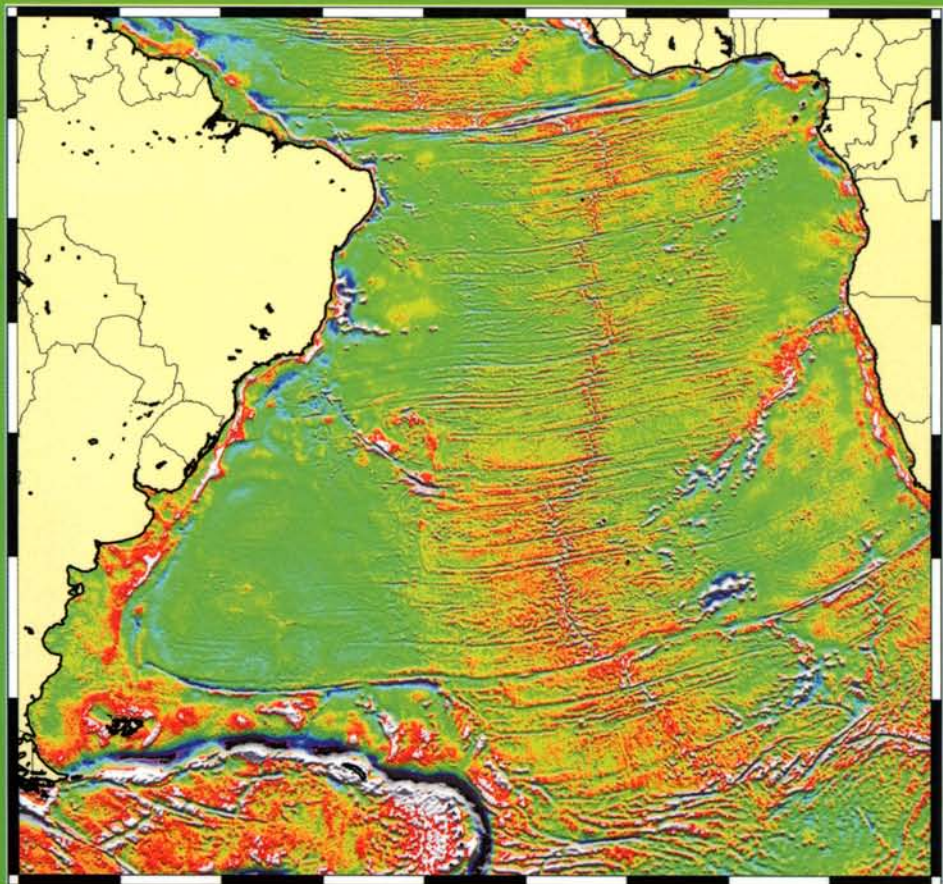


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Miocene benthonic foraminiferal morphogroups in an oxygen minimum zone, offshore Cabinda

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Abstract: Two hundred and seventy-eight benthonic foraminiferal species were recorded (126 agglutinating and 152 calcareous) from CABGOC 128-3, offshore Angola. This assemblage is comprised of a cosmopolitan fauna named the Agua Salada Fauna, known from the Caribbean, in the Vienna Basin, West Africa, Libya and Borneo. The fluctuating relative abundance of benthonic foraminiferal morphogroups in combination with 'total organic carbon' (TOC) data is suggested to reflect variation in the intensity of the oxygen minimum zone as it steadily increases upwards. An infaunal agglutinated 'opportunistic' (*r*-selected) group moves from antiphase into phase with TOC upwards in CABGOC 128-3. A morphologically comparative calcareous group displays the opposite trend, moving from phase into antiphase with TOC data. Planispiral agglutinated foraminifera emulate the steady increase in TOC upwards in CABGOC 128-3. This group includes *Cyclammina cyclops*, previously only recorded in the Arctic. Elongate, flattened calcareous morphologies undergo a sudden expansion towards the top of the well and are apparently unaffected by TOC. This overall trend is supported by concurrent poor preservation amongst distinct calcareous groups susceptible to dissolution, as expected in an area of dysaerobic conditions. The disappearance of all agglutinated faunas in the late Miocene is considered to be a reflection of oceanographic change.

Miocene sediments of equatorial upwelling regions contain a distinctive assemblage of opportunistic (*r*-selected) agglutinated foraminifera termed the Agua Salada Fauna. First identified from the Oligocene–Miocene Agua Salada Formation of Venezuela, the Agua Salada Fauna is dominated by agglutinated foraminiferal morphogroups considered to be typical of modern dysaerobic environments (Kaminski *et al.* 1995; Kaminski & Kuhnt 1995), and identified by the presence of *Valvulina flexilis*. The Agua Salada Fauna, first named by Renz (1948), has received little attention over the last 50 years. Originally examined by Cushman & Renz (1941), and mentioned by Akers (1954), the Agua Salada Fauna was then re-evaluated by Blow some years later (Blow 1959). There has been some confusion owing to changes of lithological nomenclature in the type area of the Agua Salada Fauna (Renz 1959). However, since this early work the fauna has only received fleeting reference (Basou 1976; Diaz de Gamero 1997, 1985*a, b*) until the present day (Giffuni 1991; Moreno-Vaquez 1995; Kaminski *et al.* 1998).

The fauna has been identified from diverse sites. Kaminski *et al.* (in press) identified the fauna from the Miocene of the Gulf of Mexico and compared it favourably with types from the Smithsonian Institution, Libya, and the Sabah Basin. Basou (1976) identified elements of the Agua Salada Fauna from the Guinea Bay, off-

shore Sekonda Takoradi, Ghana, while Akers (1954), in his paper relating the ecological aspects and stratigraphic significance of *Cyclammina cancellata*, refers to the Agua Salada Fauna of Venezuela and *C. cancellata*'s bearing within it. Moy (1968) recovered elements of the fauna from Oligo–Miocene sediments of Libya and Hungary. Similarly, Ujiie (1970, 1979) identified elements of the fauna from the Miocene Sandakan Formation, North Borneo.

Geological overview

Cabinda is a small detached enclave of Angola that produces most of that country's oil. The Cabinda Basin, north of Angola, is a post-rift Tertiary sequence represented exclusively by Neogene sediments. To the south (Zaire–Kwanza Basin), there is a complete Tertiary sequence grading down to Palaeocene sediments (Brun *et al.* 1984). The area's mixed carbonate–clastic system renders log analysis problematic and hinders understanding in the area (Brown 1993). Typical fields are fault-bounded rafts with one or more rotated fault blocks, separated through gravity sliding on the underlying salt decollement (McHargue 1990; Spaw & Koehler 1981).

The CABGOC 128-3 well lies offshore Angola in *c.* 100 meters water depth at 5°48'S, 11°47'E (Fig. 1). The well recovered uppermost

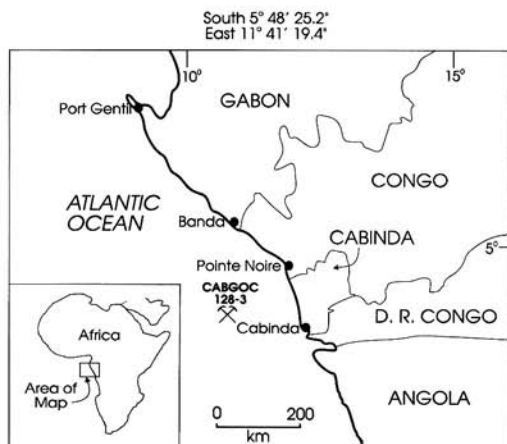


Fig. 1. Location map of CABGOC 128-3.

Oligocene–mid-Miocene lower slope laminated, fissile, silty shales containing the Agua Salada Fauna. The well is largely barren of planktonic foraminifera; similarly, calcareous nannofossil recovery is poor leading to extremely ambiguous age constraints.

The sedimentary basins of West Africa are bordered by the St Paul Fracture Zone to the north and the Walvis Ridge to the south. The African continent separated from South America in the late Jurassic–early Cretaceous, resulting in the production of a series of marginal basins: the Côte d'Ivoire–Ghana Basin; the Nigeria–Cameroon Basin; and the Gabon–Congo–Angola basins along the western African margin.

The geological history of these basins is intimately linked with the first period of rifting (Vale 1960). Alluvial and lacustrine sediments were deposited in grabens at the initial rift. The various basins then record slightly differing environments throughout the Mesozoic (Brun *et al.* 1984). The Gabon–Congo–Angola basins are characterized by Aptian lacustrine deposits corresponding to the initial period of rifting. This is succeeded by a transgressive sequence of carbonates of Albian–Turonian age, followed by a Cenomanian–Miocene clastic series.

Orogenic movements initiated in the Albian affected the Tertiary series, principally the Miocene of the Gabon and Angola basins. The movements resulted in local unconformities, isolated to individual subsiding basins accumulating Tertiary sediments. A following period of drift encouraged the development of a carbonate bank, this fragmented and eventually began to 'slide' on a Cretaceous salt decollement. The Albian–Turonian sequence of carbonates is succeeded by a Cenomanian–Miocene clastic series.

The Eocene is a regressive phase recognized in all the basins. The upper Oligocene is only identified locally (Brice *et al.* 1982).

Oceanographic overview

It is only during the past decade that physical oceanographical investigations performed over the continental margins on eastern oceanic boundaries have improved the understanding of coastal upwelling (Smith 1992). Despite the difference in their size, the tropical regions of the Atlantic and Pacific are primarily influenced by similar dominant dynamics – remote wind stress. In both oceans, equatorial undercurrents impinge their eastern boundaries and act in the formation, in the case of the Atlantic, of the Guinea and Angola Domes (Picaut 1985). However, published temporal and spatial data remain sparse offshore the Cabinda area.

The dominant oceanographic system in the South Atlantic is the South Atlantic subtropical gyre. On its eastern side it introduces northward flowing, cold, upwelled water to within 100 nautical miles of the west coast of South Africa and Namibia (Siesser 1980). This gyre is not the rectangular system often depicted, but an anticyclonic triangular gyre, confined to the southwestern Atlantic (Gordon & Bosley 1992; Peterson & Stramma 1991; Stramma 1991; Wacongne & Piton 1992). Its northeastern limb extends diagonally across the ocean from South Africa to Cabo San Roque. The northeastern South Atlantic circulates as a cyclonic gyre, implying that organic carbon and opal on the Walvis Ridge and southeastern Angola Basin could be advected from productive waters to the north. The South Atlantic surface circulation pattern and the southern hemisphere Neogene climate were both affected by the evolution of the southern Atlantic system. This, in turn, was largely driven by variations in the Antarctic ice mass. This system has gradually strengthened since the mid-Miocene and has gradually migrated northward from the Cape Basin in the south to the Walvis Ridge and Angola Dome to the north, in a series of small-scale cyclic north–south oscillations (Diester-Hass *et al.* 1990, 1992; Hay & Brock 1992). These oscillations were the product of varying Antarctic continental ice volumes.

The late Miocene was a time of major oceanographic reorganization marked by two important events. Firstly, a carbon isotope shift marks the onset of Messinian desiccation; secondly, Mediterranean isolation followed. Early in the Miocene, as the Arabian plate impinged on the Eurasian plate, the Mediterranean became cut-

off from the Tethys and Pacific Oceans. This forced the Mediterranean into a landlocked state that persisted until the late Miocene, when a connection was re-established between the Red Sea and the Indian Ocean in the south. This triggered the Messinian Salinity Crisis and the drying out of the Mediterranean, culminating in the deposition of massive evaporites.

The late Miocene is characterized by a sharp cooling, resulting in the strengthening of the thermocline and intensification of equatorial upwelling (Berger *et al.* 1981). There is evidence to suggest that the shift is intimately linked to changes in deep and bottom water production, and, in turn, a product of the isolation of the Mediterranean where it is a source of deepwaters. Simultaneously, the North Atlantic was becoming a source of deepwater, forcing a fall of the CCD and facies changes.

The Messinian Salinity Crisis, as a result of the isolation of the Mediterranean Basin and the formation of massive evaporite deposits, caused a substantial decrease in the salt content of the ocean and, in turn, facilitated ice build-up in the Antarctic. The pulsing discharge of heavy brine waters from the Mediterranean to the world's oceans led to oceanic stratification and a brief period of extreme carbonate dissolution in the latest Miocene.

Carbonate dissolution far above the CCD is a common feature of the south Atlantic system and is considered to be related to sea-level fluctuations and Antarctic ice extent (Diester-Hass 1988). Varying organic matter input, as a result of sea-level fluctuations, in turn a product of glacio-eustatic variation (the only major mechanism capable of forcing rapid worldwide sea-level fluctuations), effects carbonate dissolution.

Foraminiferal overview

Micropalaeontological investigations of the South Atlantic, and West Africa in particular, are reviewed by Jones (1996), while Reyment (1966) and refs therein provides an overview of earlier ideas. Hanse (1965) reviewed the microfauna of Angola, the benthonic fauna listed is very similar to the calcareous component found in the Cabinda Basin. The most comprehensive micropalaeontological report on West Africa, however, is still that of Kogbe & Me'hes (1986).

The majority of the pertinent foraminiferal work on West Africa has been completed by a small group of individuals. Seiglie & Frost (1979) identified the significance of mid-Tertiary larger foraminifera common to West Africa and the Caribbean, in addition, they reported observa-

tions upon species of smaller benthonic foraminifera and their cosmopolitan nature across the widening Atlantic. Cenozoic West African Tertiary agglutinated foraminifera became the focus of attention in the 1980s (Seiglie & Baker 1983; Seiglie *et al.* 1986) and, more recently, Haman *et al.* (1993) reported a new species of *Virgulinitella* from the Miocene of Cabinda. Finally, Cretaceous foraminiferal zonation of the Cabinda area is comparatively well studied with reference to sea level (Seiglie & Baker 1982), and facies and morphogroups (Dignes 1995, 1996).

Materials and methods

One hundred and seventy-eight continuous 60 ft composite ditch cutting samples spanning the Neogene were processed for foraminifera, and picked and counted for benthonic species. Preservation was often poor, many species being heavily resiliocified and internally filled with diagenetic pyrite. Following Jones & Charnock (1985) the agglutinated data were divided into seven morphogroups: A = unilocular/multilocular, tubular or branching; B¹ = unilocular, globular; B² = unilocular, multilocular, flattened; B³ = multilocular, planispiral/trichospiral (most litooids); B⁴ = unilocular/multilocular, irregular, conical; C¹ = multilocular, elongate mixed growth; C² = multilocular, elongate, quinqueloculine/milioline (C¹ and C² were combined for the purposes of this study); and D = multilocular, trichospiral, conical. Following Bernhard (1986), the calcareous forms were divided into seven morphogroups, where: 1 = elongate, flattened, ovate to flattened in apertural view, parallel to subparallel sides, biserial, lanceolate and palmate; 2 = tapering or flaring, circular in apertural view, tapering sides, triserial and multiserial; 3 = cylindrical group, circular in apertural view, parallel sides, uniserial; 4 = flattened, planispiral, discoidal, round peripheries; 5 = biumbilicate, planispiral, flattened; 6 = lenticular, biconvex, angled periphery, planispiral and coiled biserial; 7 = planoconvex, spiroconvex, umbiliconvex and trichospiral. CABGOC 128-3 contained no morphologies appropriate to Bernhard group 8. Of these groups, only agglutinated groups B⁴, C¹ and C², and calcareous groups 1 and 2 proved to be significant. For the purposes of this study, groups C¹ and C² are presented together as one group.

Opportunistic foraminiferal species are considered, in this study, to be members of agglutinated morphogroup C. Kaminski (1988a) and Kaminski *et al.* (1988, 1995) identified modern

members of this 'deepwater agglutinating foraminifera' group in the Panama Basin as infaunal opportunists (*r*-selected), capable of recolonization and tolerant of low O₂. They were characterized as small, tapered and elongate morphotypes such as *Reophax* and '*Textulara*'. The full foraminifera dataset will be published elsewhere (Preece in prep.).

'Total organic carbon' (TOC) data were measured by Chevron Overseas Petroleum Inc., by high-temperature combustion using a Leco instrument.

Results

Analysis of 178m 60 ft composite ditch cutting samples from CABGOC 128-3 revealed a diverse assemblage of agglutinated and calcareous benthonic foraminifera known collectively as the Agua Salada Fauna. This included the distinctive variant species of *C. cyclops*, previously only described from the Arctic (McNeil 1988). Planktonic foraminiferal recovery was extremely poor, similarly calcareous nannofossils were rare and age constraints at CABGOC 128-3 remain ambiguous.

Two hundred and seventy eight benthonic foraminiferal species were recorded within mud chippings spanning a depth of 570–10160 ft. The agglutinating component comprises 126 species, including various members of the genera *Cyclammina*, *Haplophragmoides*, *Recurvoides*, *Reticulophragmium*, *eggerella*, *Karreriella*,

Reophax, *Textularia* and *Valvulina*. *Cyclammina* species include a variation of *C. cyclops* previously documented as an Arctic species (McNeil 1988).

Through applying the agglutinating morphogroups of Jones & Charnock (1985) and the calcareous groups of Bernhard (1986), a distinctive cyclicity emerges. Specific calcareous genera appear to reflect this in coincident calcite dissolution. An antiphase relationship between opportunistic infaunal species and TOC values is recorded.

The uppermost 26 samples were disregarded, as they contained low total abundance counts in comparison to the majority of samples in CABGOC 128-3 (Fig. 2). Diversity varies greatly, decreasing markedly toward the top of the well (Fig. 3). Downhole, the ratio of agglutinated taxa:calcareous taxa fluctuates greatly (Fig. 4). Three cycles of increasing dominance by agglutinated taxa are recognized in the well. TOC data also displays three maxima; the TOC profile is displayed on all of the morphogroup graphs.

This pattern of a peaked maxima is mirrored to the greatest extent by agglutinated morphogroup C, the sediment-dwelling infaunals (Figs 5 and 10). The relative frequency of multilocular elongate genera (including *Alveolvalvulina*, *Ammobaculites*, *Bulbobaculites*, *eggerella*, *Gravellina*, *Jarvisella*, *Karreriella*, *Martinottiella*, *Reophax*, *Subreophax*, *Textularia* and *Valvulina*) exhibit three repetitive cycles. This group, by far the most abundant overall in CABGOC 128-3, records a low relative abundance at the base of the well but becomes dominant in the three peaks

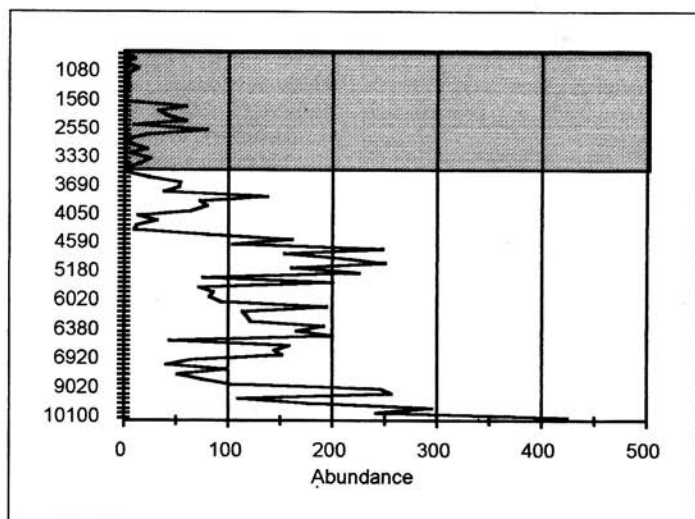


Fig. 2. Foraminiferal abundance curve at CABGOC 128-3 (the shaded area indicates samples of low total abundance which are not considered further in this study).

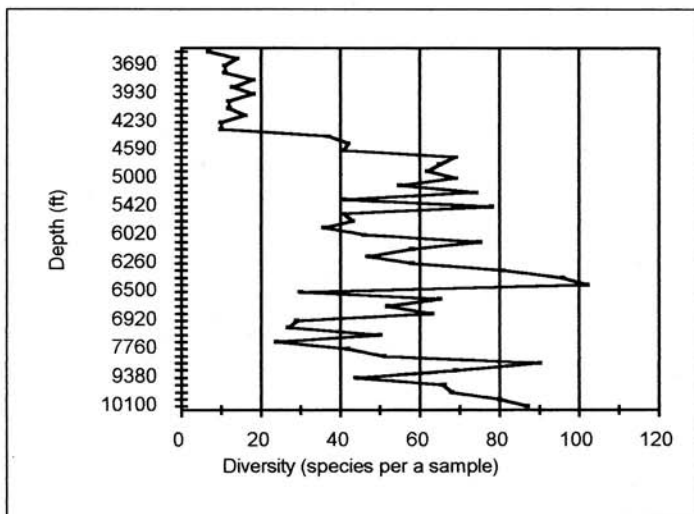


Fig. 3. Foraminiferal diversity at CABGOC 128-3 (species per sample).

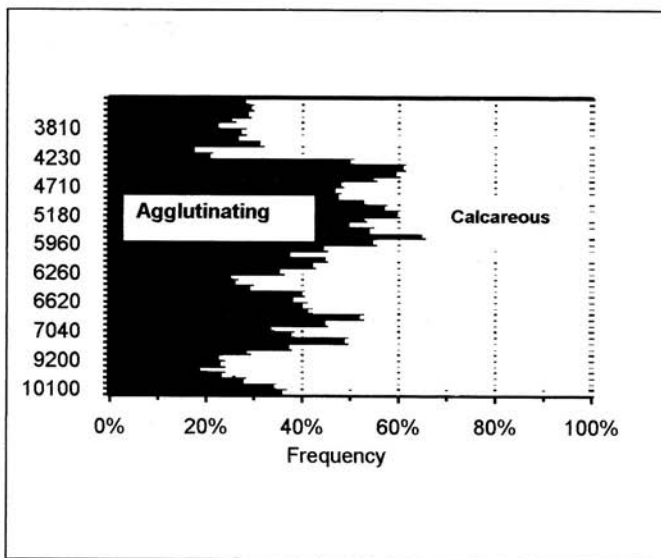


Fig. 4. Relative abundance of agglutinating to calcareous taxa at CABGOC 128-3.

increasing in dominance upwell. The cyclic nature morphogroup C is in antiphase with the TOC curve at the base of CABGOC 128-3, migrating into phase upwell.

Group B³ (Figs 6 and 10), the multilocular planispiral group, consists of the genera *Cribostromoides*, *Cyclamina*, *Discamminoides*, *Haplophragmoides*, *Reticulophragmium* and *Recurvoides*. This epifaunal group displays an increasing intensity 'sawtooth' pattern upwell, in

phase with TOC values. This group exhibits a prominent decline at the mid Miocene–upper Miocene transition.

Most calcareous genera show a constant frequency within CABGOC 128-3. However, morphogroup 1 (Figs 7 and 10), the elongate flattened, biserial, lanceolate and palmate forms (i.e. *Bolivina* and *Plectofrondicularia*), display a fluctuating low abundance until a sudden expansion coincident with morphogroup C's decline.

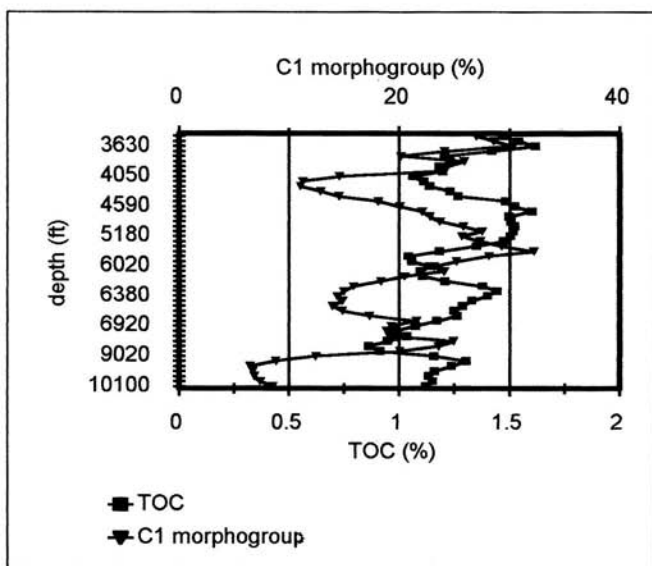


Fig. 5. Profile of morphogroup C (sediment-dwelling infaunal group) and TOC at CABGOC 128-3.

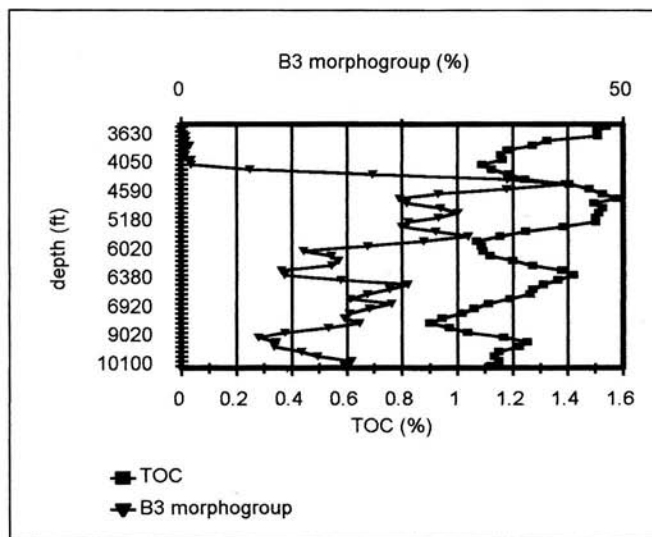


Fig. 6. Profile of morphogroup B³ (epifaunal agglutinated group) and TOC at CABGOC 128-3.

Morphogroup 2 (Figs 8 and 10), the tapering triserial and multiserial *Bulimina* and *Uvigerina* group, exhibit a triple pattern of increasing abundance similar to that of morphogroup C. This fluctuating frequency profile is an antiphase with agglutinated morphogroup C, and hence migrates from a phase relationship with TOC values into antiphase upwell. The magnitudes of

this group's profile and that of morphogroup C are comparable.

Species preserved solely as pyrite internal moulds (*Globobulimina perversa*, *G. ovata*, *Protoglobobulimina pupoides*, *Chilostomella ovidea*, *Vaginulopsis spinulosa*, *Valvulineria inequalis*, *V. palmerae*, *V. venezuela*, *Virgulina exilis* and *V. pontoni*) display a gradual fluctuating decline

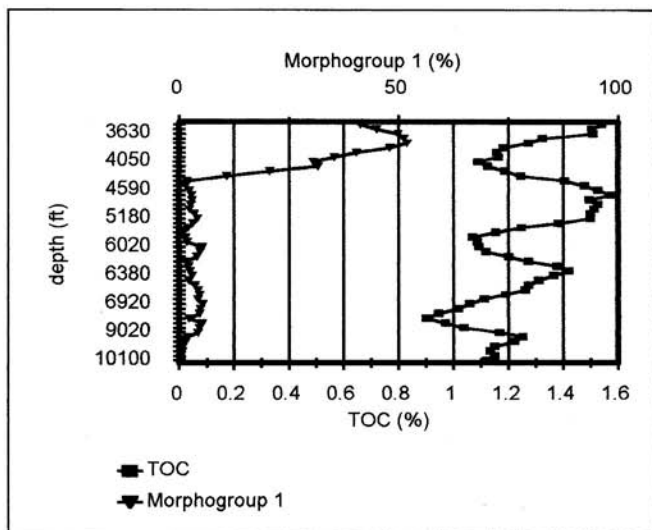


Fig. 7. Profile of morphogroup 1 (elongate flattened, biserial, lanceolate and palmate forms) and TOC at CABGOC 128-3.

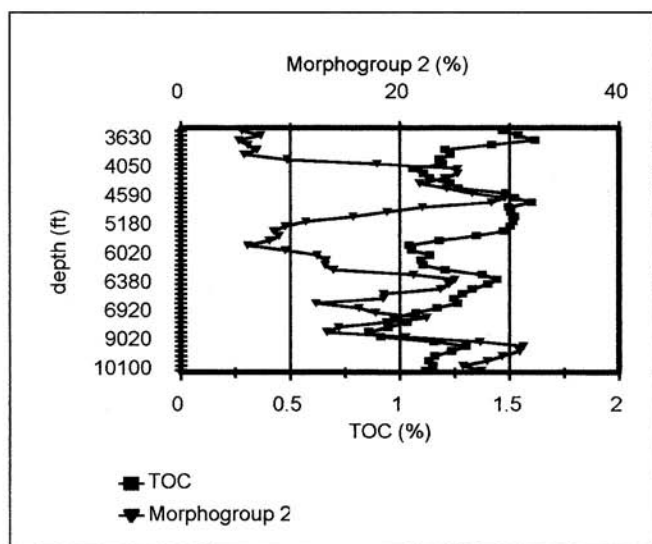


Fig. 8. Profile of morphogroup 2 (tapering triserial and multiserial group) and TOC at CABGOC 128-3.

upwards in CABGOC 128-3 (Fig. 9), until an almost complete decline at the top of the well.

Discussion

Morphogroup analysis reveals a distinctive cyclicity in CABGOC 128-3 well. This is postulated as reflecting the periodic intensification of

the local upwelling system, through the introduction of nutrient-rich waters to the surface, facilitating phytoplankton blooms, hence heightening the oxygen minimum zone upon their deposition and decay (Gooday 1988). High TOC values are interpreted as being indicative of increased surface productivity at CABGOC 128-3. The introduction of nutrient-rich upwelled waters to the continental margin expedites phytoplankton pro-

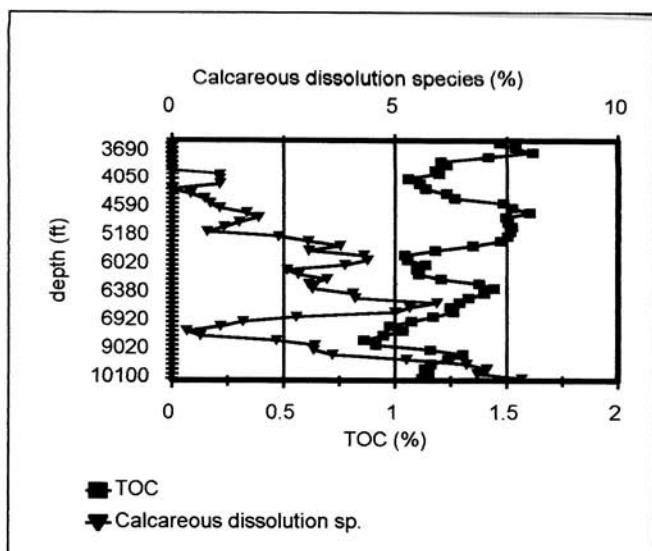


Fig. 9. Profile of genera susceptible to carbonate dissolution at CABGOC 128-3.

duction. This is essentially a function of upwelling rate and the nutrient concentration. Particulate organic matter descends through the water-column, utilizing oxygen as it is oxidized, thereby expanding the oxygen minimum zone (Demaison & Moore 1980; Southam *et al.* 1982). Hence, TOC values may reflect the intensity of the oxygen minimum zone at CABGOC 128-3. However, the response of the benthonic foraminiferal fauna to the upwelling proxy appears to shift with time upwell in CABGOC 128-3 from a food-limited environment to an oxygen-limited one (Jorissen *et al.* 1995).

Morphogroup analysis for ecological and palaeoecological interpretation is a useful tool. It is independent of species level taxonomy and is thus relatively elementary to translate from one worker to another. This approach permits comparison of assemblages of differing ages. The power of this relatively simple tool is demonstrated by the plethora of studies (e.g. Severin 1983; Katz & Thunell 1984; Jones & Charnock 1985; Bernhard 1986; Corliss & Chen 1988; Nagy 1992; Tyszka 1994). Here, the study is based on test shape, although successful work based upon wall composition and structure has also been conducted, e.g. Murray (1973).

Opportunism and morphogroup analysis has been extensively studied on modern foraminiferal faunas, however, these have concentrated mainly on calcareous forms. Hermelin & Shimmiel (1990) and Hemerlin (1992) isolated specific assemblages indicative of oxygen minimum zone conditions in the Arabian Sea, considered to be r-

selected. Sen Gupta & Machain-Castillo (1993) identified opportunistic species dominating low-oxygen environments; these species were observed as always being present in low numbers until adverse conditions predominated when they essentially 'bloomed'. In particular, they noted the predominance of elongate morphotypes (*Bolivina*) in low-oxygen conditions, but found no modern characteristic morphology indicative of poor oxygen levels. Similarly, Gooday (1993) identified modern abyssal calcareous opportunists. However, these were characteristically small, trochospiral with thin, transparent tests. These calcareous species are interpreted as being opportunistically adapted to seasonal food pulses (Smart *et al.* 1994). Infaunal taxa typified areas of intense upwelling off northwest Africa where food flux is more constant through time (Linke & Lutze 1993). Observed microhabitat preferences in living benthonic foraminifera showed a flexible approach towards food acquisition among specific faunas and were considered as opportunistic in life habit.

Kaminski *et al.* (1988, 1995) noted deepwater agglutinating foraminifera in modern seasonally dysaerobic environments to be dominated by tapered, elongate morphotypes. These were considered as infaunal and opportunistic in life habit and correlate to morphogroup C in this study. Similarly, Koutsoukos *et al.* (1990) noted elongate, tapered agglutinates in the latest Cenomanian-earliest Turonian of northeast Brazil and the Anglo-Paris Basin to proportionally increase in numbers with decreasing oxygen levels in an oxygen minimum

zone. Tyszka (1994) described Jurassic calcareous benthonic foraminiferal assemblages to decrease with interpreted falls in O_2 , while agglutinated, opportunistic faunas increased.

Through applying morphologic and taxonomic parameters upon benthonic foraminifera, Kaiho (1994) erected a dissolved oxygen index for palaeoenvironmental interpretation, although indexes have been developed using other aspects of the meiofauna, e.g. Wignall & Myers (1988).

The pattern of three maxima is demonstrated clearly by morphogroup C, the sediment-dwelling infaunals (Figs 5 and 10). Modern-day representatives of this group are regarded as opportunistic species (Kaminski & Kuhnt 1995; Kaminski *et al.* 1995) and are often interpreted as indicators of increased productivity in upwelling regions. However, at the base of CABGOC 128-3 they are in exact antiphase with TOC data, moving into phase towards the top of the well. This is regarded as a dynamic shift in environmental forcing from food acquisition to oxygen minimum zone limitation (Sen Gupta & Machain-Castillo 1993). Jorissen *et al.* (1995) define this interplay between food availability and O_2 concentration conceptually. This group is always present throughout CABGOC 128-3, increasing in dominance upwell. Towards the base of the well, abundant food supply is not coupled with low oxygen and the group is out competed by calcareous group 2. This group's opportunistic life habit becomes apparent upwards as oxygenation levels gradually fall, as expressed through increasing TOC values, and the group steadily migrates into phase with TOC. A sudden expansion of the oxygen minimum zone in the uppermost section of CABGOC 128-3 is expressed through morphogroup C's highest values.

The pattern displayed by calcareous morphogroup 2 (Figs 8 and 10) also displays three maxima, the peaks occurring between those of agglutinating group C, and hence in phase with TOC data at the base of the well, moving out of phase towards the top. To the authors' knowledge this is the only report of this juxtaposition of calcareous to agglutinated morphogroup data in combination with TOC values. Towards the base of CABGOC 128-3, morphogroup 2 maximize their food acquisition potential. As the oxygen minimum zone intensifies up well they become less dominant in a dynamic environmental forcing shifting away from food acquisition towards O_2 limitation (Sen Gupta & Machain-Castillo 1993; Jorissen *et al.* 1995) and migrate out of phase with TOC data. They suffer a dramatic decline in the uppermost part of the well coincident with group C's expansion and the sudden expansion and intensification of the oxygen minimum zone.

Group B³ (Figs 6 and 10), the epifaunal group, displays a gradual 'sawtooth' increase in dominance upwards in CABGOC 128-3. This group includes the distinctive variant species of *C. cyclops*, previously only described from the Arctic (McNeil 1988). This epifaunal group displays synchronized increases in frequency with TOC, thus implying an opportunistic life habit. They do not appear to be greatly affected by the gradual shift from food acquisition control to O_2 limitation, as experienced by morphogroups C and 2 in the Cabinda Basin. The sudden decline of this group in the uppermost part of the well (late Miocene) is coincident with the dramatic turnover experienced by the other two groups and it is postulated that this is in response to the sudden expansion and intensification of the oxygen minimum zone.

Morphogroup 1 (Figs 7 and 10) displays a sudden rise towards the top of CABGOC 128-3, having maintained a previously relatively low frequency. The genera within this morphogroup are typically small in size, have high surface area: volume ratios and are highly perforate. These are characteristics of forms adapted to dysoxic conditions (Corliss 1985; Sen Gupta & Machain-Castillo 1993). This 'bloom' is considered to reflect the sudden pronounced expansion of the oxygen minimum zone associated with late Miocene oceanographic reorganization. This group appears to be unaffected by TOC fluctuations.

Carbonate dissolution is a common phenomenon associated with high productivity zones. In CABGOC 128-3, the gradual intensification of the oxygen minimum zone is mirrored by the relative decrease in species preserved solely as internal moulds (Fig. 9). These species live infaunally, close to the redox boundary (Corliss & Emerson 1990), and are thus well adapted to low oxygen conditions. However, the sudden expansion and intensification of the oxygen minimum zone towards the top of the well severely affected this group, resulting in their disappearance. Post-mortem dissolution of other taxa is impossible to quantify.

Sedimentation rate is naturally also a controlling factor upon TOC accumulation. Lithologically, CABGOC 128-3 displays consistent laminated, fissile, silty shales and, hence, sedimentation rate is not considered to have varied greatly. The deepwater setting of CABGOC 128-3 is considered to negate any eustatic fluctuations experienced more acutely in shallower water. The nutrient content of the water mass is viewed as one of the primary factors that is capable of controlling TOC formation through the intensification of the local upwelling system. The lack of

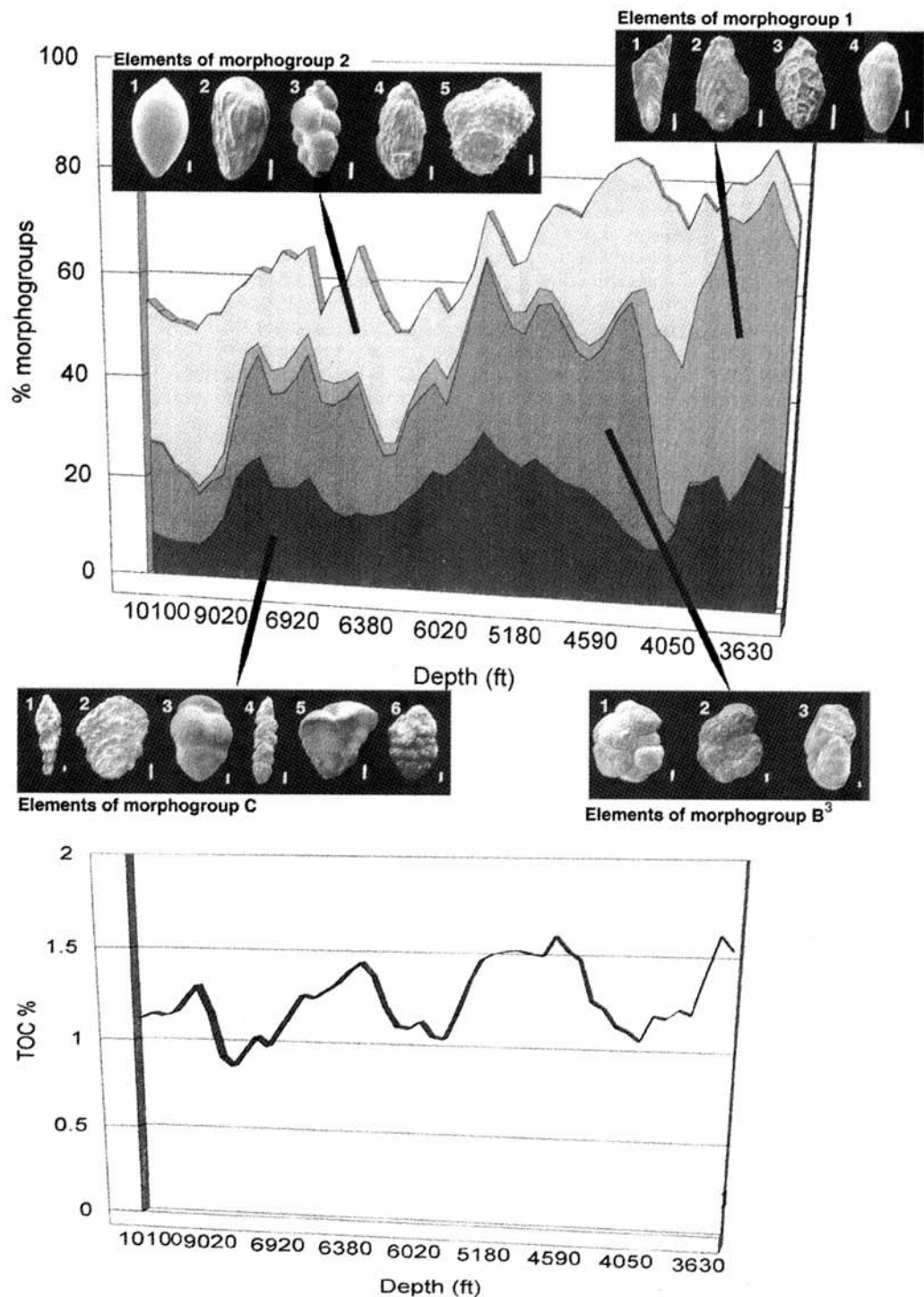


Fig. 10. Composite profile of morphogroup and TOC data at CABGOC 128-3, showing elements of morphogroups. Elements of morphogroup C: 1, *Reophax subfusiformis* Earland 1933; 2, *Pavontina styrica* Schubert 1914; 3, *Eggerella* cf. *bradyi* Cushman 1911; 4, *Karrerulina apicularis* Cushman 1911; 5, *Textularia* cf. *abbreviata*

age control in CABGOC 128-3 has rendered any sequence study impractical.

Elements of the discussed morphogroups are displayed in a composite cross-plot with TOC in Fig. 10. These data suggest that in the Cabinda Basin, a gradual intensification and expansion of the oxygen minimum zone is reflected through benthonic foraminiferal morphogroups. The groups display a migration away from food-limiting factors towards O_2 limitation. Other factors, such as pH, salinity, facies, food type and amount, etc., in addition to O_2 , may have some control on relative foraminiferal abundance, either individually or in combination. It is hoped that further investigations into the Agua Salada Fauna will elucidate this quandary.

Conclusions

The TOC profile at CABGOC 128-3 is considered to be a proxy for the local upwelling intensity in the Cabinda Basin. Upwelling forces phytoplankton proliferation and subsequent high accumulation rates of organic carbon. Oxidization of this particulate organic matter eventually leads to local dysoxic conditions.

Morphogroup analysis of a Miocene benthonic foraminiferal assemblage, coupled with TOC data, is presented as an approach for modern micropalaeontological and oceanographic study. At CABGOC 128-3 a gradually developing oxygen minimum zone is identified through morphogroup analysis. This undergoes a sudden expansion and intensification towards the top of the well in the late Miocene.

The elongate, agglutinated morphogroup (group C), considered to be opportunistic, is found to be in antiphase with TOC data at the base of CABGOC 128-3, becoming in phase towards the top. The morphologically comparative calcareous group (group 2) is in antiphase with group C and hence moves from in phase into

antiphase up CABGOC 128-3 with regard to TOC. This relationship is unprecedented within the foraminiferal literature to date, but is considered to be a reflection of an environmental shift migrating away from food as a primary limiting factor to O_2 .

Epifaunal, planispiral, agglutinated taxa (group B³) display a gradual increase in dominance up CABGOC 128-3. This group reflects TOC highs within its profile and, hence, it is inferred to be more opportunistic than previously assumed. Its sudden decline towards the top of the well is coincident with the sudden expansion and intensification of the oxygen minimum zone.

Small perforate calcareous taxa with a high surface area: volume ratio, regarded as being indicative of dysoxic conditions, exhibit a sudden increase in dominance towards the top of CABGOC 128-3. This is associated with a pronounced expansion of the oxygen minimum zone.

Calcite dissolution, as a result of acid pore waters in low oxygen conditions, is expressed by the preservation of susceptible species as internal pyrite moulds.

The dramatic decline of foraminiferal abundance within the upper Miocene of CABGOC 128-3 is regarded as a reflection of the late Miocene oceanographic reorganization. A refined stratigraphy for this area must be established before more precise timing can be determined. However, this remains problematic as planktonic foraminiferal and calcareous nannofossil recovery is extremely poor.

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d'Orbigny 1846; 6, *Valvulina flexilis* Cushman & Renz 1941. Elements of morphogroup B³: 1, *Haplophragmoides globigerinoides* Haeusler 1882; 2, *Reticulophragmium venezuelanum* Maync 1957; 3, *Cyclammina* cf. *cyclops* McNeil 1988. Elements of morphogroup 1: 1, *Plectofrondicularia longistriata* Le Roy 1939; 2, *Plectofrondicularia vaughii* Cushman 1927; 3, *Bolivina bryamensis* Cushman 1923; 4, *Bolivina tenuisstriata* Cushman & Ellisor 1939. Elements of morphogroup 2: 1, *Guttulina* sp. 1; 2, *Bulimina falconensis* Renz 1948; 3, *Uvigerina modeloensis* Cushman & Kleinpell 1934; 4, *Uvigerina peregrina* Cushman 1923; 5, *Uvigerina spinosa* Boersma 1984. Bar = 100 µm.

Appendix 1. Benthonic foraminiferal data for morphogroup analysis at CABGOC 128-3. (Overall totals include species not members of the four listed morphogroups.)

Well depth (ft)	Morphogroup C 26 Genera 64 Species	Morphogroup B3 9 Genera 23 Species	Morphogroup 1 2 Genera 16 Species	Morphogroup 2 11 Genera 42 Species	Overall Agglutinating Total	Overall Calcareous Total
	Total per sample	Total per sample	Total per sample	Total per sample		
3570	5	0	9	0	5	19
3630	9	0	22	6	9	45
3690	23	0	24	3	23	30
3750	10	0	19	2	11	28
3810	30	2	76	7	32	105
3870	18	1	36	6	20	53
3930	11	1	40	6	13	66
3990	25	0	28	1	26	38
4050	3	0	4	3	3	11
4110	4	1	11	10	5	26
4230	2	0	5	4	2	10
4290	1	2	3	2	4	6
4350	9	36	2	23	45	35
4470	28	74	0	27	104	57
4590	16	42	3	29	56	48
4710	55	62	4	90	121	127
4830	37	36	4	43	66	88
4950	46	58	9	52	100	111
5000	61	70	5	43	126	124
5120	44	61	3	27	102	59
5180	63	74	7	33	135	90
5300	22	16	4	3	39	37
5420	33	38	7	19	91	109
5540	22	25	0	9	43	29
5780	32	30	2	5	59	26
5900	27	32	0	7	53	29
6020	19	12	2	5	30	63
6080	53	22	6	30	81	113
6140	27	15	12	19	39	75
6200	32	34	1	11	71	47
6260	19	20	1	19	39	82
6320	30	20	5	36	42	149
6380	24	12	5	53	39	127
6440	26	33	1	52	64	136
6500	7	12	2	8	17	27
6620	27	48	1	43	80	78
6800	14	16	8	16	35	109
6860	29	34	10	26	67	84
6920	16	16	1	6	46	18
6980	10	11	2	10	20	21
7040	11	15	10	22	25	73
7160	12	9	0	12	19	33
7760	18	18	3	9	41	34
8180	30	12	3	9	52	50
9020	41	23	22	50	65	181
9200	25	30	4	65	55	201
9380	6	12	2	32	19	91
9920	14	22	2	54	51	125
9980	21	24	4	91	39	256
10040	17	55	0	66	76	166
10100	39	81	2	118	152	272

Appendix 2. Benthonic foraminifera species of morphogroups.**C Morphogroup**

Agglutinated sp. 2
 Agglutinated sp. 6
 Agglutinated sp. 7
Alveovalvulina suteri
Ammobaculites agglutans
A. sp. 1
A. sp. 2
A. sp. 3
A. sp. 4
Ammomargulina sp. 1
Bigenerina sp. 1
Bulbobaculites sp. 1
Eggerella cf. bradyi
E. forestensis
E. karamatensis
Gaudryina thalmani
Gravellina narivaensis
Jarvisella karamatensis
Karrerulina apicularis
K. cf. coniformis
K. conversa
K. horrida
K. microgranulosa
K. cf. microgranulosa
K. sp. 1
K. sp. 2
Liebusella pozonensis
Martinottiella cf. cyclostomata
M. sp. 1
Pavontina styrica
Pavopsammia flabellum
Pavonitina adanula
Pseudogaudryina alazanensis
Reophax acosta
R. dupex
R. subfusiformis
R. sp. 1
R. sp. 2
R. sp. 4
R. sp. 5
Spiroplectammia barrowi
Subreophax scalaris
S. sp. 1
S. sp. 2
Textularia cf. abbreviata
T. crassisepata
T. earlandi
T. isidroensis
T. kugleri
T. leuzingeri

Textularia mississippiensis
T. panamensis
T. pozonensis
T. tatumi
T. teasi
T. sp. 1
T. sp. 2
Textulariella barretti
Textulariaopsis sp. 1
Valvulina flexilis
Vermullina sp. 1
Vulvulina jacuraensis
V. pachyeilus
V. spinosa

B3 Morphogroup

Budashevella multicameratus
Cribrstromoides sp. 1
Cyclammia cancellata
C. cf. cyclops
C. placenta
C. prussila
Discamminoides tobleri
Haplophragmoides carinatum
H. emaciatum
H. globigerinoides
H. narivaensis
H. cf. narivaensis
H. obliquicameratus
Recurvoides contortus
R. higgins
R. obsoletum
Reticulophragmium
rotundirosata
R. venezuelanum
R. sp. 1
R. sp. 2
R. sp. 4
Spiropsammia primula
S. sp. 1

Morphogroup 1

Bolivina advena
B. alata
B. alazanensis
B. bryamensis
B. caudriae
B. cf. cochei
B. inconspicua
B. marginata var. multicosata
B. pisciformis
B. pozonensis

B. suteri
B. tenuisstriata
B. tongi
B. sp. 1
Plectofrondicularia longistriata
P. vaughi

Morphogroup 2

Bulimina affinis
B. cf. alazanensis
B. falconensis
B. inflata
B. inflata var. alligata
Protoglobobulimine pupoides
Buliminella cf. basistriata var.
nuda
Gumbelina cubensis
Guttulina irregularis
G. jarvisi
G. sp. 1
Pseudoglandulina comatula
P. incisa
P. laevigata
P. sp. 1
Siphogenerina lamellata
Siphogenerina smithi
Trifarina bradyi
Uvigerina altacostata
U. auberiana
U. cf. beccarii
U. capayana
U. carapitana
U. cf. hannai
U. hispida
U. laticulata
U. lirettensis
U. mantaensis
U. modeloensis
U. peregrina
U. pilulata
U. pigmae
U. proboscida
U. rugosa
U. rustica
U. spinosa
U. sp. 1
Uvigerinella sparsicostata
Virgulina exilis
V. pontoni
Virgulinea ossamagnifica

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