The evolution of the syn rift and transition phases of the central / southern Brazilian and W. African conjugate margins: the implications for source rock distribution in time and space, and their recognition on seismic data.

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Abstract

Syn-rift and early transition stage sediments, developed beneath late transition stage salt, form important source rocks on both margins of the central South Atlantic. These margins demonstrate a classical four stage (pre-rift, syn-rift, transition and drift) passive continental margin evolution. The pre-salt section is often poorly imaged on seismic data due to distortion by the overlying salt. Therefore, it is important to understand the stratigraphic and structural configuration of the pre salt section in good data areas to provide reliable models that can be applied to poor/marginal data areas.

Sequential paleogeographical reconstructions allow prediction of the regional distribution of source intervals in time and space. Early syn-rift (late Berriasian to middle Barremian) freshwater shales that were deposited in deep, narrow lakes locally form good source rocks. However, they generally suffer from a high clastic content that diminishes TOC concentration, and thereby, source effectiveness. Late syn-rift (middle to late Barremian) calcareous organic shales and marls were deposited in broad, shallow saline lakes. These deposits occur above a marked internal syn-rift unconformity and form the richest pre-salt source rocks. Organic shales were also deposited under saline conditions during the transition stage but in a basin margin position. These shales form the primary source rocks for basins adjacent to the main Aptian salt basin (e.g. Sergipe, Douala, Potiguar basins).

Seismic examples from the southern Campos Basin demonstrate the pre-salt structural configuration. The informally named Eastern Graben is considered to be the source of the majority of hydrocarbons in the Campos Basin.

Introduction

South Atlantic passive continental margins display a classic four-stage evolution with pre-rift, syn-rift, transition, and drift stages, separated by regional unconformities. Syn-rift stage sediments, and to a lesser extent transition stage sediments, form important source rocks on both margins of the central South Atlantic. Recognizing these sediments on seismic data, and understanding their stratigraphic and spatial distribution, is critical for detailed petroleum systems analysis.

Considerable discrepancy exists within the literature relating to the stratigraphy of the central South Atlantic, largely due to two main factors. First, there are few well penetrations of the entire syn-rift and pre-rift section in many basins. Second, the historical use of a litho-stratigraphic nomenclature has resulted in a poor understanding of correlations within basins and contributed to miscorrelations between basins.

In this paper a chrono-stratigraphic system is used (Figure 1) that outlines four important intervals: 1) a pre-rift / rift onset stage from late Jurassic to earliest Cretaceous (late Berriasian), 2) a syn-rift stage, with two distinct phases, from late Berriasian to early Aptian, 3) a transition stage during middle to late Aptian, and 4) a drift, or passive marine margin stage, from late Aptian to the present. The drift stage is divided into transgressive and regressive marine phases. The two phases are separated by a regional unconformity in the basal Eocene that coincides with extensive volcanic activity along the Brazilian margin.

The adoption of a chrono-stratigraphic system allows greater confidence in regional correlations between basins and allows the generation of a systematic paleogeographic evolution. With these tools a predictive model for source rock distribution in time and space is possible.

Three main phases of extrusive volcanic activity occur within the pre-rift to early drift stage sediments. They are: 1) extensive flood basalts extruded prior to the onset, or during the earliest stages of, rifting; 2) lavas extruded during the transition stage immediately prior to continent separation that are found along the axial high complex associated with the line of opening; and 3) seaward dipping reflectors (SDR) emplaced immediately after separation. It is important that these three distinct phases of volcanic activity are not miscorrelated.

Modern analogs can help with the visualization of margin evolution. The southern Red Sea is a possible rift stage analog for the central South Atlantic. Comparison of the conjugate Espirito Santo and lower Congo basins suggests that the central South Atlantic, containing these two basins, evolved as a large, roughly symmetrical basin with a central/axial basement high. We interpret that the axial high was associated with the eventual line of opening between Africa and South America. The now ruptured axial high forms outer basement highs in the deep water close to the continent-ocean boundary (COB) of both margins.

These basement outer highs act as possible trigger mechanisms for the formation of compressional linear salt fronts locally expressed as seabed escarpments. Seaward tilting of the margins during the drift stage mobilised the autochthonous salt, which moved downslope. The still structurally positive outer highs acted as steps directing the sole thrusts to the surface. The compressional salt fronts now overlie the outer highs and the SDRs. Determining the exact position of the COB is difficult because of poor seismic imaging beneath shallow highly distorted salt.

Results

Two main phases of rifting are recognized: Syn-Rift I from Late Berriasian to middle Barremian, and Syn-Rift II from middle Barremian to early Aptian. Syn-Rift I sediments are documented in basins as widely dispersed as the Potiguar Basin in equatorial Brazil to the conjugate Espirito Santo and Lower Congo basins to the south (Figure 2). This is not consistent with the classical south to north linear evolution of the South Atlantic rift system. Although sediments of Berriasian to early Barremian age have not been documented from the Santos and Campos basins to date, seismic data clearly shows a massive thickness of older syn-rift section that has not been penetrated. In the Jacuipe and conjugate northern Gabon basins however, no syn-rift sediments older than middle Barremian have been encountered. It has been proposed that this is the result of late breaching of the Congo – Sao Francisco Craton (Standlee et al 1991).

Rifting that initiated in the late Berriasian was preceded by widespread extrusion of flood basalts in two volcanic provinces, 1) the Parana Basin/ Etendeka areas to the south that are associated with the Walvis hot spot, and 2) the Benue Trough area to the north. Widespread clastic deposition occurred in a broad sag / proto rift basin between the two volcanic provinces.

Deposition during Syn-Rift I time took place in narrow, deep, freshwater lacustrine basins (Figure 3) that show a high degree of asymmetry and form half graben complexes segmented by numerous intra basin highs. Massive amounts of coarse clastic material, in the form of alluvial fans, were deposited adjacent to active faulted margins with lacustrine turbidites deposited in the deeper water. Fluvial plains and delta complexes formed on the less active margins, again feeding turbidites into the deeper water areas. Climatic conditions were warm and wet with resultant high algal bloom and high plant detritus input into the nutrient rich basins. These conditions, allied with anoxic bottom conditions, were suitable for the formation of rich source rocks (Mello & Maxwell, 1990). However, the high clastic input into the basin reduced the richness of source rocks, except for a narrow fairway in the deepest parts of the basin. With some exceptions (e.g. Reconcavo Basin) they are secondary source rocks in the major hydrocarbon producing basins.

A stratigraphic break during the early Hauterivian, is documented in many basins and may be the result of readjustment along major WNW – ESE trending suture lines that segment southern South America. This break divides the Syn-rift I section into two units.

A major change in rifting style occurred in the middle Barremian, probably associated with the onset of rifting in the equatorial region and additional readjustments in the southern South Atlantic. Also, at this time the Congo – Sao Francisco craton was breached opening a connection between central and equatorial areas (Figure 4) (Standlee et al 1991). This gave rise to the locally named "break thru" unconformity which separates Syn-rift I from Syn-rift II strata.

During Syn-Rift IIa (middle to late Barremian) deposition took place in broad, shallow lakes, as many of the intra basinal highs, active during Syn-Rift I, were flooded (Figure 5). Probable breaching of the Walvis Ridge area allowed the influx of saline waters from the southern South Atlantic. Erosion of the sediment provenance area during Syn-Rift I time resulted in a marked decrease of clastic input into basins at this time. A hot dry climate with high evaporation rates led to a stratified water column, and it has been proposed there were seasonal alkaline springs on the basin margins resulting in a high pH and phosphorous content. These conditions resulted in a high nutrient content that in turn supported a large, though limited, biomass. Saline bottom conditions resulted in permanent anoxia and very high preservation rates (Mello & Maxwell 1990). This combination of conditions produced world-class source rocks that form the primary pre-salt hydrocarbon source on both margins. At the same time some of the now flooded intra basinal highs were colonized and became shell banks. To the north of the recently breached Congo – Sao Francisco craton fresh water conditions prevailed indicating that it still exercised a strong control on depositional patterns.

During Syn-Rift IIb (late Barremian to early Aptian) uplift of the basin margins resulted in the deposition of massive amounts of clastic material, largely as fluvio-deltaic sediments. This is particularly marked in the Gabon and conjugate Sergipe Alagoas, and Camamu Almada basins. This may reflect the recent breaching of the craton and a little eroded clastic provenance.

A regional "break up" unconformity is documented in most basins during the early Aptian. This represents uplift of the basin margins prior to separation. Above this unconformity, in the early transition stage, lies a thin section of fluvial sands, lacustrine shales, and locally, restricted marine shales. It is possible that at this time limited extrusive volcanic activity started along the axial high.

During the main transition stage (middle to late Aptian) significant salt deposits formed from the Santos and South Kwanza basins in the south, to the Sergipe Alagoas and Rio Muni basins in the north. Marginal deposits include anhydrite, carbonates and organic rich shales. Evaporitic sediments are found as far north as the equatorial basins where they form important source rocks. Significant extrusive volcanic activity along the axial high is interpreted at this time. During, and immediately after, continental separation, the SDR were emplaced as thick wedges of extrusive lavas.

In the above evolutionary model we interpret that a variety of potential source sediments were deposited during the syn-rift and transition stages (Figure 6). Freshwater lacustrine shales were developed in narrow fairways along the axes of Syn-Rift I basins. Thick Syn-Rift IIa calcareous organic shales and marls were deposited under saline conditions above a marked internal syn-rift unconformity and form the richest pre-salt source rocks. Organic shales with saline affinities are also developed in the transition stage, but in basin margin positions.

The distribution of the best source rocks, thick Syn-Rift IIa sediments, bear a strong correlation to many of the most oil-rich basins in the South Atlantic (e.g. Campos, Espirito Santo, Congo). The more marginal producing basins (e.g. Sergipe Alagoas, equatorial basins) have thinner Syn-Rift IIa sediments and apparently must rely on transition or Syn-Rift I source rocks.

Seismic Examples

Excellent examples of the syn-rift section are available on seismic data from the southern Campos Basin (Figure 7). The data clearly show that the greatest development of Syn-Rift IIa strata is in the informally named Eastern Graben (Guardado et al, 2000). This area is likely the source kitchen for most of the hydrocarbons generated in the basin. This outer graben area continues considerably further to the southwest than many publications imply and thick Syn-Rift IIa source rocks are likely to be widely developed in the Santos Basin. Seismic data also implies their development in the Espirito Santo Basin. The excellent development of Syn Rift IIa section in the Congo Basin on the African margin gives encouragement that they may also be developed in the deeper water areas of the Bahia Sul basins on the Brazilian margin.

Conclusions

Source quality sediments are developed in both the syn-rift and transition stages. The high clastic content within the Syn-Rift I (late Berriasian to middle Barremian) freshwater lacustrine section diminishes the effectiveness of these sediments in most basins. Syn-Rift IIa (middle to late Barremian) calcareous organic shales and marls, that were deposited in broad saline lakes, form the richest pre-salt source rocks. They were deposited above a marked unconformity that marked a significant change in rifting styles, and this provides a good pointer for their recognition on seismic data, where imaging allows. Excellent examples of the syn-rift section are seen on seismic data in the southern part of the Campos Basin. The thickest development of these world-class source rocks is in the informally named Eastern Graben, which is considered the primary source kitchen for most of the hydrocarbons generated in the basin. Source quality shales also occur in the transition stage, but are developed in a basin margin position. They are significant contributors of hydrocarbons in the marginal and equatorial basins.

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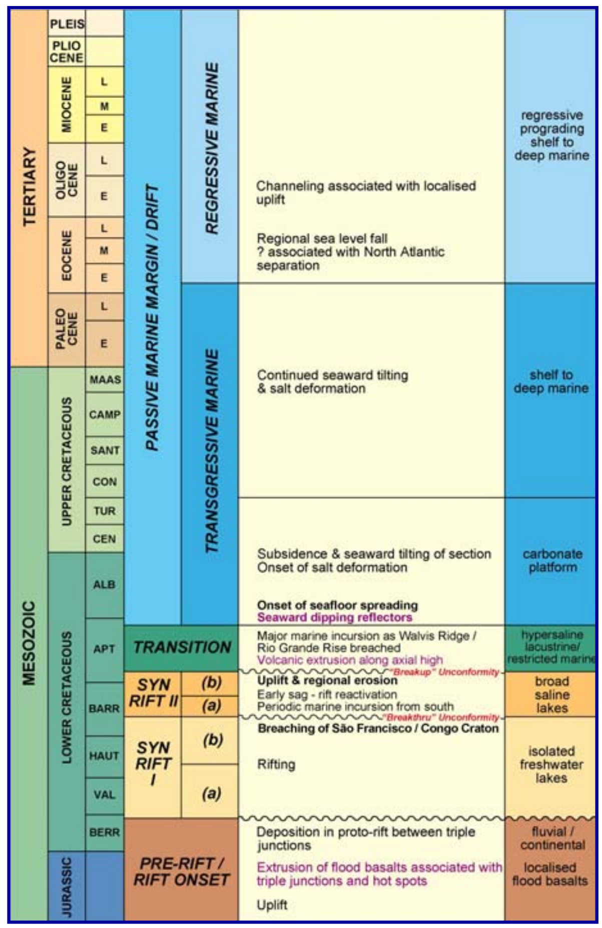


Figure 1.
Generalised chrono-stratigraphy showing four phases (Pre-Rift, Syn Rift, Transition and Drift) of evolution of central South Atlantic

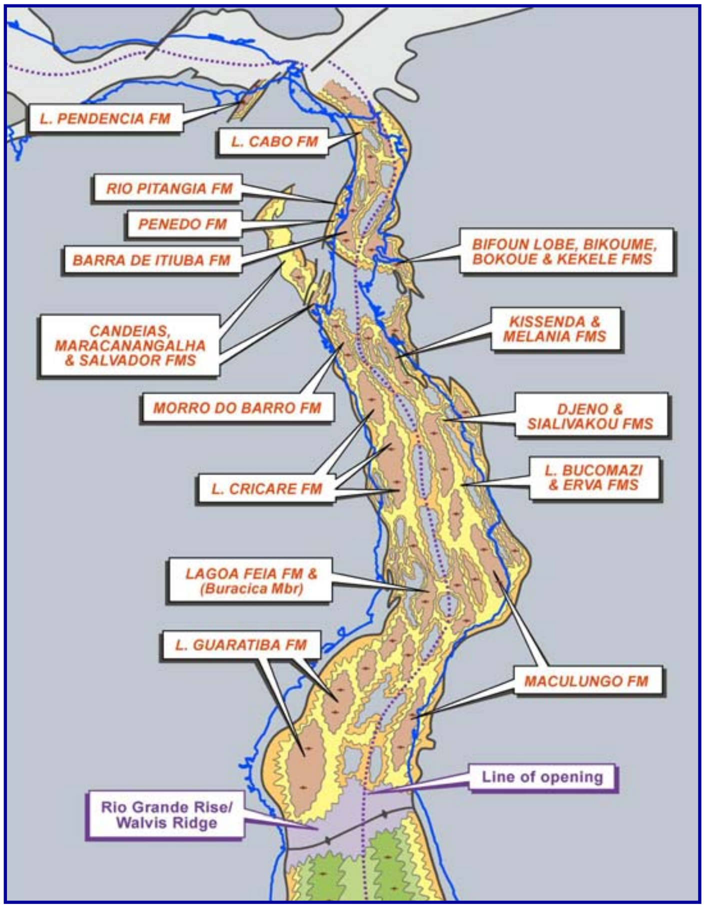
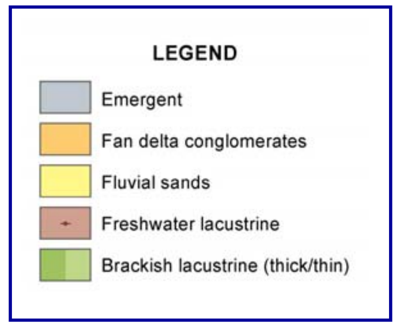


Figure 2.
Syn-Rift I (Late Berriasian – Middle Barremian) Paleogeography



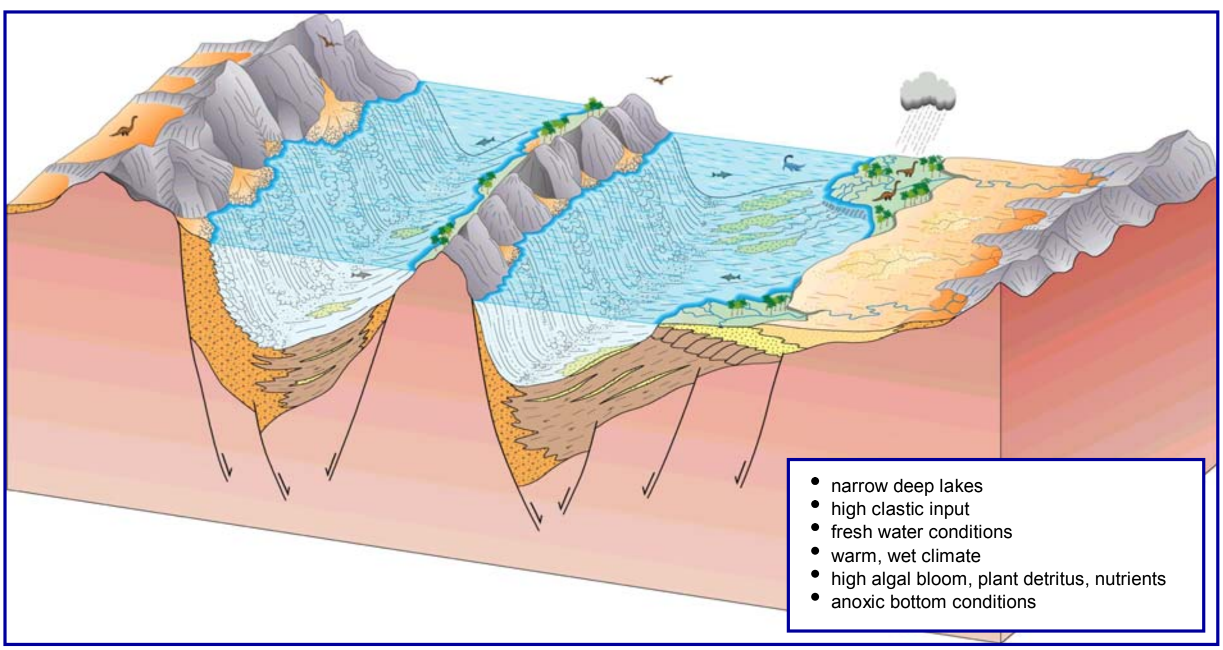
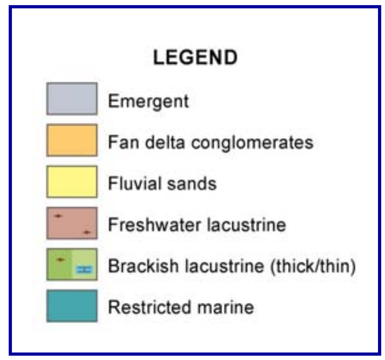


Figure 3. Syn-Rift I (Late Berriasian – Middle Barremian) Depositional Model

Figure 4.
Syn-Rift IIa (Middle – Late Barremian)
Paleogeography



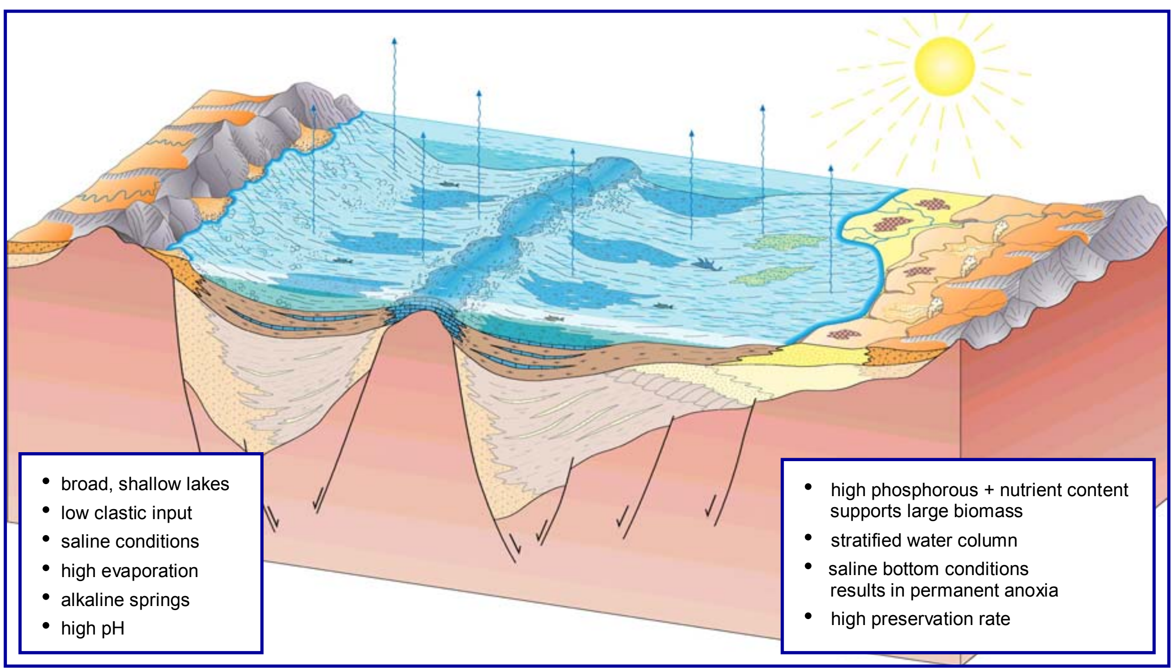


Figure 5. Syn-Rift IIa (Middle – Late Barremian) Depositional Model

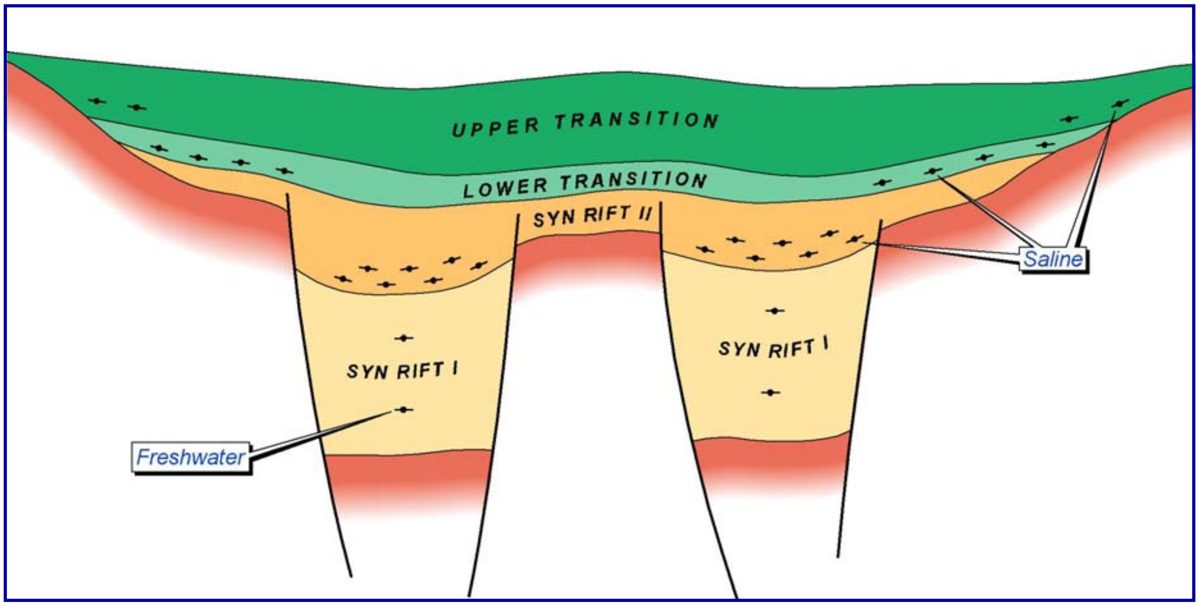


Figure 6. Syn-Rift Idealized Source Rock Distribution

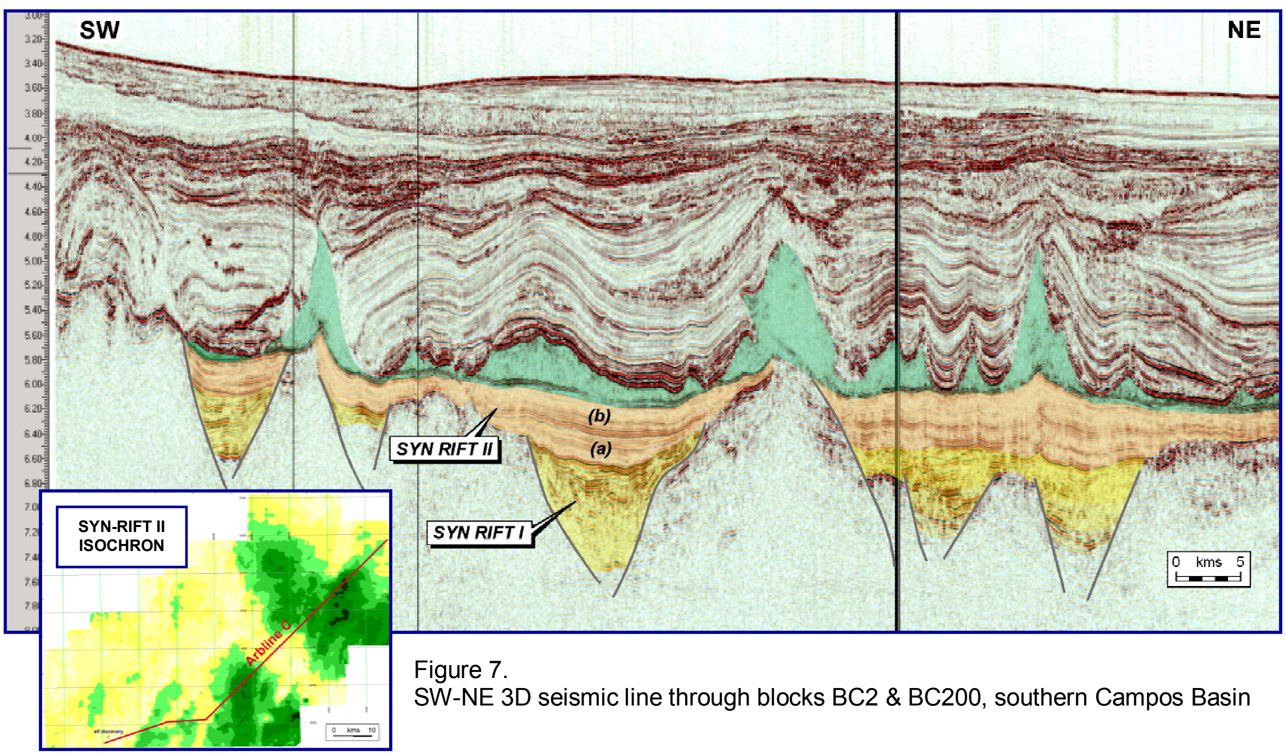


Figure 7.
SW-NE 3D seismic line through blocks BC2 & BC200, southern Campos Basin