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Late Quaternary Time Series of Arabian Sea Productivity: Global and Regional Signals

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Modern annual floral and faunal production in the northwest Arabian Sea derives primarily from upwelling induced by strong southwest monsoon winds during June, July, and August. Indian Ocean summer monsoon winds are, in turn, driven by differential heating between the Asian continent and the Indian Ocean to the south. This differential heating produces a strong pressure gradient resulting in southwest monsoon winds and both coastal and divergent upwelling off the Arabian Peninsula (Figure 1). Over geologic time scales (10^4 to 10^6 years), monsoon wind strength is sensitive to changes in boundary conditions which influence this pressure gradient. Important boundary conditions include the seasonal distribution of solar radiation, global ice volume, Indian Ocean sea surface temperature, and the elevation and albedo of the Asian continent. To the extent that these factors influence monsoon wind strength, they also influence upwelling and productivity. In addition, however, productivity associated with upwelling can be decoupled from the strength of the summer monsoon winds via oceanic mechanisms which serve to inhibit or enhance the nutrient supply in the intermediate waters of the Indian Ocean, the source for upwelled waters in the Arabian Sea (Prell, 1990).

To differentiate productivity associated with wind-induced upwelling from that associated with other components of the system such as nutrient sequestering in glacial-age deep waters (i.e. Boyle, 1988) we employ a strategy which monitors independent components (Figure 2) of the oceanic and atmospheric subsystems. Using sediment records from the Owen Ridge, northwest Arabian Sea, we monitor the strength of upwelling and productivity using two independent indicators, % *G. bulloides*

(Prell, 1984, 1990) and opal accumulation (Murray, 1990). We monitor the strength of southwest monsoon winds by measuring the grain-size of lithogenic dust particles blown into the Arabian Sea from the surrounding deserts of the Somali and Arabian Peninsulas (Clemens and Prell, 1990a).

The planktonic foraminifer *G. bulloides* is typically a subpolar species found in the Southern ocean between the Subtropical Convergence and the Antarctic Convergence. However, *G. bulloides* is also found in high abundance in tropical upwelling areas such as the northern Arabian Sea off the coast of Arabia (Hutson and Prell, 1980; Cullen and Prell, 1984) and Cariaco Trench, located off Venezuela (Overpeck et al., 1989). *G. bulloides* abundance in the Arabian Sea is negatively correlated to summer sea surface temperature (Prell and Curry, 1981) which, in turn, is negatively correlated with wind-induced upwelling during the summer monsoon (Prell and Streeter, 1982). Similarly, opal accumulation is positively correlated with nutrient distribution associated with upwelling but less influenced by regional sea surface temperatures (Murray, in preparation).

The Owen Ridge lies beneath the axis of the strong summer monsoon winds. These winds can transport lithogenic dust particles such as those found on the Owen Ridge (mean diameter of 14.4 μm) for thousands of kilometers given mean velocities of 15 m/s and values for the coefficient of turbulent exchange found in typical cyclonic storms and frontal systems (Tsoar and Pye, 1987). The largest particles (40 to 50 μm) can also be transported up to ~ 1000 km in more extreme dust storm events. These estimates of transport distances are consistent with studies which identify the Somali and Arabian Peninsulas as primary source areas for dust found in Arabian Sea sediments (Middleton, 1986; Sirocko and Samthein, 1989). Over geologic time scales, increases in the strength of monsoon winds result in the transport of larger lithogenic particles to the Arabian Sea, thus increasing the median grain size of the lithogenic component (Clemens and Prell, 1990a).

Spectral analyses of these records allow us to examine concentrations of variance held in common between these independent abiotic and biotic records of wind strength and productivity. Our results unambiguously demonstrate that all three independent records are linearly related and in phase with one another over the Earth's orbital precession cycles (23 kyr cycles; Figure 3). We interpret these relationships as indicating that: (1) to first order, all three indicators are linked by a common response to monsoon wind strength and upwelling, and (2) precessional insolation is the primary external forcing mechanism for the late Quaternary monsoon and the associated upwelling induced productivity. However, variance associated with precession accounts for only $\sim 25\%$ of the total variance in any given record. A large portion of the total variance in the biotic records is concentrated at the 41 kyr period associated with the obliquity of the Earth's orbit (Figure 4; Prell, 1990). The

grain-size record, on the other hand, contains large amounts of variance at the 29, 35, and 54-kyr periods which represent heterodyne periods of the primary orbital periods (100, 41, and 23 kyr periods; Clemens and Prell, 1990b). It is the dissimilarities between these records that contains the information possibly allowing differentiation of productivity associated with monsoon-induced upwelling from that associated with other mechanisms.

Our current hypothesis is that the variability associated with the 41 kyr power in the *G. bulloides* and opal accumulation records derive from nutrient availability in the intermediate waters which are upwelled via monsoon winds. This hypothesis is testable by comparison with Cd records of intermediate and deep waters of the Atlantic and Indian Ocean (e.g. Boyle, 1988).

The 35 and 54 kyr heterodyne periods in the grain-size record are positively correlated with large amplitude insolation events at 30° south in the Indian Ocean, the latitude of the subtropical high pressure cells from which the Indian Ocean monsoon winds initiate. The 29 kyr variability is linearly related to sea surface temperature records from the southern subtropical Indian Ocean. Both associations can be explained via the relationship between latent heat (a function of ocean-atmosphere temperature gradients) and monsoon strength as follows (Clemens and Prell, 1990b). Latent heat collected over the southern subtropic Indian Ocean is transported across the equator and released in the mid-troposphere about the Tibetan Plateau. This increases the strength of the monsoon low, resulting in increased wind strength and transport of larger lithic particles to the Arabian Sea. This hypothesis is currently being tested by development of late Quaternary sea surface temperature records from ~ 30° south. Concentrations of variance at the 35, and 54 kyr periods in these records would support the latent heat link between the insolation record and the grain size record of monsoon strength.

Confirmation of the hypotheses described above will eventually enable us to quantitatively partition variance within these records into that attributed to monsoon-induced upwelling (regional) and oceanic mechanisms of nutrient distribution (global). Identification of a global signal in regional upwelling productivity would then provide a framework for comparison of productivity records from upwelling regions throughout the world ocean.

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Location Map

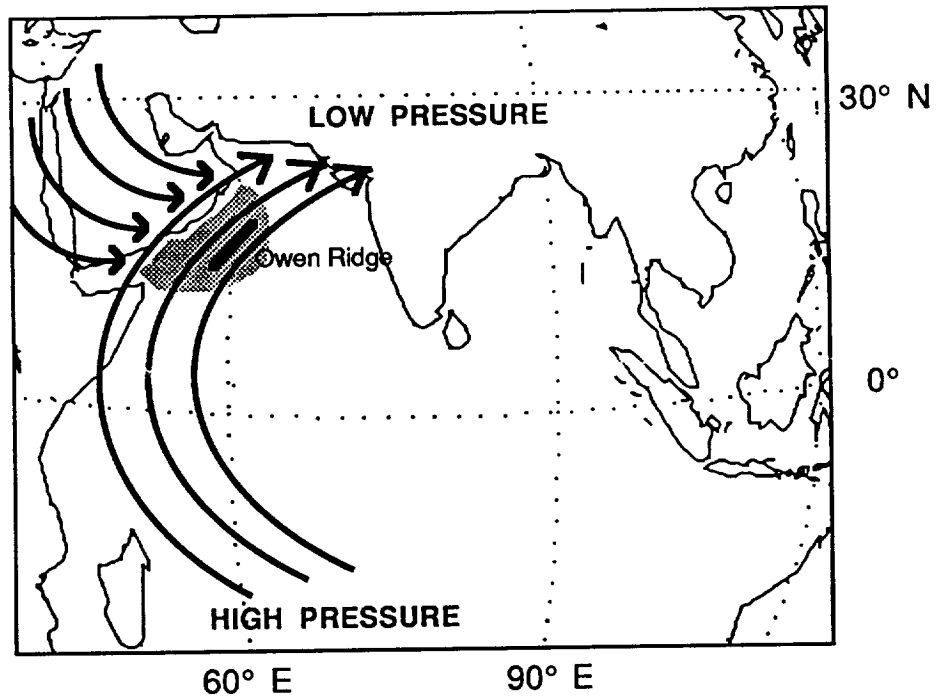


Figure 1. The lithogenic and biogenic components of Owen Ridge sediments record late Quaternary climatic changes associated with the Indian Ocean monsoon system. Strong southwest winds (arrows) flow from high pressure to low pressure inducing coastal and divergent upwelling (shaded) off the Arabian Peninsula. Upwelling productivity is recorded in the geological record of fossil planktonic foraminifera (carbonate) and radiolaria (opal) preserved in Owen Ridge sediments. Both southwest and northwest summer winds transport terrigenous dust to the Owen Ridge from deserts of Somali and Arabia. The grain size of the lithogenic component varies as a function of the strength of the transporting winds.

Time Domain

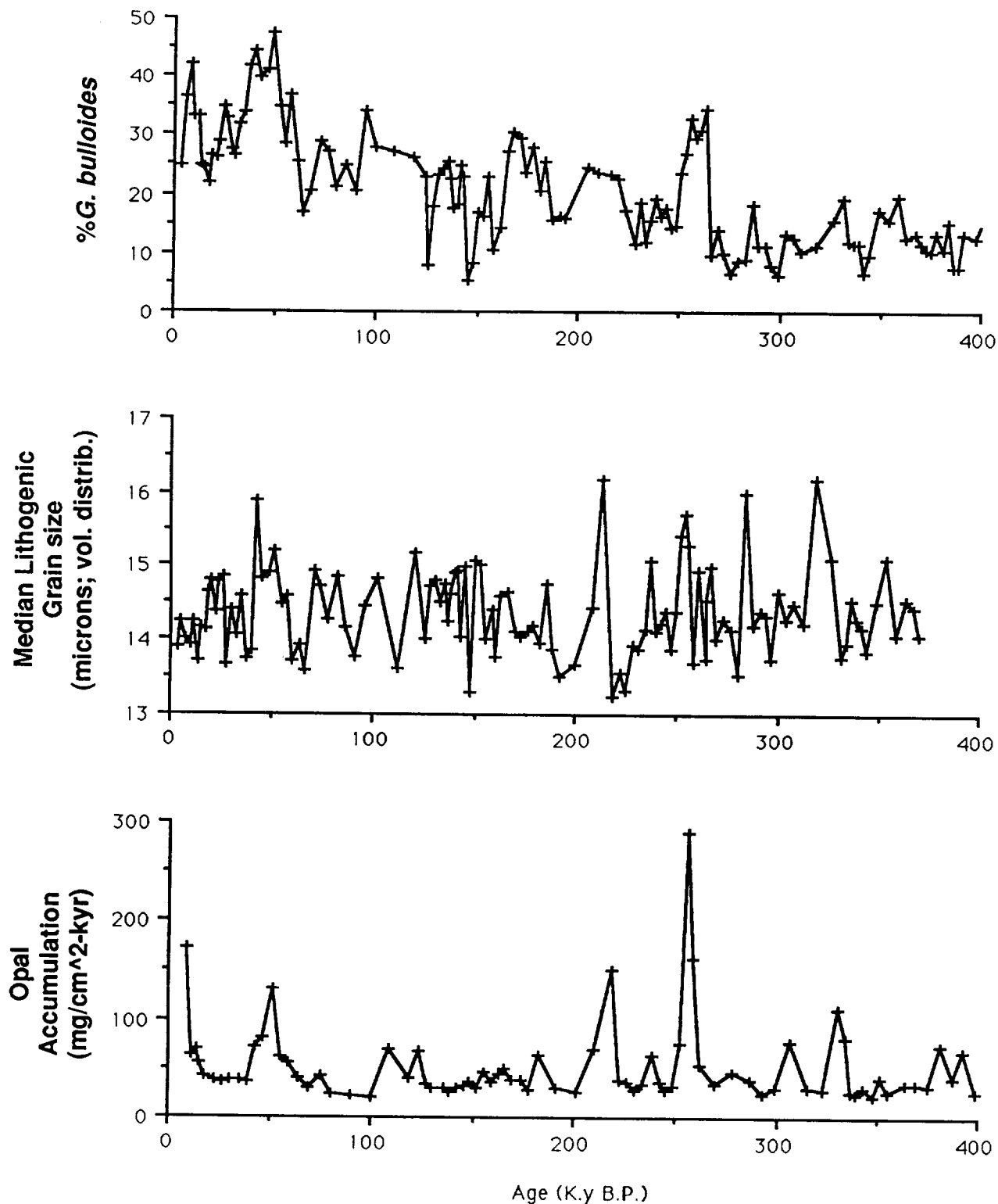


Figure 2. Lithogenic and biogenic indicators of monsoon wind strength and upwelling-induced productivity. Increased % *G. bulloides* and opal accumulation record changes in productivity associated with nutrient content of the intermediate waters upwelled during the summer monsoon. Increased grain size of the lithogenic component varies as a function of the strength of summer winds.

-PRECESSION: 23 ky CYCLE

June 21 perihelion

Max. June Rad.

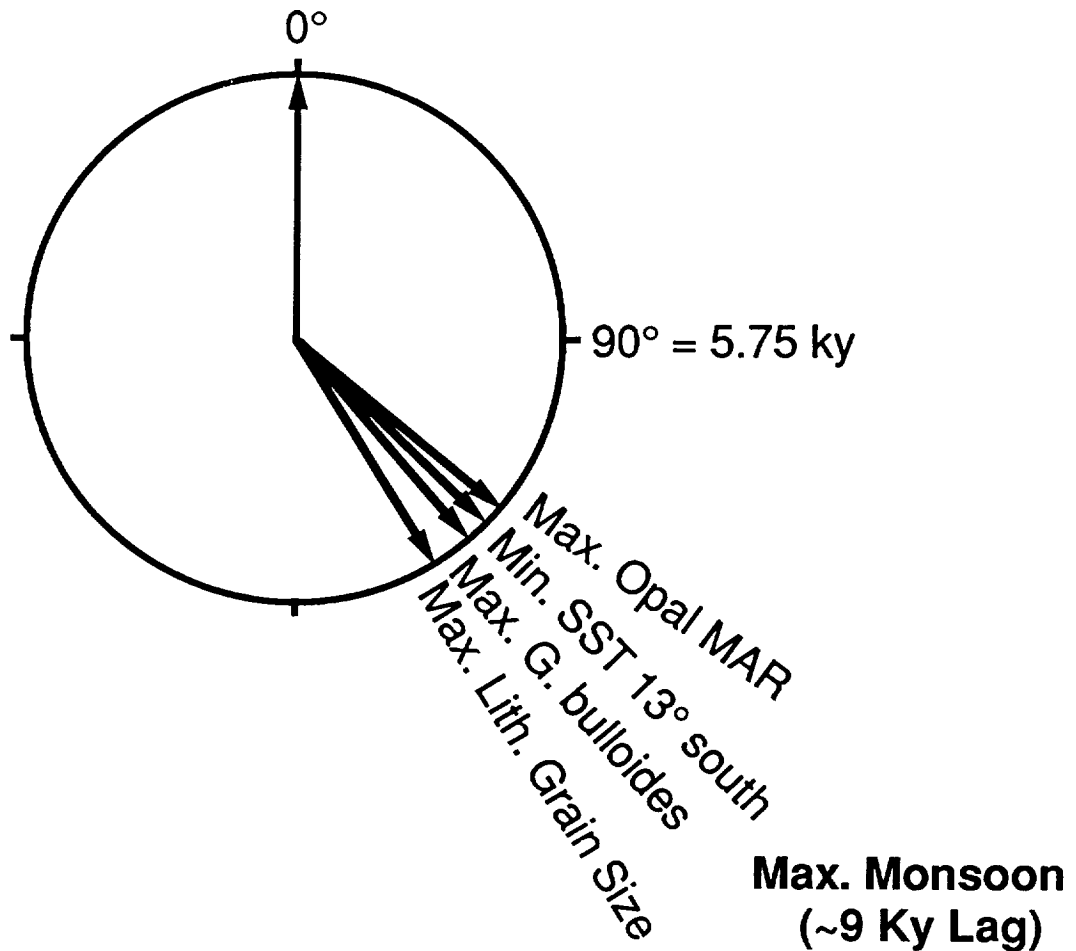


Figure 3. Precessional phase wheel summarizing the coherency and phase relationships between several monsoon indices and the Earth's orbital precession. All parameters shown are coherent (at or above the 80% confidence level) with insolation patterns driven by the precession of the Earth's orbit. The phasing indicates that all the monsoon records attain maxima ~ 9 kyrs after maxima in precessional insolation but simultaneously with minima in sea surface temperatures (SST) at 13° south in the Indian Ocean. This, similar to modern monsoon dynamics, indicates that latent heat availability in the southern subtropic Indian Ocean exerts a strong influence on the timing of strong monsoons and upwelling in the Arabian Sea over the past 400 kyrs.

Frequency Domain

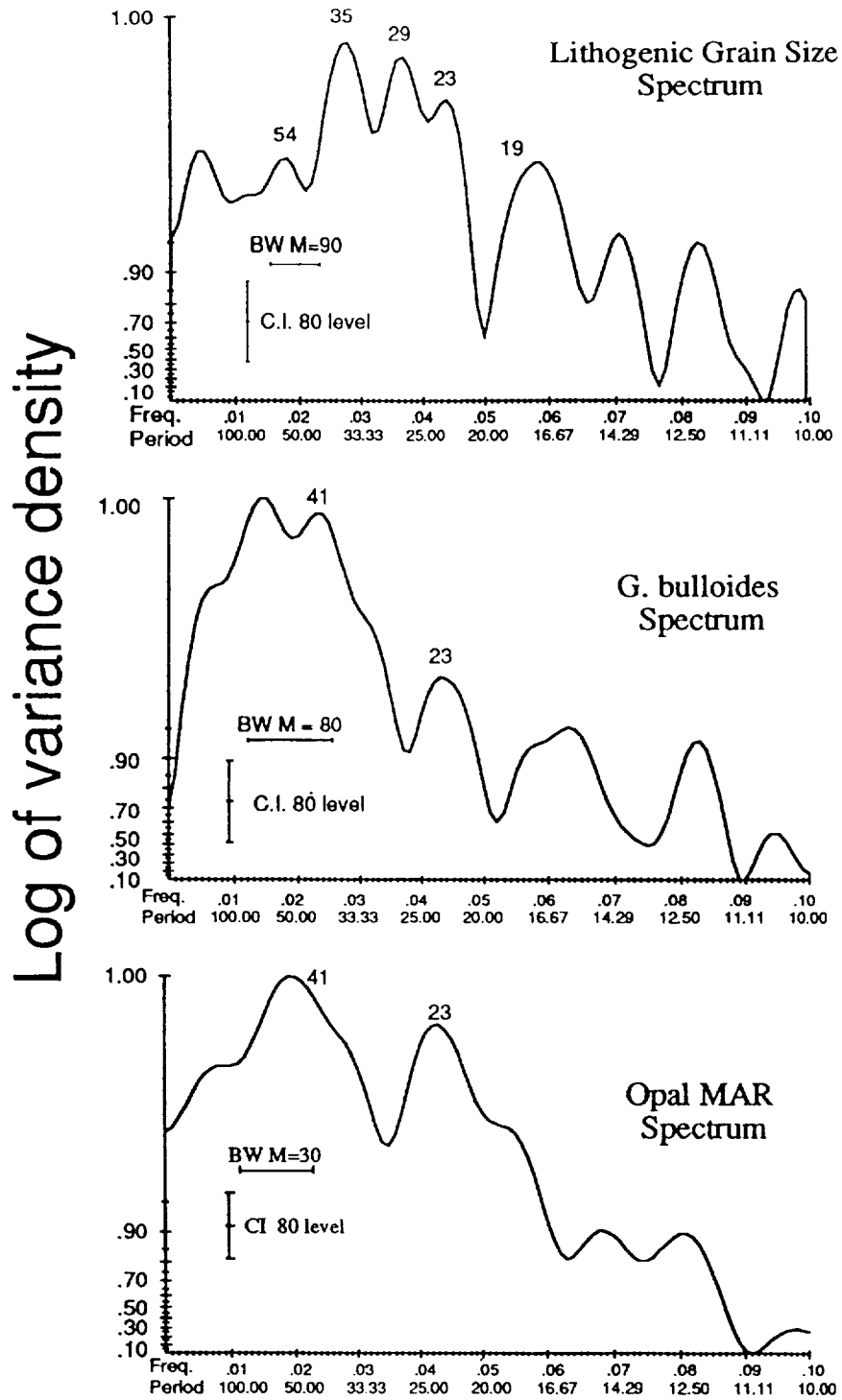


Figure 4. Spectra of the biogenic and abiogenic indicators of monsoon wind strength and the associated upwelling-induced productivity. The 41 kyr (orbital obliquity) variance in the *G. bulloides* and opal records is absent from the lithogenic (abiotic) record indicating that variance in this frequency band may not be driven by productivity due to monsoon-induced upwelling. This variance may be associated with more global oceanic mechanisms which enhance or reduce the nutrient content of the intermediate waters of the Indian Ocean. The 29, 35, and 54 kyr spectral peaks in the grain size record are linearly related to SST and insolation patterns in the southern subtropic Indian Ocean indicating a link between latent heat flux and monsoon strength as is observed in modern monsoon dynamics.