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17.3 ka以来冲绳海槽中南部有机质来源
——对古海洋环境演化的响应

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摘　要　基于AMS^{14}C测年、有机碳、氮含量及其同位素等指标分析,探讨了冲绳海槽中南部OKT-3孔末次冰消期以来沉积物有机质来源及其对古海洋环境演化的响应。结果显示,OKT-3孔沉积物中有机质主要由中国大陆和中国台湾等陆源有机质,以及海洋自生有机质组成。末次冰消期至全新世晚期(17.3~4 ka B.P.),中国大陆源有机质贡献逐渐下降,中国台湾源有机质贡献逐渐上升,表明海平面变化、黑潮变动是该阶段有机质来源的主要控制因素。4~1.5 ka期间,陆源有机质供给变化趋势与黑潮变动不一致,表明该时期陆源输入非黑潮单一控制,还可能受季风降雨等变化影响。值得注意的是,OKT-3孔海源有机质贡献在B-A和PB时期高、YD时期低,与北太平洋地区的生产力变化相似,反映了北太平洋中层水(NPIW)对海水表层生产力的控制作用,NPIW是连通冲绳海槽与北太平洋的重要纽带。

关键词　海源有机质;陆源有机质;北太平洋中层水;冲绳海槽;末次冰消期

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0　引言

海洋是地表系统中最大的碳库,海洋碳循环在全球碳循环中起着重要的作用,调节着大气二氧化碳的含量,显著影响地球气候系统[1];边缘海面积虽然只占整个海洋面积的10%,全球海洋初级生产力贡献却超过20%[2-4],埋藏的有机碳含量占到全球海洋的90%[5],在全球碳循环中扮演着重要角色。冲绳海槽是晚第四纪以来中国东部边缘海唯一保持连续沉积记录的海区,为全球气候和环境变化研究提供了高分辨率的沉积记录[6]。

冲绳海槽沉积物中有机质由两部分组成:一是长江、黄河以及台湾贡献的陆源有机质,另一部分是海源有机质。研究发现,长江、黄河等入海径流、西部边界流黑潮,以及东亚季风系统携带大量陆源有机质进入冲绳海槽[2,7-8],陆源输入过程受黑潮、海平面及气候变化控制[2,9-10]。海源有机质贡献量与初级生产力相关,供给的营养物质增多有助于提高海水表层生产力,进而提高海源有机质的贡献[2,11]。研究发现,控制海源有机质贡献的因素与古海洋环境的变化密切相关。末次冰消期低海平面时期,长江、黄河除了贡献陆源有机质之外,还提供了大量营养物质刺激浮游植物的生长,提高初级生产力;随着海平面逐渐上升,长江、黄河物质被黑潮阻隔[7,12],营养物质的供给随之发生改变,早全新世以来,营养物质供给主要受黑潮主轴摆动控制的上升流影响[13]。

最新的研究发现,近10万年来冲绳海槽生产力变化与北太平洋中层水(NPIW)演化(通风状况)密切相关,主要通过上涌的方式将NPIW携带的营养物质输送至透光层[14]。但有关冲绳海槽海洋初级生产力与北太平洋古海洋环境演化联系的相关研究较少。

本文选取冲绳海槽中南部OKT-3孔沉积物样

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品，通过分析有机碳氮含量及其同位素等指标，结合前人研究成果，探讨末次冰消期以来冲绳海槽中南部有机质来源，探讨北太平洋中层水通风状况是否影响着冲绳海槽的海洋初级生产力。

1 材料与方法

1.1 研究材料

OKT-3岩心总长5.13 m，取自冲绳海槽中南部(26.018° N，125.282° E)(图1)，水深为1 792 m，位于黑潮主轴范围内。该孔是2012年使用中国科学院的科学一号取得的重力活塞柱样。OKT-3岩心主要由灰褐色黏土质粉砂组成，呈块状结构，沉积层序不明显，没有沉积间断和浊流沉积层。之前研究已测试6个AMS^{14}C年龄[16]，本文分析基于这六个年代控制点，样品年龄通过线性内插和外推法获得，OKT-3孔底部沉积年龄为17.3 ka，保存了末次冰消期以来古海洋环境演化的记录。

1.2 测试方法

总有机碳、总氮含量测试：以大约13 cm的间隔，共采取38个样品。取一定量的沉积物样品，加入4 mol/L盐酸至过量，反应24 h，用去离子水洗酸至中性，将样品置于烘箱内60 ℃烘干，恒重后称量，研磨成粉末，过60目的筛子。准确称量约10 mg粉末样品，用4 mm×6 mm锡杯包样，使用德国Elementar公司的Vario EL Ⅲ型元素分析仪测定沉积物中总有机质碳(TOC)、总氮(TN)，含量单位为%，测量误差均在<0.05%标准偏差范围内。

有机碳的$\delta^{13}C_{TOC}$测试：取适量上述酸化的样品，用有机元素分析仪—稳定同位素质谱仪联机(Flash EA 1112 HT-Delata V Advantages, Thermo公司)测定沉积物中$\delta^{13}C_{TOC}$，测试精度为±0.2‰。

$\delta^{13}C_{TOC}$值以PDB国际标准作为参考标准，$\delta^{13}C_{TOC}$值按照以下计算公式：

$$\delta^{13}C_{TOC}(‰)=[R(^{13}C/^{12}C_{sample})/R(^{13}C/^{12}C_{VPDB})-1] \quad (1)$$

式中：R($^{13}C/^{12}C_{VPDB}$)为(Vienna Peedee Belemnite)国际标准物VPDB的碳同位素丰度比值。

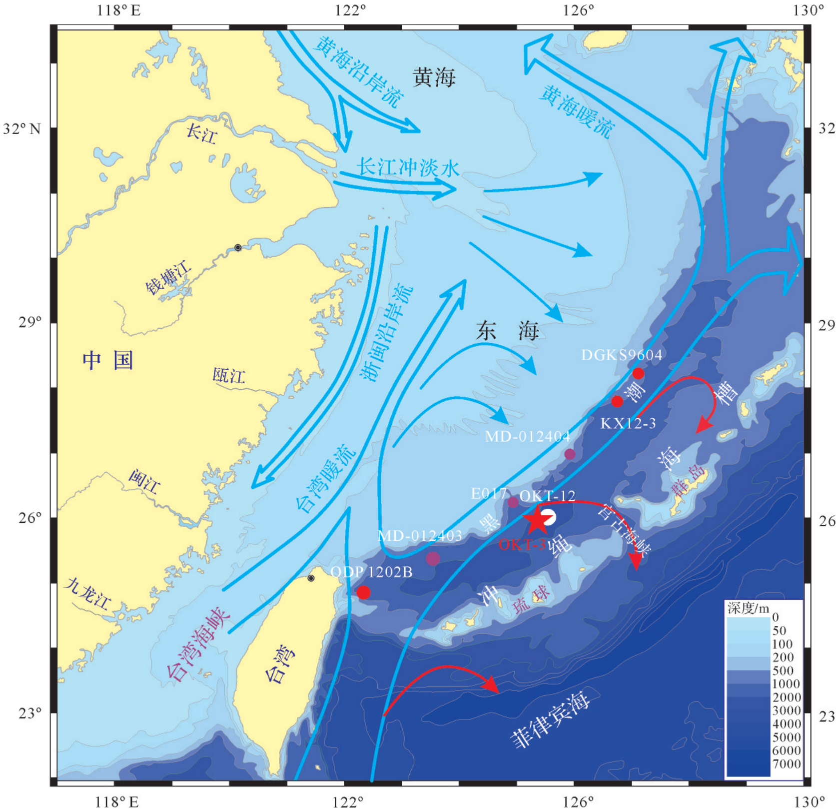

图1 东海陆架—冲绳海槽环流体系及OKT-3位置图[15]，红色曲线表示低海平面时期的黑潮分支

Fig.1 Circulation system of the East China Sea shelf, the Okinawa Trough, and location of the core OKT-3[15]; Kuroshio branch at low sea level is in red

2　结果

依据有机碳、总氮含量、C/N比值，以及$\delta^{13}C$等指标垂向变化特征，将OKT-3孔分为三个变化阶段：阶段1（17.3~11.6 ka），阶段2（11.6~4 ka），阶段3（4~0 ka）。总有机碳（TOC）和总氮（TN）变化趋势相同，在17.3~14.7 ka和11.6~9.5 ka为两个高值段，在14.7~11.6 ka和9.5~0 ka为两个低值段，整体上来说阶段1、阶段2含量高于阶段3（图2）。C/N自下往上逐渐降低，却在12.2 ka处出现一个异常的高值；$\delta^{13}C$在17.3~14.7 ka阶段逐渐增大，随后突然下降，于12.2 ka处降至最低，在11.6~9.5 ka阶段缓慢上升，9.5 ka之后数值略微降低并保持稳定（图2）。沉积速率在17.74~48.19 cm/ka之间变化[16]，自下往上沉积速率逐渐降低，在12.9~11.2 ka期间，沉积速率上升到岩心最高值48.19 cm/ka。

3　讨论

3.1　有机质含量变化的影响因素

冲绳海槽海洋沉积物中的有机质主要由陆源和海源两部分组成[2]。陆源有机质主要来自中国大陆河流（长江、黄河）以及中国台湾河流[17]。低海平面时期，东海大陆架大面积裸露，长江入海口距离冲绳海槽较近，可以输送大量陆源物质进入海槽，随着海平面上升，黑潮重新进入冲绳海槽，一方面搬运大量台湾物质，另一方面阻挡长江物质进入冲绳海槽[7,18-19]；末次盛冰期，虽然长江河口距离冲绳海槽的位置更近[18,20]，但此时，东亚夏季风较弱，降雨减少[21]，导致长江输入的陆源物质减少[22]。因此，黑潮与海平面变化及气候因素控制着陆源输入[2,9-10,23]。海源有机质的输入量受海洋初级生产力影响，如在末次冰消期低海平面时期，长江携带大量营养物质进入冲绳海槽促进海水表层初级生产力[2,11,24]；全新世以来，增强的黑潮诱导中层水产生上升流将携带的营养物质输送至表层海水同样能提高海洋初级生产力[25]，上述均会造成海源有机质输入量增加；但在北太平洋边缘海地区生产力和有机质埋藏则存在着解耦现象[26-27]，即高生产力不一定对应着高的有机质埋藏，其保存还受沉积速率、水柱的氧化状态等影响[27-30]。Li *et al.*[25]报道了冲绳海槽有机质埋藏效率受底层水通风影响：全新世的生产力虽然高于末次冰消期，但因为底层水含氧量高导致埋藏的海源有机质量明显低于末次冰消期。因此，最终埋藏在沉积物中的有机质含量是一系列因素综合作用的结果。

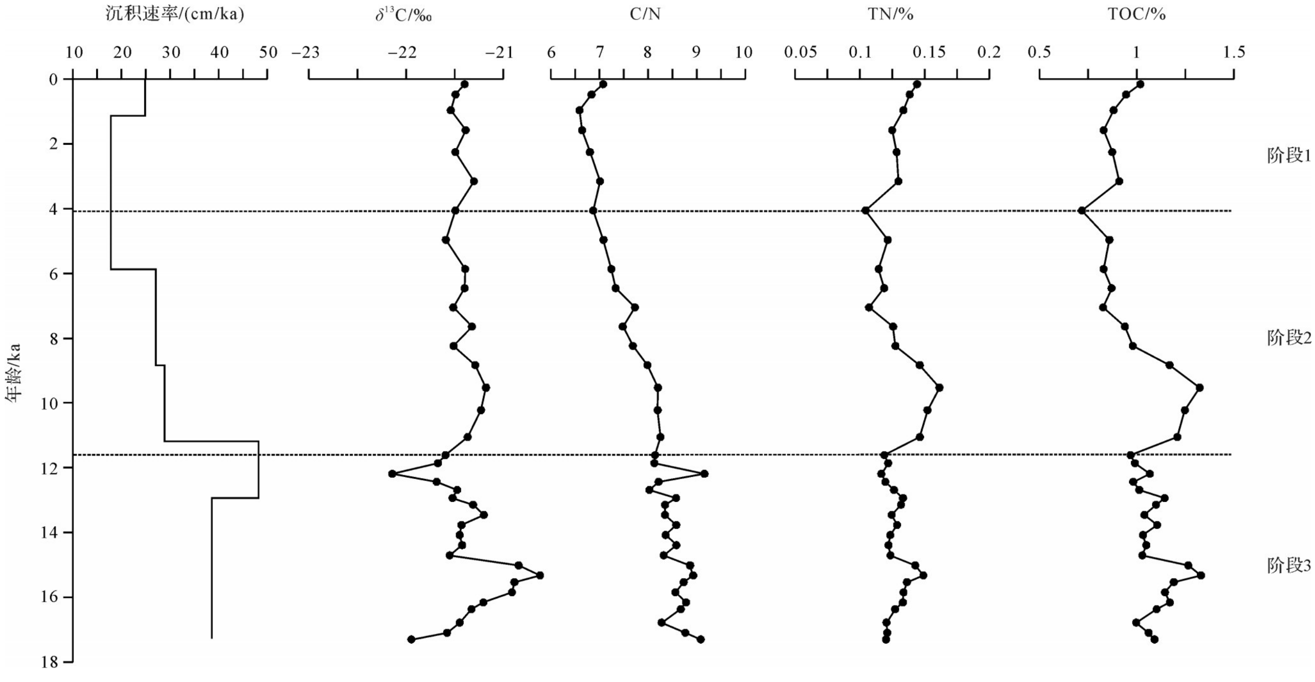

图2　OKT-3孔沉积速率、$\delta^{13}C$、C/N、总有机碳（TOC）含量、总氮（TN）含量

Fig.2　Sedimentation rates, $\delta^{13}C$ value, total organic carbon / total nitrogen (TOC/TN) ratios, TOC, and TN contents of core OKT-3

3.2　末次冰消期以来陆源有机质变化与古环境演化

为探讨冲绳海槽有机质来源及其对古海洋环境演化的响应，我们对末次冰消期以来陆源、海源有机质贡献进行定量计算。依据有机质端员供给特征，将OKT-3孔有机质分为中国大陆源、中国台湾源以及海源三个端员。以往研究证实，中国大陆源、中国台湾源以及海源三个端员δ^{13}C的端元值分别为−27‰、−25.4‰和−16‰，C/N比分别为27、5.3和7[13]。计算公式如下：

$$\delta^{13}C_{sample}=f_{dl}\cdot\delta^{13}C_{dl}+f_{tw}\cdot\delta^{13}C_{tw}+f_{m}\cdot\delta^{13}C_{m} \tag{2}$$

$$C/N_{sample}=f_{dl}\cdot C/N_{dl}+f_{tw}\cdot C/N_{tw}+f_{m}\cdot C/N_{m} \tag{3}$$

$$f_{dl}+f_{tw}+f_{m}=1 \tag{4}$$

式中：f_{dl}、f_{tw}、f_{m}分别代表中国大陆源、中国台湾源以及海源有机质在总有机质中所占比例；$\delta^{13}C_{sample}$代表OKT-3孔中的δ^{13}C，$\delta^{13}C_{dl}$、$\delta^{13}C_{tw}$、$\delta^{13}C_{m}$分别代表中国大陆源、中国台湾源以及海源有机质δ^{13}C的端元值；C/N_{sample}代表OKT-3孔中的TOC/TN比值，C/N_{dl}、C/N_{tw}、C/N_{m}分别代表中国大陆源、中国台湾源以及海源有机质TOC/TN的端元值。末次冰消期以来陆源有机质贡献变化如图3所示。

研究结果显示，末次冰消期至晚全新世（17.3~4 ka），中国大陆源和中国台湾源有机质贡献分别与长江物质、台湾物质贡献呈同步变化趋势[7]（图3）。末次冰消期，黑潮在冲绳海槽相对较弱[32]，海平面远没有达到现今位置[20]，长江入海口距冲绳海槽相对较近，长江可以携带大量物质进入海槽，导致此阶段中国大陆源有机质贡献相对最高；此时，黑潮弱的搬运能力致使冲绳海槽台湾物质含量低[18,33]，因此中国台湾源有机质贡献也相对低。全新世早期以来，海平面逐渐上升至现今水平，黑潮逐渐加强[16,33]。黑潮的加强一方面阻挡长江物质进入冲绳海槽[2,16]，长江源携带的有机质也随之减少；另一方面，黑潮搬运能力的不断增强致使台湾源有机质贡献逐渐增大[12,19]。

值得注意的是，全新世晚期4~1.6 ka期间，即使长江、台湾沉积物供给变化只有两个数据点控制，依然可以清楚地看出变化趋势：中国大陆源有机质贡献与长江沉积物供给、中国台湾源有机质贡献与台湾沉积物供给变化不一致，两两呈相反变化趋势（图3）。台湾源有机质没有随黑潮搬运能力的减弱而减少，可能是因为6.5~4.5 ka期间，台湾气候湿润、植被茂盛[34]，在4.5~1.5 ka期间增强的台风导致前阶段堆积的有机质强烈侵蚀搬运[35]，使中国台湾源有机质贡献并未下降；中国大陆源有机质的贡献没有与长江输入同步增加，可能与此时期东亚夏季风减弱、气候相对干旱、限制古土壤发育，降低了陆源输入中的有机质含量有关[36-38]。

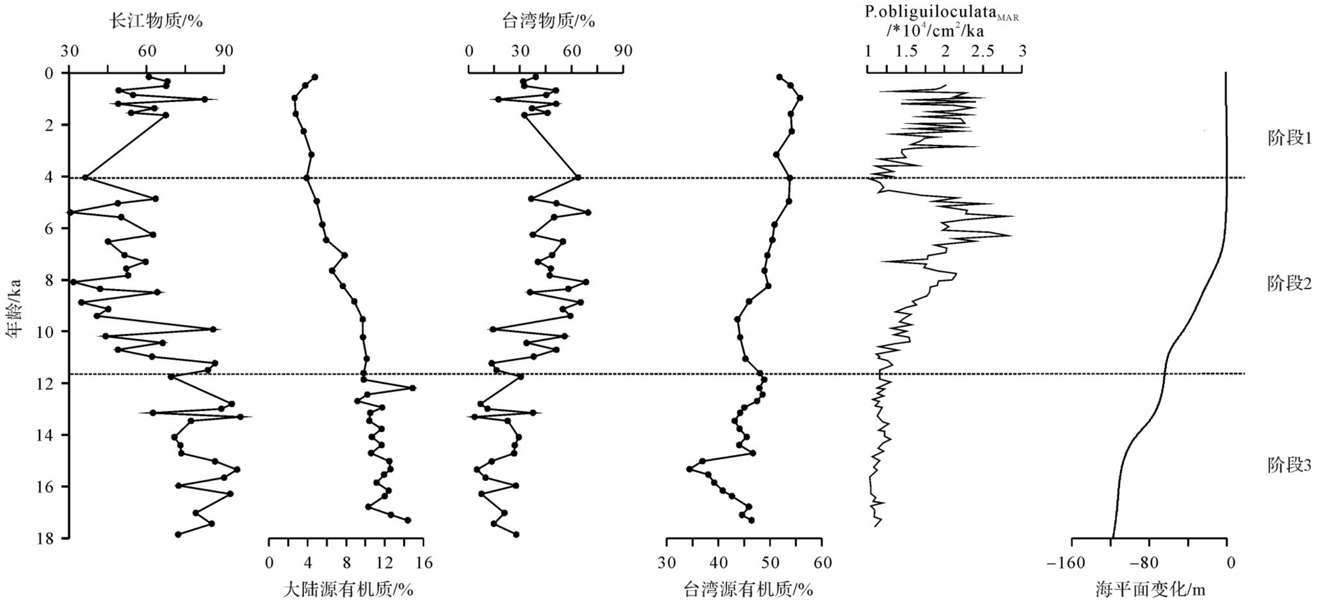

图3　OKT-3孔末次冰消期以来陆源有机质贡献变化

大陆源、台湾源有机质贡献对比长江、台湾物质[7]、海平面变化[20]、黑潮指示种*P. obliguiloiata*沉积速率[31]

Fig.3　Terrestrial organic matter contribution change from core OKT-3 since the last deglaciation

Contribution of mainland organic matter and Taiwan organic matter with the contributions of Changjiang and Taiwan derived from clay minerals[7], sea level changes[20] and accumulation rate of the Kuroshio current indicator *P. obliguiloculata*[31]

3.3　海源有机质演化对北太平洋中层水（NPIW）的响应

物理海洋观测发现，现代的冲绳海槽深层水主要来自北太平洋中层水（NPIW：300~800 m）和南海中层水（SCSIW：400~1 000 m）[39]。两股中层水通过台湾东部水道（水深755 m）和琉球中部的宫古凹陷（水深1 100 m）进入冲绳海槽，成为冲绳海槽中深层水的主要水源[39]。在冲绳海槽中部，北太平洋中层水（NPIW）为冲绳海槽透光层营养物质的主要来源[14,40]，NPIW通过宫古海峡产生上升流（图4），将携带的营养物质输送至表层海水[14,39-41]，因此NPIW的变化可能是影响海洋初级生产力的重要因素之一。

前人对北太平洋、白令海、鄂霍茨克海的研究发现，B-A和PB时期海洋初级生产力出现峰值，YD时期生产力下降[42-47]。因此，一些学者认为北太平洋海洋初级生产力变化和NPIW的通风状况有密切联系[14,48-49]。研究发现，太平洋亚北极冰期时海水表层温度与北大西洋、格陵兰岛同步降温，鄂霍茨克海、白令海形成海冰，表层海水密度增加，促进NPIW形成[50]；同时，冰期太平洋热带辐合带南移，降雨减少进一步增加表层海水密度[51]，NPIW通风状况增强。因此，冰期时NPIW向深部扩展，阻碍营养物质丰富的北太平洋深层水向上运输，使得北太平洋大部分海区生产力降低。暖期时，如B-A和PB期间，NPIW通风减弱，使得北太平洋深层水上涌海水表层生产力提高[44,48-49,52-53]。此外，暖期时东亚夏季风增强、径流量加大[21]，大量陆源营养物质（铁元素等）进入鄂霍茨克海进而至北太平洋，也是海水表层生产力提升的重要原因[54]（图5）。OKT-3孔海源有机质含量呈现明显的阶段性，末次冰消期早期（17.3~15 ka）、Bølling-Ållerød期（B-A）和Pre-Boreal期（PB）时期呈现三个高值段，Younger Dryas期（YD）和全新世期间海源有机质的贡献量呈现低值。OKT-3孔海源有机质变化与北太平洋生产力变化趋势相同，表明NPIW可能起关键作用，充当传送带，将营养物质运送至冲绳海槽，影响该区域初级生产力。

OKT-3孔海源有机质在B-A和PB时期出现两个高值，与冲绳海槽中部记录的δ^{15}N峰值出现的时间一致[55]，与北太平洋在B-A和PB时期普遍存在的δ^{15}N峰值的时间同样一致[56,59-61]（图5）。研究发现这两个时期大量冰雪融水注入鄂霍茨克海和白令海，夏季风降雨增强导致河流输入量增加，降低表层海水密度，抑制NPIW形成[47,54]，使得北太平洋深层水上涌、海水表层生产力提高[44,48-49,52-53]。高海洋初级生产力和弱底层水通风导致增强的水柱反硝化作用[55]，出现δ^{15}N峰值，这种情况在水体含氧量小于5 μmol/L的环境中最容易发生[62]。OKT-3孔海源有机质在B-A和PB阶段升高，与北太平洋δ^{15}N呈现相同的变化趋势（图5），可能表明冲绳海槽和北太平洋地区古海洋环境变化存在关联，NPIW是连通冲绳海槽与北太平洋的重要纽带。虽然OKT-3孔在B-A和PB时期海源有机质呈现高值的时间与冲绳中部以及北太平洋一致，但只有PB时期出现峰值，对比较

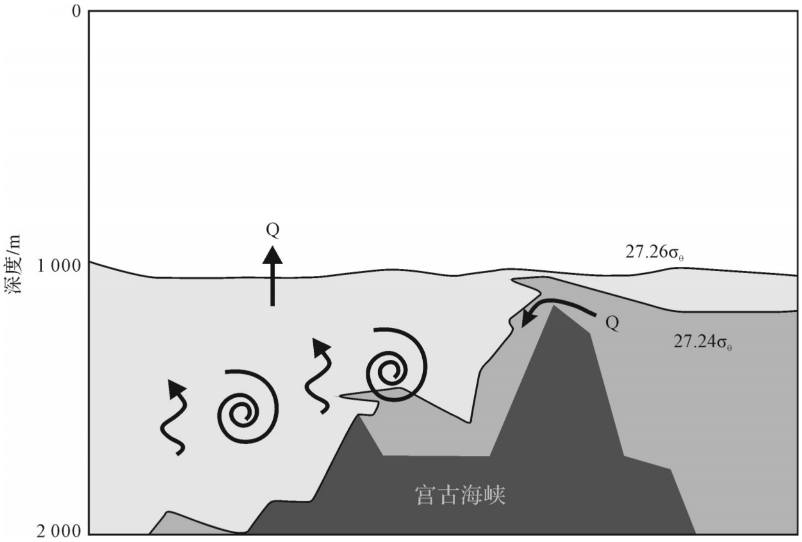

图4　北太平洋中层水（NPIW）通过宫古海峡形成上升流示意图[39]

Fig.4　The schematic view of upwelling of North Pacific Intermediate Water (NPIW) through the Kerama Gap[39]

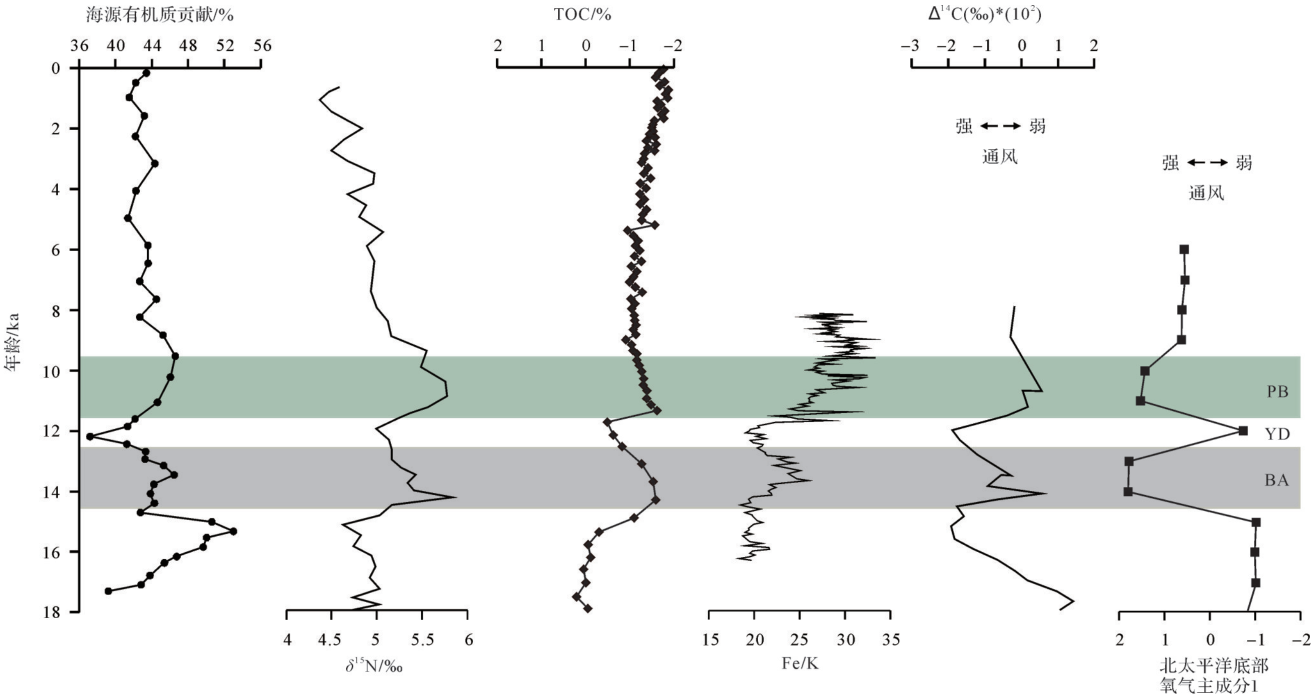

图5 OKT-3孔海源有机质对北太平洋中层水的的响应

黑龙江输入鄂霍茨克海的微量营养元素[54]、OKT-3孔海源有机质贡献、冲绳海槽中部MD-012404孔反硝化作用[55]、鄂霍茨克海南部TOC含量变化[56]、北太平洋中层水通风指标Δ^{14}C[57]、北太平洋底部氧气主成分1[58]对比

Fig.5 Response of marine organic matter to NPIW from the core OKT-3

Fe/K ratios as an indicator for Amur River-derived input of micronutrients into OSIW[54], contribution of marine organic matter in OKT-3 (this study) with water-column denitrification indicator δ^{15}N in the core of MD-01240[55], TOC content in the southern Okhotsk Sea[56], NPIW indicators of Δ^{14}C[57], and North Pacific benthic O_2 Principal Component 1[58]

好，B-A时期并没有出现峰值。可能是因为海平面较低，陆源物质大量输入对海源有机质造成稀释；或者可能是西北太平洋地区在B-A时期高的营养物质利用效率，造成NPIW进入冲绳海槽时携带的营养物质减少[63]。因此，需要开展更多的工作探讨末次冰消期以来冲绳海槽和北太平洋地区生产力变化的相关性，NPIW在其中扮演的角色，以及NPIW从起源地至冲绳海槽的过程中，携带的营养物质消耗和补给（深层水）的关系。

4 结论

通过对OKT-3孔有机碳氮含量、碳同位素以及碳氮比值的研究，探讨了末次冰消期以来冲绳海槽中南部有机质来源及其对古海洋环境演化的响应，得到如下主要结论：

（1）OKT-3孔的C/N比值与沉积速率变化趋势相同，自下向上逐渐降低；TOC和TN的变化趋势相同，在17.3~14.7 ka和11.6~9.5 ka为两个高值段，在14.7~11.6 ka和9.5~0 ka为两个低值段。

（2）17.3~4 ka中国大陆源有机质贡献逐渐下降，中国台湾源有机质贡献逐渐上升，表明海平面变化、黑潮变动是该阶段有机质来源的主要控制因素。值得注意的是，4~1.5 ka期间，陆源有机质供给变化趋势与黑潮变动不一致，表明该时期陆源输入的影响因素非黑潮单一控制，还可能受季风降雨等变化影响。

（3）OKT-3孔海源有机质贡献在B-A和PB时期出现两个明显的高值，YD时期含量明显下降，与北太平洋地区记录的生产力变化一致，表明北太平洋中层水（NPIW）可能作为传送带，通过宫古海峡产生上升流，将携带的营养物质运送至冲绳海槽海水表层，影响其海洋初级生产力；此外，OKT-3孔海源有机质在B-A和PB阶段与北太平洋δ^{15}N峰值出现的时间一致，进一步表明冲绳海槽和北太平洋地区古海洋环境变化可能存在关联，NPIW是连通冲绳海槽与北太平洋的重要纽带。

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Organic Matter Sources in the Middle Southern Okinawa Trough since 17.3 ka: A response to paleoenvironmental evolution

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Abstract: A piston core (OKT-3) is collected from the middle southern Okinawa Trough (26.018 °N, 125.282 °E) at a water depth of 1 792 m, providing depositional records since 17.3 ka. Total organic carbon, total nitrogen content, and organic carbon isotope data in this study, combined with previous data, have been analyzed to discuss the organic matter source and its response to paleoenvironmental evolution since the last deglaciation. The organic component of core OKT-3 is composed of terrestrial and marine organic matter. Terrestrial organic matter is mainly derived from the Changjiang and Taiwan Rivers, which is controlled by sea level change, the Kuroshio Current, and climate variation. The Changjiang-sourced organic matter of core OKT-3 showed a decreasing trend during 17.3~4 ka B.P., consistent with the decreasing contribution of Changjiang-derived detrital sediments. In contrast, the Taiwan-sourced organic matter, which is transported by the Kuroshio Current, showed an increasing trend. It is worth noting that the Changjiang-sourced and Taiwan-sourced organic matter did not exhibit synchronous changes with the Kuroshio Current during 4~1.5 ka B.P., which may be controlled by summer monsoon. Marine organic matter from core OKT-3 showed two peaks during Bølling-Ållerød and Pre-Boreal periods, with low values during the Younger Dryas period. Consistency between marine organic matter and primary productivity suggests that North Pacific Intermediate Water (NPIW) acts as a conveyor belt transporting nutrient from the North Pacific to the Okinawa Trough. NPIW passes through the Kerama Gap to the Okinawa Trough and carries nutrients to the surface water by way of upwelling. The consistency between marine organic matter and δ^{15}N further suggests there may exist a link between the Okinawa Trough and the North Pacific, and NPIW may play an important role.

Key words: marine organic matter; terrestrial organic matter; North Pacific Intermediate Water (NPIW); Okinawa Trough; last deglaciation