APPLICATION OF A STATISTICALLY DERIVED, INTEGRATED BIOZONATION TO A DEEPWATER MIOCENE GULF OF MEXICO FIELD

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ABSTRACT: To refine Unocal's Gulf of Mexico deepwater Miocene biozonation, a statistically rigorous methodology was applied to an extensive micropaleontological database of wells penetrating the Miocene. Over a two-year period, we analyzed, in an integrated manner, the stratigraphic distribution of calcareous nannofossil and foraminiferal species that resulted in improvements in age dating and correlation for both exploration- and development-scale projects. Our approach was to first begin with a detailed evaluation and validation of bioevents of many hundreds of Miocene-age taxa using hardcopies of species distribution charts (BugCAD plots), followed by analysis of results processed through specialized computer software (IPS and BioSlot). This process yielded the placement of the more common types of bioevents (i.e., species range tops and bases), and in addition aided in the recognition of new, useful, subordinate bioevents (e.g., first downhole increases). All bioevents were then analyzed using the ranking and scaling probabilistic sequencing method (RASC), and the correlation and scaling in time method (CASC). The RASC/CASC methods resulted in the most probable order, termed the "optimum sequence" for the Miocene-age biostratigraphic events. This optimum sequence has been empirically validated by its successful application to correlations of previously drilled wells currently in production in a deepwater Gulf of Mexico field.

KEYWORDS: Gulf of Mexico, Mad Dog, Miocene, foraminifera, calcareous nannofossil, RASC

INTRODUCTION

A fundamental task in petroleum exploration and development is subdividing basins into mappable units. Microfossils have long been the dominant tool used to develop mappable horizons for correlations across fields and throughout basins. Traditionally, the science of biostratigraphy in the petroleum industry focused on extinction levels (range tops) of species as the key horizon. However, in an effort to increase biostratigraphic resolution, it is helpful to investivate the usefulness of nontraditional bioevents (e.g., first downhole increases, acmes, etc.). The greater the number of mappable units, the greater the ability of geoscientists to understand the various elements of the petroleum system.

Many wells have been drilled throughout the Gulf of Mexico (GOM), resulting in an extensive biostratigraphic database containing abundant detailed digital data on calcareous nannofossils and foraminifera. These data are usually derived from biostratigraphic analysis performed on cuttings; however, occasionally core is taken in key stratigraphic units. This work formed the basis for a Unocal-directed summer internship project in 2003, in which all data were derived from the same contractor (BugWare Inc.). In an attempt to refine Unocal's GOM deepwater Miocene biozonation, statistical methods were used for a set of wells that penetrated the Miocene interval. As nontraditional bioevents are added to the refined biozonation, it is necessary to determine the reliability of each bioevent. The statistical tool used to determine reliability is ranking and scaling (RASC).

Gradstein and Agterberg (1982) introduced the basic concepts of RASC in a study of Cenozoic foraminifera in offshore wells drilled along the northwestern Atlantic margin. A more detailed methodology and application were later presented by Gradstein et al. (1985). Modifications of the RASC method have taken place over the past ten years (Agterberg and Gradstein, 1997a, 1997b, 1999; Agterberg et al., 1999; Gradstein and Agterberg, 1998).

For a complete explanation of the RASC technique, see Agterberg and Gradstein (1999). In summary, ranking and scaling is a statistical, probabilistic technique that computes "crossover frequencies" of pairs of species events in multiple wells. "Crossovers" are simply the occurrences of bioevents in reversed order. RASC analysis results in a composited average, or most probable order of biostratigraphic events. This is called the "optimum" sequence. For each species bioevent in the optimum sequence a standard deviation is calculated, which separates highly reliable events (low standard deviation) from less reliable events (high standard deviation). In addition to producing information about the reliability of each bioevent, it is also possible and useful to plot randomly selected wells against the optimum sequence, which provides information about sedimentation rates, unconformities, and projection of events.

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The Mad Dog Field occupies Blocks 782, 783, and 826 in the Green Canyon protraction area of the deepwater Gulf of Mexico, approximately 320 km south of New Orleans (Fig. 1). The water depth over the field ranges between ~ 1370 and ~ 2070 m. The field is a faulted, four-way closure located along the Sigsbee escarpment. Three reservoir sands have been discovered in the lower Miocene. The sands have been interpreted as turbidite sands, and are laterally continuous over several kilometers. All three sands are medium to fine grained, and represent about 110 m of total thickness (Smith et al., 2001). The field was first discovered in 1998. Production began in January 2005, and total reserves are estimated at 200–450 million barrels oil equivalent.

With the reservoir sands located under salt, and at subsurface depths greater than ~ 6100 m, seismic correlation and mapping were unreliable. Thus, biostratigraphic data proved to be an essential tool for correlating key sands. In an effort to increase success with correlations among wells in the Mad Dog Field, the Miocene optimum sequence produced in the previous project (summer 2003) was applied. The methods for creating the optimum sequence are explained below, as is the process of applying it to the Mad Dog Field.

METHODS

Thirteen wells that collectively spanned the Miocene section were chosen for analysis (Table 1). Wells were selected based on quality of biostratigraphic data, and depth of penetration within the Miocene. It was important to incorporate as many wells as possible that spanned the most complete Miocene section in order to observe all of the possible bioevents.

Defining Bioevents

The quality of statistical data produced from RASC analysis is dependent on being consistent with the rules used to define various bioevents. In order to produce additional reliable and useful bioevents, it is necessary to define the criteria that define each bioevent. Biostratigraphers may have different ideas for what constitutes nontraditional bioevents (e.g., first downhole increase, acme, etc.); uncertainty can exist in consistently defining these events from well to well (Fig. 2). For the current study, particular rules were established based on careful examination of the species abundance data. These rules were modified if necessary. A final set of rules was strictly obeyed as we worked through the data from several Miocene deepwater Gulf of Mexico wells, and are provided in Figure 3.

Capturing and Recording Bioevents

The various bioevents were captured for all calcareous nannofossil and foraminifera species using BugCAD charts (hard-copy species distribution charts generated by a BugWare Inc. software

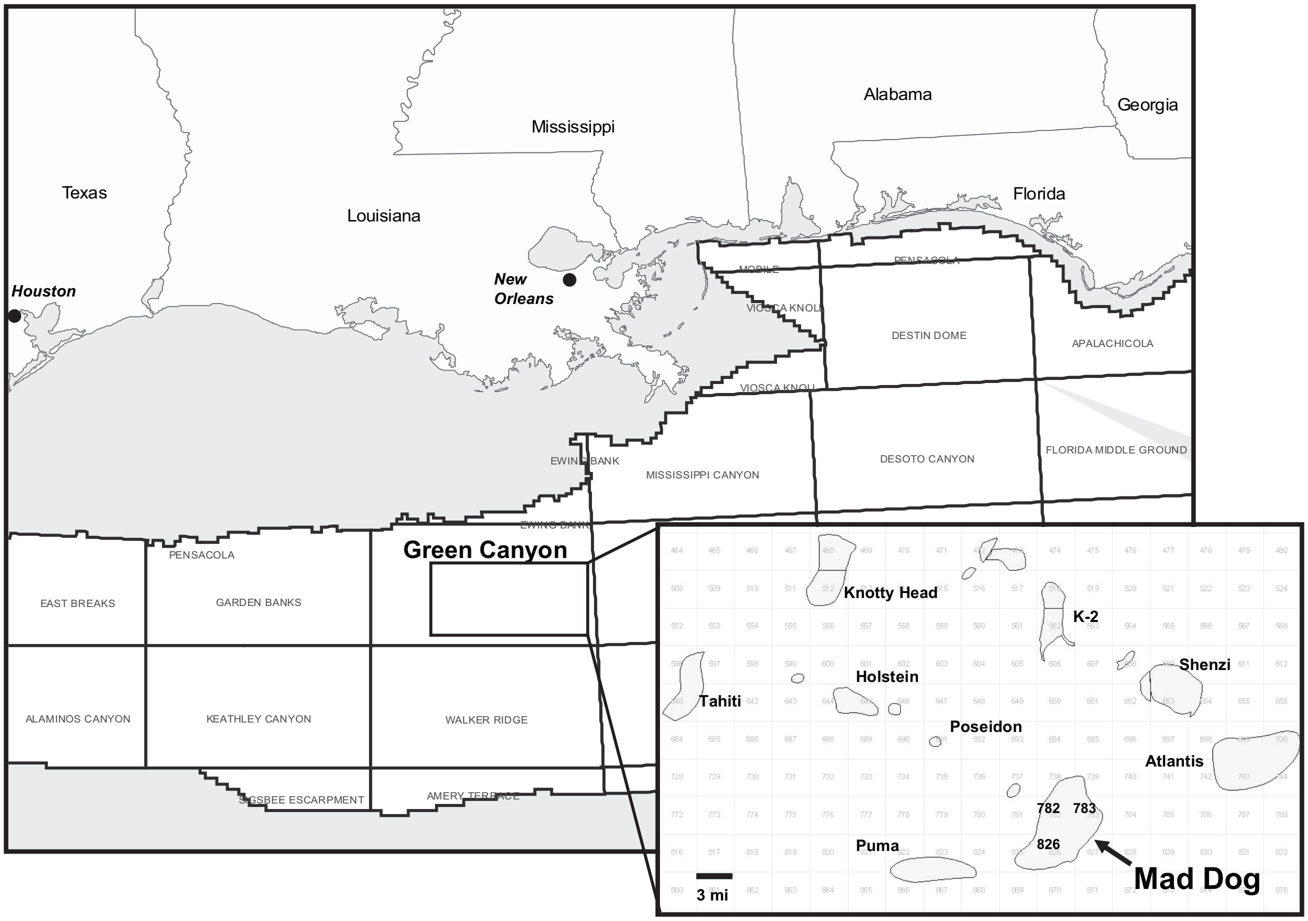

FIG. 1.—Map of Mad Dog Field, Green Canyon, Gulf of Mexico. Inset map illustrates zoomed in location of the Mad Dog Field (GC 782, 783, 826).

TABLE 1.—List of wells used to determine Miocene optimum sequence.

Protraction Area/Block	Operator	Well Number	Field
Keathley Canyon 774	Unocal	1	Ponza
Walker Ridge 456	Texaco	1 ST1	Loyal
Walker Ridge 678	Unocal	1	Dana Point
Green Canyon 782	BP	3	Mad Dog
Green Canyon 562	Conoco	1	K2
Green Canyon 562	Agip	2 ST1	K2
Green Canyon 872	BHP	1	Frampton
Green Canyon 785	Unocal	1	Dendara
Atwater 63	Unocal	1	Champlain
Mississippi Canyon 637	Unocal	1	Bohr
Mississippi Canyon 687	Shell	2 ST2	Deep Mensa
Mississippi Canyon 555	ExxonMobil	1 ST1	Timberwolf
Mississippi Canyon 776	BP	1	Thunder Horse North

program), as well as Integrated Paleontological System software (IPS from Tramontane Inc.). It was possible to correlate data on microfossil diversity and abundance in these plots to logs, and therefore determine key flooding horizons. Biostratigraphic events are chosen most reliably in intervals where there is good fossil preservation, such as times of maximum flooding or peak transgressions of sea level.

Each well has between 32 and 57 bioevents, with the average number of bioevents per well being 46. The number of bioevents in each well depends on depth of penetration (age) and quality of microfossil preservation. Data from each well were recorded in ASCII files, listing depth for each specific bioevent and the name of the particular bioevent (e.g., "*Sphenolithus dissimilis* TOP"). Recorded bioevents were then prepared for several iterations of RASC.

Ranking and Scaling Analysis

Ranking and scaling (RASC) is a two-step, statistically constrained analytical procedure that helps the biostratigrapher to create an integrated biozonation. The first step is to rank or order the bioevents in a sequence, and the second step is to statistically determine the relative distances between all the bioevents. The ordering of the bioevents is based simply on the number of times a bioevent occurs above, below, and coincident with a second bioevent in each well that the two bievents co-occur (Gradstein et al., 1990). The bioevent that occurs with the greatest frequency above the other is considered to be the stratigraphically higher event. If both bioevents in a pair have the same frequency, then their stratigraphic order is indeterminate. A complete biozonation sequence is created by calculating the bioevent order on the basis of the frequencies for all possible bioevent pairs in the biozonation.

The second step in the procedure, scaling, determines the relative separation between the ranked bioevents. The separation distance is a function of the frequency that a bioevent occurs above a second bioevent, weighted by the number of wells in which the two bioevents co-occur (Gradstein et al., 1990). The higher the frequency (i.e., the lower the number of crossovers between the two bioevents) the larger the distance, scaled as quantiles of the standard normal distribution, separating the two bioevents. If one bioevent of a pair occurs above the second with a frequency of 0.5, then there is no evidence that the two are stratigraphically separated at the resolution of sampling; therefore their separation distance is zero. A frequency of or near 0.5 results from an equal or nearly equal number of crossovers between the occurrences of two bioevents, and therefore, assuming that the occurrences are *in situ*, suggests that there is little stratigraphic separation between the two. Alternatively, crossovers can also be a result of factors such as reworking of older sediment into the section of interest, caving of younger sediment from higher in the well, diagenesis and/or misidentification of the species, and basic sampling errors (Agterberg and Gradstein, 1999).

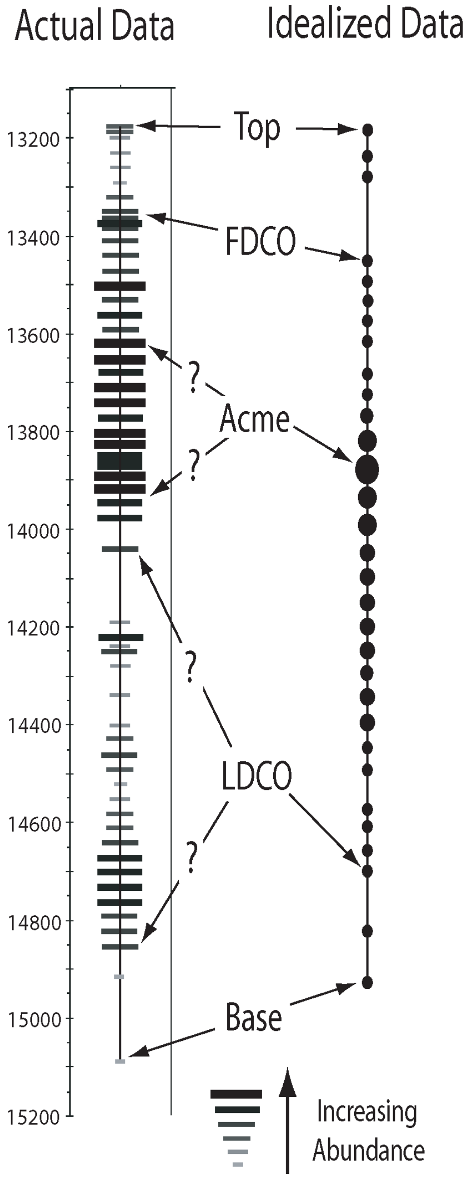

FIG. 2.—"Idealized species" vs. "actual data," illustrating the fact that there are debatable depths for certain bioevents. The depths shown are in feet (1.0 ft = ~ 0.3 m), and only represent an example.

In this study we performed two RASC runs with our data using different control parameters. The parameter with the greatest impact on the results was the minimum number of wells in which a bioevent must occur to be included in the analysis ("*k*" value). As *k* increases, the threshold conditions become more stringent, and therefore the total number of bioevents included in the sequence decreases. Conversely, a lower *k* value relaxes the conditions, resulting in a larger number of bioevents included in the sequence. Determining the appropriate value of *k* is subjec-

HO = Highest stratigraphic occurrence
- Cannot be in a sand body (potential reworking)

TOP = Extinction level
- Based on biostratigraphic interpretation

FDI = First downhole abundance increase
- Change from low abundance (few specimens) to at least 20

FDCO = First downhole common and consistent occurrence
- "Common" = 50 or more specimens per sample
- Greater than 90 ft of "common" interval
- No samples with > 50 specimens above FDCO event
- No breaks > 90 ft within "common" interval (3 continuous occurrences)

LCDO = Last downhole common and consistent occurrence
- Analogous to FDCO

ACME = Abundance spike
- Short and abrupt event
- If many possibilities, largest peak chosen

BASE = Evolutionary first appearance
- Based on biostratigraphic interpretation

LO = Lowest stratigraphic occurrence
- Cannot be in a sand body (potential caving)

FIG. 3.—Rules created to determine bioevents.

tive, requiring the biostratigrapher to balance statistical robustness with the completeness of the biozonation. In our RASC analyses we used *k* values of 6 and 7.

Application to Mad Dog Field

The optimum sequence generated during the 2003 summer internship project was used to help with correlations in the Mad Dog Field. Because this work was applied to the Mad Dog wells during the production phase, it was treated as a test to determine how the refined biostratigraphic correlations compare to accepted log and seismic correlations.

Original biostratigraphic correlations within the Mad Dog Field suffered from numerous crossovers of bioevents used for correlation among the wells. Adopting the most reliable bioevents from the optimum sequence eliminates most bioevent crossovers, and allows more accurate correlations. The primary goal was to better understand the sand geometries of the Mad Dog Field, and increase potential for future exploration and development success in equivalent sections basinwide. The four wells used in this project were analyzed in StratWorks. All previous biostratigraphic correlations were deleted and replaced with those from the optimum sequence.

RESULTS

The correlation scheme of the generated optimum sequence increased biostratigraphic resolution, eliminated less reliable bioevents, and added key nontraditional bioevents. During RASC analysis, an initial *k* value of 7 was used as the threshold parameter for the minimum number of wells in which a bioevent must occur to be included in the optimum sequence. For comparison, a *k* value of 6 was used in later iterations of RASC. The RASC run with $k = 7$ produced 71 total bioevents in the optimum sequence, 49 of which had standard deviations below the average. In contrast, the RASC run with $k = 6$ produced 91 total bioevents in the optimum sequence, with 61 bioevents possessing standard deviations lower than the average. We decided that a *k* value of 6 produced the preferred optimum sequence because it contained the most bioevents while maintaining a reliable and manageable output. Therefore $k = 6$ results in the most useful optimum sequence. After each run, bioevents that had standard deviations greater than the average were eliminated. In addition, some bioevents involving the highest occurrence (HO) and lowest occurrence (LO) of species were deleted from the optimum sequence. When compared to the accurate surrounding biostratigraphic markers, many of the HOs and LOs appeared out of place as a result of reworking or caving, respectively. This step was performed based on knowledge and experience of biostratigraphy of calcareous nannofossils. For example, *Discoaster bollii* HO appears in the Latest Miocene as a result of reworking (i.e., the true extinction of the species is older).

The average standard deviation produced by the final RASC run ($k = 6$) was 4.80. After the unreliable bioevents were omitted, a total of 38 bioevents were produced, of which 34 were calcareous nannofossil events. Table 2 illustrates the final optimum sequence, showing the list of bioevents with their standard deviations, and the number of wells in which each occurred.

The four wells in the Mad Dog field used in this study to refine the biostratigraphic correlation are the GC826 (Amoco 1 ST1), GC783 (BP 1), GC782 (BP 3), and GC782 (Unocal 4) (Fig. 4). The correlation lines are based on bioevents that were derived from the optimum sequence. Most bioevents throughout the entire Miocene have very low crossover frequencies. However, because the most crucial reservoirs in the Mad Dog Field are of Middle and Early Miocene age, the focus of the biostratigraphic correlations was directed to these intervals. Figure 4 illustrates the biostratigraphic correlations for the entire Miocene, created using the bioevents produced from the optimum sequence. The most useful nontraditional bioevents produced from this work, and used for correlation of wells in the Mad Dog field, are: *Minylitha convallis* BASE, *Discoaster bollii* BASE, *Sphenolithus heteromorphus* FDI, *Discoaster deflandrei* FDI, *Discoaster petaliformis* FDI, and *Sphenolithus heteromorphus* BASE. Of these new bioevents, *Sphenolithus heteromorphus* FDI, *Discoaster deflandrei* FDI, *Discoaster petaliformis* FDI, and *Sphenolithus heteromorphus* BASE have proven critical for the correlation of key reservoir sands in the Middle to Early Miocene.

CONCLUSIONS

Biostratigraphic correlations between wells across fields is a crucial tool for mapping key sands. The higher the biostratigraphic resolution, the greater the potential in understanding the connectivity and character of important stratigraphic units. The goal of this work was to determine new and reliable bioevents to help build a higher-resolution biostratigraphic correlation throughout the Mad Dog Field. The steps followed to achieve this goal were: to build criteria (rules) for establishing new bioevents to add biostratigraphic resolution, identify these new bioevents, run the new bioevents through RASC analysis to produce a valid optimum sequence, and use the produced optimum sequence for improved correlation of key sands in the Mad Dog Field.

The optimum sequence of bioevents generated in this study resulted in low crossover frequencies. Important nontraditional

TABLE 2.—Miocene optimum sequence produced by RASC analysis. The standard deviation and the number of wells each bioevent occurs in is listed. Calcareous nannofossils and foraminifera are listed (foraminifera events followed by asterisk).

Event	S.D. (Avg. = 4.80)	Number of Wells (out of 13)
Discoaster pentaradiatus BASE	3.19	7
Discoaster surculus BASE	3.66	7
Discoaster quinqueramus BASE	2.19	6
Discoaster bollii TOP	1.89	6
Minylitha convallis BASE	2.63	7
Discoaster bollii BASE	2.33	10
Discoaster prepentaradiatus BASE	2.26	6
Discoaster neohamatus BASE	2.12	7
Discoaster brouweri BASE	4.20	7
Catinaster coalitus TOP	1.82	8
Discoaster exilis TOP	1.73	6
Coccolithus miopelagicus TOP	3.10	12
Discoaster musicus TOP	4.44	9
Discoaster sanmiguelensis TOP	3.24	10
Calcidiscus premacintyrei TOP	2.39	9
Globorotalia peripheroacuta TOP*	4.25	9
Cyclicargolithus floridanus TOP	1.74	11
Globorotalia peripheroronda TOP*	4.81	7
Discoaster deflandrei TOP	4.66	11
Sphenolithus heteromorphus TOP	2.62	11
MMR	2.95	8
Cyclicargolithus floridanus FDI	3.90	11
Sphenolithus heteromorphus FDI	2.75	11
Calcidiscus premacintyrei FDI	3.92	6
Discoaster petaliformis TOP	1.97	11
Globorotalia peripheroacuta BASE*	3.51	8
Orbulina universa BASE*	4.11	7
Discoaster petaliformis FDI	2.91	7
Helicosphaera ampliaperta TOP	3.69	10
Discoaster petaliformis BASE	4.09	9
Discoaster deflandrei FDI	1.93	8
Helicosphaera kamptneri-carteri ACME	4.50	9
Sphenolithus heteromorphus ACME	3.58	11
Sphenolithus heteromorphus BASE	3.24	7
Sphenolithus belemnos TOP	2.17	7
Discoaster calculosus TOP	3.63	8
Discoaster deflandrei ACME	4.20	6
Triquetrorhabdulus carinatus TOP	2.27	6

bioevents were also identified. Improved biostratigraphic control led to more accurate sand correlations in the Mad Dog field, where deepwater wells are drilled to great depths, below salt, in structurally complex sections where seismic resolution decreases. Statistically derived biozonations should continue to add significant value in the Gulf of Mexico and other major basins throughout the world.

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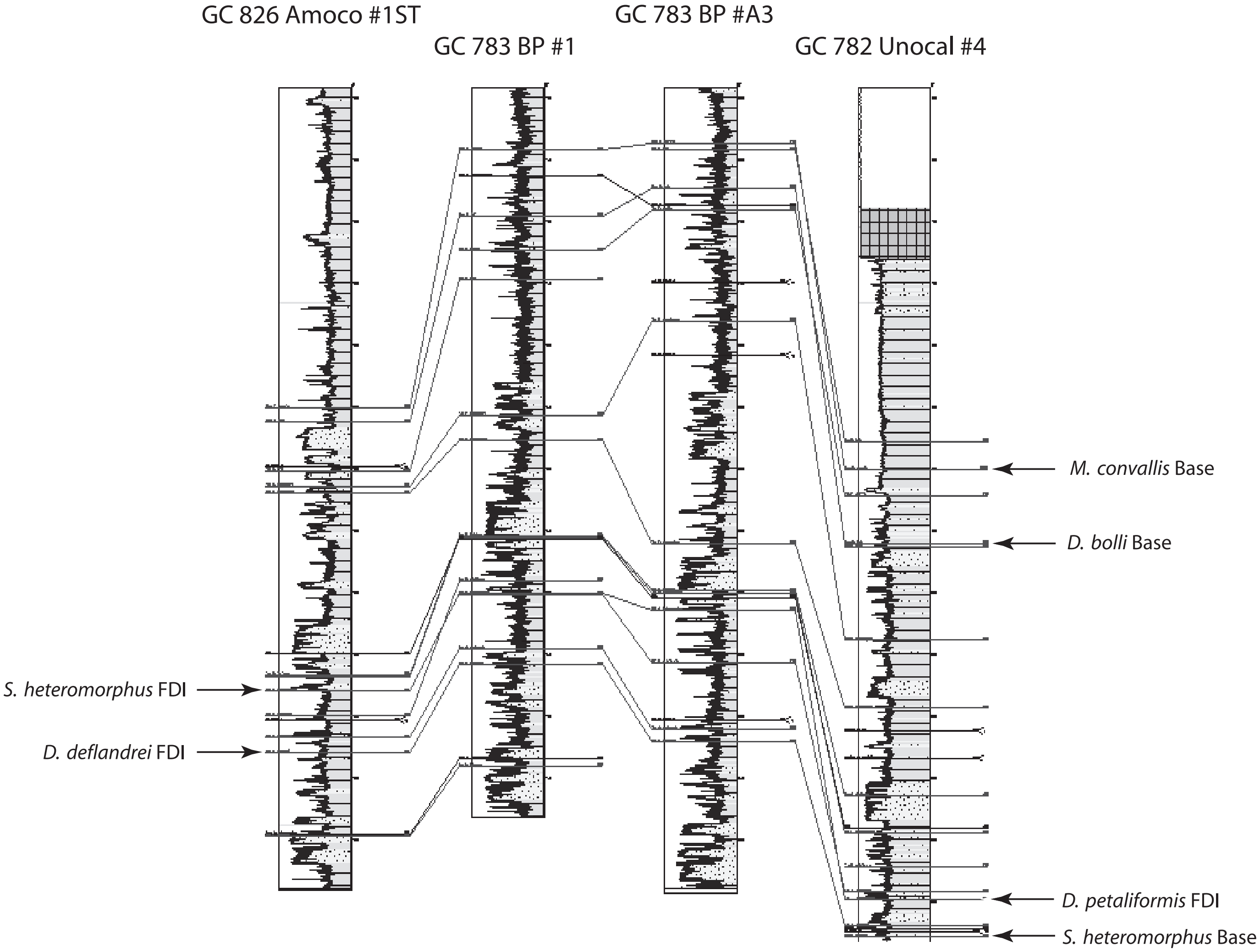

FIG. 4.—Application of nontraditional bioevents from optimum sequence used in correlation of Mad Dog Field.

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