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Deep-sea carbonate preservation in the western Philippine Sea over the past 1Ma

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ABSTRACT

In this paper, we present a continuous record of calcium carbonate (CaCO₃) content that covers the last 1 Ma from core MD06-3050 (15°57.0943'N, 124°46.7747'E; water depth, 2967 m), which was collected in the western Philippine Sea (WPS). The CaCO₃ content in this study core is characterized by maxima during deglaciations and minima during the onsets of glacial periods and generally shows Pacific-style patterns, with relatively high and low values during glacial and interglacial periods, respectively. Proxies of dissolution and primary productivity (PP), the CaCO₃ content and the oxygen isotope record from this core are compared throughout the 1 Ma study interval to improve our understanding of the mechanisms that affected carbonate preservation and dissolution at this site.

The planktonic foraminifera shell fragmentation ratio (%shell fragment) is used as a dissolution proxy in this study. The %shell fragment data from MD06-3050 provide evidence of preservation maxima during most of the deglaciations, whereas intense dissolution is recorded at the onsets of glacial periods within the past 1 Ma. The variations in %shell fragments are similar to those seen in the CaCO₃ content, which demonstrates that the bulk CaCO₃ content patterns were controlled by dissolution in deep seawater.

The primary productivity from the coccolith record shows limited similarity with the CaCO₃ content on glacial-interglacial time scales since 1 Ma, which suggests that PP played a negligible role in the glacial-interglacial CaCO₃ cycle. However, a bloom of the coccolithophores *Geophyrocapsa caribbeanica* that extended from MIS 9 to MIS 12 likely contributed to the increased CaCO₃ content observed during the Mid-Brunhes interval (MBE) over the glacial-interglacial fluctuations. Therefore, the CaCO₃ content should be used as a dissolution proxy with caution during the MBE in the tropical Pacific, especially for water depths that are shallower than the carbonate lysocline.

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1. Introduction

Deep-sea calcium carbonates (CaCO₃) represent one of the largest and most reactive reservoirs for carbon dioxide (CO₂) (Broecker and Peng, 1987). Reconstructing the history of marine CaCO₃ production and preservation is crucial in understanding

changes in atmospheric CO₂ (Barker et al., 2006) and glacial-interglacial climates. The amount of CaCO₃ that is distributed in the sediments of the global oceans indicates the characteristics of different regions because the CaCO₃ content in marine sediments are controlled by multiple factors, such as the CaCO₃ production of calcareous organisms in the surface ocean, dilution by terrigenous materials and non-carbonate matter, and dissolution that occurs in the water column, at the sea floor, and in sediment pore water (Archer, 1991; Ridgwell and Zeebe, 2005). Glacial-interglacial CaCO₃ cycles in the global oceans can be divided into Pacific-style

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and Atlantic-style patterns (Volat et al., 1980). The Pacific-style pattern is characterized by relatively high CaCO₃ content in deep-sea sediments during glacial periods compared to that during interglacial periods (e.g. Anderson et al., 2008; Broecker, 1971; Le and Shackleton, 1992; Peterson and Prell, 1985; Thompson and Saito, 1974), whereas the Atlantic-style pattern shows the opposite pattern across glacial-interglacial cycles (e.g. Berger, 1973; Crowley, 1985; Curry and Lohmann, 1990; Hodell et al., 2001; Verardo and McIntyre, 1994; Volat et al., 1980). As suggested by their names, the former pattern is mostly found in the Pacific Ocean and partially in the Indian Ocean (e.g. Peterson and Prell, 1985) and the subantarctic zone of the Southern Ocean (e.g. Hodell et al., 2001), whereas the latter mostly occurs in the Atlantic Ocean. Since the detection of the Pacific-style CaCO₃ cycle in the eastern equatorial Pacific (Arrhenius, 1952), increasing research attention has been devoted to determine the cause of the Pleistocene CaCO₃ cycles in the Pacific and establishing the connection of these cycles with the state of the oceanic carbonate system and atmospheric CO₂ (Chiu and Broecker, 2008; Huber et al., 2000; Kawahata et al., 1997). Although changes caused by the carbonate saturation state of deep water are difficult to differentiate from other controlling factors, proxies that are sensitive to dissolution alone have been employed, such as the % coarse (>63 μm) fraction (Peterson and Prell, 1985) and the ratio of >63 μm CaCO₃ to total CaCO₃ (Broecker and Clark, 1999). Most of these proxies are based on planktonic foraminifera, such as foraminiferal fragmentation (Le and Shackleton, 1992), planktonic foraminifera shell thinning (Lohmann et al., 1999), planktonic foraminifera test weights (Broecker and Clark, 2001; Lohmann, 1995), the *Globigerina bulloides* dissolution index (Dittler and Henrich, 2000; Volbers and Henrich, 2004), and the *G. menardii* fragmentation index (Ku and Oba, 1978; Mekik et al., 2002, 2010). In addition to proxies that are related to foraminifera, pteropods have been used to assess dissolution because their aragonite shells are very sensitive to post-death dissolution. For example, several studies have examined the shell preservation of the pteropod species *Limacina inflata* (Wall-Palmer et al., 2013; Gerhardt and Henrich, 2001).

Previous studies have suggested that CaCO₃ glacial-interglacial cycles were predominantly caused by enhanced dissolution during the onsets of glacial and interglacial intervals, rather than by changes in productivity, and indicated that dissolution consistently lagged behind oxygen isotope cycles in the Pacific (Anderson et al., 2008; Berger, 1973; Berger and Johnson, 1976; Ku and Oba, 1978; Le and Shackleton, 1992; Luz and Shackleton, 1975; Thompson and Saito, 1974). According to CaCO₃ stratigraphy from ten cores collected on the Ontong Java Plateau, Wu and Berger (1991) proposed that a significant portion of the amplitude in CaCO₃ cycles from deep-sea sediments in the western equatorial Pacific was caused by fluctuations in dissolution intensity. In addition, CaCO₃ dissolution begins to significantly affect sediments at a water depth of approximately 3 km in the equatorial Pacific (Wu and Berger, 1991). Yasuda et al. (1993) examined correlations between productivity indicators and dissolution proxies and attributed the observed oscillations in CaCO₃ content to dissolution fluctuations, thus suggesting that productivity variation played a minor role in causing fluctuations in CaCO₃ content during glacial-interglacial cycles in the western equatorial Pacific. Moreover, a study on the dissolution proxies in sediment cores from the eastern and western equatorial Pacific suggested that dissolution-controlled CaCO₃ cycles are basin-scale phenomena (Lalicata and Lea, 2011). Although the dissolution intensity varied among different Pacific regions, the synchronous timing of fluctuations revealed that basin-wide changes in ocean chemistry occurred during glacial-interglacial transitions (Bordiga et al., 2013; Lalicata and Lea, 2011).

Other than deep-sea CaCO₃ dissolution, the surface-water

production of CaCO₃ is the major contribution to the distribution, preservation, and accumulation of CaCO₃ on the seafloor. Generally, CaCO₃ fluxes from surface waters increase as productivity increases. However, few records support the hypothesis that Pacific CaCO₃ cycles were caused by differences in biogenic CaCO₃ production between glacial and interglacial periods (Adelseck and Anderson, 1978; Archer, 1991; Arrhenius, 1988). Considering the great depth of the cores in most previous studies, productivity likely plays a secondary role to abyssal corrosiveness in controlling the observed CaCO₃ cycles in the deep equatorial Pacific (Farrell and Prell, 1989, 1991; Wu and Berger, 1991).

In fact, some studies have suggested that CaCO₃ production in the equatorial Pacific may have been higher during glacial periods. The best estimates of paleoproductivity in the equatorial Pacific have been obtained from cores collected above the modern lysocline. These estimates indicate that glacial CaCO₃ production was 1.3–1.5 times greater than interglacial production (Adelseck and Anderson, 1978; Peng et al., 1977; Schiffler and Dorman, 1986). Recently, calcareous plankton were used to reconstruct the paleoproductivity in the northwestern Pacific, and the results showed that high productivity corresponded to abnormally high CaCO₃ content during MIS 12–MIS 9 (Bordiga et al., 2013). Although dissolution appears to be the dominant control of the CaCO₃ preservation pattern in the tropical Pacific, evidence suggests that spatial and temporal fluctuations in CaCO₃ productivity, despite being difficult to constrain, must also be considered. Ultimately, a satisfactory explanation of these CaCO₃ cycles should involve productivity and dissolution on a global scale.

The majority of previous studies that have examined the pattern of CaCO₃ cycle in the Pacific were conducted in the equatorial and eastern parts of the Pacific. However, continuous high-resolution records of the timings of these changes in dissolution and carbonate saturation are lacking. Records from low-sedimentation-rate cores collected in the Indian and Pacific Oceans represent a damped response of sedimentary CaCO₃ to changes in the carbonate saturation of deep water because of bioturbation and chemical erosion (Broecker and Peng, 1982; Oxburgh, 1998; Walker and Opdyke, 1995). Farrell and Prell (1989) reconstruction of a continuous 800 ka record of bathymetric variations in CaCO₃ preservation, which was based on sixteen deep-sea cores, also suggests that chemical erosion and exhumation of previously preserved CaCO₃ may have masked evidence of a carbonate critical depth (CCrD) deepening event in the central equatorial region of the Pacific. Similar arguments regarding truncation can be extended to even shallower cores in the Pacific (Broecker and Sanyal, 1997). Ideally, a core with high and relatively constant sedimentation rates and a young apparent age (based on the average age of sediment particles in the bioturbated layer) should be obtained because such a core would minimize the effects of bioturbation and chemical erosion (Broecker and Peng, 1982; Walker and Opdyke, 1995).

The western Pacific Ocean plays an important role in the global climate system. This region is affected by the Asian monsoon system and El Niño Southern Oscillation (ENSO). Therefore, considerable changes occur in the upper water structure of this area seasonally, annually, and over glacial-interglacial scales (Beaufort et al., 2001; Stott et al., 2002), and these changes induce variations in PP in the surface ocean. Coccolithophores are major primary producers in the western Pacific, and they contribute to both the biological carbon pump and the carbonate counter pump and influence the transfer of CO₂ between the ocean and the atmosphere. The Pacific deep water is located at the end of the global thermohaline circulation, which is characterized by high preformed nutrient concentrations and by progressive ‘aging’ of the waters along its length (e.g. Berger, 1970; Crowley, 1985; Ruddiman

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