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Marine Export Productivity and the Demise of the Central American Seaway

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Publication Date
2015

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Marine Export Productivity and the Demise of the Central American Seaway

A Thesis submitted in partial satisfaction of the requirements for the degree Master of Science

in

Oceanography

by

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Committee in charge:

Professor Richard Norris, Chair
Professor Christopher Charles
Professor Miriam Kastner

2015
The Thesis of Samantha Kathleen Trumbo is approved and it is acceptable in quality and form for publication on microfilm and electronically:

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Chair

University of California, San Diego

2015
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ACKNOWLEDGEMENTS

I would like to acknowledge Professor Richard Norris for his support as chair of my committee. Throughout the entire project and over many drafts, his advice and assistance has proved invaluable to me.

I would also like to acknowledge Alex Hangsterfer for her constant support and knowledge in the XRF lab and for her help in scanning.

Furthermore, I would like to acknowledge Professor Miriam Kastner for her immense aid in helping me understand our proxies and for teaching me to think critically about my data throughout the course of my project.

In addition, I would like to acknowledge Professor Christopher Charles for his thoughtful and constructive comments that have improved both this manuscript and my understanding of its contents.

Finally, I would like to acknowledge Eric Sawyer for his unwavering support and generous aid in utilizing computer programs necessary to the data analysis presented in this work.

This thesis is currently being prepared for submission for publication of the material: Trumbo, Samantha K.; Hangsterfer, Alexandra; Kastner, Miriam; Norris, Richard D. “Export Productivity and the Demise of the Central American Seaway”. The thesis author was the primary investigator and author of this material.
ABSTRACT OF THE THESIS

Marine Export Productivity and the Demise of the Central American Seaway

by

Samantha Kathleen Trumbo

Master of Science in Oceanography

University of California, San Diego, 2015

Professor Richard Norris, Chair

The progressive closing of the Central American Seaway (CAS) from initial shoaling in the mid-Miocene (~13 Ma)$^{1,2}$ to final closure in the late Pliocene (~3-2.7 Ma)$^{3-5}$ substantially altered the surface salinity, nutrient content, and biology of the Caribbean Sea and eastern equatorial Pacific Ocean (EEP). Studies of fossil plankton, reef development, and oceanographic models of the shoaling Isthmus of Panama suggest that there was a distinct drop in Caribbean productivity with closure of the seaway, whereas models of the EEP suggest a marked increase in production. However, there has not been a detailed comparison of export production records between the two ocean
basins. Here, we present the highest resolution paleoproductivity proxy records to date for the Caribbean and EEP, which suggest that the formation of the Isthmus of Panama had little direct effect on nearby productivity levels. Instead, export production in both basins was governed mostly by high latitude nutrient sources, as seen in the spectral dominance of high latitude orbital forcing. Export production gradually decreased in the Caribbean starting about 2.7 Ma, while remaining relatively stable in the EEP. Caribbean export production falls mostly during glacial phases in response to ventilation of the tropical thermocline by increasingly nutrient-starved Glacial North Atlantic Intermediate Water. Our findings may suggest a sensitivity of low-latitude productivity to future anthropogenic climate forcing at the high latitudes. In addition, the gradual intensification of Caribbean oligotrophy may be responsible for the well-documented delay in extinction of Caribbean reef-associated fauna relative to the CAS closure.\textsuperscript{6}
Introduction

The CAS closure widely affected global climate by modifying ocean circulation, upwelling patterns, and heat and moisture transport. An increase in Atlantic salinity resulting from the isolation of the Caribbean from the Pacific led to increased North Atlantic deep water (NADW) production, intensified meridional overturning circulation, and strengthened the Gulf Stream.\textsuperscript{7-12} Resultant increases in moisture transport to the high latitudes and Eurasian continent are hypothesized to have facilitated the intensification of Northern Hemisphere glaciation (NHG) at ~2.7 Ma.\textsuperscript{11,13}

Knowledge of the Caribbean productivity response to the seaway closure and ensuing climatic changes is primarily inferred from climate-ocean ecosystem modeling and fossil-based studies of nearshore benthic community changes. With the exception of low time-resolution foraminifera accumulation records,\textsuperscript{14} there are few direct records of Caribbean Plio-Pleistocene export production. Circulation models with an open seaway suggest that intermediate waters leaked from the Caribbean into the Pacific, whereas nutrient-rich thermocline waters shallower than ~700 m flowed eastward from the Pacific into the Caribbean.\textsuperscript{7,15} Both ecosystem modeling approaches and the development of Caribbean reef systems suggest a significant decline in Caribbean export production once this nutrient supply was cut off.\textsuperscript{6,7} In contrast, models suggest increased nutrient accumulation, concentrated upwelling, and increased production in the EEP upon seaway closure.\textsuperscript{7} These changes are thought to have led to the evolution of the modern-day productivity contrast across the Isthmus of Panama (Figure 1).
Figure 1: Map of core locations overlaid on modern day ocean color. ODP site 999 is in the western Caribbean and is characterized by oligotrophic conditions today. ODP site 846 is in the eastern equatorial Pacific in the modern cold-tongue, today characterized by strong upwelling and generally productive waters. For the purpose of modern productivity context, sites are displayed against average ocean chlorophyll data for 1997-2004, which was collected by the NASA SeaWiFs project. The background chlorophyll concentration map was obtained via the NASA Earth Observatory (http://earthobservatory.nasa.gov/IOTD/view.php?id=4097).
Methods

We test these hypotheses by comparing submillenial-resolution paleoproductivity proxy records from ODP Site 999 in the western Caribbean and ODP Site 846 in the EEP (Figure 1). Records of Ca/Fe, Si/Fe, and Ba/Fe ratios were produced using X-ray fluorescence (XRF) scanning and compared to existing paleoproxy records (Figure 2). Age models are based on astronomically tuned records for ODP Site 846\textsuperscript{16} and ODP Site 999.\textsuperscript{11,12,18,19} Assuming that sedimentary Fe is of primarily terrigenous origin, Ca and Si normalized by Fe approximate biogenic CaCO\textsubscript{3} and biogenic SiO\textsubscript{2}, respectively. Indeed, our Ca/Fe and Si/Fe XRF records closely match existing records of CaCO\textsubscript{3} and SiO\textsubscript{2} mass accumulation rates (MAR) for the same sites (Figure 2). Ba/Fe yields an estimated history of sedimentary “Ba\textsubscript{excess}” (biogenic Ba),\textsuperscript{20,21} which is highly refractory and directly tracks export production in the modern ocean without explicit taxon-dependency.\textsuperscript{22–25} Our Ba/Fe values correlate linearly with Ba\textsubscript{excess} values calculated from available shipboard sedimentary trace metal measurements (Figure 7). All three of our elemental ratio proxies are dependent on the assumption of a largely invariant terrigenous provenance, which is supported by studies of terrestrial flux to both Site 999\textsuperscript{26} and ODP leg 138 sites nearby Site 846.\textsuperscript{27} Ti and Fe follow the same trends throughout our XRF records, but because XRF better captures Fe signals, Fe was used for normalization. We do not attempt quantitative reconstruction of past export production, but instead focus on the directions and mechanisms of productivity changes, thereby minimizing the number of necessary assumptions. We interpret changes in Ba/Fe in each record as reflecting changes in Ba\textsubscript{excess} accumulation, and thus export productivity, at that site.\textsuperscript{20,21} This
interpretation is substantiated by tight correlations between Ba/Fe, Ca/Fe (CaCO$_3$), and Si/Fe (SiO$_2$) in both sites on multiple timescales (Figure 5).
Figure 2: Comparison of proxy records from the Caribbean and EEP. Benthic $\delta^{18}O$ data are from the global “LR04 stack”. Blue circles are CaCO$_3$ MAR data for ODP site 999. Purple squares and orange circles represent published CaCO$_3$ and SiO$_2$ MAR data, respectively, for ODP site 846. Previously published C$_{37}$ alkenones, an organic productivity proxy derived from some species of haptophyte algae, are also presented. In addition, published diol index and C$_{28}$ diol flux data proxies for upwelling and upwelling associated diatoms, respectively, are plotted for the nearby Site 1241. Highlighted regions mark periods of extended contrast between the abundance of calcareous and siliceous planktonic groups. Dotted lines indicate the Holocene values in our elemental ratio records.
Results and Discussion

We find that average Caribbean export production was higher during the Pliocene (5.3 – 2.6 Ma) than during the Pleistocene (2.6 – 0.0117 Ma). This sustained Pliocene period of high production relative to present values is consistent with the ongoing exchange of nutrient-rich water from the Pacific to the Caribbean that would have occurred with an open seaway. Indeed, ocean model results suggest ongoing transport of Pacific thermocline waters into the Caribbean until near complete closure, with the largest impacts on nutrient budgets occurring only after the sill shoaled above 100 m.\(^7\)

Similarly, mean annual range in temperature data indicate that strong upwelling persisted in Caribbean shelf environments until ~3.5 Ma.\(^6,28\)

A gradual decline in export production inferred from Ba/Fe begins about 2.7 Ma and continues throughout the Pleistocene. The nearly monotonic trend is not consistent with a step-wise change toward the modern Caribbean state, as would be expected by a simple dependency on inflow of Pacific thermocline nutrients. Instead, comparison with the LR04 benthic \(\delta^{18}O\) stack\(^29\) (Figure 3) and cross-spectral analysis (Figures 5 and 6) reveal that the observed decline towards the modern is primarily a result of declining Ba/Fe values associated with glacial events, which decrease at twice the rate of the interglacial Ba/Fe peaks.
Figure 3: Interglacial spikes in Late Pleistocene export production at ODP site 999. δ¹⁸O data is from the “LR04” global stack. Pulses of Ba/Fe (red, a proxy for export production) and Ca/Fe (blue, a proxy for biogenic carbonate production) indicate substantially increased Caribbean productivity during the interglacials of the last 450-kyr. We interpret this to suggest a decrease in the nutrient content of glacial thermocline source waters due to the ventilation of the low-latitude thermocline with glacial North Atlantic intermediate water (GNAIW). Cross-spectral analysis (Figure 5) reveals a similar trend back into the 41-kyr world of the early Pleistocene. The correspondence of Ca/Fe and Ba/Fe suggest that neither signal is primarily a result of dissolution bias, as opposite phasing between the two would be expected in that case.

The high-latitude origin of the decline in export production is evident in the underlying orbital beat of Ba/Fe. In ODP Site 999, 2.7 Ma marks increases in both the amplitude of Ba/Fe glacial-interglacial variability (Figure 2) and the spectral power of 41-kyr obliquity oscillations (Figure 4). 100-kyr eccentricity oscillations dominate the spectral power after ~750 ka, reflecting the mid-Pleistocene transition (Figure 4). Where the timescale is astronomically tuned (see Extended Methods), Caribbean Ba/Fe and δ¹⁸O are largely out of phase at these periods. These observations implicate a glaciation-
specific mechanism, rather than a simple cutoff of Pacific nutrients, as the main factor in the establishment of the modern oligotrophic Caribbean.

![Figure 4: Evolutive spectra of δ^{18}O and Caribbean and Pacific Ba/Fe.](image)

The evolutive spectra of Ba/Fe for ODP Site 999 in the Caribbean and ODP Site 846 in the eastern equatorial Pacific show dominance by high-latitude orbital forcing. Strong spectral power is evident in both records at the 41-kyr orbital obliquity period and 100-kyr orbital eccentricity period. Site 846 also exhibits significant power in the 19- and 23-kyr band associated with precessional variation. The evolutive spectrum of the LR04 δ^{18}O stack is included for context.

We hypothesize that the glacial-interglacial pattern of Caribbean Ba/Fe is a result of orbital timescale variability in the nutrient content of thermocline source waters. Today, the high-latitude source waters for the low-latitude Atlantic thermocline are
primarily Antarctic Intermediate Water (AAIW) and sub-Antarctic Mode Water (SAMW). However, during past glaciations, lower density glacial North Atlantic intermediate water (GNAIW) supplanted the more nutrient-rich AAIW to supply the low-latitude thermocline with nutrient-poor water. This switch in Atlantic thermocline sources has been previously offered as an explanation for the well-documented crashes of Atlantic populations of the planktonic foraminifer *G. menardii* during glacial episodes, as well as for observed deglacial pulses in export production in the subtropical North Atlantic. Our records provide further support for the hypothesis that the low-latitude productivity state is largely dictated by mechanisms affecting high-latitude source waters. The onset of NHG at 2.7 Ma would have amplified the modulation of Caribbean productivity by GNAIW, thereby causing the observed preferential decline in glacial export production during the Pleistocene (Figures 2 and 3).
The formation of the Isthmus and cessation of nutrient flow from the Pacific may also have contributed to the increased Caribbean oligotrophy, particularly during interglacial periods. The glacial phenomenon may have also been enhanced by increased North Atlantic overturning as a result of seaway closure. Prior to the intensification of NHG, weak spectral power in the obliquity band (Figure 4) and continued coherence with LR04 $\delta^{18}O$ (Figure 5) suggest orbital-scale variability in the formation of AAIW. The gradual fall in Caribbean export production may explain why Caribbean extinction rates of corals and mollusks associated with high productivity did not peak until 1-2 Ma.
In the EEP, our records of Ba/Fe, Ca/Fe, and Si/Fe suggest higher biological production for the period of ~5.1 – 4.5 Ma than for any subsequent period. These features are coincident with the well-documented Pacific “biogenic bloom” (6.7 – 4.5 Ma), in which the EEP experienced extremely elevated rates of biogenic sediment accumulation.33–35

Between 2.9 and 1.6 Ma, C_{37} alkenones, a productivity proxy derived primarily from coccolithophorids, record the “late Pliocene/Early Pleistocene productivity maximum” (Figure 2).16 Ba/Fe exhibits a corresponding increase from 2.9-1.9 Ma that is also reflected in Si/Fe, Ca/Fe, C_{28} diol flux (a diatom-associated proxy),34 and CaCO_3 and SiO_2 MAR (Figure 2). The onset of the maximum is consistent with both increased nutrient accumulation and upwelling as a result of the final seaway closure and increased nutrient leakage from high latitude source waters upon intensification of NHG.16 The Ba/Fe spectrum at Site 846 does indicate a dependence on high-latitude nutrient leakage, as seen in the continued dominance of spectral power in the 41-kyr obliquity and 100-kyr eccentricity bands throughout the record. However, neither the C_{37} alkenone record nor the XRF records indicate that the productivity maximum was sustained far into the Pleistocene. The establishment of the Southern Ocean opal belt at ~2 Ma has been suggested as a possible explanation for the termination of the productivity maximum,16 however such an explanation is not clear from our Si/Fe record.

Rather, comparison of our records with taxon-specific proxies suggests that the EEP ecosystem is dynamic and likely responsive to a complex collection of factors. For example, late Pleistocene maxima in C_{28} diol flux and the diol index upwelling proxy are not matched by equivalent features in other proxies (Figure 2). Similarly, the carbonate
and silica records are often at odds with the C\textsubscript{37} alkenone proxy (Figure 2). Indeed, cross-spectral analysis of our Ca/Fe and Si/Fe records suggest that production by calcifying and siliceous plankton alternated on glacial-interglacial timescales during much of the 41-kyr world, before finally coming in phase at \(~ 1.7\) Ma (Figure 5). During this interval, biogenic opal production by diatoms (reflected in Si/Fe) was primarily a glacial signal, while carbonate producers such as coccolithophorids and foraminifera (reflected in Ca/Fe) bloomed during interglacials. Our biological interpretation of this pattern is supported by previous studies suggesting that sedimentary CaCO\textsubscript{3} concentrations are largely independent of dissolution in this region on glacial timescales.\textsuperscript{36-39} Notable extended periods of contrast between opal- and carbonate-producing planktonic groups are highlighted in Figure 2. We suggest that the complexity of this ecosystem and the varied responses of different ecological niches to diverse forcing may partially explain the lack of a step-wise increase or long-term trend in EEP export production (as recorded in Ba/Fe) as a result of the seaway closure or of the onset of NHG. In essence, our Ba/Fe record suggests that, despite serial changes in the dominant planktonic groups, export production in the EEP was relatively stable in the face of the large-scale tectonic and climatic changes of the Plio-Pleistocene period.
**Conclusions**

Our records suggest that the evolution of Pacific-Caribbean nutrient exchange surrounding the formation of the Isthmus of Panama was not the main mechanism controlling the evolution of tropical Plio-Pleistocene export production. Instead, closure of the Central American Seaway set in motion the gradual amplification of NHG,\(^\text{11,13}\) producing a Caribbean productivity response to increasingly low-nutrient waters ventilating the tropical thermocline. In the EEP, variation in the nutrient balance of mode waters likely played a critical role in composition and production of the dominant phytoplankton groups. Given that climate change will first and foremost affect high-latitude conditions, the study of high-latitude forcing mechanisms of tropical production and the individual responses of planktonic groups may help predict the tropical biological response to future environmental change.
Extended Methods

XRF Scanning

We used the Scripps Institution of Oceanography Avaatech XRF scanner to obtain elemental abundance records for the archived halves of ODP cores from Site 999 hole A. Data were collected at 2 cm resolution over an area of 1.2 cm$^2$. To capture both light and heavy elements, each section was scanned with the following three sets of settings: 10 s, 10 kV, and .5 mA, 20 s, 30 kV, and 2 mA with a thick Pd filter, and 30 s, 50 kV, and 2 mA with a Cu filter. Cores were prepared and X-ray spectra were processed as described in Addison et al. (2013).

Archived halves of ODP cores from Site 846 holes B, C, and D were scanned in the same manner as Site 999 cores. However, due to a malfunction of the XRF scanner used, data over intervals of 0 – 2315 ka, 2321 – 2743 ka, and 2774 – 2961 ka were taken over an area of .24 cm$^2$, rather than 1.2 cm$^2$. The data were corrected to approximate the equivalent 1.2 cm$^2$ count values by applying linear relationships between counts at .24 cm$^2$ and 1.2 cm$^2$. These relationships were obtained by rescanning 5 core sections at both sample areas with 2 cm resolution. Independent relationships were applied for each element of interest. We recognize that this method may amplify edge effects in the corrected measurements, but argue that this bias is small in the face of true elemental abundance changes, precluding its importance for the semi-quantitative nature of our study. Each set of cores was scanned over an interval of 6-7 months.
Splices and Age Models

All Caribbean cores XRF scanned were from Site 999 hole A. Thus, our record was produced by simply appending sequential cores and core catchers. The age model presented in the text is based on published astronomically tuned ages for the intervals of 0-465 ka\textsuperscript{18} and 1700-5300 ka.\textsuperscript{11,19} The interval from 1700-5300 ka was further refined by tuning the original Site 999 $\delta^{18}$O data\textsuperscript{11,19} to the LR04 stack.\textsuperscript{29} There is no published age model or isotope record for the interval of 465-1700 ka. For the purposes of the text, we interpolated across this interval based on the ages on either side. We also constructed an alternate age model, in which we refined the timescale by tuning our XRF Fe record to the LR04 stack. On either side of the previously unturned interval, periods of elevated Fe counts coincide with glaciation events, so we tuned in this sense. Cross spectral analysis using this age model suggests that the out of phase relationship between ODP Site 999 Ba/Fe and LR04 $\delta^{18}$O\textsuperscript{29} persists throughout the Pleistocene. We present these results in Figure 6, as we feel they further strengthen our conclusion that Caribbean production is modulated by GNAIW. All tuning was performed using the lineage function of the Analyseries 2.0 software package.\textsuperscript{41} For ODP Site 846, we used the splice and astronomically tuned age model of Lawrence et al. (2006).\textsuperscript{16}
Figure 6: Evolutive phase and coherence relationships: alternate timescale. A. Phase relationships between ODP Site 999 Ba/Fe and the LR04 δ¹⁸O stack in the 41-kyr band. B. Phase relationships between ODP Site 999 Ba/Fe and the LR04 δ¹⁸O stack in the 100-kyr band. In both panels, Ba/Fe is shown for our alternative timescale, in which we refined our partially untuned age model by tuning XRF iron to δ¹⁸O. This age model is dependent on the assumption of increased terrestrial dust during more arid glacial phases. Under this model, the out of phase relationships observed above for the published timescale continue across the previously untuned interval. While we recognize that this is dependent on certain assumptions, we feel it strengthens our conclusion of lower Caribbean production during glaciation events.

**Ba/Fe Proxy**

Our study utilizes XRF Ba/Fe as a proxy for paleoproductivity. Our selection of Ba/Fe is based on the established correlation of Ba$_{\text{excess}}$ (Ba$_{\text{excess}}$ = Ba$_{\text{total}}$ – Ti$_{\text{total}}$(Ba/Ti)$_{\text{terrestrial}}$) to export production.$^{23-25}$ Ba$_{\text{excess}}$ calculations were performed on available shipboard sedimentary measurements of Ba and Ti for Site 999 and compared to our XRF measurements. The Ba/Ti ratio (=.108) for the Post Archaean Average Shale (PAAS)$^{42}$ was used in accordance with compositional studies of the terrigenous material at this location.$^{26}$ The linear correlation between our XRF Ba/Fe measurements and Ba$_{\text{excess}}$ values can be seen in Figure 7.
Figure 7: Correlation between XRF Ba/Fe and Ba\textsubscript{excess}. Ba\textsubscript{excess} calculations were made using available shipboard sedimentary trace metal measurements for ODP Site 999. The resulting linear correlation with our XRF Ba/Fe measurements has an $R^2$ value of .76, indicating that XRF Ba/Fe can be used as a proxy for biogenic barium in these sediments.

**Spectral and Cross-spectral Analysis**

All spectral and cross-spectral analysis was performed using the ARAND software package, which utilizes the Blackman-Tukey method.\textsuperscript{43} The iterative mode was used with 600-kyr windows, 90% overlap between windows, and 50% lag. Prior to analysis, records were interpolated to an evenly spaced .654-kyr resolution and 5-point smoothed. For the purpose of highlighting orbital-scale frequencies in the evolutive spectra, the Site 846 and Site 999 records were treated with a Gaussian notch filter centered at 0 with a bandwidth of .008 cycles/kyr to remove very low frequencies prior to spectral analysis. The LR04 $\delta^{18}$O data\textsuperscript{29} was prewhitened with a prewhitening constant of 1, thereby diminishing some of the 100-kyr power in favor of emphasizing higher frequencies.
Note

This thesis is currently being prepared for submission for publication of the material: Trumbo, Samantha K.; Hangsterfer, Alexandra; Kastner, Miriam; Norris, Richard D. “Export Productivity and the Demise of the Central American Seaway”. The thesis author was the primary investigator and author of this material.
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