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CRETACEOUS ANOXIC EVENTS IN THE SOUTH ATLANTIC

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ABSTRACT To characterize the anoxic events in Cretaceous series in the South Atlantic, detailed reinvestigations of biostratigraphy, organic geochemistry, and lithology were necessary. More than 2,000 samples from different DSDP sites were analyzed (Angola Basin: 364; Walvis Ridge: 363, 530; Rio Grande Rise: 356, 357; Cape Basin: 361; Maurice Ewing Ridge: 327, 330, 511). The chronostratigraphy was established elsewhere, and geochemical analyses were made by the Institut Français du Pétrole (total organic content, nature of organic matter, petroleum potential, maturity). The South Atlantic was affected by several events having global significance. Organic rich sediments were deposited on the Maurice Ewing Ridge as well as in the Cape Basin up to Early Albian and extended north of Walvis Ridge up to the Middle Albian. This period of anoxia also spread farther in the Magallanes Basin (Springhill formation of Hauterivian to Aptian age). Then oxidizing conditions were established from the Middle Albian and during Late Albian. This event, caused by a paleoceanographic change, could be equivalent to event E 1 in the North Atlantic (transition from Black Bahamas to Hatteras formations). Around the Cenomanian-Turonian boundary the oxic environment was interrupted by anoxic conditions which developed especially north of the Walvis Ridge and Rio Grande Rise. The Cenomanian-Turonian boundary event (CTBE), well known in the North Atlantic and the Tethys (event E 2), has a widespread distribution and is characterized by good preservation of marine organic matter, especially north of the Equatorial Fractures zone (Cape Verde Basin: Site 367). The presence of anoxia at Site 356 (Rio Grande Rise) shows that the CTBE occurred on the western as well as on the eastern margins of the South Atlantic. During Senonian times the environment again became oxic. Only minor organic matter-rich sediments were found in the Coniacian. The first anoxic period was probably a consequence of a restricted environment at the beginning of the opening of the South Atlantic. After an oxic period, the second anoxic event (CTBE) involved processes on a larger scale going beyond the framework of the only South Atlantic.

RESUMO Detalhadas reinvestigações de ordem bioestratigráfica, litoestratigráfica e geoquímica orgânica, a partir de mais de 2.000 amostras provenientes do *Deep Sea Drilling Project*, permitiram caracterizar os eventos anóxicos ocorridos no Atlântico Sul durante o Cretáceo. Sedimentos ricos em matéria orgânica depositaram-se na cadeia Maurice Ewing e na Bacia do Cabo até o Eo-Albiano enquanto ao norte da Cadeia de Walvis esta sedimentação prosseguiu até o Meso-Albiano. Este período de anoxia também se espraiou pela Bacia de Magallanes (Formação Springhill de idade hauteriviana-aptiana). Condições oxidantes estabeleceram-se do Meso-Albiano ao Neo-Albiano. Este evento, causado por uma mudança paleoceanográfica, poderia ser equivalente ao evento E 1 no Atlântico Norte (transição da Formação Black Bahamas para a Formação Hatteras). Em torno do limite Cenomaniano-Turoniano as condições óxicas deram lugar a condições anóxicas, as quais se desenvolveram sobretudo ao norte da Cadeia de Walvis e da Elevação do Rio Grande. O evento concernente à passagem Cenomaniano-Turoniano (*Cenomanian-Turonian boundary event*, CTBE), muito conhecido no Atlântico Norte e Tethys (evento E 2), tem ampla distribuição e é caracterizado pela boa preservação de matéria orgânica marinha, especialmente ao norte da Zona de Fraturas Equatorial (Bacia de Cabo Verde: *Site* 367). A presença de anoxia no *Site* 356 (Elevação do Rio Grande) mostra que o CTBE ocorreu tanto na margem ocidental como oriental do Atlântico Sul. Durante o Senoniano retornam as condições oxidantes. O primeiro evento anóxico foi provavelmente uma conseqüência de um ambiente restrito no início da abertura do Atlântico Sul. Depois de um período óxico, um segundo evento anóxico (CTBE) envolveu processos de larga escala, ultrapassando os limites do arcabouço do Atlântico Sul.

INTRODUCTION The aim of this paper is to characterize the periods favorable to the preservation of organic matter and the deposition of source rocks. A companion paper by Magniez & Muller provides revised biostratigraphical data which also allow correlation with anoxic events previously described in the North Atlantic (Graciansky *et al.* 1982, Herbin *et al.* 1982, Muller *et al.* 1983, 1984, Graciansky *et al.* 1985, Herbin *et al.* 1985).

Studied sediments are becoming from DSDP bore holes located on the various continental margins of the South Atlantic: Falklands Plateau (Sites 327, 330, and 551), Cape Basin (Site 361), São Paulo Basin (Site 356), Rio Grande Rise (Site 357), Angola Basin (Site 364), and Walvis Ridge (Site 530). Participation of the Institut Français du Pétrole in many Initial Reports of the DSDP gave the opportunity to analyse a great number of sedimentary sequences in these sites. Furthermore several stays at the Lamont Doherty Geological Observatory have enable us to describe and resample the entire Cretaceous series in the South Atlantic, i.e. about 1,500 m of cumulated series of Jurassic to Santonian age. In spite of their high petroleum potential, the analyzed black shales are immature source rocks as a

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consequence of their shallow burial. But in an other structural situation, below a thicker sedimentary column, such rocks could have given oil. So it is important to forecast their spreading in time and space. Moreover a model to explain the widespread occurrence of these black shales during Mesozoic times neither can be established without exactly knowing where, when and how they were deposited. Last but not least, a paleogreographic study and a correlation between all the data available can show the distribution of the potential source rocks and differentiate local factors from global phenomena.

METHODOLOGY Geochemical characteristics and specifically the amount of total organic carbon (TOC) has been determined by a new methodology worked out for the Rock-Eval apparatus (Espitalié *et al.* 1984). Due to the large number of samples (about 2,000) and the very low quantities of material (only a few cubic centimeters) the Rock-Eval pyrolysis method (Espitalié *et al.* 1977) was used to determine the type of organic matter. Previous studies and contributions to the Initial Report of the DSDP (Leg 71, Deroo *et al.* 1983; Leg 1975, Deroo *et al.* 1984) have shown that a good correlation exists between data coming from Rock-Eval pyrolysis and an elemental analysis of the kerogen (Fig. 1). Three types of kerogen can be distinguished. Type I and II are related to lacustrine or marine reducing environments, and are derived mainly from planktonic organisms, whereas Type III comes from terrestrial plants transported to a marine or non-marine environment with a moderate level of degradation. Intermediate kerogens are common, particularly between Types II and III. They result from a mixture of marine and terrestrially derived organic matter (OM) or from biodegradation of marine OM (Tissot & Pelet 1981). A fourth type of OM is residual OM either recycled from older sediments by erosion or deeply altered by subaerial weathering (Tissot *et al.* 1979).

DISCUSSION In the present study five periods are distinguished in the Mesozoic history of the South Atlantic.

Late Jurassic During the Araucanian movements of Late Malm age preceding the continental break, organic rich sediments were deposited in various basins of the continental margins of Argentina, e.g. the Aguaba Bandera and Cerro Guadal formations which are the source rocks in the San Jorge and Waldes Basins (Urien *et al.* 1981).

In DSDP sites Upper Jurassic sediments have been recovered in the Falklands area (Sites 330 and 511). At Site 330 sediments directly overlying the metamorphic basement contain OM of terrestrial origin even with coal particles preserved (Cores 15 to 9). During the Oxfordian (Cores 8 to 4), an anoxic environment preserved the aquatic OM with up to 5% TOC and a hydrogen index (HI) reaching 450–550 mg HC/g TOC (Fig. 2). The same enrichment occurs in the sediments of Callovian-Oxfordian/Early Tithonian age from Site 511 (Cores 70 to 63). The petroleum potential of these sediments is rather good (around 25 kg HC/t of rock).

Lower Cretaceous (Neocomian to Middle Albian) On the Falklands Plateau sedimentation of organic matter extended from Neocomian to Aptian–Early Albian

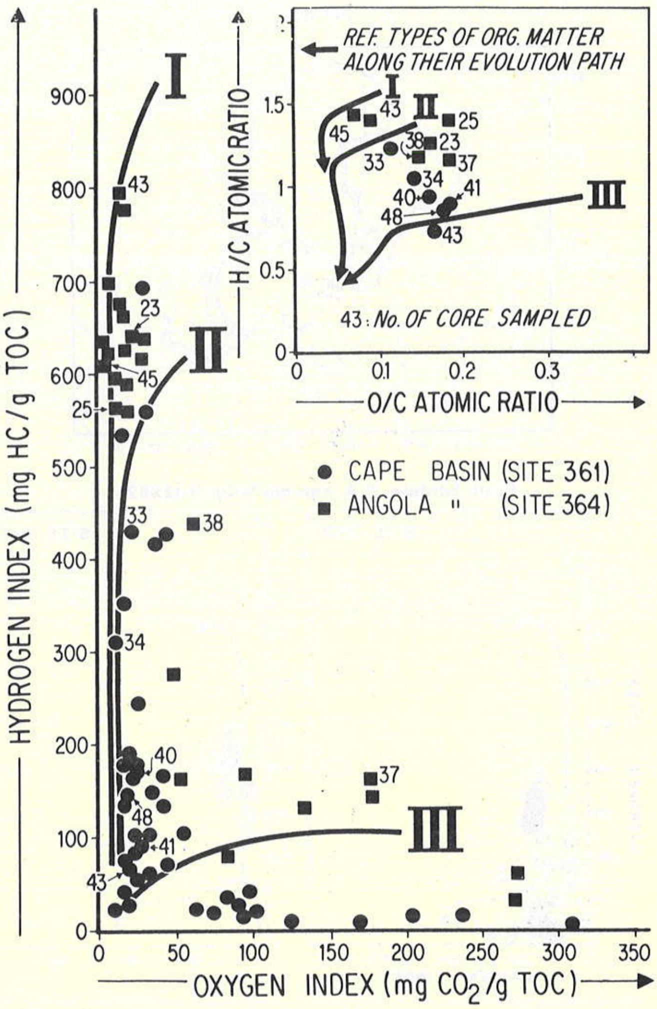

Figure 1 – Correlation between Rock-Eval pyrolysis data and elemental analysis of the kerogen in Site 361 (Cape Basin) and Site 364 (Angola Basin). Types I/II are related to lacustrine or marine reducing environments and are derived mainly from planktonic organisms, whereas Type III comes from terrestrial plants transported to a marine or non-marine environment. Below Type III, residual organic matter shows very low hydrogen indices

boundary. The black shales show the same enrichment in TOC as in the Jurassic series with a TOC content of about 6% and an HI reaching 600 to 700 mg HC/g TOC (Fig. 3). In the Cape Basin (Site 361, cores 28-48) they are richer in aquatic OM (up to 18% TOC) interbedded with turbiditic layers rich in terrigenous particles (3–25% TOC). North of the Walvis Ridge (Site 364, cores 30-45), the alternations of black shales and dolomitic limestone of Early to Middle Albian age overlie the evaporitic basal sequence. The dark levels are very rich in TOC (up to 29%) with an HI reaching 800 mg HC/g TOC (Fig. 3). The petroleum potential of these sediments is very good: from 30 to 150 kg-HC/t of rock. Anoxic conditions seem to have been the general feature of the South Atlantic during this period. They can even be extended towards the Pacific Provinces such as the Magallanes Basin where the Springhill Formation of Early Cretaceous age (Hauterivian to Aptian) is composed of black carbonaceous shales considered to be source rocks (Urien *et al.* 1981).

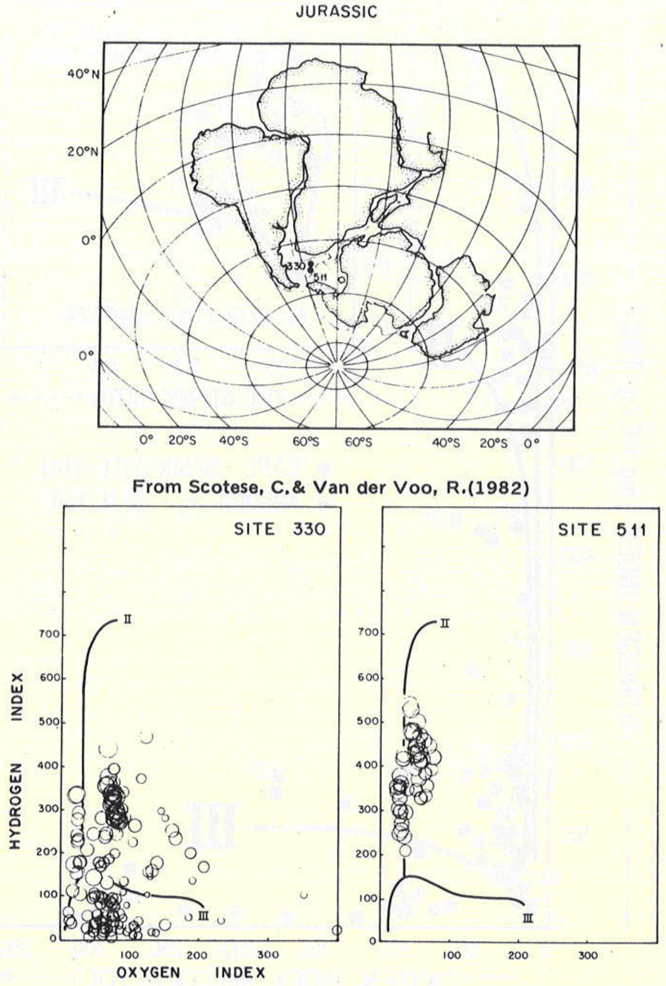

Figure 2 – Characterization of the organic matter from pyrolysis result for samples of Jurassic age in Sites 330 and 511. Size of the circles is proportional to the total organic carbon content

The end of anoxic conditions is underlined by a transition zone characterized by decreasing TOC (1–3%) with an OM of mainly terrestrial origin (the depositional conditions did not allow any preservation of aquatic OM) (Fig. 4). This transition zone indicates a progressive change towards an oxic environment. On the Falklands Plateau and in the Cape Basin, the end of the organic-rich sedimentation took place during the Early Albian (cores 58-56, Site 511 cores 23-22, Site 330; Core 27, Site 361). In the Angola Basin it occurred slightly later, i.e. Middle Albian (cores 37-38, Site 364), which indicates a short delay from the south to the north.

Middle to Late Albian This period is characterized by reddish-brown sediments interbedded with green claystones and marlstones. The whole series have low TOC (often ⩽ 0.2%) with very little residual OM (Fig. 5). For the first time since rifting, conditions were unfavorable for the preservation of aquatic and terrestrial OM. At Site 364 and at the bottom of Site 530, datings given by Magniez & Muller (1987) change the age of the black shales from Albian to Cenomanian. Thus they belong to the second anoxic event.

CENOMANIAN-TURONIAN (CONIACIAN) The second anoxic event, characterized by the reappearance of bl^ck shale sedimentation, raises a major problem for the paleogeographical reconstruction of the South Atlantic. After a general hiatus representing the Early-Middle Cenomanian and equivalent to the E 2 event in the North Atlantic (Muller *et al.* 1983), the Late Cenomanian and Early-Middle Turonian period is characterized by alternations of black shales and green claystones. This type of deposit occurred on the Brazilian as well as the African continental margins. The black shales are very rich in organic matter of aquatic origin (Fig. 6). On the São Paulo Plateau (Site 356), they content up to 15% TOC. In the Angola Basin (Site 364), they reach up to 29% TOC. The petroleum potential of these sediments ranges from 30 to 170 kg HC/t of rock. The high contents of aquatic OM indicate anoxic conditions whereas the presence of benthic foraminifers and burrowing in the grayish-green layers shows more oxidizing conditions.

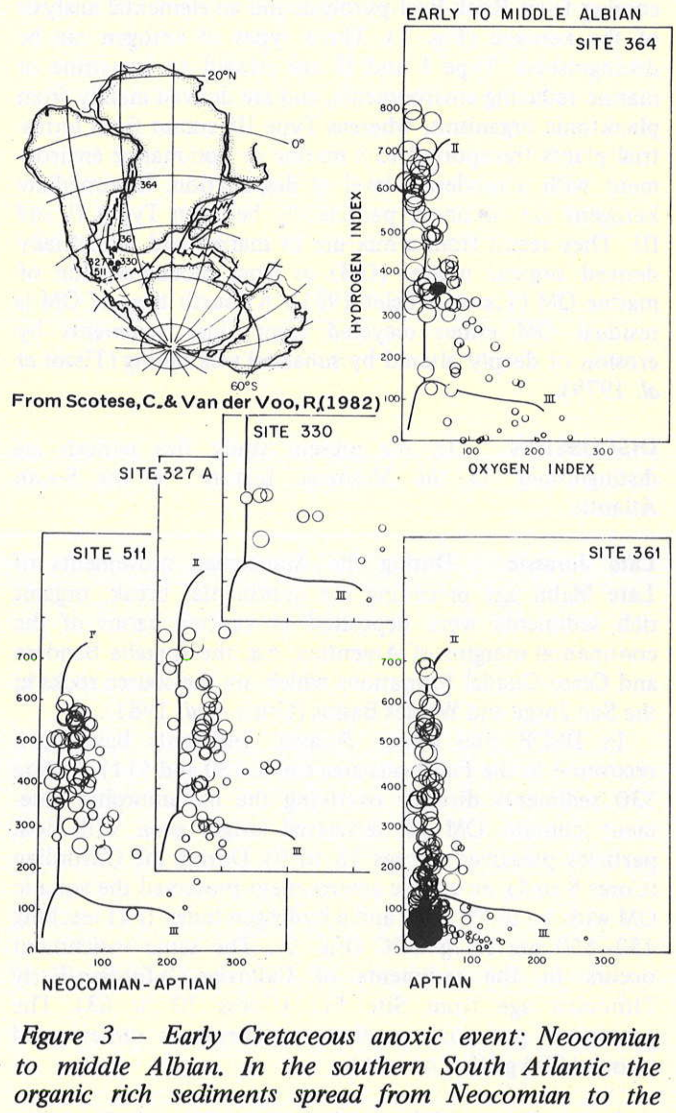

Figure 3 – Early Cretaceous anoxic event: Neocomian to middle Albian. In the southern South Atlantic the organic rich sediments spread from Neocomian to the Aptian-Early Albian boundary while in the northern South Atlantic (Site 364) they overlie the evaporitic basal sequence and last up to the middle Albian

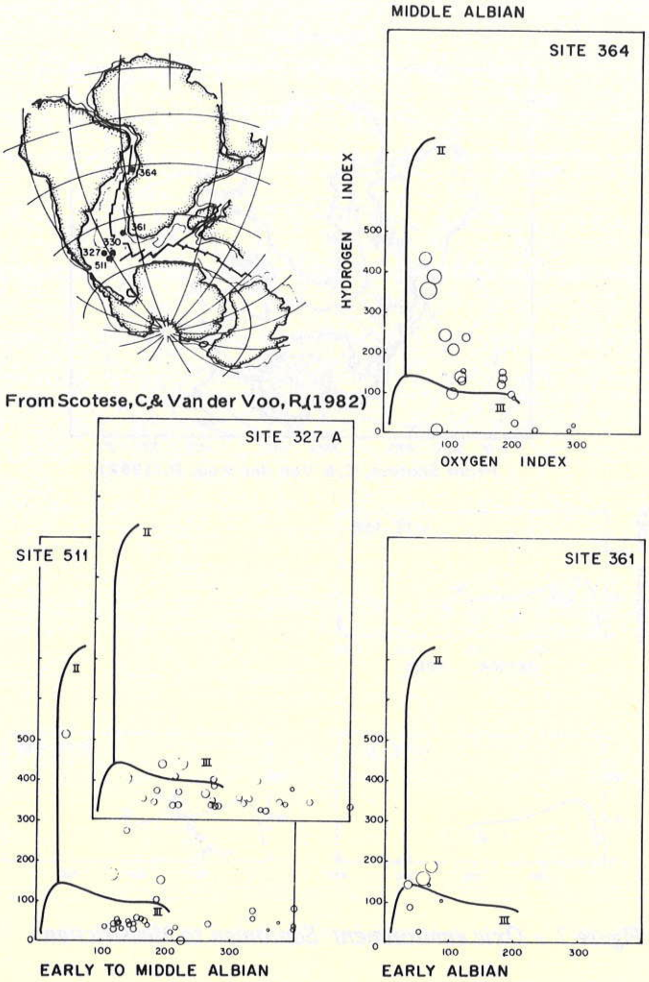

Figure 4 – Transitions zone: Early to Middle Albian. This period indicates a progressive change towards an oxic environment. It is characterized by decreasing TOC (1–3% with an OM of mainly terrestrial origin (the depositional conditions did not allow any preservation of aquatic OM). This transition zone occurred during Early Albian in the southern South Atlantic and Middle Albian in the northern South Atlantic.

Two explanations may be proposed: 1) the black mudstones were periodically reworked from anaerobic environment to aerobic one. However, the gradational contacts between oxic and anoxic layers do not suggest resedimentation. 2) The redox state in the bottom-sea waters changed episodically. *In situ* deposition and changes from oxic to anoxic conditions could explain such cycles. Moreover low accumulation rates matches better with *in situ* deposition rather than with turbiditic transportation.

Coeval OM rich sediments have been drilled on the Brazilian shelf. The marine shales of Cenomanian to Coniacian age in the southern Santos Basin contain 1-2.5% TOC (Gibbons *et al.* 1983). South of the Rio Grande Rise-Walvis Ridge, organic rich sedimentation has not yet been recovered. On the Falklands Plateau a hiatus which lasted Cenomanian and Turonian times prevents any study of the anoxic event. On the other hand, in the Cape Basin, sediments of Turonian age contain a relative enrichment (1-4% TOC) but OM is of detrital origin (HI ⩽ 100; Fig. 6).

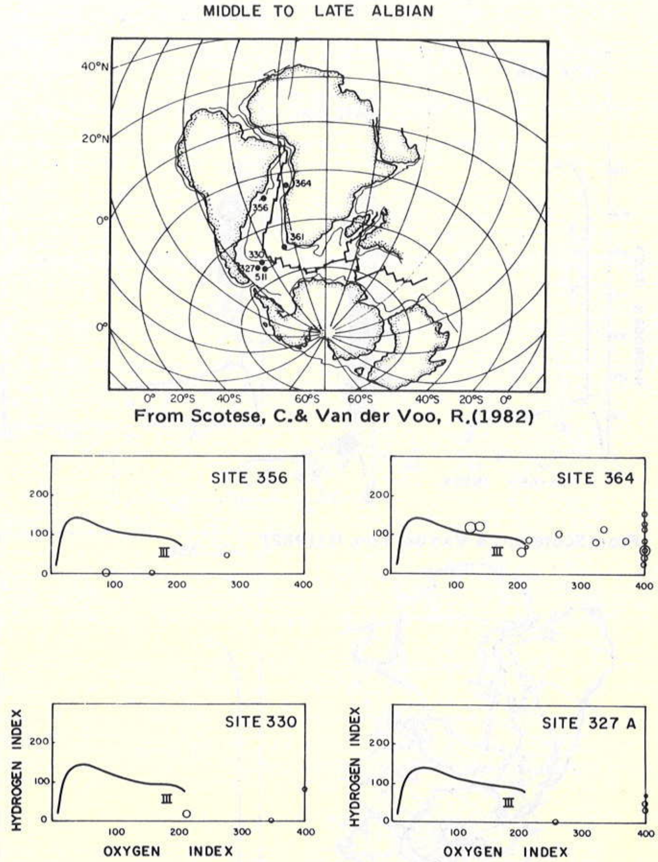

Figure 5 – Oxic environment: Middle and Late Albian

The occurrence of terrestrial OM in the southern South Atlantic is similar to what is known in the northern North Atlantic (e.g. Celtic Margin: Site 551; Iberian Margin: Site 398; and Plenus Marl Formation in North Sea, Herbin *et al.* 1985) as if the aquatic OM was poorly preserved in the higher latitudes.

Santonian to Maastrictian Whatever the area studied is, this period corresponds to oxic sedimentation devoid of OM (⩽ 0.2% TOC) (Fig. 7).

CONCLUSION The Mesozoic history of the South Atlantic is characterized by two general anoxic events favorable to the deposition of OM rich sediments.

The first one lasted from the Early Jurassic to Aptian-Early-Middle Albian (Figs. 8 and 9) and was related to restricted physiography during the first stages of the continental break. Depositional conditions were probably similar to these in the East African rift system today, with transition from a brackish to a marine environment during Early Cretaceous times. After a transition zone characterized by terrestrial OM, oxidized sediments with residual OM were deposited during Middle and Late Albian times. This event might have been due to paleogeographic evolution linked to a change in plate movement between 107 and 111 My BP (Rabinowitz & La Brecque 1979). Indeed, prior to the Late Aptian, the spreading rate was approximately 1.3-1.5 cm/yr in the region now located at 45ºS while it increased to 3.4-3.5 cm/yr after. The widening of the South Atlantic could explain the disappearance of restricted conditions from Middle Albian times.

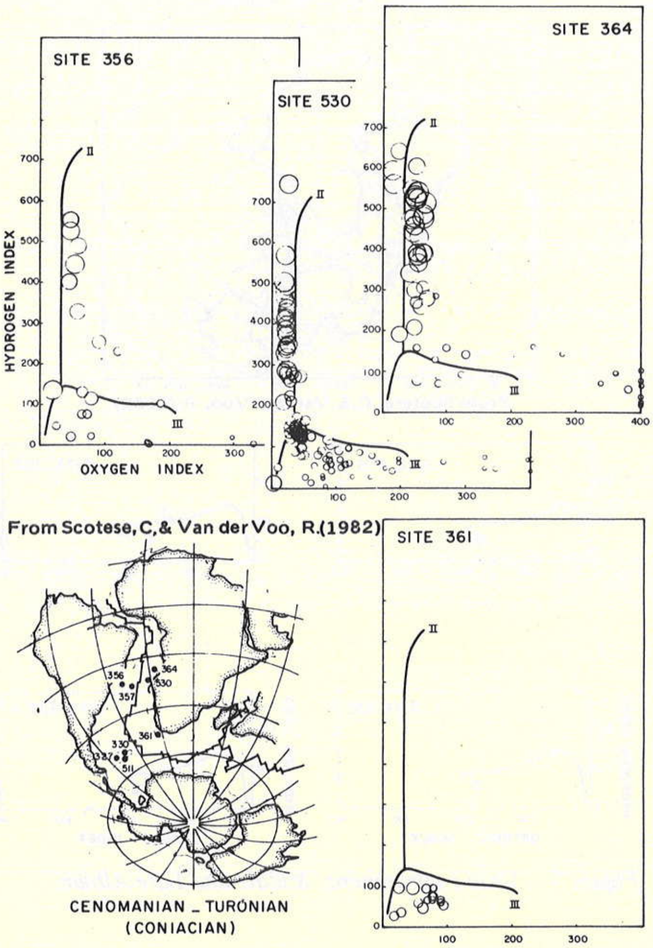

Figure 6 – Late Cretaceous anoxic event: Cenomanian-Turonian/Coniacian. The organic rich sediments spread on the Brazilian as well as the African continental margins in the northern South Atlantic. On the Falklands Plateau a hiatus prevents any study of the anoxic event. In the Cape Basin sediments of Turonian age contain a relative enrichment of terrestrial OM

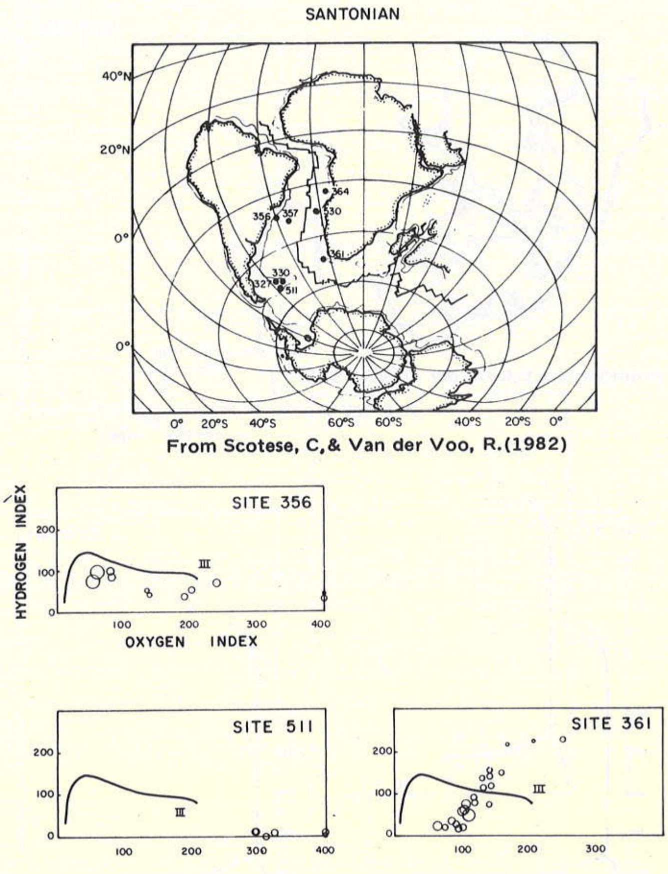

Figure 7 – Oxic environment: Santonian to Maastrictian

The Cenomanian-Turonian (Coniacian) anoxic event occurred during the period of rapid drift (3.4-3.6 cm/yr), halting the previously oxic sedimentation of the Middle/Late Albian. Deposition of black shales extending from Late Cenomanian to Middle Turonian with few recurrences during the Coniacian is mainly found at low latitudes, north of the Rio Grande-Walvis Ridge (Figs. 8 and 9). Previous studies in the North-Atlantic have shown an enrichment of OM at the lower latitudes (Cape Verde Basin, Site 367; Casamance area; Venezuelan margin) (Herbin *et al.* 1985). The present data also suggest that preservation of the aquatic OM improved on both sides of the Equatorial fracture zones during the Cenomanian-Turonian.

Numerous models have been proposed to explain such organogenic sediments. They involve either an upwelling system with high primary productivity, formation of a local minimum-oxygen zone, and resedimentation of black shales in deep areas, high primary productivity linked to the large-scale transgression, or stratification of the water masses with the formation of dense warm saline bottom water resulting from climatic alternation between humid and arid periods. Each of these hypotheses stemming from present-day observations can explain local phenomena. But something more global must be considered to explain the widespread synchronous distribution of the organic rich sediments. For example, consequences of intense tectono-magmatic processes on the mid-oceanic ridge and the fracture zones, with high hydrothermal activity, in a basin undergoing a low rate of oxigen renewal in deep water, are misunderstood.

The proposal submitted by the French Committee of the ODP program, with the title *Paleocommunication between the North and South Atlantic Seas during the Cretaceous: Formation of the Atlantic Ocean* fully intends to obtain more data in the area located between the Angola Basin (Site 364) and the Cape Verde Basin (Site 367), which perhaps partly contains the key to the Cenomanian Turonian Boundary Event.

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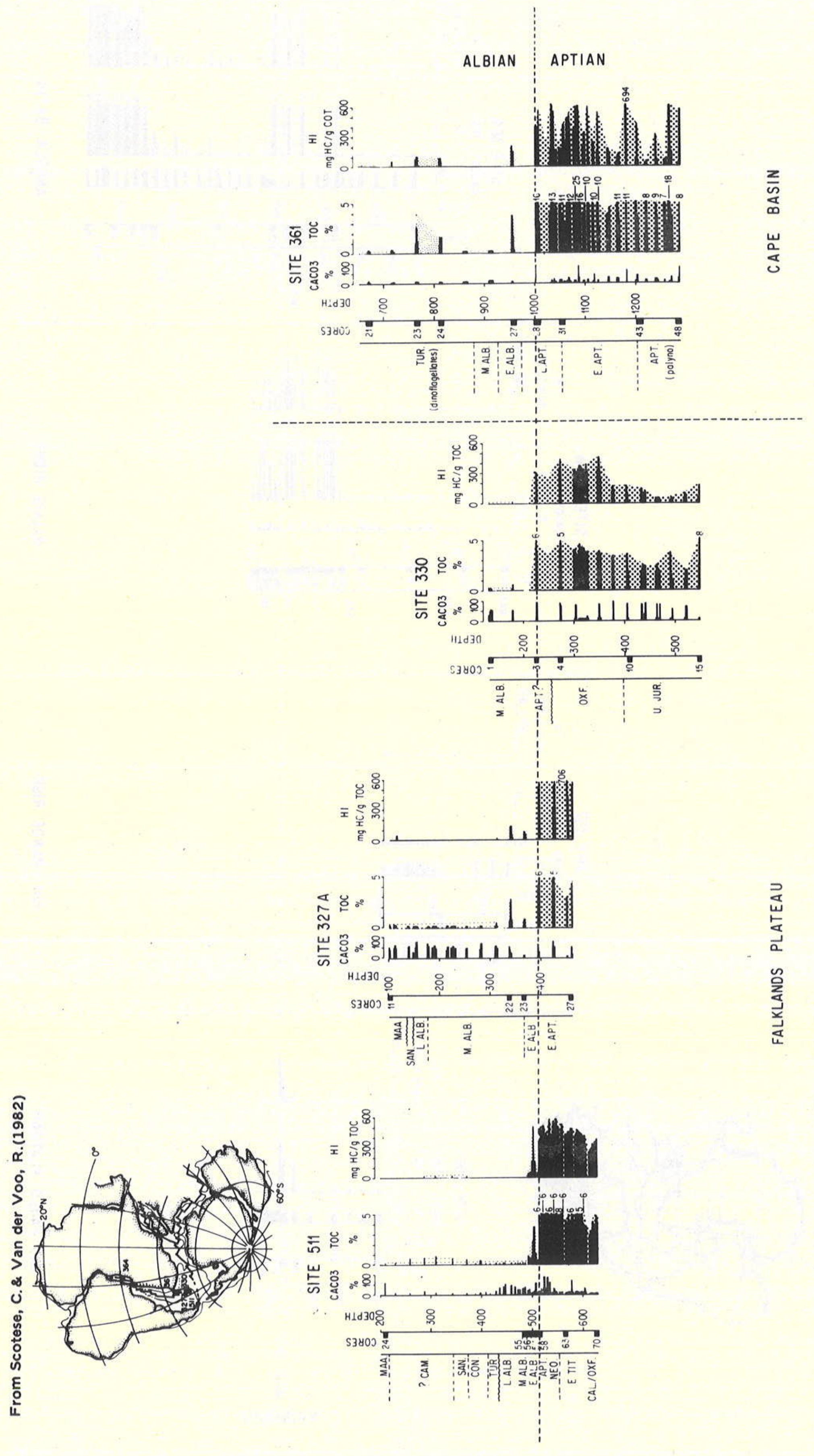

Figure 8 – Correlation of Early Cretaceous anoxic event in the southern South Atlantic (Falklands Plateau and Cape Basin). Log of carbonate and total organic carbon content with hydrogen indices

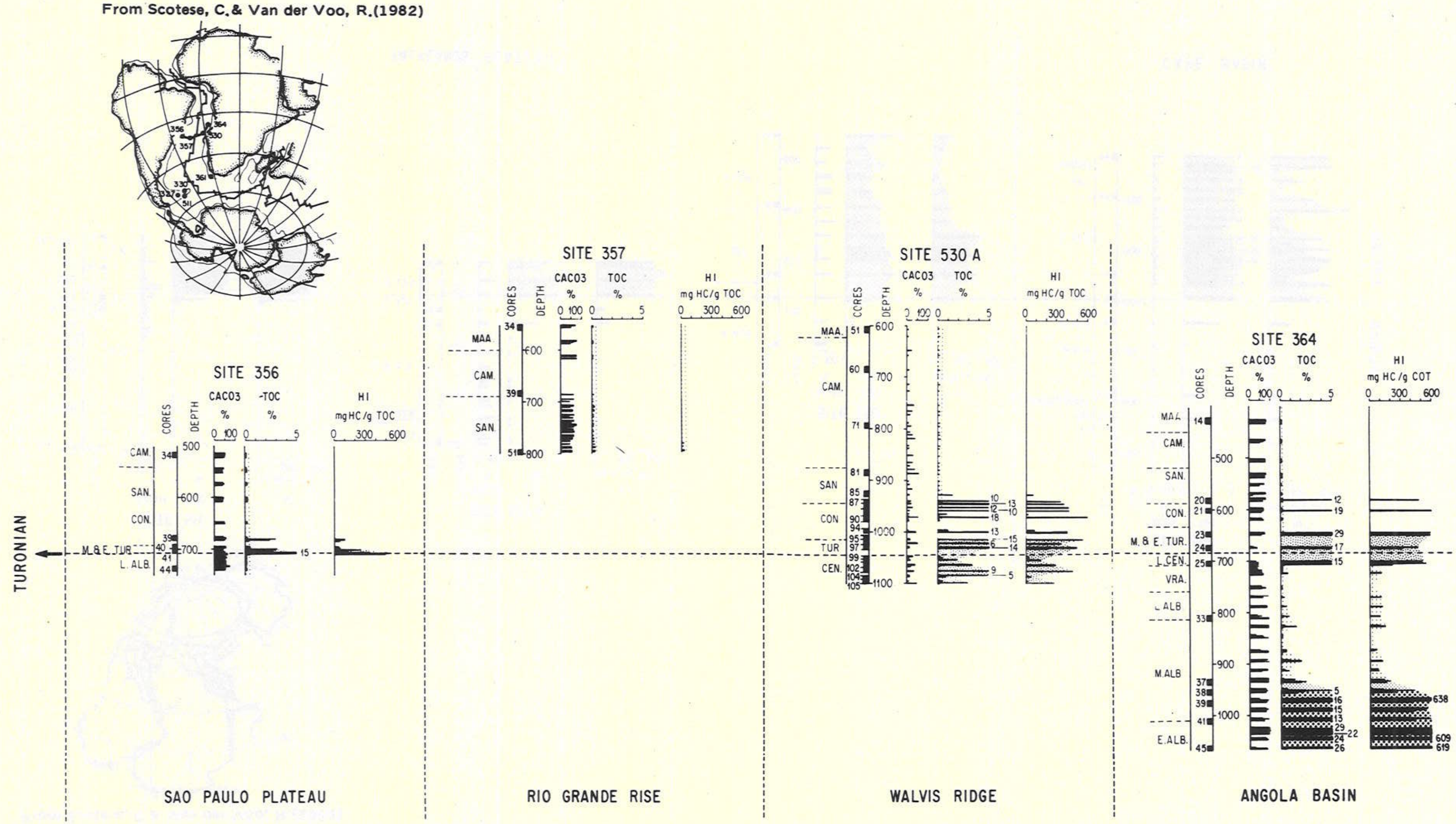

Figure 9 – Correlation of the Cenomanian-Turonian anoxic event in the northern South Atlantic (São Paulo Plateau, Walvis Ridge, Angola Basin)

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... os géologos freqüentemente nada ganham pelas descobertas minerais, exceto satisfação profissional, que pode ser erodida se o processo de descoberta não é plenamente descrito pela imprensa.

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