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Orbital Variations of Biogenic $CaCO_3$ and Opal Abundance in the Western and Central Equatorial Pacific Ocean During the Late Quaternary

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ABSTRACT

Biogenic $CaCO_3$ and opal abundances were measured in two piston cores (PC313 and PC5101) collected, respectively, along the equator in the western and central Pacific Ocean. The age model for core PC313, which extends to about 750 ka, was developed by comparing the oxygen isotope stratigraphy of planktonic foraminifera (*N. dutetrei*) to the SPECMAP stack. The age model for core PC5101, which extends to about 600 ka, was developed by stratigraphic correlation of $CaCO_3$ contents to those in the well-dated core RC11-210 (Chuey et al. 1987). Both cores distinctly exhibited a series of $CaCO_3$ and opal variations, which are mainly controlled by the orbital eccentricity cycle of about 100-kyr. The orbital-scale cyclic variations of $CaCO_3$ and opal contents appear to be contrasting in both cores such that high $CaCO_3$ and low opal contents occurred during the glacial periods. In contrast, during the interglacial periods, low $CaCO_3$ and high opal contents occurred. Mostly remarkable is the distinct occurrence of a mid-Bruhnes event (MBE) at around 350 ka. The $CaCO_3$ content was higher in core PC5101 than in core PC313 before the MBE, whereas biogenic opal abundance became higher in core PC5101 after the MBE. Such a characteristic discrepancy of biogenic ($CaCO_3$ and opal) production, i.e., a succession of primary producers from coccolithophore to diatom, between cores PC313 and PC5101 may be attributed to the prevailing dominant hydrographic conditions (i.e., the South Equatorial Current), in the path of which both cores are located. The intensity of westward propagation might have been an important factor in contrasting biogenic production centering around the MBE.

Key words: $CaCO_3$, Opal, Glacial-interglacial, Mid-Bruhnes event, Equatorial Pacific, Late Quaternary

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1. INTRODUCTION

Measurement of atmospheric CO_2 in polar ice cores revealed that global CO_2 concentrations were significantly lower during glacial periods (EPICA community members 2004). Pleistocene glacial periods are also marked by higher $CaCO_3$ accumulations in deep-sea pelagic sediments of the equatorial Pacific Ocean (Chuey et al. 1987; Farrell and Prell 1988, 1991; Archer 1991, 1996; Berger 1992; Oxburgh and Broecker 1993; LaMontagne et al. 1996; Kawahata et al. 1998; Murray et al. 2000; Lyle et al. 2002; Zhang et al. 2007; Anderson et al. 2008). In general, enhanced primary production in specific areas of glacial oceans, such as in low-latitude equatorial regions, was to some extent attributed to the decline of atmospheric CO_2 concentrations (Farrell and Prell 1988; Berger 1992; Murray et al. 2000). Thus, in terms of productivity, the response of the equatorial Pacific Ocean to orbital forcing is fundamental to understanding the ocean's role in natural carbon cycling and, indirectly, the tropical ocean's role in global climate change.

The equatorial Pacific Ocean is an important region which can substantially influence global climatic events, which are underscored by physical perturbations such as El Niño/Southern Oscillation (ENSO) (e.g., Clement et al. 1999). El Niño conditions are characterized by an eastward displacement of the warmest surface water from the warm pool in the western equatorial Pacific toward the central equatorial Pacific Ocean. This leads to a lower gradient of sea surface temperature that weakens the trade winds, equatorial upwelling and east-west thermocline tilt. This system

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then swings back to the opposite phase (La Niña) with westward movement and contraction of the warm surface water, strengthening the trade winds, equatorial upwelling, and zonal thermocline tilt.

The ENSO cycle is closely related with primary production in the equatorial Pacific Ocean (e.g., Murray et al. 1994). Lower equatorial productivity is generally expected during El Niño when equatorial upwelling is curtailed, whereas increased equatorial productivity occurs during La Niña when equatorial upwelling is enhanced. Productivity changes during the glacial periods might result from a different response to the oceanographic condition of the equatorial Pacific Ocean, which are essentially associated with global climates. This is because the tropical Pacific region may have a direct link to global atmospheric CO_2 changes (Emerson and Archer 1992). Thus, paleoproductivity reconstruction in the equatorial Pacific Ocean could help ascertain whether either an El Niño-like or La Niña-like mode prevailed in the past with respect to the interglacial-glacial phase. A La Niña-like mode during glacial periods would occur frequently with stronger trade winds, as evidenced by aeolian dust grain size distribution (e.g., Hovan et al. 1991) and numerical simulation (e.g., Bush and Philander 1999).

Cyclic variations of biogenic $CaCO_3$ sediments reported from the equatorial Pacific Ocean have been explained by two hypotheses. The first is the "degree of surface-water productivity" (Pedersen 1983; Arrhenius 1988; Lyle et al. 1988; Archer 1991; Herguera and Berger 1991; Murray et al. 1993), where, for example, the rain rate of planktonic carbonate tests is a controlling factor on $CaCO_3$ accumulation rates (e.g., Archer 1991). The second is the "degree of deep-water corrosiveness" (Farrell and Prell 1988; Wu and Berger 1989; Hebbeln et al. 1990; Emerson and Archer 1992; Le and Shackleton 1992; Stephens and Kadko 1997), where, for instance, a potential factor is the degree of dissolution governed by the production of respiratory CO_2 within the sediment or by the bottom water carbonate saturation.

Despite diverse investigations concerning the state of productivity during glacial periods, a consensus has not yet been reached. It appears more general to accept that productivity increased during the glacial period, supporting a La Niña-like glacial climate with stronger trade winds and higher upwelling rate. However, the recognition of productivity change along the equator is not widespread, although accumulation rates of biogenic materials in sediments have been reported from specific locations in the equatorial Pacific Ocean (Archer 1996; LaMontagne et al. 1996; Weber and Pisias 1999; Murray et al. 2000; Pichat et al. 2004; Zhang et al. 2007; Anderson et al. 2008).

Regardless of the ongoing debate in a mutually exclusive framework, the appropriate linkage between these two processes (i.e., surface-water productivity and deep-water corrosiveness) has been synthesized with glacial-interglacial variations in productivity being perhaps responsible for changes in carbonate dissolution (e.g., Berger 1992). Here we document the deposition of biogenic $CaCO_3$ and opal sediments along the equatorial Pacific Ocean during the Late Quaternary and attempt to compare their variations for the purpose of better understanding the role of the equatorial Pacific Ocean on climatic system (for example, mid-Bruhnes event) in the deposition of biogenic $CaCO_3$ and opal sediments.

2. MATERIALS AND METHODS

Two piston cores (PC313 and PC5101) were collected along the equator in the western and the central Pacific Ocean, respectively (Fig. 1). The water depths at these sites are critical given that the modern $CaCO_3$ transition zone from ~4000 m deep, to the carbonate compensation depth (CCD) at ~5000 m (Berger and Winterer 1974), has most likely fluctuated between glacial-interglacial periods (see summary by Farrell and Prell 1989). Two additional cores [RC11-210 from Chuey et al. (1987) and Site 847

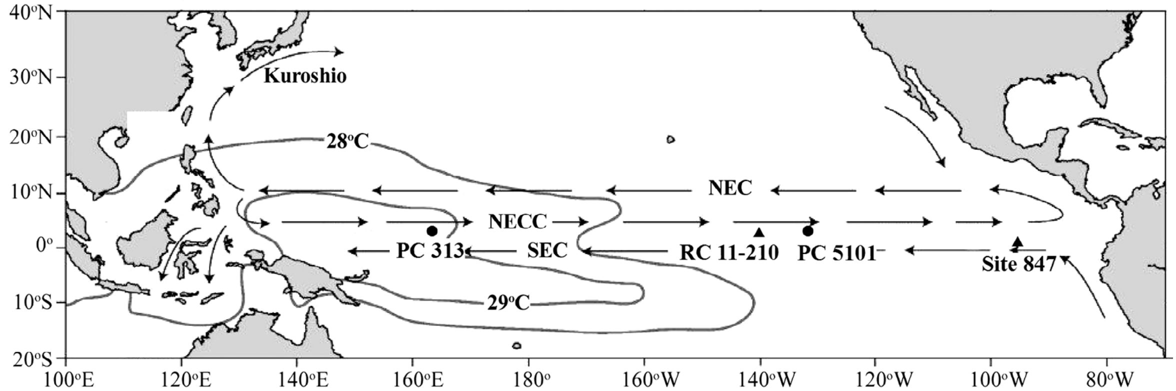

Fig. 1. Map showing the location of sediment cores (PC313 and PC5101 as closed circles) with the surface circulation pattern in the equatorial Pacific Ocean. Core RC11-210 and ODP Site 847 as closed triangles are adopted from Chuey et al. (1987) and Murray et al. (1995), respectively.

from Murray et al. (1995)] were also used for comparative analyses. Surface-water circulation in the equatorial Pacific Ocean is depicted in Fig. 1. The westward flowing South Equatorial Current (SEC) is driven by the southeast trade winds and because it extends from around 10°S to ~5°N across the equator; the SEC is dominant at the coring sites. The strength of this current fluctuates following the seasonal cyclic strength of the southeast trade winds; the SEC is strongest during the austral winter, when atmospheric circulation is strengthened, but weakens during the austral summer (Fiedler and Talley 2006). Information on each core is summarized in Table 1.

For oxygen isotopic analysis, specimens of planktonic foraminifera (*Neogloboquadrina dutertrei*) were hand-picked from the coarse section (> 250 μm) of core PC313, and cleaned by soaking in methanol and sonification. Isotope measurements were made using a Carousel-48 automatic carbonate preparation device coupled to a Finnigan MAT 251 mass spectrometer at the University of Michigan. Results are expressed in δ-notation referring to the Vienna Pee Dee Belemnite (V-PDB) standard. The analytical precision of NBS-19 was approximately ±0.08‰ for $\delta^{18}O$.

Biogenic silica content was analyzed using a wet alkaline extraction method (DeMaster 1981). The relative error of biogenic silica content in sediment samples was less than 1%. Opal content was calculated by multiplying biogenic silica content by 2.4 (Mortlock and Froelich 1989). Total inorganic carbon (TIC) content was measured using a UIC CO_2 coulometer (Model CM5014). The TIC content was then converted to $CaCO_3$ content as a weight percentage by multiplication with factor of 8.333. The analytical precision as a relative standard deviation was 2%. Total carbon (TC) content was measured by a Flash 2000 Series Elemental Analyzer. The analytical precision is less than ±0.1%. Total organic carbon (TOC) content was calculated by the difference between the TC and TIC.

To quantify and display the true variability of each biogenic component, avoiding the limit of percentage data, the mass accumulation rate (MAR) or flux of each component was calculated. MAR values are the product of the linear sedimentation rate (LSR), dry bulk density (DBD), and weight percent of the component;

$$MAR\,(g\ cm^{-2}\ kyr^{-1}) = \frac{biological\ component\ (\%) \times DBD \times LSR}{100} \tag{1}$$

LSR was determined from an age model. DBD was calculated from an empirical formula relating water content to DBD. MAR was only obtained from core PC5101, because the water content was unavailable in core PC313.

3. RESULTS

3.1 Chronostratigraphy Establishment of Cores PC313 and PC5101

Shackleton (1967) has shown that ice-sheet growth and decay is primarily responsible for the changing oxygen isotope composition of seawater during the Pleistocene, although the temperature at which carbonate precipitation occurs also affects the $\delta^{18}O$ values of foraminiferal tests. Thus, the $\delta^{18}O$ record of planktonic foraminifera can be very useful for both stratigraphic and paleoclimatic purposes. The age determination of core PC313 in the western equatorial Pacific was conducted by matching oxygen isotope record of planktonic foraminifera (*N. dutertrei*) to the SPECMAP standard (Imbrie et al. 1984). The $\delta^{18}O$ data ranged from about -1.0 to 0.5‰, relative to V-PDB (Fig. 2a). Variations in the $\delta^{18}O$ record are generally similar with each other, but in some intervals there are noticeable differences between the two curves, mainly due to the selective dissolution. Despite the lack of still more complementary dates such as biostratigraphy and magnetostratigraphy, the age of core PC311 in the western equatorial Pacific extends to about 750 ka at a first approximation (Fig. 2a).

Figure 2b shows the $CaCO_3$ stratigraphy of well-dated RC11-210 core collected near the site of core PC5101 in the central equatorial Pacific (Fig. 1), which was reported by Chuey et al. (1987). The age of core RC11-210 was estimated by the correlation of SPECMAP with the $\delta^{18}O$ stratigraphy of planktonic foraminifera (*Globorotalia tumida*), suggesting ~950-kyr record (Fig. 2b). The $CaCO_3$ content of core RC11-210 varies from 50% to 95%, indicating a high $CaCO_3$ content during glacial periods. Figure 2c also shows

Table 1. Information about the sediment cores used in this study.

Core	Latitude	Longitude	Water depth	Source
PC313	02°00’N	164°34’E	4259 m	this study
RC11-210	01°49’N	140°03’W	4420 m	Chuey et al. (1987)
PC5101	02°01’N	131°34’W	4425 m	this study
Site 847	00°12’N	95°19’W	3334 m	Murray et al. (1995)

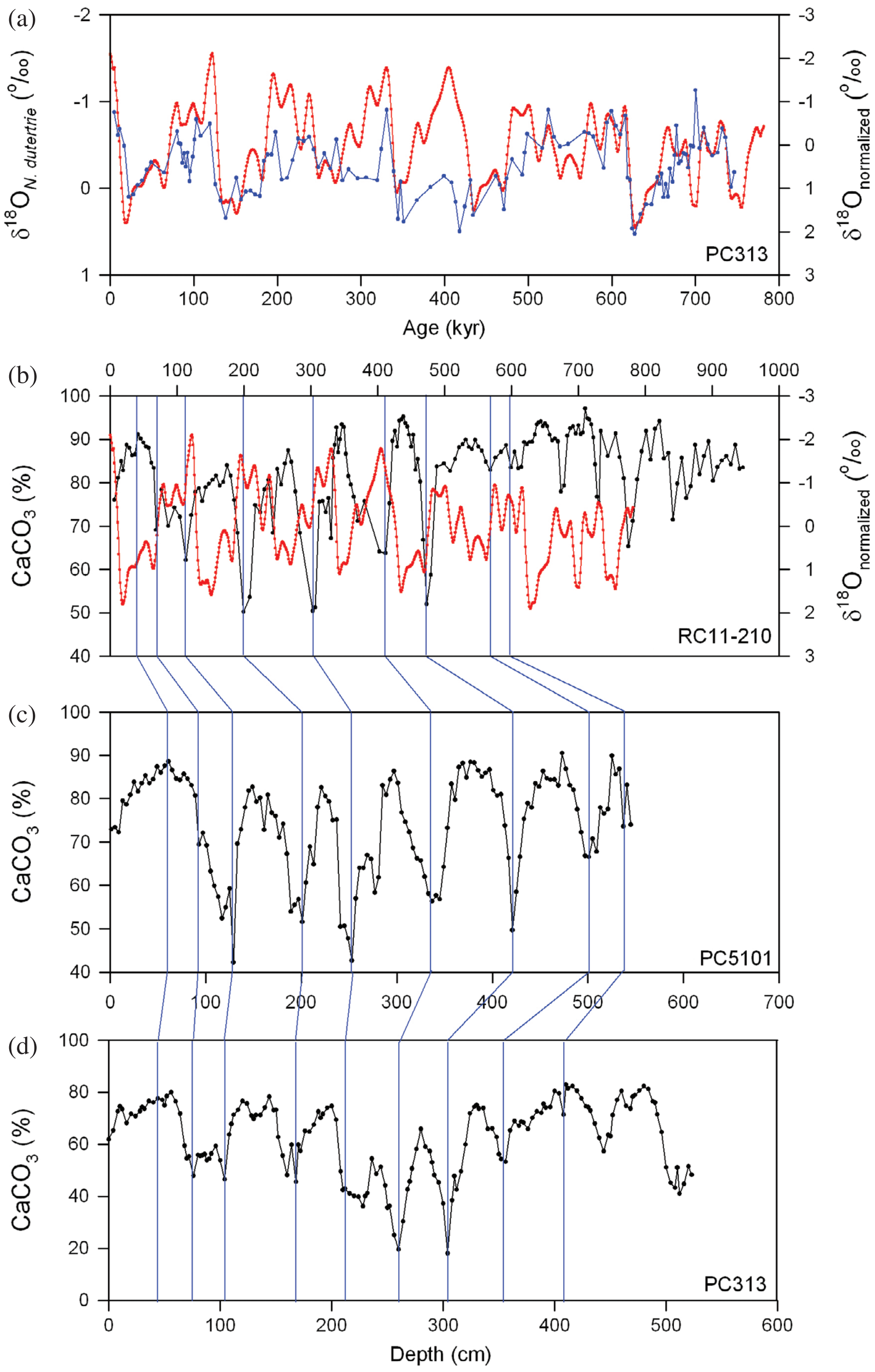

Fig. 2. (a) Age determination of core PC313 based on the oxygen isotope stratigraphy of planktonic foraminifera *N. dutertrei* with comparison to the SPECMAP stack in red. (b) $CaCO_3$ profile with the age of core RC11-210 (Chuey et al. 1987) in comparison with the SPECMAP stack in red. (c) Age determination of core PC5101 based on the graphic comparison of $CaCO_3$ profile with the core RC11-210. (d) Correlation of $CaCO_3$ content between cores PC5101 and PC313.

the $CaCO_3$ stratigraphy of core PC5101 in the central equatorial Pacific, and its age was estimated by stratigraphic correlation of $CaCO_3$ contents to those in core RC11-210. For the purpose of determining the age of core PC5101, the quasi-periodic cycles of $CaCO_3$ contents between the two profiles were matched by peaks and troughs (Figs. 2b and c). $CaCO_3$ variation between the two cores is obviously in parallel, although $CaCO_3$ content of core PC5101 is somewhat lower (40% to 90%) than those of core RC11-210. As a result, the age of core PC5101 was estimated to be about 600 ka (Fig. 2c). In addition, the quasi-periodic cycles of $CaCO_3$ contents (20% to 80%) of core PC313 were similarly correlated with those of core PC5101 (Fig. 2d).

3.2 Biogenic $CaCO_3$ and Opal Abundance During the Late Quaternary

The relationship between the percentage of content and flux data (opal, $CaCO_3$, and TOC) was examined in core PC5101, which determines the valid usefulness of percentage data to avoid from the limitation of dilution (Fig. 3). Opal forms from 2% up to about 20% of the pelagic sediment in PC5101. Its profuse down core distribution is exactly parallel with opal flux data (Fig. 3a) and indicates that both variables depend on the balance between production and dissolution. These two variables may preserve a more clear record of sea surface activity. As with opal, $CaCO_3$ also shows the consistent fluctuations of percentage content and flux data, emphasizing the fact that the percentage content reflects flux data without a dilution effect (Fig. 3b). Unlike opal and $CaCO_3$, low TOC content (mostly less than 1%) exhibits unclear cyclic fluctuations parallel to the opal and $CaCO_3$ abundance, although TOC content and flux varied consistently with each other (Fig. 3c). Rea et al. (1991) calculated TOC content from an empirical relationship with opal and $CaCO_3$ contents. However, in our study, the different techniques to measure TC and TIC by the elemental analyzer and colorimeter, respectively, are the main reason we were unable to detect a low TOC content. Although TOC cannot be guaranteed to represent biological productivity, opal and $CaCO_3$ contents are apparent indicators necessary and sufficient to judge the degree of biological productivity in the surface water.

Figure 4 compiles the downcore variation of biogenic $CaCO_3$ and opal contents of cores PC313 (western equatorial) and PC5101 (central equatorial), in addition to core RC11-210 (central equatorial) and ODP Site 847 (eastern equatorial). Based on the visual inspection of these downcore profiles, in general, the variation patterns of biogenic $CaCO_3$ and opal contents are consistently similar among all

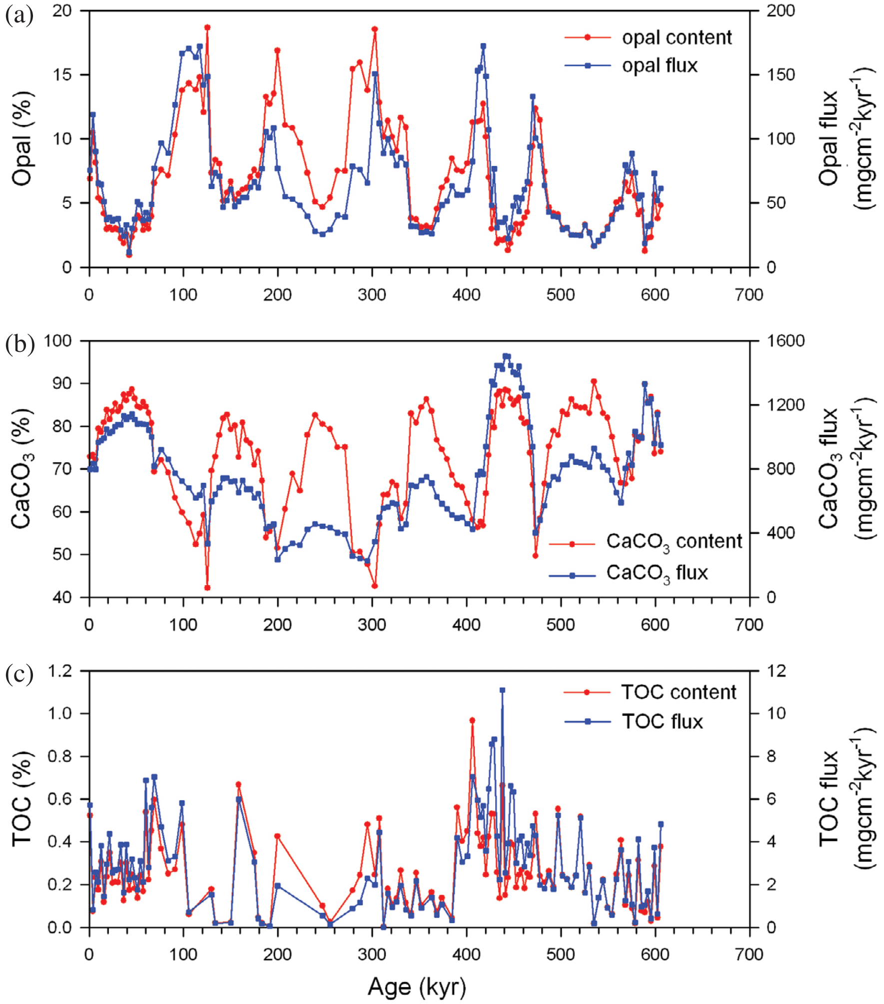

Fig. 3. Downcore profiles of (a) opal content and flux, (b) $CaCO_3$ content and flux, and (c) TOC content and flux of core PC5101.

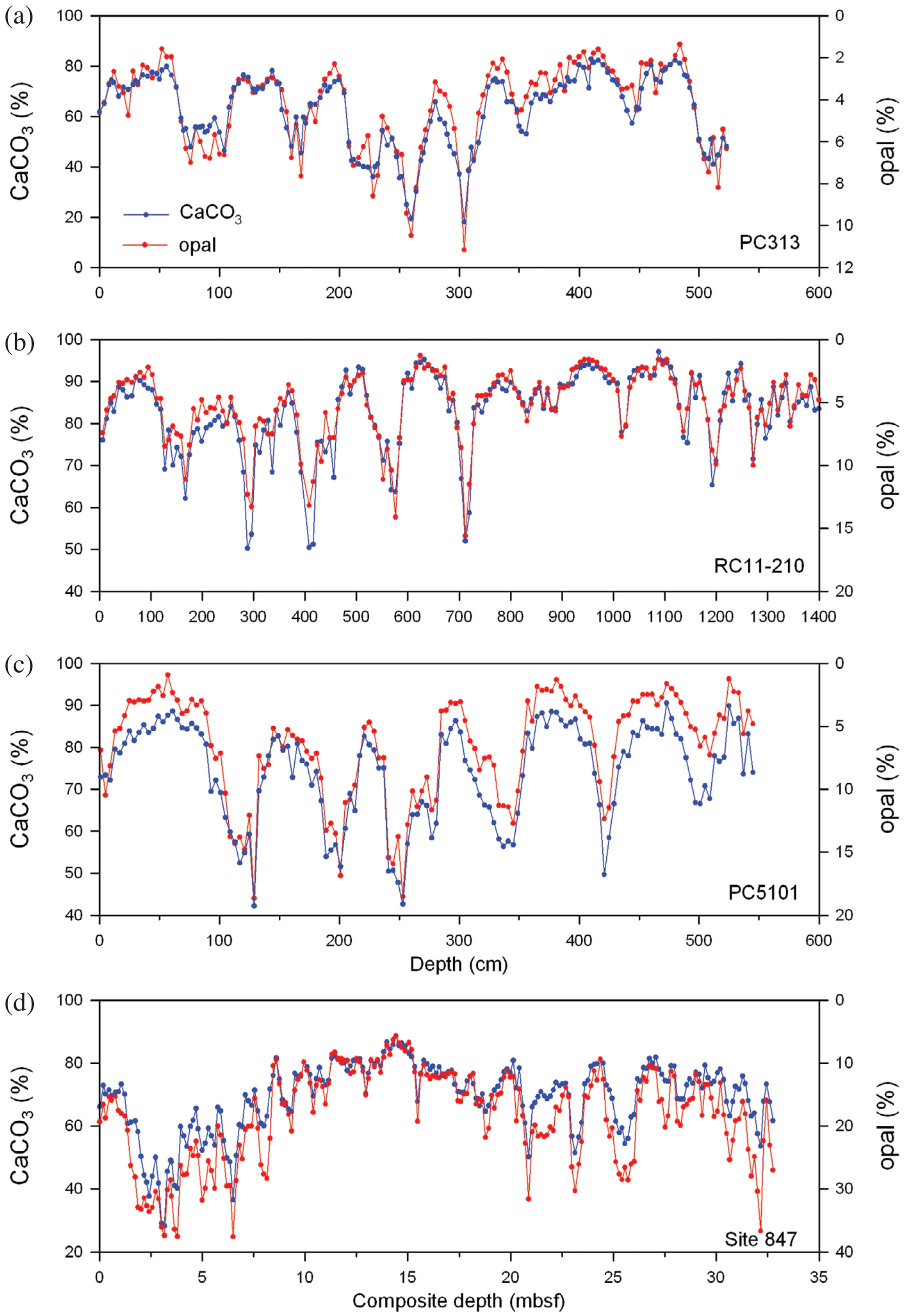

Fig. 4. Downcore profiles of CaCO$_3$ and opal abundances of (a) core PC313, (b) core RC11-210, (c) core PC5101, and (d) Site 847 in the equatorial Pacific Ocean. Note that the right axis of opal abundance is inversed.

cores. In addition, downcore distribution of opal abundance is exactly opposite to that of CaCO$_3$ contents in all cores (Fig. 4). CaCO$_3$ contents of core PC313 vary between 80% and 20%, showing quasi-periodic cycles with relatively lower values between 200 and 300 cm (Fig. 4a). CaCO$_3$ contents of core PC5101 in the central equatorial Pacific Ocean are much higher (from 90% to 40%), showing larger fluctuations compared with those of core PC313 in the western equatorial Pacific Ocean (Fig. 4c). Biogenic opal concentrations make up 2% to 11% of the sediment in core PC313, showing the highest concentration at the lowest CaCO$_3$ content (Fig. 4a). Similar to CaCO$_3$ content trends, core PC5101 in the central equatorial Pacific Ocean is also characterized by a higher opal concentration and larger fluctuation than those of core PC313 in the western equatorial Pacific Ocean (Fig. 4c).

The opal record is a good example of minor component abundance pattern responding to major CaCO$_3$ component variation. The variation patterns of both CaCO$_3$ and opal contents are critical in depicting the complete inverse relationship in all cores (Fig. 4). Such a relationship between $CaCO_3$ and opal abundance is emphasized in Fig. 5, where the opposite variation is exhibited with a high inverse correlation ($r^2 = 0.88$ for PC313, $r^2 = 0.92$ for PC5101, $r^2 = 0.88$ for RC11-210, $r^2 = 0.90$ for site 847). Such a negative correlation between $CaCO_3$ and opal content is consistent with the combined effect of (i) dilution of $CaCO_3$ by opal under variable productivity condition and (ii) dissolution of $CaCO_3$ in oxygen-deficient conditions. We can therefore recognize that biogenic $CaCO_3$ and opal abundances in cores PC313 and PC5101 are apparently inversed, both of which were collected in the western and central equatorial Pacific (at about 2°N), respectively. The variation patterns of biogenic $CaCO_3$ and opal abundances are also comparably consistent in both cores; the collection sites are 3500 km apart. Along the east-west transect, opal content increases eastward, whereas $CaCO_3$ abundance decreases.

4. DISCUSSION

$CaCO_3$ content of pelagic sediments can be controlled by a number of factors: (1) extent of carbonate supply to the seafloor at constant dissolution intensity (the productivity effect), (2) variations in carbonate intensity at a constant carbonate supply rate (the dissolution effect), (3) change in the ratios of calcareous particles to siliceous particles in the flux, and (4) dilution by non-biogenic material such as aeolian and volcanic particles. At first blush, we interpreted the variation of the $CaCO_3$ content from deep-water sites in the western (PC313) and central (PC5101) equatorial Pacific as records of $CaCO_3$ production/dissolution with respect to $CaCO_3$ abundance (Fig. 4). Previous studies reported that $CaCO_3$ abundance co-varies with $CaCO_3$ preservation indices based on fauna and lithology (e.g., Wu and Berger 1989; Herguera and Berger 1991; Le and Shackleton 1992; Oxburgh and Broecker 1993) and with a $CaCO_3$ accumulation rate (e.g., Chuey et al. 1987; Lyle et al. 1988; Rea et al. 1991; Murray et al. 2000) in the equatorial Pacific Ocean. Dilution from terrigenous sediments appears to be insignificant in the studied equatorial Pacific region, perhaps because the collection site of core PC5101 is so far away from the continental margins. Thus, the dramatic fluctuations in biogenic sedimentary abundance in the equatorial Pacific Ocean have been interpreted as reflecting either elevated particles fluxes that responded to surface-water productivity or decreased dissolution of biogenic phases caused by the lower dissolved oxygen concentration in deep waters.

Pisias and Rea (1988) pointed out that $CaCO_3$ accumulation in the lysocline zone in the central equatorial Pacific is predominantly attributed to dissolution as modulated by sea-level change, while the changing primary productivity plays a secondary role. Farrell and Prell (1989) also supported the dissolution hypothesis to explain why the $CaCO_3$ cycles reflect changes in the gradient of the calcite saturation state with water depth driven by bottom water chemistry. Hebbeln et al. (1990) documented the apparent depth of deposition (ADD) showing that shallower ADD levels are in parallel with the greater $CaCO_3$ accumulation in the western equatorial Pacific Ocean during glacial periods. This was supported by planktonic foraminiferal test fragmentation by Wu and Berger (1989) and the Berger dissolution index by Le and Shackleton (1992). Thus, glacial/interglacial changes in the shape and depth of the lysocline have regularly responded to glacial forcing, with higher calcite preservation during glacial times than interglacial. This trend corresponds to the interglacial-glacial cycles of $CaCO_3$ contents in cores PC313 and PC5101 (Fig. 4).

On the basis of fossilized plankton tests in the equatorial Pacific, the planktonic communities in surface waters oscillate on geological time scales between two distinct assemblages, one of which is calcareous (i.e., coccolithophore) while the other is siliceous (i.e., diatom) (Lyle et al. 1988; Murray et al. 1995; Kawahata et al. 1998; Weber and Pisias 1999). A biological cycle changing the ratio of organic carbon to calcite in the sinking particles should have had a major effect on the preservation of carbonate sediments. Although Lyle et al. (1988) suggest that opaline phytoplankton communities vary independently in their contribution to total productivity, opal accumulation in deep-sea sediments also reflects the balance between productivity and dissolution. Rea et al. (1991) reported that opal may preserve a much more clear record of surface-water activity in the central equatorial Pacific Ocean. Opal dissolution remains generally uniform with increasing water depth, unlike $CaCO_3$ dissolution. Once below the surface waters, opal dissolves at a more constant rate with increasing water depth than $CaCO_3$ (Archer et al. 1993). Because there is less ensuing breakdown of opal on the seafloor than $CaCO_3$, fluctuations in opal accumulation might better record the supply-productivity function. Broecker and Peng (1982) argued that the rate of opal burial is important in preservation of opal, supporting the assertion that opal accumulation should reflect surface production. Although Rea et al. (1986) reported that variability in surface water opal productivity and/or seafloor preservation in the eastern equatorial Pacific is not simply correlated with glacial or interglacial periods, cores PC313 and PC5101 exhibited systematic fluctuations of opal abundance between interglacial and glacial periods (Fig. 4). Thus, a series of biogenic opal abundance in the two cores suggests that opal production depends on orbital cyclic variation of ENSO; El Niño-like (low opal content during the glacial) and La Niña-like (high opal content during the interglacial) conditions.

Despite inverse relationship between $CaCO_3$ and opal abundance (Fig. 5), the variation patterns of these two biogenic sediments between cores PC313 and PC5101 are obviously consistent (Fig. 4). This indicates that the dominant controlling factors on $CaCO_3$ and opal abundance have played similar role in the western (PC313) and central (PC5101) equatorial Pacific during the Late Quaternary. Figure 6 compares the time-series variation of $CaCO_3$ and opal abundance between the western and central equatorial Pacific Ocean during the last 600 kyr. Visual inspection indicates clear co-variation between downcore profiles, reflecting a first-order pattern that visually appears to have a 100-kyr periodicity. Spectral analyses performed using standard menu-driven software based on the Blackman-Tukey method (Jenkins and Watts 1968) confirm that $CaCO_3$ and opal abundances in the equatorial Pacific are mainly controlled by an eccentricity forcing. In eccentricity climatic cycles, glacial conditions lead to stronger wind-driven circulation which enhances productivity, which in turn results in enhanced oceanic and atmospheric carbon dioxide and minimum ice volume. Lea et al. (2000) also reported a strong 100-kyr signal in sea surface temperature estimates in the western and eastern equatorial Pacific Ocean.

It is worth noting that variation of $CaCO_3$ and opal abundances of two cores (PC313 and PC5101) should be compared in terms of the difference between two cores (Fig. 6). The difference of $CaCO_3$ contents between two cores shows that $CaCO_3$ contents of core 5101 were higher before 350 ka (Fig. 6a). After this time, the difference became insignificant, showing consistent and comparable $CaCO_3$ content between both cores. In contrast, the opal contents of core 5101 were higher after 350 ka (Fig. 6b). Before this time, opal abundance of these cores was comparable. $CaCO_3$ and opal abundances of core PC313 (western equatorial) and core PC5101 (central equatorial) were different, centering around 350 ka, despite the comparison of relative abundance. This resulted in more $CaCO_3$ abundance before 350 ka and more opal abundance afterward in the central equatorial Pacific. This difference also indicates that hydrographic conditions associated with the production, preservation and/or dissolution of $CaCO_3$ and opal have changed between the western and central equatorial Pacific at about 350 ka. For example, such contrasting between carbonate and opal abundance may imply the succession by a major community structure change from carbonate-producing pri-

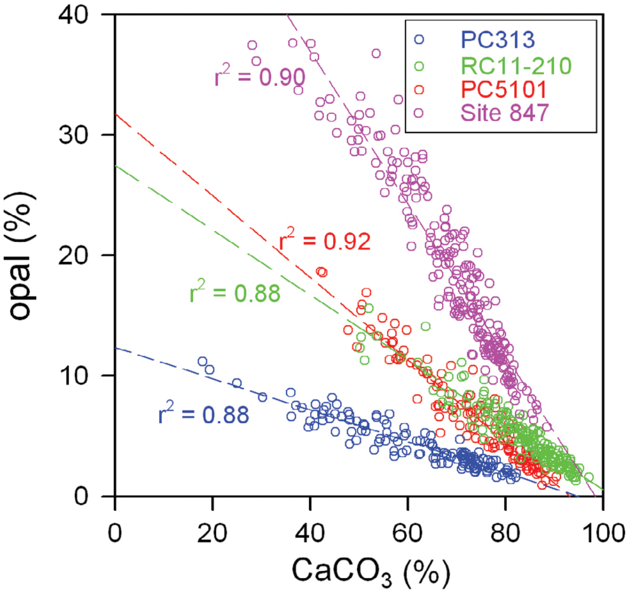

Fig. 5. Relationship between $CaCO_3$ and opal abundances of cores PC313, RC11-210, PC5101 and Site 847.

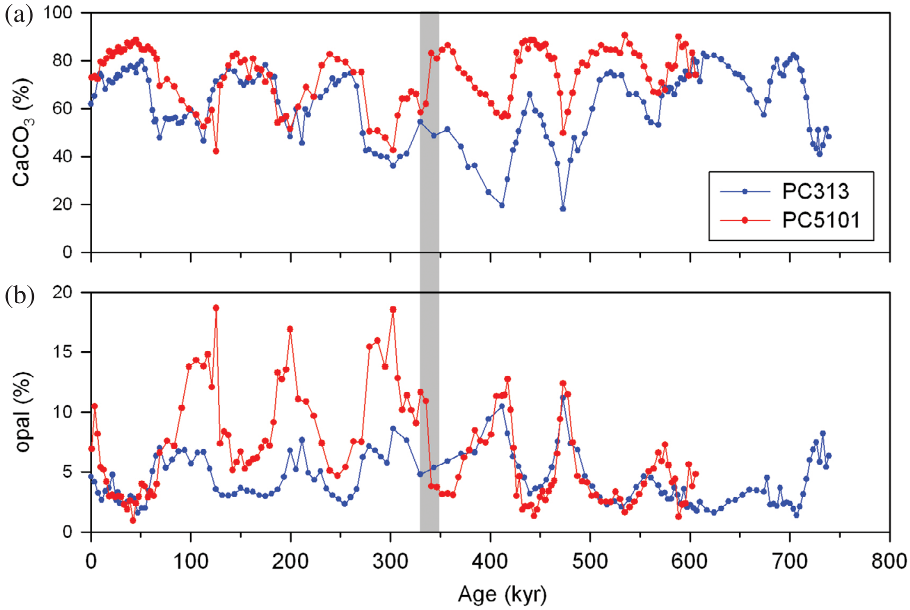

Fig. 6. Comparison of (a) $CaCO_3$ content and (b) opal abundance between core PC313 in the western equatorial Pacific and core PC5101 in the central equatorial Pacific Ocean. Shaded interval represents the occurrence of mid-Brunhes event.

mary producer (e.g., coccolithophores) to silica-producing primary producers (e.g., diatoms), although the dissolution effect of carbonate cannot be ruled out.

Farrell and Prell (1991) suggested that a 600-kyr Brunhes Dissolution Cycle (BDC) be superimposed on glacial/interglacial 100-kyr cycles during the Late Pleistocene in the central equatorial Pacific. The BDC is clearly apparent as a lower-frequency envelope on the 100-kyr cycles (Barker et al. 2006; López-Otálvaro et al. 2008), being observed in a wide variety of marine and continental records (e.g., Jansen et al. 1986). On a longer timescale, pelagic $CaCO_3$ production was proposed to reveal a primary candidate driver for the BDC representing apparent mid-Brunhes dissolution (MBD) or the mid-Brunhes event (MBE), but its cause remains unknown (Pisias and Rea 1988). The MBE event has been reported in various places of the Atlantic, Pacific, Indian, and Southern Oceans as well as the Red Sea (as summarized in Barker et al. 2006). A change in the $CaCO_3$ record analyzed from our cores at about 350 ka can be correlated with a distinct MBE (Fig. 6). It seems that core PC313 experienced stronger MBE than core PC5101, which indicates that the central equatorial Pacific maintained more carbonate preservation than the western equatorial Pacific.

The MBE, characterized by a more zonal circulation in the Northern Hemisphere, was terminated by a global southward migration of polar and subtropical fronts (Jansen et al. 1986). As such, more glacial conditions became prevalent in the Northern Hemisphere. Glacial climates are represented by intensified atmospheric and surface-water circulation along the equator. The enhanced east-west tilt of the thermocline is a consequence of surface-water response to intensified trade winds (Rea et al. 1986; Pisias and Rea 1988). Consequent thermocline dynamics might be a controlling factor of biological productivity along the equatorial Pacific Ocean. Accompanying the redistribution of global heat by the southward migration of polar and subtropical fronts, the wind intensity in the central equatorial Pacific has also changed (Chuey et al. 1987). The hydrogrographic system strengthens the trade winds, equatorial upwelling, and zonal thermocline tilt. More opal abundance in core PC5101 relative to core PC313 after about 350 kyr seems to be evidence that indicates the effect of MBE termination (Fig. 6b). Therefore, the change of wind intensity followed by shift of climatic systems in the equatorial Pacific Ocean may have caused dramatic variations associated with nutrient distribution and its related productivity.

5. CONCLUSIONS

The equatorial Pacific Ocean has played an important role in strongly influencing global climatic events. For example, cyclic variations of biogenic $CaCO_3$ sediments have been reported from the equatorial Pacific Ocean, suggesting the two hypotheses (the degree of surface-water productivity and the degree of deep-water corrosiveness) which have been synthesized with glacial-interglacial variations. Two piston cores (PC313 and PC5101) were collected, respectively, along the equator in the western and the central Pacific Ocean. At the coring sites, the westward flowing South Equatorial Current driven by the southeast trade winds is dominant. Biogenic $CaCO_3$ and opal abundance was measured from two piston cores for the purpose of comparing their variations, which provides an important role of the equatorial Pacific Ocean on climatic systems during the Late Quaternary.

The age of core PC313 was judged by the comparison of oxygen isotope stratigraphy of planktonic foraminifera (*N. dutetrei*) to the SPECMAP stack, which constrains about 750 ka. Age of core PC5101 was estimated indirectly by graphic comparison of $CaCO_3$ contents to those in the well-dated core RC11-210, resulting in about 600 ka. Deposition of $CaCO_3$ and opal was higher in the central equatorial (core PC5101) than in western equatorial (core PC313) Pacific. It is worth noting that both cores showed a series of $CaCO_3$ and opal variations, but their variations appear to be contrasting in both cores; high $CaCO_3$ and low opal during the glacial periods, which coincides with El Niño-like mode. Nevertheless, these contrasting variations are mainly controlled by an orbital eccentricity cycle of about 100-kyr. Another important result is an occurrence of the mid-Bruhnes event (MBE) such that the variation patterns of $CaCO_3$ and opal abundance between the western and central equatorial Pacific Ocean were different centering around 350 ka. The difference of $CaCO_3$ contents between the two cores was large before the MBE, whereas the difference in biogenic opal abundance became large after the MBE. Such a variation pattern may be attributed to the discrete effect of prevailing dominant hydrographic conditions between the western and central equatorial Pacific Ocean because both cores are located in the same path of the South Equatorial Current. Thus, the intensity of westward propagation of the South Equatorial Current might have played a critical role in contrasting biogenic production centering around the MBE.

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