Facies control on carbonate $\delta^{13}$C on the Great Bahama Bank

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ABSTRACT

The carbon isotopic ($\delta^{13}$C) composition of shallow-water carbonates often is interpreted to reflect the $\delta^{13}$C of the global ocean and is used as a proxy for changes in the global carbon cycle. However, local platform processes, in addition to meteoric and marine diagenesis, may decouple carbonate $\delta^{13}$C from that of the global ocean. We present new $\delta^{13}$C measurements of benthic foraminifera, solitary corals, calcifying green algae, ooids, coated grains, and lime mud from the modern Great Bahama Bank. We find that vital effects, cross-shelf seawater chemistry gradients, and meteoric diagenesis produce carbonate with $\delta^{13}$C variability rivaling that of the past two billion years of Earth history. Leveraging Walther’s Law, we illustrate how these local $\delta^{13}$C signals can find their way into the stratigraphic record of bulk carbonate.

INTRODUCTION

Carbon isotope composition ($\delta^{13}$C) is widely studied in the stratigraphic record because it may be a window into Earth’s ancient carbon cycle. The apparent reproducibility of carbonate $\delta^{13}$C trends, both within basins and between continents (e.g., Knoll and Walter, 1992; Halverson et al., 2005; Saltzman and Thomas, 2012), supports the model of $\delta^{13}$C being a reliable proxy for ancient ocean chemistry. However, the high amplitude of ancient $\delta^{13}$C variability can be hard to reconcile with reasonable global carbon-cycle dynamics (e.g., Berner, 2006; Belcher et al., 2010). Additionally, recent work on and around modern carbonate platforms suggests important roles for meteoric and marine diagenesis (Allan and Matthews, 1982; Swart and Eberli, 2005; Oehlerlert and Swart, 2014; Higgins et al., 2018), local platform processes (Patterson and Walter, 1994a; Swart et al., 2009; Geyman and Maloof, 2019), and organism-specific isotope fractions (Weber, 1967; Weber and Woodhead, 1969; Land, 1989; Gischler et al., 2009) in decoupling the $\delta^{13}$C of shallow carbonates from global ocean chemistry. In other words, stratigraphic $\delta^{13}$C records likely represent a convolution of (1) a primary global seawater signal, (2) primary bank-top variability, and (3) meteoric and marine diagenesis. Deconvolving these three signals could allow better insight into both the evolution of Earth’s global carbon cycle and the changing physical/geochemical processes occurring on ancient platforms. Here, we try to shed light on items (2) and (3) by exploring the extent to which vital effects, cross-shelf seawater chemistry gradients, and meteoric diagenesis shift the $\delta^{13}$C of bulk limestone away from that of global mean seawater, and how such shifts find their way into the stratigraphic record.

METHODS

We focus on the region of northwestern Andros Island (NWA, Bahamas; Fig. 1A) because of the diverse array of facies and grain types found in a navigable 2900 km$^2$ area. During the ca. 100–10 ka sea-level lowstand of the last glacial period, highstand last interglacial (LIG) coral boundstones, shallow marine mudstones to grainstones, and carbonate aeolianites were partially dissolved and cemented into strongly lithified karst by meteoric waters (Newell et al., 1959). This pre-Holocene lithified sediment consists of the island-forming bedrock. Where the lithified LIG bedrock is below mean sea level today, the LIG strata are overlain by a 0–6-m-thick blanket of unconsolidated Holocene supratidal, intertidal, and subtidal <6 ka mudstones, wackestones, packstones, grainstones, and microbially precipitated carbonates (Enos, 1974; Maloof and Grotzinger, 2012; Harris et al., 2015). We surveyed 409 sites across the study area (Fig. 1A), documenting sedimentary facies and collecting water and sediment samples for $\delta^{13}$C analysis. Sample processing and lab procedures are described in the Supplemental Material.

RESULTS

Our 4910 $\delta^{13}$C measurements of carbonate grains found on the modern surface in NWA capture the full range of $\delta^{13}$C values seen in the stratigraphic record of the past two billion years of Earth history (Fig. 1D; Saltzman and Thomas, 2012). Figure 1E illustrates how each grain type has a unique fingerprint that contributes to this $\delta^{13}$C variability. We explore three examples of how the range of $\delta^{13}$C values observed in the study area today could have contributed to $\delta^{13}$C changes in the stratigraphic record.

Spatial Gradients across a Shallow Platform

The mud fraction of carbonate sediment is transported easily across the shelf, and this transport homogenization is evident in the near-constant $\delta^{13}$C values of mud across NWA (Fig. 2C). In contrast, the coarse fraction is not as easily transported and tends to reflect the local $\delta^{13}$C of dissolved inorganic carbon (DIC), which decreases across water aging contours (Fig. 2A) and adjacent to terrestrial inputs of freshwater carrying remineralized organic carbon (Fig. 2D). To illustrate the effect of this DIC gradient on locally precipitated shells, Figures 2B and 2E depict a ~4‰ cross-shelf gradient in the $\delta^{13}$C of benthic foraminifera (Peneroplis), with a near-constant offset from the $\delta^{13}$C of local DIC. Therefore, due to the cross-shelf gradients in seawater $\delta^{13}$C, a series of mudstone-to-grainstone facies transitions could show increasing (zone 1) or decreasing (zone 2) $\delta^{13}$C trajectories (Fig. 2F).

$\delta^{13}$C Trends across Meter-Scale Parasequences

The $\delta^{13}$C of NWA surface sediments is set by both the spatial gradient in the $\delta^{13}$C of DIC (Fig. 2A) and the local facies-controlled mixing
Figure 1. (A) RapidEye satellite image of northwestern Andros Island (NWA), Bahamas. Black dots depict sampling locations, and squares depict those locations where we also sampled the underlying last interglacial (LIG) surface (Fig. 4). (B) Histogram of water depths in NWA (Geyman and Maloof, 2019). (C) Index map showing location of Andros Island (dark gray) on the Great Bahama Bank (light gray). (D) δ¹³C cross-plot of NWA sediment and rock. (E) Histograms of δ¹³C variability for each common carbonate grain type in NWA. In E, black labels in italics represent lithified sediments and rocks (<130 ka), and labels in normal font represent unconsolidated surficial sediments and grains (<6 ka). Vertical gray line and light gray bar depict the mean (μ) ± 1 standard deviation (1σ) of bulk sediment δ¹³C. In B and E, the vertical axes represent the relative abundances of different water depths and δ¹³C ranges, respectively.
of carbonate constituents (Fig. 1E). To estimate bulk sediment δ13C across the study area, we first generate maps of estimated δ13C and associated uncertainty for each grain-size fraction (<63, 63–125, 125–500, 500–1000, >1000 μm; see the Supplemental Material). We recombine these size-specific δ13C maps (Fig. 3A) using a weighted average based on (1) the relative proportions of each grain size in the different facies categories (Fig. 3B), and (2) the facies map of Geyman et al. (2021) (Fig. 3C). The final map in Figure 3D incorporates both the long-wavelength spatial δ13C gradients (Fig. 2), and the local facies-controlled δ13C shifts caused by varied contributions of mud and grains.

While the total δ13C variability in NWA bulk sediments is ~5‰ (Fig. 3D), a single meter-scale parasequence is unlikely to record that full variability. To estimate parasequence-scale δ13C shifts, we perform a simple simulation based on Walther’s Law, which states that sequential layers in a stratigraphic column represent laterally adjacent facies patches at the time of deposition (Walther, 1894). We use the methods of Geyman et al. (2021) to simulate random walks (Fig. 3F) and shallowing-upward walks (Fig. 3H) from 500 different initial locations. Along each traverse, we sample the local facies and δ13C, and use the water depth to modulate erosion and deposition. The resulting parasequences (0–6 m thick) record δ13C variability of ~1‰ (Figs. 3F–3I).

Crossing a Parasequence Boundary

The LIG-Holocene parasequence boundary juxtaposes recrystallized LIG sedimentary rock with overlying unconsolidated Holocene sediment (Fig. 4B). Comparing samples across this parasequence boundary reveals a 0‰ to 13‰
shift in δ¹³C, depending primarily on the severity of meteoric alteration and cementation in the underlying LIG sedimentary rock (Fig. 4A).

DISCUSSION

Important Drivers of Bank-Top δ¹³C Variability

In NWA, the major levers driving carbonate δ¹³C away from contemporaneous open-ocean values include:

1. Vital effects and microenvironmental conditions. Vital effects may explain, for example, why foraminifera δ¹³C is 3.1‰ higher (Fig. 2E) and coral δ¹³C is ~6‰ lower (Fig. 1E; Chen et al., 2018) than expected for calcite and aragonite precipitating in equilibrium with local seawater, respectively.

2. Environmental control on grain type and abundance. Mixing the relative proportions of the carbonate constituents in Figure 1E shifts sediment δ¹³C by as much as 10‰ in theory, but only 0‰ to 3‰ in practice (Fig. 3) because NWA sediments rarely host monospecific grain populations. Note that the local environment also impacts the biostratigraphic record of origination and extinction, since fossil first and last appearance datums commonly appear at facies boundaries, where organism habitat appears/disappears locally (Holland, 2020). Therefore, the stratigraphic record of extinctions and δ¹³C shifts would, in some cases, be inextricably linked and partly a function of facies changes.

3. The diurnal carbon engine. The δ¹³C composition of carbonate grains in the northern part of the study area—including non-skeletal grains such as ooids (Fig. 1E)—is too high for the grains to have been precipitated in equilibrium with local seawater (Fig. 2A). The diurnal cycle of photosynthesis and respiration,
Homogenization of Primary Grain-to-Grain δ13C Variability

In Paleozoic rocks, the δ13C differences between bulk carbonate rock, micrite, and various well-preserved shells commonly are <2‰ (e.g., Batt et al., 2007; Brand et al., 2012; Husson et al., 2016). This result is at odds with our observations (Fig. 1E) and those of previous workers who have studied δ13C variability in modern carbonate environments (e.g., Weber, 1967; Land, 1989; Gischler et al., 2009; Swart et al., 2009; Ingalls et al., 2020). We think it is unlikely that skeletal grains occupied a much narrower range of primary δ13C values in the past. Even in the Precambrian, when grains were non-skeletal (and perhaps sourced more narrowly than Phanerozoic grains), it seems likely that intrashelf gradients could have imparted some δ13C signal on grain composition (Fig. 2). However, during physical abrasion and the diagenetic conversion of primary metastable aragonite and high-Mg calcite to low-Mg calcite and dolomite, the varied constituents in a carbonate rock commonly become homogenized in both mineralogy and δ13C. Whether isotope homogenization occurs through physical mixing during abrasion and transport (Gischler et al., 2013) or through chemical exchange during diagenesis (Patterson and Walter, 1994b), the original δ13C values of constituent carbonate grains could exert an important control on final bulk-rock chemistry, even if the original grain-to-grain δ13C variability cannot be recovered at the millimeter scale by microdrilling ancient carbonate rocks (e.g., Husson et al., 2016).

The Bahamas as an Imperfect Analog

Northwestern Andros Island is an incomplete template for interpreting ancient carbonates in the geologic record. For example, we recognize that the large glacioeustatic fluctuations of the Pleistocene may be fairly rare in Earth history. Also, there is evidence that before developing a rich terrestrial biosphere in the Paleozoic Era (Algeo and Scheckler, 1998), subaerial exposure surfaces may not have imparted deep δ13C shifts on shallow carbonates because δ13C depletion is enhanced through the incorporation of remineralized terrestrial organic carbon (Jones et al., 2015). Nevertheless, even without such intense meteoric alteration, there is still ~10‰ of variability in grain δ13C composition across just 2900 km² of a modern carbonate platform (Fig. 1). Furthermore, the contributions of varied grain populations to bulk δ13C need not be limited to the meter-scale parasequence-style patterns described in this paper. Large-scale migration of facies belts, reorganization of bank-top environments, varying cross-shelf δ13C gradients, changes in grain populations, and origination and extinction of different shell-making organisms all could occur in response to local or global forcing, and all could impart changes to bulk geochemistry on stratigraphic length scales of 1 m to 1 km. We do not think that all—or even most—δ13C trends are due to isotope homogenization of varied constituent grains. However, coupling δ13C measurements to bed-by-bed facies descriptions that include quantitative and reproducible information about grain populations offers the possibility of deconvolving chemostratigraphic trends from local facies control, bringing us one step closer to reconstructing ancient carbon-cycle dynamics.

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