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Climate of the Past

Enhanced climate variability in the tropics: a 200 000 yr annual record of monsoon variability from Pangea's equator

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Abstract. A continuous series of 209 000 evaporite varves from the equator of arid western Pangea (age = −255 ma), as a proxy for surface temperature, has a complete suite of Milankovitch cycles and harmonics as expected for a rectified reaction to precession-modulated insolation at the equator. Included are modes of precession (23.4 kyr, 18.2 kyr), semi-precession (11.7 kyr, 9.4 kyr), and harmonics at ∼7 kyr and 5.4 kyr. An oscillation of ∼100 kyr, with 35 % of total variance, originates as an amplitude modulation of precession cycles. An exceptionally strong 2.3 kyr quasi-bimillennial oscillation (QBMO) appears to have had its own source of forcing, possibly solar, with its amplitude enhanced at Milankovitch frequencies. Seasonal information in varves traces the rectifying process to asymmetrical distribution of Pangea relative to the equator, and its effect on monsoonal circulation and heat flow near the equator during summer solstices in the hemispheres.

1 Introduction

An unusually long and continuous annual recording of monsoonal climate has been reconstructed from a sequence of evaporite varves that accumulated in a geologic basin that was near or possibly directly on the equator of western Pangea (Fig. 1). The 209 000 yr annual recording has a proxy for surface temperature that displays all the astronomical periods of insolation forcing expected for the equator from mathematical calculations (Berger et al., 2006). The recording's considerable variability affirms an observation of Berger et al. that changes in insolation at the equator and their effects on tropical climate have largely been overlooked as a source region for climate change.

That the tropics and monsoons are especially sensitive and respond nonlinearly to changes in insolation was recognized in an early study with a general circulation model (GCM) that compared how Earth's regions, since 18 kyr, responded to forcing (Kutzbach and Guetter, 1986). Their most important result, in regard to this study, was a striking response of the tropical monsoon system to the seasonal cycle of solar radiation, for which changes in precipitation were $3.7X$ than corresponding differences in radiation. Much of the amplifying effect was attributed to the nonlinear relationship between temperature and vapor pressure, and they also recognized the importance of different thermal properties of land and ocean and the monsoon's reaction to insolation, as modulated by precession (Hagelberg et al., 1994). For the monsoon example presented here, an amplified response of similar magnitude appears to be present in the reaction of surface temperature as modulated by precession, suggesting that a climatic amplifying can be achieved in the tropics without a large contribution from a vapor pressure effect.

That changes in surface temperature will also respond nonlinearly to the insolation forcing is supported by geographic climate modeling experiments conducted by Short et al. (1991) and by Crowley et al. (1992) for Pangean geography. They employed an efficient seasonal energy balance climate model (EBM) to generate 800 kyr series of annual maximum surface temperature ($T_{\max}$), and demonstrated that the amplified reaction in surface temperature was confined to the equatorial region. For Pangean geography, for which different thermal properties of land and ocean are for a much larger land area, the modeled response of $T_{\max}$ in the EBM-generated series is almost indistinguishable from that of the natural reaction in both the varve series and its spectrum, to be described here.

In the natural series, an amplified response in surface temperature appears at all known frequencies of astronomically modulated insolation: orbital, precessional, and semi-precessional. In addition, the varve series has a strong, nearly

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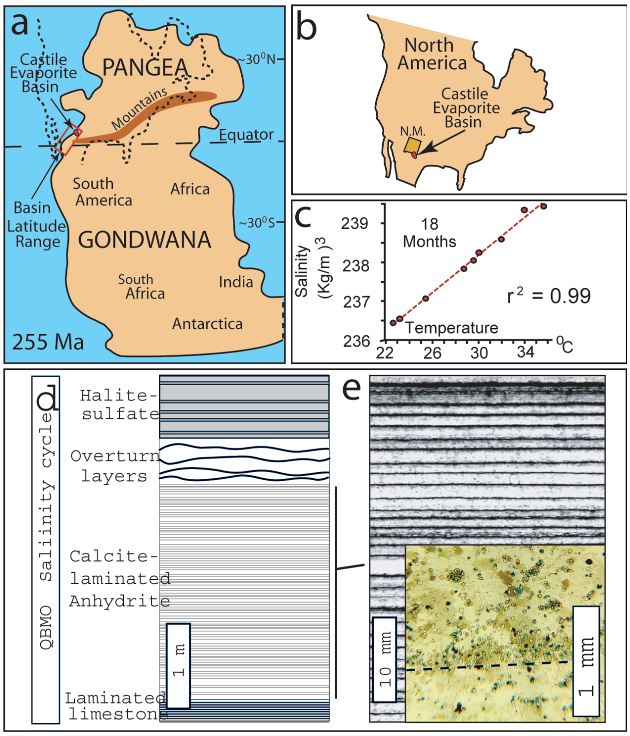

Fig. 1. Location, petrologic cycles, and varves of Castile Fm. **(a)** Map of Pangea in Late Permian (after Scotese, 2010). Rectangle is range in location of Castile evaporite. Dashed map is location of North America in Late Permian Pangea. **(b)** Map of North America (dashed) and location of Castile evaporite basin relative to New Mexico. **(c)** Linear relationship of salinity and temperature in Dead Sea surface brine (Gertman et al., 2009). **(d)** Complete petrologic-salinity cycle and varve types of the QBMO. Low salinity varves at base to high salinity halite varves at top. **(e)** Photo of typical carbonate-sulfate layers (varves) in laminated Castile Fm. Dark, thin layer is organic-enriched calcite, light layer is anhydrite. Inset shows colored rhombic crystals of calcite comprising a carbonate layer. Dashed lines marks onset of monsoon.

regular climatic cycle at a sub-Milankovitch frequency that is expressed as stratigraphic units in the varve series (Fig. 1d), and is described here as a quasi-bi-millennial oscillation (QBMO). It will be shown that amplified reactions in surface temperature at all frequencies, including the QBMO, appear to reinforce one another, which further adds to amplified responses of surface temperature. Thus, the long varve series reported on here recorded reactions of the monsoon climate system that are unique to equatorial latitudes and appear to have enhanced the sensitivity of tropical climates to the insolation forcing.

Amplified climatic reactions recorded in the varve series are the theme of this report, and their description could not be contemplated if it were not for the preservation of seasonal relationships and associations in the evaporite varves. Such associations allow one to trace long-term (Milankovitch) modulations of insolation to the season of their climatic expression during the annual cycle and thereby recognize climatic associations. Demonstrating climatic origins for the recorded oscillations, however, requires a necessary skepticism, largely because there is inadequate information about how climate signals are recorded in geological time series (Sect. 1.2). An overview of the varved Pangean climate record is helpful in considering how the Castile example overcomes some of the suspected limitations of geoclimatic recordings.

1.1 Castile varve series – overview

The equatorial climate record was obtained from the entirely laminated evaporite of the Upper Permian Castile Fm. now in southeast New Mexico (NM), USA (Fig. 1a). The varves are composed of seasonal layers of evaporite minerals, for which changes in varve thickness were a function of seasonal rates of evaporation, as largely determined by the monsoon. From the relation of evaporation and temperature, varve thickness is an approximation of changes in surface temperature during a hot season. At the time of evaporite accumulation, the deep basin was located on the arid coast of western Pangea where a dry and persistent western Pangean monsoon arrived on schedule every year, as is confirmed by the varve series having recorded a complete suite of astronomically modulated climate cycles at close to their expected frequencies (Sect. 4.1).

Most of the climate oscillations to be considered can be identified in an un-tuned series of raw annual (varve) thickness values (Fig. 2) in which the density of annually plotted data characterizes the climate response without the need of filtering. For example, most observers will recognize 9 to 11 prominent oscillations in the density of plotted thickness values, as represented by a running mean (white and yellow traces), which define the response of varve thickness (surface temperature) to the modulation of insolation by the precession term. As is observed in the spectrum for the series, the prominent oscillations have a period close to the two modes of climatic precession (Fig. 3a, 23.4 kyr, 18.2 kyr). A longer, ∼100 kyr oscillation in Fig. 2 (polynomial, blue dashed line) originates as a systematic amplitude modulation over the course of 4 to 5 "precession cycles", and is most easily recognized in the first half of the series. Parts of two oscillations do not define a period, and here it is assumed, for later discussion, that the systematic amplitude modulation is distinctive enough to represent the eccentricity term in the modulation of insolation. Note: a similar amplitude modulation of 4 to 5 cycles assigned to the precession period was sufficient to suspect an association with orbital eccentricity in a monsoonal climate record of similar length from Africa (Fig. 3c; Pokras and Mix, 1985, 1987).

Also present in the varve series are cycles that have the half-period of precession, and are most easily recognized as two maxima in thickness between $T_0+\sim45$ kyr to ~57 kyr (Fig. 2). Semi-precession cycles have almost the precise

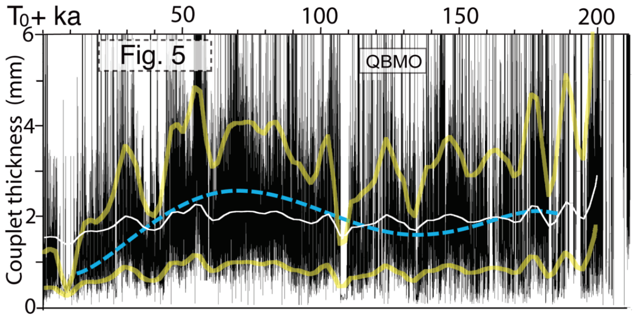

Fig. 2. Castile time series. Raw, un-tuned, annually plotted series of varve couplet thickness in Castile Fm. White trace is a 1 kyr running mean thickness. Lower transparent trace (yellow) is white trace placed near lower bound of dense annual data. Upper transparent trace is 4X lower trace, and outlines cycles of climatic precession and semi-precession near upper bound of dense annual data. Dashed line is 5th-order polynomial showing ∼100 kyr oscillation as an amplitude modulation of precession cycles. Plotted values of dense annual data above 5 mm are mainly quasi bi-millennial oscillations (QBMO).

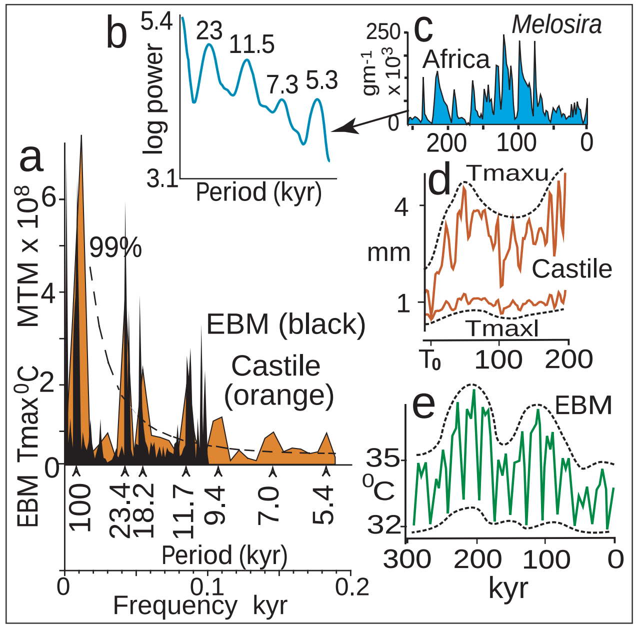

Fig. 3. Rectified series and their spectra. **(a)** Castile spectrum (brown) for series in Fig. 2 compared with spectrum for EBM $T_{\max}$ series (solid black, from Crowley et al., 1992). Confidence line applies to Castile spectrum only. Castile spectrum, MTM, resol. = 1 window = 1, $N = 1620$). **(b)** Spectrum for African *Melosira* dust record with precession cycle and harmonics. **(c)** African *Melosira* dust series with ∼5 prominent, sharp, amplitude-modulated precession cycles comprising a ∼100 kyr oscillation. Note secondary maxima with lagged and sloped shoulders – **(b)** and **(c)** from Pokras and Mix, 1987. **(d)** Castile series depicted by transparent traces in Fig. 2. Note amplitude-modulated precession and semi-precession cycles, and secondary lagged maxima with sloped shoulders. **(e)** EBM-generated $T_{\max}$ series for Pangea, with secondary maxima, amplitude-modulated precession cycles, and covariant upper and lower bounds (from Crowley et al., 1992).

half-period of cycles assigned to precession. Double maxima are recognizable in more than half of the Castile series' precession cycles, and are most clearly seen at the upper bound of densely plotted data (yellow trace), as also depicted in Fig. 3d. Higher harmonics of the precession period are present in the series (Fig. 2, T_0 + ∼12 kyr to ∼30 kyr, <4 mm) but are difficult to recognize. A strong QBMO persists throughout the series, for which thickness values extend above the upper yellow trace and commonly reach the 6 mm limit in Fig. 2. Spectral analysis at high resolution places a larger increase in variance at a period of 2.3 kyr, and a lesser increase at 1.5 kyr. The QBMO has sufficient strength and persistence to suggest its own source of forcing, which is an assumption adopted here.

1.2 Rectifying of geoclimatic recordings

Climatic amplifying processes (Sect. 4.2) are related to the varve series having been rectified by processes about which almost nothing specific is known. The most obvious indication of a rectified geoclimatic record is the presence of harmonics of the precession period; harmonics are the signature of a simple half cycle rectifier (Hagelberg et al., 1994). Another sign is the presence of an oscillation with the half-period of precession, which can be considered a 2nd harmonic of precession or a primary response to the twice-annual passage of the Sun over the equator. Still another indicator is expression of the ∼100 kyr amplitude modulation in cycles that have the precession period.

Previously reported geological recordings with signs of having been rectified are from present or former low latitudes and associated with monsoons. For example, Olsen and Kent (1996) described long records of monsoon-supported changes in lake levels in Upper Triassic Pangea that were probably within ∼10° N latitude and contained many lake-level cycles of ∼400 kyr and ∼100 kyr as evidence of having been rectified. A younger Middle Eocene geological record from ∼9° N is associated with ∼400 kyr and ∼100 kyr compositional cycles, but its relation to a monsoon is less certain (Westerhold and Roehl, 2010). Some rectified geoclimatic series are recognized from the presence of harmonics of the ∼23 kyr climatic precession period, as reported by Pestiaux et al. (1988) in a marine isotopic record of the Indian monsoon. Semi-precession cycles (2nd harmonic) are reported in Late Pleistocene marine sediments from low latitudes (Hagelberg et al., 1994; McIntyre and Molfino, 1996). A rectified Late Pleistocene monsoonal record of dust shed from the African continent (Pokras and Mix, 1985, 1987) bears a close resemblance to the record reported here from Pangea, including a complete suite of precession harmonics and an amplitude modulation of 4 to 5 precession cycles (Fig. 3a–d).

Other geological examples of rectified series appear as "bundles" of strata that are organized so that 4 to 5 layers of thinner strata comprise a thicker unit, or a ∼100 kyr bundle. Such bundles are commonplace at low latitudes when Pangea straddled the equator and had a strong monsoon circulation (e.g. Oglesby and Park, 1989; Olsen and Kent, 1996; Herbert, 1997); one record is reported from the middle Cambrian geological Period (−535 ma, Bond et al., 1993), and another monsoon record, which may represent the latitude limit of a rectifying effect, is from ∼30° S latitude (Park et al., 1993). Herbert and Fisher (1986) noted that the mineral-chemical composition within bundles changed systematically over the course of the 4 to 5 layers assigned to the precession period. Citing Wigley (1976), who had obtained a similar amplifying effect by applying a nonlinear function to a series of calculated insolation values, they suggested that the climate system might perform an analogous nonlinear amplifying function.

A general understanding of how a series of values with a waveform is rectified is aided by likening the process to an amplitude-modulated (AM) radio signal, as it is amplified by a rectifying diode. The regular precession cycle can be considered an analog of the carrier wave, and the AM signal is the ∼100 kyr oscillation (modulation) at the carrier wave's upper and lower bounds. Before rectifying, the AM signal at upper and lower bounds are exactly opposed and the signal cancels. But if the lower bound of the carrier wave is "clipped" (rectified), the upper bound remains intact and the ∼100 kyr signal is expressed (amplified). The diode analogy describes a final effect, but little is known of how geoclimatic series were rectified because the climate system reacts seasonally to the insolation forcing and geological recordings rarely supply the needed seasonal information. Descriptions of the process are thus generalized, such as the climate or recording system responding to the largest seasonal difference in insolation, or climate sensitivity to insolation minima (Hagelberg et al., 1994), or a process of maximum and minimum selection of seasonal forcing (Berger et al., 2006).

From lack of information, there is no consensus on how rectifying of geological recordings is accomplished, with some geologists believing that the ∼100 kyr cycle in strata is an orbit-related climatic response. Other observers assume that the orbital amplitude modulation of insolation cancels and is not a real (forcing) cycle (Ruddiman, 2008, p.129). As a result, ∼100 kyr and ∼400 kyr responses in monsoonal geoclimatic records are assumed to result from encountering a non-climatic threshold (Ruddiman, 2008, p.141), with the rectifying effect being an artifact introduced by seasonal geological (or biological) recording processes (Huybers and Wunsch, 2003) such as runoff, erosion and sediment transport, deposition, and non-deposition.

Uncertainty in interpretation of the rectifying phenomenon has consequences for our understanding the tropical climate system because the system itself may function as a rectifier and important amplifier of the insolation forcing, which is the theme of this report. Such an assumption is warranted for the Castile example from seasonal information preserved in varves, and also because its geochemical recording system rules out the possibility of geological or biological recording artifacts (Sect. 2.5). My purpose is to describe the climate record in enough detail to allow amplified reactions to be examined by others. As a single example, descriptions will need to be confirmed in other recordings or by climate models, and are provided here to help evaluate the wealth of information in this rare recording of climate from the equator.

2 Castile varves and geologic-hydrologic setting

The great size of the Pangean landmass and positioning of a substantial part of the continent on the equator increased seasonality and induced a strong, nearly global monsoonal circulation, as is observed in output from GCMs (Kutzbach and Gallimore, 1989; Kutzbach and Ziegler, 1994). The two seasonal layers that comprise Castile sulfate-carbonate varves represent continental and maritime phases of a "dry" monsoon on the equator of Pangea's western coast, an arid region un-reached by monsoon moisture carried in distant easterly airstreams. The western coast was hot and dry enough for the deep basin near the coast to accumulate 300 m of layered evaporate, including 100 m of halite varves.

2.1 Annual character of Castile varves

Kirkland (2003) has published copious geochemical and other evidence of the annual nature of Castile varves, which is not summarized here because the laminated evaporite, in recording a complete suite of Milankovitch cycles close to their expected periods (Berger and Loutre, 1989), is considered sufficient evidence of seasonal and annual lamination. Location of the evaporite on the western coast of Pangea assured that inland dissipation of the maritime monsoon did not result in many skipped seasons, and the monsoon's traditional regularity is confirmed by spectral power at known frequencies, which would not be present if the annual cycle was not recorded, and the layers accurately interpreted (Figs. 2 and 3a).

2.2 Castile varves in regional context

Most Castile varves are couplets in which thin layers of calcium carbonate with included dark-colored algal organic matter, alternate with thicker, light-colored layers of nearly pure calcium sulfate (Fig. 1e). The thicker sulfate layer chemically precipitated and accumulated during a prolonged hot-dry season when high rates of evaporation persisted for 8 to 9 months of year, including the summer solstice in the Northern Hemisphere (NH) and parts of spring and fall equinox, from heating as the sun passed over the equator.

Heating of the equator during the summer solstice in the NH was from the advection of hot, dry northeasterly surface winds from the continent's northern interior that moved from mid latitudes toward the equator, as indicated by coeval wind directions recorded in Pangean dune fields (Parish and Peterson, 1988; Loope et al., 2004).

The thin, dark-colored layers of calcium carbonate represent the arrival of westerly equatorial surface winds and a 3 to 4 month dry maritime monsoon season when relatively cool air temperatures penetrated the continents' interior and lowered rates of evaporation. What is usually a sharper, lower contact of the carbonate layer with the underlying sulfate layer marks the onset of the maritime monsoon, and a more transitional upper contact represents a more gradual termination (Fig. 1e, inset, dashed line). As depicted in a GCM for the same time interval (Kutzbach and Ziegler, 1994), the maritime monsoon that reached Pangea's western equator corresponds in annual timing to the season of extreme heating over the larger landmass in the Southern Hemisphere (SH) when daytime surface temperature near the summer solstice reached 45 °C (Crowley et al., 1989), and a net radiation deficit drew maritime equatorial westerlies (a monsoon) in over the equator and the evaporite basin on the dry western coast of Pangea (Figs. S3 in the Supplement and 5a, lower panel).

2.3 Geologic-hydrologic controls on varve thickness

The laminated Castile evaporite accumulated in a bathymetrically deep basin on the extremely arid equatorial western coast of Pangea (Fig. 1a). The 25 000 km^2 basin was encircled by a tall reef, and once cut off from the ocean, the isolated "lake" maintained its water level from ocean-sourced groundwater recharge seeping through the reef and from groundwater seepage elsewhere. In an arid climate, water in the basin quickly concentrated to a chloride brine in which dense, non-circulating stagnant brine at depth was overlain by a layer of less-dense circulating brine above and separated by a pycnocline. The deep Castile basin and brine pool has a close modern analog in the Dead Sea (Anati, 1997), both having chloride brines and intermittent pycnoclines (Fig. S1 in the Supplement).

Varve layers are composed of crystals of calcite ($CaCO_3$) and gypsum ($CaSO_4 2\ H_2O$), which, based on modern analogs, were chemically precipitated at the air-brine interface in response to seasonal differences in salinity from evaporative concentration that was largely controlled by surface temperature. Nucleation occurred at and near the brine-air surface when seasonal increases in evaporative concentration and salinity exceeded solubility products of calcium and bicarbonate and calcium and sulfate. Once reaching critical size, calcite and gypsum crystals rained through the upper brine layer and the stagnant lower layer to settle directly on the floor of the basin, where they accumulated as discrete layers of calcite crystals alternating with crystals of gypsum, which subsequently transformed to anhydrite (Fig. 1e). Correlation coefficients of +0.99 over tens of kilometers for groups of seasonal laminations (Kirkland, 2003) testify to efficient circulation and uniform salinity in the upper brine layer, where ions removed by crystal growth at the brine-air interface were replaced from below by circulating brine above the pycnocline. The thickness of varves and their variation increased steadily over the course of 209 kyr as layers of evaporite accumulated to partly fill the deep basin. The hydrological-geochemical effect of decreasing brine volume is seen in a systematic increase in amplitude of varve thickness over time (Fig. 4a), which is not a climatic signal but a result of increased sensitivity of the hydrologic system to effects of forcing.

2.4 Stratigraphic units and varve types

Over 90 % of the Castile varves were chemically precipitated under usual or ordinary climatic conditions, and these are composed of thin layers of calcium carbonate, alternating with layers of calcium sulfate (Fig. 1e). Occasionally, prolonged episodes of freshening of the upper brine layer lowered salinity and interrupted chemical precipitation of the sulfate layer for several hundred years, forming stratigraphic units of pure, algal-laminated limestone that comprise ∼2–3 % of the varves.

Under prolonged conditions of high surface temperature, evaporation, and drawdown in brine level, increased salinity and high brine density eliminated the pycnocline and resulted in overturn and deep circulation of brine (Fig. S1 in the Supplement). Circulation and mixing of brines greatly increased the rate of sulfate precipitation and produced anomalously thick and diagenetically distorted annual layers of calcium sulfate (Fig. 1d). Episodes of seasonal overturn, probably triggered by strong winds, persisted from a few decades to over a century, and about 3 % of varves were anomalously thickened. If drawdown was extreme, and concentration of brine exceeded the solubility of NaCl, seasonally precipitated layers of halite alternated with layers of calcium sulfate (Fig. 1d).

Different petrologic types of varves are organized into stratigraphic units and cycles of increasing and decreasing salinity, which, when complete, progress from laminated limestone at the base to calcite-laminated anhydrite, to thick, distorted layers of anhydrite, and, if complete, to anhydrite laminated halite (Fig. 1d). The usual duration of salinity and petrologic cycles is 2.3 kyr, the period of the QBMO. The response of varve thickness to QBMOs is usually confined to thick stratigraphic units of calcite-laminated anhydrite, but QBMOs also produced complete stratigraphic cycles.

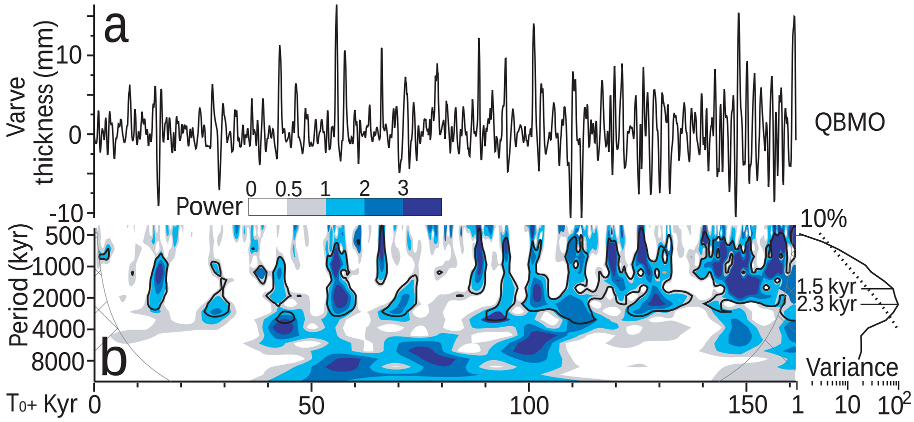

Fig. 4. Quasi-bi-millennial oscillation (QBMO) in Castile series. **(a)** Filtered series after removing ∼100 kyr oscillations with polynomial. Note systematic increase in amplitude of QBMO over time, and intermittent expression of larger oscillations. **(b)** Morlet wavelets of series in **(a)** as defined by 10 % noise limit (black outline; Torrence and Campo, 1998). Temporal separation of outlined centroids corresponds to precession period in first half of series. Separation includes semi-precession period in second half. Centroids spaced at precession and semi-precession periods are amplified in 2.3 kyr to 1.5 kyr (QBMO) band in global spectrum. **(a)** Series of Castile decadal values trimmed to 2 std. Dev. > 1 kyr running mean; ∼100 kyr oscillations removed with 3rd-order polynomial. Series filtered with 590 yr triangular filter and re-sampled at ∼100 yr. **(b)** Morlet wavelet of series in **(a)**, black outline = 10 % red noise limit.

2.5 Castile recording system and climate proxy

Describing the several processes that enhanced climate sensitivity to the insolation forcing is based on the seasonal layers of evaporite having recorded a response to changes in surface temperature. A faithful response in varve thickness as a proxy for surface temperature is assured by the evaporite's entirely geochemical recording system, for which changes in varve thickness were governed by a chain of essentially linear chemical reactions to seasonal changes in surface temperature. Support for a nearly linear recording system comes from studies carried out on brine in the Dead Sea, which is a close modern analog for the Pangean evaporite basin in its great depth and composition and density of brine. Both basins have, or had, a lower layer of dense, chloride brine separated from a circulating upper layer by a pycnocline that would break down intermittently. The upper brine layer in the Dead Sea is saturated with respect to gypsum (sulfate), which chemically precipitates as gypsum throughout the year. Reznik et al. (2009) directly observed mineral precipitation of gypsum (sulfate) from Dead Sea brine and showed it to be a linear function of salinity and density, a finding that is consistent with laboratory studies of gypsum nucleation (Prisciandaro et al., 2001).

Other observations of density (salinity) and temperature of surface brine in the Dead Sea, carried out over an 18 month interval, demonstrate a strong correlation of $r^2 = 0.99$ between salinity and temperature over a 13 °C range in annual temperature (Fig. 1c) (Gertman et al., 2009). Linear responses to temperature in Dead Sea brine, if applied to Castile brine, would assure a faithful proxy for temperature in varve thickness. And after crystals of calcite and gypsum nucleated and grew to a critical size near the brine's surface they rained directly to the floor of the evaporite basin to accumulate as seasonal layers that have only minor differences in thickness over the entire ∼25 000 km^2 evaporite basin (Kirkland, 2003). This lateral continuity assures that nonlinear mechanical geological processes and threshold effects, such as from bottom currents, did not alter primary, temperature-induced changes varve thickness. The nonlinear relation between temperature and saturation vapor pressure in monsoon precipitation (Kutzbach and Guetter, 1986) is not expected to be a factor because little rainfall and extreme aridity is indicated by the thick evaporite. From the above observations it is assumed with reasonable confidence that any nonlinear contribution from the geological recording system was minor and that changes in Castile varve thickness represent changes in surface temperature. As a result, descriptions of varve thickness oscillations and amplifying processes are expressed in climatic terms, with assurance that described responses are not false signals or recording artifacts.

In 90 % or more of varves, calcium sulfate averages 85 %, by weight, and the sulfate layer is the main contributor to changes in varve thickness. The principal control on sulfate thickness was salinity, as determined by rates of evaporation and surface temperature at different seasons. Although the annual sum of varve thickness included a cool season, the greatest rate of chemical precipitation of calcium sulfate occurred during the hottest months of the year so that varve thickness serves as a reasonably accurate estimator (proxy) for changes in annual maximum surface temperature (T_{max}).

3 Analytical methods and previous Castile information

A complete account of the Castile Fm and its varves, geologic setting, hydrology, and geochemistry is found in Kirkland (2003) and his references. The Castile varve series was collected from a single core of the entire Castile Formation with virtually 100 % recovery. The thickness of each of 209 000 varves was interpreted and measured by R. Y. Anderson over the course of several decades. Varves were measured on 3X-enlarged photographs and values are accurate to ∼0.5 mm. Each varve in the series is numbered, with the oldest varves at the base of the series designated T_0, T_0+1, etc. Other procedures of varve collection, measurement, and compilation are in the Supplement (S1) or previously published (Anderson, 1982; Anderson et al., 1972).

Owing to the occasional occurrence of less-than-annual climatic responses (e.g. semi-annual layers of carbonate and sulfate), the tendency was to over-count varves, possibly increasing the number of varves and length of estimated cycle periods by as much as 5 %. Even so, periods estimated for climatic precession and semi-precession by spectral analysis are close to those estimated for pre-Quaternary Milankovitch frequencies from astronomical parameters (Berger and Loutre, 1989), confirming a reasonably accurate varve interpretation.

Standard spectral methods were employed in estimating the distribution of spectral power, principally multi-taper (MTM) analysis (Dettinger et al., 1995) as implemented by kSpectra Toolkit for Mac OS X, and Analyseries (Paillard et al., 1996). Analysis employed computation of Periodograms, Blackman-Tukey and Maximum Entropy spectra, and the use of Wavelet Analysis (Torrence and Compo, 1998). All methods resolved similar spectral responses in the range of precession and its harmonics, and illustrated here are mainly MTM spectra. Spectral analysis was applied to a segment from $T_0+11\,000$ to +173,000 yr. Although the complete series has 209 000 varves, the shorter segment avoided less stable hydrologic conditions near the onset and termination of varve accumulation and is believed to provide the best estimates of frequency and relative power. Analyses were performed after the varve series was completely interpreted and compiled. Re-sampling of the series employed linear interpolation (Analyseries-2, Paillard et al., 1996), and some filtering was accomplished with a weighted triangular filter. Information related to data acquisition and the time series is in the Supplement (S1).

4 Results

Results are presented in two categories, the first as brief descriptions of the several periods of response to forcing. Amplified reactions expressed at more than one period are described in categories of amplifying processes.

4.1 Climate reactions to insolation forcing

4.1.1 Amplitude-modulated cycles with precession period

A ∼100 kyr amplitude modulation of cycles assigned to the precession period is observed in the raw annual series, where it is traced by a 5th order polynomial (Fig. 2, dashed blue trace). A second ∼100 kyr oscillation is less clearly an amplitude-modulation, although the oscillation continues and its less regular expression is attributed to a less stable hydrologic (recording) system (Sect. 2.3).

The amplitude modulation of precession cycles, as represented by a running mean (white trace), when placed near the lower bound of densely plotted annual data, is seen to be covariant with a $4X$ amplified upper bound (Fig. 2, yellow traces). Visually, the fitted polynomial has an oscillation of roughly 100 kyr, for which various spectral methods assign a maximum variance of ∼85 kyr to ∼120 kyr. Although the annual Castile series has only two ∼100 kyr oscillations, they originate as an amplitude modulation of cycles having the precession period and account for 35 % of total variance.

4.1.2 Cycles with precession period

The 9 to 11 prominent oscillations in varve thickness, mentioned briefly in the introduction and outlined by annual plot density (Fig. 2, upper yellow trace), express the dominant mode of climatic precession at a period of 23.4 kyr, and the less prominent mode at a period of 18.2 kyr (Fig. 3a). Of chief interest, other than the ∼100 kyr amplitude modulation, is the covariance and difference in amplitude of the lower and upper bounds of annual plot density (yellow traces). The lower bound of plotted annual values of equal density corresponds to cooler than average years, and the upper bound to warmer than average years. Because adjacent and nearly adjacent values in the annual series represent virtually the same insolation values, there is a nonlinear, $4X$ larger response in varve thickness (surface temperature) to the same forcing for warmer than average years that originated in nonlinear processes related to rectifying mechanisms (Sect. 4.2).

Confirming a $4X$ amplifying factor in surface temperature (T_{max}) and its relation to Pangean geography and its monsoon, is a series of T_{max} values generated for the Pangean equator by a seasonal energy balance climate model (EBM) for Pangea (Crowley et al., 1992). The covariant upper bound of the EBM series also is ∼$4X$ lower bound (Fig. 3e), which the authors recognized as resulting from a nonlinear (rectifying) effect associated with the monsoon. Although the configuration of Pangea employed in the EBM was for a geologic time period that was younger by 35 ma, there was little difference in geography relative to the equator, and both model-generated and natural series have covariant bounds and a $4X$ amplifying factor (Fig. 3d and e). Inasmuch as the EBM had no component comparable to a nonlinear geological process, the 4X factor would not be a recording artifact. Conceivably, the EBM result, by employing T_{max} as a variable with nonlinear properties, might account for some of the rectifying effect observed in EBM T_{max}, if due to model processing. However, sensitivity of the EBM was comparable to that of the GCM of Kutzbach and Guetter (Short et al., 1991), and the 4X factor in varve thickness is assumed to result from a nonlinearly amplified (rectified) response in surface temperature to a warmer than average year.

4.1.3 Cycles with semi-precession period

Oscillations that have the semi-precession period appear as increases in varve thickness that continue above the yellow 4X trace of running-mean thickness values, as between $T_0+{\sim}45$ kyr to ∼57 kyr (Fig. 2). These oscillations appear as secondary maxima in cycles with the precession period and originated from the Sun's heating of the equator during its twice-annual passage at the equinoxes (Crowley et al., 1992). Double maxima have less than half the amplitude of precession cycles in the Castile series, and relationships between primary (precession) cycles and cycles with a semi-precession period are most readily observed in the EBM-generated series of T_{max} values where secondary maxima have a consistent lag following previous precession minima (Fig. 3e). In about half the cycles that have the precession period, the older of the double maxima has a lesser increase in T_{max}, which gives about half the ∼23 kyr cycles a unique sloped shoulder facing in the older time direction.

Comparing the amplified upper bound of Castile varve thickness and the upper bound of EBM-generated T_{max} values shows that the two series share a similar lag in their double maxima, and about half of the maxima assigned to the precession period in both series have a sloped shoulder that faces in the older time direction (Fig. 3d and e). That the precession term modulated changes in surface temperature at the equinoxes is confirmed by the semi-precession cycle having almost precise half-periods of the two modes of climatic precession: at periods of 11.7 kyr and 9.4 kyr (Fig. 3a). Designation of the semi-precession cycle as a 2nd harmonic of the precession period, however, may not be entirely appropriate if there is a separate response in heating of land at the equinoxes, in which case a more regularly expressed 5.4 kyr harmonic in the Castile series would be a

4.1.4 Harmonics and basin-related hydrodynamic processes

Not easily recognized, but visible as thickness values from T_0+10 kyr to T_0+30 kyr that reach ∼3 mm (Fig. 2), are a less-stable 3rd (∼7 kyr) harmonic, and a more consistently expressed 4th (5.4 kyr) harmonic of climatic precession (Fig. 3a). Harmonics in the Castile series derived some of their variance from hydrodynamic processes that operated within the basin and affected varve thickness. Two basin-related, threshold-type reactions are recognized: (1) overturning of the upper brine layer (Sect. 2.3), which produced anomalously thick varves of nearly pure calcium sulfate; and (2) prolonged events of brine freshening (Fig. 2, T_0+110 kyr), which resulted in anomalously thin varves and units of laminated limestone. Both processes, as episodic events, introduced abrupt transitions in thickness values that have a potential to distort the amplitude of spectral power.

Contributions to varve thickness and effects on spectral variance from brine overturn were evaluated by reducing maximum thickness values and examining the effect in spectra (see S2.2 and Fig. S2a, b in the Supplement). Mean varve thickness is 1.8 mm, and reducing maximum thickness values to 5 mm and then to 3 mm produced no shift in the frequency of any spectral peak. Power at the precession frequency was largely unchanged, whereas power at harmonic frequencies of climatic precession, especially 2nd and 3rd harmonics, was reduced by about half (Fig. S2c, d in the Supplement). Lesser power at the semi-precession period after removing the harmonic artifact indicates that abrupt, nonlinear overturn events (Fig. 1d) were favored at times of direct heating of the equator at equinoxes, when overturn was probably triggered by winds in the spring or fall.

Exaggeration of spectral power at harmonic frequencies was confirmed by applying a 2 kyr moving variance to accentuate of overturn and freshening events (Supplement, S2). In this case a short 2 kyr moving variance appears to have accentuated the square wave character of harmonics, as is confirmed in the spectrum. These abrupt events added sharp "corners" to the series, which is known to introduce an analytical artifact that increases power (Hagelberg et al., 1994) and is inherent in the Fourier method (Dima and Lohmann, 2009). Removing anomalous thickness values provides a series and spectrum that more accurately characterizes the T_{max} response, as depicted where Castile and EBM spectra for Pangea are compared (Fig. 3a).

4.1.5 Quasi-bi-millennial climatic oscillation (QBMO)

The quasi-bi-millennial climate oscillation (QBMO) in the Castile series was the only climate perturbation large enough to produce changes in salinity that resulted in stratigraphic units of laminated limestone, anhydrite, and halite (Fig. 1d). Although the changes in geochemistry that resulted in different strata partly depended on the scale of the 25 000 km^2 basin and its hydrology, large and persistent perturbations in surface temperature would still be required for changes in evaporation and salinity to consistently produce stratigraphic units of different geochemical composition. A 30 m halite unit, for example, has 1063 varves and represents the hotter half of a QBMO. Within laminated sulfate units, changes in salinity from the QBMO appear only as changes in varve thickness, which are observed as groups of thickness values that extend well above the upper yellow transparent trace and usually attain a thickness of at least 6 mm (Fig. 2).

The QBMO appears as an especially prominent and regular oscillation in a filtered plot of varve thickness values from which the ∼100 kyr orbital oscillation has been removed (Fig. 4a). Notice that the amplitude of the QBMO in varve thickness gradually increased over time. This steady increase is a hydrological response and not a climatic trend (Sect. 2.3), and the QBMO maintains a visually stable period over the entire varve sequence, even as the amplitude markedly increases after $\sim T_0 + 100$ kyr (Fig. 4a). Persistence of the QBMO within a relatively narrow frequency band is affirmed in a plot of Morlet wavelets where centroids that define the 10 % red noise limit show a recurrence of higher variance at the QBMO period through the entire length of the series, and for which the global spectrum has maximum variance between 2.3 kyr and 1.5 kyr (Fig. 4b).

A fascinating feature, and a potentially important amplifying phenomenon, is observed in the temporal spacing of centroids that define increased variance in the QBMO. The spacing in first half of the wavelet sequence corresponds approximately to the dominant mode of climatic precession, which thereafter is joined by less well-defined centroids spaced at half-precession intervals, which is attributed to a lesser response of rectified surface temperature to semi-precession forcing (Fig. 3a). Importantly, temporal spacing of the centroids that define amplified responses to precession and semi-precession, when traced to the above filtered QBMO series of varve thickness, shows that responses of one to three QBMO events, or cycles, were consistently amplified at the spacing of the two Milankovitch periods (Fig. 4a and b), which, in turn, were amplified by a rectifying process. Although less noticeable in the filtered series, there appears to be a build up to a maximum response of the QBMO near $T_0 + 55$ kyr that corresponds with the maximum amplitude modulation of precession cycles (∼100 kyr oscillation). Thus, all frequencies of Milankovitch forcing could be expected to enhance the QBMO.

4.2 Amplified reactions to insolation forcing

Amplified responses of the QBMO at Milankovitch frequencies appear to be a simple constructive addition of energy (surface temperature) from waveforms of different frequency. Thus, assessment of the reinforcing effect on the QBMO and tropical climate system requires an understanding of climatic processes that rectify and amplify surface temperature, about which little is known. A potential breakthrough in recognizing a source for climatic rectifying processes that operate through the equinoxes and solstices was a discovery made with a geographic and seasonal energy balance model (EBM) (Short et al., 1991), for which the output of annual maximum temperature (T_{max}) was rectified and exhibited ∼400 kyr and ∼100 kyr oscillations only at the equator. A second EBM T_{max} series and its spectrum, when generated using Pangean geography (Crowley et al., 1992), bear a striking resemblance to the series and spectrum of Castile varve thickness in having cycles and power at all Milankovitch frequencies expected for the equator. EBM and Castile results, when combined, identify two potential climatic mechanisms for rectifying a long T_{max} series near the equator, one operating through the equinoxes and the other through the solstices.

Evidence for both rectifying processes appears to present in the Castile series, and because their effects are expressed in different seasons, they could be complementary. There is an indication in the Castile series that the solstice mechanism is dominant, possibly to the extent that rectifying effects from an equinox process might be relatively minor.

4.2.1 Amplifying processes over land (equinoxes)

Short et al. (1991), noting the rectified character of long, 800 kyr series of T_{max} values generated by their a seasonal EBM, as found in expression of ∼400 kyr and ∼100 kyr oscillations, suggested that the series had been rectified from alignment of perihelion during the Sun's passage over the equator (equinox). Crowley et al. (1992), suspecting that the long cycles were related to monsoons over equatorial land areas, substituted Pangean geography in the EBM and confirmed a much larger rectifying effect. They also combined effects of forcing during several seasons to illustrate how secondary, semi-precession maxima (from equinox) can result in a clipped T_{max} reaction to insolation forcing. Although EBM experiments identified clipping effects, they did not provide information about specific climatic processes, making it difficult to recognize how components of the climate system contributed to the rectifying function. A rough estimate of the equinox contribution relative to a precession contribution is obtained by comparing relative amplitudes of rectified precession and semi-precession cycles (primary and secondary maxima), and indicates that about 1/5th of the variation in the EBM series and about 1/3rd in the Castile series might be accounted for by an equinox rectifying mechanism (Fig. 3d and e).

The presence of secondary maxima alone, however, does not necessarily assure an effective rectifying process because the Castile series identifies a second rectifying mechanism that could also result in secondary maxima. The equinox process requires only that a continent be positioned at the equator because the rectifying effect is in response to heating of the land surface and distributed by a continental monsoon. In contrast, the Castile series and its varves provide evidence that the monsoon performs a more direct and active function in a rectifying process that operates through the solstices and employs thermal properties of both land and ocean.

4.2.2 Monsoon as climatic amplifier, earth as diode

Describing how a maritime monsoon could function as a rectifying agent, and demonstrating how modulated insolation could be transformed near the equator, is aided by first

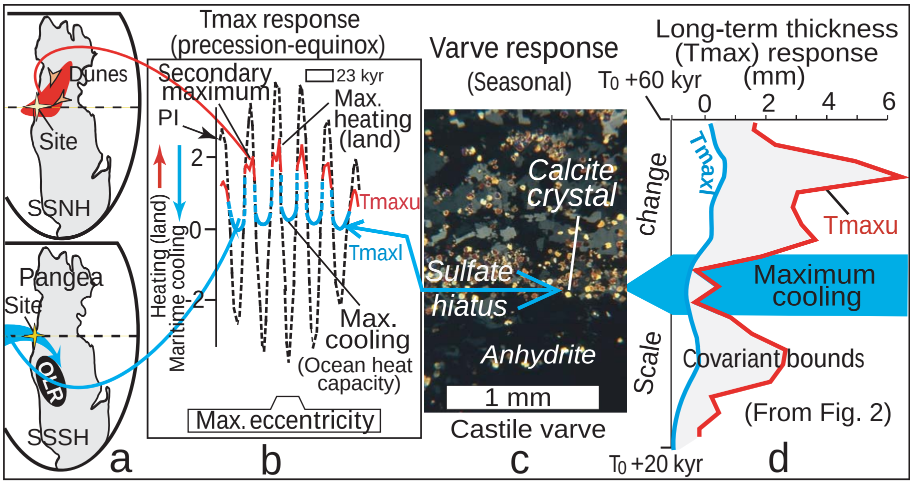

Fig. 5. Conceptual model for rectified response of varve thickness (T_{max}) **(a)** (below) Pangea and maritime monsoon (blue arrow), which moved inland over equator near summer solstice in SH. (Above) area near Pangean equator (red) heated directly by radiation with heat directed to equator by dry northeasterly winds. Heating at equinoxes gives 8–9 month hot season. **(b)** Response of surface temperature at equator to global insolation as depicted in a Precession Index (dashed black). Red line is maximum linear seasonal response to insolation in red area. Secondary maxima are from heat added by rectifying surface temperature at equinoxes. Solid blue line represents monsoon (ocean) cooling effect on surface temperature. Covariant lower bound (T_{maxl}, solid blue trace) represents limited capacity of ocean cooling to completely cancel effect of heating during cool years. **(c)** Petrographic microscope photo of thin-section of Castile varve couplet (crossed nicols). Anhydrite (black-gray matrix) is hot-dry season. Sharp contact of calcite crystals (bright, yellow-brown rhombs) mark onset of cool monsoon season and sulfate hiatus. **(d)** 40-kyr segment of Castile series showing effect of the seasonal sulfate hiatus in the continuum of variability as cycles having wavelengths of precession and semi-precession. Note: Maximum cooling – **(d)**, red trace – from heating in SH is applied from the amplified upper bound of the thickness series, whereas maximum cooling in **(b)** (blue trace) is applied from the clipped lower bound or "cool side" of the PI. Cooling (varve thinning) applied from upper bound is not a contradiction because seasonal heating and cooling, with reference to the PI, is timed by solstices in opposing hemispheres.

recognizing that the ultimate source of the rectifying effect was the positioning of an asymmetrical Pangean continent on the equator. In a hypothetical example, a perfectly symmetrical continent, as was employed in an early GCM for Pangea (Kutzbach and Gallimore, 1989), has surface wind vectors that result in two equal (semi-annual) seasons of westerly monsoon-like circulation and cooling of land north and south of the equator of western Pangea, which is a geometry that would not result in the seasonality needed to produce annual layering (varves) in an evaporite near the equator. In contrast, and as illustrated by surface wind vectors in the GCM of a highly asymmetrical Pangea (Kutzbach and Ziegler, 1994, Fig. S3 in the Supplement), the Pangean equator had a single season of strong, westerly maritime monsoonal circulation that produced Castile varves and rectified precession cycles.

That Pangea's asymmetry about the equator was critical to a rectifying process that operated through the solstices is provided by seasonal information contained in Castile varves. Surface wind vectors in the GCM of Kutzbach and Ziegler (1994) show a western monsoon coming onshore near the equator in December, near summer solstice in the larger SH (Fig. S3 in the Supplement). Six months later (summer solstice in the NH), the western equator received hot, dry northeasterly surface winds from mid latitudes in the NH, as shown by wind vectors and confirmed by prevailing wind directions reconstructed from Pangean dune fields (Parish and Peterson, 1988; Loope et al., 2004; red area in Fig. 5a, upper panel). Semi-precession cycles recorded in the varves' sulfate layer represent the equinoxes and show that hot, dry conditions at the equator, established during summer in the NH, persisted for 8 or 9 months of the year. To complete the annual cycle, and produce a varve, Pangea's profound asymmetry, through heating and a net radiation deficit in the SH, resulted in a strong western maritime monsoon that terminated the hot season at the equator.

The key feature within a Castile varve that identifies the maritime monsoon as a rectifying (clipping) agent is the thin, dark layer of calcium carbonate (Fig. 1e), which coincided with the onshore flow of the maritime monsoon into equatorial western Pangea. The thin layers of carbonate, when viewed through a petrographic microscope, are seen to be an accumulation of small, brightly colored rhombic crystals of calcite that are sandwiched within a interlocking mosaic of crystalline anhydrite (Figs. 1e, inset, 5c). As recognized by Kirkland (2003), calcite crystals were nucleated near the surface of a layer of brine that was continuously saturated throughout the year with respect to calcium and bicarbonate. *A critical observation is that calcite rhombs chemically precipitated throughout the year*, and inspection of magnified layers through a petrologic microscope reveals a sharp lower contact of calcite rhombs with the underlying mosaic of sulfate crystals (Fig. 5c). This contact marks a seasonal interruption (hiatus) in chemical precipitation and accumulation of sulfate crystals, during which calcite rhombs accumulated as a discrete layer during the seasonal hiatus in sulfate accumulation. The sharper lower contact of the carbonate layer marks the sudden onset of a season of cooling, a lowered rate of evaporation, reduced salinity, and an interruption in sulfate accumulation that resulted in Castile varves.

The rhombic crystals of calcite, which rained through dense layers of underlying brine throughout the year, accumulated on the floor of the basin during the maritime monsoon season. Sulfate (as gypsum) and calcite rhombs, which accumulated in hot and cool seasons, respectively, were then locked in place and retained their relationship with the two seasons. Calcite rhombs, which accumulated during the hiatus in sulfate precipitation, formed discrete, thin carbonate layers only when the solubility product of Ca^{2+} and SO_4^{2-} was no longer exceeded, owing to seasonally lowered salinity from reduced evaporation and lowered surface temperature that accompanied the western monsoon and persisted for 3 to 4 months of the year.

Arrival of the maritime monsoon may have been accompanied by a cloud cover that promoted cooling and reduced evaporation (brine salinity), but the amount of moisture in onshore monsoonal flow must have been minor for the balance between atmospheric precipitation and evaporation to produce several hundred meters of pure evaporite, including thick, 30 m units of halite. Webster's (1987) description of a strong temperature inversion and dry monsoon on a dry western coast may be appropriate. Exceptional purity of the evaporite indicates an absence of seasonal runoff (Kirkland, 2003), although it is possible that some rain may have fallen directly on the lake's surface. From the relationship between temperature and salinity in the Dead Sea (Fig. 1c), surface temperature was the main factor controlling evaporation, salinity, chemical precipitation of the sulfate layers and varve thickness.

How Pangea's marked asymmetry resulted in a climatically rectified series of surface temperature values can be visualized in a conceptual model (Fig. 5) by recognizing that the climate system reacts primarily to seasonal rather than annual changes in insolation, as does a climatically driven clipping process. Arrival of the western maritime monsoon supplied a strong seasonal cooling effect over land, in opposition to what otherwise would have been a permanently hot equator with a semi-annual heating cycle. Maritime cooling literally clipped the combined effects of annual and semi-annual heating. As a consequence of seasonal heating and cooling, and because annual and semi-annual heating cycles over land are largely linear responses to insolation, the upper bound of the varve series, when compared with the potential for forcing, as represented by the "warm side" of the PI (Fig. 5b), was, to a large extent, unaffected by seasonal monsoonal clipping. In contrast, the lower bound of the series was severely clipped in a ∼1/4 ratio by a nonlinear cooling reaction, which is depicted in the conceptual model as operating from the "cool side" of the PI.

5 Discussion

The series of evaporite varves from Pangea has been described in terms that allow the monsoon to function as an amplifier of variable surface temperature near the equator, as was initially recognized in atmospheric precipitation by Kutzbach and Guetter (1986). Required, and indicated by the magnitude of the recorded response, is a limited geographic exception to the expectation that the orbital, amplitude-modulation of the precession forcing will cancel (Ruddiman, 2008, p.129). A geographical rectifying effect is especially clear in the Castile example, owing to the enormous land area of Pangea and its marked asymmetry. However, there seems no reason to expect that the principle would not apply to some lesser degree, to other continents positioned about the equator and their monsoon systems; possibly with a summer monsoon inherently functioning, to some degree, as a rectifier – a supposition that can be tested with an appropriate climate model.

Partial confirmation of a *monsoon-as-rectifier* hypothesis may be provided by the African continent, which, geographically, has major features in common with Pangea, including an asymmetrical but reversed positioning about the equator and a westerly maritime monsoon – in this case during summer in the NH owing to a larger northern land area. The Castile varve series and African dust record also share a prominent ∼100 kyr oscillation as an amplitude modulation of precession cycles, semi-precession cycles that appear as secondary maxima with sloped shoulders, and the same precession harmonics, as expected if the two asymmetrical positioned continents shared a monsoonal rectifying process (Fig. 3c, d). An important difference, when comparing the two series, is a reversal in the direction of the unique sloped shoulders of secondary maxima in the African series, relative to the EBM-generated series for Pangea (compare Fig. 3c and e). Late Pleistocene insolation values were employed in the EBM (Crowley et al., 1992) so the reversal is not from a different orbital configuration, and is most simply explained if rectifying was sensitive to Africa's reversed asymmetry. Testing the reversal effect with a GCM has the potential to determine if continental asymmetry induces a rectifying process.

A conceptual model summarizes how seasonal reactions to precession-modulated insolation were transformed into Milankovitch-scale responses in surface temperature (Fig. 5). Panel 5a shows the asymmetric Pangean geography that annually placed strong seasons of heating and cooling in opposition at the equator. Panel 5b illustrates the effect of seasonal clipping of surface temperature (T_{max}) in relation to insolation as modulated by precession-eccentricity (Precession

Index (PI); upper, "warm side", and lower "cool side", black dashed trace). Notice that nonlinear seasonal cooling (clipping effect on surface temperature), as provided by the maritime monsoon, is applied from the "cool side" of the PI, and results in a less variable, "clipped", but still-covariant lower bound of the $T_{\max}$ series (blue trace). In contrast, the nearly linear heating response to insolation over land is amplified by about $4X$ and expresses as both primary (precession-solstice) and secondary (semi-precession-equinox) maxima (red trace). In panel 5c, the seasonal clipping (cooling) effect is traced to the annual sulfate hiatus in a varve, and then traced further in panel 5d to oscillations in response to precession and semi-precession that resulted from summed effects of changes in varve thickness (segment in Fig. 2). The lesser covariance of the lower bound of $T_{\max}$, relative to the $4X$ more variable upper bound, when compared with insolation changes (cool and warm sides of the PI, panel 5b) is from a strong monsoonal cooling effect, which ultimately resulted from the ocean's large heat capacity. The retention of some covariance in the lower bound appears to reflect a limited capacity of nonlinear ocean (monsoon) cooling to completely cancel the linear response of heating over land.

5.1 QBMO and tropical effects of Milankovitch forcing

In order for the QBMO to be recognized as an amplified oscillation it must be assumed that the quasi-periodic cycle was sufficiently regular to have its own source of forcing. A logical candidate for an internal, somewhat regular forcing is thermohaline circulation (e.g. Broecker, 1991). However, Pangea in the Late Permian had a single sluggish ocean (Winguth et al., 2002; Wignall and Twitchett, 1996) and was nearly ice free, and deep ocean circulation would be less likely to pace a strong bi-millennial climate cycle.

A candidate for external forcing is variable solar activity, a supposition that appears to be supported by the largest deviations in the Δ^{14}C proxy for solar activity, albeit in a short Holocene the tree-ring record, also expressing a period of 2.3 kyr (Damon and Sonett, 1991). The most prominent band of increased variance for the QBMO is bracketed between 2.3 kyr and 1.5 kyr in the global spectrum for the filtered QBMO series (Fig. 4b).

It is not the purpose here, nor is it necessary to demonstrate a connection with solar activity in order to illustrate a mutually reinforced amplifying effect, but the two periods of the QBMO do fall within the range of abrupt interstadial or Dansgaard-Oeschger events, for which a solar association has commonly been suggested (e.g. Bray, 1968, 1970; Denton and Karlen, 1973; Stuiver et al., 1997; Bond et al., 2001; Higginson et al., 2004; Braun et al., 2005; Dima and Lohmann, 2009). Also, one need not assume that direct heating of land from radiation is needed to have a regular and enhanced solar-climate response. For example, the climate model of Meehl et al. (2009) suggests that stratospheric heating from feedback between ozone and ultraviolet (UV) radiation propagates to heat the surface at near-equatorial latitudes; variable cosmic ray flux would not be excluded. The response of the QBMO also suggests that any quasi-regular climate phenomena, regardless of source of forcing, its effect will be amplified at Milankovitch frequencies, possibly as was reported for ENSO in climate model of the tropical Pacific (Clement et al., 1999).

Relevance of the QBMO, based on the Castile example, will likely depend on establishing a solar association in order to establish its permanence as climatic cycle. If forcing of the QBMO were from changes in solar radiation, then higher frequencies of variable solar activity, such as the 11 + yr Schwabe cycle, also would be amplified at lower frequencies. An unrecognized tropical amplifying effect might help account for why some climate models appear to lack sensitivity to changes in solar radiation.

5.2 Amplifying effects in younger climate records

Presence of a real ∼100 kyr monsoonal climatic oscillation at the Pangean equator would raise the prospect of a low-latitude contribution to the timing of Late Pleistocene glaciations, for which skipping the ice-melting response to the 41 kyr obliquity modulation of insolation is now a preferred explanation (Huybers and Wunsch, 2005). The amplifying effect on tropical temperature for Pleistocene geography would be small, possibly well less than half of the effect for Pangea (Crowley et al., 1992), but there still might be a potential to increase equator-to-pole thermal gradients and export additional tropical moisture to high latitudes (Lindzen and Pan, 1994; Raymo and Nisancioglu, 2003). Clemens and Tiedemann (1997), citing the EBM results of Short et al. (1991), suggested that ∼400 kyr and ∼100 kyr (glacial) cycles in the marine $\delta^{18}0$ record, before 1.2 ma, might result from truncating (rectifying) colder portions of the insolation forcing. Another indication of a tropical influence on glacial climate is northward propagation of the equatorial semi-precession cycle coincident with the onset of ∼100 ka glacial cycles (Rutherford and D'Hondt, 2000). One curiosity is that the periods of the two most enigmatic cycles in late Pleistocene climate, glacial cycles and DO type events, were present in force and reinforced each other in Pangea's monsoonal system.

6 Summary

A climate record from equatorial Pangea, compiled from evaporite varves: (1) shows a climatic rectifying of the insolation forcing at near equatorial latitudes that is not an artifact of the geological recording system, (2) may support a rectifying (amplifying) process related to equinox, (3) supports a second, more effective monsoonal rectifying process that occurs at the solstices, and (4) identifies what appears to be a strong and forced quasi-bi-millennial climate oscillation

(QBMO) at tropical latitudes for which there is a mutual amplifying effect with Milankovitch climate cycles.

Supplementary material related to this article is available online at: http://www.clim-past.net/7/757/2011/ cp-7-757-2011-supplement.pdf.

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