Rapid $\delta^{18}O$ and $\delta^{13}C$ Isotopic Shifts in Late Pleistocene Marine Varves on the California Margin

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ABSTRACT: Upper Pleistocene sediments on the continental slope off Northern California contain alternations of varves and bioturbation produced by fluctuations in intensity of the coastal upwelling system. Stable isotopic analyses of benthic Foraminifera across a particularly well developed varve/bioturbation sequence deposited ~26,000 years ago reveal rapid shifts of ~0.25 ‰ in $\delta^{18}O$ and ~0.4 ‰ in $\delta^{13}C$. The $\delta^{18}O$ shift occurs within a varved section. Based on varve counts, the isotopic change occurred in less than 100 years. Timing and magnitude of the shift coincide with similar shifts observed in almost all other high-resolution $\delta^{18}O$ records that have been interpreted as primarily representing global in-volume fluctuations.

INTRODUCTION

High-resolution sedimentary records in oceanographically sensitive areas offer the potential to examine oceanographic variability at a higher frequency than with open-ocean records. On the California margin, where sediment accumulation rates are in excess of 30cm/Kyr, cyclic alternations of varves with zones of bioturbation are found in upper Pleistocene sediments. The intermittently varved and bioturbated sediments reveal an oceanographic and climatic regime vastly different from that of the Holocene (Linsley et al., 1987; Anderson et al., in press). Periodic intensifications of the wind-driven coastal upwelling system resulted in a depletion of dissolved oxygen in the oxygen-minimum zone (OMZ) and the resultant development of anoxic or extreme dysaerobic conditions at the sediment surface. These conditions allow the seasonal signal of sedimentation to be preserved as varves. Bioturbated intervals resulted from a relaxation of wind stress and upwelling, which allowed dissolved oxygen levels in the OMZ to rise above some critical threshold.

Radiocarbon dating has constrained the age of varve/bioturbation cycles to between 12,000 and 45,000 years ago. Although no single core contains this entire time interval, a suite of cores has preserved portions of the time 12,000 to 45,000 years ago.

The marine varves are best preserved at a water depth of about 700 m. This depth corresponds to the lowest concentration of dissolved oxygen found in the present oxygen-minimum zone (Gardner and Hemphill-Haley, 1986). The diatomaceous clay-rich sediments are not continuously varved, but contain alternations of varves and bioturbation. Varved intervals have biogenic silica mass accumulation rates (MAR, in gm/cm) and bioturbation. Varved intervals have biogenic silica mass accumulation rates (MAR, in gm/cm²/Ka) of ~0.9-2.0 gm/cm²/Ka and organic carbon accumulation rates of ~0.3-0.39 gm/cm²/Ka (Figure 1).

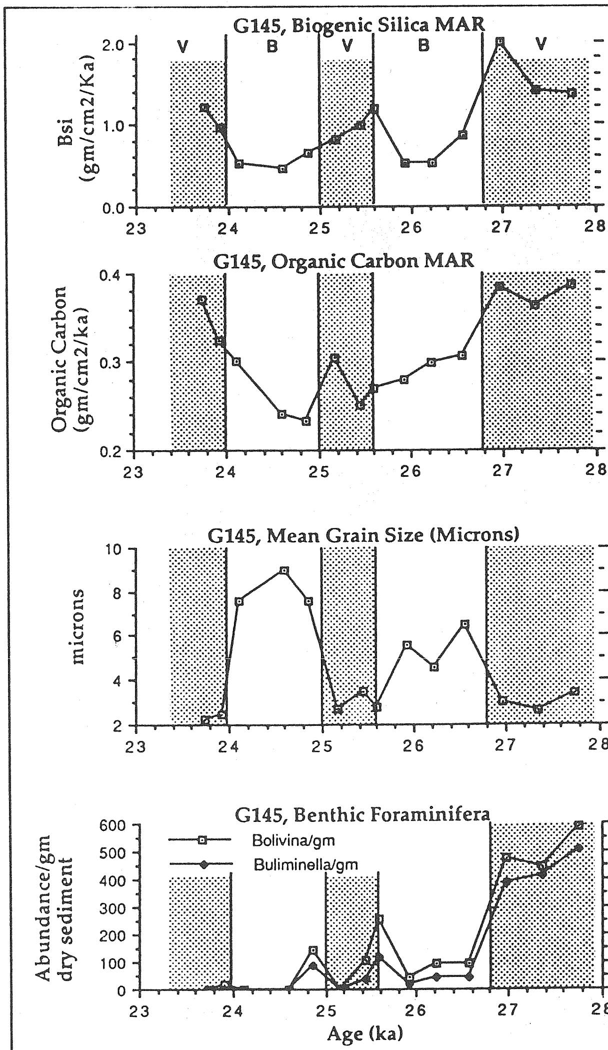

Figure 1. Mass accumulation rates (MAR) of Biogenic Silica, organic carbon, benthic Foraminifera per gram, and mean grain size in varve/bioturbation cycles in core G145 collected at 700m off the Russian River, northern California margin. Varved intervals are indicated by shading.

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Diatom abundance patterns in the varved sections are indicative of deposition under an intensified coastal upwelling system. Species of benthic Foraminifera known to favor low dissolved oxygen and/or high organic carbon content are also generally more abundant in the varved intervals. Enrichment of the metals Fe, Ba, Ni, Cu, Li, along with elemental sulfur, in the varves also supports the interpretation that the laminae are preserved under reducing and low dissolved oxygen conditions (Figure 2). The compositional relationships observed in G145 are also found in several other varved cores from within the OMZ on the California margin.

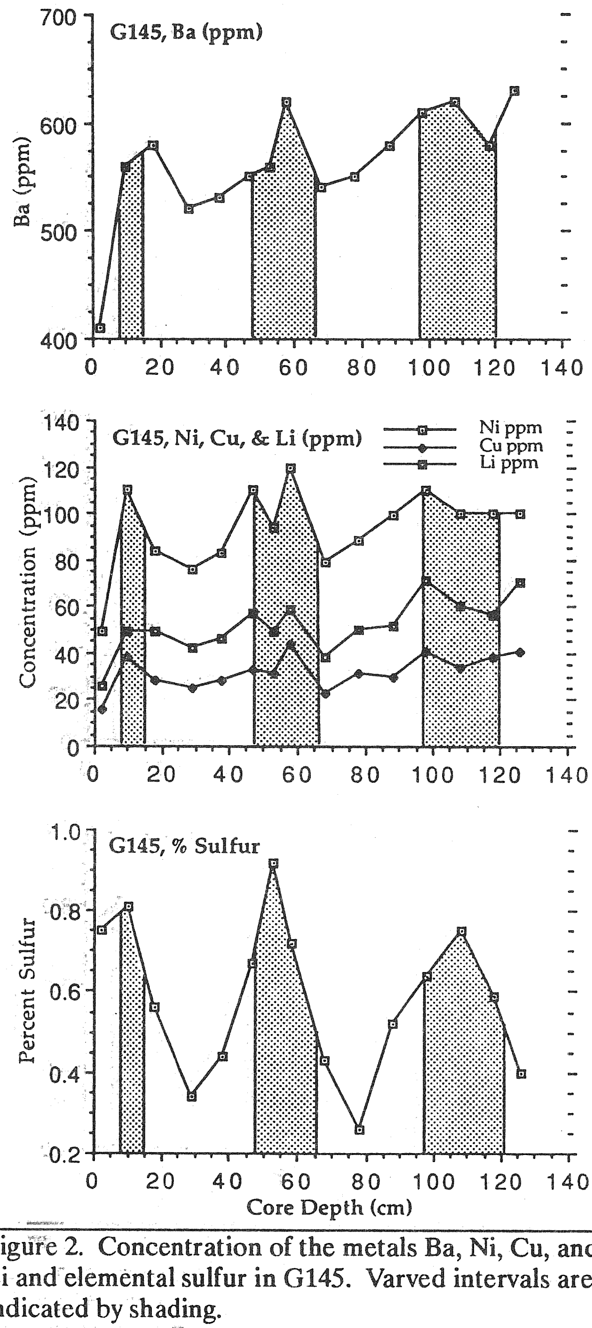

Figure 2. Concentration of the metals Ba, Ni, Cu, and Li and elemental sulfur in G145. Varved intervals are indicated by shading.

In contrast, bioturbated sediments generally have lower accumulation rates of both biogenic silica (~ 0.4-0.6 gm/cm^2/Ka), and organic carbon (0.23-0.28 gm/cm^2/Ka) (Figure 1), and contain large burrow structures. Relative to the varves, the bioturbated intervals are not enriched in metals or forms of benthic Foraminifera tolerant of low dissolved oxygen.

There is evidence of a minor component of reworked, off-shelf sediment in both the varved and bioturbated intervals. In G145, a few individuals of benthic Foraminifera indicative of neuritic, shallow-water environments (Quinterno and Gardner, 1987) are found in the assemblages from both varved and bioturbated sections. However, a robust tychopelatic diatom *Stephanopyxis* comprises 50-60% of the diatom flora in the bioturbated intervals is ~ 1.3 gm/cm^3 compared to 0.8 gm/cm^3 in the varves. This evidence may suggest that winnowing or a greater component of off-shelf transport has occurred during formation of the bioturbated intervals. However, the benthic foraminiferal assemblages, large bioturbation structures, and lack of apparent hiatuses support the conclusion that off-shelf transport was a relatively minor component throughout the deposition of G145.

Recent attention has focused on a series of North Atlantic climatic "jumps" recorded in Greenland ice cores during the time interval 60,000 to about 20,000 years ago (Dansgaard et al., 1985; Hammer et al., 1985; Beer et al., 1985; Broecker et al., 1988). So far these events have not been conclusively documented outside of Greenland, although there is some evidence in North Atlantic cores and European Bog sediments (Broecker et al., 1988). The varve/bioturbation cycles on the California margin occurred during the same time as the Greenland climatic shifts and, based on our partially complete record, appear to have a similar frequency. This would suggest that the millennial changes in wind stress, upwelling, and productivity recorded by the varve/bioturbation cycles may be more than regional in extent. However, the association between the climatic oscillations on the California margin and the Greenland climatic shifts is tentative.

STABLE ISOTOPIC ANALYSES

The stable isotopic composition of the benthic Foraminifera *Bolivina spissa* and *Uvigerina peregrina* were analyzed in a sample series across the middle varve/bioturbation cycle in Figure 1 (core G145, 700 m water depth). Foraminifera were ultrasonically cleaned, roasted at 250°C, and analyzed on a Micromass 602 ES at the Department of Geology and Geophysics at Rice University. Due to inconsistent abundance of *Uvigerina peregrina*, specimens of *Bolivina spissa* were also analyzed in separate samples. There appears to be good correspondence between both species in duplicate samples. The analytical precision for the NBS-19 carbonate standard was $\pm$0.034 ‰ for $\delta^{18}O$, and $\pm$0.050 ‰ for $\delta^{13}C$.

RAPID ISOTOPIC SHIFTS

The isotope analyses show a rapid and significant shift in benthic $\delta^{18}O$ and $\delta^{13}C$ shortly after 26,000 years ago (Figure 3). The ~0.25 ‰ shift in $\delta^{18}O$ occurs within a varved interval and is slightly preceded by a ~0.4 ‰ shift in $\delta^{13}C$. Both changes occur at the onset of increased organic carbon and biogenic silica preservation, interpreted as a time of intensified upwelling and productivity.

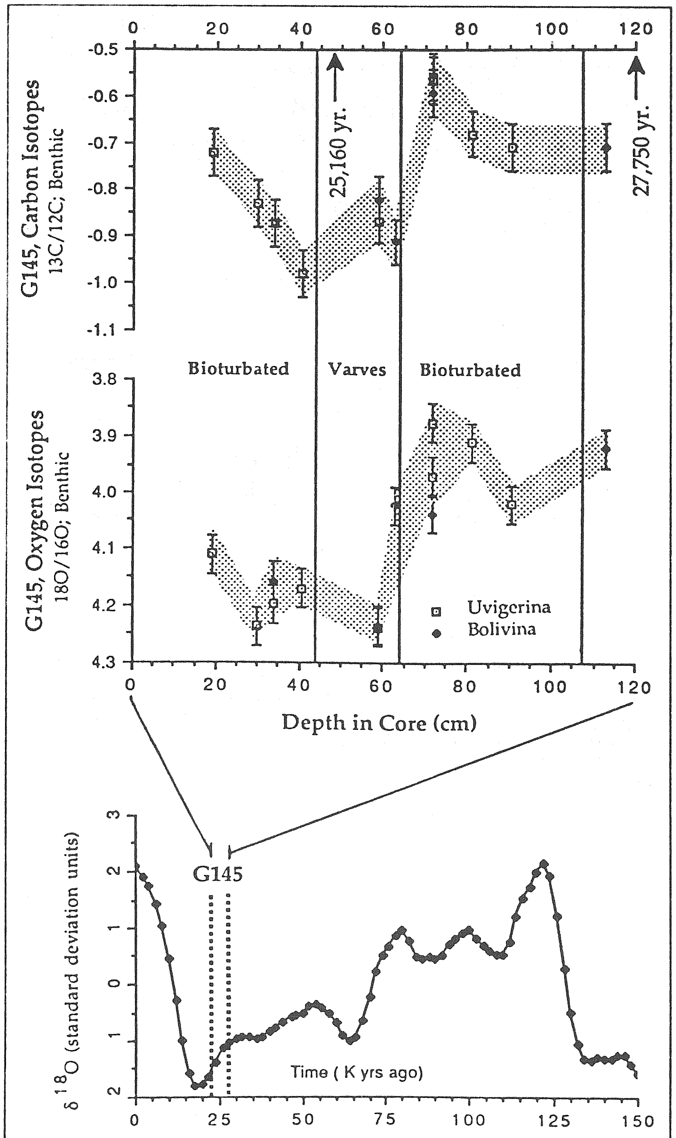

Figure 3. Rapid shift in isotopic ratios of oxygen and carbon in benthic Foraminifera species *Uvigerina peregrina* and *Bolivina spissa* from core G145. The oxygen isotopic shift occurs in less than 100 varve years. Note that the shift corresponds to a shift of similar magnitude in the stacked, smoothed planktonic foraminiferal isotopic record compiled by Imbrie et al. (1984).

The carbon isotopic composition of benthic Foraminifera tends to reflect the $\delta^{13}C$ of the total dissolved inorganic carbon (TDC) of the water in which they form. In general, the $\delta^{13}C$ of TDC in oceanic water masses is a function of the relative age of the water mass (Deuser and Hunt, 1969; Craig, 1969; Kroopnick et al., 1972). The organic matter oxidation signals dominate the $\delta^{13}C$ of TDC (average $\delta^{13}C$ = ~–20 to –25 ‰) (Sackett et al., 1965), such that the $\delta^{13}C$ will progressively decrease as a water mass ages and as organic matter is added. Therefore, the consumption of dissolved oxygen through oxidation of organic matter and a decrease in $\delta^{13}C$ should accompany one another (Kroopnick et al., 1972; Kroopnick, 1974). The ~0.4 ‰ $\delta^{13}C$ change across the varved zone in G145 (Figure 2) is apparently reflecting the addition of isotopically light organic matter or aging water mass conditions, which resulted from increased upwelling driven productivity. Furthermore, the $\delta^{18}O$ shift is preceded by the shift in $\delta^{13}C$, suggesting that whatever forced the $\delta^{18}O$ signal lags the intensification of upwelling.

The 0.25 ‰ enrichment in $\delta^{18}O$ values observed within a varved interval in G145 is coeval and of almost the same magnitude as a shift found in almost all high-resolution $\delta^{18}O$ records. Timing of the $\delta^{18}O$ enrichment appears during buildup to maximum ice-volume conditions during the last glacial maximum. Given the > 1000-year mixing time of the oceans, it is intriguing that such a rapid shift (< years in G145) in benthic $\delta^{18}O$ should occur synchronously in cores widely separated oceanographically and geographically. The similar magnitude of the shifts in cores from widely separated regions of the world's oceans suggests that local temperature or salinity changes on the California margin may not be the sole contributing factors and that some global ice-volume signal was preserved in this relatively shallow-water locale.

The sudden shift in G145 could be due to enhanced upwelling effects that occurred during this time of rapid ice buildup to the last glacial maximum. Identification of similar rapid isotopic shifts in other alternately varved and bioturbated cores will be a priority of future studies on the California margin. We will continue to concentrate on separating local from regional effects in an attempt to test whether climatic oscillations responsible for the varve/bioturbation cycles are more than regional in extent, and perhaps related to the North Atlantic Greenland climatic "jumps" and other fluctuating global climatic phenomena.

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