Terr. Atmos. Ocean. Sci., Vol. 26, No. 4, 441-450, August 2015 doi: 10.3319/TAO.2015.02.09.01(Oc)

Biogenic $CaCO_3$ and Opal Depositions and Their Latitudinal Comparison During the Past 600 ka in the Central Equatorial Pacific

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Received 1 April 2014, revised 9 February 2015, accepted 9 February 2015

ABSTRACT

The orbital-scale variations in biogenic $CaCO_3$ and opal abundance in two piston cores collected in the central equatorial Pacific (core PC5101 from a southern site at 2°N, and core PC5103 from a northern site at 6°N) were compared to assess latitudinal differences. The correlation between the oxygen isotope stratigraphy of planktonic foraminifera (*Globigerinoides sacculifer*) of PC5103 with the LR04 stacks provides the age of PC5103 to be approximately 950 ka. The age of PC5103 was further refined by correlating the $CaCO_3$ content with the well-dated core RC11-210. The age of PC5101 was also constrained by the same $CaCO_3$ chronostratigraphic correlation with RC11-210, resulting in an age of approximately 650 ka. Distinct orbital-scale series of $CaCO_3$ and opal variations appear to be parallel between the two cores during the past 600 ka, which are controlled mainly by eccentricity with an approximate periodicity of 100 ka. It is worth noting that the biogenic $CaCO_3$ and opal deposition patterns in the two cores differ between interglacial and glacial periods. During interglacial periods the biogenic opal content is higher in the southern core than in the northern core, which corresponds with the present-day condition. In contrast the $CaCO_3$ content is higher in the northern core, which is contradictory to the present-day northward decreasing $CaCO_3$ deposition pattern from the Equator. The collection site of PC5101 is approximately 350 m deeper than that of PC5103, which significantly promotes $CaCO_3$ dissolution and causes unexpectedly high $CaCO_3$ content at the northern site in contrast to the biogenic opal content.

Key words: $CaCO_3$, Opal, Glacial-interglacial, ITCZ, Equatorial Pacific, Late Quaternary

Citation: Khim, B. K., C. M. Yoo, H. J. Kim, K. Hyeong, H. Takata, S. Kim, S. B. Chi, and Y. T. Ko, 2015: Biogenic $CaCO_3$ and opal depositions and their latitudinal comparison during the past 600 ka in the central equatorial Pacific. Terr. Atmos. Ocean. Sci., 26, 441-450, doi: 10.3319/TAO.2015.02.09.01(Oc)

1. INTRODUCTION

The decrease in atmospheric CO_2 concentrations from interglacial to glacial stages has occurred repeatedly, coinciding with Milankovitch solar insolation cycles (Sigman and Boyle 2000). For example, based on the $p\mathrm{CO}_2$ record from Antarctic ice cores, the atmospheric CO_2 concentration during the last glacial period was on average as low as 180 - 200 ppm (e.g., Augustin et al. 2004). Atmospheric CO_2 changes are known to be closely linked to global climate change, although the direct linkage remains unknown. Thus, no single explanation for changes in atmospheric CO_2 has been widely accepted (Archer et al. 2000).

One of the most striking features used to elucidate the missing atmospheric CO_2 related to paleoclimatic change is the quasi-regular variability pattern in the biogenic ($CaCO_3$ and opal) content of Pleistocene marine sediment in the Equatorial Pacific (e.g., Anderson et al. 2008). The Equatorial Pacific $CaCO_3$ cycles, with higher contents during glacial than interglacial periods, reflect a preservation-production signal, where the oceans are more productive during glacial times (e.g., Lyle et al. 1988; Archer 1991; Herguera and Berger 1991; Murray et al. 1993). In particular, $CaCO_3$ fluctuations may be controlled by surface water productivity in areas where sediments are deposited above the lysocline. However, in general, the Pacific $CaCO_3$ cycles appear to also be influenced by the corrosiveness of deep water,

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which reflects a preservation-dissolution signal where the oceans are less corrosive during glacial times (e.g., Farrell and Prell 1989; Wu and Berger 1989; Hebbeln et al. 1990; Le and Shackleton 1992).

Biogenic opal may provide a more accurate record of sea surface biological productivity than biogenic $CaCO_3$. Whereas $CaCO_3$ dissolution increases with water depth, opal dissolution below the surface water depends little on water depth. Instead, the export production of biogenic opal from the surface water directly controls the deposition of siliceous particles. Thus, under modern conditions, silica deposits, which mainly represent biogenic opal grains, indicate the degree of surface water productivity (Leinen et al. 1986). The glacial and interglacial biogenic opal production variations are not straightforward in the equatorial Pacific. In fact, Rea et al. (1986) observed a negative correlation between the mass accumulation rates (MARs) of carbonate and opal for the past 150 ka in the eastern equatorial Pacific. Later, Rea et al. (1991) reported a negative correlation between carbonate and opal contents; however, MARs were positively correlated in the central equatorial Pacific.

Phytoplankton fossil records from the equatorial Pacific show that the surface water planktonic communities have oscillated between calcareous and siliceous assemblages in response to interglacial-glacial conditions (e.g., Weber and Pisias 1999). Verardo and McIntyre (1994) reported on the glacial and interglacial cyclicity of $CaCO_3$ and opal concentrations and their MARs in the equatorial Atlantic, identifying late Pleistocene signals of regional paleoclimatic change. Similarly, a series of quasi-regular variations in biogenic $CaCO_3$ and opal content, which are mainly controlled by the orbital eccentricity cycle of approximately 100 ka, were clearly observed along the Equator in the equatorial Pacific (Khim et al. 2012).

In this study we document the depositional pattern of biogenic $CaCO_3$ and the opal components of two sediment cores (PC5103 and PC5101) collected from a northern site (6°N) and a southern site (2°N), respectively, in the central equatorial Pacific. We compare the orbital-scale variations in $CaCO_3$ and opal contents in the two cores during the past 600 ka, with an emphasis on production and dissolution, and discuss the different variation patterns with respect to the latitudinal position.

2. MATERIALS AND METHODS

The surface water circulation in the equatorial Pacific includes the South Equatorial Current (SEC), the North Equatorial Current (NEC), and the North Equatorial Counter Current (NECC) (Fig. 1). The position and strength of these surface currents in the equatorial Pacific are closely related to the intertropical convergence zone (ITCZ) position (Fiedler and Talley 2006). The NECC position represents the approximate present-day location of the ITCZ; however, the ITCZ migrates south toward the Equator during winter (Fig. 1).

Two piston cores were collected from the central equatorial Pacific (Fig. 1). Core PC5101 (02°01'N, 131°34'W; 4425 m deep) was collected near the Equator, whereas core PC5103 (06°00'N, 131°29'W; 4095 m deep) was retrieved a little farther north. The hydrographic lysocline at 135°W is located near 3700 m in water depth (Metzler et al. 1982). The depth of the foraminiferal lysocline in the central equatorial Pacific has been reported to range from 3700 m (Parker and Berger 1971) to 4000 m (Berger 1968) and 4200 m (Thompson 1976). The water depths at the core sites in this study are therefore somewhat critical, with the modern $CaCO_3$ transition zone located from ~4000 m to the carbonate compensation depth at ~5000 m (Berger and Winterer 1974). Thus, the depositional characteristics of these two core sites have most likely fluctuated within the transition zone during glacial-interglacial cycles (see the summary by Farrell and Prell 1989).

For oxygen isotopic analysis planktonic foraminifera (*Globigerinoides sacculifer*) specimens were handpicked from the coarse fraction (250 - 355 μm) of PC5103, and cleaned by soaking in methanol with 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, USA. Results are expressed in the δ-notation referring to the Vienna Pee Dee Belemnite (V-PDB) standard. The analytical precision of NBS-19 was approximately ±0.08‰ for $\delta^{18}O$.

The total inorganic carbon (TIC) content of PC5103 sediment was measured using a UIC CO_2 coulometer (Model CM5014). The TIC content was converted into $CaCO_3$

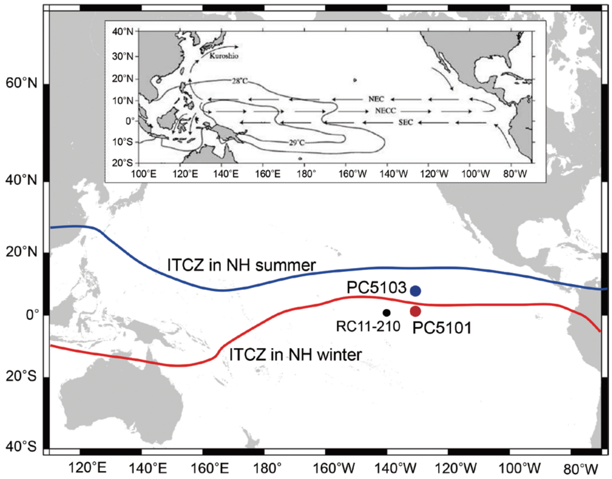

Fig. 1. Location of sediment cores (PC5101 and PC5103) in the context of surface circulation (NEC: North Equatorial Current, NECC: North Equatorial Counter Current, SEC: South Equatorial Current) and seasonal movement of the intertropical convergence zone (ITCZ) in the equatorial Pacific Ocean (Fiedler and Talley 2006). Core RC11-210 was recovered and analyzed by Chuey et al. (1987).

content as a weight percentage by multiplying by 8.33. The analytical precision as a relative standard deviation was 2%. The biogenic silica content for the same sediments was analyzed using a wet alkaline extraction method (DeMaster 1981). The relative error of the biogenic silica content in the sediment samples was less than 1%. The opal content was calculated by multiplying the biogenic silica content by 2.4 (Mortlock and Froelich 1989). The $CaCO_3$ and opal contents of PC5101 were previously reported by Khim et al. (2012).

3. RESULTS

3.1 Age Models of Cores PC5103 and PC5101

The foraminiferal $\delta^{18}O$ values primarily record the growth and decay of continental ice-sheets, despite the temperature effect of carbonate precipitation (Shackleton 1967). As a result, the foraminiferal $\delta^{18}O$ record has provided the basic chronostratigraphy for late Pleistocene paleoclimate research (Imbrie et al. 1984). The age model for PC5103 was determined by matching the oxygen isotope record of planktonic foraminifera (*Globigerinoides sacculifer*) to the LR04 stacks (Lisiecki and Raymo 2005) because the SPECMAP record only extends to 780 ka (Fig. 2a). The $\delta^{18}O$ data of PC5103 ranged from approximately -1.3 to 0.1‰, relative to V-PDB (Fig. 2b). The variability patterns in the two $\delta^{18}O$ records are generally similar, with some noticeable differences between the two curves. The $\delta^{18}O$ record can be used to develop a time-scale for PC5103 back to 600 ka. However, the lower part of PC5103 is difficult to distinguish, especially for marine isotope stage (MIS) 18 - 22, due to the imperfect correlation. Despite no biostratigraphic and magnetostratigraphic dating, the age model of PC5103 extending to approximately 950 ka at the first approximation. The model is robust for ages younger than 650 ka (Fig. 2b).

Although the oxygen isotope stratigraphy of PC5103 was established, we correlated the $CaCO_3$ stratigraphy of PC5101 and PC5103 with the well-dated RC11-210 core (Fig. 1; 01°49'N, 140°03'W; 4420 m deep). Chuey et al. (1987) established the stratigraphic chronology of RC11-210 by correlating the $\delta^{18}O$ values of planktonic foraminifera (*Globorotalia tumida*) to the SPECMAP standard (Imbrie et al. 1984). In RC11-210 the $\delta^{18}O$ variability from -0.2 to 2.1‰ matches the SPECMAP $\delta^{18}O$ record. In addition, the lower part of RC11-210 is correlated with the age-dated V28-239 core (Chuey et al. 1987). Therefore, to provide consistent age determination we compared the oxygen isotopes from RC11-210 with LR04 (Fig. 3a) and produced a new $CaCO_3$ chronostratigraphy (Fig. 3b). This $CaCO_3$ record serves as a reliable and detailed means of chemostratigraphic correlation (Berger and Vincent 1981). High- and low-$CaCO_3$ intervals develop a distinct sequence of events, which can be correlated over wide areas of the equatorial Pacific (e.g., Khim et al. 2012). RC11-210 shows quasi-periodic cycles in $CaCO_3$ content (50 - 97%; Fig. 3b). The $CaCO_3$ stratigraphy of PC5103 and PC5101 is plotted in Figs. 3c and d, respectively, and their age models were estimated using chronostratigraphic correlation of $CaCO_3$ content to RC11-210. For PC5103 and PC5101 the peaks and troughs of the quasi-periodic $CaCO_3$ cycles were well matched between these cores (PC5103 and PC5101) and RC11-210 profiles (Figs. 3c and d). Farrell and Prell (1989) reported that high $CaCO_3$ content coincided with glacial

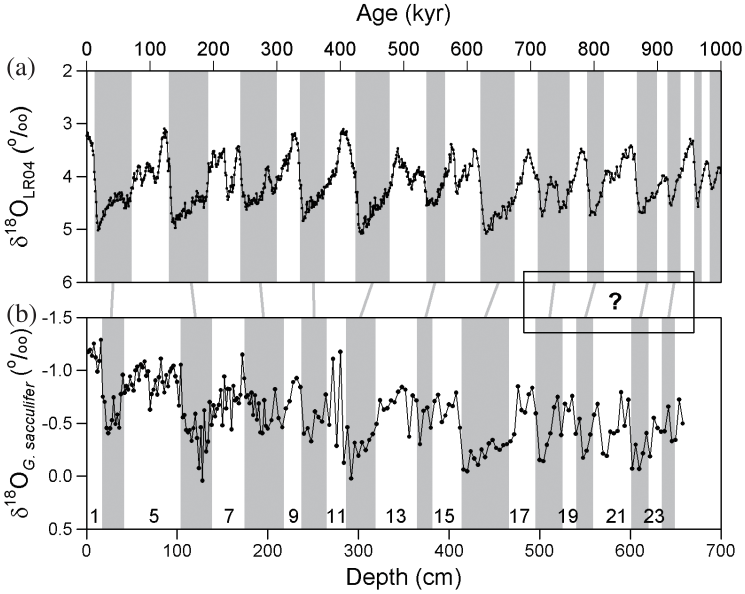

Fig. 2. (a) Oxygen isotope stratigraphy of composite benthic foraminifera (Lisiecki and Raymo 2005). (b) Age estimate of core PC5103 based on the graphic correlation of the oxygen isotope stratigraphy of planktonic foraminifera (*Globigerinoides sacculifer*) with the LR04 stacks (Lisiecki and Raymo 2005). Gray intervals represent glacial periods and the numbers the marine isotope stage.

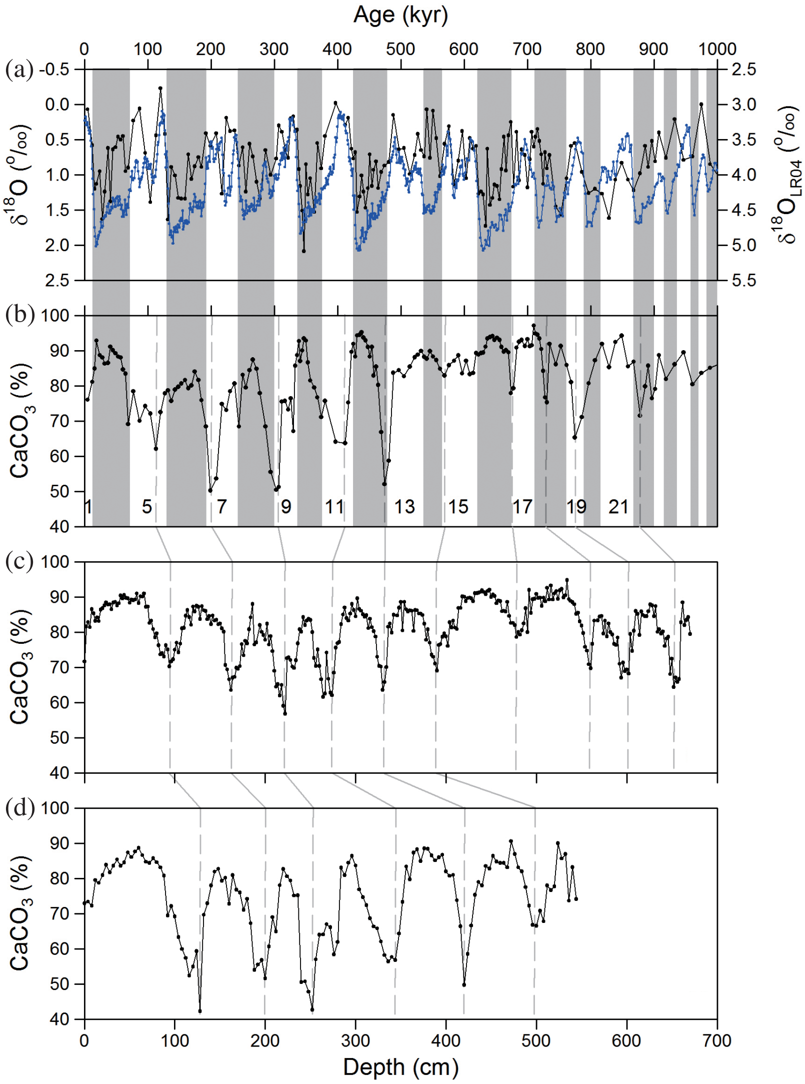

Fig. 3. (a) Age determination of core RC11-210 using correlation with LR04 with the δ^{18}O stratigraphy of planktonic foraminifera (*Globorotalia tumida*) (Chuey et al. 1987). (b) $CaCO_3$ stratigraphy of core RC11-210 based on the age correlation of LR04. Gray intervals represent glacial periods and the numbers the marine isotope stage. (c) Age determination of core PC5103 based on the graphic correlation of the $CaCO_3$ profile with core RC11-210. (d) Age estimate of core PC5101 based on the graphic correlation of the $CaCO_3$ profile with cores PC5103 and RC11-210.

periods in the equatorial Pacific. The $CaCO_3$ changes between the two cores are clearly synchronous, although the $CaCO_3$ content of PC5101 is somewhat lower than that of PC5103. The age of PC5101 was therefore estimated to extend to 650 ka (Fig. 3d). Although complementary absolute dating was not performed for PC5101, the estimated age of this core appears to be plausible with respect to the interglacial-glacial time scales.

3.2 Variability Pattern in Biogenic ($CaCO_3$ and Opal) and Terrestrial Components During the Past 600 ka

The down core variations in biogenic $CaCO_3$ and opal contents in PC5101 and PC5103 during the past 600 ka are shown in Fig. 4. The biogenic $CaCO_3$ and opal content of both cores exhibit a distinct orbital-scale variability cyclic pattern. $CaCO_3$ content of PC5103 is slightly higher (51 - 93%) than that of PC5101 (41 - 89%) (Fig. 4a). Opal concentration of PC5103 varies between 1 and 9% (Fig. 4b). PC5101 is characterized by high opal content (1 - 19%). The fluctuations in biogenic $CaCO_3$ and opal contents are larger in PC5101 because of its low $CaCO_3$ and high opal content during interglacial periods (Fig. 4). In both cores the variations in opal abundance are out of phase with those in $CaCO_3$ content.

In general, the biogenic $CaCO_3$ and opal variability pattern is consistent between the two cores during the past 600 ka. The opal contents of both cores show quasi-periodic cyclicity (Fig. 4), where the $CaCO_3$ content is low and the opal content is high during interglacial periods, and vice versa during glacial periods. Visual inspection of these profiles for the two indices indicate clear co-variation between the down core profiles, reflecting a first-order pattern that appears to have a 100 ka periodicity. Rea et al. (1991) reported that the $CaCO_3$ and opal contents of RC11-210 also show a prominent 100 ka spectral peak. Based on spectral analysis performed using standard menu-driven software applying the Blackman-Tukey method, Khim et al. (2012) confirmed that the $CaCO_3$ and opal abundances of PC5101 are controlled primarily by eccentricity forcing.

Based on the assumption that the sediments of the two cores consist only of terrestrial and biogenic ($CaCO_3$ and opal) components, we calculated the sediment terrestrial fractions and show their variation patterns during the past 600 ka (Fig. 4). Similar to the biogenic components, the terrestrial fraction also represents the quasi-cyclic variation patterns. Both cores show that the terrestrial fraction was higher during the interglacial periods than during the glacial periods. The precise reason for such variations will not be discussed because it is beyond the scope of this study.

4. DISCUSSION

The time-series of biogenic $CaCO_3$ and opal content in the two cores (PC5103 and PC5101) in the central equatorial Pacific show that the changes in these two biogenic components are consistent during the late Pleistocene (Fig. 4). These findings suggest that the dominant factors influencing biogenic $CaCO_3$ and opal abundances have consistently affected both the northern (PC5103) and southern (PC5101) sites in the central equatorial Pacific. Both cores display higher $CaCO_3$ contents during glacial periods than during interglacial periods, and vice versa for opal. Khim et al. (2012) already reported on the similar geochemical properties in the western equatorial Pacific, which were compared regionally with those in the eastern equatorial Pacific (Murray et al. 1995), showing consistent orbital-scale variation. The fluctuations in these biogenic components in both cores are greater during interglacial than during glacial periods (Fig. 4).

4.1 Glacial-Interglacial Cyclicity of Biogenic $CaCO_3$ Deposition

The cyclic deposition of late Pleistocene biogenic $CaCO_3$ sediments has been well established in the equatorial Pacific (e.g., Weber and Pisias 1999; Anderson et al. 2008). The deposition pattern of biogenic $CaCO_3$ is characterized by good preservation during glacial stages and poor preservation during interglacial stages. In general, there are two possible causes for this glacial-interglacial $CaCO_3$ pattern: surface water productivity and deep water corrosiveness. Surface water productivity is primarily derived from the co-variation of $CaCO_3$ MARs and other biogenic phases in sediments, and appears to be at a maximum during glacial periods (Chuey et al. 1987; Lyle et al. 1988; Archer 1991; Murray et al. 1993; Anderson et al. 2008). Khim et al. (2012) reported on co-variations between $CaCO_3$ content and the

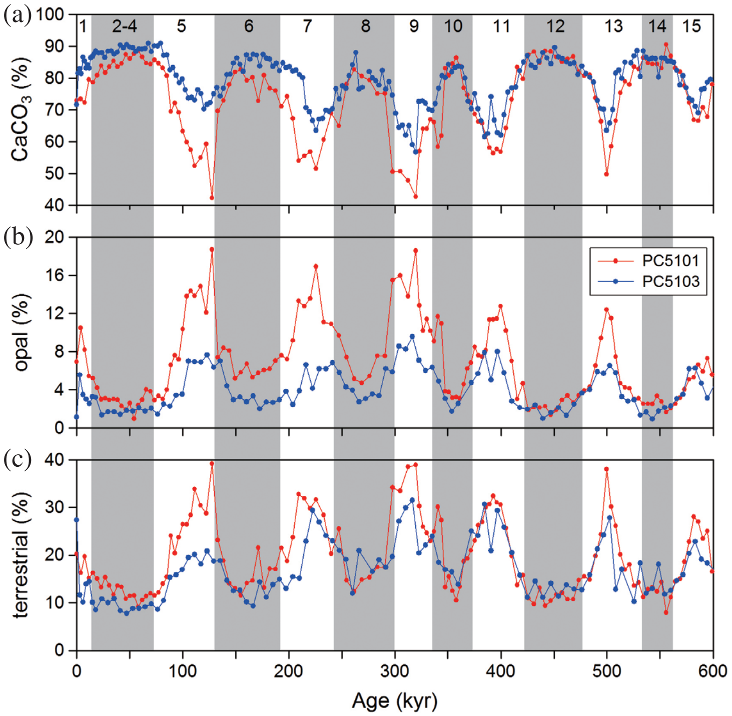

Fig. 4. (a) Down core profiles of the biogenic $CaCO_3$ contents in cores PC5101 and PC5103 during the past 600 ka. (b) Down core profiles of the biogenic opal content in cores PC5101 and PC5103 during the past 600 ka. (c) Down core profiles of the terrestrial fraction in cores PC5101 and PC5103 during the past 600 ka. Gray intervals represent glacial periods.

MARs of PC5101 sediments. Previous studies indicated that glacial climates are characterized by intensified atmospheric and surface water circulations along the equator (e.g., Rea et al. 1986; Pisias and Rea 1988). The enhanced east-west tilt of the thermocline is a consequence of the surface water response to stronger trade winds. The surface water productivity records from the equatorial Pacific should reflect the efficiency in the supply of nutrient-rich waters controlled by equatorial divergence and upwelling driven by surface trade winds. Thus, higher production of $CaCO_3$ particle in the surface water and a subsequent increase in export production lead to higher $CaCO_3$ preservation in PC5101 and PC5103 during glacial periods (Fig. 4).

The second hypothesis for the high $CaCO_3$ content during glacial periods is related to deep water corrosiveness (Farrell and Prell 1989; Wu and Berger 1989; Hebbeln et al. 1990; Le and Shackleton 1992; Anderson et al. 2008). $CaCO_3$ dissolution increases with water depth, which is attributed primarily to the hydrostatic pressure effect on $CaCO_3$ solubility (Hawley and Pytkowicz 1969). Pisias and Rea (1988) pointed out that enhanced $CaCO_3$ accumulation in the lysocline zone of the central equatorial Pacific during glacial periods is caused mainly by deepening of dissolution level in response to sea level change. Farrell and Prell (1989) also found that variations in $CaCO_3$ dissolution during interglacial-glacial cycles are controlled by changes in the calcite saturation state with water depth, which is driven predominantly by bottom water chemistry. A remarkable similarity has been reported between $CaCO_3$ content and dissolution indices based on lithologic and microfossil evidence. For example, Hebbeln et al. (1990) documented the apparent depth of deposition (ADD), which showed that shallower ADD levels corresponded to greater $CaCO_3$ accumulation during glacial periods in the western equatorial Pacific. This finding was supported by a planktonic foraminifera fragmentation study by Wu and Berger (1989), as well as by the Berger dissolution index developed by Le and Shackleton (1992).

The $CaCO_3$ MARs decreased in the equatorial Pacific since the last glacial period; however, $CaCO_3$ fluxes in the seawater have either remained nearly constant or increased (e.g., Farrell and Prell 1991). These findings indicate that enhanced $CaCO_3$ dissolution was a key factor in the decline of $CaCO_3$ MARs during interglacial periods. Anderson et al. (2008) concluded that surface water productivity is not the principal factor controlling $CaCO_3$ accumulation in equatorial Pacific sediments, because $CaCO_3$ fluxes are not correlated with geochemical proxies (barite fluxes and $^{10}Be/^{230}Th$ ratios) indicative of export production. However, based on the relative abundance of coarse foraminiferal fragments, the foraminiferal dissolution index, and the relative abundance of benthic foraminifera, LaMontagne et al. (1996) argued that $CaCO_3$ abundance in the eastern equatorial Pacific cannot be exclusively attributed to dissolution. They suggested that the productivity and dissolution signals are likely to be coupled. Nonetheless, changes in carbonate concentration in the bottom water are likely to be more effective in driving changes in $CaCO_3$ sedimentation, highlighting a possible cause of $CaCO_3$ dissolution. Thus, the cyclic deposition of biogenic $CaCO_3$ sediments, as recorded in both cores in the central equatorial Pacific, appears to be related to the interplay of surface water productivity and dissolution in deep water, as previously reported in other areas of the equatorial Pacific (Lalicata and Lea 2011).

4.2 Glacial-Interglacial Variations in Biogenic Opal Deposition

Opaline phytoplankton communities vary independently in their contribution to the surface water productivity of the equatorial Pacific (Lyle et al. 1988). Because of the observed links between diatom productivity and export production (Romero and Armand 2010), biogenic opal has been considered an indicator of the efficiency of the biological pump and export production (Dugdale et al. 1995). Diatoms in the equatorial Pacific are less abundant than other non-Si-using phytoplankton because of low $Si(OH)_4$ concentrations in upwelling water from the equatorial Pacific as a result of the low $Si(OH)_4$ concentration that originates from the Southern Ocean (Chavez et al. 1990; Bidigare and Ondrusek 1996). The biogenic opal record has been regarded as a minor component of the abundance pattern responding to changes in the major $CaCO_3$ component in the equatorial Pacific (Lyle et al. 1988; Archer 1991; Weber and Pisias 1999). However, Broecker et al. (1982) reported that the rate of opal burial is important in opal preservation, supporting the assertion that opal accumulation should reflect surface water production. Furthermore, Rea et al. (1991) confirmed that biogenic opal may provide a greater preservation record of surface water activity in the central equatorial Pacific.

The biogenic $CaCO_3$ and opal abundance patterns in PC5101 and PC5103 are apparently inverted (Fig. 4). Similarly, Lyle et al. (1988) reported that alternating periods of biogenic opal and $CaCO_3$ deposition occur every 100 ka (the main Milankovitch frequency). The dilution effect seems to be negligible because the core sites are located far from continents. The negative correlation between $CaCO_3$ and opal abundance is consistent with the combined effects of production and dissolution. Biogenic opal dissolves because seawater is undersaturated with silica. Unlike $CaCO_3$ dissolution, opal dissolution remains generally consistent at a more constant rate with water depth. Because there is less dissolution of opal at the seafloor compared with $CaCO_3$, fluctuations in opal content might provide a better record of the supply-productivity process. Thus, systematic fluctuations in opal abundance between interglacial and glacial periods appear to be controlled by the degree of opal production in the surface water.

A change in the ITCZ location is a likely cause of the meridional difference in opal abundance between interglacial and glacial periods. The ITCZ has a negative influence on diatom production because it is associated with heavy precipitation that limits the supply of nutrients and metals (Murray et al. 1993). Changes in diatom production between interglacial and glacial periods can be inferred from the trends in opal abundance in PC5103 and PC5101 (Fig. 4). Pisias and Mix (1997) reported spatial and temporal variations in radiolarian microfossil data associated with ITCZ migration in the eastern equatorial Pacific. Overall, such an orbital-scale deposition of biogenic opal between the two cores is attributed partly to the different response and effect of ITCZ migration in the central equatorial Pacific between interglacial and glacial periods.

The present-day ITCZ shows a cyclic seasonal migration between 4°N during winter and 10°N during summer, with a mean annual position at 6°N in the East Pacific (Pettke et al. 2002). Koutavas and Lynch-Stieglitz (2004) reported that the ITCZ shifted southward during the last glacial period compared with the present-day position. Such southward ITCZ displacement during glacial periods may result in a negative effect on diatom production in equatorial regions. Thus, both cores show reduced biogenic opal content during glacial periods. During interglacial periods, however, the ITCZ moves northward, as during the modern-day summer, and is located somewhere between the two core sites in this study area. As a result, diatom production is enhanced in the southern core (PC5101) area near the Equator, compared with the northern core (PC5103) where the ITCZ acts to suppress diatom production.

4.3 Latitudinal Variations in Biogenic $CaCO_3$ and Opal Contents

Sharp latitudinal gradients in surface-water biological productivity (Peña et al. 1990), benthic recycling of organic carbon (Martin et al. 1991), and the contribution of eolian supply (Murray and Leinen 1993) have been clearly observed across the transect at 135°W in the central equatorial Pacific. The $CaCO_3$, opal, and organic carbon budgets across the 140°W meridian in the equatorial Pacific also show broad equatorially symmetric biogenic fluxes that show the peak at the equator (Berelson et al. 1997). Consequently, the meridional profiles of biogenic $CaCO_3$ and opal content in the surface sediments are characterized by sharp peaks with maxima centered at the Equator. Such a unique pattern suggests a strongly linear relationship between the proxies and surface water productivity (Murray et al. 1993). Therefore, high biogenic production at the Equator is associated with the upwelling of nutrient-rich water into the shallow thermocline depth due to equatorial surface-water divergence, whereas the reduction in biogenic production away from the Equator is associated with the ITCZ, which results in enhanced terrigenous input due to heavy precipitation and rainfall.

Although the biogenic opal content during glacial periods was consistently low at both sites (Fig. 4), latitudinal comparison between PC5101 and PC5103 is worthy of note, showing that biogenic opal content during interglacial periods was higher at PC5101 (2°N) than at PC5103 (6°N). This corresponds exactly to the modern latitudinal trend where biogenic opal production decreases northward away from the Equator. Murray et al. (2000) summarized the meridional profiles of $CaCO_3$ concentration, bulk sediment MAR, and elemental ratios (Al/Ti, Ba/Ti, P/Ti) in surface sediments, all of which reveal a sharp peaked profile with the maxima centered at the Equator. These spatial patterns are consistent with well-established patterns of biological productivity and the rain of biogenic debris onto the seafloor (Anderson et al. 2008). As shown in Fig. 4, the higher $CaCO_3$ content during glacial periods is comparable at both sites, suggesting that preservation in terms of production and dissolution is similar between the sites. However, $CaCO_3$ content during the interglacial periods is clearly lower at the southern site than at the northern site (Fig. 4). This contradicts the current pattern of surface sediment characteristic across the central equatorial Pacific transect (Murray et al. 2000). Thus, such an unusual $CaCO_3$ deposition pattern, opposite to the opal deposition, requires an additional contributing factor to account for this contradiction.

Farrell and Prell (1989) presented a time-depth diagram of $CaCO_3$ preservation over the past 800 ka based on the compilation of $CaCO_3$ time-series data from 16 sediment cores in the equatorial Pacific. The difference in $CaCO_3$ content between PC5101 and PC5103 in the central equatorial Pacific during interglacial periods appears to be related to the shape and depth of the lysocline, which has regularly responded to interglacial forcing with lower $CaCO_3$ preservation during interglacial times (Fig. 4). The only discernible difference between the two core sites is water depth, being deeper by approximately 350 m at the southern site. According to the $CaCO_3$ preservation diagram of Farrell and Prell (1989), this difference in water depth accounts for 20 - 40% dissolution in $CaCO_3$ content. Although the southern core (PC5101) is located in a more productive area close to the Equator, the greater water depth has a stronger effect on $CaCO_3$ preservation through an increase in the dissolution rate. Therefore, biogenic $CaCO_3$ and opal deposition is closely related to the degree of surface water production, $CaCO_3$ deposition is more sensitive to the water depth that controls the degree of dissolution, rather than solely the abundance of biogenic opal.

5. CONCLUSIONS

The equatorial Pacific Ocean has played a significant role in influencing global climatic events. For example, cyclic variations in biogenic $CaCO_3$ abundance have been reported from the equatorial Pacific Ocean. Despite the continuing debate on the exclusive factor on the variation biogenic $CaCO_3$ abundance, a linkage between the degree of surface-water productivity and deep-water corrosiveness has been found where glacial-interglacial variations in productivity may have caused changes in carbonate dissolution. The meridional migration of the ITCZ between interglacial and glacial periods also appears to control the biogenic production rate in the surface waters of the equatorial Pacific. This study analyzed two piston cores (PC5101 and PC5103) collected from the central equatorial Pacific Ocean that show a clear series of biogenic $CaCO_3$ and opal variations that were controlled mainly by eccentricity with a periodicity of approximately 100 ka. These orbital-scale cyclic variations show that PC5101 at the southern site (2°N) has a higher biogenic opal content than PC5103 at the northern site (6°N) during interglacial periods, which corresponds to the modern latitudinal state where biogenic opal production decreases northward from the Equator. In contrast, the southern site has lower $CaCO_3$ contents than the northern site during interglacial periods, which is opposite to the present-day pattern. This contradiction results from the difference in water depth between the two sites. The greater water depth at the southern site plays an important role in $CaCO_3$ preservation by increasing the dissolution rate, although the core was located in a more productive area close to the Equator.

Acknowledgements We appreciate the constructive comments from the two anonymous reviewers which improved the quality of this manuscript. This study was supported by the Ministry of Oceans and Fisheries, Korea (PM58520) and the Korea Institute of Ocean Science and Technology (PE99291).

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