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末次冰消期以来冲绳海槽深水氧化性与通风演化研究进展与展望

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摘要: 过去二十年, 末次冰消期以来冲绳海槽深层水沉积氧化性与通风演化、碳埋藏与释放等研究一直备受关注。尽管目前该研究方向已开展了大量的工作, 但由于多种替代指标的复杂性和局限性, 与冲绳海槽黑潮动力学相关的深水环流和沉积氧化还原研究目前仍然存在较大争议。本文系统总结了末次冰消期以来冲绳海槽深层水沉积氧化性与通风演化的研究进展, 发现高有机质沉降通量和高古生产力是末次盛冰期（LGM）至冰消期期间冲绳海槽深层水缺氧的主要原因; Younger Drays(YD) 和 Heinrich Stadial 1(HS1) 事件期间深水通风增强、含氧量增加与北太平洋中层水（NPIW）强化和侵入有关; 早全新世以来黑潮加强引发的深水通风抵消了上升流驱动的生产力提高的影响, 使得冲绳海槽深层水处于氧化状态。最后提出未来冲绳海槽古海洋学研究应加强对轨道-千年尺度深层水水源识别与演化示踪、不同气候状态下古生产力与沉积氧化还原耦合关系, 以及深层水演化的环境与气候效应等方面的研究。

关键词: 沉积氧化性; 深层水通风; 古生产力; 耦合关系; 冲绳海槽
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Research progress and prospects on the evolution of deep water oxygenation and ventilation in the Okinawa Trough since the last Deglaciation

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Abstract: The sedimentary oxygenation and evolution of deepwater ventilation, as well as carbon burial and release in the Okinawa Trough have been highly concerned since the last glacial period over the past two decades. Although many researches have been carried out on this research regime, the coupling relationships between redox conditions and deepwater circulations, biological productivity evolutions are still controversial because of the complexity and limitations of multiple alternative proxies. This paper systematically summarizes the research progress on the oxidation and ventilation evolution of deepwater deposition in the Okinawa Trough since the last glacial period. It was found that the high paleoproductivity and organic matter flux were the main reasons for deep water hypoxia in the Okinawa Trough during the LGM to last deglaciation period. The increase in oxygen content and strengthened deepwater ventilation during the HS1 and YD periods may be related to the intrusion of stronger North Pacific Intermediate Water (NPIW). Since the early Holocene, the deepwater ventilation caused by the Kuroshio has offset the impact of the productivity increase driven by the upwelling, making the deepwater oxidized in the Okinawa Trough. We propose that future research on the paleoceanography of the Okinawa Trough should strengthen the identification and evolution tracing of deep water sources on the orbital millennium time scale, the coupling relationship between paleoproductivity and sedimentary redox under different

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climate states, and the environmental and climatic effects of deep water evolution.

Key words: sedimentary oxygenation; deepwater ventilation; paleoproductivity; coupling relationship; Okinawa Trough

北太平洋中深层环流与生物生产力之间的相互作用，其变化与深层水氧化还原变化耦合紧密[1-3]，影响北太平洋大气 CO_2 水平和海洋氧浓度[4-6]。因此，北太平洋过去深层水氧化性与通风演化研究对于了解过去海洋和大气 CO_2 循环过程、探索气候系统演化具有重要意义[7-8]。

位于亚热带北太平洋西部的冲绳海槽是东亚大陆边缘典型弧后盆地。晚第四纪，冲绳海槽通过上部水体—西部边界流黑潮的水汽热量传输[9]、中深层水体与开阔太平洋内部水体交换[10]，在亚热带海区与亚北极北太平洋之间，建立了气候-海洋动力学之间的遥相关关系，深刻影响着北太平洋中-高纬度气候变化。过去二十年，冲绳海槽晚第四纪深层水通风、表层生物生产力、沉积氧化性演化以及相关的碳埋藏与释放研究一直备受关注[11-15]（图 1a）。然而，末次冰消期以来，冲绳海槽千年时间尺度上深层水沉积氧化性与通风变化的过程与机制仍存在较大争议[8,16-18]。究其原因是黑潮、生物生产力、深层水通风等多种因素的复杂影响，深层水氧化性多大程度受到南向扩张的 NPIW 的影响，或生物生产力在氧化性演化中起多大作用目前仍不清楚[15-19]。

本文在系统梳理以往研究成果的基础上，结合获得的数据资料，总结了冲绳海槽末次冰消期以来深层水通风与沉积氧化性的进展，对深层水通风演化的过程与机制进行探讨，以期为晚第四纪亚热带北太平洋深层水流通与气候演变研究提供思路。

1　冲绳海槽水文与环流体系

冲绳海槽水文和环流体系相当复杂（图 1）。表层水、次表层水体通过黑潮与热带海区相联系。黑潮是北太平洋最大的西部边界流，发源于北赤道洋流。黑潮分为黑潮表层水（0～100 m）、黑潮次表层水（100～400 m）和黑潮中层水（＞400 m）。黑潮次表层水盐度最大，营养成分随深度逐渐增加，黑潮中层水是东海大陆架营养物质的主要来源[20]。黑潮将大量温暖的咸水从低纬度海域带到中高纬度地区，其强度可以显著影响西北太平洋地区的表层水特征、生物地球化学循环和气候[21-22]。黑潮主轴从台湾东北部宜兰海脊进入冲绳海槽，并沿着东海大陆架的外缘向东北流动，通过 Tokara 海峡流入西北太平洋。黑潮分支继续北上，形成对马暖流和黄海暖流，分别进入日本海和黄海[23-24]。黑潮的北向运输受到东亚季风的影响，夏季输运量多于冬季。年际尺度上受到厄尔尼诺和拉尼娜的影响，厄尔尼诺年份黑潮运输量较少，拉尼娜年份的运输量大[25]。但在现代海洋中，季节变化大于年际时间尺度上的变化。长江冲淡水是长江水与海水的混合，密度小于海水。营养丰富的长江冲淡水会影响东海甚至冲绳海槽的季节性水文条件。受东亚季风的季节变化控制，长江冲淡水在夏季沿浙闽沿岸流向北移动，而冬季向南和东北扩散[26]。

冲绳海槽中深层水主要来源于 NPIW 和南海中层水（SCSIW）[27]。冰期时，北太平洋中高纬度边缘海（鄂霍次克海、阿拉斯加湾）海冰盐析作用产生高密度陆架水下沉，并与开阔大洋水团混合形成 NPIW[28-29]。现今 NPIW 的分布在水深 300～800 m，以低盐（33.8‰）、低密度（26.4～27.2 σθ）为显著特征[29]。SCSIW（400～1 500 m）是由南海深层水在南海南部上升形成的，含氧浓度低[30-31]。NPIW 和 SCSIW 通过台湾东北部海峡和宫古海峡（Kerama Gap, 1 100 m）两个通道进入冲绳海槽，成为冲绳海槽中深层水的主要水源[27]。同时由于宫古海峡内部强烈的湍流混合，能够为深层水上涌提供所需浮力，引起强烈的上升流，约有 30%～40% 的 NPIW 可以上升至冲绳海槽表层[32]。

2　末次冰消期以来冲绳海槽深层水氧化性与通风演化

2.1　古氧化还原演化示踪指标

多种替代指标被用于评估过去深层水氧化还原的变异性。底栖有孔虫栖息在沉积物-水界面附近的海底，特定底栖有孔虫物种分布受海水表层生产力、海底有机质通量以及底层水溶解氧含量的控制[33-36]。因此，底栖有孔虫属种组合变化、堆积速率（BFAR）和碳、氧同位素是追溯有机质通量变化和沉积氧化性演变的理想替代指标[36-38]。如底栖有孔虫内生种 *Uvigerina* 和 *Bulimina* 属常用来指示高有机质通量和低氧浓度的沉积环境，*Cibicidoides hyalina* 和 *Globocassidulina subglobosa* 为底层水高溶解氧含量的典型指示种[39]。

过渡金属元素在沉积物中自生富集情况或在

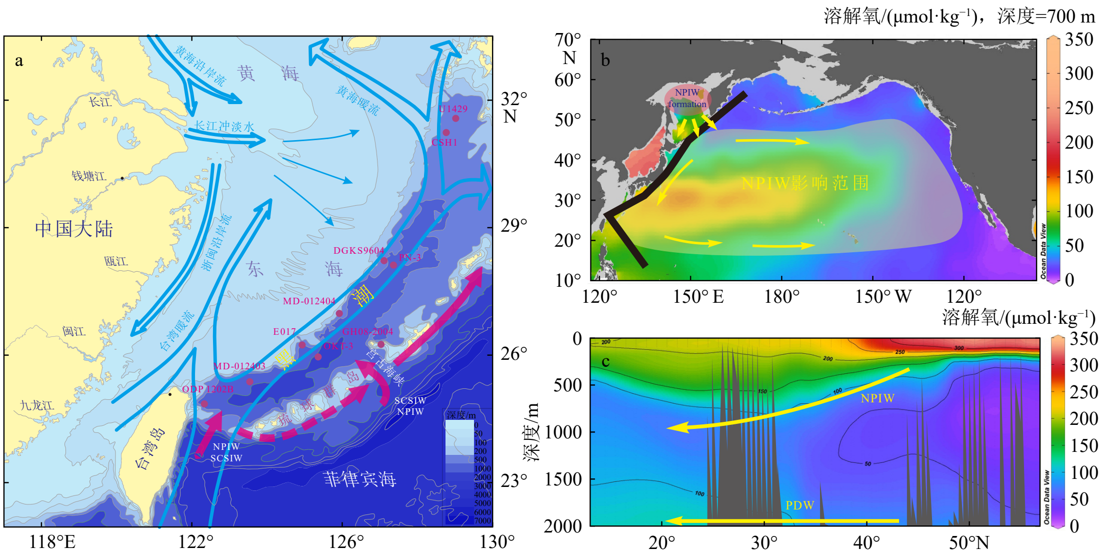

图 1 东海环流体系与研究北太平洋中层水影响范围

a. 东海水文环流体系（深层水环流据[27,32]）和以往研究岩芯，b. 北太平洋 700 m 水深处溶解氧含量的空间分布，c. 溶解氧含量的经向测深断面。溶解氧数据来源于 World Ocean Atlas 2018（https://odv.awi.de/en/data/ocean/world-ocean-atlas-2018/），由 ODV 软件生成（http://odv.awi.de/）. NPIW：北太平洋中层水；PDW：太平洋深层水；SCSIW：南海中层水。

Fig.1 The circulation system in the East China Sea and the influence range of the North Pacific Intermediate water

a: Hydrological Circulation System in the East China Sea (Deep water circulation data[27,32]) and previous research cores; b: spatial distribution of dissolved oxygen content at a depth of 700 meters in the North Pacific Ocean; c: meridional sounding section for dissolved oxygen content. Dissolved oxygen data is sourced from World Ocean Atlas 2018 (https://odv.awi.de/en/data/ocean/world-ocean-atlas-2018/), generated by ODV software (http://odv.awi.de/). NPIW: North Pacific Intermediate Water; PDW: Pacific Deep Water; SCSIW: South China Sea Intermediate Water.

孔隙水中含量变化是指示沉积物氧化-还原条件变化的代用指标[40]。根据元素含量和相关比值的变化，可以反演沉积时上覆水体（底层水）的氧化还原状况以及有机质输入量的变化[41-42]。氧化还原敏感元素（如 Mo、U、Cd、Re 和 V 等）在氧化条件下更易溶解，在缺氧还原沉积环境下自生富集[43-45]。以往研究发现，当 U 和 V 发生富集而 Mo 不富集时，可能指示缺氧环境；而当它们同时显著富集时则指示硫化环境[40,43,46-47]。

氧化环境下富集的元素包括 Mn 和 Ce。Mn 在含氧的水体中多以自生氧化物 MnO_2 形式沉积下来[48]。然而，Mn 含量与氧化还原之间并没有一定的相关性，本身并不适合作为氧化还原条件的直接鉴别指标，它的主要作用是输送能反映氧化还原条件的一些微量元素进入沉积物[40]。还原环境下，水中不溶的 Ce^{4+}被还原为可溶的 Ce^{3+}，而在氧化环境下则相反。海水及沉积物中的 MnO_2 的一个最大特点就是优先富集 Ce，使得海水中的 REEs 有明显的 Ce 负异常[49-51]。

此外，黄铁矿矿化度（DOP）是目前判别古海洋氧化还原环境最有效的指标之一[52]。沉积岩中黄铁矿矿化程度（DOP）等与沉积环境的氧化还原条件密切相关，可以很好地指示沉积时的氧化还原状态[43,53]。$DOP=Fe_{pyrite}/(Fe_{pyrite}+Fe_{reactive})$，其中，$Fe_{reactive}$ 原指沉积成岩过程中可以参加化学反应的那部分铁[54]，实际应用中表示实验分析中运用浓盐酸溶解的铁，Fe_{pyrite} 表示黄铁矿中的铁，该值可根据对应原子数比用黄铁矿中的硫（S）来代替。

2.2 末次冰消期以来深层水氧化性与通风研究进展

研究发现，末次冰期时黑潮可能已经转移到琉球群岛东部，或仍流经冲绳海槽[55-60]。因此，冰期时与冲绳海槽黑潮动力学相关的深水环流和氧化还原状况研究目前仍然存在争议[19,61-62]。关于 LGM 期间冲绳海槽深层水氧化性与通风问题有两种观点：一是由于海平面下降和/或琉球-台湾陆桥的出现，LGM 时黑潮流入冲绳海槽减缓/缺失，深层水形成且垂直通风可能已经停止，导致底层水缺氧[11-12,16]。之后黑潮在大约 14～7 ka 重新进入海槽或加强[58-60,63]，全新世期间深层水通风强烈。另一种观点反对 LGM 期间冲绳海槽黑潮的缺失[19,62,64-66]，认为 LGM 至末次冰消期深层水通风比目前强得多，并以含氧底层水入侵为特征[17,67-68]。

冲绳海槽过去沉积氧化性的不确定性，可能源

表 1　冲绳海槽深层水沉积氧化性与通风演化相关研究

Table 1　Relative study on sedimentary oxygenation and ventilation evolution of deep water in the Okinawa Trough

区域	钻孔	经纬度	指标	氧化性变化特征	影响因素	参考文献
海槽北部	U1429	31.37°N、128.59°E	U	间冰期缺氧，冰期氧化	冰期NPIW侵入含氧量增加	[8]
	CSH1	31.23°N、128.72°E	氧化还原敏感元素(Mo、U)	YD, H1冷期和8.5 ka以来氧化性增强；B/A等暖期氧化性降低	冷期与NPIW有关、8.5 ka后氧化性增强与黑潮有关	[15]
海槽中部	MD01-2404	26.65°N、125.81°E	TS, DOP, Mn, P_{react}, OC_{marine}	全新世含氧量升高	黑潮引起深水通风	[13-14,16]
	E017	26.57°N、126.02°E	底栖有孔虫	冰期-冰消期深层水流通较差	冰期隔绝状态，与太平洋水体交换减弱	[12]
	MD01-2403	25.07°N、123.28°E	TS	全新世含氧量升高	黑潮引发深水环流增强	[16]
	KX12-3	—	Hg	全新世含氧量升高	黑潮增强使深水部通风增强	[18]
海槽南部	255	25.2°N、123.12°E	底栖有孔虫	冰消期底层水体氧含量低	生产力和沉积物中有机质含量高低	[11]
	1202B	24.48°N、122.30°E	δCe	LGM和冰消期氧化环境，全新世缺氧环境	LGM通风增强，全新世通风减弱，黑潮引发水体分层	[17]

于黑潮强度和路径变化的较大争议，致使对影响冲绳海槽深水流通的复杂因素的理解不明确[62,69-70]。各种复杂的水文或地质过程对冲绳海槽的深层水氧化性和流通产生影响。最近基于冲绳海槽表层水和温跃层水的 Mg/Ca 温度以及浮游有孔虫指标研究，认为北太平洋副热带环流的水文条件受到黑潮和 NPIW 之间相互作用的影响[71]。除了黑潮，长江等大河的陆源输入量（与东亚夏季风和海平面振荡以及地形相关）调节了冲绳海槽表层生产力状况，并对底层水氧化性产生影响[72-75]。

3　深层水氧化性与通风演化的过程与机制

研究发现，冲绳海槽深水氧化还原条件与黑潮引发的水体垂向混合、深层水与太平洋水体交换、以及初级生产力变化等过程密切相关[15-16,71]（表 1）。上述因素中的一种或多种的变化都会导致冲绳海槽轨道-千年尺度上沉积氧化性与通风状况的剧烈变化。

3.1　古氧化还原环境与生产力耦合关系

在大多数情况下，输出生产力提高被认为是中深层水贫氧的重要原因，因为耗氧量极高。研究发现，至少在过去 1 Ma 内，整个北太平洋在每个冰消期都出现生产力的峰值[76-79]，生产力呈现冰期低、间冰期高的变化模式[80-81]。输出生产力的变化可能由陆源营养物质供应量或者黑潮引发的上升流驱动。前者主要由长江等河流流量及与东亚季风季节性降水变化相关径流的调节[82-83]，后者主要源于黑潮中层水上升流造成的物质侵蚀，携带营养物质输送到海水温跃层和混合层[72,84-86]。

末次冰消期以来冲绳海槽古生产力变化如图 2 所示。底栖有孔虫及 TOC 等指标显示，LGM 至末次冰消期，由于海平面较低，径流带来的陆源营养物质直接注入海槽区，冲绳海槽具有较高的表层海水古生产力和有机质沉降通量，底层水含氧量较低；末次冰消期以来，随着海平面上升，海槽区陆源营养物质减少，全新世表层生产力下降[11-13,87]。相似的研究也发现，冲绳海槽全新世输出生产力下降主要由环流变化导致对透光带的营养供应减少所致，加之与海平面快速上升相关的黑潮增强，限制了陆架的营养供应[88]。然而，沉积物中活性磷浓度证据表明，冲绳海槽输出生产力在末次冰期较低，而在全新世较高，其变化受北太平洋中层水渗透深度的影响[14]。在千年时间尺度上，输出生产力也在 Younger Drays（YD）、Heinrich Stadial 1（HS1）等冷事件期间降低，而 Bølling-Allerød（B/A）等暖事件期间增加[84]。由此可见，不同指标体现的末次冰消期以来冲绳海槽古生产力演变的不一致性，可能导致其对深水氧化性的影响存在一定争议。

LGM 至末次冰消期期间，冲绳海槽深层水缺氧可能与该阶段高生产力有关（图 3），该阶段较高的表层海水古生产力和有机质沉降通量是深层水耗氧的主要原因[11-12]。而在全新世中晚期，虽然黑潮加强可引发上升流，但有机碳埋藏效率显示较低值，低输出生产力不可能是深层水氧化还原状况的制约因素，深层水的氧气消耗受深层水体交换和黑潮入侵引起的深水通风等过程控制[84]。

3.2　黑潮和 NPIW 对深层水通风与氧化性的制约

北太平洋中层水体与冲绳海槽深层水的交换，

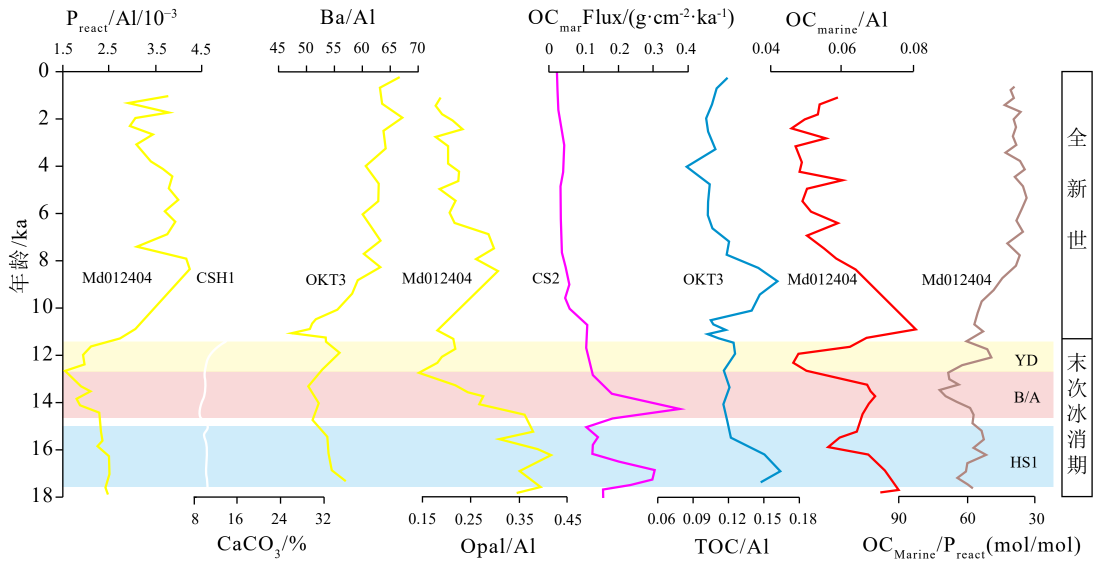

图 2 末次冰消期以来冲绳海槽古生产力演化（P_{react}/Al[14]、$CaCO_3$[15]、Ba/Al（未发表数据）、Opal/Al[14]、OC_{mar}Flux[88]、TOC/Al（未发表数据）、OC_{marine}/Al[14]、OC_{marine}/P_{react}[14]）

Fig.2 Paleoproductivity evolution in the Okinawa Trough since the Last Deglaciation (P_{react}/Al[14]、$CaCO_3$[15]、Ba/Al(unpublished data)、Opal/Al[14]、OC_{mar}Flux[88]、TOC/Al(unpublished data)、OC_{marine}/Al[14]、OC_{marine}/P_{react}[14])

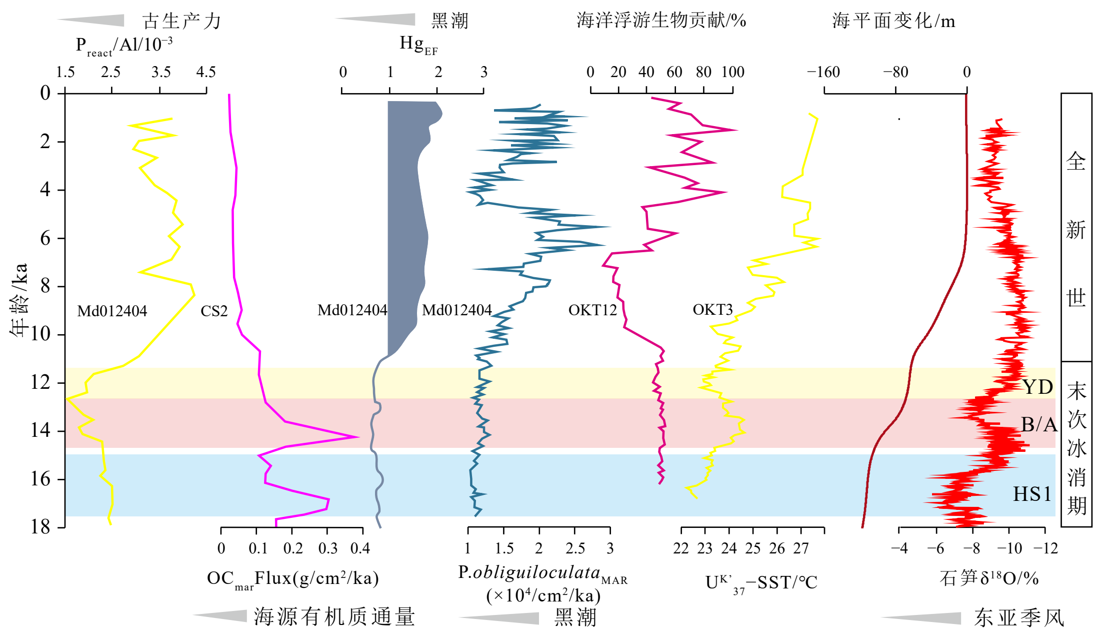

图 3 末次冰消期以来冲绳海槽古生产力演化与其控制因素对比（P_{react}/Al[14]、OC_{mar}Flux[88]、Hg_{EF}[89]、P.obliguiloculata$_{MAR}$[90]、海洋浮游生物贡献[91]、$U^{K'}_{37}$-SST[92]、海平面变化[93]、东亚季风[94]）

Fig.3 Comparison of paleoproductivity evolution and the control factors in the Okinawa Trough Since the Last Deglaciation (P_{react}/Al[14]、OC_{mar}Flux[88]、Hg_{EF}[89]、P.obliguiloculata$_{MAR}$[90]、Contribution of marine plankton[91]、$U^{K'}_{37}$-SST[92]、sea level[93]、the East Asian monsoon[94])

是调节冲绳海槽深水氧化还原条件的重要因素。现代物理海洋观测表明，冲绳海槽深层水主要由 NPIW 和 SCSIW 组成[27]。然而，盐度指标证实南极中层水（AAIW）并没有越过 15°N[95]，冲绳海槽底层水体的性质可能主要受 NPIW 的影响。NPIW 具有在冰期增强、间冰期减弱的特征[96-98]（图 4）。在末次冰消期，NPIW 在 HS1 和 YD 等冷期加强，而在 B/A 暖期明显减弱[99]，在 HS1 期间 NPIW 向深水渗透增强[99-104]。冰期（冷期）增强的 NPIW 产生了强大的下游效应，将营养物质从高纬海洋带到太平洋的低纬海区，并对赤道太平洋东部中低纬度地区的通风和氧化性产生了重大影响[105-108]。LGM 至末次冰消期，海槽中部底层水通风比目前强，底层水含氧量高[17]。与其一致的自生 U 记录也发现，冰期 NPIW

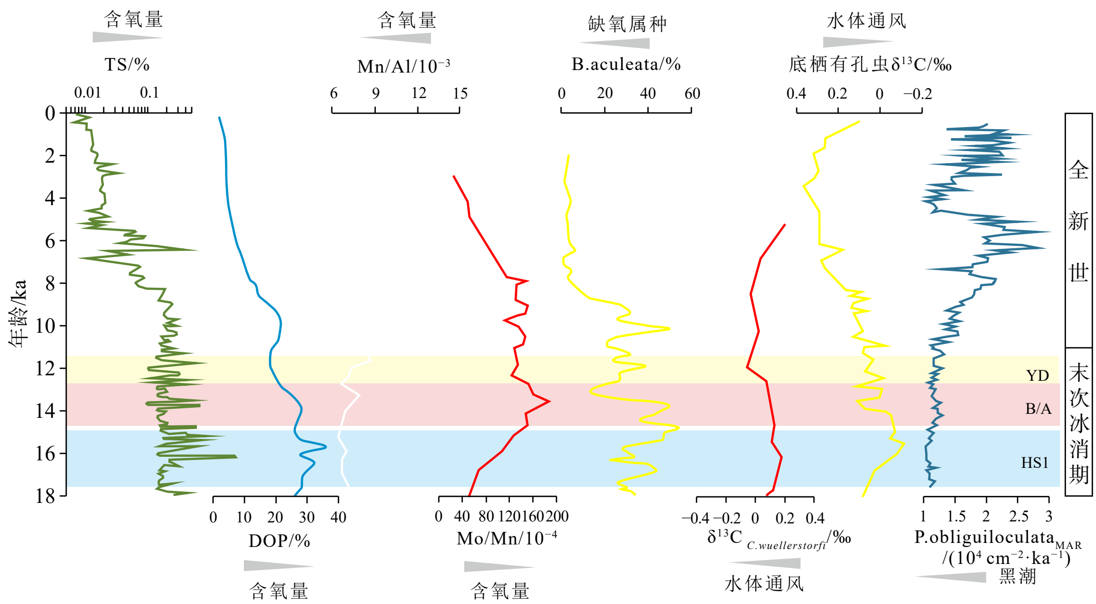

图 4　末次冰消期以来冲绳海槽沉积氧化性[13-16]与黑潮演变[90]、深层水通风[12,86,68]、古生产力变化[14-15]的耦合关系

Fig.4　The coupling relationships between the sedimentary oxygenation of the Okinawa Trough [13-16] and the evolution of the Kuroshio Current[90], deep water ventilation [12,86,68], and changes in paleoproductivity [14-15]since the last deglaciation period

入侵使得冲绳海槽北部深水含氧量提高[8]。然而，有研究认为 LGM 至末次冰消期阶段，冲绳海槽仅在 HS1 和 YD 等冷期时深层水通风增强并致使含氧量增加[15]，且深层水通风状况整体较冰后期弱，反映冰期西北太平洋中层水流通没有对底层水团性质产生影响[11-13,18]。

除深部水体与太平洋水体流通外，黑潮也是控制冲绳海槽深水通风的关键因素[15-16]。黑潮加强时不仅可以引发上升流，还可能引发冲绳海槽深水环流增强，并伴随着沉积物-水界面氧气增加[18,109]。由于 LGM 时黑潮减弱或移出冲绳海槽，黑潮对冲绳海槽沉积氧化性的影响非常有限，末次冰消期时逐渐增加[15,110]。全新世早期以来，黑潮增强引发的深水通风可以抵消上升流驱动的生产力增加量[111-112]，使得全新世冲绳海槽深层水处于氧化状态。沉积物 DOP 和总硫等证据表明，早全新世冲绳海槽沉积氧化性发生转变的时间与黑潮加强时间基本一致[16,109]，加强的黑潮促进了底层水和表层水之间的垂直混合和交换，深水通风加强导致深层水氧含量逐渐增加[16,18]。全新世沉积物汞含量异常高值证实，海底热液侧向输运与黑潮强化引发的冲绳海槽深层水环流增强有关[18]。

4　总结与展望

过去二十年，末次冰消期以来冲绳海槽深层水沉积氧化性与通风演化、碳埋藏与释放研究一直备受关注。冲绳海槽深水氧化还原条件与黑潮引发的水体垂向混合、深层水与太平洋水体交换以及输出生产力变化等过程密切相关。上述因素中的一种或多种的变化都会导致冲绳海槽千年尺度上沉积氧化性的剧烈变化。东亚夏季风季节性降水变化与长江等河流径流的调节，或者黑潮引发的上升流，都可以使海水表层生产力发生变化，进一步影响冲绳海槽深水氧化性。

尽管目前对冲绳海槽深层水沉积氧化性与通风演化开展了大量的研究，然而氧化还原条件变化与深层水通风、生物生产力演变的耦合关系仍存在较大争议，亚热带北太平洋在调节区域大气 CO_2 收支中发挥多大作用目前仍不清楚，有许多重要问题还未解决，简述如下。

（1）轨道-千年时间尺度冲绳海槽深层水水源定性识别及其对沉积氧化性演化影响。以往开展的工作主要从沉积氧化性、有机质通量等角度反演深层水通风状况，目前还没有建立合适指标追踪 NPIW 在冲绳海槽深层水中水源信号，评估 NPIW 演化对冲绳海槽沉积氧化性演化影响。自生 Fe-Mn 氧化物 Nd 同位素是具有广泛应用前景的替代指标。

（2）不同气候态冲绳海槽古生产力演化与沉积氧化性的耦合关系。生产力受多种环境因素影响，并且对环境变化的响应存在差异。如陆坡离岸近海区，陆源有机碳输入和横向搬运、上升流等因素影响大，这些环境因素可能会导致重建的古生产力演化与深水区相反。需采用古生物和地球化学方

法，重建不同环境因素影响下冲绳海槽古生产力演化，综合考虑陆源输入量与沉积速率变化、黑潮演化、深层水通风等过程，是解读古生产力演化与沉积氧化性耦合关系的合理方案。

（3）冲绳海槽深层水演化的环境与气候效应。NPIW 在 HS1 和 YD 等冷期加强、B/A 等暖期减弱的特征在亚北极北太平洋众多钻孔已证实，在调节过去海洋和大气 CO_2 循环过程发挥重要作用。NPIW 的“下游效应”，尤其是冰期（冷期）对亚热带北太平洋深水通风和氧化性、碳埋藏与释放等生物地球化学循环过程产生多大影响，以及这些过程在调节区域大气 CO_2 收支中发挥多大作用需进行重点评估。

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