-77 are compatible with the deposition and removal of a 500 m thick section above the Palaeogene section. There is no sonic coverage of the shallow section in the other wells.

Oligocene strata are found in the upper part of the drilled section in BAS-77; there are Oligocene strata above and below the interface between the Rio Doce-Caravelas Fms and the Urucutuca Fm at 300 m below seabed (nano zones 510 and 520, respectively). This indicates that the section that is likely to have been removed during the Miocene belonged to the Rio Doce-Caravelas Fms. Whereas the Urucutuca Fm is interpreted as a deepwater deposit according to the stratigraphic charts, the Rio Doce Fm is considered to be sandy deposits from the coastal zone.

Given the regional character of the post-rift exhumation events in the area, there are likely implications of the burial and exhumation history in the three inshore wells in the Camamu and Almada Basins:

- The exhumation following the Cenomanian event was completed during the Late Cretaceous prior to Paleocene burial; this is documented for the inshore parts of the basins and may also apply to the onshore areas to the west of these basins, to the NW Camamu Basin (BAS-113) and even to the Recôncavo and Tucano Basins.
- Paleogene burial is also likely to have taken place in the onshore areas immediately west of the Camamu and Almada Basins in which case the Miocene palaeothermal peak identified in outcrop samples, represents maximum Cenozoic burial prior to Miocene exhumation (cf. the coastal deposits of the Rio Doce Fm). A similar scenario may apply to the NW Camamu Basin (BAS-113) and even to the Recôncavo and Tucano Basins.
- Any Palaeogene deposits in the Recôncavo and Tucano Basins were removed by Eocene exhumation at c. 45 Ma. No deposition took place until the Early Miocene Sabiá transgression flooded the post-Eocene erosion surface in these areas.
- The Eocene exhumation event did only affect the offshore areas to a limited extend.

- The Miocene exhumation event affected both onshore and inshore areas removing a section of some 500–1000 m, partly Cenozoic sediments.

In the inshore parts of the Almada Basin, the section drilled (including the Palaeogene sediments) are however, now at maximum burial in the inshore well BAS-88 (supported by AFTA data; Geotrack onshore report 1013). There may however, well be a Neogene unconformity in BAS-88 above the post-Eocene section which is only 242 m thick. Given the sensitivity of the sonic method, a late Cenozoic cover up to 500 m thick could have been present in BAS-88 without being detected by the method. This indicates that this well is located on a block that has experienced a different tectonic history than most of the coastal zone (see Fig. 6-1).

The sediments in well BAS-118 are also at maximum burial, but this well is located further offshore where it penetrated a 900 m thick section above Paleocene strata. Early Eocene deposits are found at a depth of 771 m and this upper section might include the equivalent to the post-Eocene section that has been removed in other inshore wells.

Table 7-1. *Wells where the rift section has been more deeply buried and where a Palaeogene sequence is present.*

Well /Basin	Section removed after 75 Ma (km)	Youngest formation below unconformity /Thickness	Post-exhumational burial	Dated strata above unconformity /Depth b. seabed /Thickness	Onshore AFTA sample, GC990- /Distance from well
BAS-77 Almada	1.5	Algodões Fm 47 m	771	Pal.-Olig. 167 m 586 m	#107 50 km
BAS-79 Almada	1.1	Algodões Fm 24 m	419 m	Pal.-L.Eo. 105 m 284 m	#106 40 km
BAS-107 Camamu	1.1	Algodões Fm 300 m	299 m	Camp*.-Pal. 104 , 54 m	#108, 109 30 km

*) Redeposited sediments at 234 m KB: Nanozones 250, -260, -265; Albanian to Campanian age. Youngest age most likely.

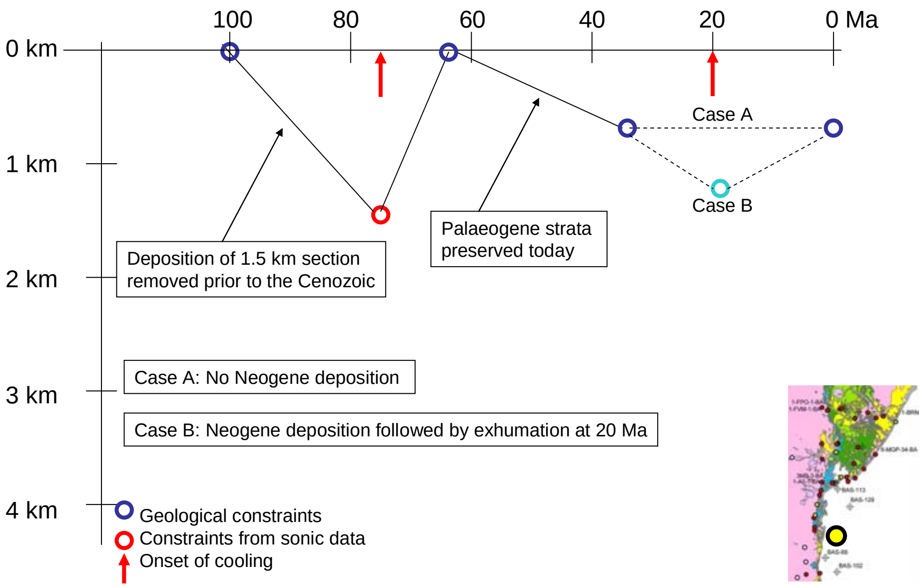


Figure 7-1. *Schematic burial curve for the Albian Algodões Fm in well BAS-77. The deposition of the Algodões Fm was followed by burial by a section of c. 1.5 km Upper Cretaceous sediments. This section was removed after the Campanian exhumation event, but prior to the Cenozoic as evidenced by the Paleocene sediments overlying the unconformity in the well. A column of c. 600 m of Palaeogene sediments are buried below less than 200 m of sediments of unknown age. Two alternatives are possible for the Neogene development. Case A: No Neogene deposition or Case B: Neogene deposition followed by removal of the Neogene deposits after the regional, Miocene exhumation event.*

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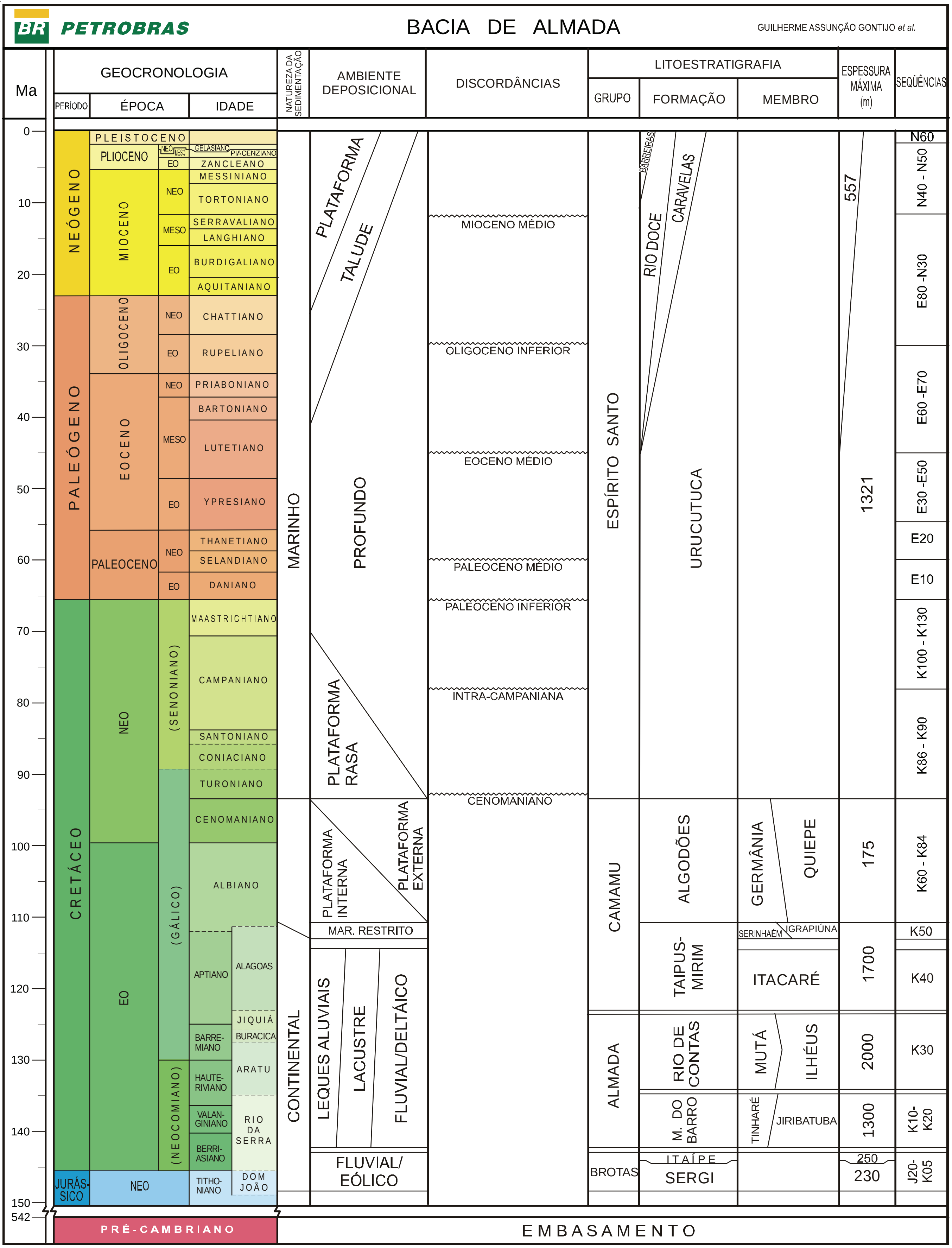
Appendix A. Stratigraphy and well data

Subsequent pages:

Figure A-1. *Almada Basin stratigraphic charts (Gontijo et al. 2007).*
Figure A-2. *Camamu Basin stratigraphic charts (Caixeta et al. 2007).*
Figure A-3. *Recôncavo Basin stratigraphic charts (Silva et al. 2007).*



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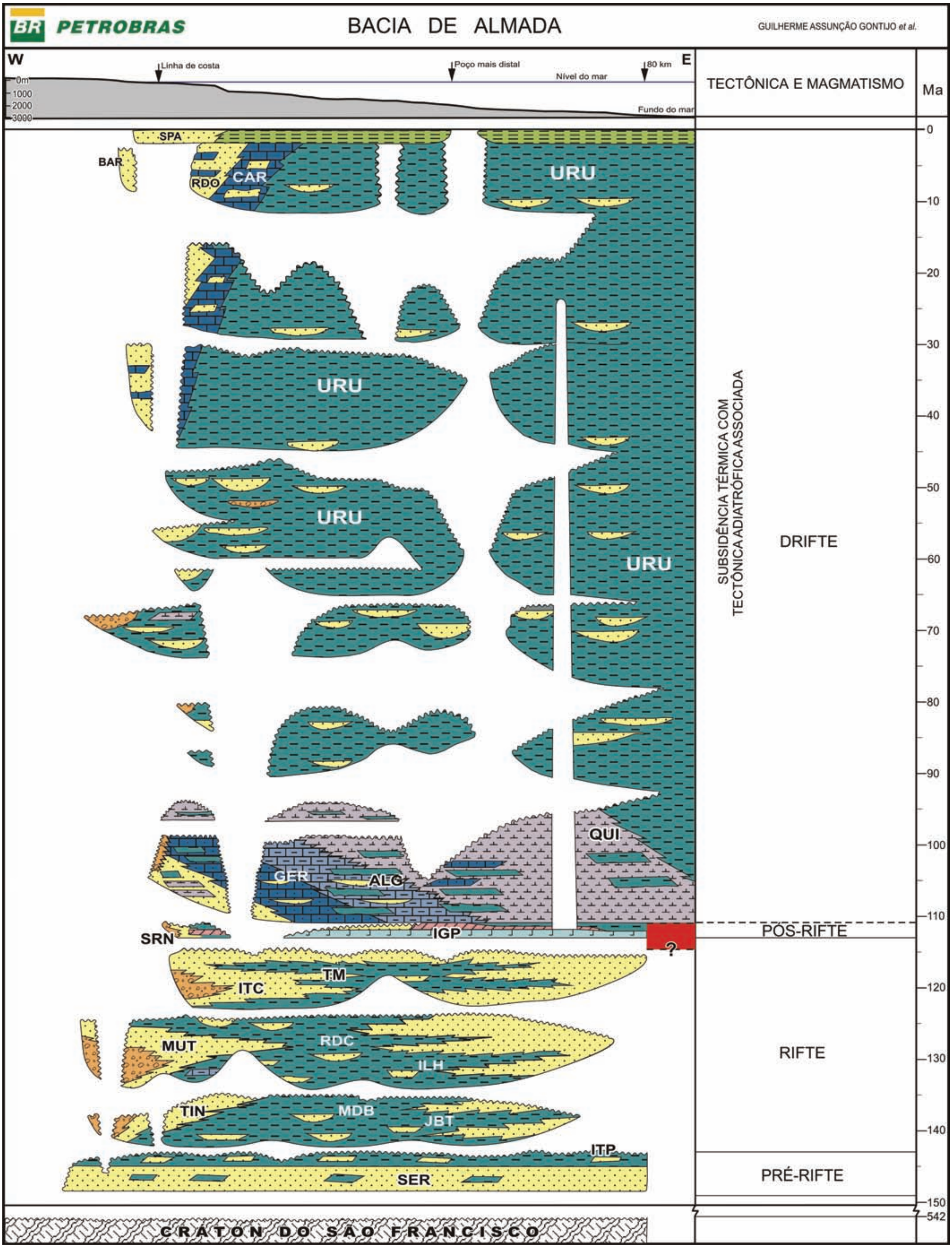
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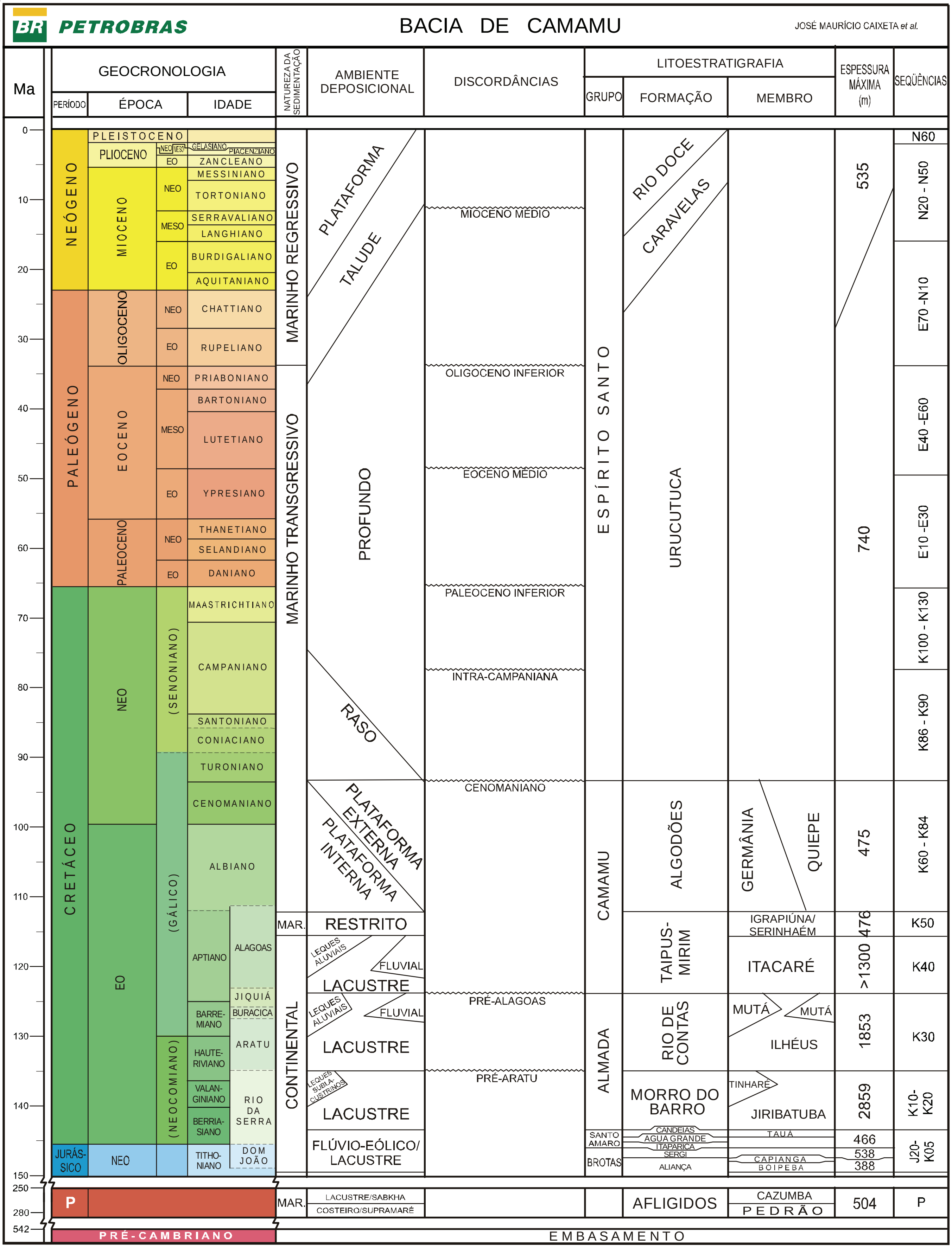
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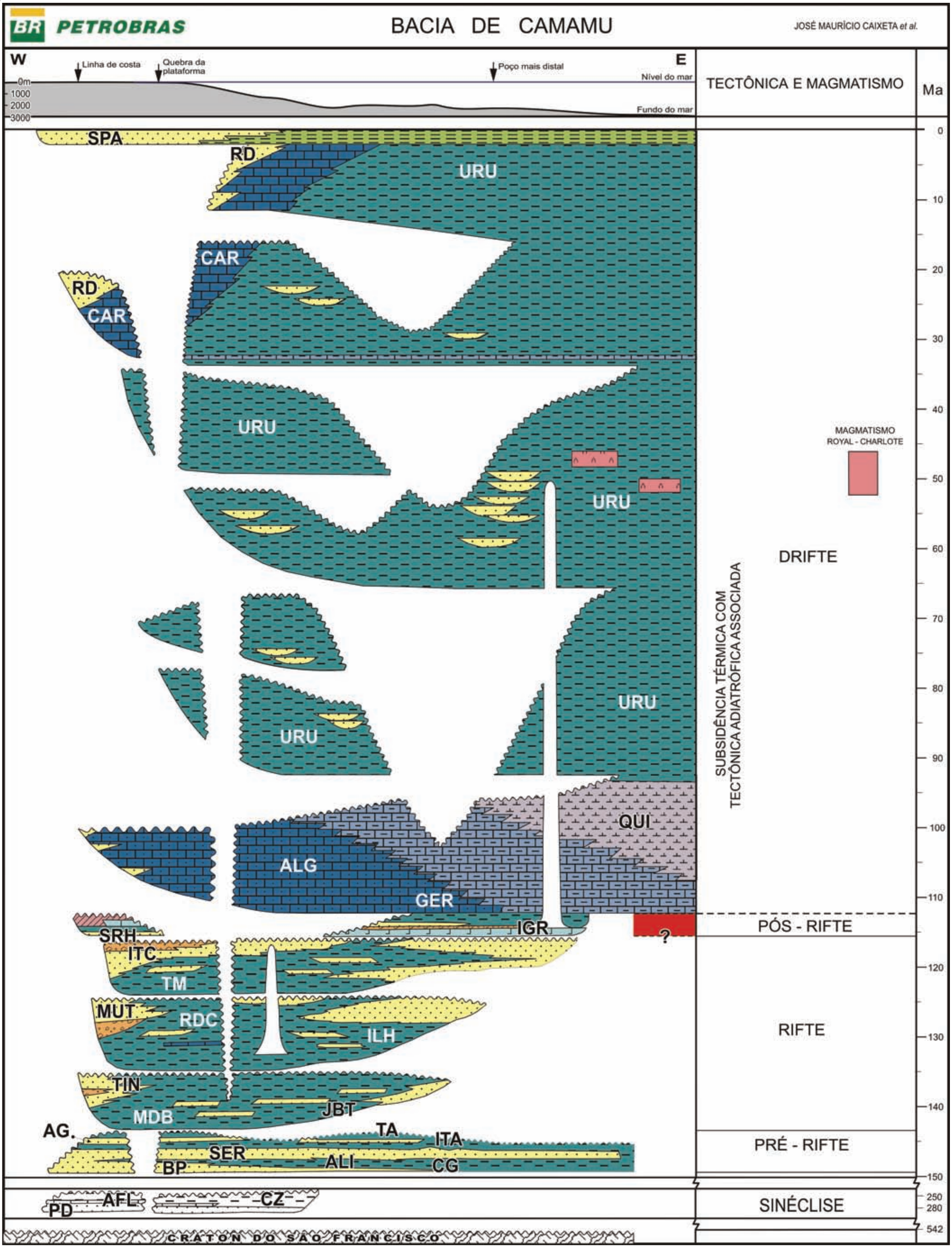
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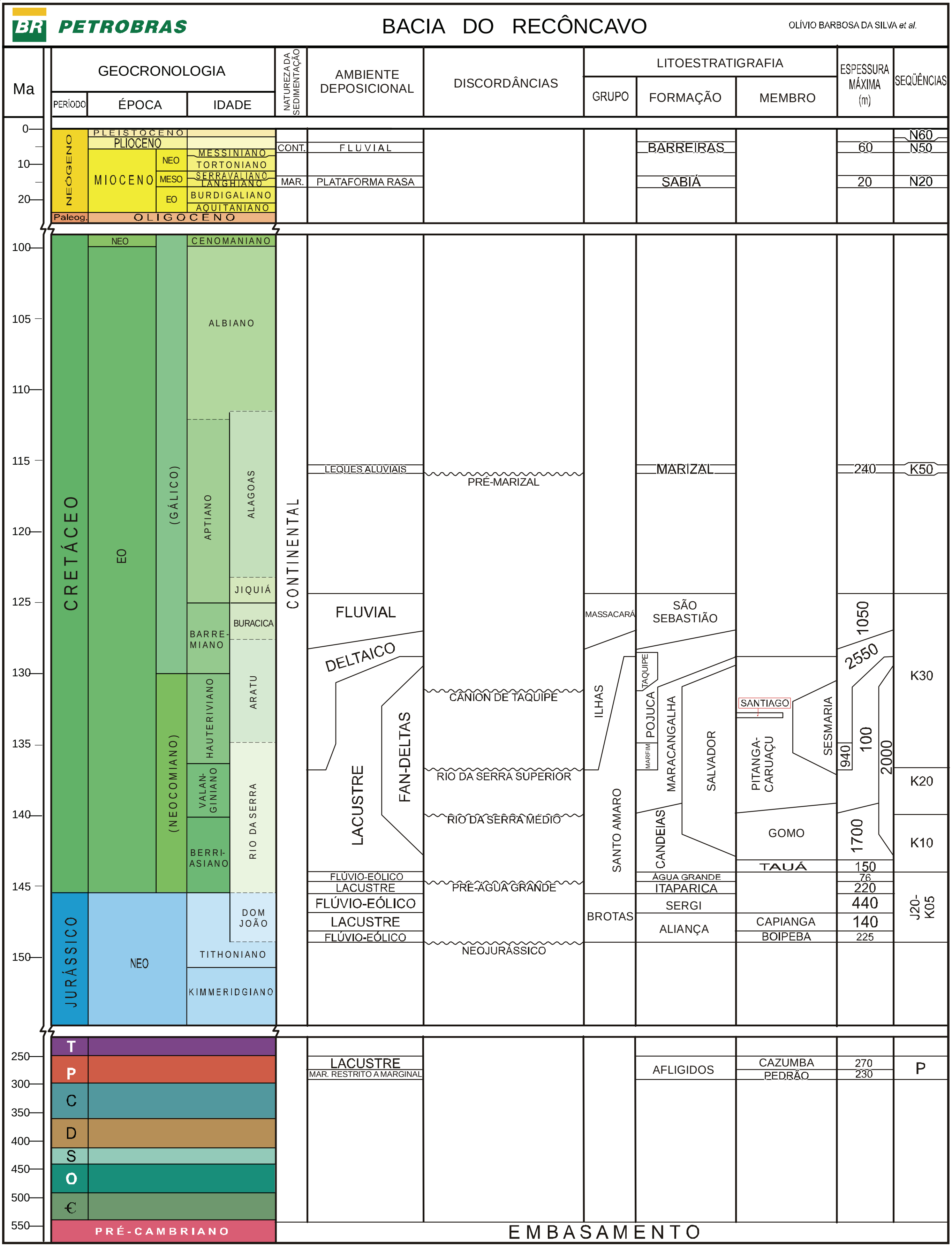
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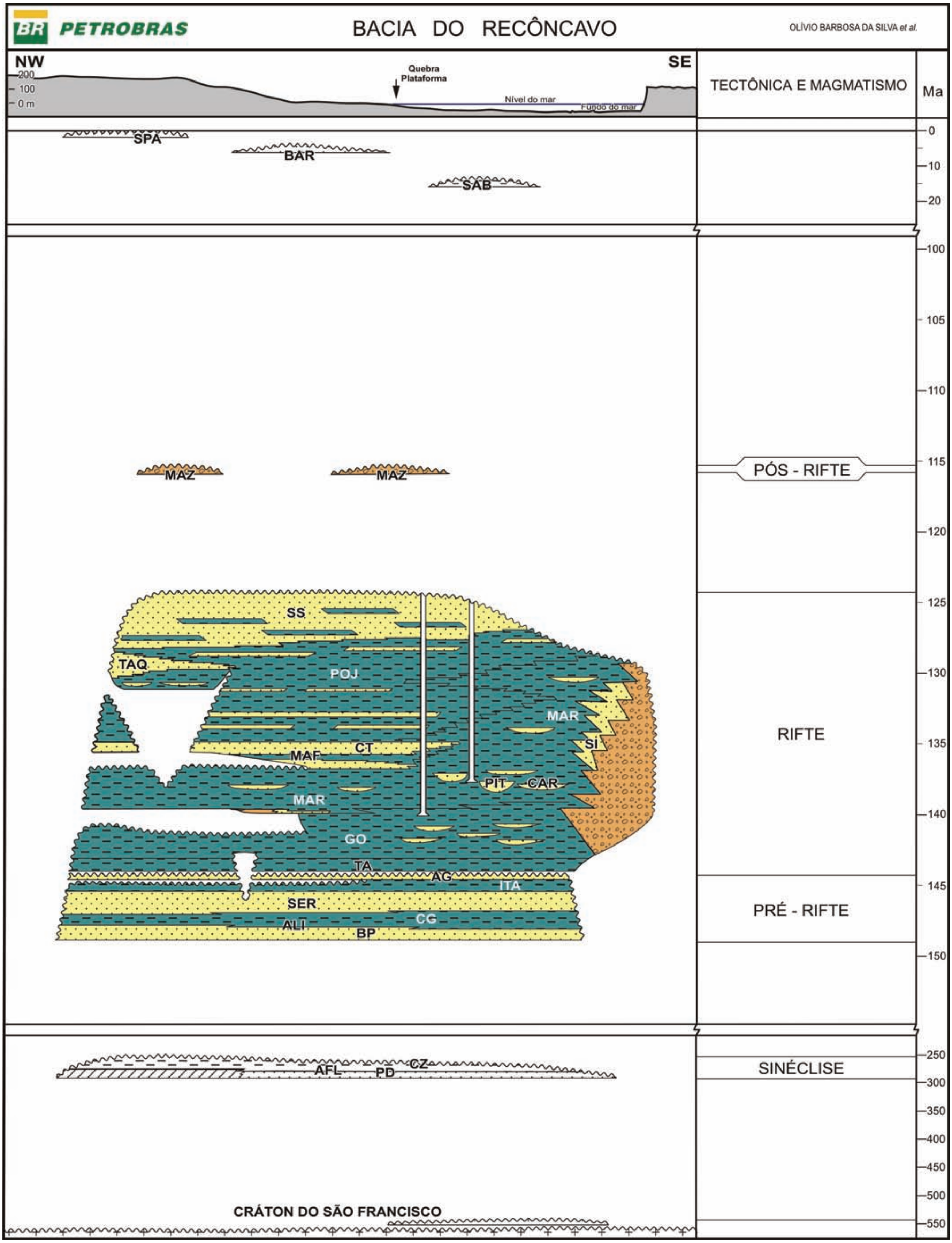

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Table A-1. Well database

Well	Basin	Water depth (m)	Surface elevation (m a msl)	KB elev (m a msl/surf)	Lat	Long
1-BRN-1	S. Tucano	0	252	10	-11.6524	-38.2912
1-FLU-1	W. Bahia	0	474	9	-12.9448	-44.0384
1-FPO-1	S. Tucano	0	333	9	-11.5287	-38.6070
1-FVM-1	S. Tucano	0	318	9	-11.6032	-38.5432
6-MGP-34	Reconcavo	0	101	9	-12.3402	-38.2152
BAS-021	Camamu	46	0	24	-13.6665	-38.8144
BAS-064	Camamu	30	0	25	-13.7399	-38.8652
BAS-071	Almada	34	0	25	-14.6317	-38.9878
BAS-074	Camamu	21	0	25	-13.7474	-38.8811
BAS-077	Almada	78	0	24	-14.1892	-38.8678
BAS-079	Almada	41	0	26	-14.5679	-38.9349
BAS-084	Camamu	27	0	31	-13.1250	-38.5858
BAS-088	Almada	55	0	27	-14.4910	-38.9270
BAS-097	Camamu	26	0	29	-13.9391	-38.8956
BAS-102	Almada	1801	0	14	-14.7723	-38.7018
BAS-107	Camamu	49	0	27	-13.8828	-38.8412
BAS-113	Camamu	20	0	27	-13.1575	-38.6895
BAS-118	Almada	823	0	12	-14.3802	-38.8434
BAS-129	Camamu	1918	0	17	-13.5004	-38.4534

Table A-1. Well database (continued)

Well	utm, x	utm, y	utm zone	Start log (m b KB)	End log (m b KB)	Cali-per	Com po-site log	Litho Log	Litho-strat
1-BRN-1	577,260	8,711,785	24	17	4993	x	x	no	x
1-FLU-1	-47,128	8,563,577	24	5	1014	x	no	no	no
1-FPO-1	542,736	8,725,559	24	11	4195	x	x	no	x
1-FVM-1	549,525	8,717,323	24	10	5653	x	(x)	no	x
6-MGP-34	585,548	8,635,596	24	8	3632	x	x	no	x
BAS-021	520,072	8,489,142	24	374	3394	no	x	no	x
BAS-064	514,578	8,481,028	24	50	3461	x	no	x	x
BAS-071	501,312	8,382,403	24	390	2935	x	x	x	x
BAS-074	512,856	8,480,201	24	35	2828	x	x	x	x
BAS-077	514,266	8,431,336	24	157	3385	x	x	x	x
BAS-079	507,013	8,389,463	24	436	2957	x	x	x	x
BAS-084	544,895	8,549,000	24	50	3946	x	x	x	x
BAS-088	507,866	8,397,964	24	440	4129	x	x	no	x
BAS-097	511,280	8,458,998	24	99	2983	x	x	x	x
BAS-102	532,096	8,366,834	24	1864	5198	x	x	x	x
BAS-107	517,163	8,465,221	24	117	2387	x	x	x	x
BAS-113	533,652	8,545,421	24	13	3820	x	x	x	x
BAS-118	516,885	8,410,215	24	1140	4388	x	x	x	x
BAS-129	559,150	8,507,454	24	2340	5200	x	x	x	x

(x) Composite log without log traces, only interpreted lithology

Table A-2. Well stratigraphy

Lithostratigraphic subdivision of the wells in the study. Unconformities (yellow) are indicated with the minimum time span according to the maximum ages for the lithostratigraphic units. Chronostratigraphic markers (grey) are indicated for the Cenozoic section where available.

BAS-21	KB (m) =	24	Sea bed (m) =	46
Lithostrat	**Top (m MD)**	**Top (m b sb)**	**Thickness (m)**	**Age (Ma)**
Unconformity	*70*	*0*		*93?-0*
Algodões Fm	70	0	330	110-93?
(Albian)	170	100		100
Taipus-Mirim Fm	400	330	232	123-110
Rio de Contas Fm	632	562	420	133-123
Morro de Barro Fm	1052	982	2254	142-135
Itaipe Fm	3306	3236	87	144-142
TD	3393	3323		

BAS-64	KB (m) =	25	Sea bed (m) =	30
Lithostrat	**Top (m MD)**	**Top (m b sb)**	**Thickness (m)**	**Age (Ma)**
Rio Doce-Caravelas Fm	55	0	31	45-0
Unconformity	*86*	*31*		*93?-45*
Algodões Fm	86	31	365	110-93?
(Albian)	180	149		100
Taipus-Mirim Fm	451	396	185	123-110
Rio de Contas Fm	636	581	614	133-123
Morro de Barro Fm	1250	1195	801	142-135
Itaipe Fm	2051	1 996	319	144-142
Sergi Fm	2370	2315	535	147-144
Alianca Fm	2905	2850	259	151-147
Unconformity	*3164*	*3109*		*249-151*
Afligidos Fm	3164	3109	297	280-249
TD	3461	3406		

BAS-71	KB (m) =	25	Sea bed (m) =	34
Lithostrat	**Top (m MD)**	**Top (m b sb)**	**Thickness (m)**	**Age (Ma)**
Rio Doce-Caravelas Fm	57	0	93	45-0
Urucutuca Fm	150	93	312	93?-10
Unconformity	*462*	*405*		*123-93?*
Rio de Contas Fm	462	405	1394	133-123
Morro de Barro Fm	1856	1799	744	142-135
Itaipe Fm	2600	2543	235	144-142
Sergi Fm	2835	2778	67	147-144
Unconformity	*2902*	*2845*		*540-147*
Basement	2902	2845	1	>540
TD	2903	2846		

BAS-74 **KB (m) = 25** **Sea bed (m) = 21**

Lithostrat	Top (m MD)	Top (m b sb)	Thickness (m)	Age (Ma)
Rio Doce-Caravelas Fm	46	0	5	45-0
Unconformity	*51*	*5*		*93?-45*
Algodões Fm	51	5	382	110-93?
Taipus-Mirim Fm	433	387	164	123-110
Rio de Contas Fm	597	551	563	133-123
Morro de Barro Fm	1160	1114	745	142-135
Itaipe Fm	1905	1859	297	144-142
Sergi Fm	2202	2156	538	147-144
Alianca Fm	2740	2694	39	151-147
Unconformity	*2779*	*2733*		*540-151*
Basement	2779	2733	1	>540
TD	2780	2734		

BAS-77 **KB (m) = 24** **Sea bed (m) = 78**

Lithostrat	Top (m MD)	Top (m b sb)	Thickness (m)	Age (Ma)
Rio Doce-Caravelas Fm	102	0	300	30-0
Unconformity	*102-269*	*0-167*		*<28*
(L. Oligocene N-520)	269	167		28
Urucutuca Fm	402	300	471	93?-10
(E. Oligocene N-510)	531	429		31
(L. Eocene)	639	537		34
(M. Eocene)	747	645		40
(E. Eocene)	783	681		49
(Paleocene)	855	753		56
Unconformity	*873*	*771*		*93?-56*
Algodões Fm	873	771	47	110-93?
(Albian)	891	789		100
Taipus-Mirim Fm	920	818	205	123-110
Rio de Contas Fm	1125	1023	1065	133-123
Morro de Barro Fm	2190	2088	1195	142-135
TD	3385	3283		

BAS-79 **KB (m) = 26** **Sea bed (m) = 41**

Lithostrat	Top (m MD)	Top (m b sb)	Thickness (m)	Age (Ma)
Rio Doce-Caravelas Fm	67	0	369	45-0
Unconformity	*67-172*	*0-105*		*<34*
(L. Eocene)	172	105		34
(M. Eocene)	276	209		40
(E. Eocene)	420	353		49
Urucutuca Fm	436	369	50	93?-45
(Paleocene)	456	389		56
Unconformity	*486*	*419*		*93?-56*
Algodões Fm	486	419	24	110-93?
Taipus-Mirim Fm	510	443	1011	123-110
Rio de Contas Fm	1521	1454	1436	133-123
TD	2957	2890		

BAS-84	**KB (m) =**	**27**	**Sea bed (m) =**	**27**
Lithostrat	**Top (m MD)**	**Top (m b sb)**	**Thickness (m)**	**Age (Ma)**
Rio Doce-Caravelas Fm	54	0	366	45-0
Unconformity	*420*	*366*		*123-45*
Rio de Contas Fm	420	366	1980	133-123
Morro de Barro Fm	2400	2346	1027	142-135
Itaipe Fm	3427	3373	466	144-142
Sergi Fm	3893	3839	56	147-144
TD	3949	3895		

BAS-88	**KB (m) =**	**27**	**Sea bed (m) =**	**55**
Lithostrat	**Top (m MD)**	**Top (m b sb)**	**Thickness (m)**	**Age (Ma)**
Rio Doce-Caravelas Fm	82	0	345	45-0
Unconformity	*82-324*	*0-242*		*<34*
(L. Eocene)	324	242		34
(M. Eocene)	396	314		40
Urucutuca Fm	427	345	1304	93?-45
(E. Eocene)	720	638		49
(Paleocene)	792	710		56
(Maastrictian)	1008	926		66
Unconformity	*1731*	*1649*		*110-93?*
Taipu-Mirim Fm	1731	1649	33	123-110
Rio de Contas Fm	1764	1682	1385	133-123
Morro de Barro Fm	3149	3067	726	142-135
Itaipe Fm	3875	3793	228	144-142
Sergi Fm	4103	4021	206	147-144
Unconformity	*4309*	*4227*		*540-147*
Basement	4309	4227	1	>540
TD	4310	4228		

BAS-97	**KB (m) =**	**29**	**Sea bed (m) =**	**26**
Lithostrat	**Top (m MD)**	**Top (m b sb)**	**Thickness (m)**	**Age (Ma)**
Rio Doce-Caravelas Fm	55	0	75	45-0
Unconformity	*130*	*75*	*0*	*93?-45*
Algodões Fm	130	75	368	110-93?
Taipus-Mirim Fm	498	443	162	123-110
Unconformity	*660*	*605*	*0*	*135-123*
Morro de Barro Fm	660	605	1418	142-135
Itaipe Fm	2078	2023	31	144-142
Sergi Fm	2109	2054	331	147-144
Alianca Fm	2440	2385	217	151-147
Unconformity	*2657*	*2602*		*249-151*
Afligidos Fm	2657	2602	186	280-249
Unconformity	*2788*	*2733*		*540-280*
Basement	2788	2733	1	>540
TD	2789	2734		

BAS-102	KB (m) =	14	Sea bed (m) =	1801
Lithostrat	**Top (m MD)**	**Top (m b sb)**	**Thickness (m)**	**Age (Ma)**
Urucutuca Fm	1815	0	1125	90-10
Unconformity ?	*1815-2160*	*0-345*		*<40*
(E. Eocene)	2160	345		40
(Paleocene)	2376	561		56
(Maastrictian)	2592	777		66
(Cenom.-Santon. F110)	2934	1119		90
Algodões Fm	2940	1125	1165	110-90
(Albian)	3186	1371		100
Taipus-Mirim Fm	4105	2290	748	123-110
Rio de Contas Fm	4853	3038	345	133-123
TD	5198	3383		

BAS-107	KB (m) =	27	Sea bed (m) =	49
Lithostrat	**Top (m MD)**	**Top (m b sb)**	**Thickness (m)**	**Age (Ma)**
Rio Doce-Caravelas Fm	76	0	299	c. 70-0
Unconformity	*76-180*	*0-104*		*<60*
(E. Paleocene)	180	104		60
(Alb.-Camp, N-250, -260, -265)	234	158		(>)70
Unconformity	*375*	*299*		*93?-70*
Algodões Fm	375	299	292	110-93?
Taipus-Mirim Fm	667	591	176	123-110
Rio de Contas Fm	843	767	797	133-123
Morro de Barro Fm	1640	1564	747	142-135
TD	2387	2311		

*) Redeposited sediments at 234 m KB: Nanozones 250, -260, -265; Albanian to Campanian age. Youngest age most likely.

BAS-113	KB (m) =	27	Sea bed (m) =	20
Lithostrat	**Top (m MD)**	**Top (m b sb)**	**Thickness (m)**	**Age (Ma)**
Rio Doce-Caravelas Fm	47	0	75	45-0
Unconformity	*122*	*75*		*123-45*
Rio de Contas Fm	122	75	96	133-123
Morro de Barro Fm	218	171	3254	142-135
Itaipe Fm	3472	3425	299	144-142
Sergi Fm	3771	3724	49	147-144
TD	3820	3773		

BAS-118	KB (m) =	12	Sea bed (m) =	823
Lithostrat	**Top (m MD)**	**Top (m b sb)**	**Thickness (m)**	**Age (Ma)**
Urucutuca Fm	835	0	1303	93?-10
Unconformity ?	*835-1606*	*0-771*		*<49*
(E. Eocene)	1606	*771*		49
(Paleocene)	1746	*911*		56
Unconformity	*2138*	*1303*		*110-93?*
Taipus-Mirim Fm	2138	1303	819	123-110
Rio de Contas Fm	2957	2122	910	133-123
Morro de Barro Fm	3867	3032	521	142-135
TD	4388	3553		

BAS-129	KB (m) =	17	Sea bed (m) =	1918
Lithostrat	**Top (m MD)**	**Top (m b sb)**	**Thickness (m)**	**Age (Ma)**
Urucutuca Fm	1935	0	1221	93?-10
Unconformity ?	*1935-2448*	*0-513*		*<35*
(L. Eocene)	2448	513		35
(M. Eocene)	2484	549		40
(E. Eocene)	2730	795		46
(Paleocene)	2979	1044		56
Unconformity ?	*2979-3156*	*1044-1221*		*93?-56*
Algodões Fm	3156	1221	105	110-93?
Taipus-Mirim Fm	3261	1326	1939	123-110
TD	5200	3265		

1-BRN-1	RT (m) =	10	Grnd level (m) =	242
Ltihostrat	**Top (m MD)**	**Top (m b gl)**	**Thickness (m) =**	**Age (Ma)**
Unconformity	*10*	*0*		*115-0*
Marizal Fm	10	0	119	116-115
Unconformity	*129*	*119*		*125-116*
São Sebastião Fm	129	119	3652	128-125
Salvador Fm	3781	3771	1206	143-130
TD	4987	4977		

1-FLU-1	RT (m) =	9	Grnd level (m) =	474
Lithostrat	**Top (m MD)**	**Top (m b gl)**	**Thickness (m)**	**Age (Ma)**
Unconformity	*9*	*0*		*540-0*
Proterozoic undivided	9	0	1005	2500-540
unknown lithology	9	0	9	
shales/limestones	40	31	165	
limestones	205	196	395	
shales/limestones	600	591	50	
limestones	650	641	327	
basement (igneous)	977	969	43	
TD	1020	1011		

1-FPO-1	**RT (m) =**	**9**	**Grnd level (m) =**	**323**
Lithostrat	**Top (m MD)**	**Top (m b gl)**	**Thickness (m)**	
Unconformity	*9*	*0*		*115-0*
Marizal Fm	9	0	273	116-115
Unconformity	*282*	*273*		*125-116*
São Sebastião Fm	282	273	2544	128-125
Ilhas Group (undivided)	2826	2817	775	137-127
Candelas Fm	3601	3592	562	144-140
Sergi Fm	4163	4154	40	147-146
TD	4203	4194		

1-FVM-1	**RT (m) =**	**9**	**Grnd level (m) =**	**318**
Lithostrat	**Top (m MD)**	**Top (m b gl)**	**Thickness (m)**	**Age (Ma)**
Unconformity		*0*		*115-0*
Marizal Fm	9	0	100	116-115
Unconformity		*100*		*125-116*
Massacará Grp undiff	109	100	3123	128-125
Ilhas Grp undiff	3232	3223	1248	137-127
Candeias Fm	4480	4471	1141	144-140
Sergi Fm	5621	5612	32	147-146
TD	5653			

6-MGP-34	**RT (m) =**	**9**	**Grnd level (m) =**	**92**
Lithostrat	**Top (m MD)**	**Top (m b gl)**	**Thickness (m)**	**Age (Ma)**
Unconformity	*10*	*1*		*125-0*
São Sebastião Fm	10	1	632	128-125
Pojuca Fm	642	633	586	135-127
Marfim Fm	1228	1219	611	137-135
Maracangalha Fm	1839	1830	1467	140-120
Candeias Fm	3306	3297	126	144-140
Agua Grande Fm	3432	3423	35	145-144
Itaparica Fm	3467	3458	126	146-145
Sergi Fm	3593	3584	35	147-146
TD	3628	3619		

Appendix B. Interpretation and plots of sonic data

Legend

Depths are given in km below sea bed or ground level, also in comments where depths in round numbers are indicated for reference in the diagrams. Depth is displayed as negative numbers in order to produce plots where depth increases downwards.

Log plots (left hand page)

Vp, P-velocity: Sonic p-wave velocities
rhob: Bulk density (blue curve)
Nphi: Neutron porosity converted to limestone densities, -1.6667*nphi + 2.71 (red curve)
Plots of caliper and sonic logs for detection of bad-hole data is displayed on the lower side of the left-hand page. Sonic data that correlate with bad-hole conditions are colour-coded in red on the first two plots and deleted in the final data set shown in the third plot.

Plots for interpretation of the burial anomaly (right hand page)

<u>Upper right plot</u> displays all sonic datapoints after removal of bad-hole data. Colour coded according to lithology according to the LithoLog, if available.

<u>Lower right plots</u> displays the edited sonic data averaged over intervals of 10 m.

Selected lithostratigraphic units are indicated in the diagram with a colour corresponding to the colouring of that part of the sonic log.

Biostratigraphic control on the post-Campanian succession is indicated with arrows along the depth axis.

Main unconformities are marked with green lines. Possible unconformities are indicated by dashed lines and intervals where Cenozoic unconformities may be present are marked with a green, dotted box. Abbreviations used in the names of the unconformities:

RdC	Rio de Contas Fm
RD-C	Rio Doce-Caravelas Fms
MdB	Morro do Barro Fm
TM	Taipus-Mirim Fm

Identified datapoints for low-velocity shale and high-velocity sandstone are plotted on the displays. The datapoints are readings of depth and velocity from the respective lithological units as identified on the composite log and the LithoLog if available.

Full lines indicate baselines for the respective lithologies:

sh_o (or Vsh-o) – baseline for organic-rich shale; full cyan line (Eq. 5-6).
sh (or Vsh) – baseline for shale; full red line (Eq. 5-1; Japsen 2000)
BR00, BR05 – baseline for sandstone with 0% and 5% clay; full blue and green lines (Eq. 5-5). Slightly modified in this report after Japsen et al. 2007.

Dashed lines indicate the same baselines only shifted upwards by the burial anomaly to fit the data trend.

Burial anomaly = 0: normal compaction
Burial anomaly (= magnitude of burial anomaly, rather than the formally defined negative values in case of removed overburden thickness) >0: indicative of exhumation
Exhumation = Burial anomaly + post-exhumational reburial

.
Paleocene strata).

Unconformities
Post-Algodões unconformity (110–0 Ma): Above Algodões Fm (365 m thick; Albian strata reported) and below thin cover of RD-C Fms (31 m).

Caliper
No caliper available, but the sonic data are well-defined over most of the drilled interval.

Sonic log and composite log (without sonic displayed)
Mixed lithologies above MdB, including 100 m thick RdC sandstone at c. 0.8 km.

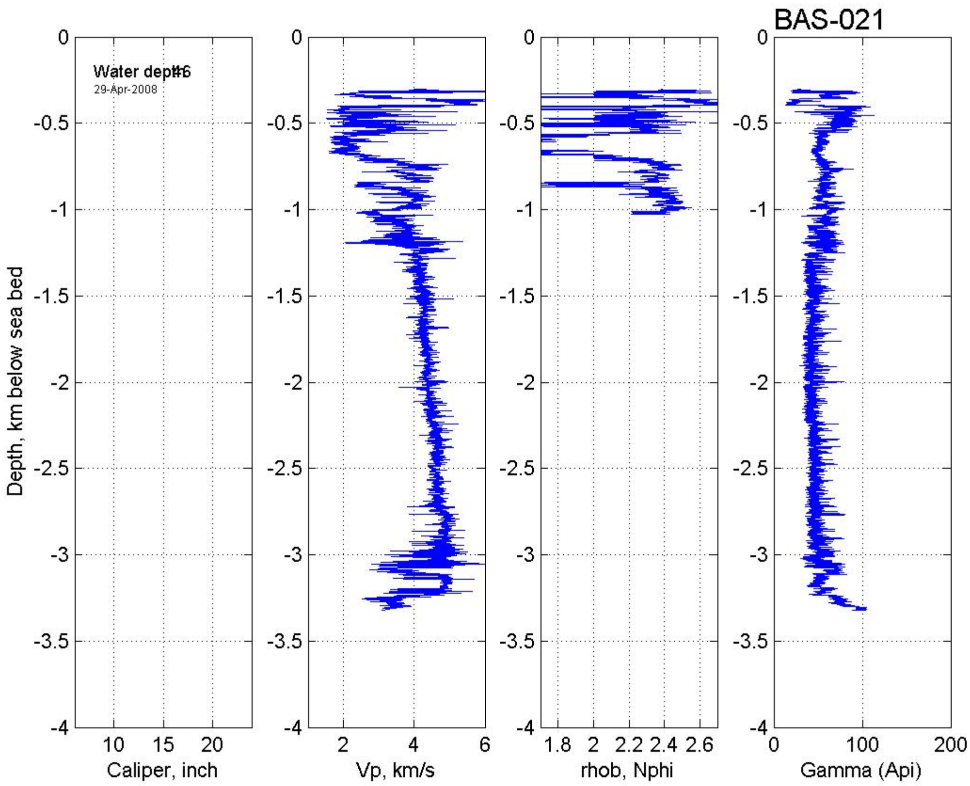
Massive MdB sandstone between 1.3 and 3.0 km with velocities ranging between c. 4 and 5 km/s. The sonic data for this interval was used for calibration on the sandstone trends, BR00 and BR05.

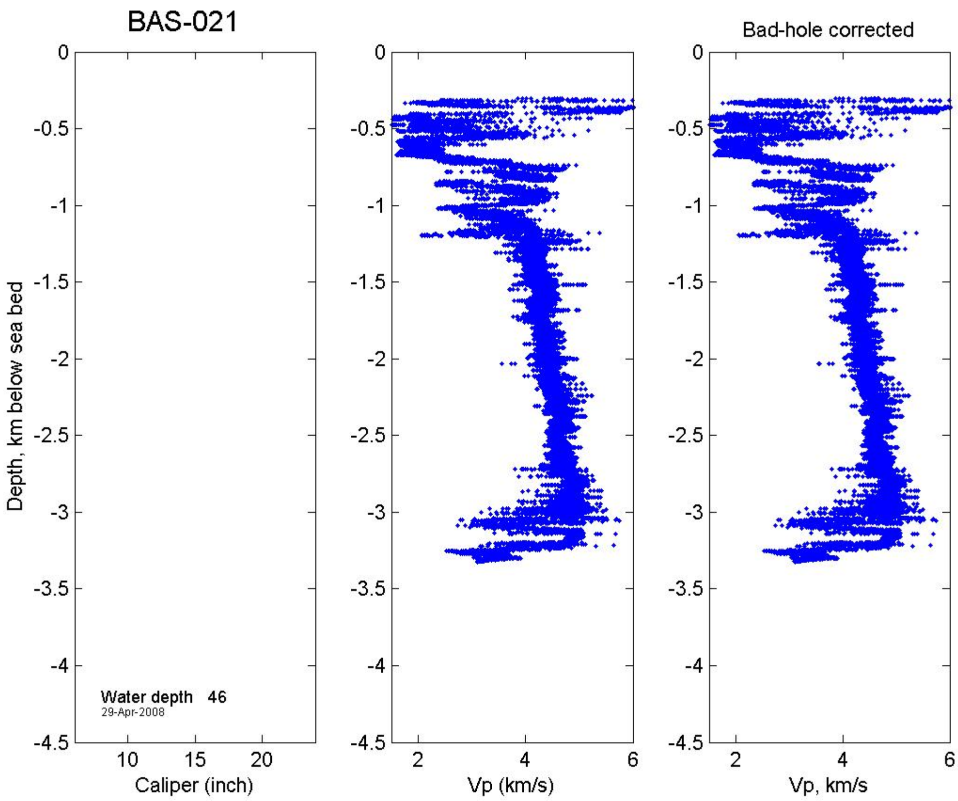
Burial anomaly
1.9 ± 0.2 km (relative to the baselines) gives a good match between the sandstone data between 0.8 and 3.1 km and the absolute values and the curvature of the baselines for pure sandstone. BR00 and BR05 were calibrated after this dataset by shifting the trends towards more shallow depths than those of SS00 and SS05 and thus reducing the estimated burial anomaly.

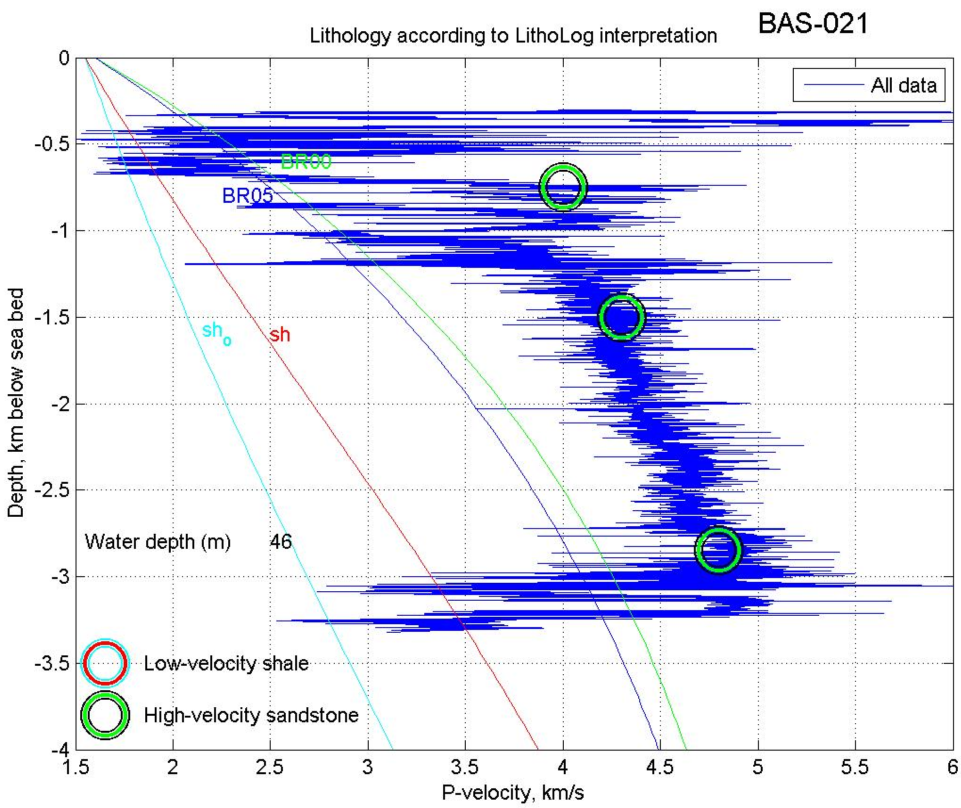
Post-exhumational burial
0.0 km.

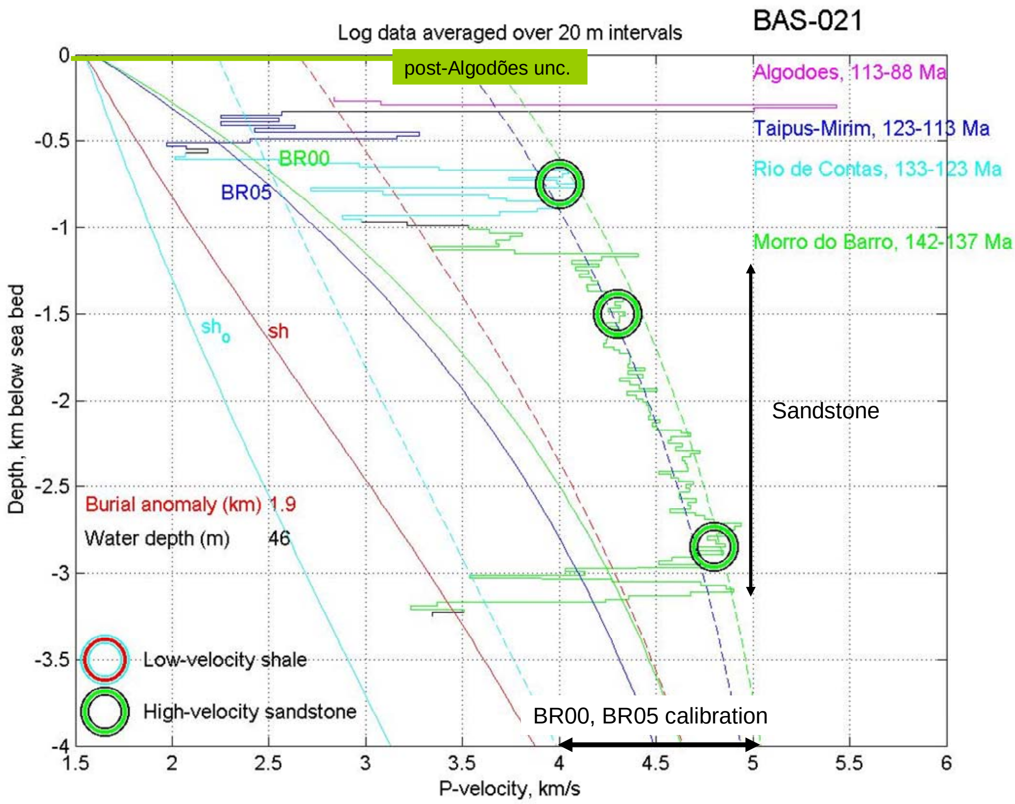
Removed section

1.9 ± 0.5 km (allowing for the uncertainty of the baselines); probably corresponding to the upper part of the Algodões Fm (0.4 km preserved) and the lower part of the Urucutuca Fm (missing).


BAS-021
Water depth 46
29-Apr-2008
Depth, km below sea bed
Caliper, inch
Vp, km/s
rhob, Nphi
Gamma (Api)


BAS-021
Bad-hole corrected
Water depth 46
29-Apr-2008
Depth, km below sea bed
Caliper (inch)
Vp (km/s)
Vp, km/s





cf. BAS-74 (near-by), -97, -113 (thick MdB sandstone)

BAS-64

Unconformities
Post-Algodões unconformity (110–0 Ma): Above Algodões Fm (365 m) and below thin cover of RD-C Fms (31 m).

Caliper
Very high calliper values over most of the interval below 1 km.

Sonic data and LithoLog
The well is drilled very near to BAS-74 and the depths to the stratigraphic units encountered in these wells are very similar, but the details of the sonic log differ significantly. Very high Vp-values above c. 0.4 km represent the shelf carbonates of the Algodões Fm. A pronounced sonic low at c. 2.2 km is probably due to bad-hole conditions, and most of the data in the interval between 2 and 2.4 km is filtered due to bad-hole conditions.

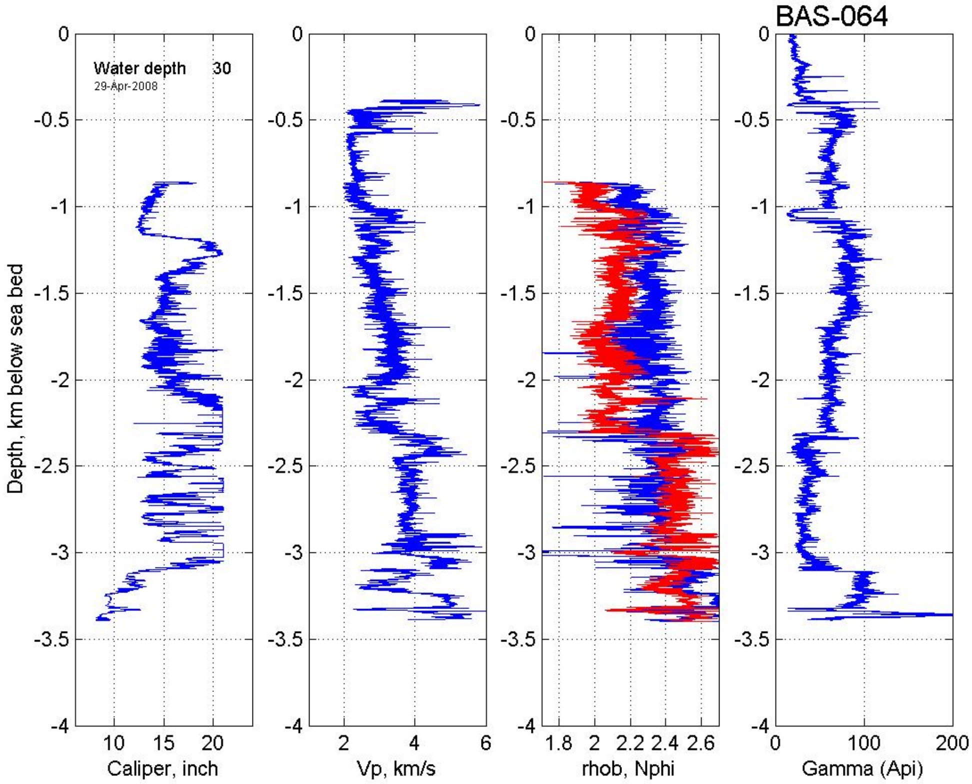
Thin, but well-defined shale units in the interval 0.8-2 km (RdC Fm and MdB Fms). The sonic data for this interval were used for definition of the baseline for organic-rich shales, Vsh-o.

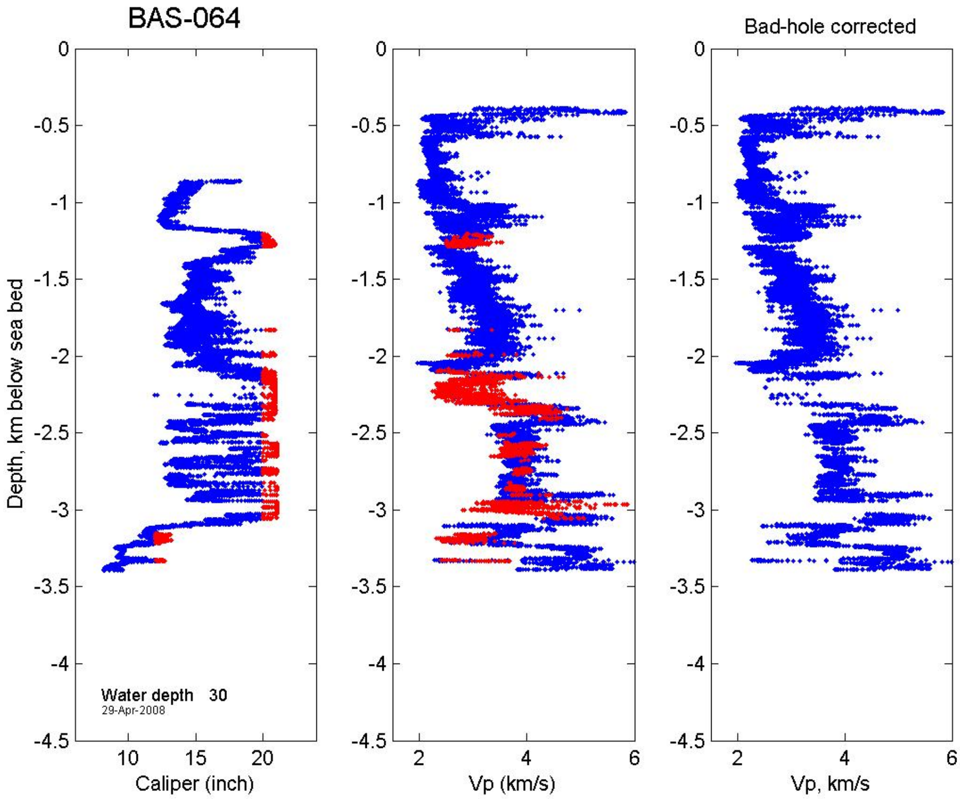
Well-defined high-velocity sandstone units in the Sergi and Aliança Fms.

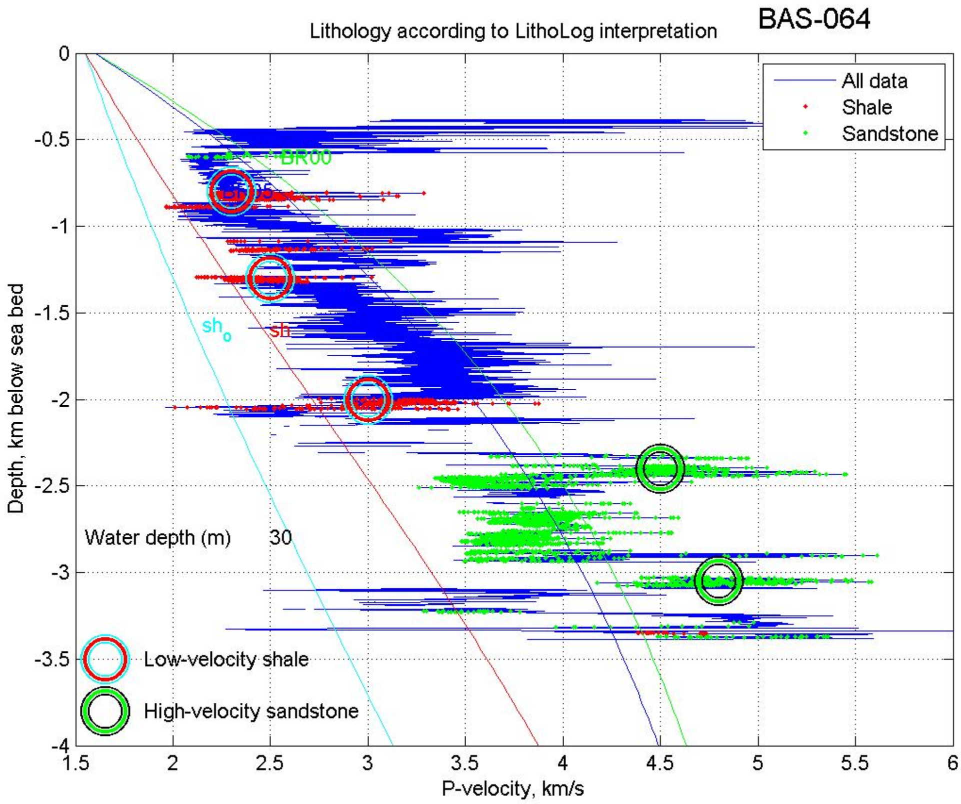
Burial anomaly
1.4 ± 0.4 km (relative to the baselines) based on a match with high-velocity sandstone units and low-velocity shale units. The quality of the sonic data for this well is not the best (cf. the wide variations of the caliper).

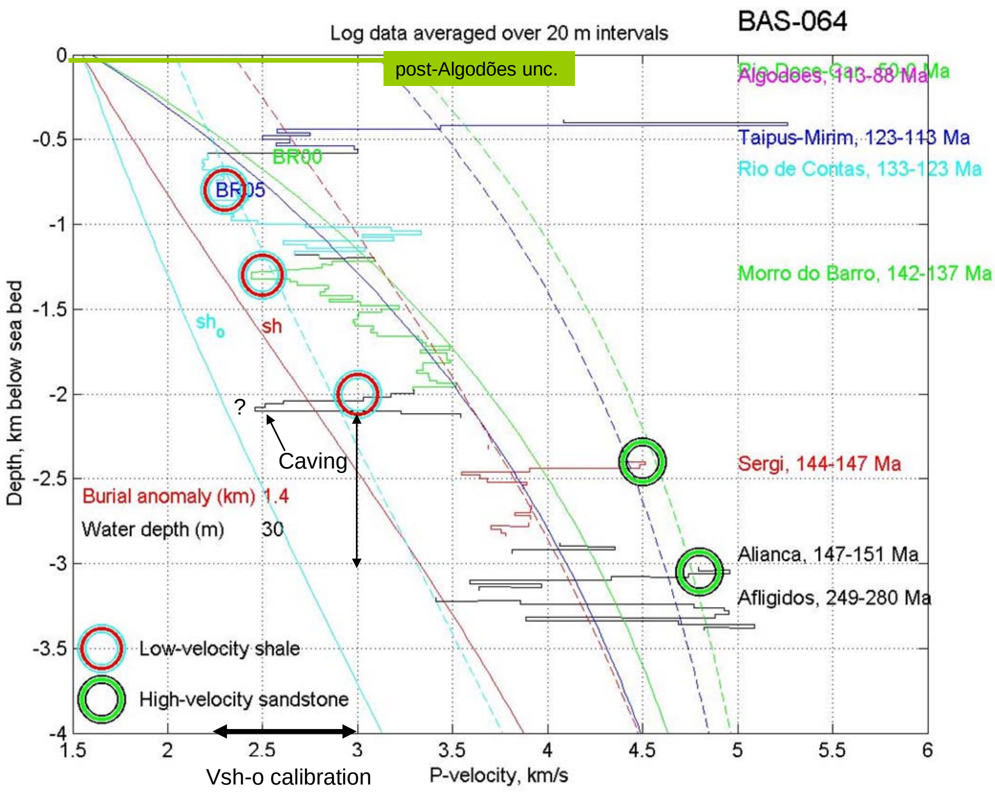
Post-exhumational burial
0 km.

Removed section
1.4 ± 0.4 km (allowing for the uncertainty of the baselines); probably corresponding to the upper part of the Algodões Fm (o.4 km preserved) and the lower part of the Urucutuca Fm (missing).


BAS-064
Water depth 30
29-Apr-2008
Depth, km below sea bed
Caliper, inch
Vp, km/s
rhob, Nphi
Gamma (Api)


BAS-064
Bad-hole corrected
Water depth 30
29-Apr-2008
Depth, km below sea bed
Caliper (inch)
Vp (km/s)
Vp, km/s





cf. BAS-74 (near-by)

BAS-71

Unconformities
Post-RdC unconformity (123–? Ma): Above thick RdC Fm (1394 m) and below/within Urucutuca Fm; Algodões and TM Fms missing.

Caliper
Very high calliper values c. 1.5-2 km.

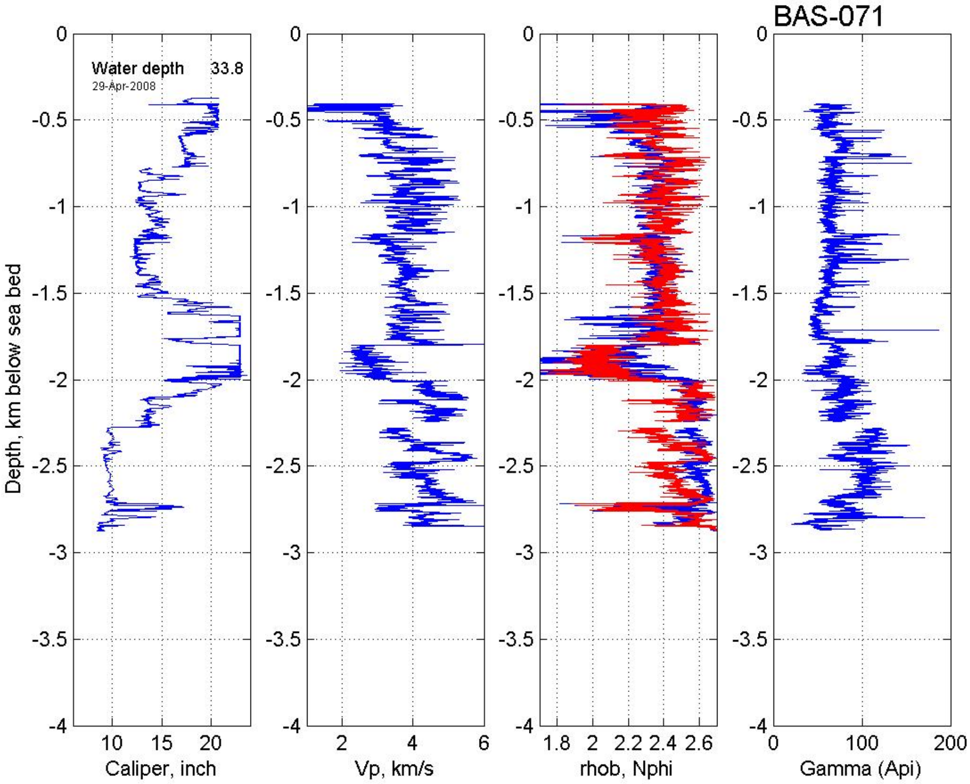
Sonic data, LithoLog and composite log
Thin shale units within the rift sequence with lower velocities than the surrounding sand units, but significant data scatter in the section below 2 km. The sonic data for this interval were used for definition of the baseline for organic-rich shales, Vsh-o.

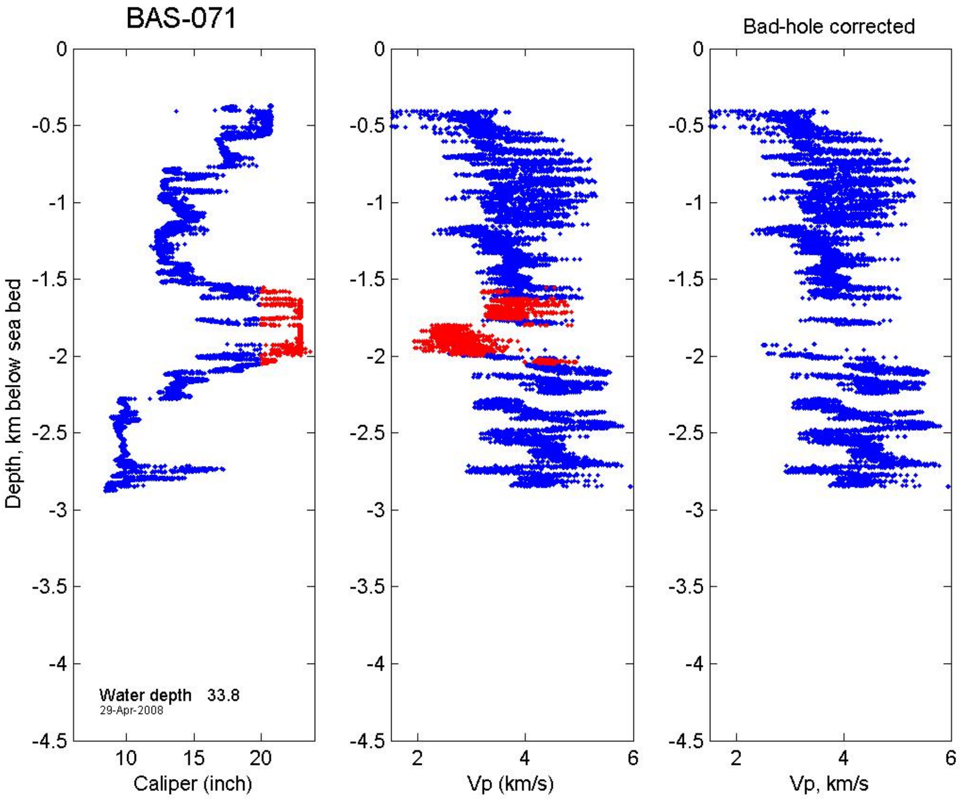
Mainly sandstone between 0.5 and 1.8 km (RdC), but very irregular sonic data. Thick sandstone units between 2.1 and 2.4 m (MdB). These sandstones also have strongly varying velocities (typically between 4.5 and 5.0 km/s), but over thicker units. The lower range of the velocities are taken as most representative, partly because the resulting minor magnitude of the estimated the burial anomaly fits better with the results from the near-by wells.

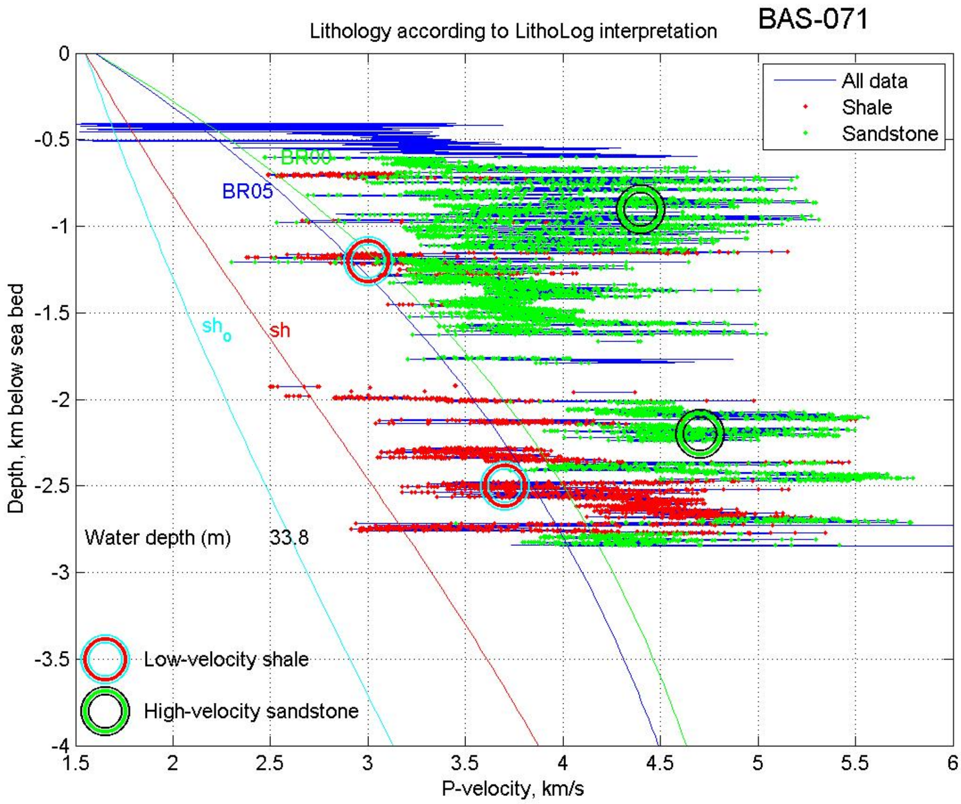
Burial anomaly
2.5 ± 0.4 km (relative to the baselines) based primarily on a match between the general sonic level for the deeper sandstone units.

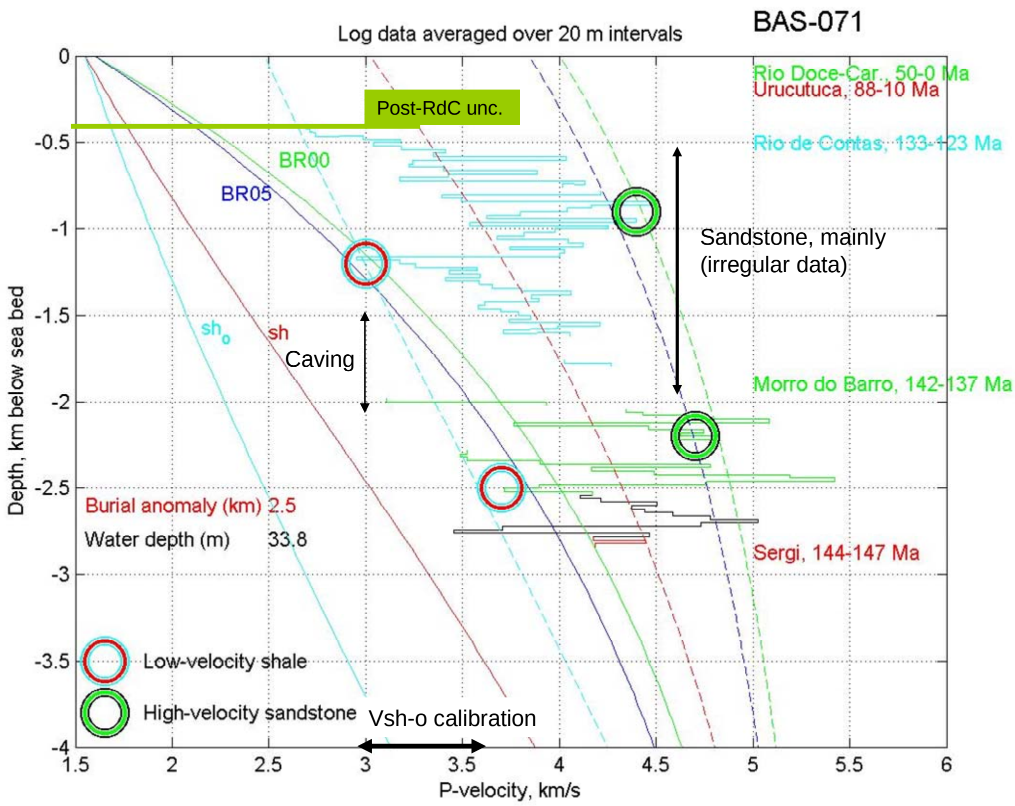
Post-exhumational burial
0.4 km; burial of the post-RdC unconformity.

Removed section
2.9 ± 0.9 km (allowing for the uncertainty of the baselines); probably corresponding to the upper part of the RdC Fm (1.4 km preserved), the TM and Algodões Fms and the lower part of the Urucutuca Fm (all missing)


BAS-071
Water depth 33.8
29-Apr-2008
Depth, km below sea bed
Caliper, inch
Vp, km/s
rhob, Nphi
Gamma (Api)


BAS-071
Bad-hole corrected
Water depth 33.8
29-Apr-2008
Depth, km below sea bed
Caliper (inch)
Vp (km/s)
Vp, km/s





cf. BAS-79 (near-by)

BAS-74

Unconformities

Post-Algodões unconformity (110–0 Ma): Above Algodões Fm (382 m) and below thin cover (5 m).

Caliper

Relatively narrow spread of calliper values. Above c. 1 km, the values are cut of artificially, Vp are within a narrow interval. High values in the 1.1-1-4 km interval correspond to a wide range of Vp-values and the values below 2.5 km/s are thus probably due to bad-hole conditions. These low values do however, not affect the mean calculated over 10-m intervals.

Sonic data, LithoLog and composite log

The well is drilled very near to BAS-74 and the depths to the stratigraphic units encountered in these wells are very similar, but the details of the sonic logs differ significantly maybe because BAS-64 has more severe bad-hole problems. High sonic values in the logged part of the TM Fm with limestone and dolomite beds.

In the shale-dominated interval between 0.6 and 2.2 km there is a moderate increase in Vp with a lower bound defined by shale units and higher velocities related to beds of limestone etc (RdC, MdB and Itaipe Fms). The sonic data for this interval were used for definition of the baseline for organic-rich shales, Vsh-o.

Thick sandstones of the Sergi and Aliança Fm (2.2-2.7 km). The high velocities at the base of this unit are not representative for the general trend of the sandstone as estimated from the details of the composite log.

Burial anomaly

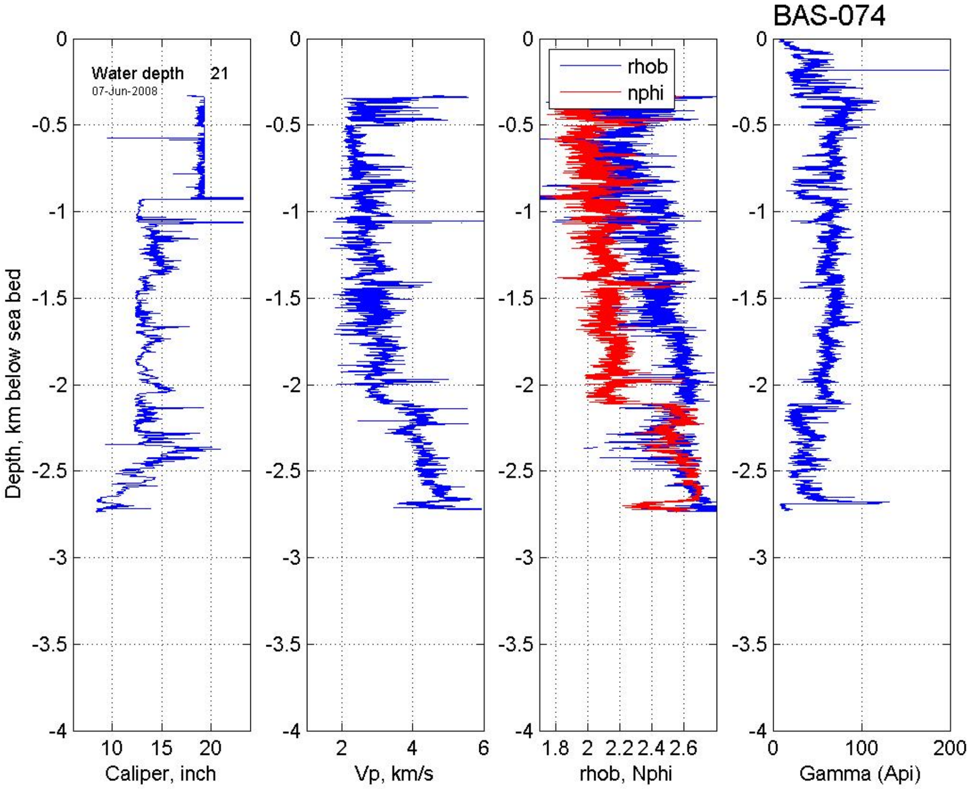
1.4 km ± 0.4 km (relative to the baselines) estimated from the sonic values of the sandstone around 2.4-2.7 km and the well-defined lower bound of shale velocities over a 1.5 km interval (this dataset was used for defining Vsh-o).

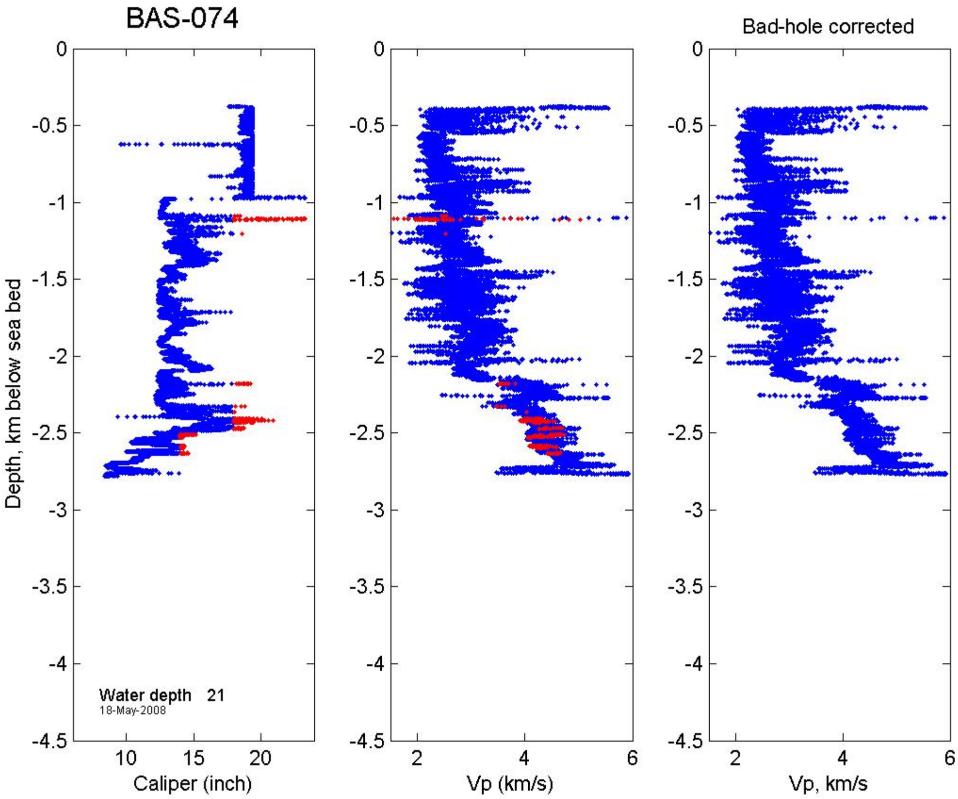
Post-exhumational burial

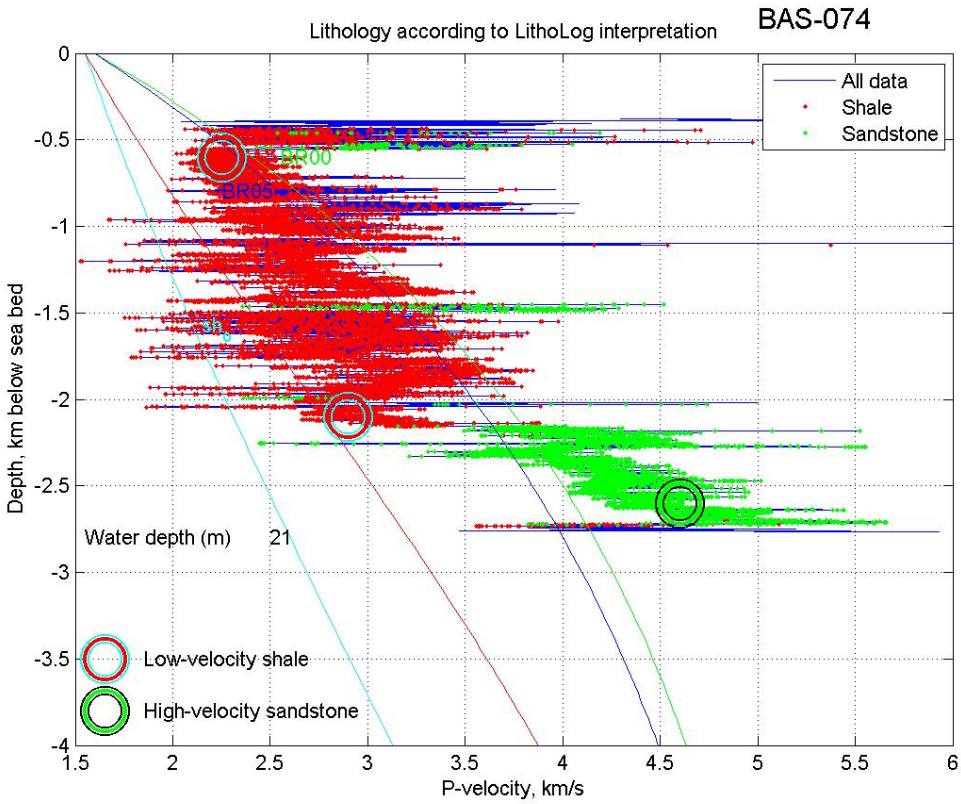
0.0 km.

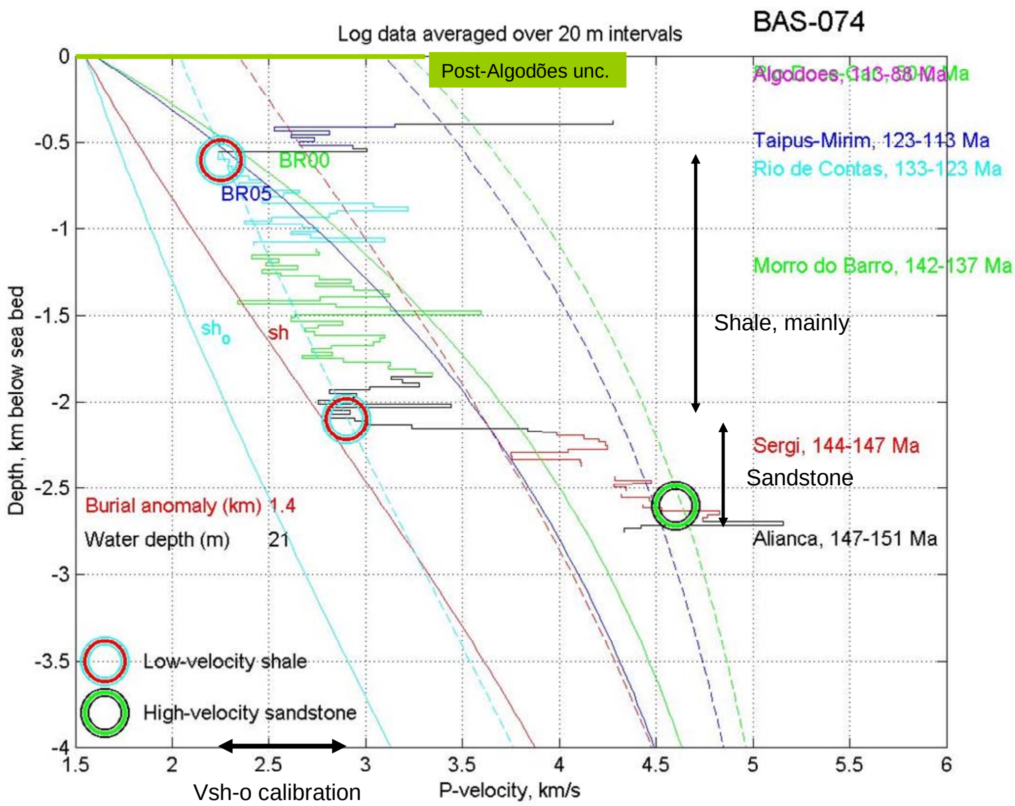
Removed section

1.4 ± 0.7 km (allowing for the uncertainty of the baselines); probably corresponding to the upper part of the Algodões Fm (0.4 km preserved) and the lower part of the Urucutuca Fm (missing).


BAS-074
Water depth 21
07-Jun-2008
Depth, km below sea bed
Caliper, inch
Vp, km/s
rhob
nphi
rhob, Nphi
Gamma (Api)


BAS-074
Bad-hole corrected
Water depth 21
18-May-2008
Depth, km below sea bed
Caliper (inch)
Vp (km/s)
Vp, km/s





cf. BAS-64 (near-by)

BAS-77

Unconformities

Post-Algodões unconformity (110-65 Ma): Above thin Algodões Fm (47 m; Albian strata reported) and below Urucutuca Fm (818 m) with Paleocene strata reported at the base.

Post-mid Oligocene unconformity (28–0 Ma): Above Paleocene-Oligocene succession and within thin overlying section (167 m, RD-C Fms) with Late Oligocene strata at the base.

Caliper

Generally narrow range of calliper values, but not recorded above 1 km. Some pronounced peaks that do not appear to correlate with scatter in the sonic data; e.g. around 2.5 km where the sonic log is very stable. Consequently few datapoints are deleted.

Sonic data, LithoLog and composite log

The LithoLog records very few datapoints as pure shale, but rather as 'claystone-sandy' (pink). However, the composite log generally shows such intervals as 'shale'; such as most of 0.5-0.7 km (basal Urucutuca Fm), most of 1.8-2.7 km (RdC) and 3.1-3.3 km (basal MdB Fm). These 3 intervals all correspond to low vp-values.

Thick sandstone units, RdC upper part, 1.1-1.3 km. Uniform sandstone unit, MdB (50 m thick), 2.4 km. Sandstone units, MdB, c. 2.8-3.1 km.

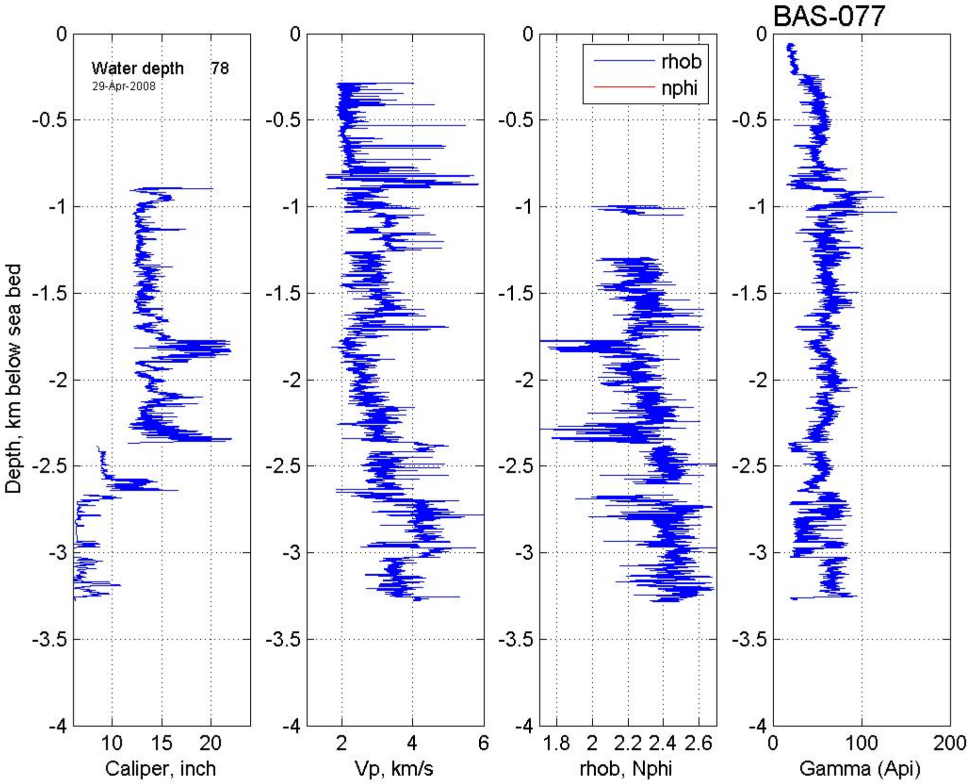
Burial anomaly

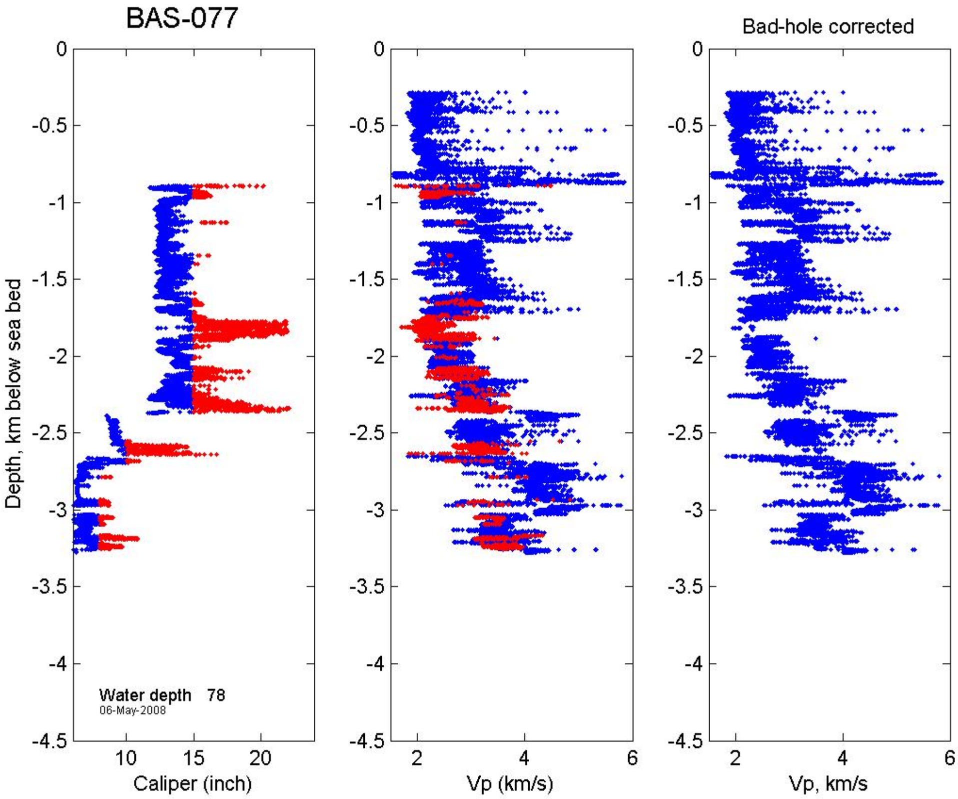
0.7 km ± 0.4 km (Mesozoic sequence relative to the baselines) is chosen as a good match between the low-velocity bound for the shale data between c. 1.5 and 2-5 km and the upper bound for the sandstone units between 1 and 3 km. The low-velocity shale units are thus interpreted to be organic-rich; an alternative interpretation of these as being dominated by pure shale (and thus at their present maximum burial) is however, ruled out by the high velocities from three sandstone units that all indicate that these units have been more deeply buried.

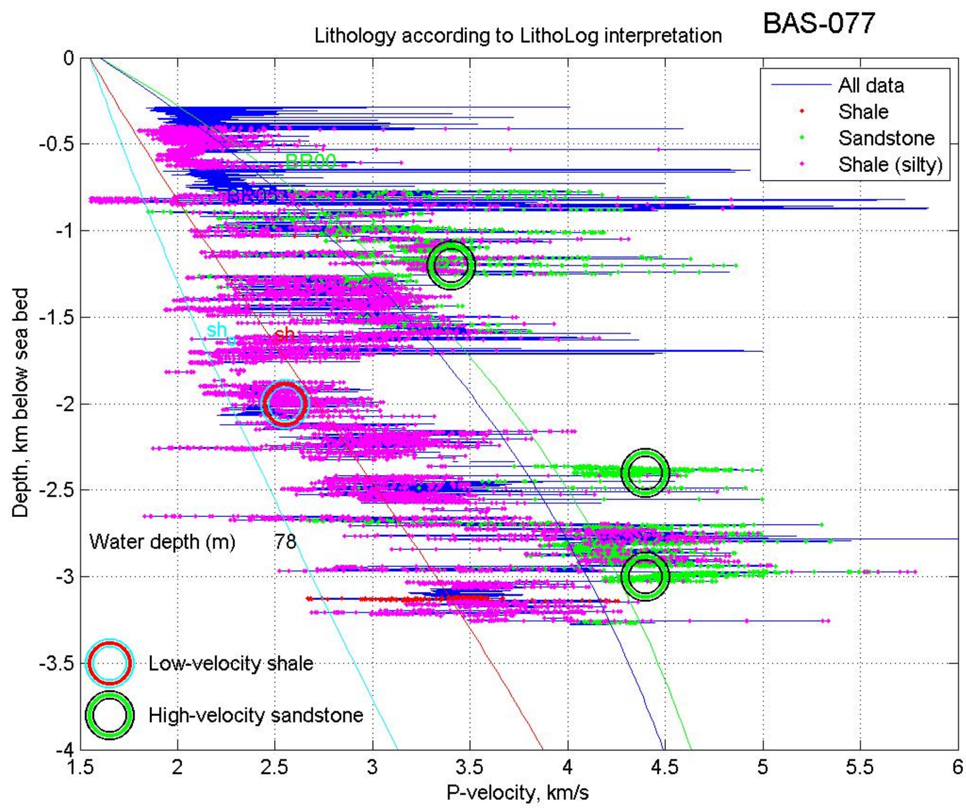
<0.5 km (Palaeogene sequence relative to the baselines); the sonic data for the Urucutuca shale interval (0.5-0.7 km) vary significantly, but plot above Vsh, thus indicating that the Paleogene shale may have been more deeply buried.

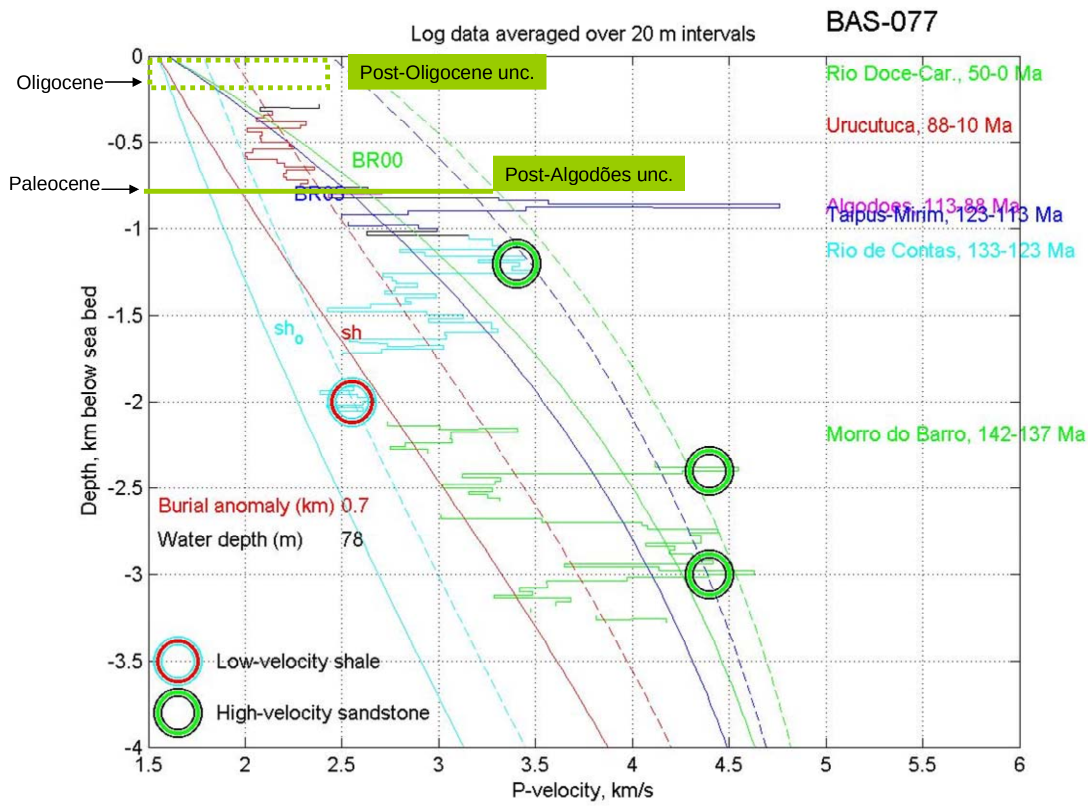
Post-exhumational burial

0.8 km; burial of the post-Algodôes unconformity.
<0.2 km; burial of the post-mid Oligocene unconformity. (Continued on p. 74)


BAS-077
Water depth 78
29-Apr-2008
Depth, km below sea bed
Caliper, inch
Vp, km/s
rhob
nphi
rhob, Nphi
Gamma (Api)


BAS-077
Bad-hole corrected
Water depth 78
06-May-2008
Depth, km below sea bed
Caliper (inch)
Vp (km/s)
Vp, km/s





cf. BAS-118 (near-by)

Removed section
1.5 ± 0.7 km (allowing for the uncertainty of the baselines); probably corresponding to the upper part of the Algodões Fm (47 m preserved) and the lower part of the Urucutuca Fm (missing).

<0.7 km, post-mid Oligocene sediments of the RD-C Fms (relative to a Neogene event)

BAS-79

Unconformities

Post-Algodões unconformity (110–-65 Ma): Above thin Algodões Fm (24 m) and below RD-C and Urucutuca Fms (419 m thick) with Paleocene strata reported at the base.

Post-Eocene unconformity (34–0 Ma): Above Paleocene-Upper Eocene section and within thin overlying section (105 m, RD-C Fms).

Caliper

Small calliper variation, limited bad-hole conditions at 0.4 km.

Sonic data, LithoLog and composite log

No significant shale intervals indicated in the interpretation of the lithology.

Dominantly sandstone below 0.8 km with different lithologies interbedded. Sandstone c. 100 m thick around c. 1.1 km (TM) with steady level of the sonic log above the sandstone baselines. Sonic peaks in the RdC Fm correlates with units of conglomerate.

Burial anomaly

0.7 ± 0.4 km (relative to the baselines); only constrained by the thick high-velocity sand unit within the TM Fm.

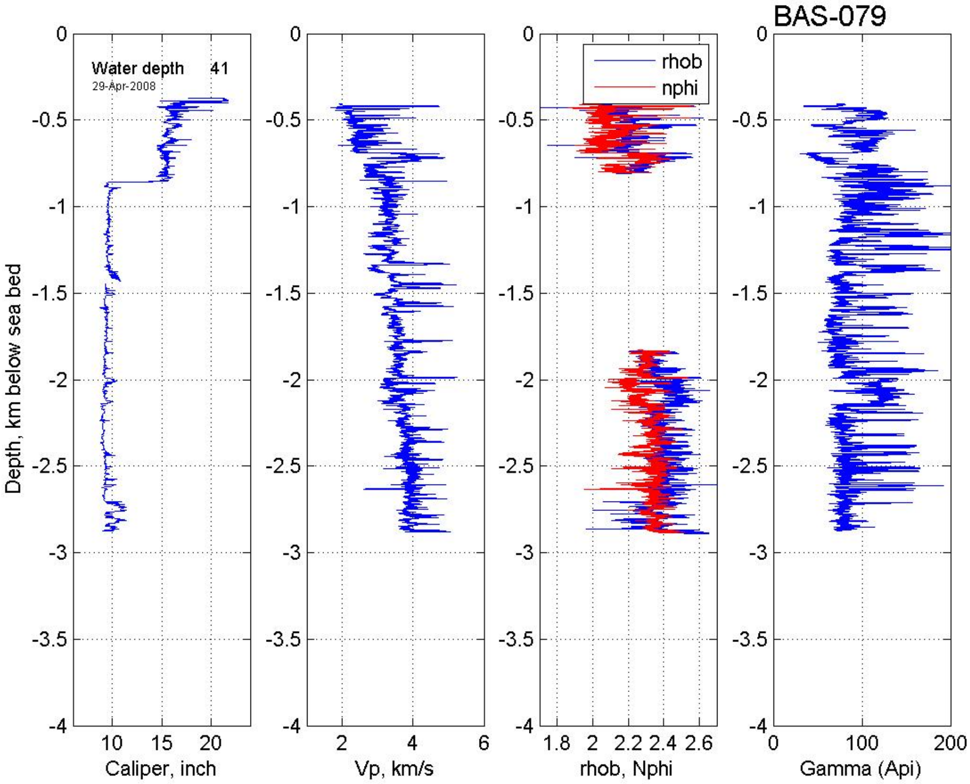
Post-exhumational burial

0.4 km; burial of the post-Algodões unconformity.
<0.1 km; burial of the post-Eocene unconformity.

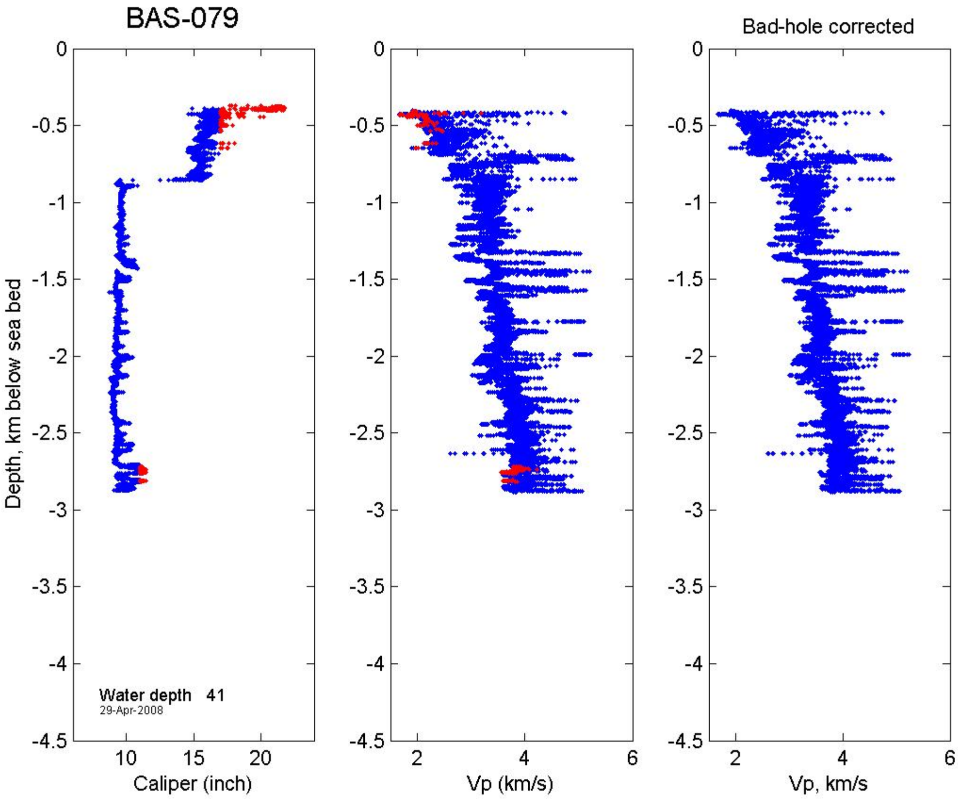
Removed section

1.1 ± 0.7 km (allowing for the uncertainty of the baselines); probably corresponding to the upper part of the Algodões Fm (24 m preserved) and the lower part of the Urucutuca Fm (missing).

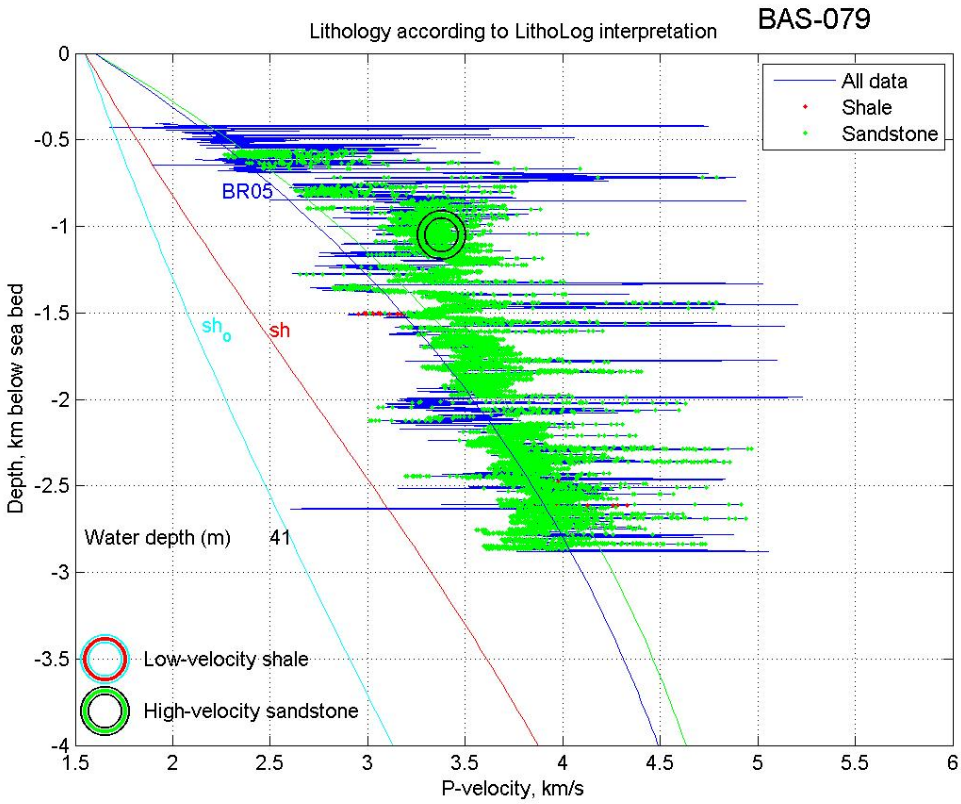
? km; possible removal of an unknown section above the Eocene strata near seabed. No sonic data to constrain the exhumation

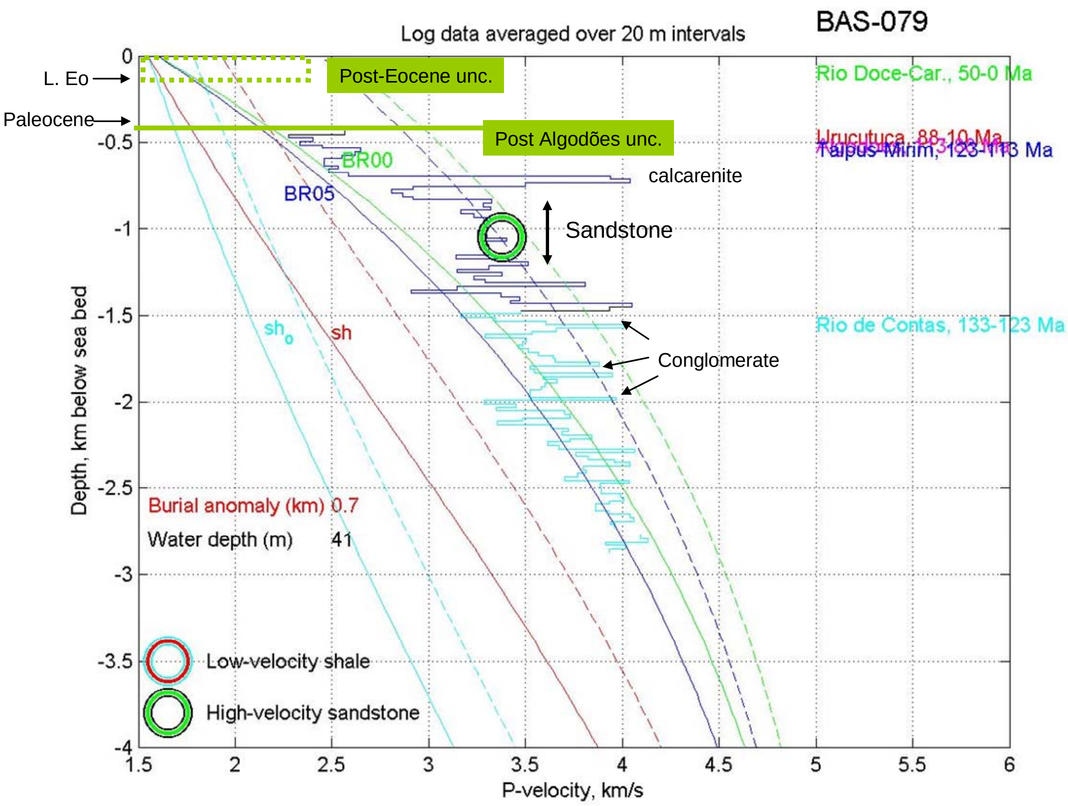


BAS-079
Water depth 41
29-Apr-2008
Depth, km below sea bed
Caliper, inch
Vp, km/s
rhob
nphi
rhob, Nphi
Gamma (Api)



BAS-079
Bad-hole corrected
Water depth 41
29-Apr-2008
Depth, km below sea bed
Caliper (inch)
Vp (km/s)
Vp, km/s





cf. BAS– 71, 88 (near-by)

BAS-84

Unconformities
Post-RdC unconformity (133–50 Ma): Above thick RdC Fm (1980 m) and below RD-C Fms; the TM, Algodões and Urucutuca Fms are missing.

Caliper
Very wide range of calliper values over the entire depth range. Clear relation with low sonic values. Many datapoints deleted.

Sonic data, LithoLog and composite log
Widely scattered sonic data over most of the drilled section. Low reliability of sonic minimum values in the Itaipe Fm around 3.5 km.

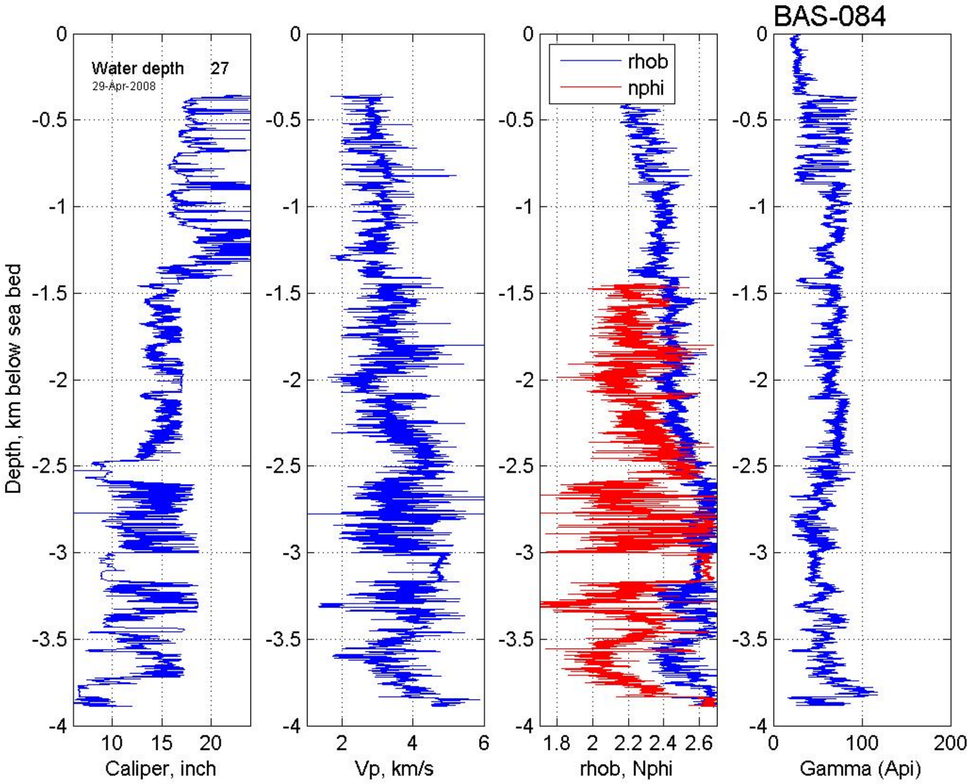
Two loosely defined low-velocity shale units at 1.3 and 2.2 km.

Thick sandstone unit with alternating units of shale and siltstone in the upper part of RdC, (0.4-0.9 km). Uniform sandstone unit with small sonic variations in the basal part of MdB Fm (3.0-3.2 km). Uniform sandstone in the Sergi Fm (3.8 km).

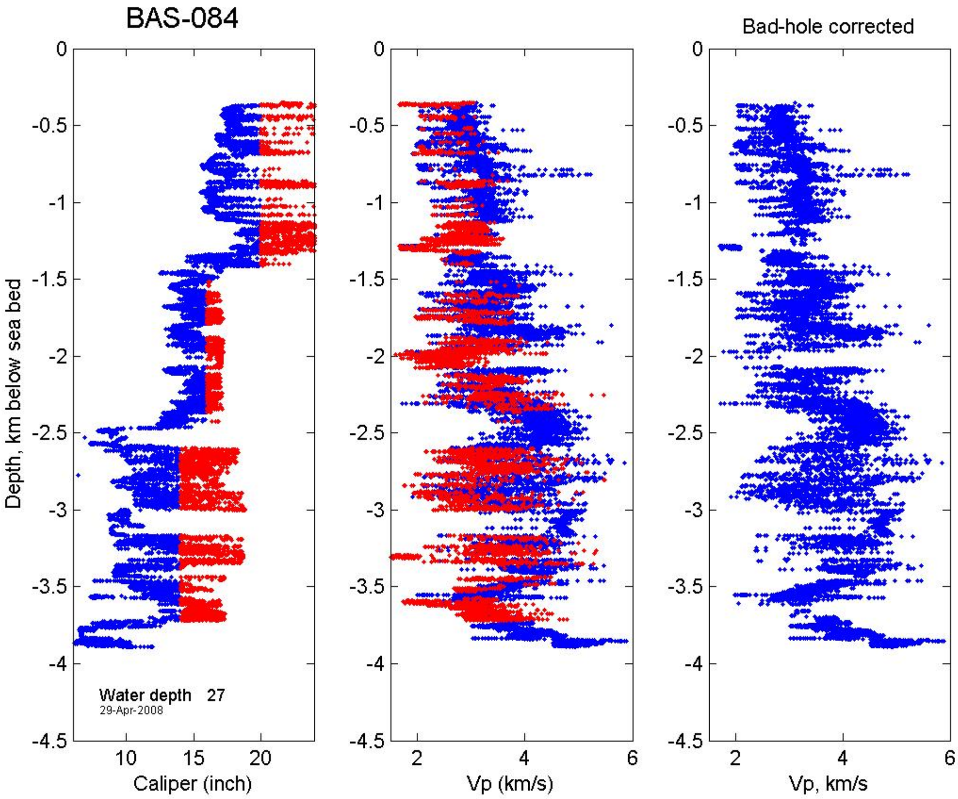
Burial anomaly
2.0 ± 0.4 km (relative to the baselines) is chosen as a good match between the baselines and the datapoints 1) the uniform sand units at 3.1 and 3.8 km and 2) low-velocity bound for the shale data above 2.3 km.

Post-exhumational burial
0.4 km; burial of the post-RdC unconformity.

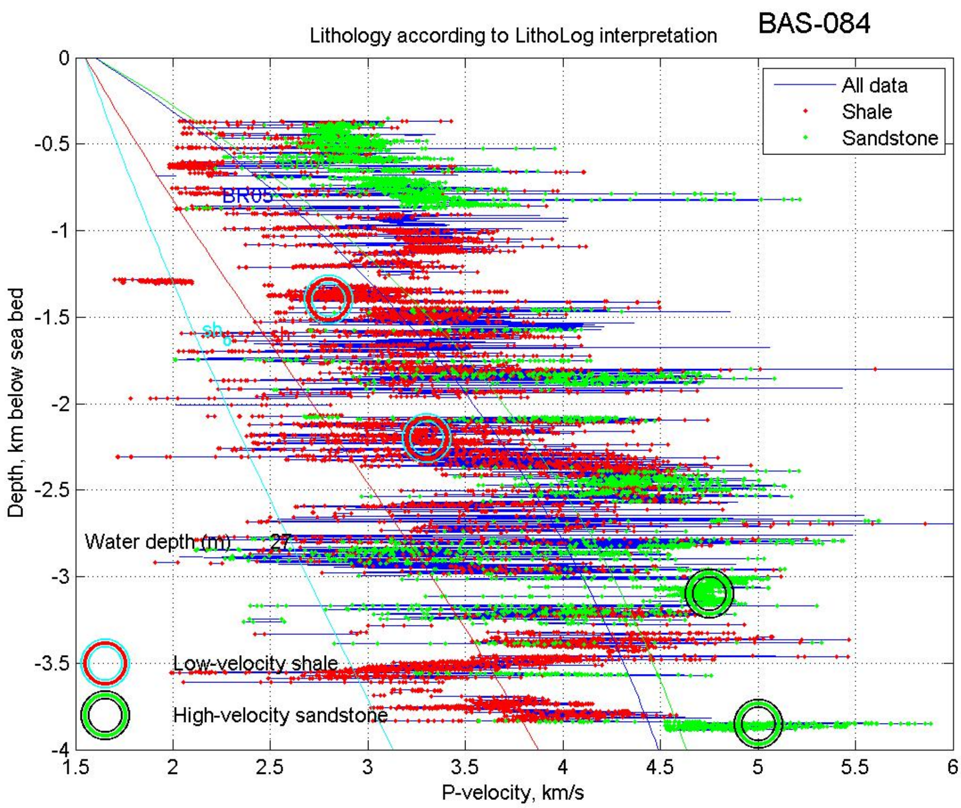
Removed section
2.4 ± 0.7 km (allowing for the uncertainty of the baselines); probably corresponding to the Algodões and TM Fms (missing) and the lower part of the Urucutuca Fm (missing).

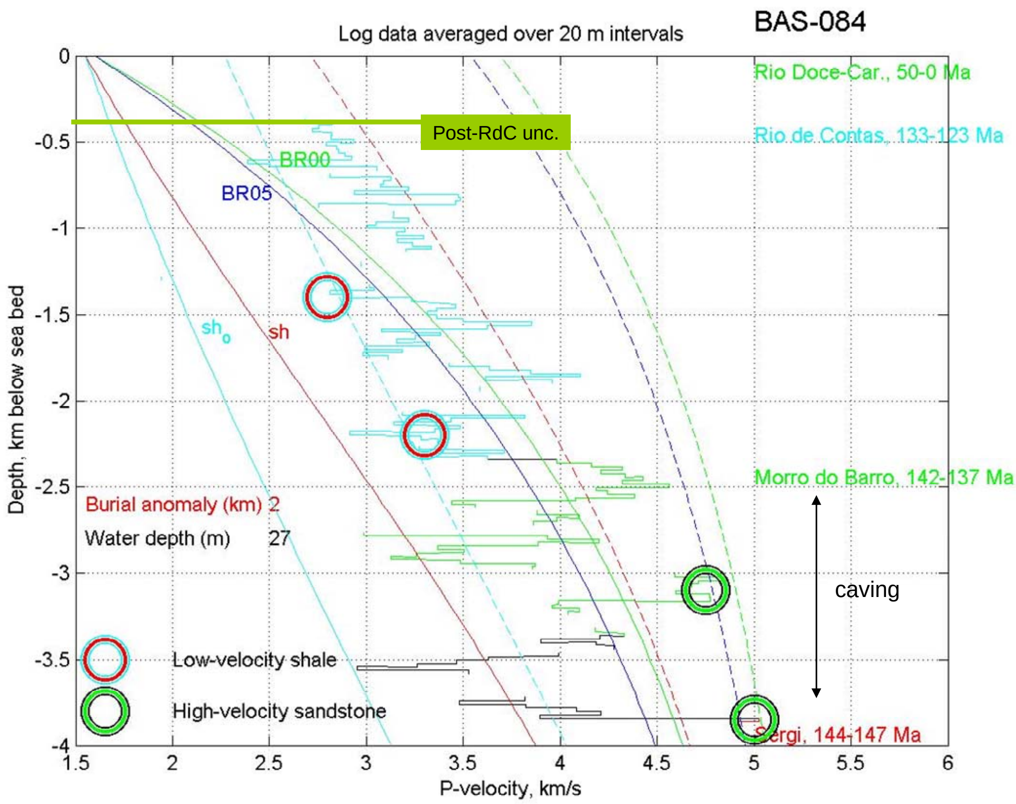


BAS-084
Water depth 27
29-Apr-2008
Depth, km below sea bed
Caliper, inch
Vp, km/s
rhob
nphi
rhob, Nphi
Gamma (Api)



BAS-084
Bad-hole corrected
Depth, km below sea bed
Water depth 27
29-Apr-2008
Caliper (inch)
Vp (km/s)
Vp, km/s





cf. BAS-113 (near-by)

BAS-88

Unconformities
Post-Taipus Mirim unconformity (123–70 Ma): Above thin TM Fm (31 m) and below thick Rio Doce-Caravelas and Urucutuca Fms (1649 m) with Maastrichtian strata reported 926 m below seabed; Algodões Fm missing.

Post-Eocene unconformity (34-0 Ma): Above Late Eocene strata and within thin overlying section (242 m, RD-C Fms).

Caliper
Wide calliper range over much of the drilled interval, but only clear correlation with low velocities around 4 km.

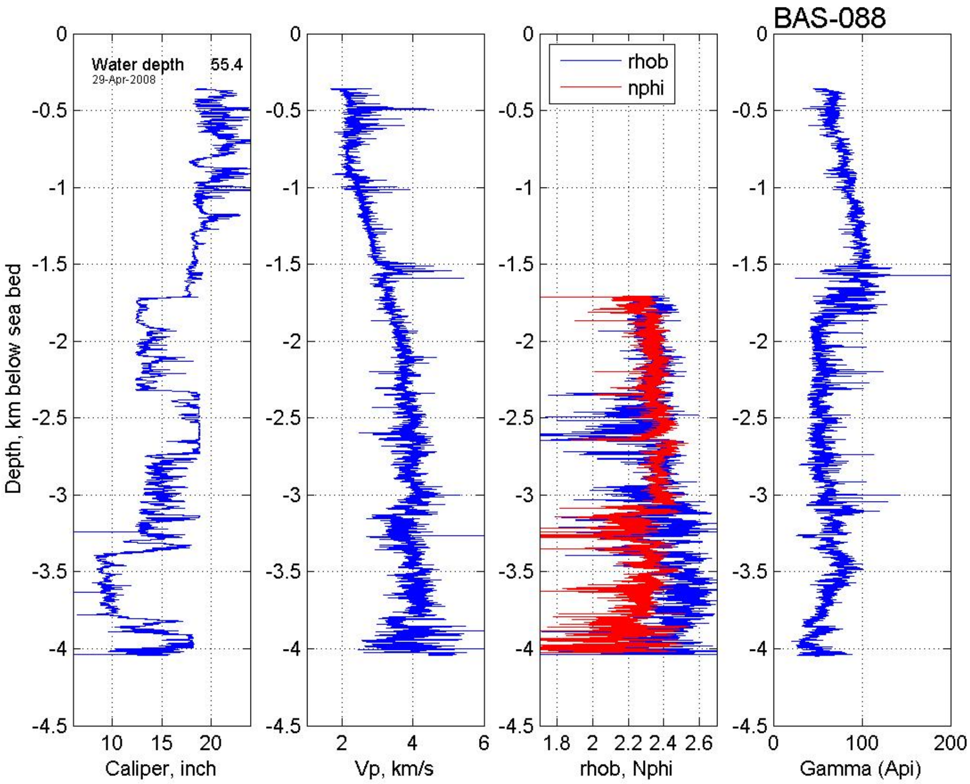
Sonic data and composite log
Steady increase of Vp with depth over the interval from 0.9 to 1.5 km generally plotting below the sandstone baselines; dominated by shale with calcilutite intercalations (Urucutuca Fm). Low-velocity shale in the upper part of MdB. Datapoint plot near Vsh.

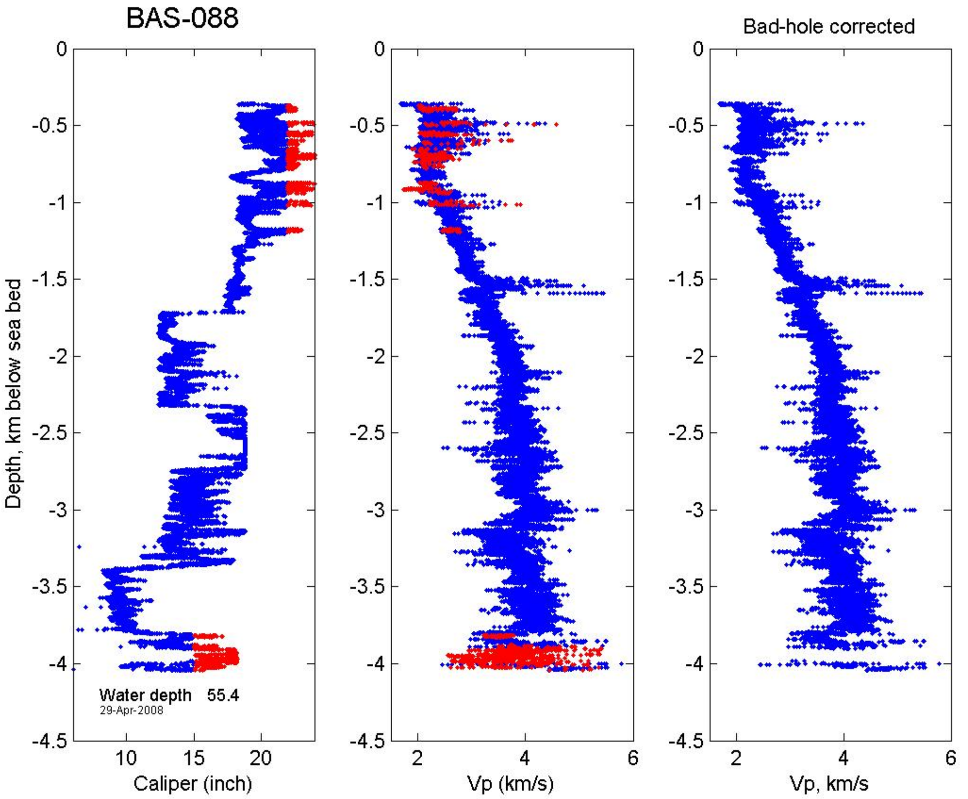
The RdC Fm is predominantly sandstone 1.9 to 3.1 km with velocities ranging between c. 3.5 and 4.4 km/s. The sonic data for this interval was used for calibration on the sandstone trends, BR00 and BR05.

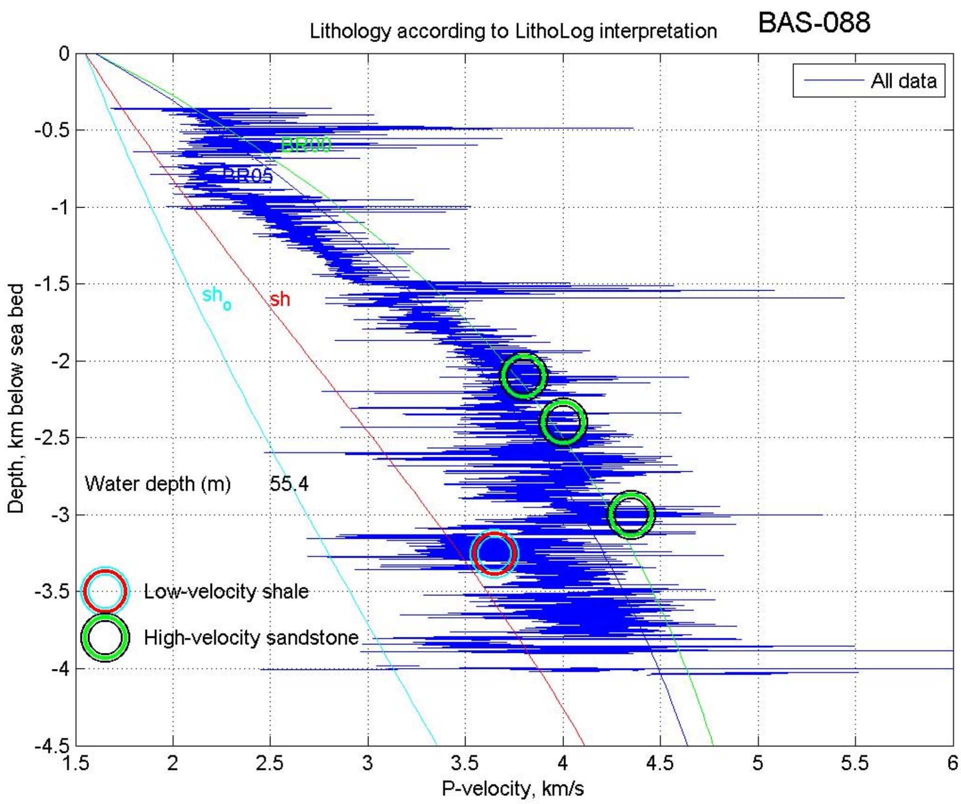
Burial anomaly
0 ± 0.2 km (Mesozoic section relative to the baselines): The Mesozoic sequence – and thus the Cenozoic sequence as well – is at maximum burial. Based on the observation that the RdC thick sandstones plot near the baselines for pure sandstone – not only BR00 and BR05 that were partly calibrated after data from this interval, but also near the SS00 and SS05 baselines.

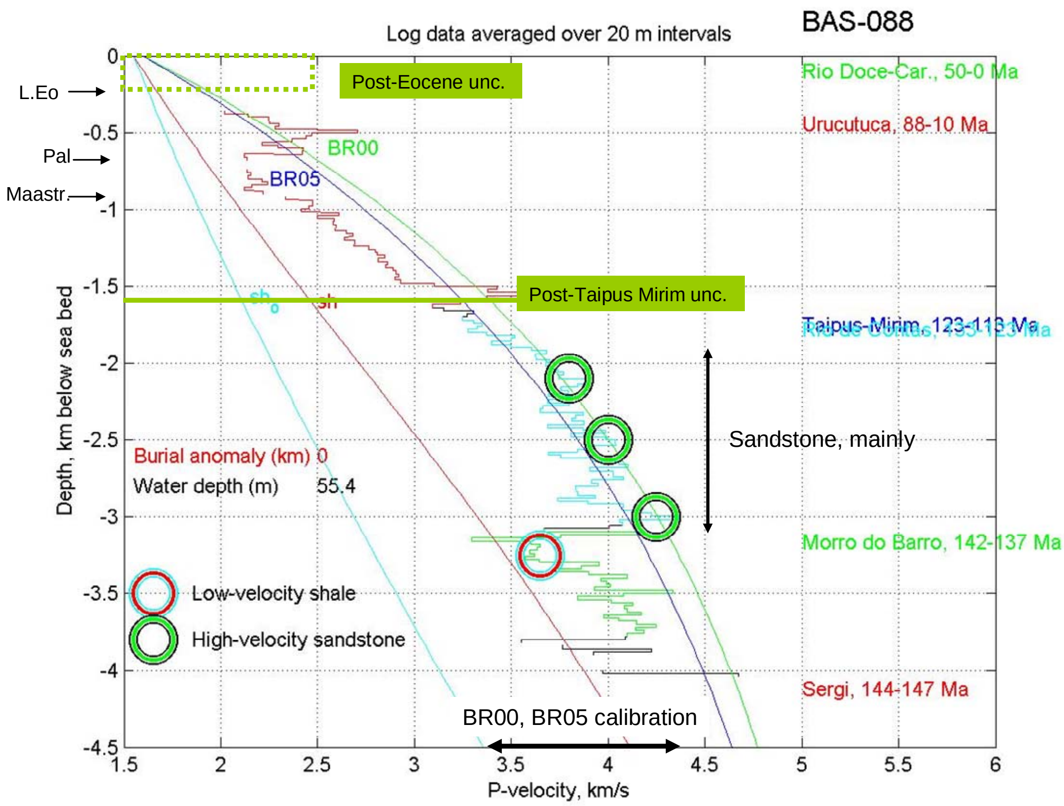
Post-exhumational burial
1.6 km; burial of the post-TM unconformity.

Removed section
- ; since the rift sediments are at maximum burial today any exhumation at the post-TM unconformity must be less than 1.6 km; potentially corresponding to the upper part of the TM Fm (31 m preserved), the Algodões Fm and the lower part of the Urucutuca Fm.


BAS-088
Water depth 55.4
29-Apr-2008
Depth, km below sea bed
Caliper, inch
Vp, km/s
rhob
nphi
rhob, Nphi
Gamma (Api)


BAS-088
Bad-hole corrected
Depth, km below sea bed
Water depth 55.4
29-Apr-2008
Caliper (inch)
Vp (km/s)
Vp, km/s





cf. BAS-118, -79 (both near-by)

AFTA

BAS-97

Unconformities
Post-Algodões unconformity (110–0? Ma): Above Algodões Fm (368 m thick) and below thin Rio Doce-Caravelas Fms (75 m); Urucutuca Fm missing.

Caliper
Significant variations above 0.7 and below 1.7 km. Widely scattered sonic values between 1.7 and 2.1 km reflect both calliper and lithological variations. The casing diameter is reduced to 9 5/8” at 2.1 km below witch depth huge caliper variations correlate with small Vp. Between 2.1 and 2.5 km most data points are deleted, including most sonic data for the Sergi Fm.

Sonic data, LithoLog and composite log
Discrepancy between supplied lithostratigraphic tops and those of the ANP composite log; e.g. a difference of 127 m at top basement; 2788 m and 2915 m (MD) respectively.

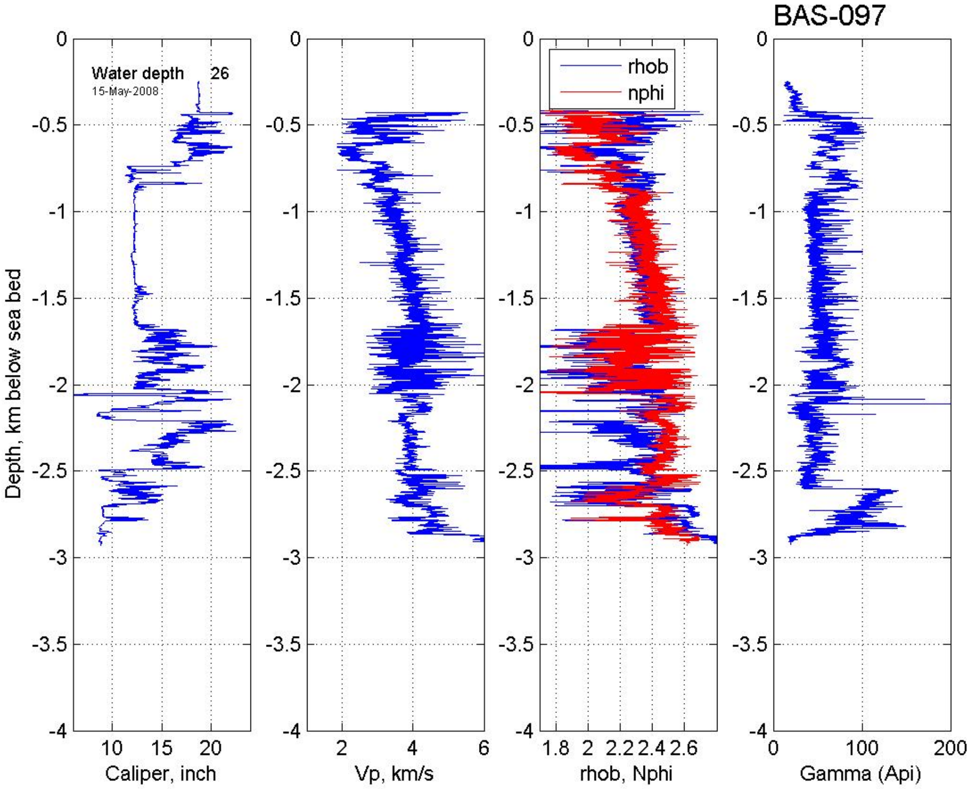
Low-velocity shale unit at the top of MdB at 0.7 km. Minimum vp values may be due to data problems; reference value chosen above minimum. vp for Afligidos shale unit at 2.7 could reflect pure shale.

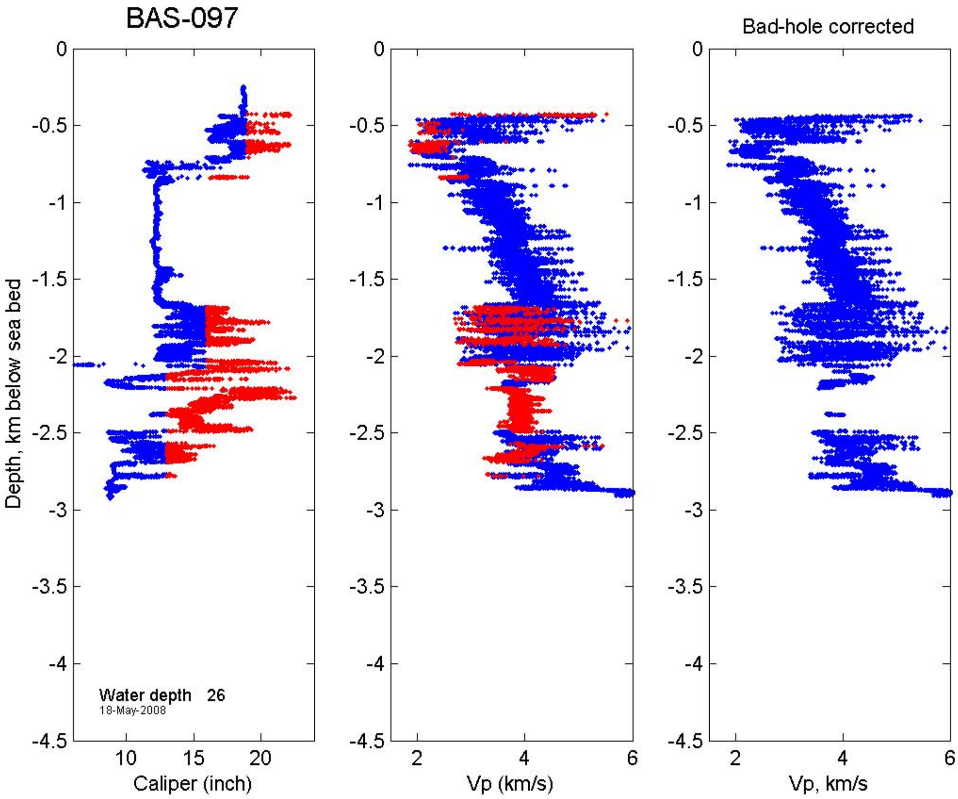
Dominantly MdB sandstone between 0.8 and 1.7 km Reflected in a steadily increasing Vp values with a narrow spread. The velocity increases relatively strongly over the sandstone interval; c. 0.5 km/s over 0.5 km => a velocity gradient of 1 1/s. This trend probably reflects a shift from pure to impure sand towards more shallow depths. High-velocity sandstone units between 1.5 and 2.0 km interpreted as representing pure sandstone. Possibly a bit too high vp-values. Vp for the Sergi Fm is low and ranges between 3.7 and 4.1 km/s between 2.2 and 2.5 km, but these data are deleted due to caving problems.

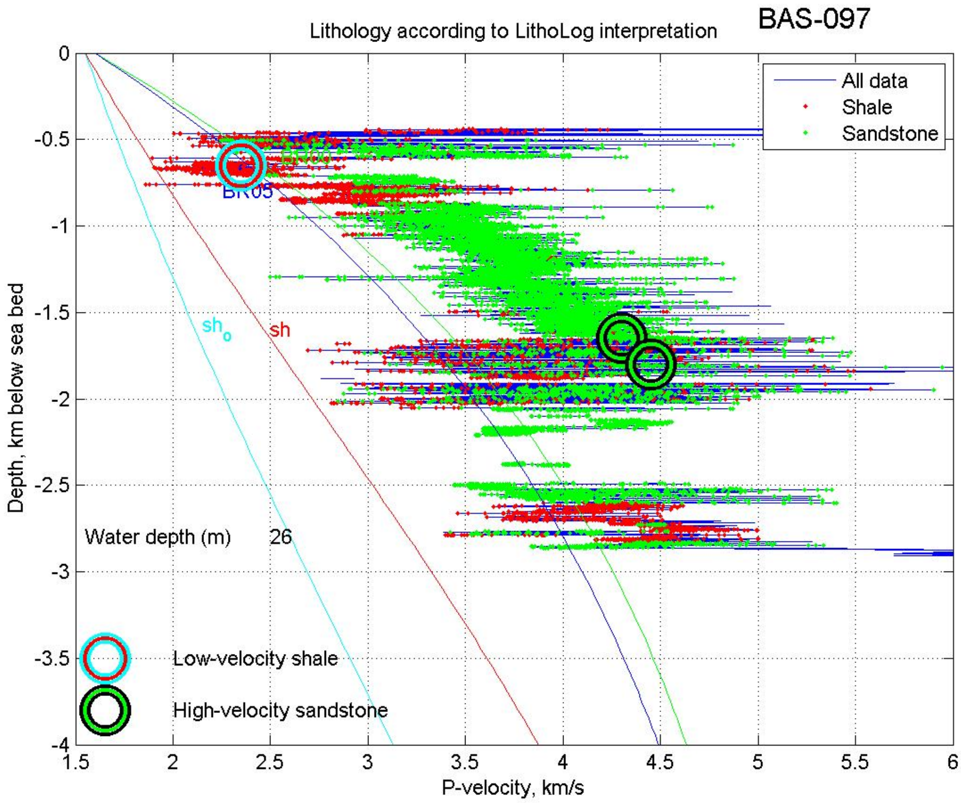
Burial anomaly
1.6 ± 0.2 km (relative to the baselines) honours both sandstone data around 1.75 km and the shale data at 0.7 km.

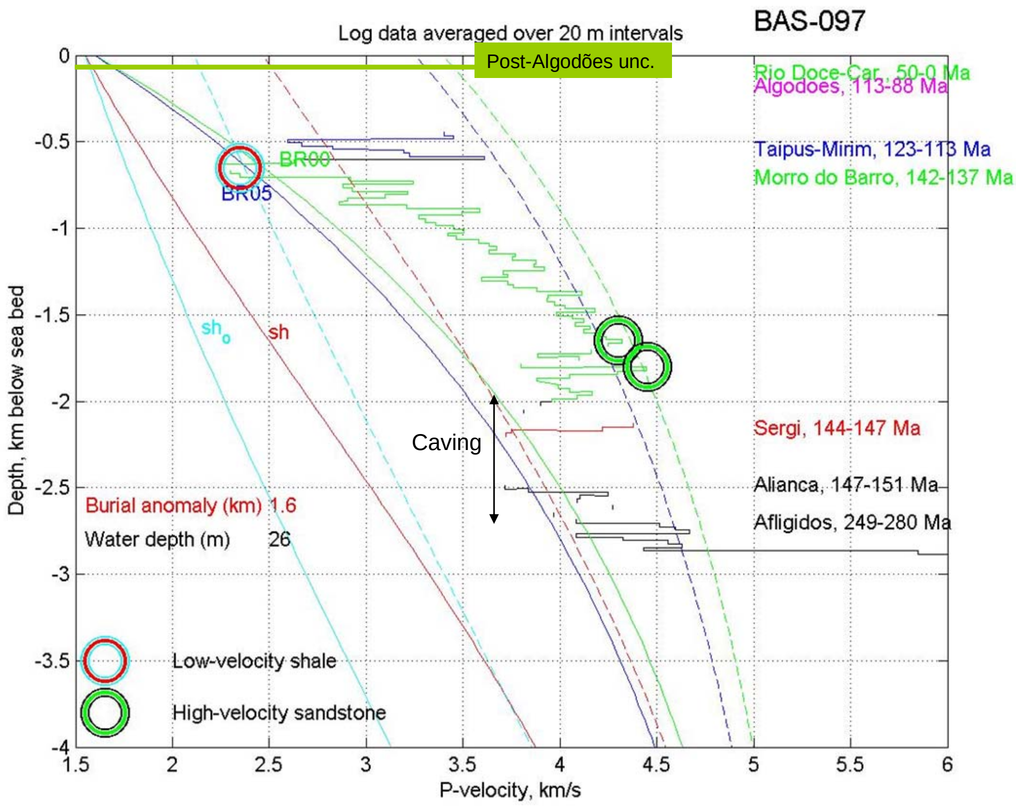
Post-exhumational burial
0.1 km; burial of the post-Algodões unconformity.

Removed section
1.7 ± 0.5 km (allowing for the uncertainty of the baselines); probably corresponding to the upper part of the Algodões Fm (0.4 km preserved) and the lower part of the Urucutuca Fm (missing).


BAS-097
Water depth 26
15-May-2008
Depth, km below sea bed
Caliper, inch
Vp, km/s
rhob
nphi
rhob, Nphi
Gamma (Api)


BAS-097
Bad-hole corrected
Water depth 26
18-May-2008
Depth, km below sea bed
Caliper (inch)
Vp (km/s)
Vp, km/s





cf. BAS-107 (near-by), -21 (comparable MdB)

BAS-102

Unconformities

No post-Algodões unconformity: Thick Algodões Fm (1165 m; Albian strata reported) below thick Urucutuca Fm (1125 m) with Cenomanian/Santonian - Maastrichtian strata documented.

Post-Early Eocene unconformity? (post-40 Ma): No constraints on a possible unconformity within the uppermost 345 m (Urucutuca Fm).

Caliper

Wide oscillations dominate the interval 2.5-3.0 km where relatively low velocities are recorded, although with a wide spread. Several datapoints in this interval are deleted, however there might be a depth shift between the sonic and the calliper log so that the higher velocities rather than the low velocities are deleted in this interval.

Sonic data, LithoLog and composite log

A general increase in velocity with depth is observed from 0.3 to 2.4 km with velocities close to the sandstone baselines. Shale with calcarenite units dominates the Urucutuca Fm from 0.3 to 1.1 km. Sandstone with shale and halite units from 1.7 to 2.4 km (Algodões-TM Fms). Varied lithology, relatively low velocities and wide calliper variations between 2.5 and 3.0 km: some shale data plot close Vsh.

Sand unit 100 m thick at 2.2 km with well-defined sonic level; also at 3.1 km.

Burial anomaly

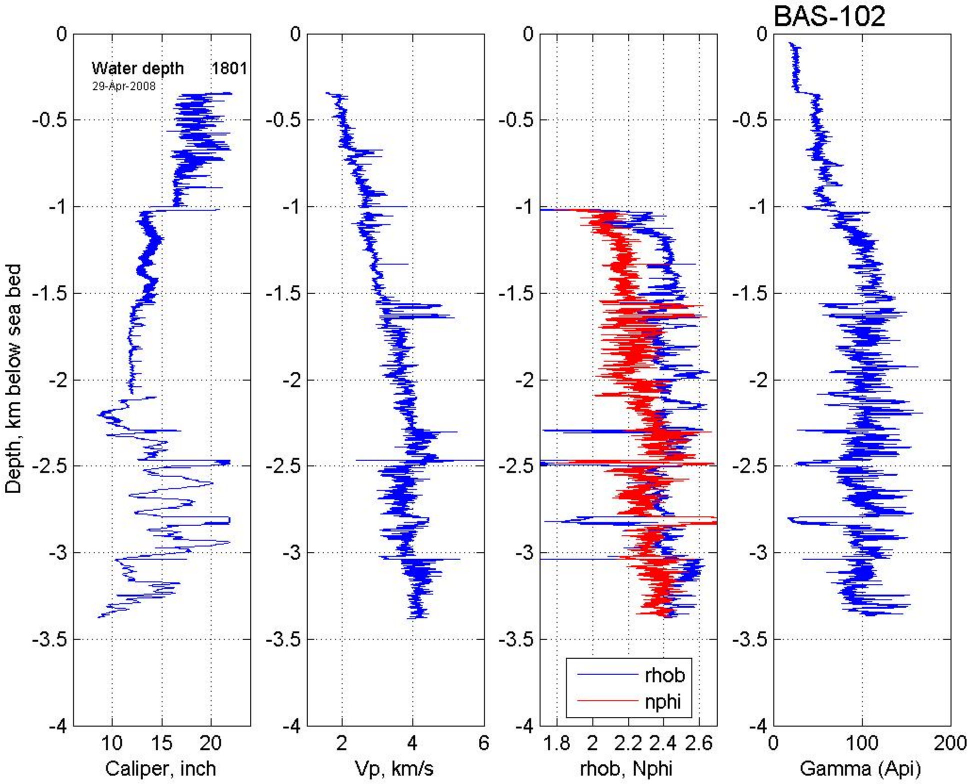
0 ± 0.2 km (Mesozoic section relative to the baselines): The Mesozoic sequence – and thus the Cenozoic sequence as well – is at maximum burial. Sandstone units (Algodões and RdC Fms) close to sandstone baseline. No post-Algodões unconformity.

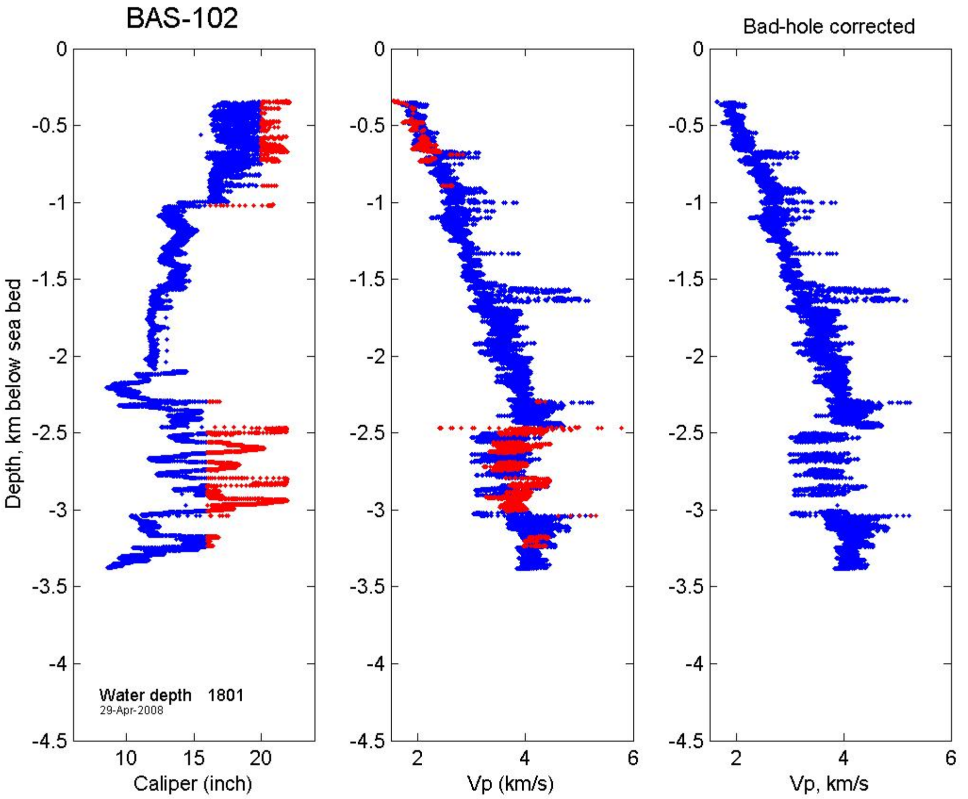
Post-exhumational burial

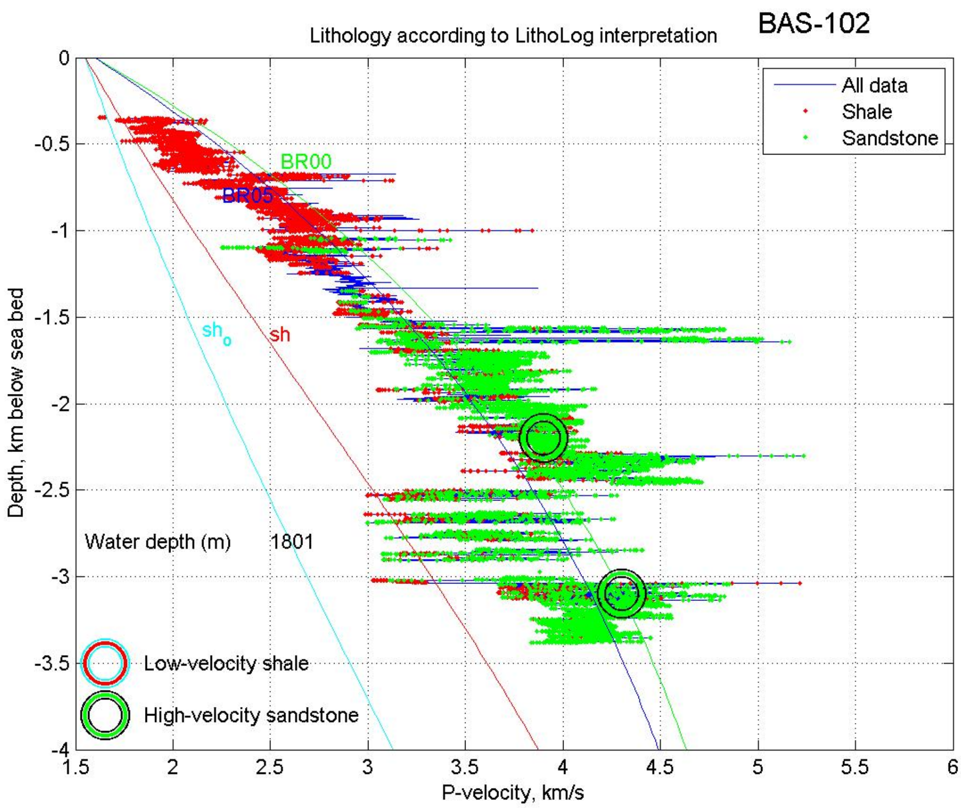
-

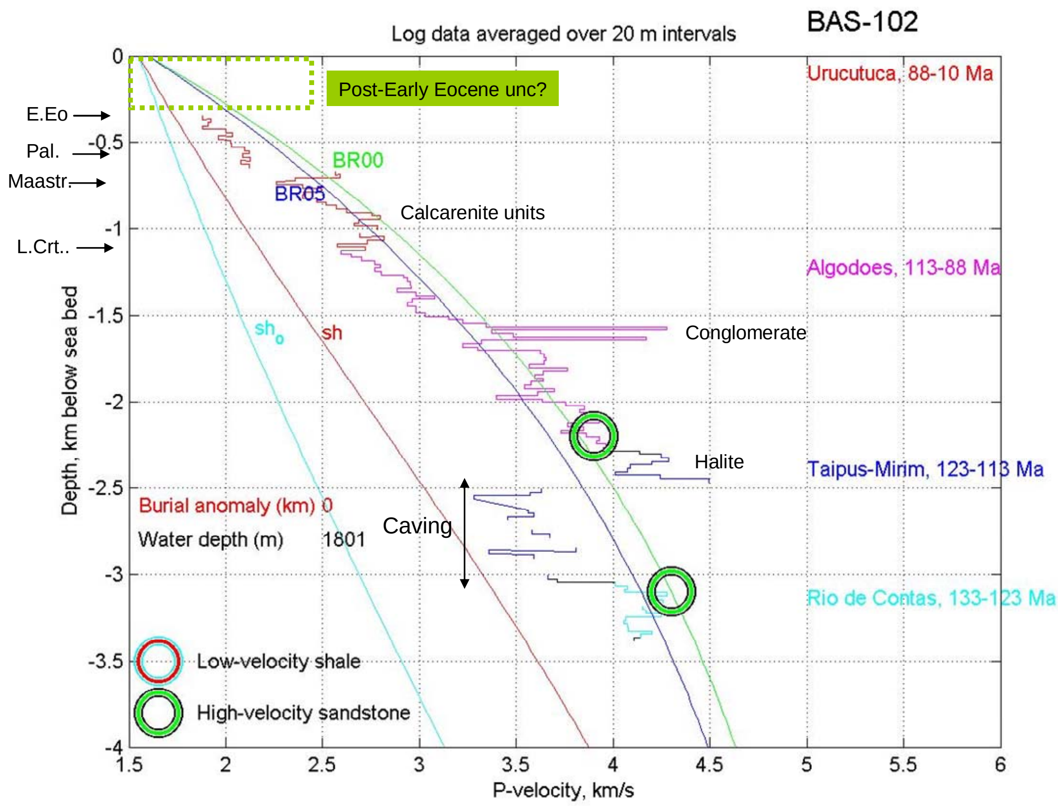
Removed section

0 km.


BAS-102
Water depth 1801
29-Apr-2008
Depth, km below sea bed
Caliper, inch
Vp, km/s
rhob
nphi
rhob, Nphi
Gamma (Api)


BAS-102
Bad-hole corrected
Water depth 1801
29-Apr-2008
Depth, km below sea bed
Caliper (inch)
Vp (km/s)
Vp, km/s





cf. BAS-71, 79 (at some distance near the coast)

AFTA

BAS-107

Unconformities

Post-Algodões unconformity (123–84 Ma): Above Algodões Fm (292 m) and below RD-C Fms (299 m) with Campanian and Paleocene sediments documented.

Post-Paleocene unconformity (65–0 Ma): Above Paleocene strata and within thin overlying section (105 m, RD-C Fms).

Caliper

Moderate variation with no clear correlation with the sonic log, apart from above c. 0.7 km where a wide caliper range correlates with a widely scattered sonic data which is deleted as strongly affected by caving.

Sonic data, LithoLog and composite log

Irregular sonic variations. Few intervals in this well have been interpreted as ‘shale’ whereas most of the drilled section between 0.8 and 1.8 is characterized as ‘shale (silty)’. The sonic velocity for this interval shows a general increase with depth.

No significant sandstone units. The rapid increase of velocity with depth throughout most of the MdB Fm is probably due to the increasing number of sandstone, dolomite etc units.

Burial anomaly

0.8 ± 0.6 km (relative to the baselines), only based on a match between low-velocity shale data and Vsh-o (in analogy with near-by wells as BAS-74).

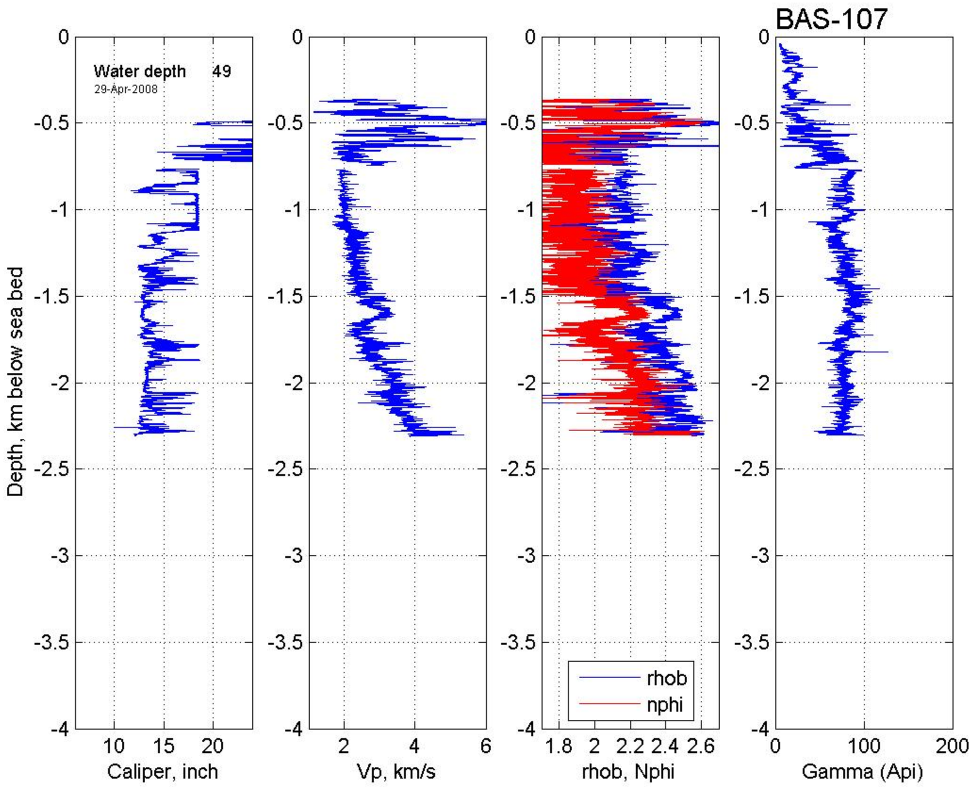
Post-exhumational burial

0.3 km; burial of the post-Algodões unconformity.
<0.1 km; burial of the post-Paleocene unconformity.

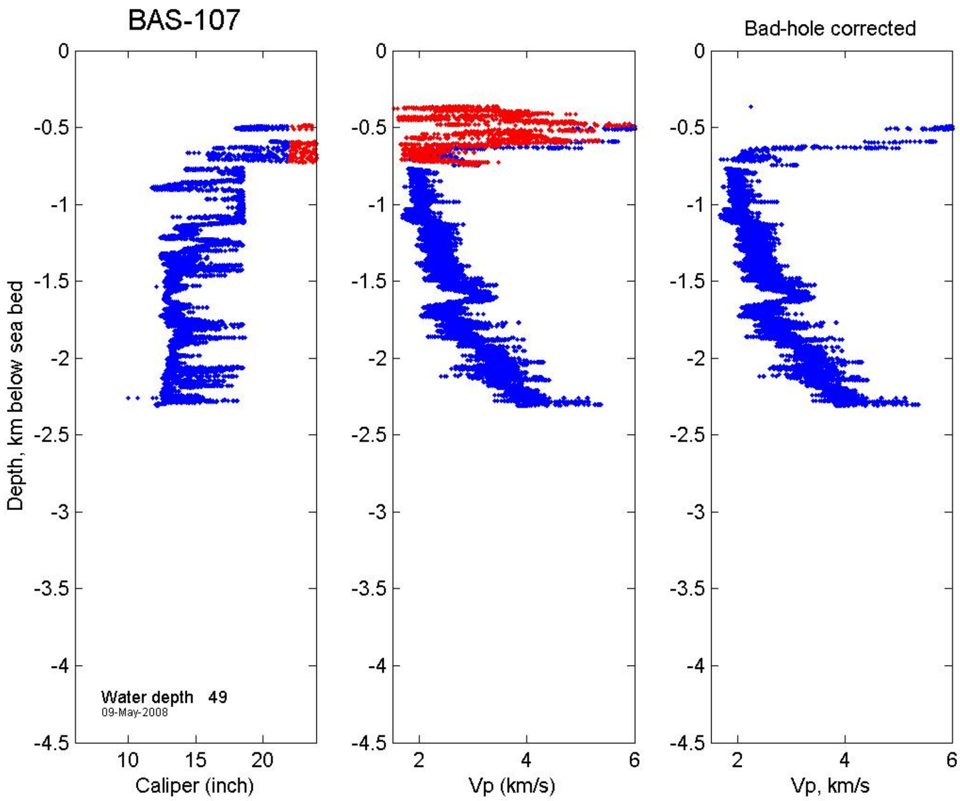
Removed section

1.1 ± 0.9 km (allowing for the uncertainty of the baselines); probably corresponding to the upper part of the Algodões Fm (0.3 km preserved) and the lower part of the Urucutuca Fm (missing).

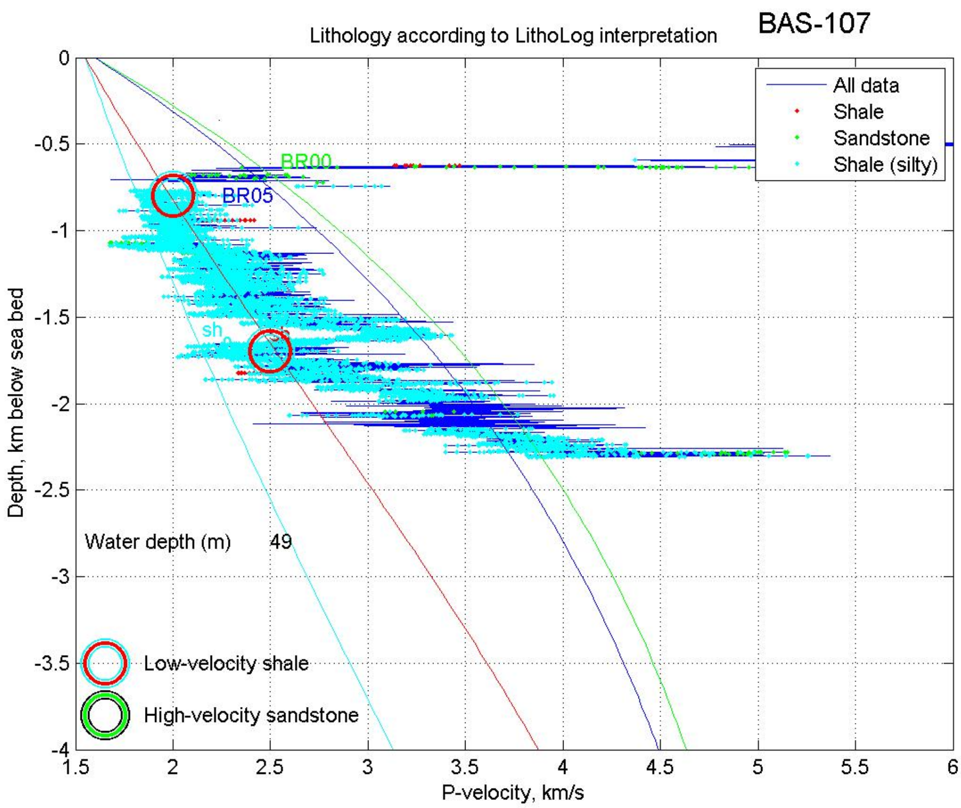
? km; possible removal of an unknown section above the Paleocene strata near seabed. No sonic data to constrain the exhumation.

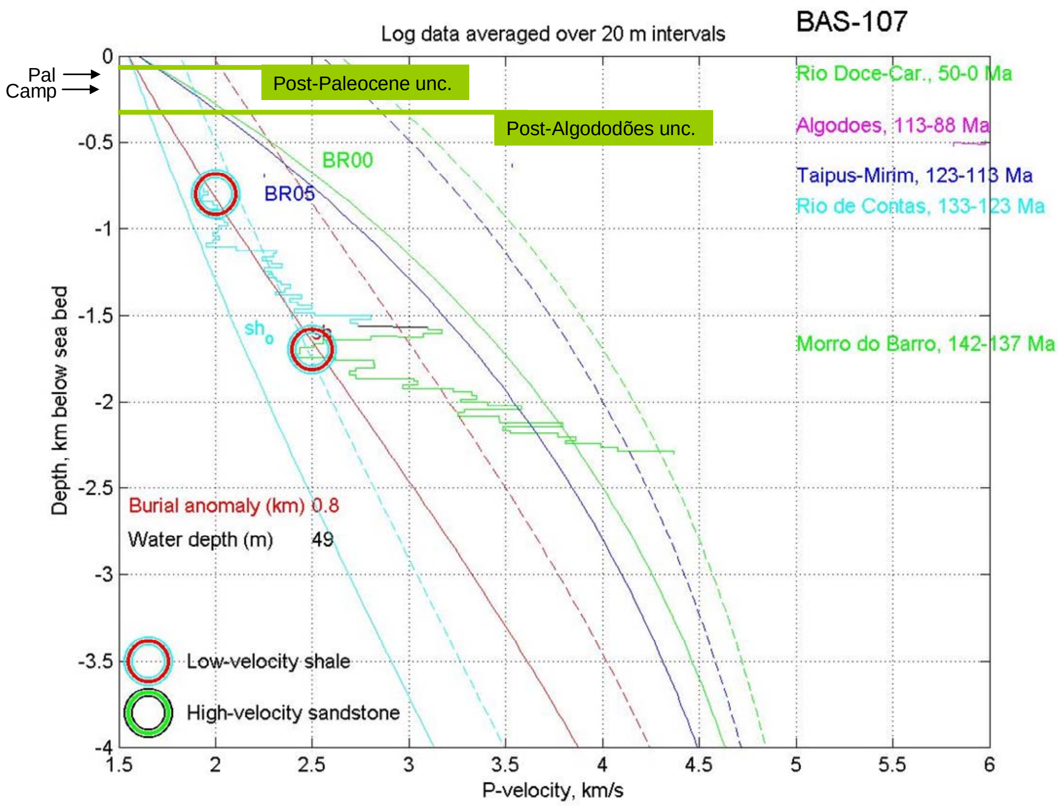


BAS-107
Water depth 49
29-Apr-2008
Depth, km below sea bed
Caliper, inch
Vp, km/s
rhob, Nphi
Gamma (Api)
rhob
nphi



BAS-107
Bad-hole corrected
Water depth 49
09-May-2008
Depth, km below sea bed
Caliper (inch)
Vp (km/s)
Vp, km/s





cf. BAS-97, 74 (near-by)

BAS-113

Unconformities

Post-RdC unconformity (133–0 Ma): Above thin RdC Fm (96 m) and below thin RD-C Fms (75 m); Algodões and TM Fms missing.

Caliper

Constant calliper down to 1.3 km, then moderate fluctuation down to 3.4 km and finally considerable fluctuations in the deepest part of the well (below 3.4 km) coinciding with low velocities (<4 km/s), and these datapoints are consequently deleted.

Sonic data, LithoLog and composite log

The sonic log varies significantly (e.g. between 2.5 and 4 km/s) over small depth intervals between 0.5 and 2.8 km. According to the composite log, this is due to a rapidly changing lithology (sand, shale, limestone, dolomite). Low-velocity shale units define a lower bound for the sonic data above 2.4 km and two points on this trend is highlighted.

A thick and uniform sandstone unit with small velocity variations is present in the basal part of the MdB Fm (2.8-3.4 km).

Burial anomaly

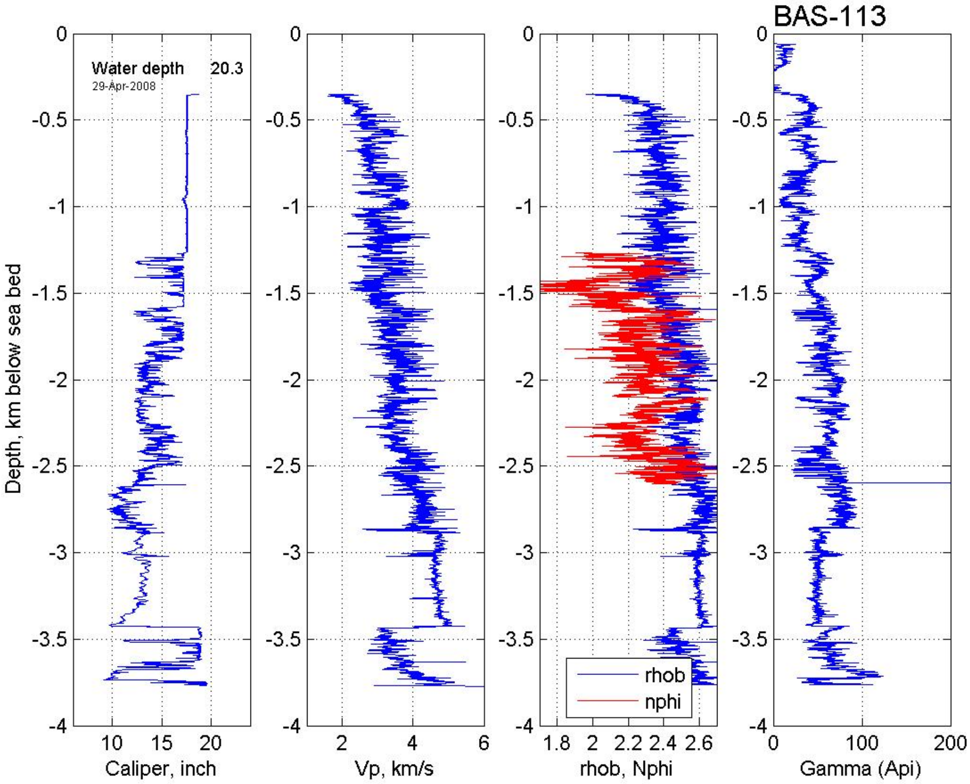
2.2 ± 0.2 km (relative to the baselines) is chosen as a good match between the baselines and the datapoints for 1) the high-velocity sand units between 2.8 and 3.4 km and 2) the low-velocity shale trend above 2.4 km.

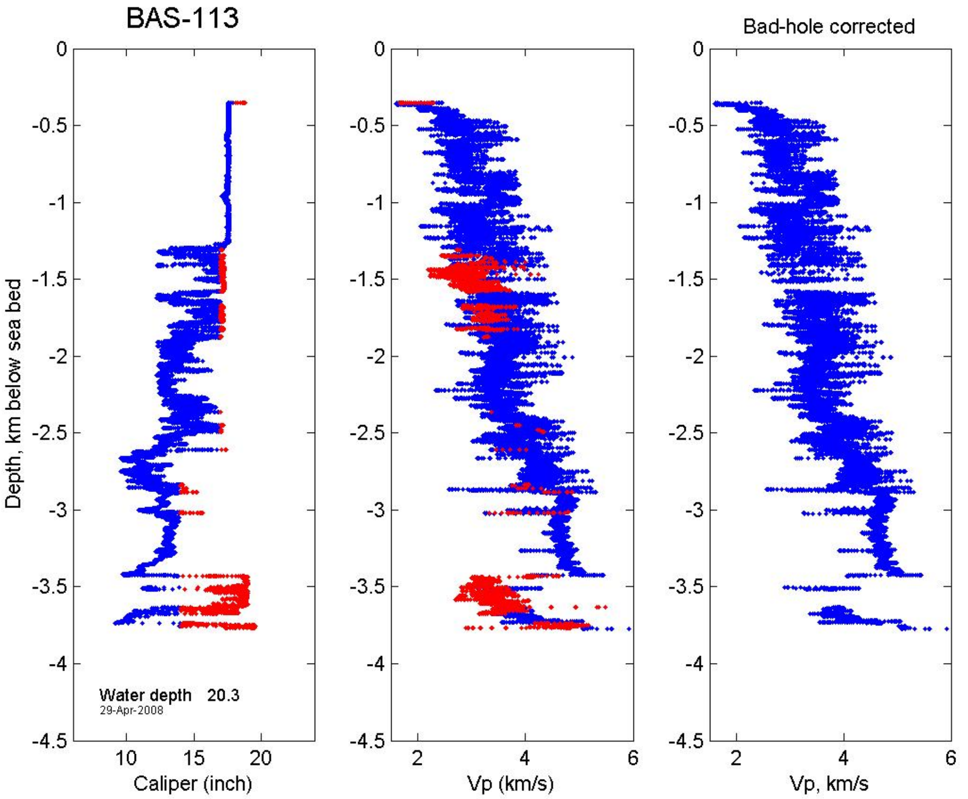
Post-exhumational burial

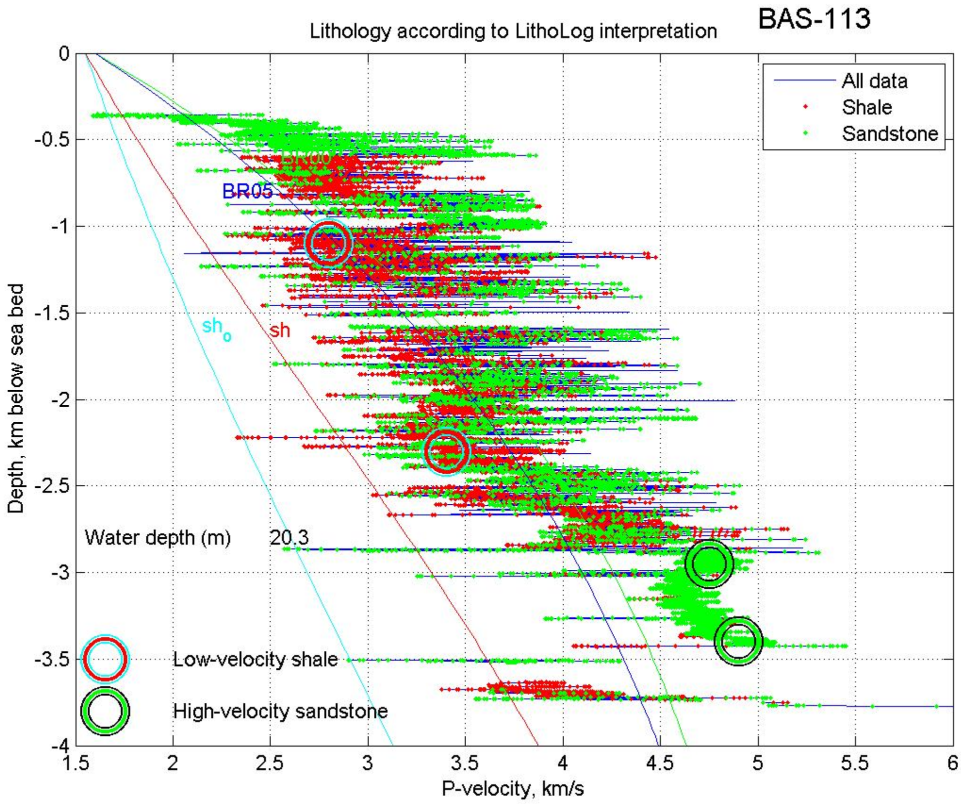
0.1 km; burial of the post-RdC unconformity.

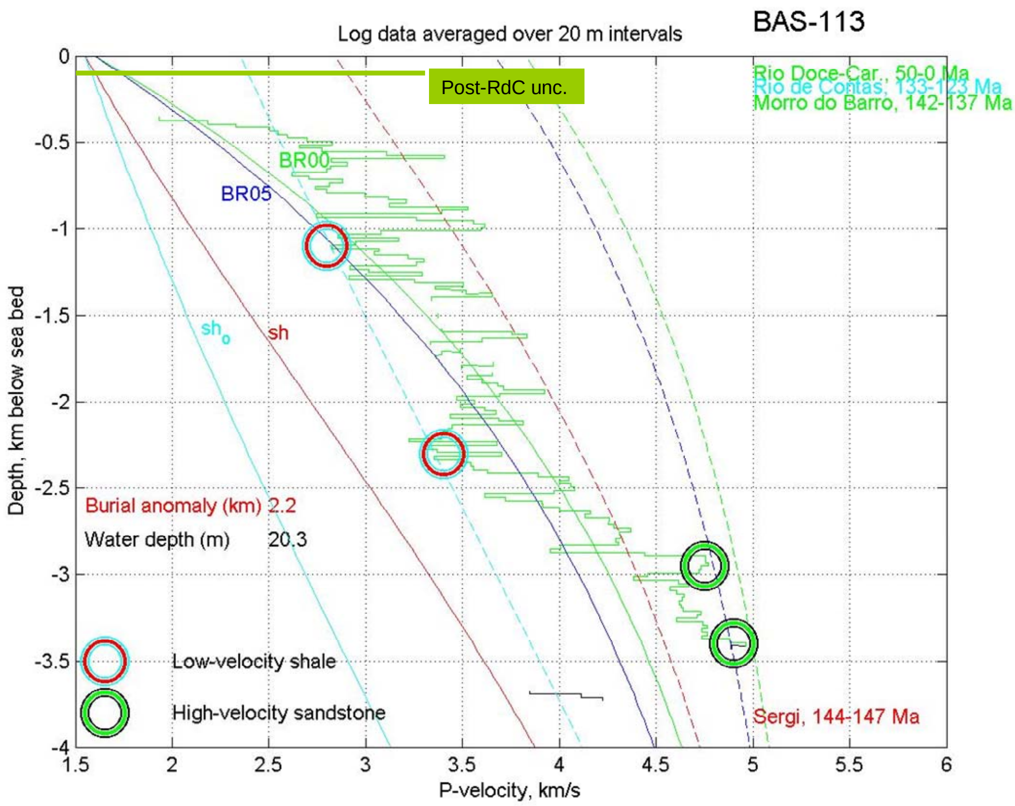
Removed section

2.3 ± 0.5 km (allowing for the uncertainty of the baselines); probably corresponding to the upper part of the RdC Fm (96 m preserved), the TM and Algodões Fms (missing) and the lower part of the Urucutuca Fm (missing).


BAS-113
Water depth 20.3
29-Apr-2008
Depth, km below sea bed
Caliper, inch
Vp, km/s
rhob, Nphi
rhob
nphi
Gamma (Api)


BAS-113
Bad-hole corrected
Depth, km below sea bed
Water depth 20.3
29-Apr-2008
Caliper (inch)
Vp (km/s)
Vp, km/s





cf. BAS-84 (near-by), -21 (thick MdB)

AFTA

BAS-118

Unconformities

Post-Taipus Mirim unconformity (110–65 Ma): Above the TM Fm (809 m thick) and possibly within lower part of thick Urucutuca Fm (1303 m thick) with Paleocene strata documented 911 m below seabed; Algodões Fm missing.

Post-Early Eocene unconformity? (40–0 Ma): Possibly above Early Eocene strata and within overlying section (771 m, Urucutuca Fm).

Caliper

Moderate variations in the calliper log. Caving at c. 2.4 km correlates with low Vp readings. No calliper below 2.5 km, so it cannot be controlled if low velocities at 2.9 km are due to bad-hole conditions.

Sonic data, LithoLog and composite log

A general increase of velocity with depth between 0.3 and 1.3 km generally along the sandstone baselines (Urucutuca Fm). Thick claystone units (sandy according to the LithoLog) below 2.7 km (RdC and MdB) with irregular sonic data, but with a lower bound that plots just above Vsh (velocities below 3.5 km/s at 2.8 km are probably caused by caving).

Alternating sand and shale units within the TM Fm; 100 m thick sandstone at 2.1 km (2.9 km MD). Thick sandstone units at c. 2.5 km (RdC) with steady sonic level.

Burial anomaly

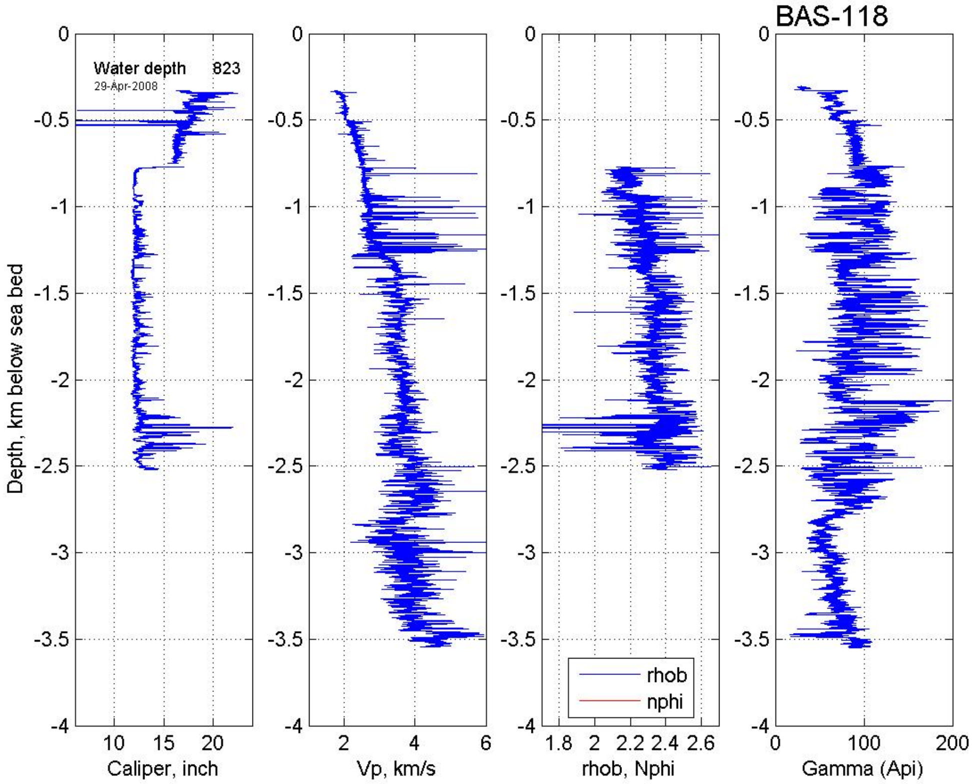
0 ± 0.4 km (Mesozoic section relative to the baselines): The Mesozoic sequence – and thus the Cenozoic sequence as well – is at maximum burial. The thick sandstone units in the lower part of the TM Fm and in the upper part of the RdC Fm plot near BR00 and BR05. The relatively high velocities of the basal RdC claystones are interpreted to be due to lithological properties corresponding to Vsh (if the lower bound represented Vsh-o that would indicate a burial anomaly in excess of 1 km which is incompatible with the sandstone data).

Post-exhumational burial

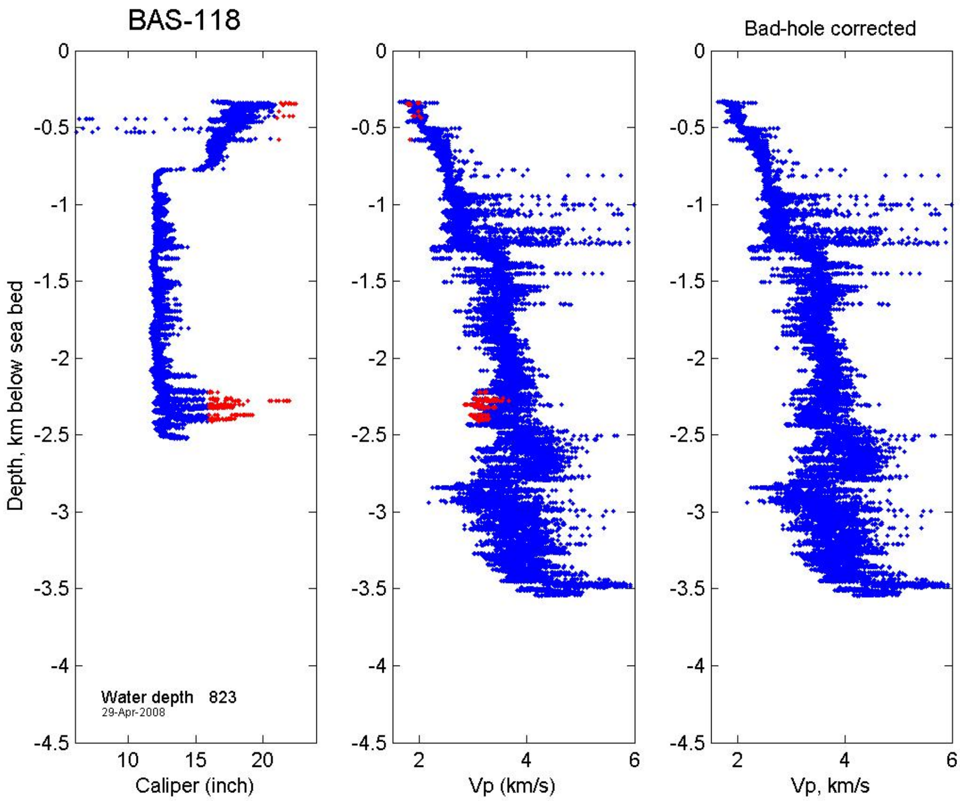
1.3 km; burial of the post-TM unconformity.

Removed section

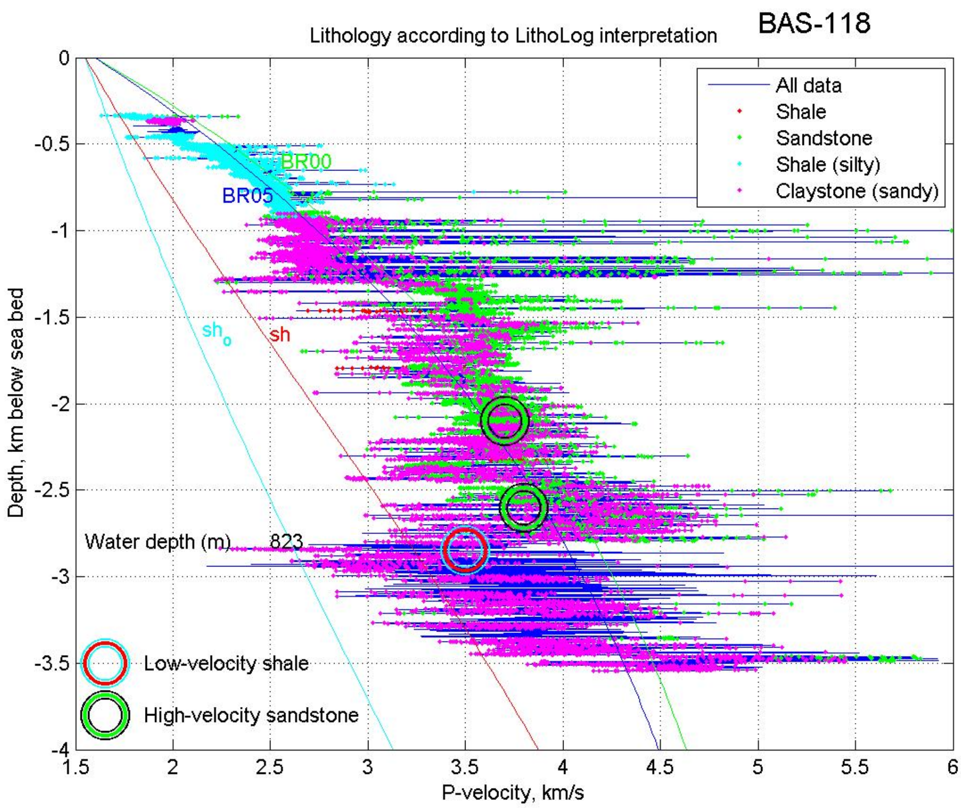
- ; since the Mesozoic sediments are at maximum burial today any exhumation at the post-TM unconformity must be less than 1.3 km; potentially corresponding to the upper part of the TM Fm (0.8 km preserved), the Algodões Fm and the lower part of the Urucutuca Fm.

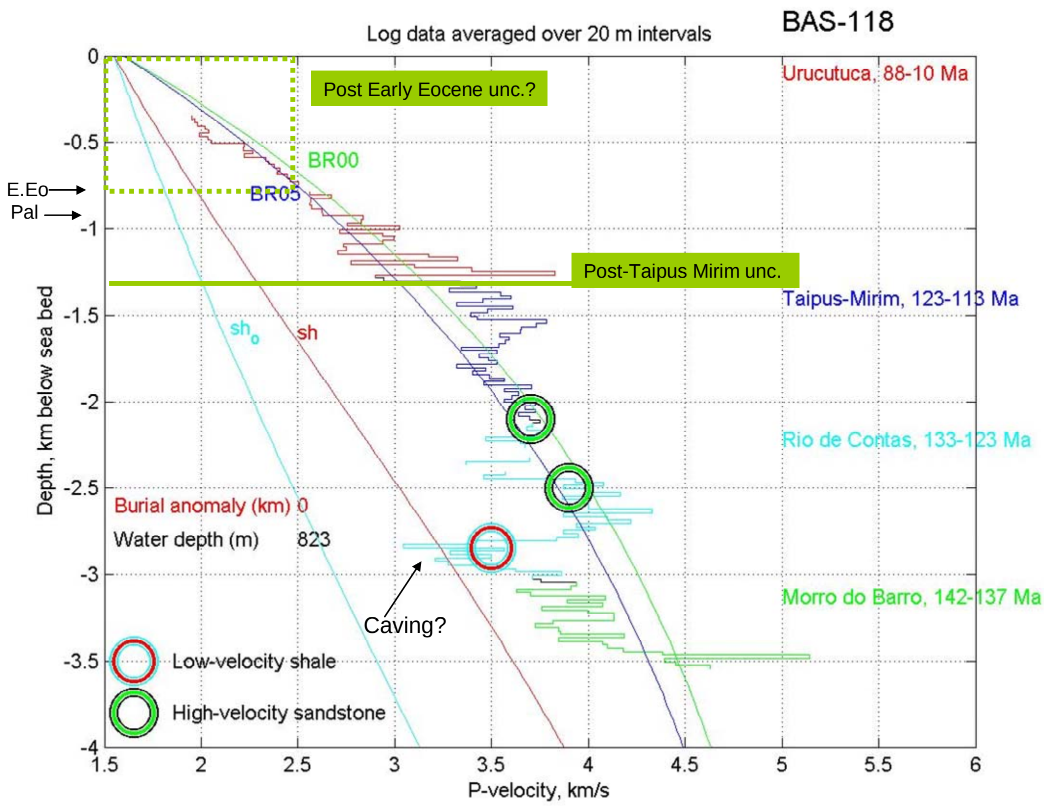


BAS-118
Water depth 823
29-Apr-2008
Depth, km below sea bed
Caliper, inch
Vp, km/s
rhob, Nphi
rhob
nphi
Gamma (Api)



BAS-118
Bad-hole corrected
Water depth 823
29-Apr-2008
Depth, km below sea bed
Caliper (inch)
Vp (km/s)
Vp, km/s





cf. BAS-88, -77 (near-by)

BAS-129

Unconformities

Post-Algodões unconformity? (110–65 Ma): Possibly above thin Algodões Fm (105 m) and within lower part of thick Urucutuca Fm (1221 m) with Paleocene strata documented at 1044 m below seabed.

Post-Eocene unconformity? (34–0 Ma): Possibly above Paleocene-Eocene sediments and within a 513 m thick overlying section (Urucutuca Fm).

Caliper

Narrow calliper variations over the limited interval with data.

Sonic data, LithoLog and composite log

Velocity peaks associated with anhydrates and conglomerates within the TM Fm. Shale in the upper part of the TM Fm is interbedded with limestone etc. has high velocity.

Sandstone units in the basal part of the Urucutuca Fm and within the TM Fm.

Burial anomaly

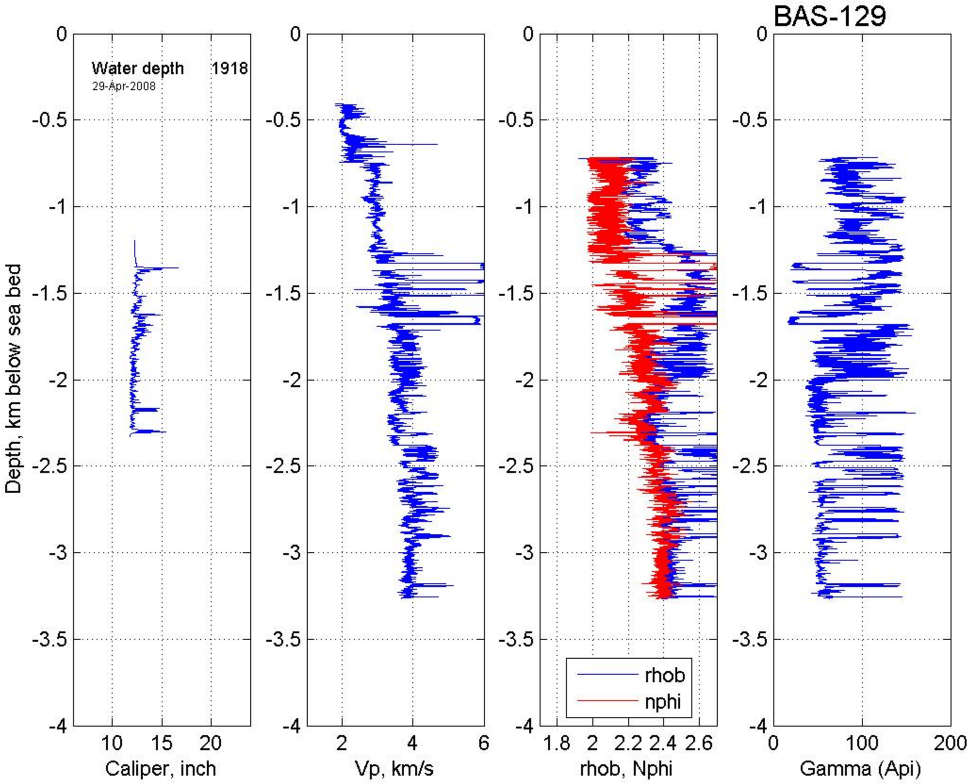
0 ± 0.2 km (drilled section relative to the baselines): The drilled sequence is at maximum burial. Only minor scatter between sandstone data and BR00, BR05 over a wide depth range both above and below the Algodões Fm.

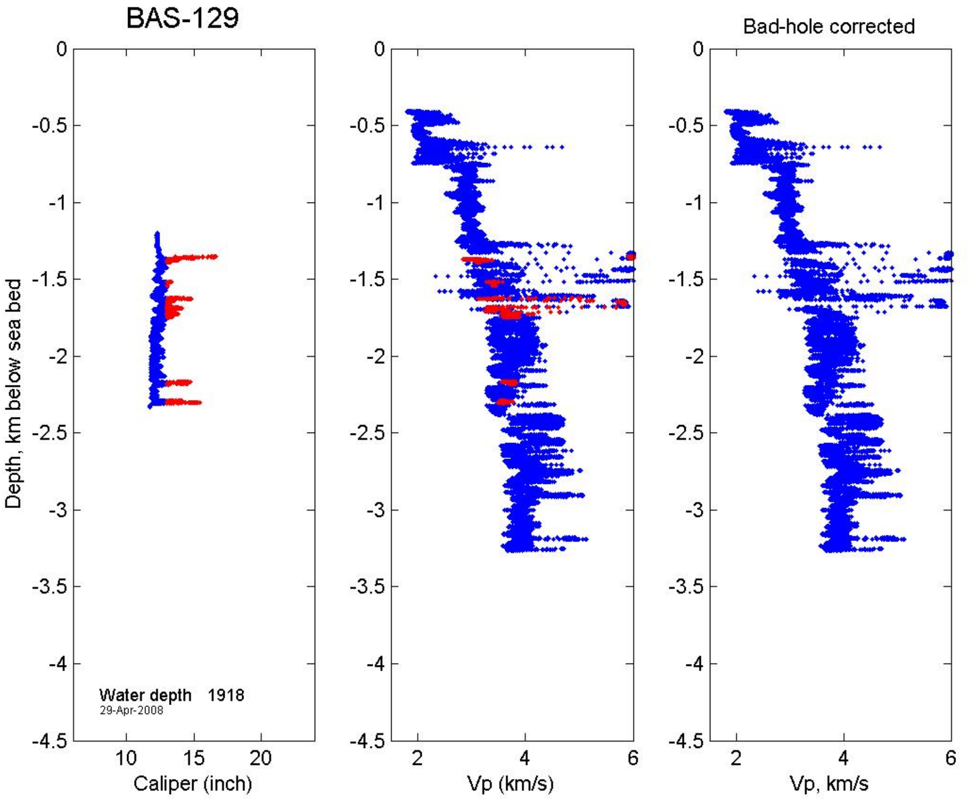
Post-exhumational burial

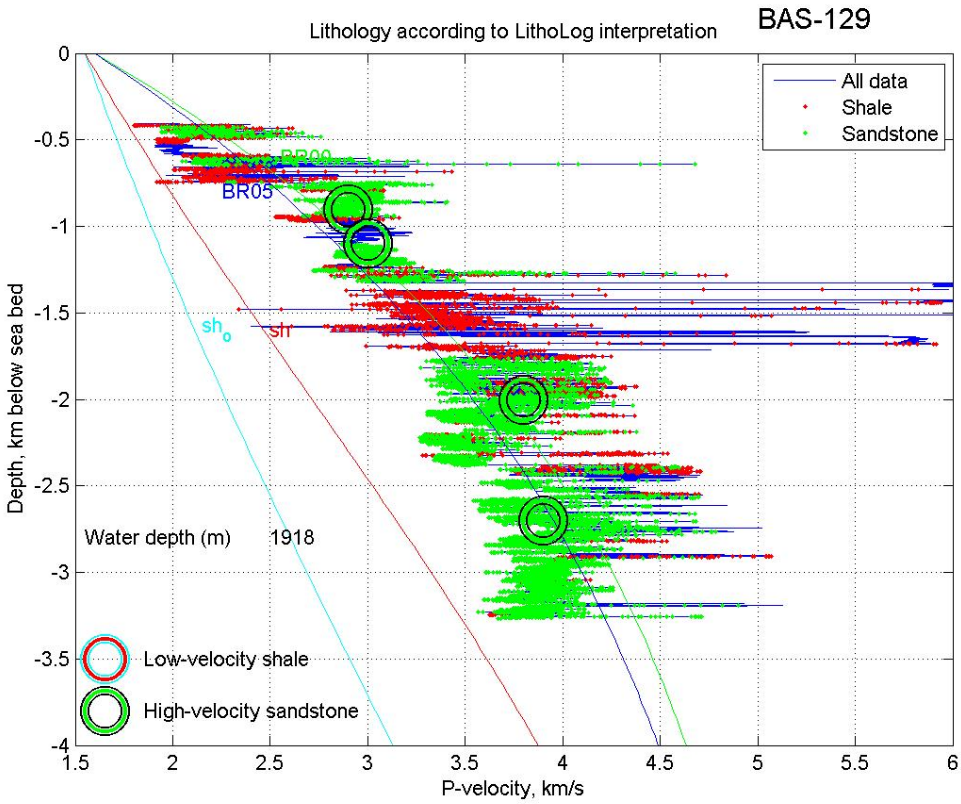
1.2 km; burial of the post-Algodões unconformity. (relative to a possible Late Cretaceous event)

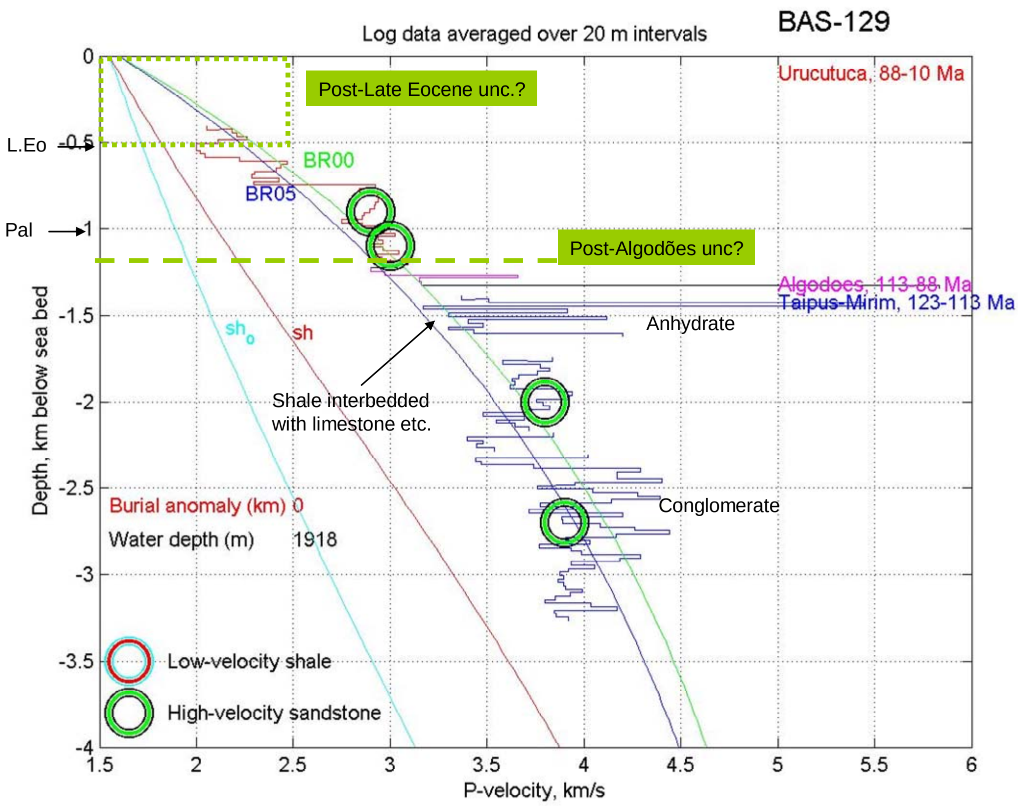
Removed section

- ; since the all sediments are at maximum burial today any exhumation at the post-Algodões unconformity must be less than 1.2 km; potentially corresponding to the upper part of the Algodões Fm (0.1 km preserved) and the lower part of the Urucutuca Fm (0.2 km preserved below


BAS-129
Water depth 1918
29-Apr-2008
Depth, km below sea bed
Caliper, inch
Vp, km/s
rhob, Nphi
rhob
nphi
Gamma (Api)


BAS-129
Bad-hole corrected
Water depth 1918
29-Apr-2008
Depth, km below sea bed
Caliper (inch)
Vp (km/s)
Vp, km/s





no wells near-by

AFTA

BRN-1

Unconformities
Post-Marizal unconformity (115–0 Ma): Ground level.

Caliper
Few caliper variations where data are available (below 2 km).

Sonic data and composite log
A data set dominated by multiple conglomerate units above 2.6 km and almost entirely by conglomerate deposits between 2.6 and 3.5 km (São Sebastião Fm) and finally, coherent conglomerate deposits 1.5 km thick below that depth with velocities higher than 5.5 km/s (São Sebastião and Salvador Fms). No baseline has been defined for conglomeratic deposits.

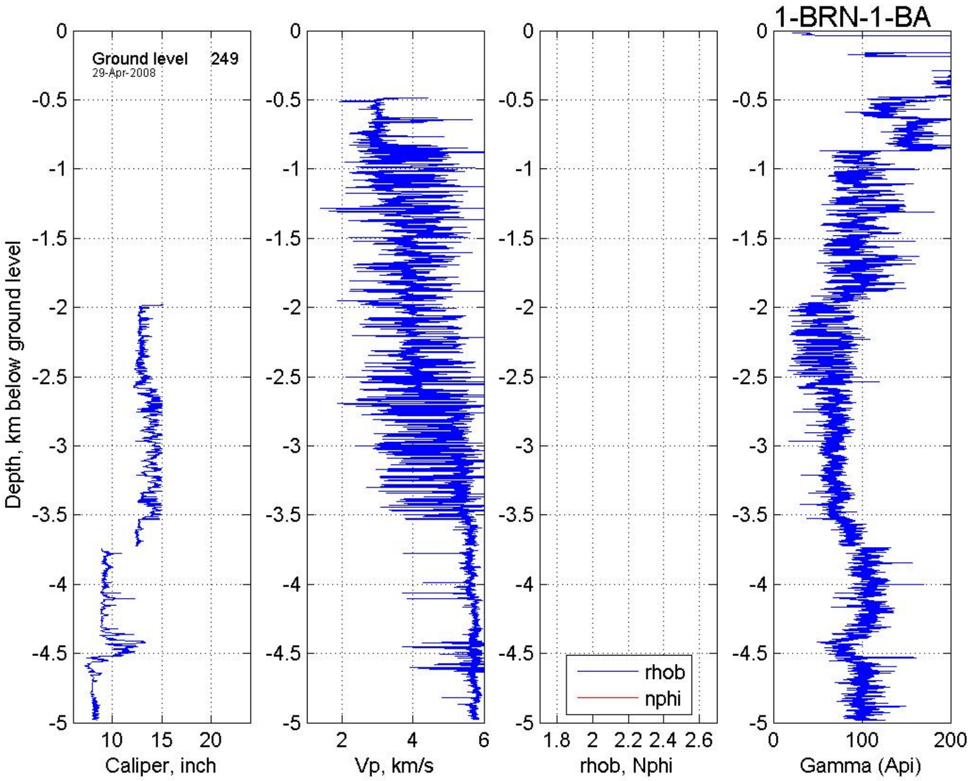
Only thin shale units for which the velocity cannot be reliably estimated.

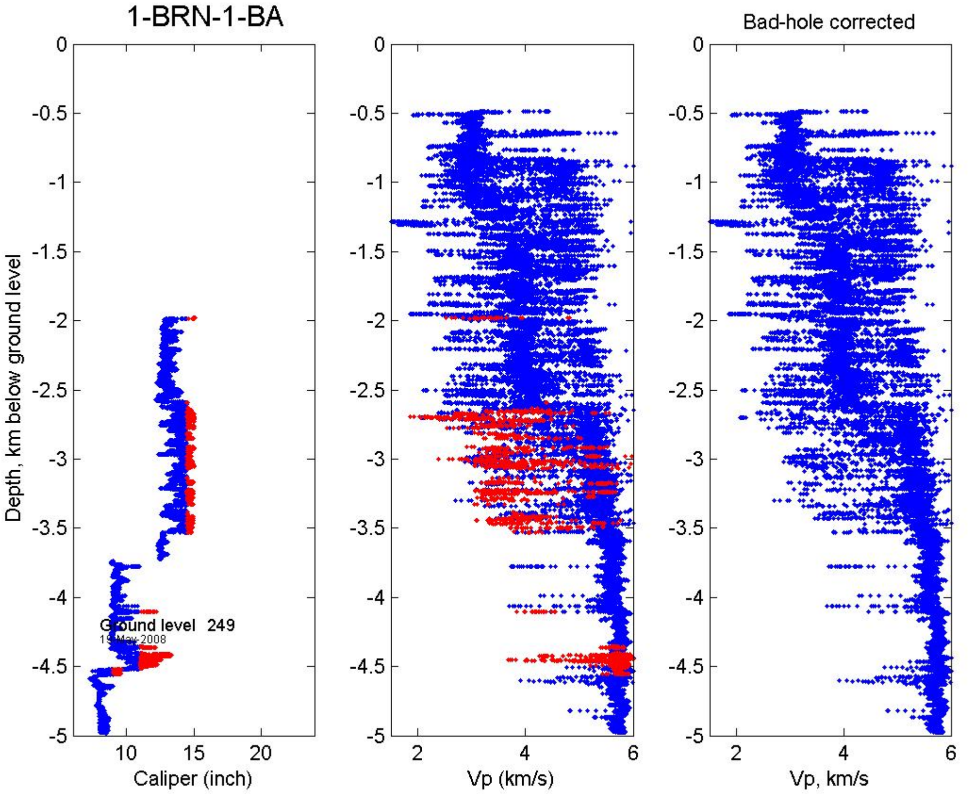
Intervals dominated by sandstone (interbedded with conglomerate and shale units) are found at 1.7 and 2.5 km (São Sebastião Fm).

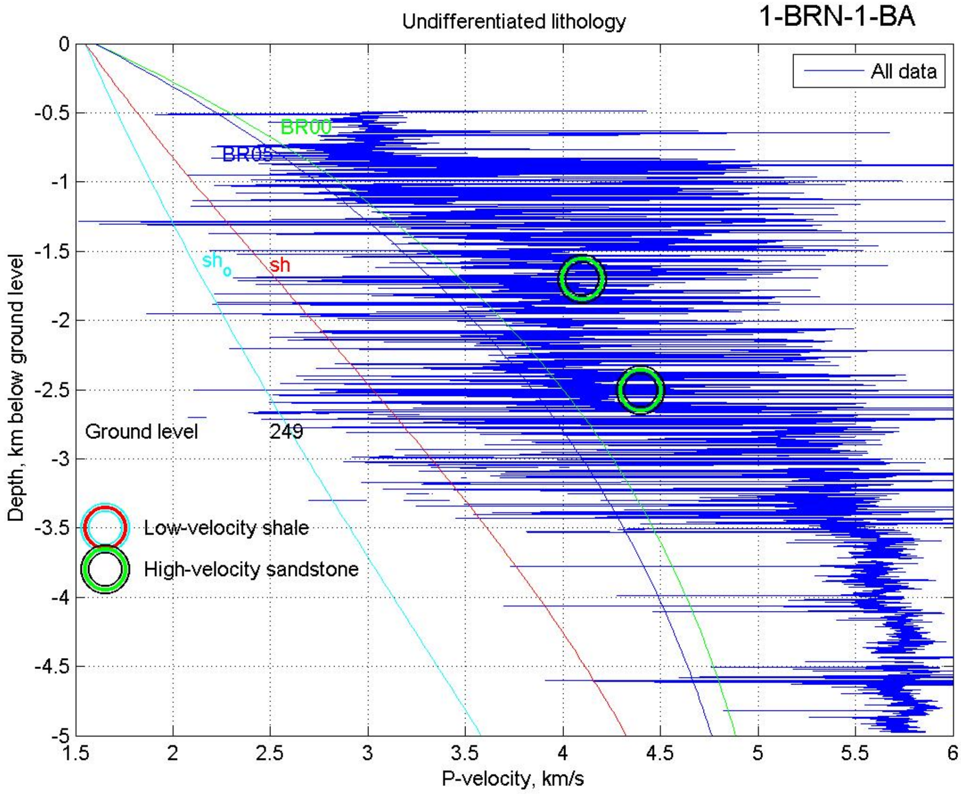
Burial anomaly
Between 1.5 and 3.5 km. The sandstone datapoints defines a lower limit for the magnitude of the burial anomaly because these intervals in between conglomerate and shale units probably represent impure sandstone. This interpretation is supported by the much larger estimates of exhumation in the other wells in southern Tucano (FPO-1, FVM-1). The shift is c. 3.5 km between the baselines for pure sandstone and the velocity of c. 5 km/s for the conglomerates at depths of 2.5 km; this shift is the upper limit for the burial anomaly of the sediments in this well assuming that some of the intervals with this velocity represent sandstone.

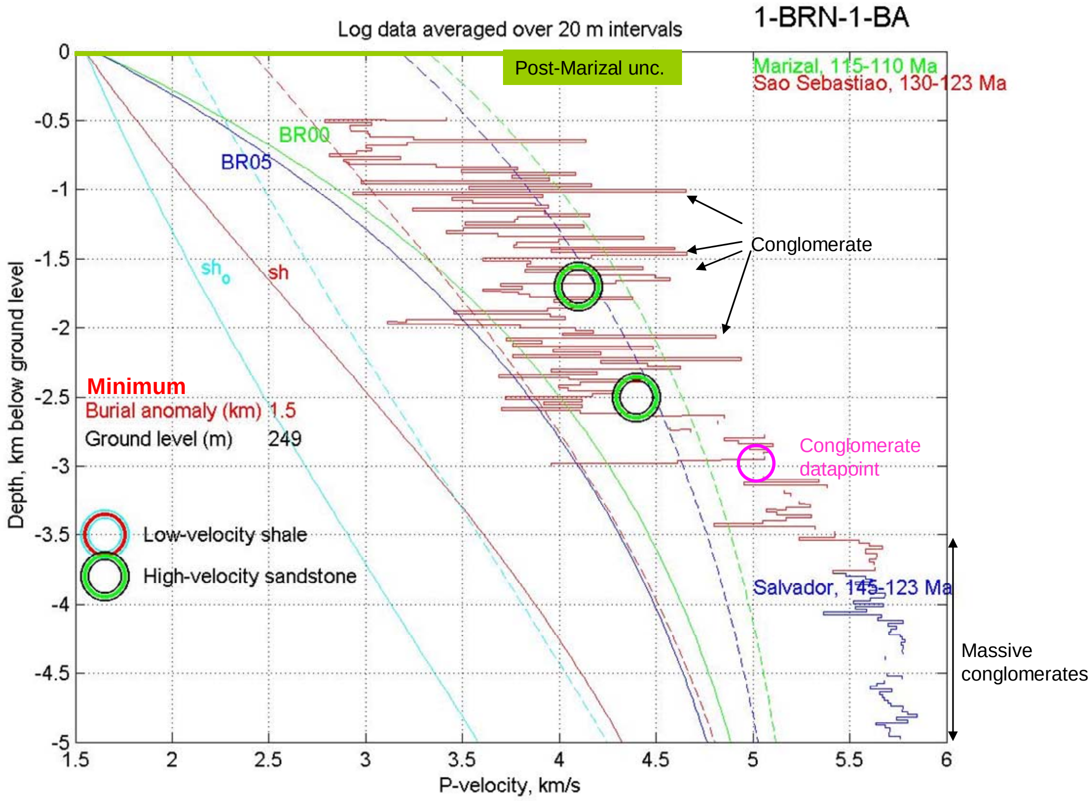
Post-exhumational burial
0 km.

Removed section
Between 1.5 and 3.5 km. Marizal Fm and younger units.


1-BRN-1-BA
Ground level 249
29-Apr-2008
Depth, km below ground level
Caliper, inch
Vp, km/s
rhob
nphi
rhob, Nphi
Gamma (Api)


1-BRN-1-BA
Bad-hole corrected
Depth, km below ground level
Ground level 249
Caliper (inch)
Vp (km/s)
Vp, km/s





Near FPO-1, FVM-1

AFTA

Unconformities
Post-Marizal unconformity (115–0 Ma): Ground level.

Caliper
Considerable variations throughout the borehole. Clear correlation between bad-hole conditions and low sonic velocities; overall trend of the data not affected by the data editing.

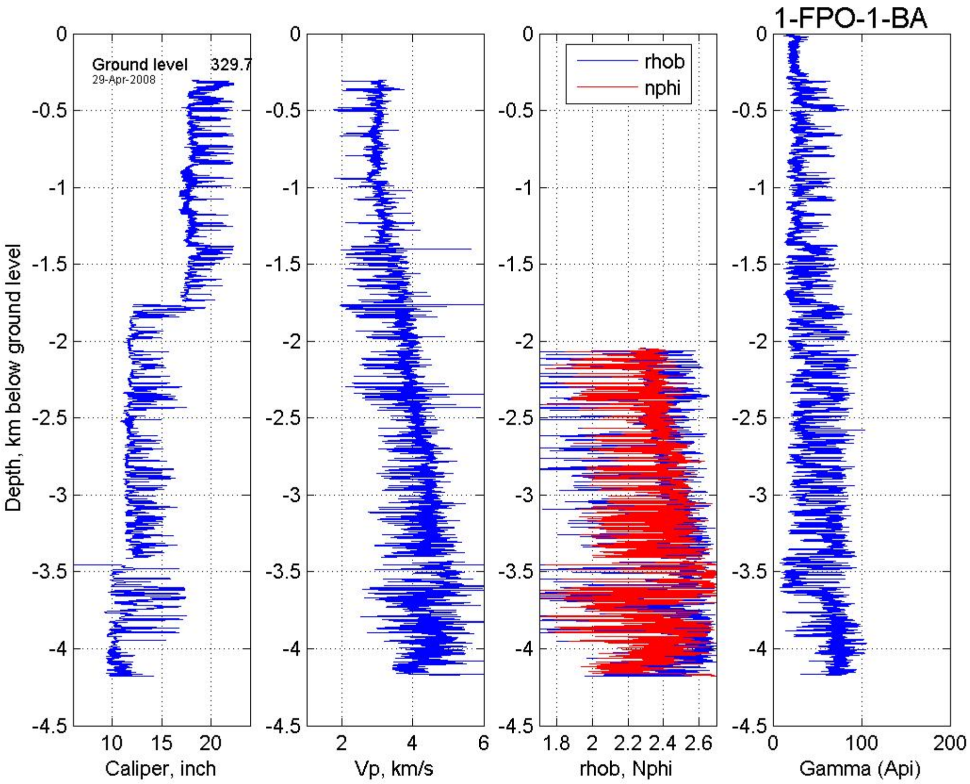
Sonic data and composite log
Well-defined trend of sonic velocities increasing with depth between 1 and 3.5 km; constant velocity level above 1 km and relatively low velocities in the Candeias Fm below 3.5 km. Shale dominated interval between 3.6 and 4.1 km (Candeias Fm); some scatter in the sonic data, but reliable reading at c. 4 km. Estimation of shale velocities difficult in the upper part of the well because of severe bad-hole conditions. Very low velocities in shale interval at 4.1 km with may reflect very organic-rich shales.

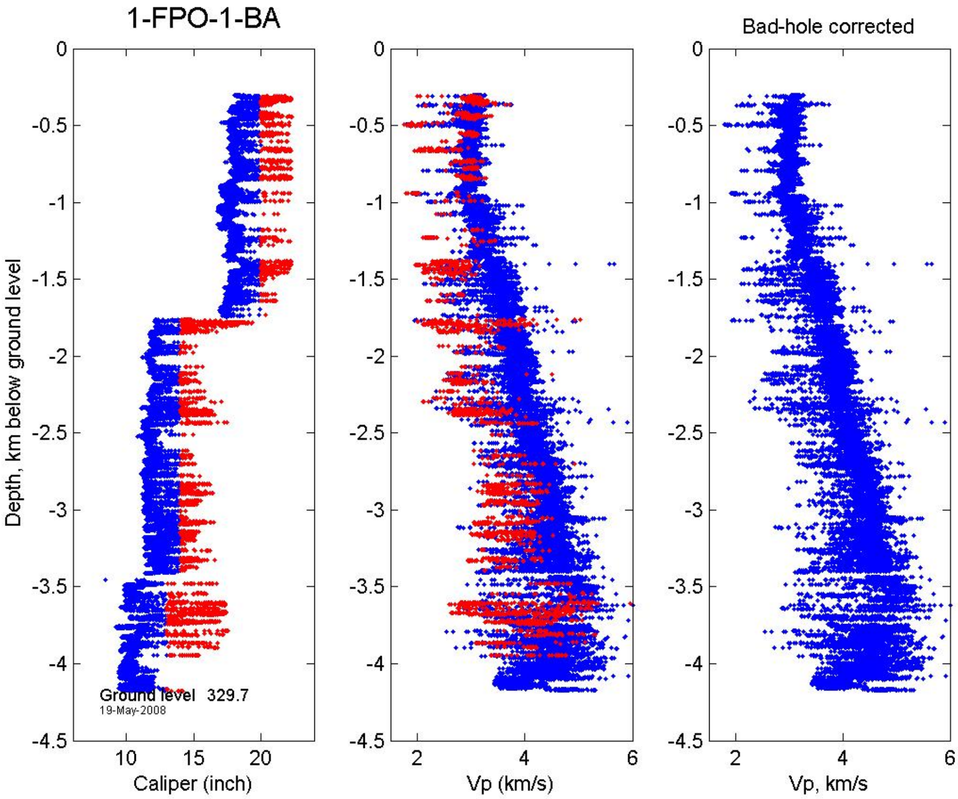
Thick sandstone units over a 150 m thick interval at c. 3.5 km with well-defined sonic level (Ilhas Group).

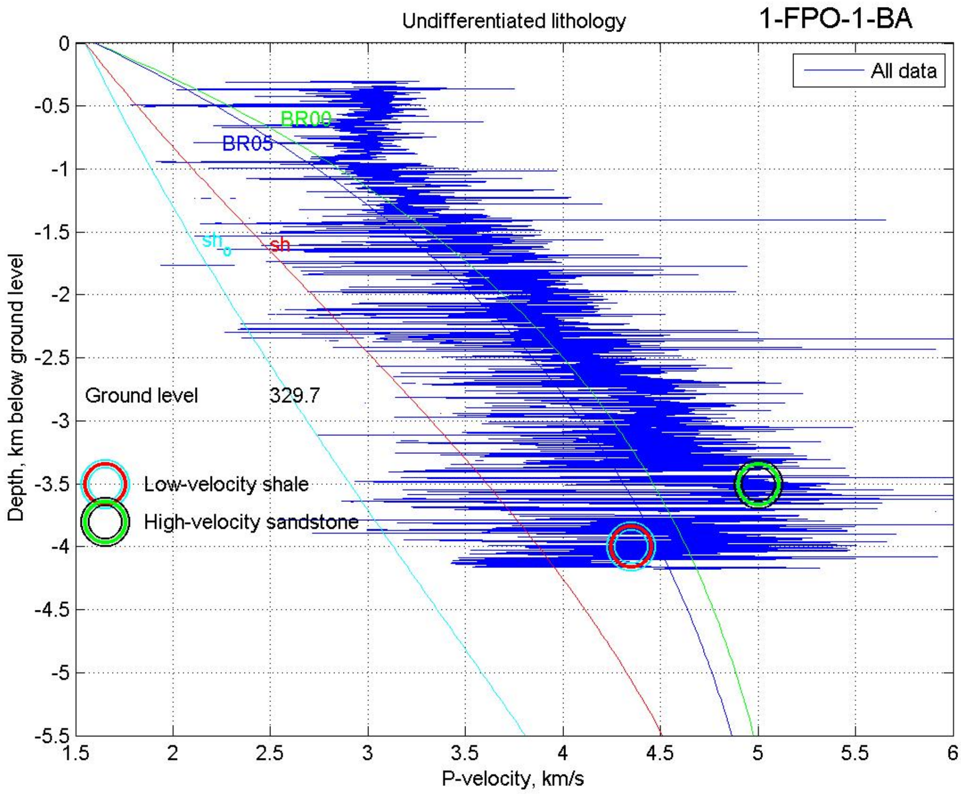
Burial anomaly
2.5 ± 0.3 km (relative to the baselines); based on sandstone data at 3.5 km consistent with estimated shale velocity of the Candeias Fm matching Vsh-o at 4.0 km. Coincidence between sonic data around 1 km and Vsh-o suggests that these sediments are organic-rich and that this condition explains the low velocities in the upper part of the borehole.

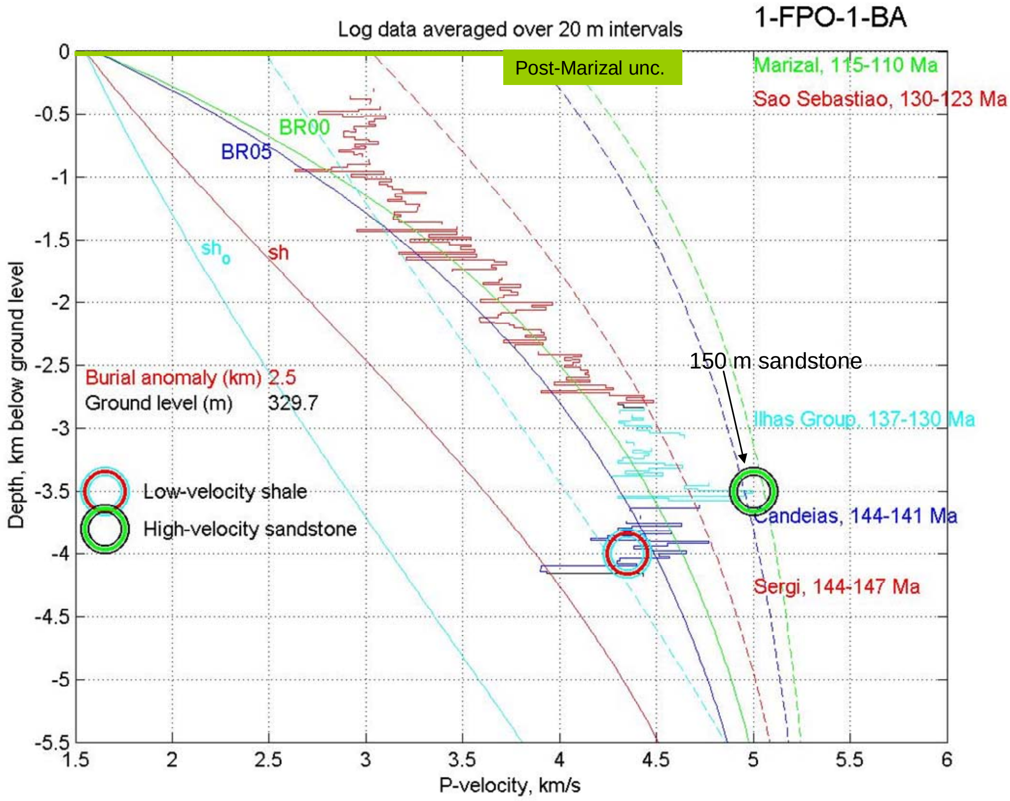
Post-exhumational burial
0 km.

Removed section
2.5 ± 0.6 km (allowing for the uncertainty of the baselines); Marizal Fm and younger units.


1-FPO-1-BA
Ground level 329.7
29-Apr-2008
Depth, km below ground level
Caliper, inch
Vp, km/s
rhob
nphi
rhob, Nphi
Gamma (Api)


1-FPO-1-BA
Bad-hole corrected
Ground level 329.7
19-May-2008
Depth, km below ground level
Caliper (inch)
Vp (km/s)
Vp, km/s





Near FVO-1

AFTA

Unconformities
Post-Marizal unconformity (115–0 Ma): Ground level.

Caliper
Considerable variations throughout most of the borehole. Clear correlation between bad-hole conditions and low sonic velocities; overall trend of the data not affected by the data editing.

Sonic data and composite log
Considerable data scatter below 3.5 km. Well-defined trend of sonic velocities increasing with depth between 1.3 and 4.5 km; velocity inversion above 1.3 km must be due to lithological variations since there is no overpressure in the basin. Low velocities in the Candeias Fm below 4.5 km.

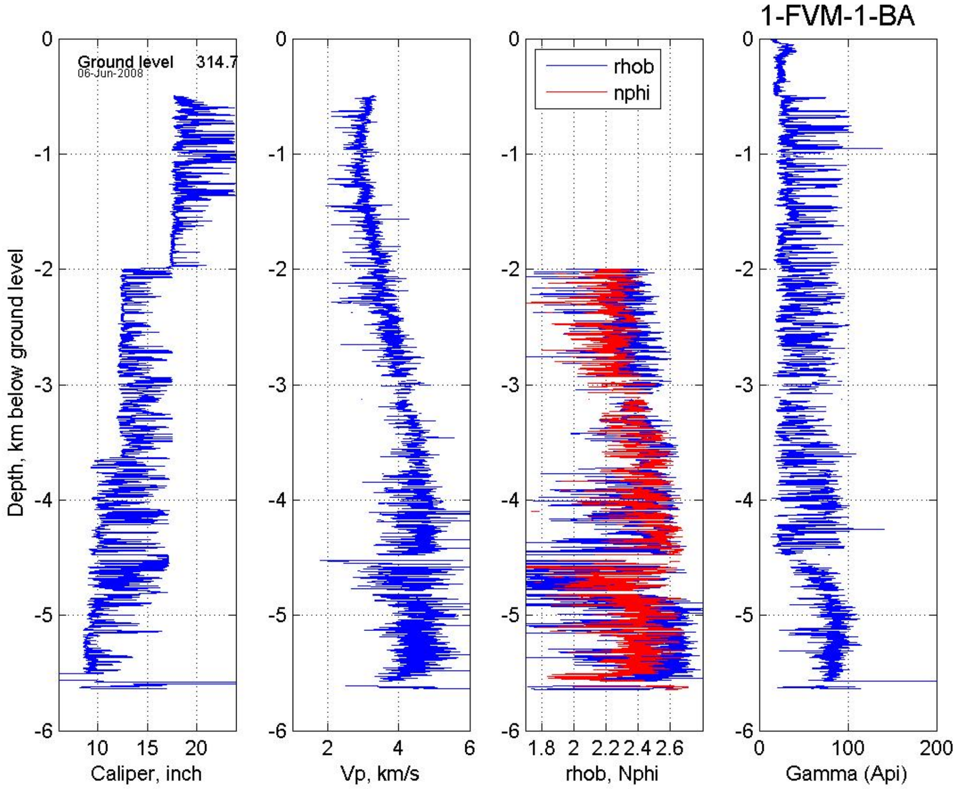
Thick shale units dominate between 4.8 and 5.6 km (Candeias Fm), but considerable scatter in the sonic data makes reliable reading of a typical shale velocity difficult. The average level in the interval between 5.05 and 5.10 km is taken to be representative,

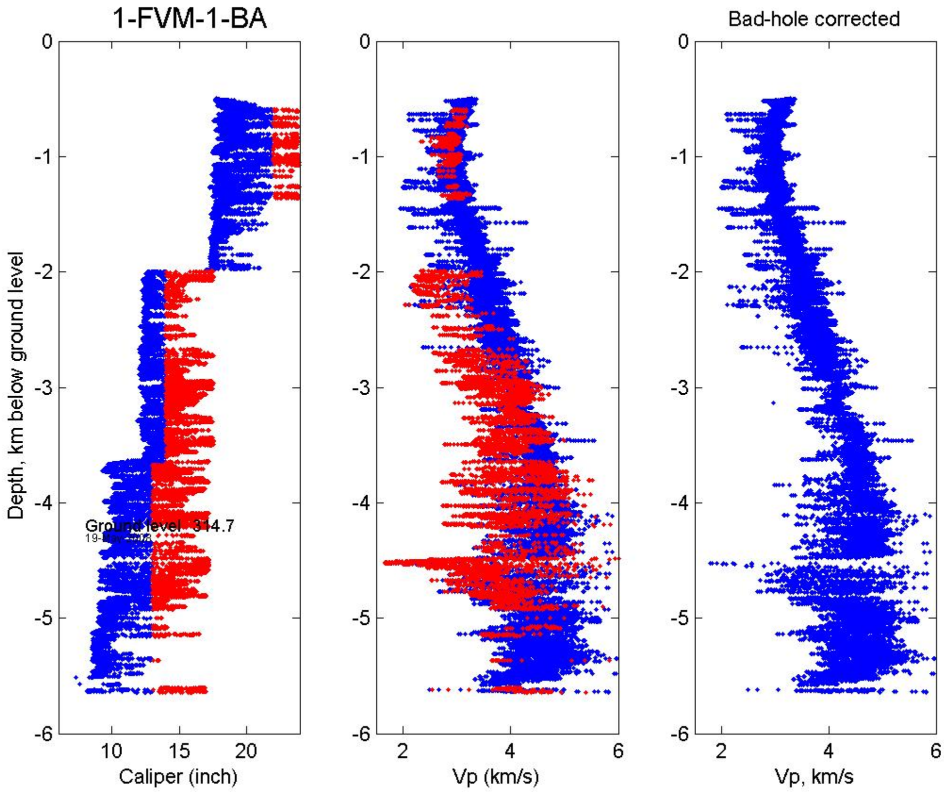
Thick sandstone units over a 200 m thick interval above c. 4.4 km (Ilhas Group). Due to significant scatter in the sonic data, the velocity level does not show up in the plot of mean velocities, but can with some uncertainty be estimated from sonic log.

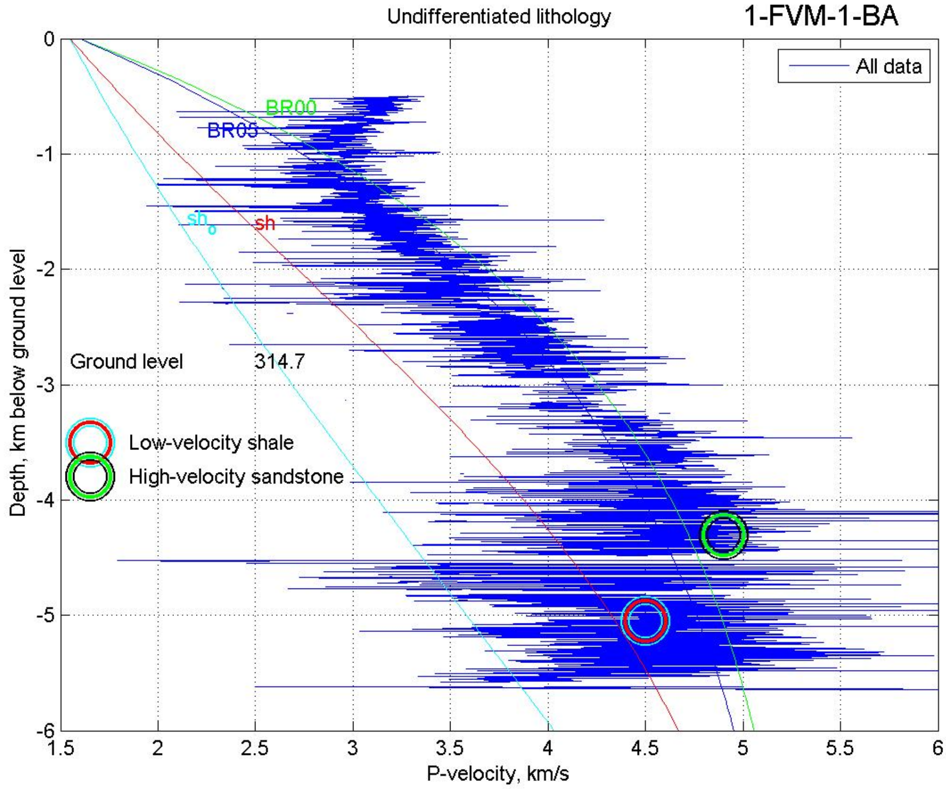
Burial anomaly
Minimum 1.8 km (relative to the baselines); based on scattered sonic data that only allow for uncertain determination of values for high-velocity sandstone and low-velocity shale. The estimated burial anomaly is probably a minimum value. Coincidence between sonic data around 1.3 km and Vsh-o suggests that these sediments are organic-rich and that this condition explains the low velocities in the upper part of the borehole.

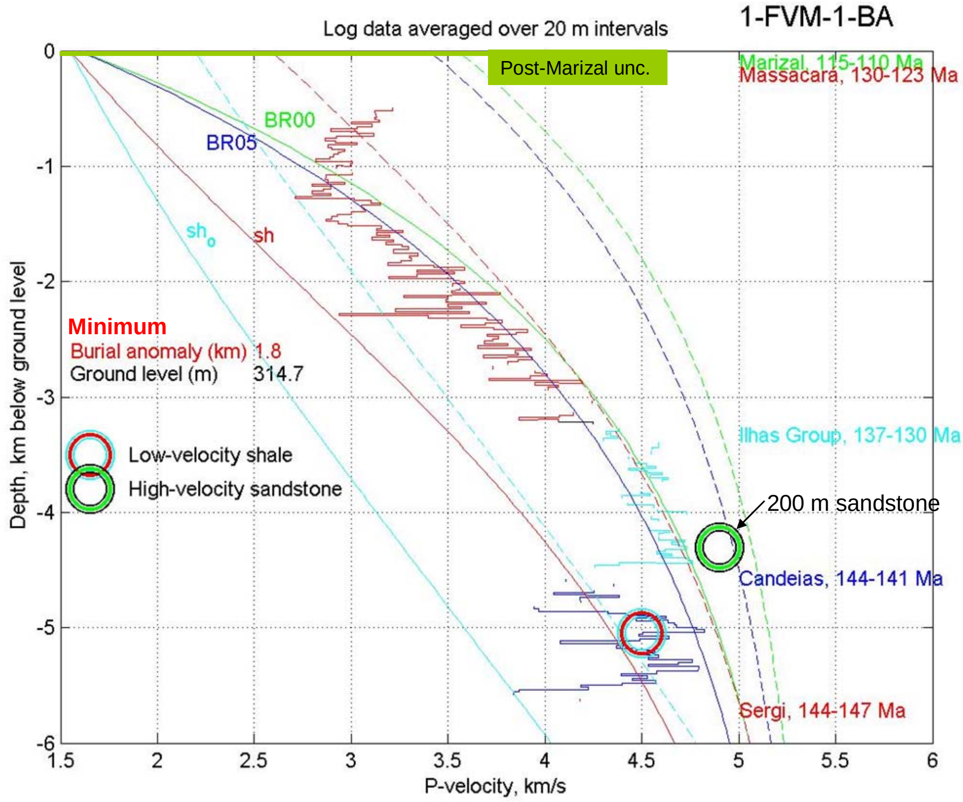
Post-exhumational burial
0 km.

Removed section
Minimum 1.8 km (allowing for the uncertainty of the baselines); Marizal Fm and younger units.


1-FVM-1-BA
Ground level 314.7
06-Jun-2008
Depth, km below ground level
Caliper, inch
Vp, km/s
rhob
nphi
rhob, Nphi
Gamma (Api)


1-FVM-1-BA
Bad-hole corrected
Depth, km below ground level
Caliper (inch)
Vp (km/s)
Vp, km/s





Near FPO-1

AFTA

FLU-1

Unconformities
Post-Proterozoic unconformity (540–0 Ma): Ground level.

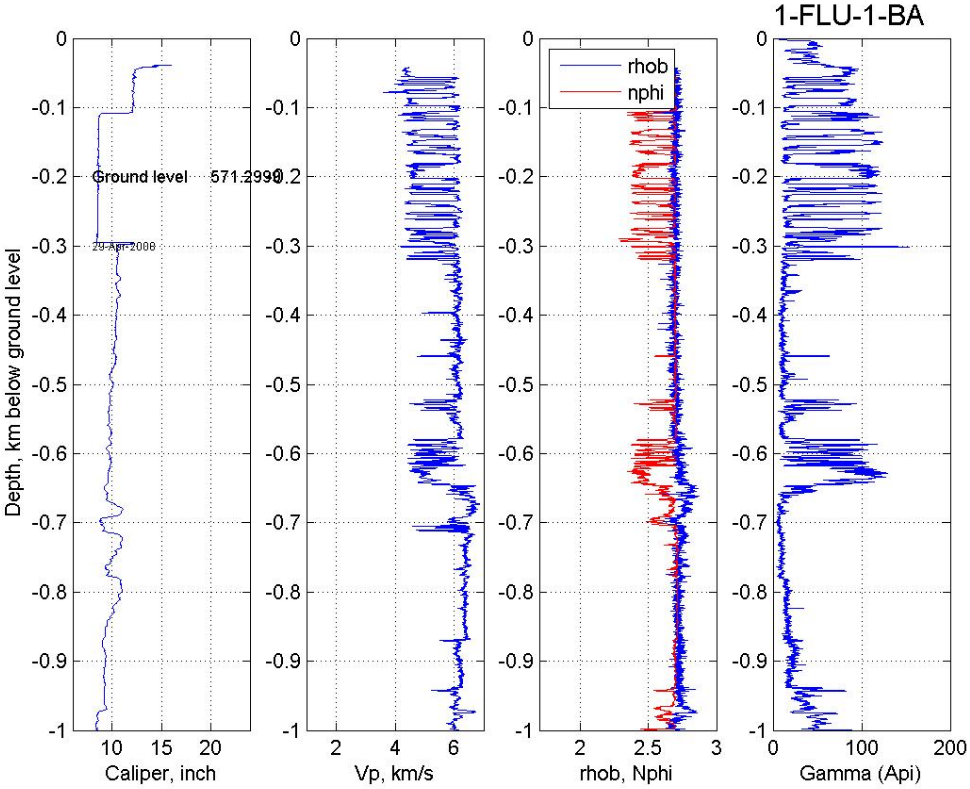
Caliper
Narrow range of caliper values.

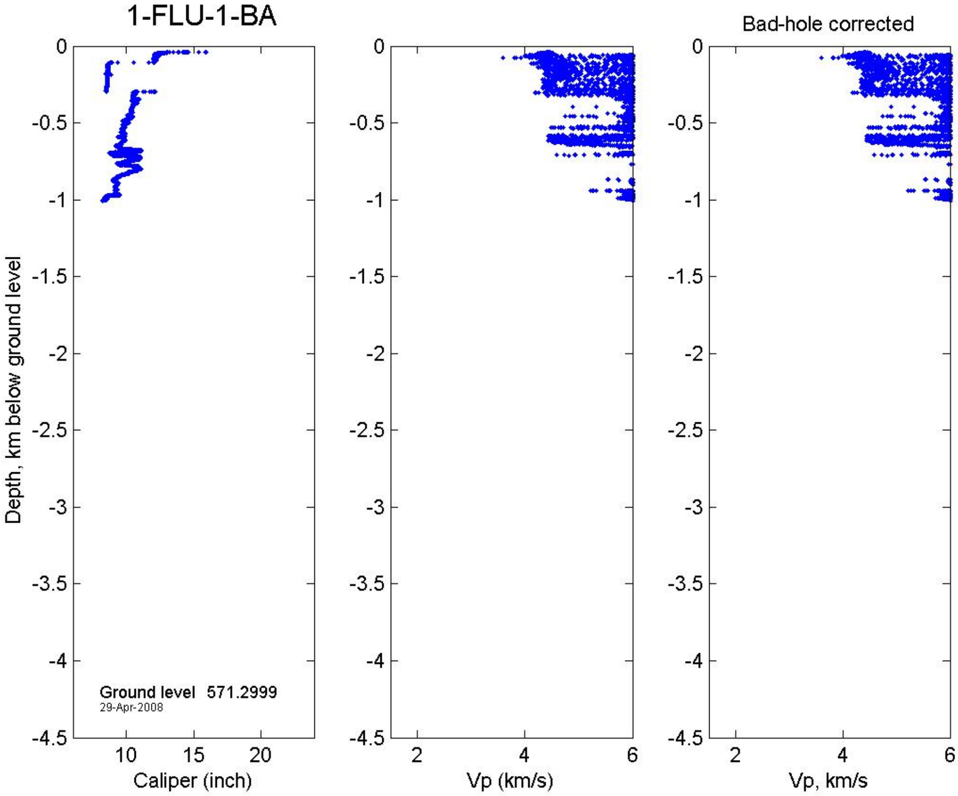
Sonic data and lithological subdivision
The sonic variations in the upper part of the drilled section clearly reflect the lithology. Minimum velocities around 4.5 km/s characterize the shale units (above 0.6 km), whereas velocities above 6 km/s characterize the limestone intervals. Note that the velocity-depth gradient for shale intervals is similar to that of Vsh.

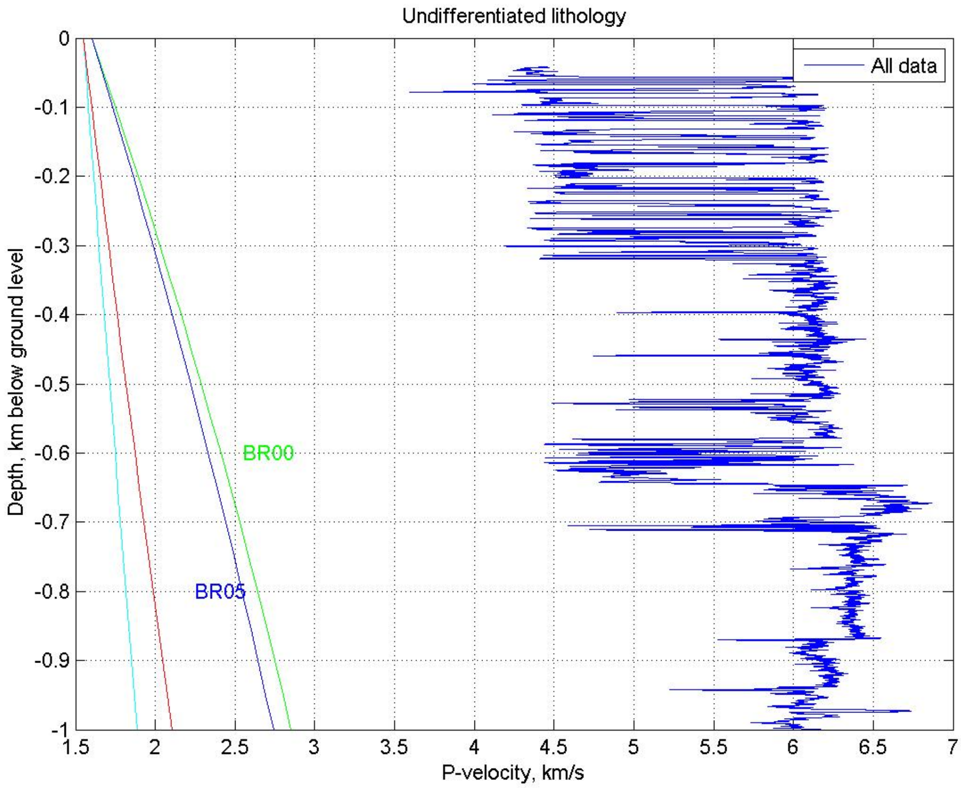
Burial anomaly
5.0 ± 0.5 km (relative to the baselines); based on a comparison between the velocity of the shale units (almost 4.5 km/s at the surface of the earth) and Vsh (4.5 km/s predicted at a depth of just below 5 km).

Post-exhumational burial
0 km.

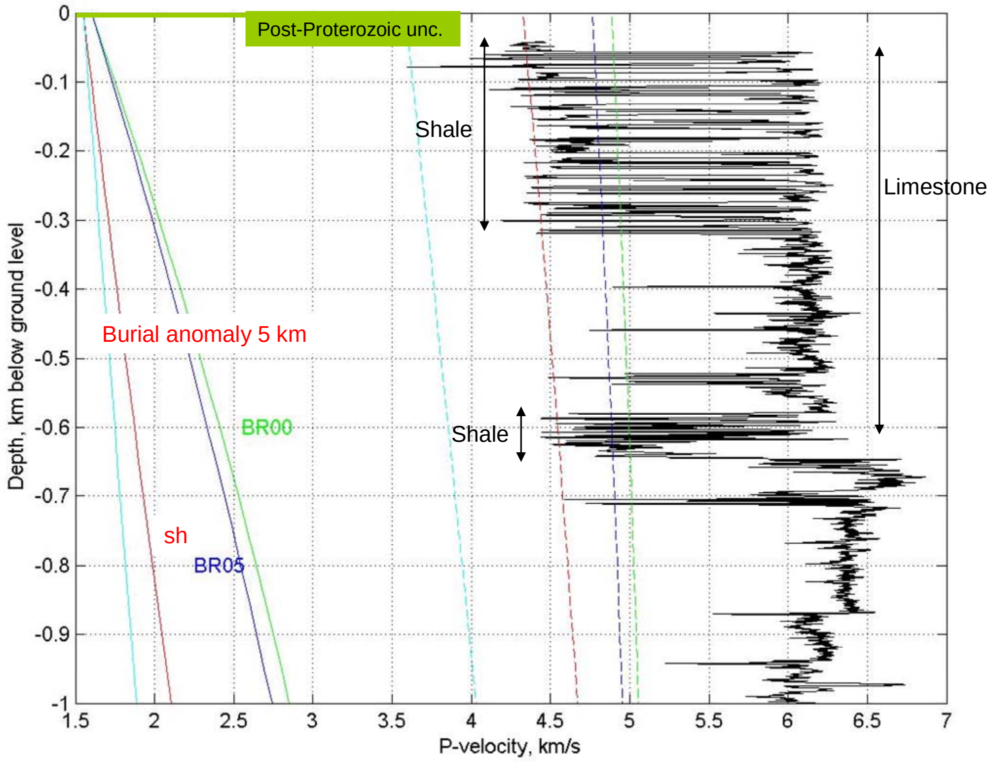
Removed section
5.0 ± 0.8 km (allowing for the uncertainty of the baselines); Phanerozoic sediments that must have been removed prior to the Cenozoic because the borehole is located near the present extent of Upper Cretaceous sediments in the Sanfranciscana Basin.


1-FLU-1-BA
Ground level 571.2999
29-Apr-2008
Depth, km below ground level
Caliper, inch
Vp, km/s
rhob
nphi
rhob, Nphi
Gamma (Api)


1-FLU-1-BA
Bad-hole corrected
Ground level 571.2999
29-Apr-2008
Depth, km below ground level
Caliper (inch)
Vp (km/s)
Vp, km/s



FLU-1



No near-by wells

AFTA

Unconformities
Post-São Sebastião unconformity (125–0 Ma): Ground level.

Caliper
Very small variations in the caliper; few datapoints deleted due to bad-hole conditions.

Sonic data and composite log
Good-quality sonic log with a wide data range that is clearly related to the lithological changes in the drilled sequence (mainly low-velocity shale vs high-velocity sandstone units).

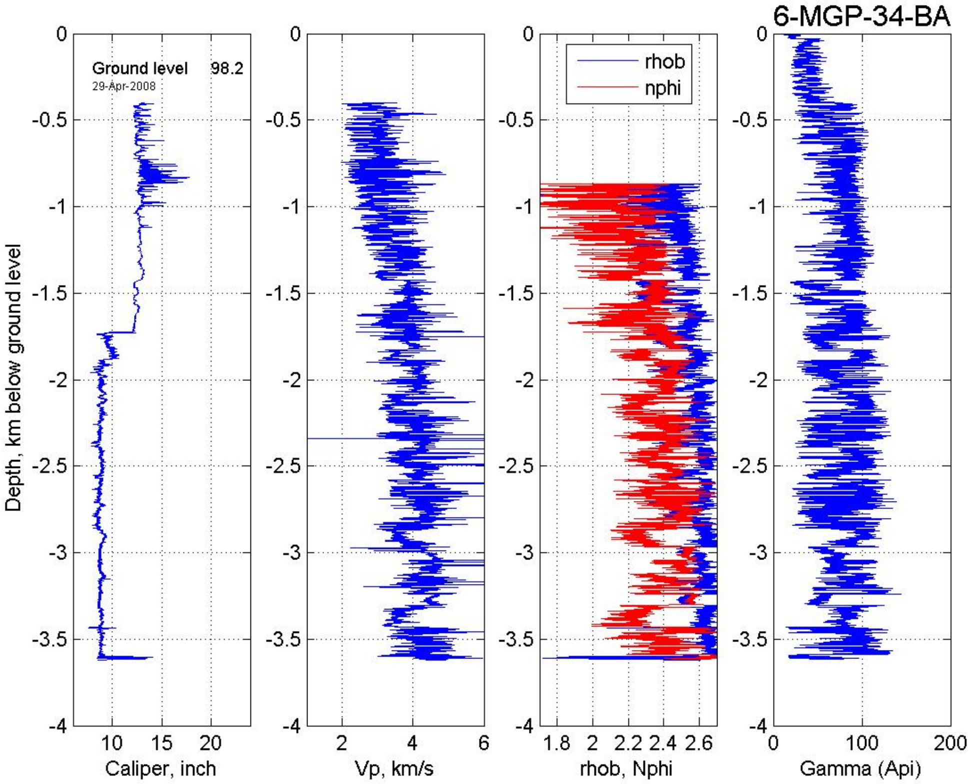
Low-velocity shale data: Well-defined sonic level at 1.4 km (Marfim Fm), at 2.15 and 2.85 km (Marancangalha Fm), 3.4 km (Candeias Fm).

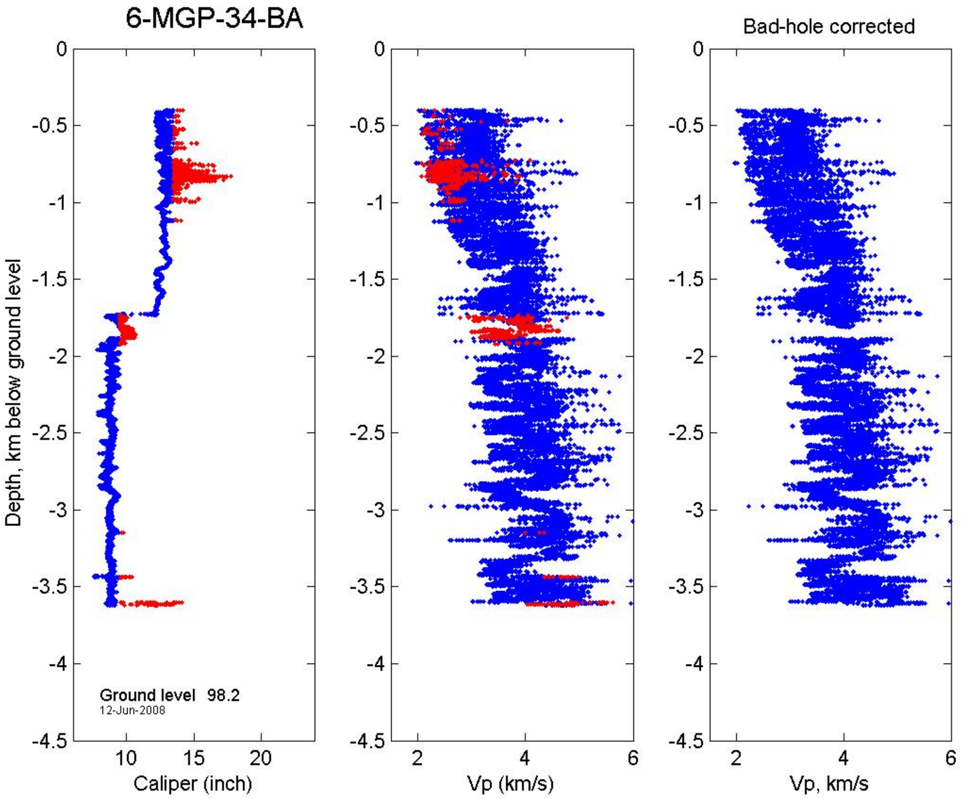
High-velocity sandstone: Well-defined sonic level at 2.4 and 3.1 km (Marancangalha Fm) and 3.6 km (Sergi Fm; based on the raw sonic log).

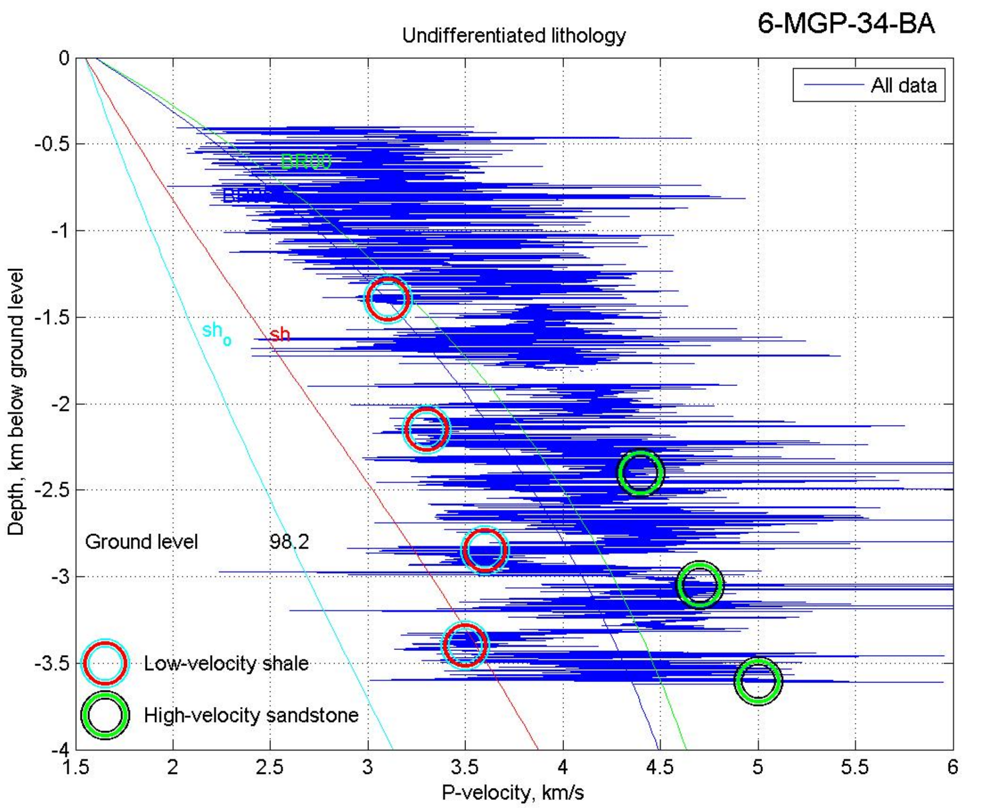
Burial anomaly
2.5 ± 0.5 km (relative to the baselines); primarily based on high-velocity sandstones in the deepest part of the borehole, but also on a general fit between low-velocity datapoints and Vsh-o. Sandstone units in the shallow part of the well plot c. 0.5 km below the shifted baselines; this is interpreted as being due clay content. The two deepest shale datapoints have identical sonic values but are separated by 500 m; the low velocity for the deepest datapoint is interpreted as being due to very high organic content in the Candeias Fm which is the main source rock in the basin.

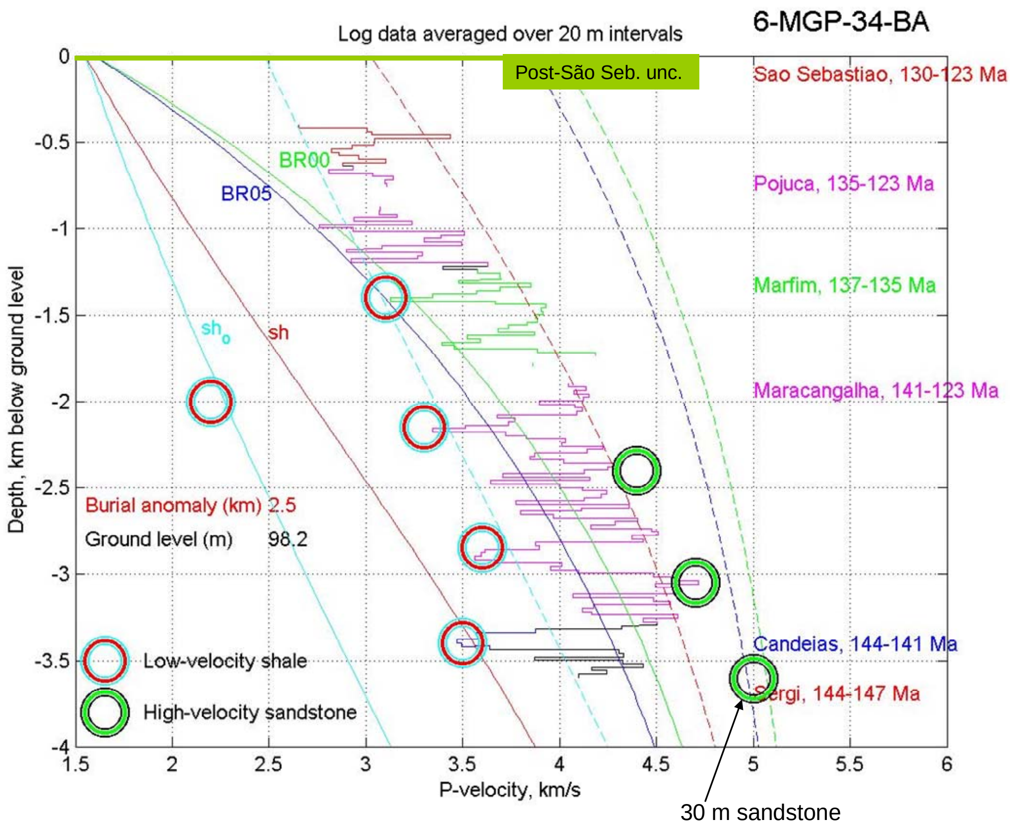
Post-exhumational burial
0 km.

Removed section
2.5 ± 0.8 (allowing for the uncertainty of the baselines); São Sebastião Fm and younger units.


6-MGP-34-BA
Ground level 98.2
29-Apr-2008
Depth, km below ground level
Caliper, inch
Vp, km/s
rhob
nphi
rhob, Nphi
Gamma (Api)


6-MGP-34-BA
Bad-hole corrected
Depth, km below ground level
Ground level 98.2
12-Jun-2008
Caliper (inch)
Vp (km/s)
Vp, km/s





Between BRN-1 and BAS-113

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