

NEOGENE BENTHIC FORAMINIFERAL BIOFACIES, PALEOBATHYMETRY, AND PALEOENVIRONMENTS OF A GULF OF MEXICO TRANSECT

MIRIAM E. KATZ^{1,*}, KENNETH G. MILLER², MICHAEL A. KAMINSKI³ AND JAMES V. BROWNING²

ABSTRACT

We document Neogene benthic foraminiferal biofacies changes on a depth transect of six Gulf of Mexico industry wells (sidewall and cutting samples) that is oblique to the coast and extends from Main Pass to Green Canyon (offshore Alabama to Louisiana, USA). Calcareous nannofossil and planktonic foraminiferal biostratigraphic control provides the framework to make interwell comparisons of the benthic foraminiferal biofacies; these comparisons provide the basis for paleobathymetric and paleoenvironmental interpretations and to identify useful benthic foraminiferal biostratigraphic markers in this region.

Benthic foraminiferal faunas indicate that Neogene paleodepths were slightly shallower at the eastern wells and deepened towards the western wells. Calcareous benthic foraminiferal biofacies dominated by *Uvigerina* spp. indicate that paleoenvironments characterized by low-oxygen conditions and/or high productivity occurred periodically during deposition along the transect. This is supported by repeated occurrences of a distinctive assemblage of agglutinated foraminifera (known as the “Agua Salada Fauna”) that is typical of dysaerobic environments.

Evidence of intensified low-oxygen/high-productivity environments are recorded in lowermost Middle Miocene sediments at some locations and are present at all wells in Upper Miocene deposits. In Upper Miocene-Pliocene sediments, oxygen levels appear to have been related to paleodepth, indicating that the development of lower oxygen conditions was the result of an expansion or migration of the oxygen minimum zone. Our results are consistent with a global cause for the expansion of the oxygen minimum zone during the Late Miocene and widespread increase in export production. Our study shows that despite problems in well cuttings (cavings, inconsistent sampling) and complications in regional salt and fault tectonics, well transects can provide coherent benthic foraminiferal biofacies patterns that reveal paleobathymetric and paleoenvironmental changes in the Gulf of Mexico.

INTRODUCTION

Benthic foraminiferal faunas have been used to assess paleobathymetry and paleoenvironmental parameters. Bandy (1960) advocated the idea that benthic foraminifera have distinct depth ranges, while Streeter (1973) and

Schnitker (1974) proposed that deep-water (>200 m) benthic foraminifera are associated with water-mass properties that may vary independently of depth. Subsequent papers have explored these ideas in detail in many regions (e.g., Lohmann, 1978; Corliss, 1979; Schnitker, 1979; Murray, 1984, 1995; Boersma, 1985; Miller & Katz, 1987; Mackensen et al., 1993; Schmiedl & Mackensen, 1997), including the Gulf of Mexico (e.g., Pflum & Frerichs, 1976; Denne & Sen Gupta, 1991, 1993; Jones & Sen Gupta, 1991).

Food availability, sedimentary organic carbon, and/or oxygen levels as primary controls on benthic foraminiferal distributions have been documented in numerous studies (e.g., Lutze, 1978; Schnitker, 1979; Miller & Lohmann, 1982; Boersma, 1984; Katz & Thunell, 1984; Thomas, 1986; Katz & Miller, 1987, 1993b; Corliss & Chen, 1988; Corliss & Emerson, 1990; Hermelin & Shimmiedl, 1990; Gooday, 1994; Rathburn & Corliss, 1994; Smart et al., 1994; Jorissen et al., 1995; Thomas & Gooday, 1996; Schmiedl et al., 1997, 2000; Gooday & Rathburn, 1999; Kaiho, 1999; Van der Zwaan et al., 1999; Morigi et al., 2001; Gooday et al., 2003; Jorissen et al., 2007; Kaminski, 2012; McGowran, 2012). In addition, benthic foraminiferal distributions may be affected by other factors, such as carbonate availability/corrosivity (e.g., Bremer & Lohmann, 1982; Mackensen et al., 1993, 1995; Schmiedl et al., 1997), substrate (e.g., Miller & Lohmann, 1982; Schmiedl et al., 1997), and surface-water productivity (e.g., Thomas & Vincent, 1987; Gooday, 1988; Loubere, 1994; Thomas & Gooday, 1996; Loubere & Fariduddin, 1999; Gooday et al., 2003; Jorissen et al., 2007; McGowran, 2012).

Physiochemical properties in the oceans vary spatially and temporally; as a result, benthic foraminiferal biofacies have migrated through depth and over time (e.g., Douglas & Woodruff, 1981; Tjalsma & Lohmann, 1983; Kurihara & Kennett, 1986, 1988, 1992), and the depth preferences of individual taxa have changed through time (e.g., van Morkhoven et al., 1986; Katz et al., 2003; Holbourn et al., 2013). In spite of the potential variables, benthic foraminifera have been used successfully to reconstruct paleobathymetry.

Tjalsma & Lohmann (1983) pioneered the calibration of benthic foraminiferal age-paleodepth changes using an independent means of backtracking paleobathymetry (Berger & Winterer, 1974). Their study focused on Paleocene and Eocene foraminifera in bathyal and abyssal sections from the Atlantic Ocean, Caribbean Sea, and Gulf of Mexico. Katz et al. (2003) applied similar techniques to Oligocene sections. Together, these two publications document changes in the distributions of Paleocene to Oligocene benthic foraminifera throughout the Atlantic Ocean. This technique was also employed by Woodruff (1985) and Woodruff & Savin (1989) to calibrate the depth distributions of Miocene benthic foraminifera in the Pacific Ocean. Once established, these paleobathymetric distributions can be used at locations

¹ Department of Earth & Environmental Sciences, Rensselaer Polytechnic Institute, 110 8th St., Troy, NY 12180, USA

² Department of Earth and Planetary Sciences, 610 Taylor Rd., Rutgers University, Piscataway, NJ 08854, USA

³ Geosciences Department, College of Petroleum Engineering & Geosciences, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia

* Correspondence author. E-mail: katzm@rpi.edu

where backtracking and/or backstripping are not readily applicable/available, with the caveat that the physiochemical properties that affect benthic foraminiferal distributions can vary independent of water depth (as discussed above). For example, Wood et al. (1985) used the age-paleodepth data of Tjalsma & Lohmann (1983) to estimate paleobathymetry in the Eocene to Oligocene sections of Barbados, and Katz & Miller (1993a) used the age-paleodepth data of van Morkhoven et al. (1986) to reconstruct paleobathymetric changes of carbonate platforms off the northeast Australian margin.

The Miocene sediments of the Gulf of Mexico contain a distinctive assemblage of calcareous- and organically-cemented agglutinated foraminifera that are collectively known as the “Agua Salada Fauna.” This assemblage, first described from the Upper Oligocene to Middle Miocene Agua Salada Formation of Venezuela (Cushman & Renz, 1941), is characterized by numerous agglutinated forms with complex inner structures. Although the systematics and evolutionary history of these alveolar forms are still poorly understood, it is generally believed that their evolutionary radiation represented an adaptation to life in an oxygen minimum zone (Cetean & Kaminski, 2011). The Agua Salada Fauna is dominated by tapered, elongated (presumably motile) forms that occur in dysaerobic environments. Many taxa have thin walls and/or alveolar inner structures, perhaps to facilitate gaseous exchange. Encrusting and presumed suspension-feeding forms are rare or absent. Elements of the Agua Salada Fauna, which typically contains specimens of the genera *Arenogaudryina* (= *Valvulina* in previous studies), *Alveovalvulina*, *Alveovalvulinella*, *Jarvisella*, *Popovia*, *Reticulophragmium*, and *Cyclamina*, have been found throughout the Caribbean (e.g., Cushman & Stainforth, 1945; Cushman & Renz, 1947, 1948; Renz, 1948; Bermúdez, 1949; Preece et al., 2000), Vienna Basin (Marks, 1951), and continental margin settings in West Africa (Seiglie & Baker, 1983; Preece et al., 1999; Kender et al., 2008; Cetean & Kaminski, 2011), including the Sirte Basin of Libya (Berggren, 1974) and the Sabah Basin off Borneo (M. Kaminski, personal observation). Therefore, the Agua Salada Fauna is cosmopolitan and may constitute a general indicator of Neogene increased organic productivity in upwelling zones that caused oxygen-deficient environments in upper bathyal settings along low-latitude continental margins (Kender et al., 2008).

In this study, we examine an oblique dip transect of six industry wells from the Gulf of Mexico for benthic foraminifera, with an emphasis on biofacies, stratigraphy, paleobathymetry, and paleoenvironments. We focus on the Neogene of the Gulf of Mexico that contains a thick record complicated by folds and faults due to sediment loading (growth faults) and salt tectonics (e.g., Weimer, 1989). The biostratigraphic framework of correlations and chronology used here was established in a concurrent analysis of calcareous microfossils in the same wells and on the same samples (Aubry et al., in press). This allows us to link together wells at the subseries level (e.g., Lower, Middle, and Upper Miocene), despite the tectonic complexities and attendant unconformities and hiatuses delineated in these wells (Aubry et al., in press).

Our objective is to evaluate paleoenvironmental changes across a broad swath of the Gulf of Mexico to determine the controls on these patterns (e.g., productivity, oxygen, water mass changes) and if regional (not just local) patterns can be discerned. In addition to providing constraints on the oceanographic evolution of the Gulf of Mexico, we aim to place further constraints on the stratigraphic and paleobathymetric ranges of benthic foraminiferal species. We outline the biofacies changes and identify ranges of key depth-diagnostic taxa in the six wells to estimate paleobathymetric and paleoenvironmental changes. In addition, we update information on biostratigraphically useful benthic foraminiferal markers in this region that are discussed in van Morkhoven et al. (1986).

MATERIALS AND METHODS

Samples were provided by a consortium of oil companies. The transect extends from Main Pass (offshore Alabama) to Green Canyon (offshore Louisiana) and includes wells from Chevron Main Pass Block 254, UNOCAL-Texaco Viosca Knoll Block 736, SOHIO Viosca Knoll Block 817, UNOCAL Mississippi Canyon Block 455, BP Ewing Bank Block 788, and Marathon Green Canyon Block 152 (Fig. 1). Present water depths range from 92–482 m (Table 1). The well transect examined here sampled Pleistocene through upper Oligocene strata, though our results focus primarily on the thick Neogene (Miocene–Pliocene) sections with common benthic foraminifera.

Site-to-site biostratigraphic comparisons reveal that sections vary in thickness and completeness (Aubry et al., in press). The shallowest section is the thinnest with the most complete Upper Miocene–Pleistocene record. The deepest section is the thickest, but has the least complete Pliocene–Pleistocene record. Unconformities associated with 1–2 Myr hiatuses vary little along the transect (see Aubry et al., in press, for chronology, distribution of unconformities, and allostratigraphy).

Both sample cuttings and sidewall samples were examined for this study. Sample cuttings were recovered from recirculated drilling muds, and may have mixed with material from above the sampled interval; therefore, only species highest occurrences (HO) within the wells and qualitative assemblage characterizations based on dominant taxa are reliable from cuttings samples. In contrast, sidewall samples are taken from known levels within the wells, making quantitative analyses possible using these samples. We studied cuttings samples from five of the six wells [sampling interval of 176–386 ft (53.6–118 m)]; therefore, these wells were examined qualitatively rather than quantitatively, and the biofacies associations described here are based on dominant taxa within each sample. We were able to conduct a quantitative study (taxon percentages) of sidewall samples from Chevron Main Pass Block 254 (Appendix 1). To be consistent with the other wells, we rely largely on biofacies from Chevron Main Pass Block 254 for our interpretations.

Washed sample residues were provided by the oil companies. Benthic foraminifera were picked from aliquots of the >150- μm size fraction and mounted on reference slides. Our benthic foraminiferal identifications (Table 2) follow the taxonomy of Boersma (1984), van Morkhoven et al.

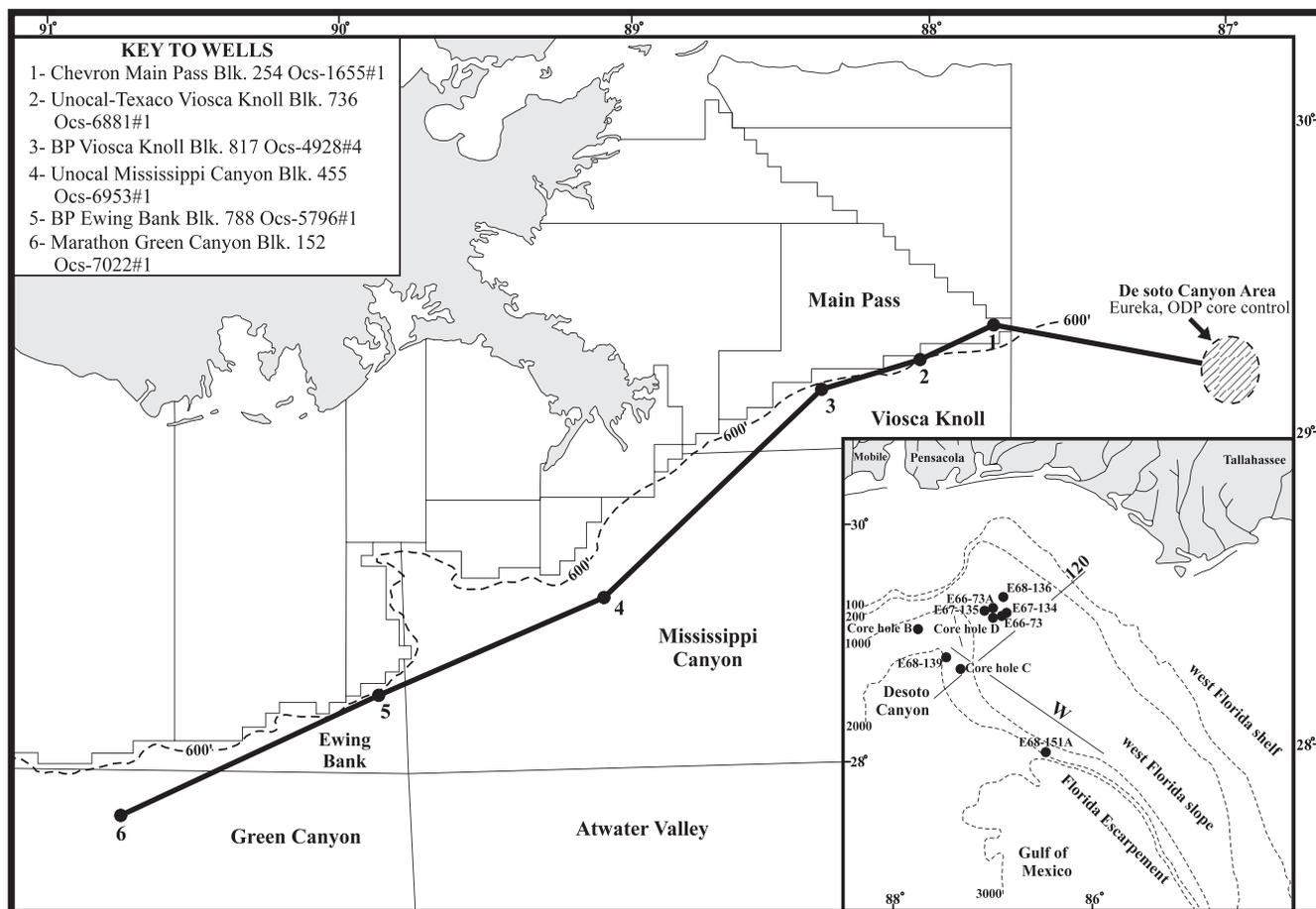


FIGURE 1. Location map showing wells included in this study (from Aubry et al., in press, fig. 1).

(1986; this reference includes Gulf of Mexico data), Miller & Katz (1987), and Katz & Miller (1993a, b, c). Our agglutinated benthic foraminiferal taxonomy is based primarily on Cushman & Renz (1941) and the monographs of Renz (1948) and Bermúdez (1949).

Benthic foraminifera are seafloor-dwelling microfossils that provide the means to reconstruct paleobathymetry (see “Introduction”). Different species typically colonize certain water depth ranges, with key depth-indicator species providing an invaluable tool for reconstructing paleobathymetry (e.g., Olsson et al., 1987; Browning et al., 1997; Miller et al., 1997; Pekar et al., 1997; Katz et al., 2003). Therefore, the

paleodepth history of a site can be determined by documenting benthic foraminiferal changes through time. Our primary sources for paleobathymetric information on calcareous benthic foraminiferal species are van Morkhoven et al. (1986) and Katz & Miller (1993b). We use the following paleobathymetric zones: outer neritic, 100–200 m; upper bathyal, 200–600 m; and middle bathyal, 600–1000 m (e.g., van Morkhoven et al., 1986).

Age control is provided by integrated calcareous nanofossil and planktonic foraminiferal biostratigraphy from more than 1500 samples (Aubry et al., in press). We use formal subseries nomenclature (Aubry, 2016; Head et al., 2017).

TABLE 1. Industry wells included in this study. Kelly bushing (KB) refers to an adapter that connects the rotary table to the “kelly,” which is attached to the top of the drillstring in rotary drilling; depth measurements are commonly referenced to feet below kelly bushing (ftbkb).

Lease area	Well	Water depth (m)	Water depth (ft)	KB elevation (ft)	KB elevation (m)
Chevron Main Pass Block 254 #1	OCS-G 1655 #1	92	303	60	18
UNOCAL-TEXACO Viosca Knoll Block 736 #1	OCS-G 6881 #1	196	643	84	26
SOHIO Viosca Knoll Block 817 #4	OCS-4928 #4, P42	200	656	73	22
UNOCAL Mississippi Canyon Block 455 #1	OCS-G 6953 #1	426	1397	83	25
BP Ewing Bank Block 788 #1	OCS-G 5796 #1	215	611	77	23
Marathon Green Canyon Block 152 #1	OCS-G 7022 #1	482	1581	37	11

TABLE 2. List of benthic foraminiferal taxa in this study.

<i>Alveovalvulina suteri</i> (Brönnimann)
<i>Alveovalvulinella pozonensis</i> (Cushman & Renz)
<i>Ammolagena clavata</i> (Jones & Parker)
<i>Amphistegina</i> spp.
<i>Anomalinooides globulosus</i> (Chapman & Parr)
<i>Anomalinooides pseudogrosserugosus</i> (Colom)
<i>Anomalinooides semicribratus</i> (Beckmann)
<i>Arenogaudryina flexilis</i> (Cushman & Renz)
<i>Bolivina</i> spp.
<i>Bulimina aculeata</i> d'Orbigny
<i>Bulimina exilis</i> Brady
<i>Bulimina marginata</i> d'Orbigny
<i>Bulimina</i> spp.
<i>Cibicidoides compressus</i> (Cushman & Renz)
<i>Cibicidoides crebbsi</i> (Hedberg)
<i>Cibicidoides grosseperforatus</i> van Morkhoven & Berggren
<i>Cibicidoides guazumelensis</i> (Bermúdez)
<i>Cibicidoides havanensis</i> (Cushman & Bermúdez)
<i>Cibicidoides incrassatus</i> (Fichtel & Moll)
<i>Cibicidoides matanzasensis</i> (Hadley)
<i>Cibicidoides mundulus</i> (Brady, Parker & Jones)
<i>Cibicidoides pachyderma</i> (Rzehak)
<i>Cibicidoides robertsonianus</i> (Brady)
<i>Cibicidoides</i> sp. 11 of van Morkhoven et al. (1986)
<i>Cibicidoides</i> spp.
<i>Cyclammina cancellata</i> Brady
<i>Cyclammina rotundidorsata</i> Hantken
<i>Cyclammina</i> spp.
<i>Globocassidulina punctata</i> Berggren & Miller
<i>Globocassidulina subglobosa</i> (Brady)
<i>Glomospira gordialis</i> (Jones & Parker)
<i>Gyroidinooides</i> spp.
<i>Hanzawaia mantaensis</i> (Galloway & Morrey)
<i>Haplophragmoides carinatus</i> Cushman & Renz
<i>Lenticulina</i> spp.
<i>Melonis pompilioides</i> (Fichtel & Moll)
<i>Planulina ariminensis</i> d'Orbigny
<i>Planulina foveolata</i> (Brady)
<i>Planulina rugosa</i> (Pfleger & Parker)
<i>Planulina subtenuissima</i> (Nuttall)
<i>Plectofrondicularia parri</i> Finley
<i>Plectofrondicularia vaughni</i> Cushman
<i>Recurvooides azuaensis</i> Bermúdez
<i>Rectuvigerina multicostata</i> (Cushman & Jarvis)
<i>Rectuvigerina nodifera</i> (Cushman & Kleinpell)
<i>Rectuvigerina transversa</i> (Cushman)
<i>Saccamina</i> spp.
<i>Praesphaerammina subgaleata</i> (Vašiček)
<i>Textularia tatumi</i> (Cushman & Ellis)
<i>Uvigerina hispida</i> Schwager
<i>Uvigerina mexicana</i> Nuttall
<i>Uvigerina pigmea</i> d'Orbigny
<i>Uvigerina</i> spp.

RESULTS

CHEVRON MAIN PASS BLOCK 254 #1

We quantitatively examined 74 sidewall samples from the Pleistocene to Oligocene section at Chevron Main Pass Block 254 #1 (present depth 92 m) for benthic foraminifera (Figs. 2, 3). A shallow-water *Amphistegina* spp. biofacies with secondary miliolids dominates the section from 992–1614 feet (302–492 m) below Kelly bushing [ftbkb (mbkb), see Table 1], representing Pleistocene to Upper Pliocene Zones N22–N23/Pt1a–Pt1b to PL4–PL5 and NN20 to NN16; this is similar to the carbonate bank biofacies of

Jones et al. (2003). The shallow-water *Amphistegina* spp. biofacies is mixed with *in situ* outer neritic to upper bathyal faunas, indicating downslope transport in this section.

From 1650–6415 ftbkb [(503–1955 mbkb; Upper Pliocene to Upper Miocene Zones PL4–PL5 to N17/M13b and NN16 to NN11a(?)], the benthic foraminiferal assemblages are characterized by abundant *Uvigerina* spp. (dominated by *U. pigmea*; Figs. 2, 3). In addition, several isolated samples within this section contain high percentages of a single dominant taxon, such as *Bolivina* spp., *Bulimina* spp., *Cibicidoides pachyderma*, or agglutinants; *Uvigerina* spp. are frequently present as secondary components in these samples. The uppermost part of this section represents outer neritic to upper bathyal paleodepths, based on the absence of species found below that have an upper depth limit of 200 m. The stratigraphic HO of these species, which are typically found >200 m (e.g., *Bulimina aculeata*, *Cibicidoides mundulus*, and *Globocassidulina punctata*), together with species typically found <600 m (e.g., *Bulimina marginata*, *Globocassidulina punctata*), indicates upper bathyal paleodepths (200–600 m) in most of the section (Fig. 2).

Four taxa dominate the biofacies from 7093–7572 ftbkb [(2162–2308 mbkb); lower Middle Miocene–uppermost Oligocene Zones N10/M7 to indeterminate; and NN5 to NP23]: *Lenticulina* spp., *Gyroidinooides* spp., *Globocassidulina subglobosa*, and *Cibicidoides mundulus* (Figs. 2, 3). This faunal association at Main Pass is similar to a biofacies identified in previous studies at deepwater Atlantic locations. *Gyroidinooides* spp., *G. subglobosa*, *Oridorsalis umbonatus*, and *Cibicidoides praemundulus* are ubiquitous in the Oligocene Atlantic (e.g., Miller, 1983; Miller et al., 1985; Wood et al., 1985; Miller & Katz, 1987; Katz et al., 2003) and the Eocene (e.g., Tjalsma & Lohmann, 1983), with *Lenticulina* spp. joining these as a dominant taxon at bathyal depths (e.g., Tjalsma & Lohmann, 1983; Katz & Miller, 1996; Katz et al., 2003).

A transition zone from 6467–6972 ftbkb [1971–2125 mbkb; Upper to Middle Miocene Zones N16–N17 to N10 (= M13b to M7); and NN11a to NN6–NN7] is characterized by *Uvigerina* spp. along with these four taxa. The Lower Miocene section contains several species generally found at upper bathyal (200–600 m) or shallower depths, including *Cibicidoides guazumelensis*, *Cibicidoides* sp. 11, *Planulina subtenuissima*, *Rectuvigerina nodifera*, and *R. transversa*. The lowermost sample examined [7572 ftbkb (2308 mbkb); Oligocene Zone NP23] also contains several specimens of species (*Anomalinooides semicribratus* and *Cibicidoides havanensis*) that indicate that this sample may represent a slightly greater water depth than overlying samples (probably deposited near the upper/middle bathyal boundary, ~600 m; Fig. 2).

The change in biofacies observed at Main Pass is similar to the biofacies changes in the Middle Miocene at the Gulf of Mexico Eureka boreholes (Fig. 1; Katz & Miller, 1993b). The Q-mode Principal Component II of the combined Eureka borehole dataset shows that a Late Oligocene to middle Middle Miocene assemblage (characterized by *Lenticulina* spp., *O. umbonatus*, and *Gyroidinooides* spp.) is replaced by a *Uvigerina pigmea*-dominated assemblage by the Late Miocene (see fig. 15 of Katz & Miller, 1993b). As at the Main Pass well (Figs. 2, 3), there is a middle Middle Miocene

Main Pass Block 254 #1

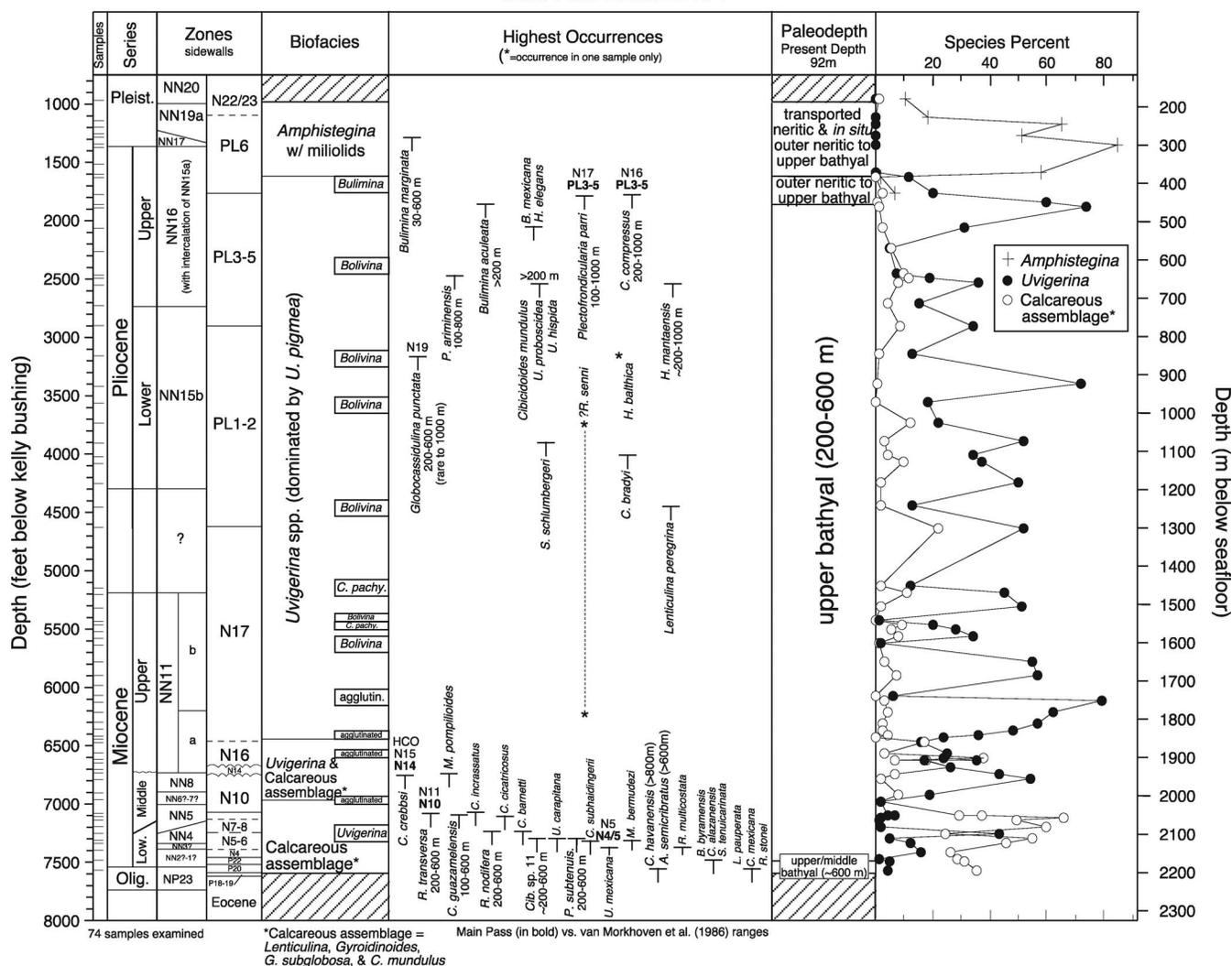


FIGURE 2. Chevron Main Pass Block 254, OCS-G 1655 #1: Benthic foraminiferal biofacies, paleobathymetric interpretations, and useful biostratigraphic and paleobathymetric species are based upon sidewall samples. Biostratigraphy from Aubry et al. (in press).

transition between the two faunas at the Eureka boreholes (Katz & Miller, 1993b).

Some benthic foraminiferal HOs in the Main Pass section are biostratigraphically useful, comparing well with the ranges of van Morkhoven et al. (1986): *Cibicides crebbsi* [N14 vs. highest common occurrence (HCO) N15; rare specimens found through PL1 at the Gulf of Mexico Eureka boreholes (Katz & Miller, 1993b)], *Globocassidulina punctata* (PL1–2 vs. N19), *Planulina subtenuissima* (N8 vs. N9), *Rectuvigerina transversa* (N10 vs. N11), and *Uvigerina mexicana* (N4–5 vs. N5). The highest occurrences of several species are higher in the section than predicted by van Morkhoven et al. (1986), including *Cibicides compressus* and *Plectofrondicularia parri*.

UNOCAL-TEXACO VIOSCA KNOLL BLOCK 736 #1

We examined 41 cuttings samples from the Miocene section recovered at UNOCAL-TEXACO Viosca Knoll Block

736 #1 (196 m present depth, (Fig. 4). The biofacies in most of the Upper Miocene section [7020–9180 ftbkb (2140–2798 mbkb); Zones N17/M13b to N15–N16/M13a; and NN11b to NN10] is characterized by abundant *Uvigerina* spp. and agglutinants. In addition to these taxa, some samples within this biofacies contain a third taxon in high abundance (along with minor assemblage constituents), either *Cibicides* spp., *Bolivina* spp., or *Bulimina* spp.

Uvigerina spp. dominates the remaining lowermost Upper to Middle Miocene section [9360–13860 ftbkb (2853–4425 mbkb); Zones N15–N16 to N7–N9 (= M13a to M5–7 and NN10–NN5), along with common *Bolivina* spp. in many samples and abundant *Lenticulina* spp., *Bulimina* spp., or agglutinants in several samples. Below this (14041–14220 ftbkb (4280–4334 mbkb); Zones N4–N6/M1–M3 and NN5 to NN4), agglutinants dominate the biofacies, with *Uvigerina* spp. as the second most abundant taxon.

In general, the benthic foraminiferal assemblages indicate upper to middle bathyal paleodepths (200–1000 m) at

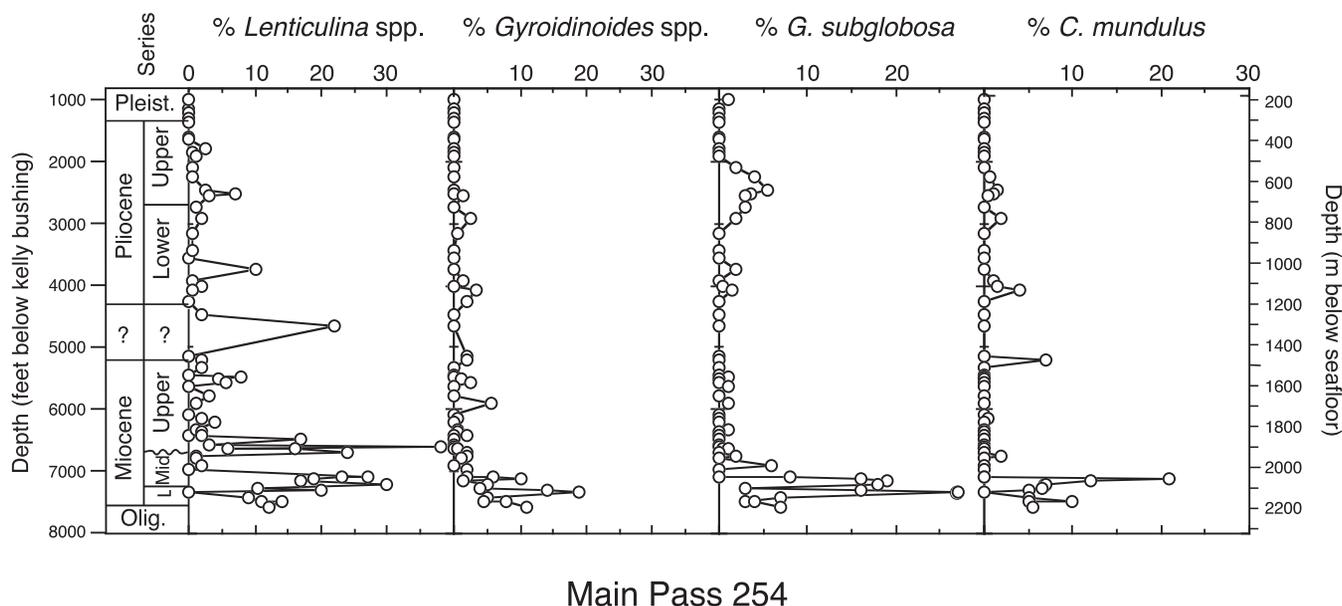


FIGURE 3. Chevron Main Pass Block 254, OCS-G 1655 #1. Abundance plots of the most common *in situ* calcareous benthic foraminifera at this location shown are based upon sidewall samples. Biostratigraphy from Aubry et al. (in press).

Viosca Knoll Block 736, including species such as *Rectuverina multicostrata*, *Melonis pompilioides*, *Plectofrondicularia vaughni*, *Hanzawaia mantaensis*, *C. compressus*, and *Planulina ariminensis* (Fig. 4). However, there are isolated occurrences of a number of species that are generally found at upper bathyal or shallower depths (*B. marginata*, *Cibicidoides matanzasensis*, *Planulina foveolata*, *G. punctata*, *Cibicidoides crebbsi*, and *Cibicidoides incrassatus*) along with those generally found at middle bathyal or deeper depths (*Anomalinoidea globulosus*, *Anomalinoidea pseudogrosserugosus*, *C. havanensis*, *Cibicidoides robertsonianus*, and *Planulina rugosa*). Based on the co-occurrences of species typically found shallower than 600 m with species typically found deeper than 600 m, we interpret this section to have been deposited at depths near the upper/middle bathyal boundary (~600 m; Fig. 4).

In agreement with ranges reported in van Morkhoven et al. (1986), stratigraphically useful HO at Viosca Knoll Block 736 include *C. crebbsi* [N16 vs. HCO N15; rare specimens found through PL1 at the Gulf of Mexico Eureka boreholes (Katz & Miller, 1993b)], *P. parri* (N17), and *P. vaughani* (N15–16 vs. N17). The HO of *Cibicidoides compressus* and *C. matanzasensis* in the section (Fig. 4) is higher than expected based on van Morkhoven et al. (1986). However, the *C. matanzasensis* occurrence was a single specimen found in one sample only, which may have been reworked (Fig. 4).

SOHIO VIOSCA KNOLL BLOCK 817 #4

We examined 55 cuttings samples for calcareous benthic foraminifera from the Pleistocene through Miocene section at SOHIO Viosca Knoll Block 817 #4 (present depth 200 m; Fig. 5). A calcareous biofacies dominated by *Lenticulina* spp., *Cibicidoides* spp., *Planulina* spp., and *Uvigerina* spp. characterizes the upper Pleistocene to Upper Miocene interval [1700–6830 ftbkb; Zones N22 to N15–N17 (= Pt1b to

M12–M14); and NN20 to NN11]. Components of the Agua Salada Fauna occur in low numbers scattered through this section, with higher abundances at 5180–5210 ftbkb (1579–1588 mbkb) of several distinctive organically-cemented taxa with their HOs in these samples. These include typical elements of the Agua Salada Fauna, such as *Alveovalvulina suteri*, *Alveovalvulinella pozonensis*, *Cyclammina cancellata*, *Haplophragmoides carinatus*, and *Recurviroidea azuaensis*, as first described from the Caribbean (Cushman & Renz, 1941).

Older occurrences of the Agua Salada Fauna increase in the Upper Miocene (Zone NN11), and the Agua Salada Fauna dominates the lower Upper to Middle Miocene section [6620–12020 ftbkb (2018–3664 mbkb); Zones N15–N17 to N12–N14 (= M12–M14 to M9b–M11) and NN11b to NN6–NN7]. Agglutinated assemblages are dominated by *A. suteri*, *H. carinatus*, and *R. azuaensis* down to 8060–8090 ftbkb (2457–2466 mbkb). The indicator of the Agua Salada Fauna, *Arenogaudryina flexilis*, is also present in this interval, increasing in numbers downhole to 8000 ftbkb (2438 mbkb), where it constitutes the dominant taxon. Also at 8000 ftbkb, the HOs of *Cyclammina rotundidorsata* and *Praesphaerammina subgaleata* were observed. These two species were first described from the Paleogene of Central Europe, and this paper is the first report of their presence in the Upper Miocene of the Gulf of Mexico. The interval from 8720–8750 ftbkb (2658–2667 mbkb) to 9560–9590 ftbkb (2914–2923 mbkb) is dominated by *A. suteri*, *R. azuaensis*, and *V. flexilis*, but contains a more diverse assemblage. In the lower part of the interval, *Textularia tatumi* increases in relative abundance downhole, while abundances of *A. suteri* and *V. flexilis* decrease. The lowermost sample examined [12050 ftbkb (3673 mbkb), upper Middle Miocene Zone N12?] is similar to the calcareous biofacies from the top of the section, with sparse agglutinated taxa (Fig. 5).

UNOCAL-TEXACO Viosca Knoll Block 736

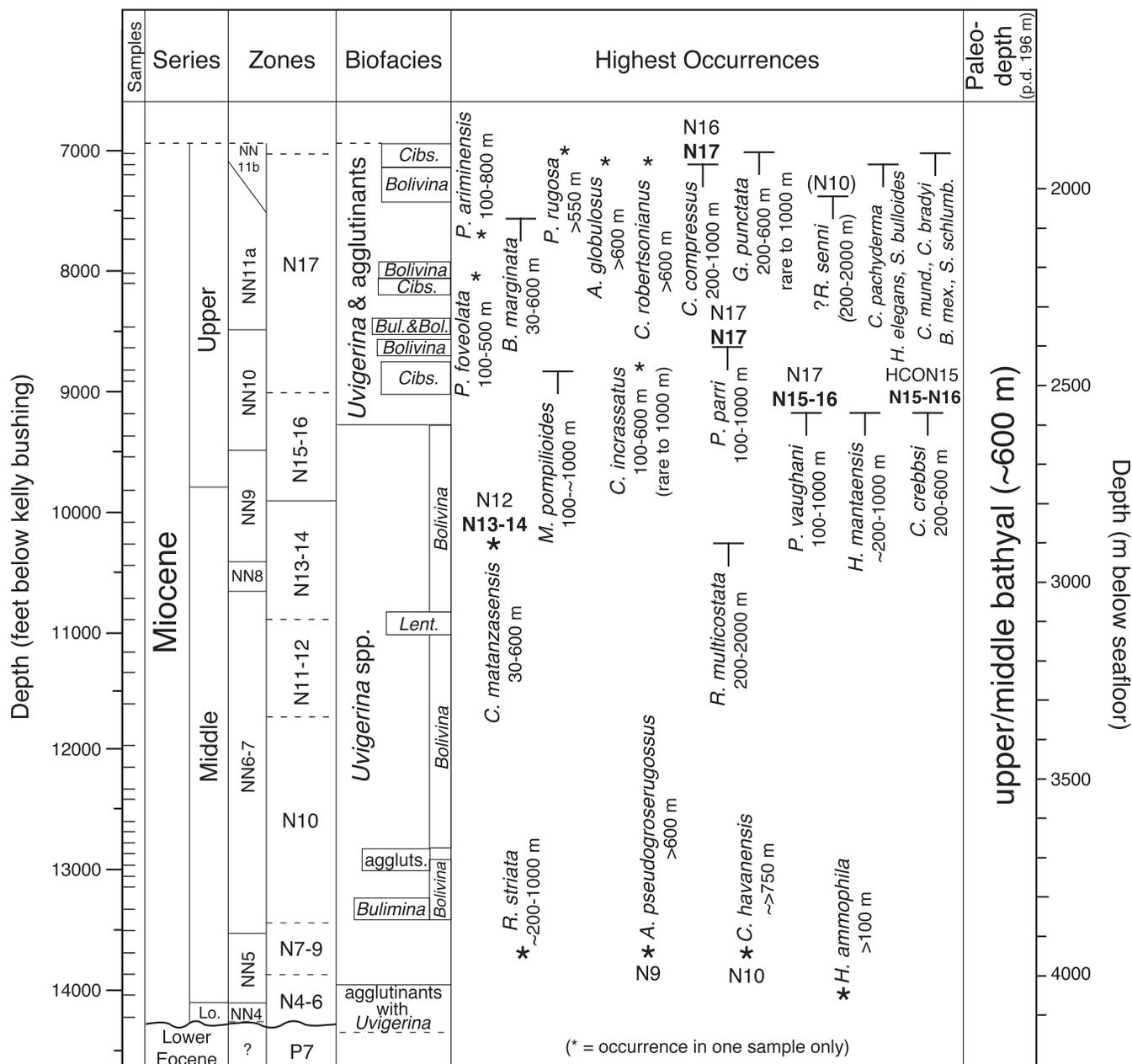


FIGURE 4. UNOCAL-Texaco Viosca Knoll Block 736, OCS-G 6881 #1. Benthic foraminiferal biofacies, paleobathymetric interpretations, and useful biostratigraphic and paleobathymetric species are shown. Cutting samples were analyzed. Biostratigraphy from Aubry et al. (in press).

The co-occurrences of species with lower depth limits of ~600 m (*B. marginata*, *C. incrassatus*) with species with upper depth limits of 200 m (*H. mantaensis*, *Uvigerina hispida*) indicate an upper bathyal paleodepth for Viosca Knoll Block 817 (Fig. 5). This is consistent with the occurrence of the Agua Salada Fauna (which also indicates upper bathyal depths). We note that lower depth limits can be complicated by downslope transport, but in the absence of micropaleontological or sedimentological indicators of transport, we consider specimens to be *in situ*. The presence of species typical of the outer neritic through middle bathyal zones is

consistent with this paleodepth estimate (*P. parri*, *M. pompilioides*, and *P. ariminensis*). In addition, co-occurrences of *Planulina foveolata* (100–500 m) and *Bulimina exilis* (500–1000 m) indicate that this section was deposited near 500 m. This is consistent with more diverse agglutinated benthic foraminiferal faunas, which indicate slightly increased depths below 8750 ftbk (2667 mbk).

In agreement with ranges reported in van Morkhoven et al. (1986), stratigraphically useful HO's include *C. crebbsi* [N15–17 vs. HCO N15; rare specimens found through PL1 at the Gulf of Mexico Eureka boreholes (Katz

Sohio Viosca Knoll Block 817 #4

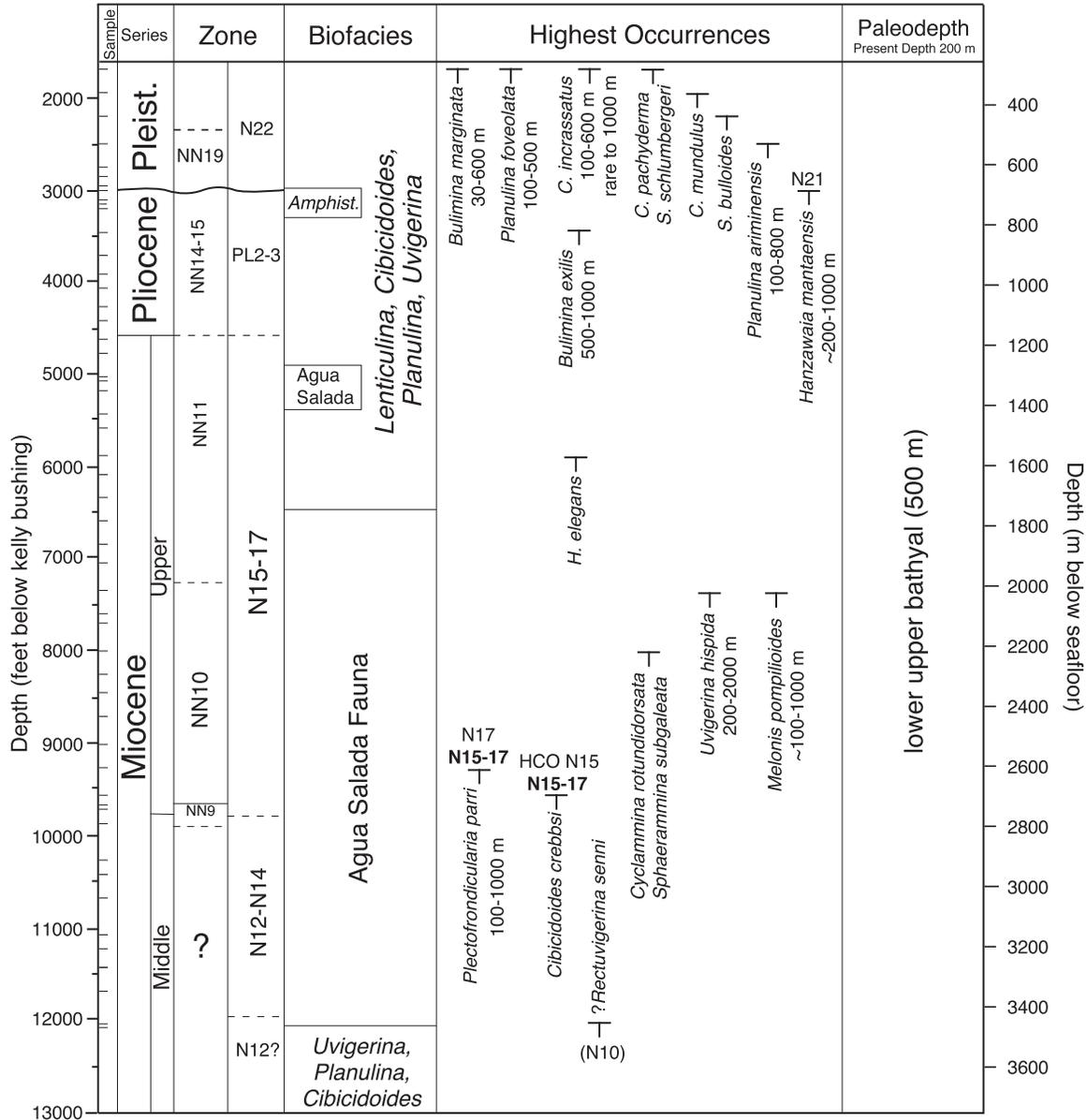


FIGURE 5. SOHIO Viosca Knoll Block 817, OCS-4928 #4, P42. Benthic foraminiferal biofacies, paleobathymetric interpretations, and useful biostratigraphic and paleobathymetric species are shown. Cutting samples were analyzed. Biostratigraphy from Aubry et al. (in press).

& Miller, 1993b)] and *Plectofrondicularia parri* (N15-17 vs. N17).

UNOCAL MISSISSIPPI CANYON BLOCK 455 #1

We examined 29 cuttings samples for benthic foraminifera from the Pleistocene through Miocene section at UNOCAL Mississippi Canyon Block 455 #1 (present depth 426 m; Fig. 6). Nine samples were examined in detail for agglutinated assemblages from 11160-16830 ftkbk (3402-5130 mbkb). The Pleistocene section [5010-5768 ftkbk (1527-1758 mbkb); Zones N22/Pt1a-b and NN19c] is characterized by a *Bulimina* spp.-dominated biofacies with common *Cassidulina* spp. or *Cibicidoides* spp. in several sam-

ples. Below this, a *Uvigerina* spp. biofacies is typical of the Pliocene to uppermost Miocene section [6120-10860 ftkbk (1865-3310 mbkb); Zones PL4 to N15-N17/M13b-M14 and NN16a to NN11b]; in addition to *Uvigerina* spp., *Bulimina* spp. is common in the upper part of the section.

This biofacies is underlain by the Agua Salada Fauna (with scattered occurrences of common *Uvigerina* spp.) in much of the Upper Miocene section [11160-16380 ftkbk (3402-5130 mbkb); Zones N15-N17/M13b-M14 to M12-M13b and NN11b to NN10]. Two agglutinated assemblages were distinguished in this section (Fig. 6). The upper fauna [11160-14490 ftkbk (3402-4417 mbkb); Zones N15-N17/M13b-M14 to M12-M13b and NN11b to NN11a] is characterized by *Alveovalvulina suteri*, *Haplophragmoides*

BP Ewing Bank Block 788 #1

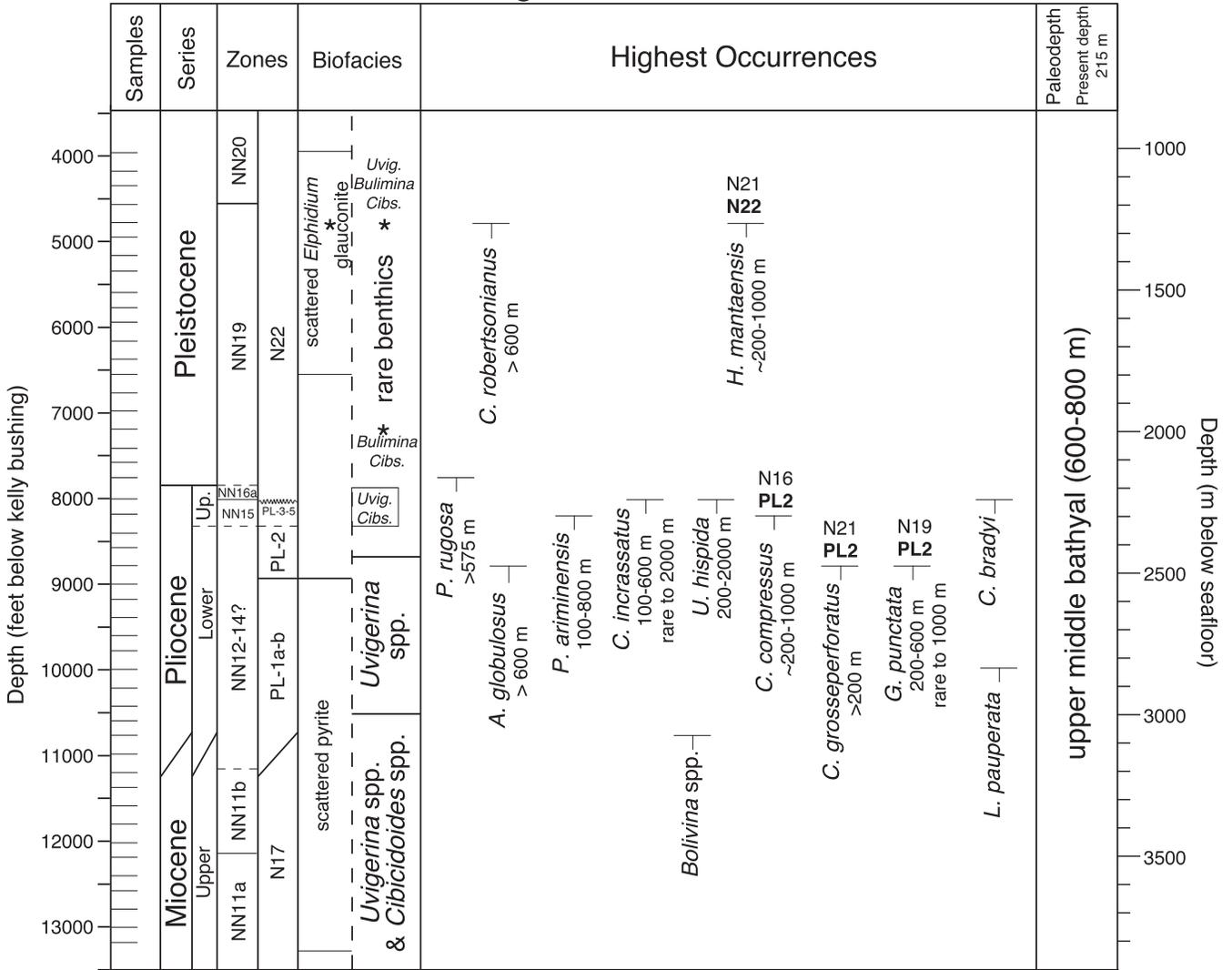


FIGURE 7. BP Ewing Bank Block 788, OCS-G 5796 #1. Benthic foraminiferal biofacies, paleobathymetric interpretations, and useful biostratigraphic and paleobathymetric species are shown. Cutting samples were analyzed. Biostratigraphy from Aubry et al. (in press).

balthica, *C. compressus*, *Uvigerina hispida*). This is consistent with the Agua Salada Fauna, which indicates upper bathyal depths.

Stratigraphically useful HOs include *G. punctata* (Zones PL2-3 vs. N19; Fig. 6). The HO of *Cibicidoides compressus* is higher in the section than expected based on van Morkhoven et al. (1986; Fig. 6).

BP EWING BANK BLOCK 788 #1

We examined 47 cuttings samples from the Upper Miocene through Pleistocene section at BP Ewing Bank Block 788 #1 (present depth 215 m; Fig. 7). The Pleistocene to Upper Pliocene section contains only rare foraminifera [3990-8580 ftbkb (1216-2615 mbkb); Zones N22 to PL2 and NN20 to NN15-NN14]. The few samples that yielded enough benthic foraminifera to describe the assemblages are characterized by *Bulimina* spp., *Cibicidoides* spp., and *Uvigerina* spp. Below this, a *Uvigerina* spp.-dominated bio-

facies [8790-10440 ftbkb (2679-3182 mbkb); Zones PL2 and PL1b and NN14-?NN12] overlies a *Uvigerina* spp. and *Cibicidoides* spp.-dominated biofacies [10590-13170 ftbkb (3228-4014 mbkb); Zones PL1a-b to N17/PL1a-b and NN12-NN14? to NN11a].

The presence of *C. robertsonianus* (>600 m), *A. globulosus* (>600 m), and *P. rugosa* (>575 m) with *P. ariminensis* (100-800 m) at Ewing Bank indicates an upper middle bathyal paleodepth (~600-800 m; Fig. 7). Two species found in this well, *C. incrassatus* and *G. punctata*, are generally found shallower than 600 m, although there may be rare occurrences deeper than this (van Morkhoven et al., 1986). These two taxa were found deeper at the Gulf of Mexico Eureka boreholes (Katz & Miller, 1993b) and therefore do not pose a conflict in our paleobathymetric estimate at this well. Occurrences of additional species typical of upper to middle bathyal depths (200-1000 m) are consistent with this estimate (*H. mantaensis*, *C. compressus*, *Cibicidoides grosseperforatus*, and *U. hispida*).

TABLE 3. Benthic foraminifera found to be biostratigraphically useful in this transect study: **A** Useful highest occurrences. **B** Revised highest occurrences; vM = van Morkhoven et al. (1993), na – not applicable, other abbreviations refer to wells from which samples were obtained (see Table 1).

A								
Species	vM	MP254	VK736	VK817	MC455	EwB788	GC152	Eureka
<i>C. crebbsi</i>	HCON15	N14	N16	N15–17	na	na	na	rare thru PL1
<i>G. punctata</i>	N19	PL1–2	na	na	PL2–3	PL2		na
<i>H. mantaensis</i>	N21	na	na	na	na	N22	PL4–6	na
<i>P. subtenuissima</i>	N9	N8	na	na	na	na	na	na
<i>P. parri</i>	N17	na	N17	N15–17	na	na	na	na
<i>P. vaughani</i>	N17	na	N15–16	na	na	na	na	na
<i>R. transversa</i>	N11	N10	na	na	na	na	na	na
<i>U. mexicana</i>	N5	N4–5	na	na	na	na	na	na
Agua Salada Fauna	na	na	na	NN11	NN11	na	na	na
B								
Species	vM	MP254	VK736	VK817	MC455	EwB788	GC152	Eureka
<i>C. compressus</i>	N16	PL3–5	N17	na	PL4	PL2	PL1	na
<i>H. mantaensis</i>	N21	na	na	na	na	N22	PL4–6	na

The HO of *G. punctata* at this well may be stratigraphically useful (PL2 vs. N19; Fig. 7). The HOs of several species are higher in the section than expected based on van Morkhoven et al. (1986), including those of *C. compressus* and *H. mantaensis* (Fig. 7).

MARATHON GREEN CANYON BLOCK 152 #1

We examined 58 cuttings samples from the Pliocene section at Marathon Green Canyon Block 152 #1 (present depth 482 m; Fig. 8). As at the Ewing Bank well, benthic foraminifera were often too rare to allow us to characterize the assemblages in most of the samples. However, several samples yielded sufficient numbers of benthic foraminifera. The Pleistocene to upper Lower Pliocene section [6490–14800 ftbkb (2115–4511 mbkb); Zones N22/Pt1a–b to PL2–PL3 and ?NN19c to indeterminate] contains calcareous assemblages characterized by *Bulimina* spp., *Cibicides* spp., *Gyroidinoides* spp., *O. umbonatus*, and *Uvigerina* spp. (based on five samples). The remaining Lower Pliocene section [14800–18780 ftbkb (4511–5724 mbkb); Zone PL1] contains an agglutinant-dominated biofacies with the calcareous component dominated by *Uvigerina* spp. and *Gyroidinoides* spp. (based on four samples; Fig. 8).

The occurrences of *C. robertsonianus* (>600 m), *A. globulosus* (>600 m), and *P. rugosa* (>575 m) with *H. mantaensis* (~200–1000 m) and *C. compressus* (200–1000 m) indicate middle bathyal paleodepths at this location (Fig. 8). The absence of species with firm lower depth limits <600 m supports this. The presence of *C. incrassatus* below ~13000 ftbkb (~3962 mbkb) indicates the upper part of the middle bathyal zone (~600–800 m), although the sporadic occurrences of benthic foraminifera make this refinement a speculative paleobathymetric estimate.

The HO of *H. mantaensis* may be stratigraphically useful (PL4–6 vs. N21), whereas the HO of *C. compressus* is higher in the section than expected (Fig. 8) based on van Morkhoven et al. (1986), that is, PL1 vs. N16.

DISCUSSION

Calcareous nannofossil and planktonic foraminiferal biostratigraphic control (see appendix of Aubry et al., in press) facilitates interwell comparisons of benthic foraminiferal biofacies (Fig. 9). Sections vary in thickness and completeness, punctuated by apparently coeval unconformities (Fig. 9) associated with 1–2 Myr hiatuses along the transect (Aubry et al., in press). Benthic foraminiferal biofacies reveal consistent patterns along the transect at the stage/age level, providing the means to reconstruct regional stratigraphic, paleobathymetric, and paleoenvironmental changes (Fig. 9) despite punctuation by unconformities with attendant short hiatuses.

BENTHIC FORAMINIFERAL STRATIGRAPHY

The HOs of several benthic foraminifera at the transect wells are consistent with the ranges compiled by van Morkhoven et al. (1986), and therefore appear to be useful in this region of the Gulf of Mexico for correlation purposes (Table 3). Two species in at least one transect well occur in sediments younger than reported by van Morkhoven et al. (1986) (Table 3).

Useful biostratigraphic markers in this region (Table 3) include *C. crebbsi* (LCO N15), *G. punctata* (HCO = N19, = PL1–3), *H. mantaensis* (HCO = N21, = PL4–6), *P. subtenuissima* (N9), *P. parri* (N17), *P. vaughani* (N17), *R. transversa* (N11), and *U. mexicana* (N5). At most of the locations studied here, the HO of *C. compressus* is in the Pliocene rather than Upper Miocene, as reported by van Morkhoven et al. (1986). The HO of *H. mantaensis* is consistent with the van Morkhoven et al. (1986) compilation at Green Canyon 152, although it is younger at Ewing Bank.

Several of the Agua Salada taxa reported here (*Praesphaerammina subgaleata*, *Cyclammina rotundidorsata*, and *Cyclammina acutidorsata*) have not been identified previously from Middle and Upper Miocene strata. The HO of the Agua Salada Fauna is within Zone NN11 at both the UNOCAL Mississippi Canyon 455 #1 well and the SOHIO 817 #4 well, which constitutes the youngest documentation

Marathon Green Canyon Block 152 #1

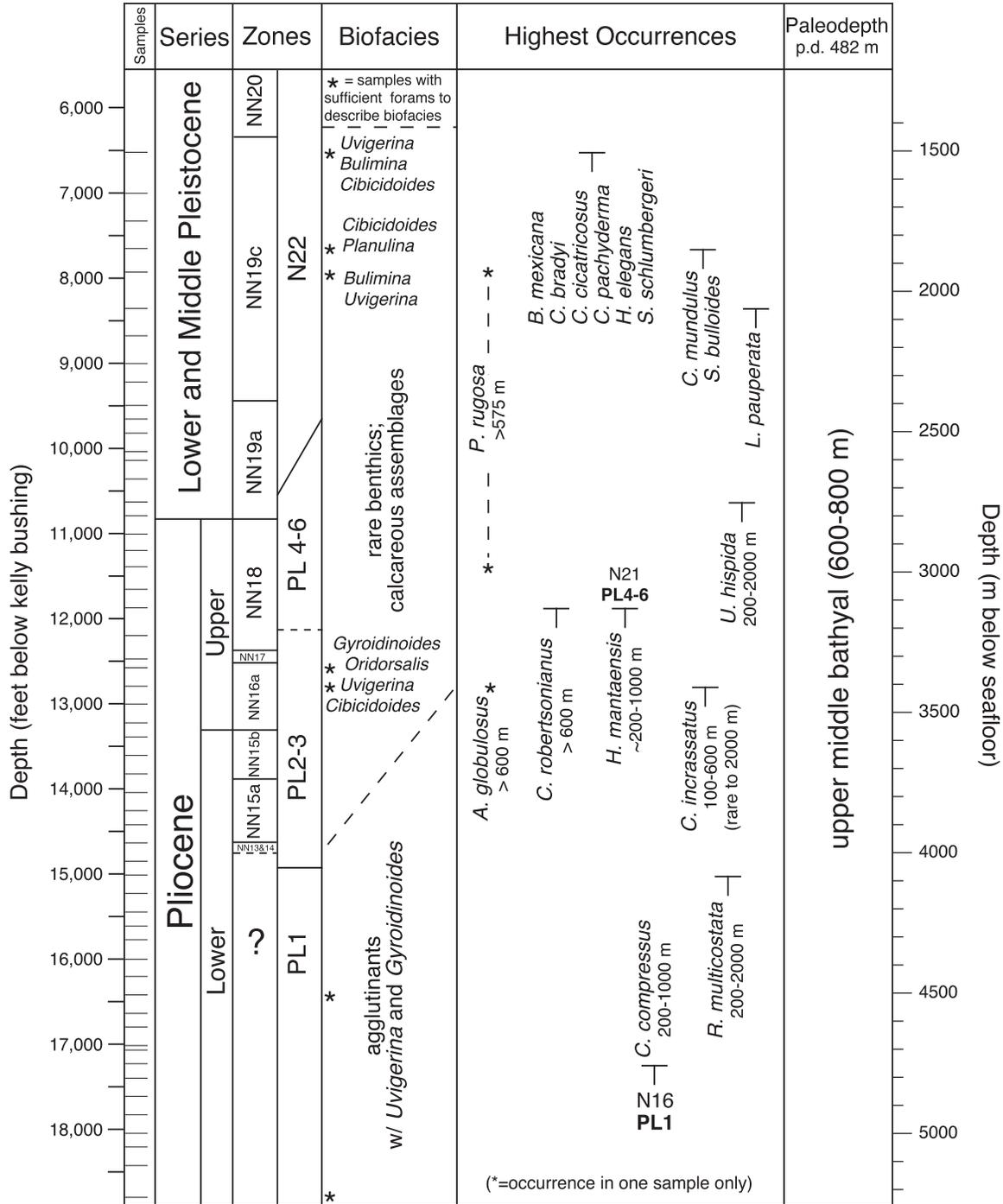


FIGURE 8. Marathon Green Canyon Block 152, OCS-G 7022 #1. Benthic foraminiferal biofacies, paleobathymetric interpretations, and useful biostratigraphic and paleobathymetric species are shown. Cutting samples were analyzed. Biostratigraphy from Aubry et al. (in press).

of this agglutinated benthic foraminiferal biofacies occurrence and indicates that the assemblage may be useful for correlation purposes in this region.

PALEOBATHYMETRY

Benthic foraminifera with calibrated paleodepths (van Morkhoven et al., 1986; Katz & Miller, 1993b) are found

throughout the wells examined in this study (Figs. 2–8). This provides an opportunity to establish paleobathymetry at each well and to reconstruct the regional paleobathymetric history using inter-well correlations (Fig. 9). Paleobathymetries range throughout the bathyal zone in the Miocene through Pleistocene sections and vary both spatially and temporally. Our reconstructions show that the eastern wells appear to have had slightly shallower

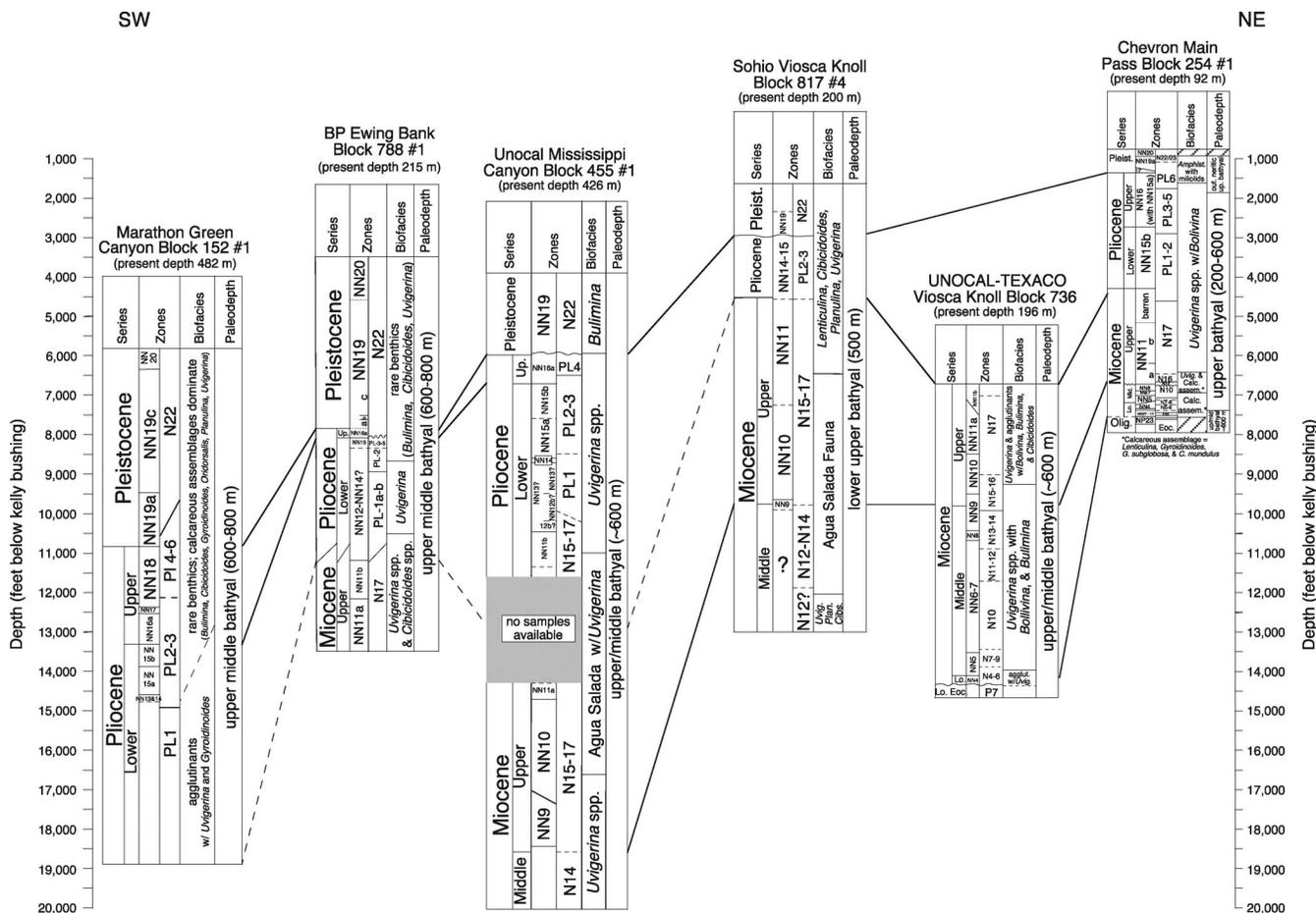


FIGURE 9. Paleodepth interpretations: The eastern wells appear to have had slightly shallower paleodepths than the western wells, while the western wells have accumulated greater thicknesses during the Plio-Pleistocene. Biostratigraphy from Aubry et al. (in press). See Aubry et al. for discussion of sedimentary patterns along the transect.

paleodepths than the western wells, while the western wells have accumulated greater thicknesses during the Plio-Pleistocene (Fig. 9), as shown also in Aubry et al. (in press).

PALEOENVIRONMENTS: OXYGEN LEVELS AND PRODUCTIVITY

Export production from the surface waters and dissolved oxygen levels near the seafloor determine the amount of food available to benthic foraminifera. Elevated levels of export productivity deliver more organic matter to the seafloor, making more food available to benthic foraminifera while also drawing down dissolved oxygen levels as the organic matter is oxidized. The balance between these parameters can influence the species composition of benthic foraminiferal assemblages. The relationship between benthic foraminiferal distributions and food availability, sedimentary organic carbon content, and/or oxygen levels has been documented in numerous studies (e.g., Lutze, 1978; Schnitker, 1979; Miller & Lohmann, 1982; Boersma, 1984; Katz & Thunell, 1984; Thomas, 1986; Katz & Miller, 1987, 1993b; Corliss & Chen, 1988; Corliss & Emerson, 1990; Hermelin & Shimmield, 1990; Gooday, 1994; Kaiho, 1994, 1999; Rathburn & Corliss, 1994; Smart et al., 1994; Jorissen et al., 1995; Thomas & Gooday, 1996; Schmiel et al., 1997, 2000;

Gooday & Rathburn, 1999; Van der Zwaan et al., 1999; Morigi et al., 2001; Kaminski, 2012).

Certain species of calcareous infaunal taxa (especially many species of *Uvigerina*, *Bullimina*, and *Bolivina*) often are associated with environments of elevated organic carbon and low oxygen levels (e.g., Lutze, 1978; Miller & Lohmann, 1982; Boersma, 1984; Katz & Thunell, 1984; Katz & Miller, 1987, 1993b; Corliss & Chen, 1988; Corliss & Emerson, 1990; Hermelin & Shimmield, 1990; Preece et al., 1999). In the case of the agglutinated foraminifera, the Agua Salada Fauna is also dominated by infaunal morphotypes, providing a proxy for increased organic productivity in upwelling zones that can cause oxygen-deficient environments in upper bathyal settings along low-latitude continental margins (Kender et al., 2008). The expansion of oxygen-deficient conditions in the Late Oligocene to Early Miocene, in turn, provided the opportunity for the diversification of new genera and species of infaunal benthic foraminifera that were adapted for life in dysoxic environments (Kaminski et al., 2014).

Biofacies composition and variations provide important insight about the fluctuations of low-oxygen conditions throughout this region of the Gulf of Mexico. The occurrences of the Agua Salada Fauna and the

Uvigerina-dominated calcareous biofacies (accompanied by sporadic floods of *Bulimina* and *Bolivina*) in the wells studied indicate that paleoenvironments were intermittently characterized by high organic matter/low-oxygen conditions.

Benthic foraminiferal faunas indicate paleoenvironments with fluctuating oxygen levels at different depths in different wells with low oxygen conditions that began by the earliest Middle Miocene at Viosca Knoll 736 (in the oldest Miocene samples, ca. 15.5 Ma using the chronology of Aubry et al., in press) and in the Middle Miocene at Main Pass 254 (Fig. 9; ca. 13.5 Ma using chronology of Aubry et al., in press). Main Pass 254 yielded the oldest sediments with benthic foraminiferal assemblages that indicate normal oxygen levels, but the presence of ~1–2 Myr unconformities (Aubry et al., in press) makes it difficult to pinpoint the onset of low oxygen conditions in this region, except to note that at the paleodepths of Viosca Knoll (~600 m), a strong oxygen minimum zone existed by ca. 15.5 Ma. Intensified low oxygen paleoenvironments became evident at all wells by the Late Miocene with the earliest occurrences of the Agua Salada Fauna in at least two, and probably three, wells (Viosca Knoll 736, Viosca Knoll 817, and Mississippi Canyon 455) and the development of a *Uvigerina* spp. biofacies at two wells (Ewing Bank 788 and Main Pass 254). The Agua Salada Fauna occurred at Viosca Knoll 736 and Mississippi Canyon 455 in Late Miocene (Biochron NN10; ca. 8–7 Ma using chronology of Aubry et al., in press), while it occurred earlier at Viosca Knoll 817 (Middle Miocene, Biochron N12–14; ca. 9–7 Ma using chronology of Aubry et al., in press). While the section at Green Canyon 152 contains no Miocene sediments, the Lower Pliocene is characterized by abundant agglutinants with common *Uvigerina* spp. and *Gyroidinoides* spp., possibly indicating oxygen depletion.

The disappearance of the Agua Salada Fauna in late Biochron NN11 (Late Miocene) appears to be synchronous at two wells (Viosca Knoll 817 and Mississippi Canyon 455; there are no samples above this at Viosca Knoll 736). This may indicate increased oxygenation as more normal paleoenvironmental conditions returned to this region. Better oxygenated conditions are recorded in the calcareous faunas at Viosca Knoll 817 by the latest Miocene and at Green Canyon 152 in the late Early Pliocene, while *Uvigerina*-dominated biofacies indicate that lower oxygen conditions still prevailed (although weakened) through the Pliocene at Main Pass 254 and Mississippi Canyon 455 (3–4 Ma using chronology of Aubry et al., in press).

The expansion of the uvigerinid biofacies in the Gulf of Mexico Eureka boreholes (Katz & Miller, 1993b) provides additional evidence of the development of lower oxygen conditions as the result of an expansion or migration of the oxygen minimum zone in the Middle to Late Miocene. This expansion of low oxygen conditions was progressive, beginning in the earliest Middle Miocene, peaking in the Late Miocene, and continuing into the Pliocene:

- 1) The *Uvigerina* biofacies appears in the earliest Middle Miocene at Viosca Knoll 736 (in the oldest Miocene samples, ca. 15.5 Ma using the chronology of Aubry et al., in press) and Middle Miocene at Main Pass 254 (ca. 13.5 Ma using chronology of Aubry et al., in press),

as it does in the Gulf of Mexico Eureka coreholes (Katz & Miller, 1993b).

- 2) The Agua Salada biofacies dominated in the Late Miocene (ca. 8–7 Ma using chronology of Aubry et al., in press) at Viosca Knoll 736 and Mississippi Canyon 455 and earlier at Viosca Knoll 817 (ca. 9–7 Ma using chronology of Aubry et al., in press), perhaps indicating the lowest oxygen conditions.
- 3) Low oxygen conditions continued into the Pliocene (3–4 Ma using chronology of Aubry et al., in press), as indicated by the dominance of *Uvigerina* and agglutinants.

An expansion of the oxygen minimum zone during the Late Miocene has been reported widely in other basins (e.g., Indian Ocean, Dickens & Owen, 1999; offshore West Africa, Preece et al., 1999), along with a widespread increase in export production (e.g., Filipelli, 1997; Diester-Haas et al., 2002, 2006; see summary in Cawthorn et al., 2014). Our study documents a Middle Miocene–Pliocene decrease in oxygen across the bathyal zone of the Gulf of Mexico, with lowest oxygen in the Late Miocene, supporting a global cause for this event, as advocated by Cawthorn et al. (2014).

SUMMARY AND CONCLUSIONS

We document Neogene benthic foraminiferal biofacies changes in a transect of six Gulf of Mexico industry wells (sidewall and cutting samples). The transect is located offshore from Alabama to Louisiana and extends from Main Pass to Green Canyon. Occurrences of benthic foraminifera that are useful for stratigraphy, paleoenvironments, and/or paleobathymetry are documented. This allows us to reconstruct the regional paleobathymetric and paleoenvironmental history of the area.

Benthic foraminiferal faunas indicate that Neogene paleodepths increased along the transect from shallowest in the east to deepest in the west. The distribution of assemblages dominated by the Agua Salada Fauna and *Uvigerina* spp. in this transect provides important insight on lateral and vertical variations of low-oxygen conditions through time in the northern Gulf of Mexico, which provides the framework for interpreting and correlating environmental changes in nearby sections.

Low-oxygen/high-organics conditions occurred periodically by the earliest Middle Miocene (ca. 15.5 Ma) at ~600 m paleodepth and intensified at all locations by the Late Miocene. In Upper Miocene–Pliocene sediments, changes in oxygen levels appear to have been related to paleodepth, in response to expansion or migration of the oxygen minimum zone. Our findings support a global cause for this event (see summary in Cawthorn et al., 2014). Our study shows that transects using industry wells (sidewall and cutting samples) can be used to reconstruct benthic foraminiferal distributions in space and time, and to reconstruct paleobathymetric and paleoenvironmental changes.

ACKNOWLEDGMENTS

We thank Tom Dignes and an anonymous reviewer for their comments on this manuscript and Mitch Lyle for useful advice. We are grateful to Marie-Pierre Aubry and Bill

Berggren for detailed comments and especially for their meticulous attention to the biostratigraphy cited herein. This paper stems from research undertaken at the request of a consortium of oil companies as a contribution to the Deep Water Benthic Foraminiferal Project (DWBF) funded through the Woods Hole Oceanographic Institution from 1975 to ~1995. British Petroleum, Chevron, Marathon, and UNOCAL contributed well samples and data; this project was also supported by Texaco.

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Received 7 February 2018

Accepted 16 August 2018

APPENDIX 1

Taxon percentages of sidewall samples from Chevron Main Pass Block 254. This appendix can be found on the Cushman Foundation website in the JFR Article Data Repository (<https://cushmanfoundation.allenpress.com/JournalofForaminiferalResearch/DataRepository>) as item number JFR_DR_2018010