日本海中部 60 ka 以来的风尘沉积对西风环流演化的指示

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摘要 对位于西风环流下风区日本海中部LV53-23岩芯沉积物的粒度特征进行了研究, 重建了日本海末次冰期(~60 ka)以来的西风环流演化历史和空间变化规律. 结果显示, 岩芯沉积物以粉砂为主且粒度频率分布曲线多呈单峰分布, 与现代日本黄砂和前人报道的邻近区域的岩芯粒度特征一致, 具有典型的风尘沉积特征. 众数粒组-粉砂组分的中值粒径分析表明, 粉砂组分中值粒径可以用作岩芯沉积反映西风环流的替代性指标. 在亚轨道及千年尺度上, 粉砂组分中值粒径在MIS 3期的冰阶-间冰阶千年尺度旋回与西风环流密切相关: 冰阶时, 粉砂组分中值粒径增大, 这与西风急流轴较长时间位于青藏高原南部, 西风环流影响范围变大, 风速增强, 能携带更多近源的蒙古戈壁-中国东北沙地风尘至日本海有关; 间冰阶时, 粉砂组分中值粒径减小, 这是由于西风急流轴位于青藏高原北部, 携带更多远源的塔克拉玛干沙漠风尘至日本海. 而在轨道尺度上, 末次盛冰期时粉砂组分中值粒径的稳定低值与北半球65°N日照辐射量良好对应, 表明北半球日照辐射量和中高纬温度梯度差对西风环流远距离输运粉尘起到重要作用, 盛冰期时西风急流轴受北半球冰盖扩张影响显著南移导致西风环流范围也随之南移, 从而对日本海40°~50°N上空西风影响减弱.

关键词 风尘沉积, 粉砂组分中值粒径, 敏感粒级, 西风环流, 日本海

在末次冰期, 千年尺度的剧烈气候波动记录在格陵兰冰芯^[1]和北大西洋深海沉积中^[2]. 在一些特殊的边缘海如圣巴巴拉海盆^[3]、委内瑞拉的卡里亚科^[4]、阿拉伯海^[5]及日本海^[6]存在明暗交替的纹层沉积现象, 这些半远洋沉积具有千年尺度振荡特征, 被认为与D-O旋回有关^[3~7]. 西风环流是传递北大西洋经向环流 (Atlantic Meridional Overturning Circulation,

AMOC)变化信号到北太平洋地区的重要纽带^[8], 西风环流千年尺度变化对东亚季风区雨带进退以及西风控制区的湿度变化具有重要意义^[9~11], 因而认识西风环流演化对理解全球变化具有特殊意义.

已有观测揭示了现代西风急流轴的季节转换特征^[12]及其空间变化规律^[13], 但末次冰期以来的西风环流演化过程尚不清晰. 前人在北太平洋对西风环

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流进行过相关研究,但受限于低沉积速率,大多集中于重建亚洲内陆干旱化历史^[14]。日本海是北太平洋中纬度地区最大的边缘海^[15],位于西风环流和东亚冬季风下风区,加之日本海又没有大河注入^[15],沉积物中风尘物质的贡献较大^[16],因而不只记录了本身区域性的环境演化,同时也可反映亚洲大陆环境和气候变化的信息。前人对西风环流演化历史研究主要集中在日本海南部岩芯^[10,16~18],而缺少研究报道的日本海中部大和海脊,由于被郁陵海盆、大和海盆和日本海盆隔离(距离陆地最近也有400 km,距最近的粉尘源区科尔沁沙地有至少1000 km^[19]),本州岛小河流物质很难搬运如此长的距离,因此推测相较南部的MD01-2407站位(图1),大和海脊沉积物受河流、洋流携带物质影响更小,更多陆源碎屑物质由风搬运而来,更适宜反演西风演化。而且西风环流的冰阶-间冰阶的模式转换^[17]会导致西风所携带的粉尘源区的范围变化,日本海沉积中部记录的缺失导致我们难以全面地认识西风环流演化历史,开展纬向对比研究对探索西风环流时空变化具有重要意义。本文利用加权平均方法对采自日本海大和海脊的LV53-23柱状沉积物岩芯进行了粒度分析,计算了粉砂组分中值粒径,通过与日本海南部岩芯、北太平洋2个近似纬度的岩芯对比,揭示了西风急流轴南北摆动及其影响范围变化对海区沉积物粉砂组分中值粒径变化的影响,并探讨了60 ka以来的西风环流在轨道和千年尺度上演变过程和空间变化规律。

1 材料和方法

1.1 研究材料

LV53-23岩芯(40°18'N, 134°19'E, 水深1282 m)是国家海洋局第一海洋研究所于2010年实施中俄日本海联合调查航次期间,利用俄罗斯“拉夫任捷耶夫院士号”科学考察船在日本海中部大和海脊北部采集的柱状沉积物岩芯。岩芯长7.53 m,按1 cm间距分样,共采集样品746个。该岩芯位于亚极地锋(subpolar front, SPF)北部,春季锋面两侧30°~40°N与40°~50°N上空西风环流风速显著不同^[18],锋面位置受西风急流控制^[20]。

1.2 分析方法

取适量沉积物放入小烧杯中,加入15 mL 15%的

双氧水浸泡12 h去除有机质,然后加入5 mL 10%的稀盐酸浸泡12 h去除碳酸盐,再用去离子水洗盐。超声振荡分散后上机测试,所用仪器为Malvern 2000型激光粒度仪,测量范围为0.02~2000 μm ,粒度分辨率为0.01 Φ ,采用Folk沉积物分类法^[21]划分沉积物类型。

粉砂组分中值粒径此前已经被认为其可作为一种西风代用指标^[16,17],日本海南部MD01-2407岩芯距离陆地较近,电子自旋共振(electron spin resonance, ESR)数据显示黏土组分更接近本州岛河流特征, Nagashima等人^[16]为消除来自日本岛弧的影响,分离出更接近亚洲内陆粉尘特征的粉砂组分^[22],进而将其中值粒径的变化作为西风信号。LV53-23岩芯中粉砂组分为众数粒组,因此本文是将激光粒度仪中导出的粉砂组分各粒级含量加权平均至100%,使用GRADISTAT^[23]软件计算而得。本文还采用粒级-标准偏差方法计算敏感组分^[24,25]以检验粉砂组分中值粒径的环境敏感程度。粒级-标准偏差曲线反映了不同层位沉积物在同一粒级的含量变化,在同一粒级含量变化越大,标准偏差也就越大,而标准偏差较大的粒级即为对沉积环境变化敏感的粒级组分,即环境敏感粒级。

1.3 年代框架

LV53-23岩芯的年代框架引自文献[26],其年龄控制点由6个AMS¹⁴C年龄、1个火山灰标志层和DOI(间冰阶,被认为对应日本海深色纹层^[6],其年代取自NGRIP冰芯^[1])事件确定,岩芯底部年龄为75 ka,岩芯平均沉积速率为13 cm/ka,最高沉积速率出现在间冰阶DOI 14时,达30 cm/ka,最低沉积速率出现在全新世。在129~131 cm处的火山灰层年龄为29.37 ka的A-Tn^[27]火山灰,其他年龄控制点则详见文献[26]。

2 结果

2.1 粒度特征

LV53-23岩芯沉积物类型绝大部分以粉砂为主,含少量砂质粉砂。粉砂组分(4~63 μm)含量为58%~84%,平均值为75%,砂含量变化则较大。在A-Tn火山灰层^[27]处(129~131 cm),砂含量达到40%,粒度频率曲线峰值位于88~148 μm ,属于砂质粉砂,除本岩芯外,它还被记录于日本海南部的MD01-2407岩芯^[28]和KCES-1^[29~31]中。剔除火山灰后,砂含量为0~13.3%,

图1 日本海位置及大气环流模式示意图. (a) 冬季; (b) 夏季. 红色五星为本文研究站位, 其余为引用站位. 浅红色为 200 hPa 西风环流影响区域, 深红色为西风急流轴位置. 黑色实线为夏季风, 绿色实线为冬季风, 蓝色虚线为亚极地锋, 黑色虚线为夏季风界线. 底图参考Nagashima 等人^[17]编绘

Figure 1 Maps showing atmospheric circulation patterns over East Asia in winter (a) and summer (b) modified after Nagashima et al.^[17]. Light red arrows show areas where westerly jet (200 hPa) occurs frequently, dark red arrows show the main axis of surface wind of East Asian summer monsoon (black arrows), winter monsoon (green arrow) subpolar front (blue dotted line) and location of core LV53-23 (red star) are also shown, dark dotted line shows the boundary line of East Asian summer monsoon

其高值多分布于全新世, 黏土组分含量介于35%~15%, 平均值为24%. 沉积物平均粒径变化范围6.1~7.3 Φ (14.075~6.02 μm), 平均值为6.88 Φ ; 分选系数介于1.2~2.1, 平均值为1.5, 属于分选较差; 偏态介于-1.6~1.8, 平均值为0.99, 为正偏; 峰态介于1.7~2.7, 平均值为2.05, 沉积物频率分布曲线为单峰, 宽峰态. 该岩芯众数粒组为粉砂组分, 但从众数值向两端变化不同, 向粗粒端曲线平滑而陡峭, 向细粒端坡度相对较缓, 这与风尘堆积形成的黄土样品粒径分布具有相似性^[32]. 依据Gorbarenko等人^[26]建立的年代框架可以看到(图2), 在DOI 8, 12, 14三次持续时间较长

的间冰阶事件期间, 显著发育的深色纹层都伴随显著升高的沉积速率, 而在全新世沉积速率达到最低值; 在其余时段, 沉积速率与之前报道的日本海平均沉积速率(5~20 cm/ka)^[28,33]接近, 也表明了年龄框架的可靠性.

2.2 粒级-标准偏差曲线

沉积物粒度的频率分布曲线能直观地反映其所包含的粒度组分(单组分或多组分)信息, 通过求解不同组分的分布范围和相对量, 从而实现追索单个沉积组分对应的来源和运输方式^[34]. 从LV53-23岩芯不

图2 LV53-23 岩芯深度-年龄转换模式、沉积速率和粒度参数变化曲线图。实心圆为 ^{14}C 和A-Tn火山灰(图中红色阴影)定年,三角为事件定年,黄色阴影为长持续时间DOI事件,蓝色阴影为末次盛冰期

Figure 2 Depth-age relationship estimated deposition rates and grain-size parameter of core LV53-23. Solid circles, dating of ^{14}C ; red bar, A-Tn tephra layer; triangle, DOI and Heinrich events; yellow bar, long term DOI events; blue bar, Last Glacial Maximum

同层位粒度频率分布曲线可以看出,以单峰特征为主。

利用边缘海沉积物的敏感粒级重建古气候、古环境取得了一系列成果^[25,34,35],但海洋沉积物敏感粒级所记录的时间序列大多为百年尺度或中全新世以来的冬季风变化^[34,36~38],在此我们利用敏感粒级组分来进一步区分粒级组分的个数及其粒级范围。依据沉积物中各粒级组分含量来选取敏感粒级组分的方法主要有利用端元粒度模型^[39]和粒级-标准偏差^[24],这两种方法反映的粒级组分相同^[25]。本文依据粒级-标准偏差的变化来提取LV53-23岩芯的敏感粒级组分。图3(a)显示了粒级组分变化较大的2个敏感粒级组分,分布范围分别为3.9~9.29, 18.58~26.28 μm ,分别标记为组分1和2,组分1和组分2存在明显的反相波动变化,这也与在中国边缘海得到的规律相同^[25,34]。

3 讨论

3.1 日本海风尘沉积与西风环流的关系

早春3, 4月,中高纬地区温度梯度差巨大^[41],此时西风急流轴开始间歇性北移,然后束窄在青藏高原北部^[12,13],诱使本已衰退的西伯利亚冷空气南下至沙漠地区,引发大范围沙尘暴,但此时西风急流轴

大部分时间依然位于青藏高原南部^[12,13]。在地表垂直气流的作用下,10%的尘暴满足携带粉尘进入对流层的条件,从而实现远距离传输^[42],如1998年4月18~20日的特大沙尘暴^[43],近地表风速达30 m/s,远超粉尘排放的关键风速(>6.5 m/s)^[44,45],成为西风环流风尘的源区之一^[41];而塔克拉玛干沙漠由于四周都是海拔在5000 m左右的天山、昆仑山,因此来自塔克拉玛干沙漠的粉尘只能通过西风携带^[46],这与Shi和Liu^[47]对日本海风尘物质来源的模拟结果相符。

尽管Matsuki等人^[19]在2500和4000 m以上高空区域都观测到风尘气溶胶,Shi和Liu^[47]通过模拟也发现蒙古戈壁风尘可以通过850和500 hPa高空传输到日本本州岛南部,但由于春季时冬季风和西风环流具有近乎一致的风向,加之抵达日本的黄沙多具有双层结构,4000~8000 m高空含量达到峰值^[48],很难判断风尘物质是单独由冬季风携带而来。基于中国北方沙尘暴及日韩黄沙(Kosa)峰值日期的不匹配,宋连春等人^[49]认为日本黄沙主要是由西风环流携带而来,这与Nagashima等人^[18]通过判定现代黄沙主要源区为西北沙漠和北方沙漠,进而认为黄沙是通过西风环流携带的观点一致。这与LV53-23的单峰粒径频率曲线十分吻合(图3(b)),而与之之前通过Weibull函数分

图3 LV53-23岩芯标准偏差随粒级变化曲线(a), LV53-23, LV53-18^[40]和石川、札幌春季^[18]黄沙粒度频率分布曲线(b). 1和2分别表示2个变化比较大的敏感粒级组分

Figure 3 Result of grain-size analysis in core LV53-23. (a) Diagram of standard deviation/grain-size classes, numbers 1–2 represent the two grain size components respectively, and the italic numbers indicate boundary size for each component (b) grain-size distribution curves of LV53-23, LV53-18^[40] and typical Kosa^[18]

离出西风 and 冬季风两种物质来源的黄土高原^[50]以及韩国济州岛玛珥湖风尘沉积^[51]的近双峰粒度频率分布曲线很不一样。而单峰曲线并不满足分离出两种传输方式的特征, 因此可以推断是单一传输方式主导。与现今日本春季黄沙(石川、札幌)、日本海南部沉积物的粒度频率分布曲线一致^[16], 两者均被认为是由西风环流携带而来^[17,18]。位于日本海北部陆坡的LV53-18岩芯距陆地仅30 km^[33], 其陆源物质可能来自黑龙江(阿穆尔河)输入、冬季风及西风环流的搬运^[40], 且其粒度频率分布曲线表现出多峰特征, 这也证明其具有多种物质来源。

LV53-23岩芯粉砂组分中值粒径介于9~15 μm , 平均值11.4 μm ; 其北部的LV53-18岩芯粒径在12~28 μm 之间, 平均为18 μm ^[33,40]; 而其南部的MD01-2407岩芯则介于6.9~9.2 μm 之间, 平均值为8.2 μm ^[16], 可

见日本海沉积物粉砂组分中值粒径呈现出从西北向东南逐渐减小的趋势, 这与其距亚洲内陆距离越来越远以及MD01-2407距本州岛河流更近有关。孙东怀等人^[50]分离出黄土中由西风带来的细粒组分的分布范围为4~20 μm , 也说明日本海中部和南部风尘物质主要与西风环流有关。

3.2 60 ka以来西风环流演化历史

北半球夏季65°N太阳辐射量的变化, 可以指示高纬地区夏季温度的变化, 不仅反映在冰芯中的氧同位素记录^[1], 还通过控制夏季冰雪融化速率影响劳伦斯冰盖高度, 改变西风急流的路径, 影响北大西洋海冰的扩展及AMOC强弱的变化, 进而在全球范围出现冰阶(冷, AMOC弱)-间冰阶(暖, AMOC强)千年尺度旋回^[52,53]。本文将LV53-23的粉砂组分中值粒径

变化曲线与NGRIP冰芯氧同位素曲线^[1]进行对比,从旋回性明显的DOI 17(59.2 ka)开始,探讨西风环流对Marine Isotope Stage (MIS) 3期冰阶-间冰阶(千年尺度)和冰期-间冰期(轨道尺度)的响应过程。

(i) 冰阶-间冰阶尺度. Nagashima等人^[17]通过对比MD01-2407岩芯沉积物与亚洲内陆九大沙漠表土样品^[54]的ESR和结晶度数据指出:冰阶时,MD01-2407沉积物粉砂组分ESR(10~14.5)更接近于蒙古戈壁(12~13.6),证明西风急流在冰阶时更接近于现今冬季西风环流模式,主轴位于喜马拉雅山南部,其影响范围达到蒙古戈壁,携带了更多蒙古戈壁及中国东北地区沙地等更近源区的粉尘,且西风急流此时风速更高,沉积物粒度增大^[17];间冰阶时,MD01-2407沉积物粉砂组分ESR(9~12.5)倾向于塔克拉玛干沙漠(6.6~9.2)与蒙古戈壁(12~13.6)粉尘的混合产物,这与现今的冬季-夏季西风季节转换类似,而风尘物质粒度一方面受西风环流束窄影响(图1(b)),对蒙古戈壁影响减弱^[13,17],加之此时中高纬温度梯度差变小,抑制了高纬气旋的南下,造成风沙活动减少,来自近源的粉尘减少;另一方面,温暖的气候和大量冰融水会促进植被发育,对沙地、沙漠起到固定作用,减少了粉尘的“源”,沉积物粒度亦随之减小。

每一次D-O旋回被认为可分为3个阶段^[55]: (1) 一个相对逐渐变冷的过程,持续600~2000 a温度下降5~10℃; (2) 在300~700 a内下降5~10℃,温度剧烈下降,达到冰期的最低温度,称为冰阶; (3) 非常迅速地升温,每个世纪上升3~5℃,称之为间冰阶。日本海沉积物中来自蒙古戈壁风尘增多,粉砂组分中值粒径和ESR在冰阶处于高值,在冰阶临近结束时,中值粒径和ESR快速降低(对应阶段(3),图4蓝色阴影),在间冰阶初期达到极小值,此后慢慢增大(对应阶段(1)),后经历一次快速增大,达到峰值(对应阶段(2)),过程类似D-O旋回^[17,26,55]。本文将LV53-23岩芯、MD01-2407岩芯^[17]与冰芯GISP 2^[56]进行比较,由于我们的年代框架是比对MD01-2407确立间冰阶事件^[28],引用NGRIP冰芯的DOI年代数据^[1]建立的,所以同时引用Nagashima等人^[17]中DOI与GISP 2冰芯^[56]的DOI对应关系及NGRIP冰芯氧同位素^[1],发现在间冰阶持续时间较长的DOI 8, 12, 14与16时段, LV53-23粉砂组分中值粒径与NGRIP冰芯近乎同相位变化,与MD01-2407岩芯也呈现相似变化趋势,虽然因为MD01-2407所采用¹⁴C测年在此时接近或超过年代上

限造成的误差较大,致使两根岩芯之间在45 ka之前存在相位差,但依然可以表明LV53-23粉砂组分中值粒径是存在明显的千年尺度的变化趋势。其中LV53-23岩芯粒度变化幅度较MD01-2407更大,根据数值模拟结果^[47]推测是由于其所处纬度更高,接受来自蒙古戈壁-中国东北沙地的物质更多一些,所以导致沉积物粒度变化幅度大。Itaki等人^[57]在白令海应用生源碳酸钙指标识别出DOI 8, 12, 14, 17事件, Harada等人^[58]发现鄂霍茨克海的高海表温度(sea surface temperature, SST)在DOI 8, 12, 14持续时间较长,证明西北太平洋边缘海对这几次事件都有记录和响应。因此,可以认为西风急流的千年尺度的转换与DO旋回具有良好的相关性,继而表明MIS 3期日本海中部沉积物中的千年尺度风尘物质粒径变化主要受西风急流轴南北摆动及其影响范围变化控制。

(ii) 冰期-间冰期尺度. LV53-23岩芯的粉砂组分中值粒径显示末次盛冰期(Last Glacial Maximum, LGM)时处于稳定低值,自H 1(始于17.5 ka)迅速变大,在B/A暖期达到峰值, B/A后期明显变小。进入全新世之后,粉砂组分中值粒径与敏感组分含量变化趋势并不一致,粉砂组分中值粒径在早全新世有所下降,随后逐渐稳定,而敏感组分含量则在晚全新世有所下降,其余阶段保持稳定。粉砂组分中值粒径在B/A时期及全新世大暖期(HO)初期达到高值,这与代表近地表冬季风风力的古浪黄土记录相反^[8]。

影响西风环流所携带的风尘粒径有3个因素: (1) 物质供给,源区内沉积物是否丰富^[59]; (2) 物质可搬运程度^[59],指能否形成特大沙尘暴将地表风尘扬升至西风环流区,进而携带至日本海,包括源区地表持续风速、源区海拔、地表裸露程度(包括土质干燥松散程度、地表裸露程度、土壤解冻时间^[18])、西风环流范围(近源风尘到日本海多少)等; (3) 风尘沉降方式,干降或湿降与降水量有关。

Lu等人^[60]认为我国北方在LGM时期处于冷、干、多风环境,古浪黄土等记录均显示此时冬季风强盛^[8],表明此时物质供给和地表持续风速是充分的。条件(2)则反映了风尘的整个扬升传输过程,现今我国北方沙尘暴主要由西风急流轴春季间歇性北移诱发^[41],但目前还缺少能直接反映末次冰期以来西风急流轴位置变化的指标。从间接指标来看,西风通过控制的亚极地锋、太平洋极地峰、欧亚大陆极地峰位置^[20]和黑潮及其延伸体(如MD01-2421岩芯所在位置)与

图4 30~60 ka期间LV53-23, MD01-2407^[17]粒径变化与冰芯^[1,56]对比图. 黑色方形为年龄控制点, 较大的为¹⁴C, 较小的为DOI和氧同位素事件点^[26,28]

Figure 4 Temporal variations in median grain size of silt fraction for core LV53-23, MD01-2407^[17] and their comparison with GISP 2^[56] and NGRIP^[1]. Age-control datums for part of core LV53-23, larger squares represent ¹⁴C^[26,28], smaller represent dark or light layer and oxygen isotope events

亲潮的相对位置^[61]来改变降水、温度等气候要素^[62]影响日本气候, 最为典型的就是日本梅雨的起始时间和持续时间^[9], Ono和Irin^[62]通过比较LGM与现今日本列岛山脉冰川位置、永久冻土和针叶林分布范围, 认为MIS2期西风急流一直处于青藏高原的南侧, 而通过比较33°, 35°和37°N三个位于现今黑潮区的岩芯沉积物中指示黑潮特征的生物种比例, 发现LGM时西风急流轴南移3°~5°左右^[62], 这与MD01-2421记录的黑潮主轴位置^[61]在LGM时显著南移相一致; Railsback等人^[63]在现今季风控制的半干旱区发现了仅在冰盛期时生长的石笋, 认为这是由于冰盛期时西西南移和夏季风的衰退, 西风控制区扩大, 西风带

来的水汽促进了石笋的生长. 尽管LGM时期地表冬季风速加快, 黄土粒径变粗^[8], 但西风急流轴不再像MIS3期间歇性的北移至粉尘源区^[17], 且中高纬地区温度梯度差减小, 致使地表垂直上升气流减弱, 导致蒙古戈壁地区粉尘扬升的促进作用减弱; 我国东北地区此时年平均气温可能介于-4℃以下, 因而形成不可渗透的广泛发育的永久冻土^[64], 降低了粉尘的可搬运程度, 从而导致蒙古戈壁进入西风环流风尘的减少. 来自近百年来器测数据与Lake Suigetsu沉积物中风尘物质对比发现^[18], 37°N的岩芯尽管接收来自40°N以北的蒙古戈壁风尘, 但其粒径及风尘通量主要受30°~40°N西风风速的控制. 我们推测40°N

以北的岩芯粒径则更多受40°~50°N西风控制, Shi和Liu^[47]的模拟结果也证明日本海北部接受蒙古戈壁粉尘更多, 这可能是导致LV53-23岩芯粉砂组分中值粒径在LGM的降低原因之一. 至于条件(3), 湿降是长

距离传输风尘的主要沉降方式, 湿降风尘的粒度要小于干降^[65], Shi和Liu^[47]模拟结果显示日本海风尘沉降90%是通过湿降, 亚洲石笋记录显示LGM时期降水量明显减少^[66], 此时干降应该增加, 这与LV53-23的

图5 60 ka以来三宝洞石笋氧同位素^[66](a)和LV53-23岩芯敏感组分平均粒径(b)、粉砂组分中值粒径与夏季65°N太阳辐射量^[67](c)、北太平洋RC14-105风尘通量^[68](d)、MD01-2407粉砂组分中值粒径及其年龄控制点^[16,17](e)、北太平洋V21-146风尘通量^[69](f)以及MD01-2421 U^{k}_{37} -SST^[61](g)的比较(g)

Figure 5 Correlation of Chinese cave $\delta^{18}O$ ^[66] (a), with mean-size of coarse grain-size components (b), and grain size of silt fraction of core LV53-23 and summer insolation at 65°N^[67] (c), dust flux of RC14-105^[68] (d), and their comparison with grain size of silt fraction of core MD01-2407^[16,17] (e), and V21-146^[69] at north Pacific (f), MD01-2421 U^{k}_{37} -SST^[61] (g)

粉砂组分中值粒径变化并不一致,因此干湿降比例变化不是造成日本海南部和中部粒径反相变化的原因。

LGM时期保持稳定的LV53-23岩芯粉砂组分中值粒径,及其总体趋势与65°N夏季太阳辐射变化类似^[67]表明北半球日照辐射量减少^[67]和冰盖面积扩张^[53]以及极地冷气团范围向南扩张,是控制西风环流南北迁移的主要因素。而西风环流在盛冰期时其急流轴相较现今冬季南移3°左右,可能进一步加大两支西风环流的风速差异,即来自30°~40°N西风风速加快,粉尘(以塔克拉玛干沙漠为主)增多,其粒径变粗,如MD01-2407粒径变粗,这与北太平洋V21-146岩芯(37°11'N)^[68]变化趋势类似;而接受更多40°~50°N西风携带的风尘物质的LV53-23则受到西风急流轴南移的影响,西风风速减弱,携带粉尘减少变细,从而成为造成LV53-23粒径变细的另一原因,这与同纬度的北太平洋RC14-105孔(39°41'N)^[69]风尘通量冰期-间冰期的变化趋势类似。

此外,粉砂组分中值粒径变化趋势与平均粒径 $d(0.5)$ 变化趋势一致(图2),表明日本海中部黏土组分并非沉积物中陆源物质的众数组分,对粒度特征影响较小,这与日本海南部MD01-2407岩芯高黏土含量特征差别较大^[16],因此平均粒径也可代表日本海中部沉积物风尘物质粒度特征。从图5可以看出LV53-23岩芯的敏感(粗)组分含量与粉砂组分中值粒径具有相似的变化趋势,而通过比较全新世与末次盛冰期沉积物粒度频率分布曲线可以看出,LGM时粒级含量减少的正是组分1,表明这一较粗组分是西风环流南移后,来自蒙古戈壁的风尘减少,导致日本海中部粒度变细的主要组分,这也与之前冰阶-间冰阶时,来自近源蒙古戈壁的风尘粒径较粗的观点一致^[17];因此我们认为敏感(粗)组分含量变化虽然并不是反映整个风尘的变化,但其代表的可能来自蒙古戈壁的物质可以响应西风急流轴南北转换这一关键因素

的变化,而细组分含量增加(减少)更多是受粗组分含量减少(增加)后,各粒级含量再平衡的结果。

4 结论

通过对比日本海中部LV53-23与日本海南部、北部和北太平洋的沉积岩芯以及冰芯记录,得到结论如下。

(1) 通过比较LV53-23岩芯沉积物与黄土高原、济州岛玛珥湖风尘沉积的粒度频率分布曲线,认为日本海中部沉积物为典型的单峰曲线,这之前证明为西风环流风尘沉积的日本海南部岩芯MD01-2407及现代日本黄沙一致,表明日本海中部风尘物质可能主要是由西风环流方式搬运而来;而粉砂组分为粒度众数组分,更接近源区的风尘地球化学特征,通过对日本海中部岩芯研究,证实粉砂组分中值粒径不仅适合日本海南部,也适合日本海中部风尘变化研究。

(2) 日本海中部LV53-23岩芯粉砂组分中值粒径在MIS 3期呈现与日本海南部相似的千年尺度变化规律,是对西风变化的良好响应。冰阶时,西风急流轴南移,但其影响范围扩大,携带更多近源的蒙古戈壁-中国东北沙地粉尘至日本海,粉砂组分中值粒径增大;间冰阶时,西风位于青藏高原北部,携带更多塔克拉玛干沙漠粉尘至日本海。

(3) 在末次盛冰期时,由于西风急流轴不再间歇性北移至粉尘源区以及中高纬度温度梯度差减小,导致蒙古戈壁垂直上升气流减弱,进入西风环流物质减少,导致LV53-23粉砂组分中值粒径较低,呈反相位变化;进一步与日本海南部及北太平洋近似纬度岩芯对比发现,相同纬度岩芯呈现相似变化,证实西风急流LGM时一直位于青藏高原南部,且自日本海至北太平洋较现今冬春季西风急流轴位置南移3°~5°,进一步加大30°~40°和40°~50°N两支西风环流的风速差异。

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Summary for “日本海中部 60 ka 以来的风尘沉积对西风环流演化的指示”

Evolution of westerly jet during the last 60 ka: Evidence from core deposits in the central Japan (East) Sea

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Aeolian dust has a significant environmental impact on the ocean biogeochemical cycles in different timescales. However, spatial and temporal variations of dust transported on long distances in the upper troposphere by the westerly jet, in particular over orbital-millennial timescales, have not been resolved yet. In this study, we present the evidence for changes in the main axis and path of westerly jet over East Asia at millennial-orbital scale during the last glacial period (~60 ka). We examine the grain size characteristics of sediment core LV53-23 collected from the central Japan (East) Sea, which lies the downwind of westerly jet to discuss the evolution of westerly jet since the last glacial period. Our results show that core sediments are composed mainly of silt characterized of eolian dust, which is consistent with those sediment cores discussed in previous studies from the Japan Sea. The median grain-size of silt fraction has similar pattern with environmentally sensitive grain size extracted by standard deviation/grain-size method. The median grain size in silt fraction increased in stadial periods and decreased in interstadial periods, which might be related to changes in the path of westerly jet. During the stadial, the westerly jet mostly located in the the south of the Tibetan Plateau. It can influence the northern part of the Tibetan Plateau extending to 50°N with high speed, which is prerequisite of dust raised to westerlies in northern China and thus carried the coarser dust from nearby Mongolian Gobi and northeastern China to the Japan Sea. During the interstadial, the provenance of the finer aeolian dust was from Taklimakan Desert when westerly jet migrated northward and concentrated within a narrow band at northern Tibetan Plateau with a longer duration. We found the multi-millennial time scales variations during DOI 8, 12, 14, 16 in cores LV53-23 and MD01-2407 located in the southwestern Japan Sea based on the results of NGRIP and GISP 2 Greenland ice cores. Contrasting with grain size variations of the loess-paleosol records (e.g., Gulang Loess sequence), the lowest grain size during the Last Glacial Maximum confirm that the silt fraction of Japan Sea sediment was mostly transported by westerlies instead of East Asian Winter Monsoon. The mechanism driving the orbital scale variability in grain size of aeolian dust in the Japan Sea is mainly forced by variations of ice volume due to summer insolation in the Northern Hemisphere. A southward migration in the main axis of westerly jet and its influential area was affected by a decrease of summer insolation and increase of ice volume in Northern Hemisphere. During the Last Glacial Maximum, although the cold surges and dust storms were intensive, the southward path of westerly jet may decreased the dust entrainment ability transported by westerlies so that downwind received finer grain size eolian dust. This argument is consistent with findings showing that the location of subarctic front in North Pacific during the Last Glacial Maximum was caused by a southward shift of the path of Kuroshio Current which is controlled by westerly jet. During the glacial period, the decreasing grain size of dust in northern site is explained by weaker westerlies in higher latitudes (40°–50°N) caused by the southward shift of westerly jet main axis, while the increase grain size in the southern site is controlled by the increasing of dust transport path because of westerlies speed in lower latitudes.

aeolian dust, median grain size of silt fraction, environmentally sensitive grain-size, westerly jet, Japan (East) Sea

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