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末次冰期以来西太平洋边缘海海洋生物泵与有机碳埋藏的变化规律及影响因子

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题名页

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Variability and mechanisms of biological pump and organic carbon burial in the western Pacific marginal seas since the last glaciation

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摘要

内容摘要

海洋生物泵在调节大气—海洋系统中二氧化碳（CO_2）的分配中发挥重要作用。但是到目前为止，人类对海洋生物泵的自然演变规律及其调控机制的认知尚存较大争议。本研究对冲绳海槽区输出生产力进行重建，获得过去 9 万年以来的高分辨率沉积记录。进一步通过数据集成，我们发现整个北太平洋中-高纬度海区输出生产力在末次冰期千年快速气候变化中呈现同步变化规律：即在北半球冷事件（例如 Heinrich 事件）对应较低的输出生产力，而暖事件对应较高的输出生产力。基于此，我们提出大气铁沉降不是该海区生物泵的主控因子。结合北太平洋与北大西洋气候变化遥相关机制，我们提出北太平洋输出生产力受控于北太平洋中层水演化，作用机制如下：在北半球快速冷期阶段，在北太平洋降水减少、温度下降、海冰增加等多种因素的共同作用下，北太平洋中层水的密度增加导致其下沉深度增大。从而驱使富含营养盐的深层水下移，造成到达上层海洋的营养盐减少以及较低的海洋生产力水平。与之相反，在暖期阶段北太平洋中层水密度减小导致该水体变浅；从而促使富营养的深层水更多的到达上层海洋并支撑较高的生产力水平。与之相反，在末次冰期快速的千年尺度气候振荡旋回中，大气铁沉降主导着南大洋亚南极海区输出生产力的变化。在此基础之上，我们提出在末次冰期南北半球气候的不对称变化阶段—“两极跷跷板（bipolar seesaw）”，北太平洋和南大洋亚南极海区输出生产力受控于不同的环境因子，海洋生物泵主导机制具有南-北半球空间差异性。综合分析输出生产力与有机碳埋藏记录，我们发现：自末次冰期以来冲绳海槽区海源有机碳埋藏与输出生产力并不耦合。有机碳埋藏（效率）高值出现在末次冰盛期和冰消期，而低值出现在在全新世。利用海洋源有机碳埋藏与输出生产力记录，我们提出一个新的有机碳埋藏效率指标——$OC_{marine}/P_{react.}$。通过结合环境敏感型金属元素测试以及有孔虫种属分析结果，我们提出冲绳海槽区有机碳埋藏效率受控于北太平洋中层水演化和海平面变化的共同作用。

南海中层水交换对南海生物地球化学过程有重要影响。例如，中层水交换影响南海真光层营养盐供给、颗粒有机碳沉降、陆坡沉积有机碳埋藏等。本研究中，我们利用 3-D 边缘海物理模型探讨海平面变化及东亚季风对南海中层水交换的影响。模型结果显示：（1）在现代气候背景驱动下，海平面降低（135 米）会使吕宋海峡中层水交换速率减少约 24%；而在末次冰盛期气候背景下，东亚冬季风强度加倍则可以弥补海平面下降的影响。（2）与现代南海环流模式相比，末次冰期吕宋西部上升流强度显著增加，同时越南外海表层西边界流显著增强。另外，古生产力指标揭示南海北部初级生产力在末次冰盛期显著增加，这与冰期增强的冬季季风搅动强化上层海水混合密切相关。结合南海东南部海区沉积锰的分析结果，我们提出，末次冰盛期南海东南部中层水氧含量降低是由南海北部初级生产力的增加造成的（高生产力会显著减少中层水氧含量）。

关键词：中国南海，冲绳海槽，水体含氧量，冰期低海平面，输出生产力，有机碳埋藏效率

英文摘要

Abstract

Mechanisms controlling the export production during the last glaciation in the North Pacific remain controversial. Here, we present a record of 92,000-year export productivity (EP), inferred from sedimentary reactive phosphorus, from the western subtropical North Pacific. On millennial timescale EP decreased during cold stadials when dust supply was high in the northern hemisphere; and vice versa during warm episodes. Millennial anti-phase relation between dust and EP suggests that instead of eolian Fe, the supply of macronutrients driven by the penetration depth of North Pacific Intermediate Water exerted a major control on EP in the subtropical North Pacific. Compiled global productivity records suggested eolian Fe most likely played a role in stimulating EP in the Subantarctic only; meanwhile, during the cold-south/warm-north phase of the bipolar seesaw, the biological pump in both hemispheres was enhanced synchronously yet by different drivers, i.e., atmospheric Fe for the Subantarctic and subsurface macronutrients for the North Pacific. In addition, we also measured contents of manganese (Mn), iron (Fe), and aluminum (Al) for a sediment core in the middle Okinawa Trough (OT) spanning over the past 30 kyr. We found the export productivity (EP, inferred from reactive phosphorus) was decoupled with organic carbon burial (e.g., high EP and low organic carbon burial in Holocene). Variability of Mn and reported total sulfur content suggested that OT deep/bottom water had experienced significant redox change in the last glacial cycle. By using the ratio of marine source organic carbon to reactive phosphorus, i.e., $OC_{marine}/P_{react.}$, we reconstructed organic carbon burial efficiency. We suggested that higher water column oxygenation reduced the burial efficiency in the Holocene resulting in the decoupling relation between reported organic (e.g., total organic carbon) and inorganic productivity proxies (e.g., biogenic Ba, $CaCO_3$). Apparently, changes in environment redox condition may alter the linkage between surface productivity and organic carbon burial. After synthesizing reported data, we concluded that the water column redox modulation was driven by the water exchange

induced by KC intrusion and lateral exchange with the North Pacific intermediated water instead of by the oxygen consumption owing to local export productivity. A conceptual model was proposed to reconcile the inconsistency among proxies and interpretations of paleo-productivity change in the Okinawa Trough over glacial-interglacial cycle.

Degree of oxygenation in intermediate water modulates the downward transferring efficiency of primary productivity (PP) from surface water to deep water for carbon sequestration, consequently, the storage of nutrients versus the delivery and sedimentary burial fluxes of organic matter and associated biomarkers. To better decipher the PP history of the South China Sea (SCS), appreciation about the glacial-interglacial variation of the Luzon Strait (LS) throughflow, which determines the mean residence time and oxygenation of water mass in the SCS interior, is required. Based on a well-established physical model, we conducted a 3-D modeling exercise to quantify the effects of sea level drop and monsoon wind intensity on glacial circulation pattern, thus, to evaluate effects of productivity and circulation-induced oxygenation on the burial of organic matter. Under modern climatology wind conditions, a 135 m sea-level drop results in a greater basin closeness and a ~24% of reduction in the LS intermediate westward throughflow, consequently, an increase in the mean water residence time (from 19.0 to 23.0 years). However, when the wind intensity was doubled during glacial low sea-level condition, the throughflow restored largely to reach a similar residence time (18.4 years) as today regardless its closeness. Comparing with present day SCS, surface circulation pattern in glacial model exhibits (1) stronger upwelling at the west off Luzon Island, and (2) an intensified southwestward jet current along the western boundary of the SCS basin. Superimposed hypothetically by stronger monsoon wind, the glacial SCS conditions facilitate greater primary productivity in the northern part. Manganese, a redox sensitive indicator, in IMAGES core MD972142 at southeastern SCS revealed a relatively reducing environment in glacial periods. Considering the similarity in the mean water residence time between modern and glacial cases, the reducing environment of the glacial southeastern SCS was thus ascribed to a

productivity-induced rather than ventilation-induced consequence.

Keywords: South China Sea; Okinawa Trough; Water oxygenation; Glacial low sea-level; Export productivity; Organic carbon burial efficiency

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第一章 南北半球高纬度生物泵主控因子的时空差异性

Differential controls on synchronous productivity response of interhemispheric oceans to the bipolar seesaw climate

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1.1 Introduction

Antarctic ice core records have revealed a coherent negative correlation between atmospheric CO_2 concentration (pCO_{2atm}) and dust deposition over Antarctica (Lambert et al., 2008; Luthi et al., 2008), suggesting a potential control of dust on climate. Two distinct, yet synergistic mechanisms – water-column stratification in the Antarctic zone and iron fertilization in the Subantarctic zone – have been proposed to account for a sizeable portion of the glacial-interglacial pCO_{2atm} variability (Hain et al., 2010; Jaccard et al., 2013). In the Antarctic zone, extended sea-ice coupled with enhanced water-column stratification reduced the ventilation of DIC-rich subsurface waters, contributing to reduction of atmospheric pCO_{2atm} during glaciation (Sigman et al., 2010; Jaccard et al., 2016). On the other hand, increased eolian Fe-bearing dust supply to the Subantarctic zone of the Southern Ocean during glacial times may have alleviated Fe limitation and thus strengthened the biological pump (BP) there (Kumar et al., 1995; Martínez-García et al., 2014). A stoichiometric teleconnection (Si/N) between the Subantarctic zone and the equatorial Tropical Pacific has been suggested further expanding the effect of polar ocean dynamics to low latitudes (Sarmiento et al., 2004). Polar ocean processes are thus largely responsible for modulating atmosphere-ocean CO_2 exchange and low latitude biogeochemistry.

Like the Southern Ocean, the subarctic North Pacific is an iron limited "high-nutrient, low-chlorophyll (HNLC)" region currently acting as a net CO_2 source to the atmosphere (Takahashi et al., 2009). An outstanding question is whether productivity in the low latitude North Pacific also responded to dust input similarly to the Subantarctic region. Unfortunately, only handful low-resolution records from the North Pacific linking dust-borne Fe and BP extend beyond the last glacial maximum (Kienast et al., 2004; Winckler et al., 2016). Due to the lack of long, high resolution records, the teleconnection pattern between the subtropical North Pacific and polar climate-ocean dynamics remains largely unconstrained, particularly during the last glaciation when the bipolar seesaw, an asymmetric millennial time scale climate oscillation between the north and south hemispheres (Wais Divide Project Members, 2015), prevailed.

Here, we present a high resolution sedimentary record of phosphorus speciation (see Supplementary Fig. S2) from core MD012404 (Fig. 1, water depth 1397 m; 26°38.84′N, 125°48.75′E) retrieved from the Okinawa Trough to infer the history of export productivity (EP) of the western subtropical North Pacific, and to establish teleconnection patterns over the last 92 kyr. Today, the major nutrient source to the Okinawa Trough (OT) is the North Pacific Intermediate Water (NPIW) (Nakamura et al., 2013; Sarmiento et al., 2004). The NPIW, characterized by a salinity minimum at depth of 400-800 m (Fig. 1), acts as a physical barrier between nutrient-depleted surface waters and nutrient-rich subsurface waters in the North Pacific (see Supplementary Fig. S1b). Thus, the penetration depth and nutrient content of NPIW may modulate the nutrient supply to the euphotic zone of the subtropical North Pacific.

At present in the western subtropical North Pacific, dissolved nutrients are almost completely utilized by phytoplankton, and are incorporated into the living biomass through photosynthesis. Some of this biomass escapes remineralization in the water column and eventually accumulates in the underlying sediment. During sedimentary burial, the labile organic P is converted through the process of sink-switching (Ruttenberg and Berner, 1993) to authigenic P mineral phases (Fe bound/absorbed inorganic P and Ca bound apatite). Here we use P_r ($P_r = P_{Fe\ oxide\text{-}associated} + P_{authigenic} + P_{organic}$) to reconstruct downcore export productivity patterns (see Supplementary Discussion). The reactive P includes the sedimentary fractions that used to be part of the bioavailable P in the euphotic zone (Anderson et al., 2001) and P_r accumulation in the sediment may therefore reflect EP.

1.2 Results

1.2.1 Export production over the past 92 kyr. In the western subtropical North Pacific, P_r varied in sync with northern hemisphere temperatures inferred from $\delta^{18}O$ measured in Greenland ice cores (Fig. 2). During the two prolonged cold stages characterized by low and relatively stable temperatures (i.e., 60-70 kyr ago and 15-30 kyr ago), P_r was also low indicating reduced EP. During cold periods in the subarctic

North Pacific, enhanced dust deposition (4-8 times higher) was accompanied with reduced EP (e.g. Kohfeld and Chase, 2011) and increased relative nitrate utilization (Brunelle et al., 2010; Ren et al., 2015), which signals a more efficient BP. Enhanced stratification has been proposed to have reduced the nutrient supply from below during these cold periods thereby reducing EP in the subarctic North Pacific (e.g. Jaccard et al., 2005; Kohfeld and Chase, 2011) (also see Supplementary Discussion). This is consistent with a growing body of evidences suggesting that enhanced atmospheric deposition of Fe-bearing dust was not a first-order control on productivity in the North Pacific in the past (e.g. Costa et al., 2016; Kienast et al., 2004; Winckler et al., 2016). During these two cold stages, elevated dust supply to the Subantarctic Atlantic stimulated both nitrate uptake and export production and resulted in higher BP efficiency (Martínez-García et al., 2014). Thus, export productivity in the North Pacific (including the subtropical and subarctic realms) and the Subantarctic are out of phase with respect to EP during these two cold stages and were forced by different drivers (see Supplementary Fig. S6 and S7). On the other hand, between the two cold periods mentioned above (i.e., 30-60 kyr ago) the Antarctic zone was generally less stratified (Anderson et al., 2009 ; Jaccard et al., 2016), Antarctic temperatures were higher and the deposition of eolian dust was globally lower (Fig. 2e and 2f), thereby reducing EP in the Subantarctic zone (Anderson et al., 2014 ; Martínez-García et al., 2014) (also see Supplementary Fig. S7). By contrast, during the same period in the northwest subtropical North Pacific, P_r displayed generally higher values compared with those for the two cold stages (i.e., 60-70 kyr ago, and 15-30 kyr ago) again revealing an opposite pattern relative to the Subantarctic zone. To summarize, the BP in the subtropical North Pacific and the Subantarctic was out-of-phase on sub-orbital time scales (see Supplementary Fig. S7).

1.2.2 Millennial productivity change. During the last glaciation, rapid millennial-scale climate variations, such as Dansgaard–Oeschger and Heinrich events, were particularly prominent in the northern high latitude (Wais Divide Project Members, 2015; Böhm et al., 2015). These climate episodes were characterized by

rapid warming operating within a few tens/hundreds years followed by gradual cooling for hundreds/thousands years revealing a bipolar seesaw pattern (anti-phase climate variations between the northern and southern hemispheres). In this specific interval, we found high (low) P_r values during millennial-scale warm (cold) events, and the oscillations varied in sync with temperature variations in the Greenland ice core records (Fig. 2c), but again out of phase with the variations in eolian dust deposition (Fig. 2f). In fact, throughout the entire record we identified a total of 15 out of the 19 cold excursions (Fig. 2), including six Heinrich events and cold spells related to Dansgaard–Oeschger cold events, to have low P_r values (when dust deposition was high). Cold episodes were characterized by intensified East Asian winter monsoon (Yang et al., 2014), which favours diapycnal mixing hence promoting vertical nutrient supply to the euphotic zone; however, monsoon wind intensities were antiphased with P_r suggesting that productivity was not linked to changes in local mixing intensity alone. Thus, the strong coherence between EP in the subtropical North Pacific and Arctic temperatures may imply a remote driver originating from high latitude ocean-atmosphere dynamics, specifically through the NPIW.

1.3 Discussion

It has previously been reported that NPIW penetrated deeper during Heinrich Stadial 1 (HS1) cold event and shoaled during the Bølling/Allerød (B/A) warm interval (Jaccard and Galbraith, 2013; Okazaki et al., 2010). Through atmospheric and oceanic teleconnections, North Atlantic and Greenland cooling would have induced deeper penetration of NPIW by the following proposed mechanisms. Firstly, the subarctic North Pacific sea surface temperature (SST) dropped simultaneously as Greenland climate cooled via atmospheric teleconnection (Okumura et al., 2009). The SST drop promoted sea-ice formation in the Okhotsk (Nürnberg et al., 2011) and Bering seas (Riethdorf et al., 2016), and increased the density of surface water, thereby resulting in deeper penetration of NPIW (Okazaki et al., 2010). Secondly, the Pacific Intertropical Convergence Zone shifted southward during northern hemisphere cold events (Schneider et al., 2014; Wang et al., 2008), resulting in reduced precipitation