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Misuse of Fischer plots as sea-level curves

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ABSTRACT

Fischer plots are graphic representations of cyclic carbonate deposits showing cumulative departure from average cycle thickness plotted against cycle number and corrected for assumed subsidence during each cycle. Observed cycle thicknesses in excess of subsidence have been interpreted to represent depositional accommodation space formed by eustatic sea-level rise. However, implicit in this interpretation is the assumption that preserved cycle thickness is a proxy for accommodation. To test this assumption, a survey of carbonate-sediment accumulation patterns (i.e., cycle thicknesses) developing during a single transgressive event (the Holocene postglacial sea-level rise) was conducted on a shallow carbonate platform (Great Bahama Bank) where accommodation was created primarily by sea-level rise over the platform margin (i.e., subsidence was minimal). This survey demonstrates that Holocene sediment (cycle) thickness and accommodation are uncorrelated ($r^2 = 0.03$). Consequently, Fischer plots constructed by using Holocene cycle thicknesses are poor representations of the Holocene transgression. In extreme examples, Holocene Fischer plots would be interpreted to show relative sea-level fall during the Holocene on Great Bahama Bank because Holocene subsidence currently exceeds sediment thickness. In addition, a simple sensitivity test shows that eustatic sea-level interpretations based on interbasinal correlation of Fischer plots are equivocal. The gross form of Fischer plots appears so overly robust as to be insensitive to broad variations in stratigraphic completeness, cycle duration, or subsidence. Because cycle thickness apparently is uncorrelated with accommodation and the gross form of Fischer plots is relatively invariant, it seems prudent to reevaluate the practice of interpreting Fischer plots as sea-level curves per se in the analysis of ancient carbonate cycles.

INTRODUCTION

Fischer (1964) introduced a graphic method of displaying relative sea-level changes (i.e., sea-level change represented as the sum of subsidence and eustasy) derived from cyclic limestones and dolostones. These Fischer plots are two-dimensional representations of stratigraphic sections; the horizontal axis is plotted as cycle number (assumed to represent total depositional duration of the stratigraphic section) and the vertical axis is a subsidence-corrected value labeled "cumulative departure from average cycle thickness" (Sadler et al., 1993; Fig. 1A).

To interpret relative sea-level changes from Fischer plots, individual cycles are plotted along the horizontal axis assuming that the depositional interval for each cycle is of uniform duration and equal to the average cycle duration, determined by dividing total time represented by the stratigraphic section by the total number of cycles (Fischer, 1964; Koerschner and Read, 1989; Hardie et al., 1991; Osleger and Read, 1991, 1993). A constant is subtracted from cycle thickness to correct for subsidence during each cycle. In some instances, an additional correction for effects of differential compaction may be applied (Bond and Kominz, 1991). Decompacted cycle thicknesses in excess of subsidence during each depositional episode are thus assumed to represent accommodation space created by eustasy (Sadler et al., 1993; Read and Goldhammer, 1988; Koerschner and Read, 1989; Read et al., 1986; Goldhammer et al., 1987, 1990; Osleger and Read, 1991, 1993).

It is clear that a eustatic interpretation of Fischer plots requires acceptance of both explicit assumptions (suppositions of constant duration for each cycle and constant subsidence throughout the cyclic succession) and implicit assumptions (stratigraphic completeness, each cycle representing a single sea-level event and decompacted cycle thickness being a reasonable proxy for accommodation), which can be difficult to affirm or reject from stratigraphic data (Bond and Kominz, 1991; Hardie et al., 1991; Kozar et al., 1990; Goldhammer et al., 1987, 1990, 1993; Koerschner and Read, 1989; Read and Goldhammer, 1988; Fischer, 1964; Tedesco and Wanless, 1991; Osleger and Read, 1991, 1993; Sadler et al., 1993; Sadler and Strauss, 1990; Drummond and Wilkinson, 1993; Rankey et al., 1994).

Of critical importance in the interpretation of Fischer plots as sea-level curves is the latter assumption that cycle thickness is a reasonable approximation of accommodation. This study reports on a unique test of this assumption utilizing data on patterns of sediment accumulation (i.e., cycle thickness) resulting from a single transgressive (i.e., accommodation) event across a mod-

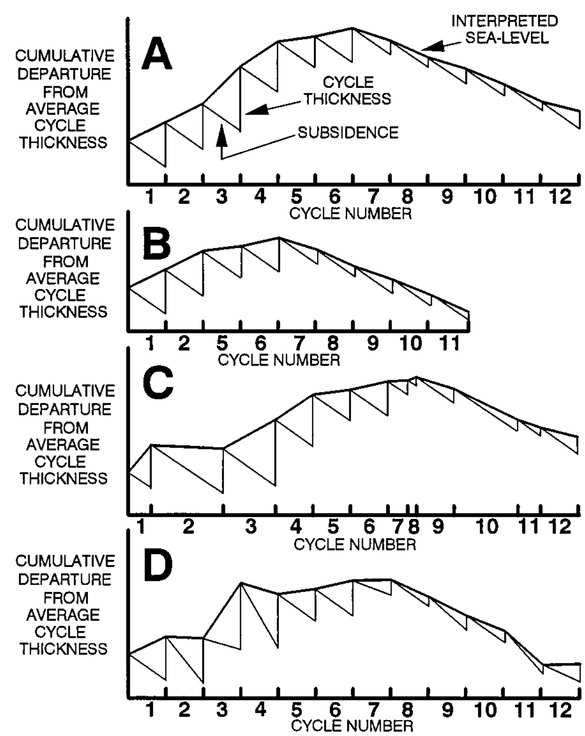

Figure 1. A: Schematic Fischer plot. Horizontal axis is cycle number but is intended to represent total duration of measured stratigraphic interval assuming constant duration for individual cyclic units. Vertical axis is cumulative departure from mean cycle thickness (Sadler et al., 1993). Solid line connecting tops of individual cycles across diagram is interpreted as eustatic sea level. B: Fischer plot constructed with stratigraphic incompleteness by omitting cycles 3, 4, and 12. C: Fischer plot constructed by arbitrarily varying cycle duration from 0.25 to 2 times duration in A. D: Fischer plot constructed by arbitrarily varying subsidence from 0.25 to 2 times relative to subsidence in A. In B through D, shape of plots is grossly similar to original (A), despite variations in stratigraphic completeness, cycle duration, or subsidence. Note also that if these four plots were assumed to represent eustatic event from four different basins, alignment of crests of these plots (i.e., coincidence of "highstand") yields spurious cycle correlations as "highstand" shifts from cycle 6 (A, B) to cycle 8 (C), to cycle 7 (D).

ern carbonate platform (northern Great Bahama Bank; Fig. 2).

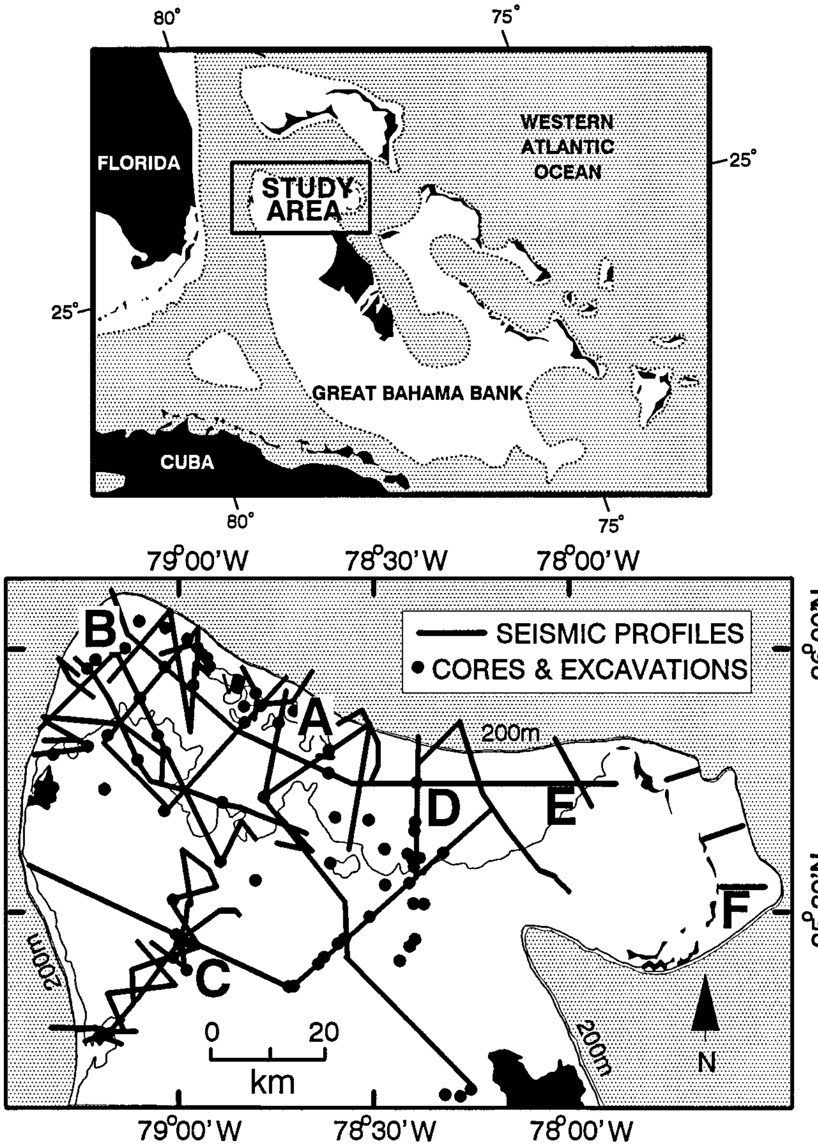

Figure 2. Location map of northern Great Bahama Bank showing positions of single-channel, high-resolution seismic-reflection profiles (lines) and "ground truth" (circles) as sediment cores (56), rock cores (12), submarine excavations (24), and bottom observations. A–F are locations of Fischer plots illustrated in Figure 5. Platform margin is defined by 200 m isobath.

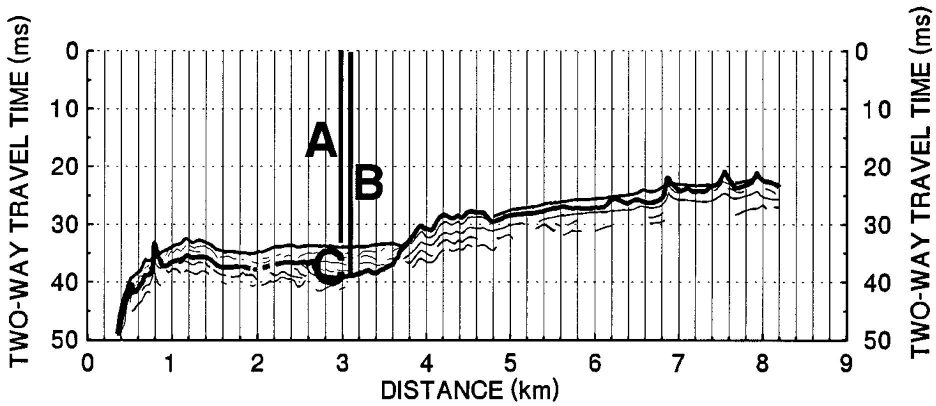

Figure 3. Digitized part of interpreted seismic profile illustrating method of measurement used in this study. Grid was overlaid on digitized data with nodes at 250 m intervals. At each node, depth (two-way traveltime in milliseconds) to Holocene sediment-water interface (A) and Holocene-Pleistocene unconformity (B) were recorded. Sediment thickness (C) was then calculated by subtracting B from A (i.e., A − B = C).

METHODS

A network of >1600 km of high-resolution, single-channel seismic-reflection profiles across the northern Great Bahama Bank provided the primary database for this study (Fig. 2). Ground confirmation consisted of sediment cores (56), rock cores (12), submarine excavations (24), and bottom observations across the platform. Processing of seismic data involved digitizing interpreted analog seismic profiles, which were then overlaid by a grid with nodes spaced at 250 m intervals (Fig. 3). At each grid node, the two-way traveltimes (in 10^{-3} s) to the Holocene sediment surface (A in Fig. 3) and the Holocene-Pleistocene unconformity (B in Fig. 3, representing total accommodation) were measured. These data were converted to depths (in metres) assuming a P-wave velocity in seawater and unconsolidated, water-saturated sediments of 1500 m/s. No corrections for increased velocity of P waves through sediments were applied (an average sediment thickness of 3.3 m and assumed P-wave velocity through sediments of 1800 m/s rather than 1500 m/s yields a maximum difference in depth-to-Pleistocene of ~0.25 m, which was considered negligible). Holocene sediment thickness (i.e., cycle thickness) was determined as the difference in depth to the Holocene sediment surface and depth to the Holocene-Pleistocene unconformity (i.e., A − B = C in Fig. 3).

RESULTS

Accommodation vs. Sediment Thickness

A plot of Holocene accommodation (i.e., depth-to-Pleistocene) vs. cycle thickness (Holocene sediment thickness) reveals that these two parameters are uncorrelated (r^2 = 0.03; Fig. 4). Thus, it may be inappropriate to consider cycle thickness as a proxy for accommodation in analyses of ancient limestone cycles.

To illustrate the danger of accepting the thickness-equals-accommodation assumption, several Fischer plots of the Holocene cycle across the northern Great Bahama Bank are shown (Fig. 5). Each plot was constructed from a bank-top location where the depth-to-Pleistocene (i.e., accommodation) was 26 m, representing a depositional interval of ~10 ka. A subsidence correction of 0.02 m/ka (Pierson, 1982) over the depositional interval was subtracted from observed cycle thicknesses. If one accepts the assumption that cycle thickness approximates accommodation, a Fischer plot similar to that labeled "Holocene transgression" (Fig. 5) should be evident for the Holocene cycle.

However, the closest approximation indicates a subsidence-corrected eustatic event of 11.2 m (Fig. 5B), or 43% of the actual eustatic rise at that site. Other observed sediment thicknesses for 26 m accommodation average 2.5 m (±2.1 m; 95% confidence interval), an order of magnitude less than the actual Holocene eustatic rise over those points. Several extreme examples would be interpreted to show a relative sea-level fall for the Holocene (Fig. 5, E and F) because subsidence currently exceeds cycle thickness. Given the range of cycle thickness and accommodation values presented in Figure 4, it is evident that at least one Fischer plot can be constructed for any desired sea level except the correct one.

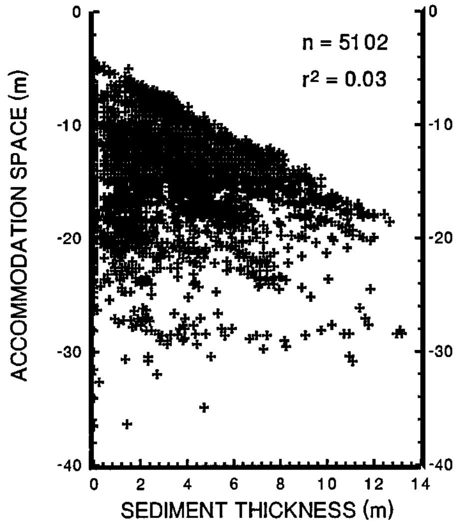

Figure 4. Scatter plot of Holocene accommodation (i.e., depth to Pleistocene) vs. cycle thickness (i.e., Holocene sediment thickness) for northern Great Bahama Bank determined from seismic data. Accommodation and cycle thickness are uncorrelated (r^2 = 0.03), indicating that cycle thickness should not be used as proxy for accommodation in analysis of ancient carbonate cycles.

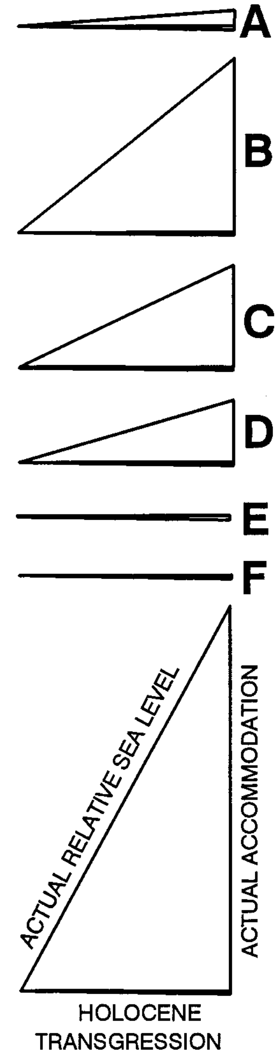

Figure 5. Representative Fischer plots constructed for Holocene cycle across northern Great Bahama Bank. Parameters used to construct these plots are cycle duration = 10 ka, subsidence = 0.02 m/ka (Pierson, 1982). Flooded interval (cycle duration) of 10 ka corresponds to accommodation depth of 26 m. Thus, if Fischer plots are valid predictors of eustasy, they should resemble plot labeled Holocene transgression. Note that maximum observed subsidence-corrected cycle thickness for 26 m accommodation (B) was 11.2 m (43% of actual eustatic rise at this point). Note that other Fischer plots are less representative of actual eustatic rise; E and F would be interpreted to show eustatic sea-level fall for Holocene because subsidence currently exceeds cycle thickness.

DISCUSSION

Relevance of Holocene Observations

It might be argued that the method employed during this study is flawed because the Holocene interval is not yet complete and observed Holocene accumulations are missing an unspecified quantity of material from the top of the cycle (i.e., that which has not yet been deposited). Three items are relevant in this regard. First, it is significant that the calculated correlation between cycle thickness and accommodation is zero, indicating that cycle thickness and accommodation are unrelated parameters. Apparently, differential sea-level rise over an irregular flooding surface (Boss, 1994) influences physical, chemical, and biological gradients across the platform that affect sediment production and sediment accumulation somewhat independently of accommodation. This result provides affirmation of the speculations of Bond and Kominz (1991) that relations among sediment accumulation rates, water depths, vertical sedimentary facies, cycle thickness, and accommodation are likely to be quite complex. Second, there are many published examples of Fischer plots where subaerial cycle tops are developed directly on subtidal facies (Fischer, 1964; Goldhammer et al., 1987, 1990, 1993; Koerschner and Read, 1989; Osleger and Read, 1991, 1993). The presence of a subaerially formed disconformity directly on marine facies indicates that an unspecified part of the top of each cycle is missing or accommodation was unfilled. Therefore, rejecting Fischer plots from Holocene settings due to incompleteness requires rejection of Fischer plots constructed from ancient cyclic limestones containing equally incomplete cycles. Finally, rejecting the observed lack of correspondence between cycle thickness and accommodation because the Holocene interval is not complete carries with it the implicit assumption that Holocene sedimentation will eventually fill available accommodation on Great Bahama Bank. Assuming that the Holocene depositional cycle represents an orbitally modulated 20 ka oscillation, filling remaining accommodation over the waning phase of the present eustatic event would require extraordinary rates of sediment accumulation (1–1.5 m/ka) which greatly exceed modal Holocene sedimentation rates (0.1–0.4 m/ka; Boss, 1994).

Fischer Plots of Peritidal Cycles, Sea Level, and Accommodation

Though the thickness of cycles dominated by subtidal deposits is a poor predictor of accommodation, this fact is less obvious in limestone and dolostone cycles capped by peritidal-intertidal facies. Many peritidal cycles are capped by subaerial exposure surfaces preserving near-surface features (e.g., desiccation cracks, evaporite pseudomorphs, evaporite-dissolution structures, fenestrae; Read and Goldhammer, 1988; Koerschner and Read, 1989; Osleger and Read, 1991, 1993), indicating little or no erosion of the cycle top and suggesting that these cycles represent filled accommodation (i.e., cycle thickness = accommodation). However, this is an ambiguous interpretation. Fischer (1964) recognized that peritidal cycles do not necessarily form at the accommodation peak but may develop at any stage along a declining accommodation trajectory. In this sense, peritidal cycles represent instantaneous accommodation, but no objective procedure exists to determine at what point on an accommodation curve (Bond and Kominz, 1991) sediments intercepted the declining accommodation surface. Thus, Fischer plots constructed from peritidal cycles are no more definitive representations of eustatic events than similar plots through subtidal cycles with subaerial caps.

Interbasinal Correlation of Fischer Plots

It has been claimed that correlation of the gross morphology of Fischer plots from different basins indicates globally instantaneous changes in accommodation effected by eustatic sea-level oscillations (Read and Goldhammer, 1988; Osleger and Read, 1991, 1993). It is noteworthy that the interpreted magnitude of eustatic changes envisioned for some studied time intervals (e.g., Cambrian Period) is on the order of 10 m (Read and Goldhammer, 1988), implying that the overall shapes of Fischer plots are sensitive to relatively low amplitude eustatic variations.

The utility of interbasinal correlations of Fischer plots as eustatic indicators was evaluated by a simple thought experiment (Fig. 1). First, an arbitrary Fischer plot was constructed assuming stratigraphic completeness, uniform cycle duration, and constant subsidence (Fig. 1A). To give this plot its gross form, there is a general pattern of cycle thinning from left to right, similar to the upward-thinning cyclic motif in many limestone and dolostone successions. Next, changes in the form of the Fischer plot caused by introducing stratigraphic incompleteness (Fig. 1B; removing 25% of cycles, including the two thickest for maximum effect), varying cycle duration (Fig. 1C; durations varied arbitrarily from 0.25–2 times initial durations in Fig. 1A), or varying subsidence rates (Rankey et al., 1994; Fig. 1D; rates varied arbitrarily from 0.25–2 times rates in Fig. 1A) were investigated.

In each case, the introduced variations alter both the amplitude and wavelength of the Fischer plot somewhat, but the gross morphology remains as in Figure 1A, suggesting that the Fischer plot shape is so overly robust as to be insensitive to broad variations in stratigraphic completeness and order-of-magnitude variations in cycle duration or subsidence. Given the results of this simple experiment, interpretations of eustasy based on correlations of Fischer plot form in different depositional basins should be viewed with suspicion; it seems unlikely that Fischer plot shape can be used to deconvolve eustatic sea level, especially when the magnitude of the eustatic oscillation is relatively small (<10 m) and the estimated errors defining other basin parameters are relatively large.

SUMMARY

Results of this study demonstrate that cycle thickness and accommodation across a single platform (Great Bahama Bank) during a single eustatic event (the Holocene postglacial rise) are uncorrelated ($r^2 = 0.03$). Consequently, cycle thickness is not a predictor of accommodation, a fact that may obviate the practice of interpreting Fischer plots as sea-level curves. The apparent overly robust nature of Fischer plot morphology (i.e., insensitivity to stratigraphic completeness, order of magnitude variations in cycle duration or subsidence) adds credence to the idea that observed oscillatory behavior of these diagrams is not necessarily caused by eustasy.

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