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El Niño - Southern Oscillation variability from the late Cretaceous Marca Shale of California.

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Supplementary Methods: Time series analysis and spectral analysis.

The Lomb-Scargle Transform algorithm of (Press et al., 1992) was used in spectral estimation as this is designed for processing irregularly-spaced data (e.g. records with missing data due to bioturbation and interruptions by turbidites). Prior to spectral estimation we applied standard linear detrending to each time series followed by a cosine taper applied to the first and last 5% of the records to suppress periodogram leakage involved in the spectral estimation. The positive bias from the Lomb-Scargle method was removed using the Monte Carlo re-shaping method of (Schulz and Mudelsee, 2002) based on the lag-1 autocorrelation. A discrete Hanning spectral window was applied three times to the periodogram estimates. Two approaches were then used to establish confidence levels for spectral peaks. Firstly, a robust first-order autoregressive model fit to the median smoothed log power versus frequency spectrum was used to locate the spectral background (Mann and Lees, 1996). Standard confidence levels were then indicated as sloping dashed lines on the plotted spectra assuming a χ^2 distribution of spectral estimates around the spectral background (Mann and Lees, 1996) with eight degrees of freedom due to the Hanning window. We considered as significant, those spectral peaks that exceeded the 95% χ^2 confidence levels which, it was found, also exceeded the 99% Monte Carlo method confidence levels.

A second, less parametric, approach to the distribution of spectral values is to use a Monte Carlo method. We generated 10,000 new first-order autoregressive (red noise) time series of the same length and the same lag-1 autocorrelation as the observed data and obtained power spectra for each simulated spectrum. Monte

Carlo spectral confidence levels (labeled "MC CL" in the figures) were then established by using, at each frequency, the proportion of cases where the spectral estimates from the original data exceeded the 10,000 estimates derived from the simulated data. This method is more general than the permutation approach of Pardo-Igúzquiza and Rodriguez-Tovar (2000) which can only be applied meaningfully to pre-whitened data (so that white noise permutation spectra are not compared with a red noise observation spectrum). For series much less than 10,000 points long the Monte Carlo approach adopted here yields more conservative confidence levels than the permutation approach.

References

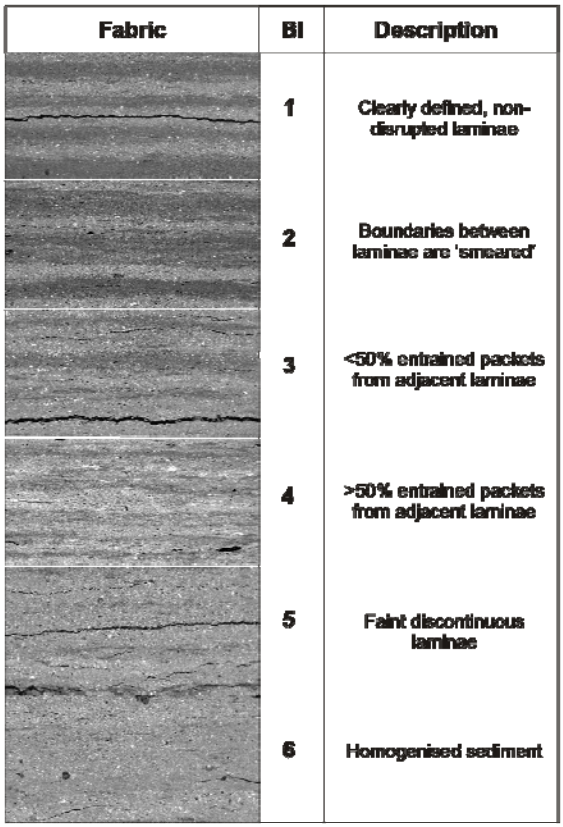
Mann, M.E., and Lees, J.M., 1996, Robust estimation of background noise and signal detection in climatic time series: Climatic Change, v. 33, p. 409-445.

Pardo-Igúzquiza, E. and Rodriguez-Tovar, F.J., 2000. The permutation test as a non-parametric method for testing the statistical significance of power spectrum estimation in cyclostratigraphic research. *Earth Planet. Sci. Lett.* **181**, pp175-189.

Press, W.H., Teukolsky, S.A., Vetterling, W.T., and Flannery, B.P., 1992, Numerical Recipes, the Art of Scientific Computing: Cambridge, Cambridge University Press, 963 p.

Schulz, M., and Mudelsee, M., 2002, REDFIT: estimating red-noise spectra directly from unevenly spaced paleoclimatic time series: Computers & Geosciences, v. 28, p. 421-426.

Supplementary Figures



Fabric	BI	Description
	1	Clearly defined, non-disrupted laminae
	2	Boundaries between laminae are 'smeared'
	3	<50% entrained packets from adjacent laminae
	4	>50% entrained packets from adjacent laminae
	5	Faint discontinuous laminae
	6	Homogenised sediment

Figure DR1. Bioturbation index derived from BSEI images. A value was allocated for each lamina based on the given criteria.

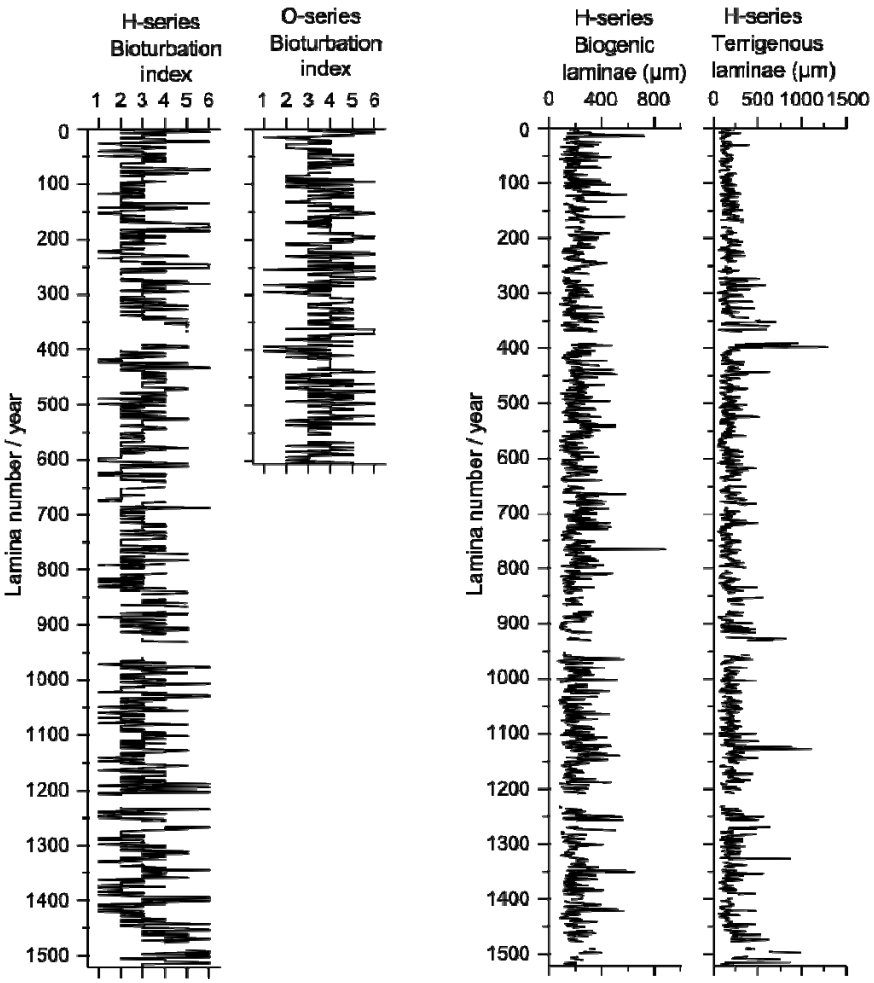


Figure DR2. Time series of H- series Bioturbation Index, O-series Bioturbation Index, and H-series Biogenic and Terrigenous lamina thicknesses.

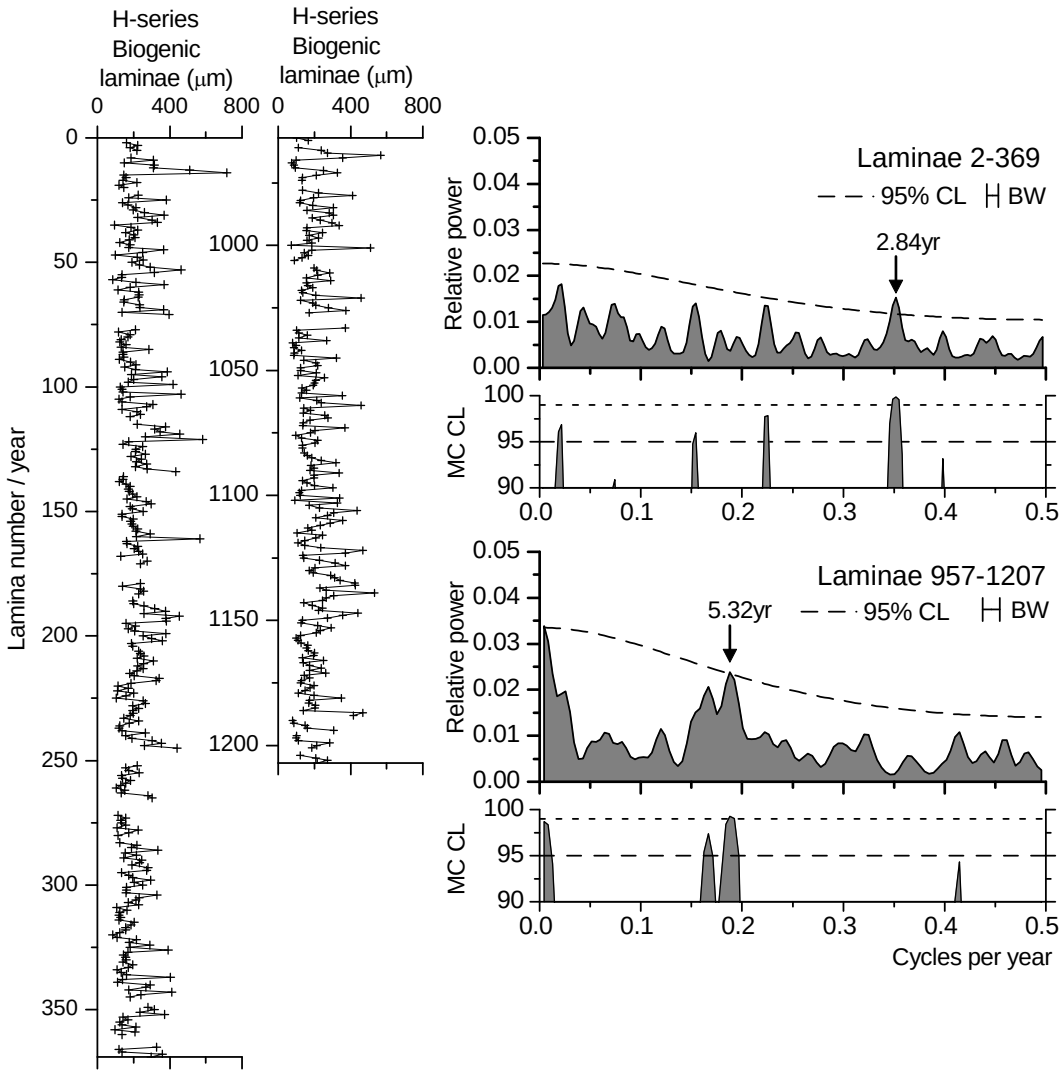


Figure DR3. Time series and power spectra of the Marca Shale biogenic laminae thickness time series for different intervals of the H series data illustrated in Fig. 3. Note that different intervals have different significant spectral periods of 2.8 and 5.3 years - consistent with the non-stationary interannual variability of the ENSO.