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张永威, 田旭, 徐方建, 陈波, 叶友权, 范德江

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7.8 kaBP 以来海南岛东南陆架陆源碎屑来源及其环境响应

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摘要: 对取自海南岛东南部的 X2 站柱状样品进行了粒度、全岩稀土元素和重矿物分析, 探讨了 7.8 kaBP 以来海南岛东南陆架陆源碎屑来源及其环境响应。粒度端元模拟识别出了两个端元, EM1 端元对应的是海洋流系搬运的近源与远源细粒物质的混合沉积, EM2 对应的主要是近源海南岛河流输入的粗粒物质, 两个端元代表着两个不同的运输机制。物源分析结果表明, 7.8 kaBP 以来 X2 站陆源碎屑来源较为稳定, 主要来源于海南岛。4 kaBP 以来, X2 站粒度、稀土元素和重矿物特征参数发生了显著改变, 与 El Nino-Southern Oscillation (ENSO) 事件开始增强有很好的对应关系, 推测频繁的 ENSO 事件导致降雨量增加是研究区风化程度增强的主要原因。与全岩稀土元素特征指标相比, X2 站重矿物组合受源区风化剥蚀的影响更为显著, 后期在环境演化研究中, 应适当关注重矿物这一指标。

关键词: 陆架; 稀土元素; 重矿物; 物质来源; 海南岛

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Provenance and environmental response of terrigenous debris in the southeastern continental shelf of Hainan Island since 7.8 kaBP

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Abstract: Grain-size, bulk Rare Earth Element (REE), and heavy mineral analysis of Core X2 at southeastern Hainan Island were carried out. The provenances of terrigenous clasts and their environmental responses of this study area since 7.8 kaBP were discussed. Two endmembers were identified by grain-size endmember simulation. The EM1 endmember corresponded to the fine-grained material transported by the ocean current system, while the EM2 endmember corresponded to the coarse-grained material input from nearby rivers in Hainan Island; therefore, the two endmembers represented two different transport mechanisms. Results show that since 7.8 kaBP, the provenance of terrigenous detrital of Core X2 was relatively stable, mainly from Hainan Island. After 4 kaBP, the grain size, REE, and heavy mineral characteristic parameters of Core X2 had changed significantly, which has a good correspondence to the intensification of El Nino and Southern Oscillation (ENSO). It is speculated that the

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increase of rainfall caused by frequent ENSO events is the main reason for the enhancement of weathering degree in the study area. Compared with the characteristics of REE, the heavy mineral assemblages of Core X2 were more significantly affected by weathering and denudation in the source area. Therefore, study on heavy mineral index is suggested in the future study of environmental evolution.

Key words: continental shelf; rare earth element; heavy mineral; provenance; Hainan Island

南海北部陆架接受了来自周围陆地的巨量物质输入,其沉积物有效地记录了物质运移、海陆变迁、气候变化等地质和环境信息^[1-2]。前人通过环境磁学^[3]、矿物学^[4]、地球化学^[5]、沉积学^[6]等多种方法对海南岛东南陆架沉积物来源进行了研究,认为海南岛、珠江和台湾岛为主要的物质供给区,由于输沙量较小,海南岛是否能为周边海域提供充足的物质供给存在一定争议^[2,4]。

稀土元素(REE)具有极为相似的化学性质,在风化、剥蚀、搬运、沉积和早期成岩作用过程中不易迁移,而且其组成受粒度影响较弱,很大程度上能够用来反映物源区物质的地球化学特征,因此被广泛用于示踪沉积物来源^[7-8]。重矿物在河流流域、河口或近海很快发生沉降分异^[9],也常被用于沉积环境分析^[10-13]和古气候事件的识别^[14-15]。泥质沉积与砂质沉积可能不是来自同一物源,在进行沉积物物质来源分析时,有必要对不同粒级的沉积物分别讨论^[16]。本文对取自于海南岛东南陆架泥质区的X2站柱状沉积物开展了粒度、全岩稀土元素和重矿物分析,探讨了7.8 kaBP以来海南岛东南陆架陆源碎屑物质来源及其环境响应。

1 区域地质背景

南海北部发育复杂的海洋流系,主要包括广东

沿岸流、表层洋流、北部湾环流以及深水洋流等^[17]。研究区受东亚季风影响,风向和流向具有季节性变化特点,即夏季在盛行的西南向季风影响下发育东北向表层洋流,冬季则相反(图1)^[18]。海南岛附近具有热带季风型海洋性气候特色,终年高温,年平均气温为22~26℃,雨量充沛^[19]。海南岛岩石类型以花岗岩、玄武岩和砂页岩为主,这些岩石和第四纪沉积物可为周边近海沉积提供物质来源^[20]。海南岛地势中部高、四周低,岛内约有150条河流呈辐射状独立直流入海^[21]。

2 材料与方法

2.1 样品来源

研究采用的X2站柱状样于2012年9月利用重力取样器采自于海南岛东南侧陆架(18°25.753'N、110°17.079'E,水深约77 m,图1),岩芯长度240 cm。在实验室对样品进行详细描述和分样。

2.2 分析方法

X2站4个层位的混合底栖有孔虫AMS¹⁴C年代测试在美国Beta实验室完成。原始测年数据利用CALIB 7.0.2软件和Marine 13程序进行日历年龄校正。现代年龄数据用-23±52 a的碳储库年龄进行校

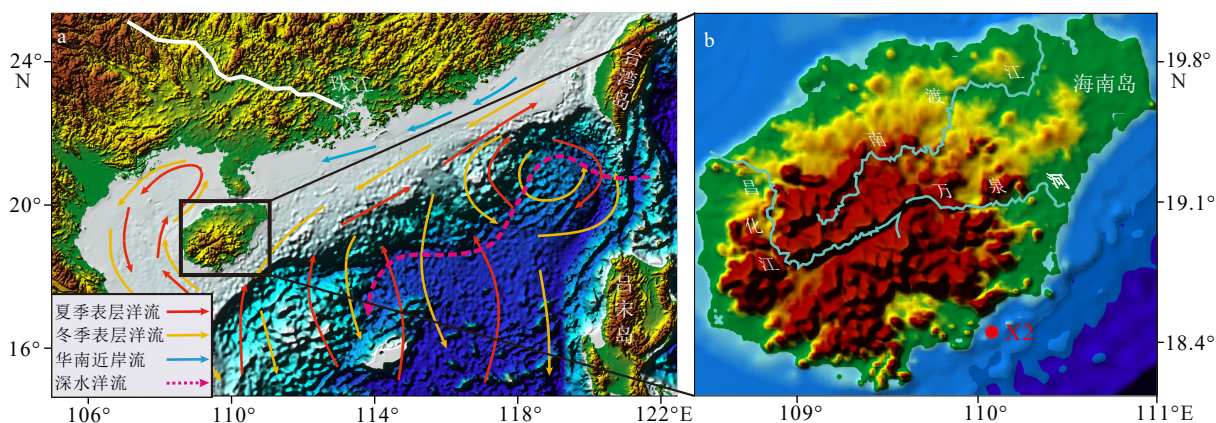


图1 南海北部流系(a)及X2站位图(b)

表层洋流、华南近岸流和深水洋流根据文献[18, 22]改绘。

Fig.1 The ocean currents in the northern South China Sea (a) and location of Core X2 (b)

Coastal current, surface current and deep water current were modified from [18, 22].

正, 7.5~5.6 kaBP 的数据用 151 ± 85 a 的碳储库年龄进行校正^[2]。

粒度样品共 120 个, 测试前使用 30% 的 H_2O_2 和 1 mol/L 的 HCl 水浴 60 °C 加热 1 h 去除有机质和钙质生物, 在中国科学院海洋研究所进行粒度测试。测试仪器为法国产 Cilas 940L 激光粒度仪, 测试范围为 0.5~2000 μm , 重复测试的相对误差小于 2%^[2]。在 MATLAB 软件中嵌入 Paterson 和 Heslop 提供的 AnalySize 程序^[23], 采用非参数化方法对粒度数据进行端元模拟。

用于分析的 60 个稀土样品按等间距取样。样品使用 30% 的 H_2O_2 和 1 mol/L 的 HCl 水浴 60 °C 加热 1 h 以去除有机质和钙质生物, 低温烘干, 在玛瑙研钵中磨碎至 200 目以下。经马弗炉高温灼烧, 用 $\text{HF} + \text{HNO}_3 + \text{HClO}_4$ 完全消解后, 在中国科学院海洋研究所使用等离子质谱分析方法 (ICP-MS) 进行测试。为了保证测试精度和准确度, 进行重复样和标样分析, 所选标准样品为 GBW07315、GBW07316、BCR-2 和 BHVO-2, 分析元素的相对误差 < 5%。

重矿物样品共 20 个, 取样间隔约为 12 cm。筛选出 63~250 μm 粒级沉积物后, 利用三溴甲烷 (密度 2.89 g/cm³) 进行轻重矿物分离。将分离出来的重矿物在双目实体显微镜下进行观察鉴定, 每个样品各鉴定 500 个以上矿物颗粒, 计算出单个矿物数量占重矿物总数的百分比。

3 结果

3.1 粒度特征及端元模拟算法分析结果

岩芯 240~120 cm 主要为黏土质粉砂, 120~0 cm 主要为粉砂质砂。根据 AMS¹⁴C 测年结果, X2 站柱状沉积物底部 240 cm 处的年龄约为 7.8 kaBP, 沉积速率较为稳定, 约为 30 cm/ka^[2]。

粒度数据模拟结果如图 2 所示。相对高的复相关系数 (R^2) 和低的角偏差值 (θ) 意味着较好的统计拟合结果。当端元个数增加时, R^2 也逐渐变大 (图 2a)。 R^2 在端元数为 2 时大于 0.9 (图 2a), 当端

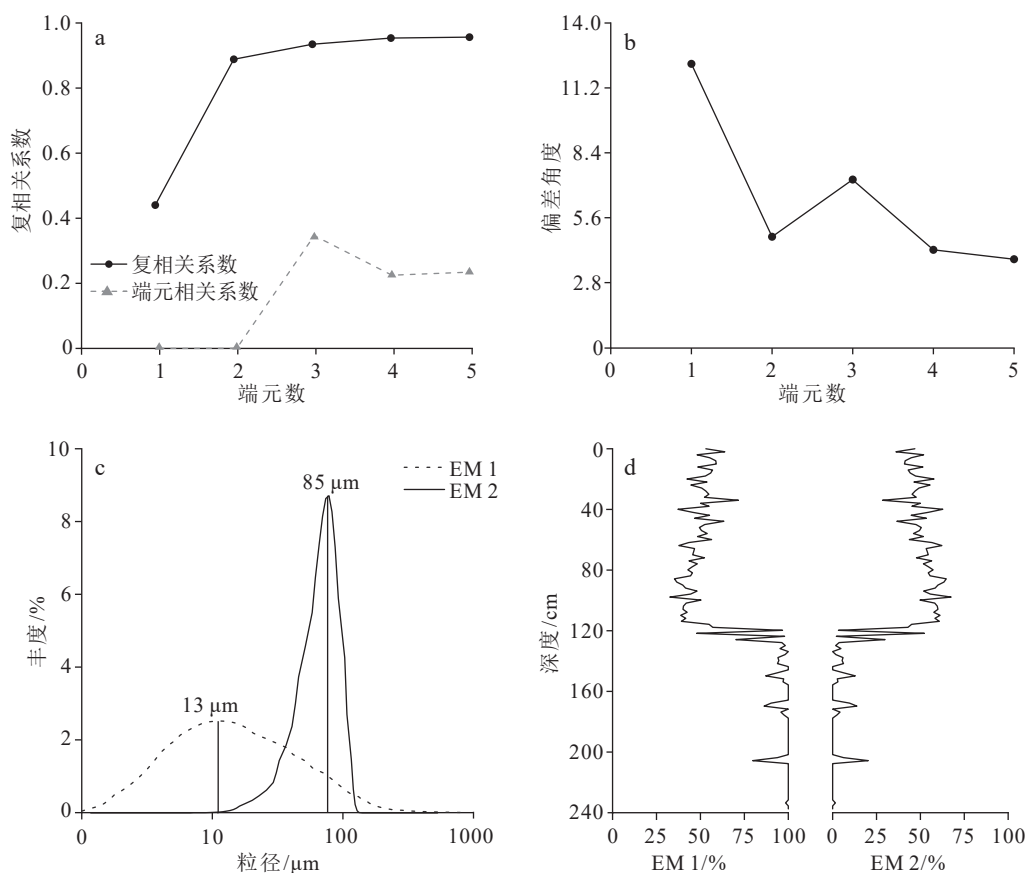


图 2 X2 站粒度端元模拟图

a. 复相关系数, b. 偏差角度, c. 各端元丰度, d. 各端元含量。

Fig.2 Results of endmember analysis of Core X2

a: Coefficients of determination b: mean angular deviation, c: grain size frequency distributions, d: variation of endmember contributions.

元数增加时, R^2 并未发生明显变化, 表明端元数至少为 2 个。为避免过度拟合, 端元间相关性应尽量低^[23], 而 2 端元以上各端元间相关性明显增加(图 2a)。为了使角度偏差尽量小, 应选取角度偏差值在 5 以下^[23], 故最终端元数为 2 时能够达到较好的拟合效果(图 3)。EM1 的众数值是 13 μm , EM2 的众数值是 85 μm 。

3.2 稀土元素含量特征

根据稀土元素物理和化学性质的差别, 一般可以分为轻稀土元素 (LREE: La, Ce, Pr, Nd, Sm, Eu) 和重稀土元素 (HREE: Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu) 两组, 其含量分别用 ΣLREE 和 ΣHREE 表示, 稀土元素含量总和用 ΣREE 表示, 稀土元素含量及各特征参数变化情况见图 4。可以看出, X2 站柱状样垂向上 ΣLREE 、 ΣHREE 与 ΣREE 具有较为一致的变化趋势, ΣREE 变化范围为 92.0~193.4 $\mu\text{g/g}$, ΣLREE 为 82.2~178.1 $\mu\text{g/g}$, ΣHREE 为 9.7~20.4 $\mu\text{g/g}$ 。岩芯上段 (120~0 cm) 较下段 (240~120 cm) ΣLREE 、 ΣHREE 与 ΣREE 等参数变小, 各参数波动幅度变大。前人研究显示^[2], X2 站沉积物经 UCC 标准化后不同层位的配分模式基本一致, 与上地壳^[24] 和世界页岩^[25] 非常一致, 均表现为轻稀土富集、重稀土元素含量低和轻重稀土分异较强, 具有强烈的陆源特征。X2 站沉积物 Eu 中度亏损, δEu 为 0.5~0.7, 平均为 0.6。

3.3 重矿物特征

X2 站柱状样中共检测出 17 种重矿物, 其中黄铁矿 (18.3%)、磁铁矿 (16.5%)、钛铁矿 (15.2%)、锆石 (12.9%) 等的百分含量都超过 10%, 绿帘石 (6.9%)、赤褐铁矿 (6.2%)、锐钛矿 (4.8%)、白钛石 (4.1%)、角闪石 (4.3%)、辉石 (3.1%)、磷灰石 (2.5%)、金红石 (1.6%)、电气石 (1.3%) 的百分含量都在 1%~10% 之间, 榍石 (0.9%)、石榴子石 (0.6%)、透闪石 (0.6%)、独居石 (0.3%) 的含量均低于 1%。本文根据重矿物的稳定性和成因, 结合前人的分类标准^[26-28], 将重矿物分为稳定矿物 (锆石、金红石、锐钛矿、白钛石、电气石、石榴子石、赤褐铁矿、钛铁矿、磁铁矿、独居石、榍石), 不稳定矿物 (磷灰石、绿帘石、辉石、角闪石、透闪石) 和自生矿物 (黄铁矿)。重矿物变化大致以 120 cm 为界可以分为两段 (图 5), 240~120 cm 重矿物变化特点不明显, 120~0 cm 不稳定矿物和自生矿物开始减少, 大部分稳定矿物含量开始增加, 锐钛矿、石榴子石和赤褐铁矿减少, 磁铁矿和独居石开始出现。

4 讨论

4.1 粒度端元组分的指示意义

沿海和近岸沉积物的来源通常比较复杂, 既有

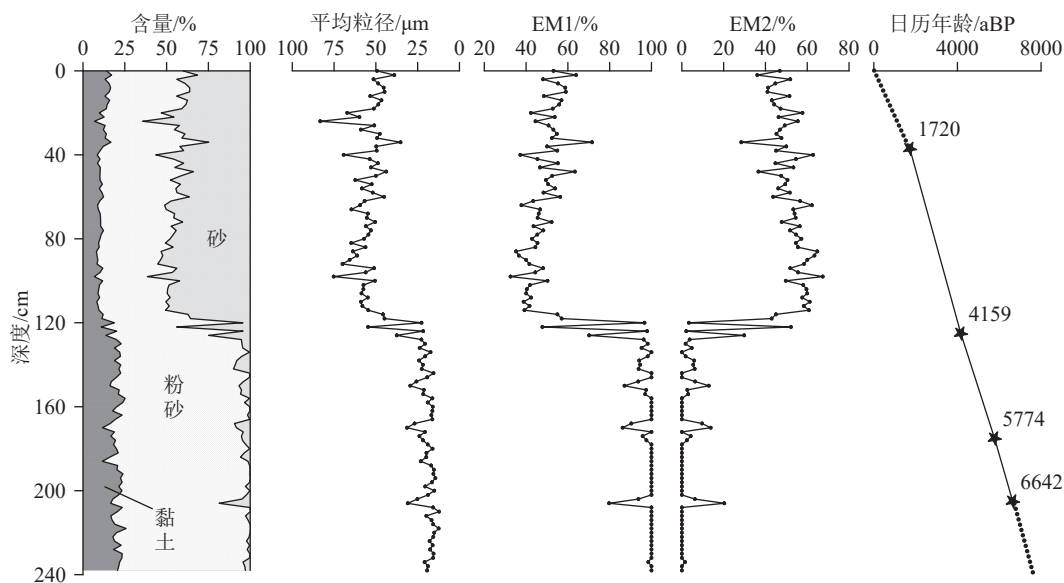


图 3 X2 站各端元与粒度参数
粒度和年代数据引自文献 [2]。

Fig.3 End member and particle size parameters of Core X2

Grain-size and age data were obtained from [2].

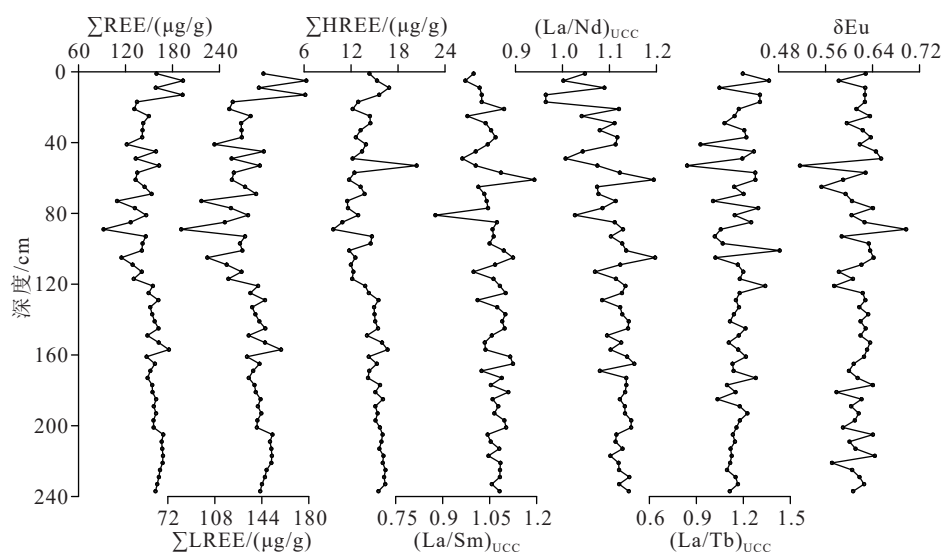


图 4 X2 站稀土元素及其参数垂向变化特征

Fig.4 Vertical variation of rare earth elements and its parameters in Core X2

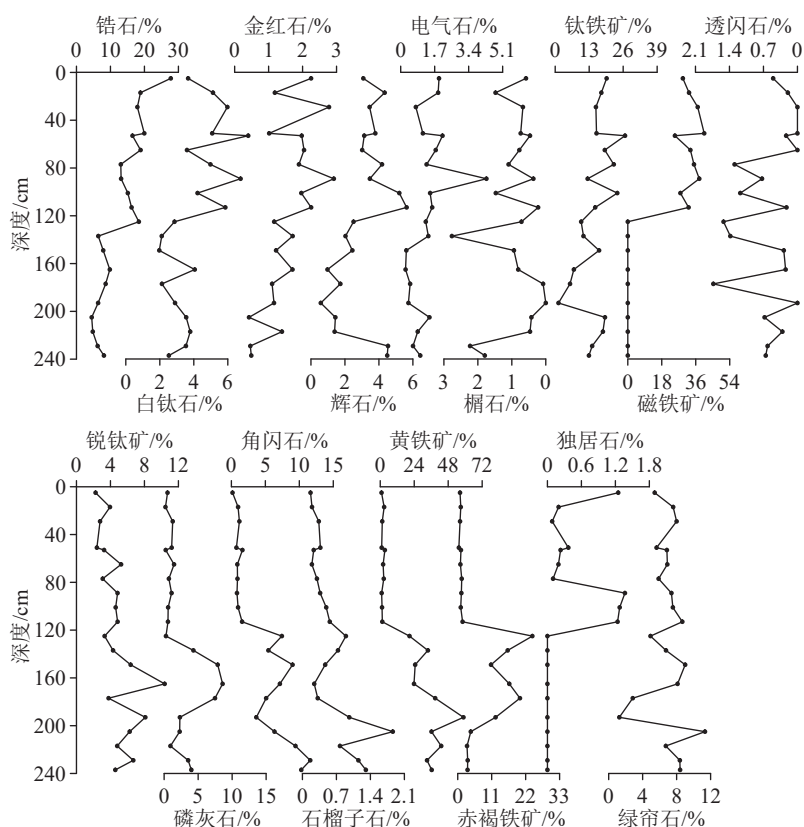


图 5 X2 站重矿物变化特征

Fig.5 Variation of heavy minerals in Core X2

河流的输入, 又有海洋流系(沿岸流和表层洋流等)的输送^[29]。河流的直接输入提供的主要是粗粒物质, 而海洋流系可以将近源河流输入中较细的物质进行搬运, 同时也可以带来远源的细粒物质^[30-31], 因此海洋流系搬运的主要是细粒物质。海南岛河流众多, 洪水期含砂量增大^[32], 河流物质入海后除了

在河口沉积外, 也会在沿岸流的作用下沿岸沉积, 同时表层洋流也可以带来外海物质, 因此海南岛东部陆架沉积物质既有海南岛河流的输入, 又有海洋流系的输送^[4,33-34]。据此推断, EM1 对应的是海洋流系搬运的近源与远源细粒物质的混合沉积, EM2 对应的主要是近源海南岛河流来源的粗粒物质, 因此

两个端元代表着两个不同的输运机制。由于该区域海洋动力比较稳定^[35],而河流动力受降雨量影响有很大变化,因此河流动力强时,带来粗粒物质增多,致使研究区粒度变粗,反之则变细。

4.2 物质来源分析

X2站沉积物 ΣREE 平均值 $149.9\text{ }\mu\text{g/g}$,与中国黄土($\Sigma\text{REE}=171.0\text{ }\mu\text{g/g}$)^[36]和上地壳($\Sigma\text{REE}=146.4\text{ }\mu\text{g/g}$)^[24]相近,可以推断X2站沉积物均来自于上地壳这一大的地质背景,具有明显的陆源属性。前人研究显示,红河的沉积物主要沉积在三角洲海岸,同时由于海南岛的阻挡,难以到达海南岛东部^[37],吕宋岛的物质难以跨越深水盆地^[38],长江物质难以越过台湾海峡^[39],所以研究区的潜在物源为珠江、海南岛和台湾岛。虽然稀土的含量受到了粒度变化的影响,但代表稀土内部分馏情况的 $(\text{La}/\text{Nd})_{\text{UCC}}$ 、 $(\text{La}/\text{Tb})_{\text{UCC}}$ 、 $(\text{La}/\text{Sm})_{\text{UCC}}$ 以及 δEu 等指标等受粒度的影响较小,所以基本反映的是源区的状况。因此进一步采用 $(\text{La}/\text{Sm})_{\text{UCC}}-\delta\text{Eu}$ (图6a)与 $(\text{La}/\text{Nd})_{\text{UCC}}-(\text{La}/\text{Tb})_{\text{UCC}}$ (图6b)交汇图进行物源判别。X2站大部分层位处于海南岛范围,只有极个别层位位于珠江和台湾岛范围内。因此,可以认为自中全新世以来X2站沉积物主要来自于海南岛。

前人研究发现,珠江入海物质主要沉积于珠江口至海南岛东北侧之间^[18],在珠江口至雷州半岛之间形成了一条平行海岸线的全新世泥质条带^[40]。因此,可能只有少量珠江细粒物质经长距离搬运而到达海南岛东部陆架。虽然海南岛河流输沙量较小,

但受季节性降雨和地形的影响,海南岛东部河流可携带泥沙直流入海^[41],从而为距离较近的X2站提供较多的物质供给。台湾岛入海的巨量物质不仅是南海北部的主要物源,而且有向西南方向运移的趋势^[18]。因此,X2站全岩沉积物主要来自于海南岛,少量的珠江和台湾岛物质也有可能被输送到研究区。

4.3 重矿物变化对环境的指示意义

海南岛东南部母岩以花岗岩为主,强烈的风化作用产生钛铁矿-锆石型重矿物组合,但是局部地区岩性组成仍存在差异,从而导致河流沉积物受局部物源的影响,具有不同的重矿物组合特征^[44-47]。因为重矿物常常存在于较粗的组分中,具有近源沉积的特点,而且X2站含有较高的钛铁矿和锆石的情况与海南岛相似,所以推断X2站的重矿物来自于海南岛,这与前人的研究一致,即海南岛东部陆架重矿物由海南岛小型河流携带入海^[34,44,46]。由于重矿物受气候影响较大^[48-49],稳定性强的矿物较难远距离搬运且可在较高的化学风化作用下富集^[10],所以可以利用重矿物来分析研究区环境的变化。

X2站沉积物在120 cm(4 kaBP)处粒度、稀土元素和重矿物特征参数都发生了显著改变,表明4 kaBP以来环境发生了重大变化。EM2的增大说明源区水动力增强,研究区降雨量增加。黄铁矿是自生矿物^[50],可在还原环境、水动力弱的条件下快速形成,富集条件也十分严格^[51]。4 kaBP以来黄铁矿含量迅速减少,也说明了研究区水动力变强和水

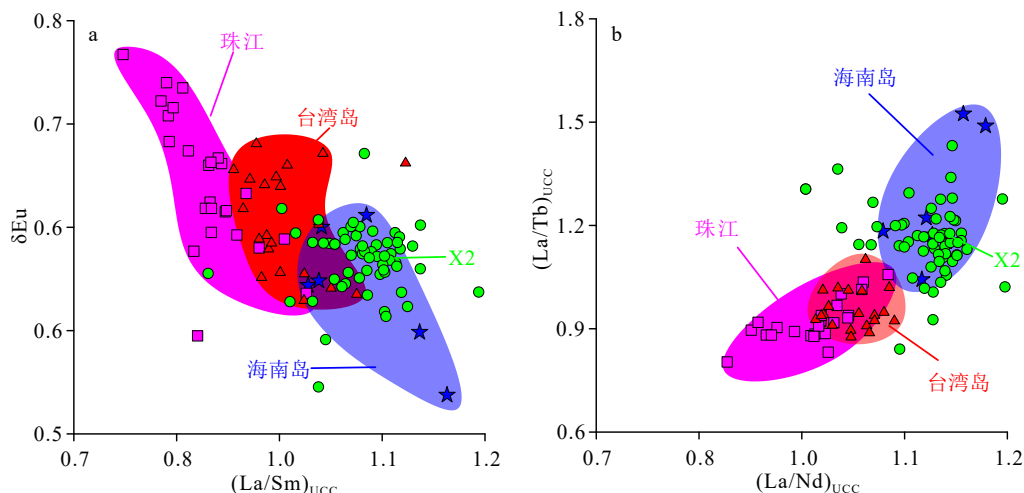


图6 X2站物源判别

a: $(\text{La}/\text{Sm})_{\text{UCC}}-\delta\text{Eu}$; b: $(\text{La}/\text{Nd})_{\text{UCC}}-(\text{La}/\text{Tb})_{\text{UCC}}$ 。海南岛数据源自文献[2],珠江数据源自文献[42],台湾数据源自文献[43]。

Fig.6 Provenance discrimination of Core X2

a: $(\text{La}/\text{Sm})_{\text{UCC}}-\delta\text{Eu}$; b: $(\text{La}/\text{Nd})_{\text{UCC}}-(\text{La}/\text{Tb})_{\text{UCC}}$ (The REE data for the Hainan Island, Pearl River, and Taiwan were obtained from [2, 42] and [43], respectively.)

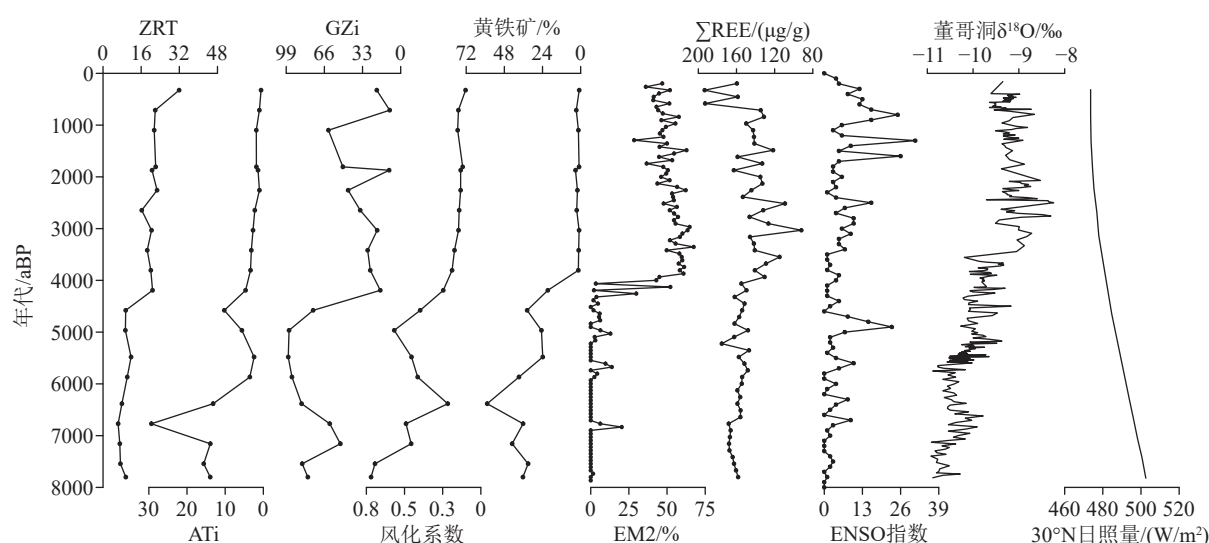


图 7 X2 站对环境变化的响应

ENSO 指数引自文献 [58], 董哥洞 $\delta^{18}\text{O}$ 引自文献 [59], 30°N 光照强度引自文献 [60]。

Fig.7 Response to environmental change at Core X2

The data for the ENSO Index, Dongge Cave $\delta^{18}\text{O}$, and insolation at 30°N were obtained from references [58], [59] and [60], respectively.

体氧化。较强的水动力可将不稳定矿物带走,使得稳定矿物富集。然而 X2 站一些稳定性较强的矿物含量也变小,可能是由于强烈的风化作用导致的。同时, ZRT (ZRT=锆石 % + 电气石 % + 金红石 %) 的增大, ATi (ATi=100×磷灰石/(磷灰石+电气石))、GZi (GZi=100×石榴子/(石榴子+锆石)) 和 风化系数 (风化系数=不稳定矿物/稳定矿物) 的减小,也揭示了 4 kaBP 以来源区风化程度的增强。其次,由于降雨量的增加,海南岛河流集水面积增加,从而受局部物源的影响重矿物含量发生变化,如磁铁矿和独居石开始出现 (图 5)。

4.2 kaBP 左右发生的冷事件标志着全新世大暖期的结束 [52], 此后中国气候发生了显著改变,东亚季风开始减弱,中低纬度地区 ENSO 事件频繁 [53-55] (图 7), 因此推断研究区环境的改变是此次气候转变的响应。4 kaBP 以来,季风开始减弱 (图 7), 减弱的季风并不太可能使得研究区降雨量增加或风化加强;同时,全新世大暖期结束后,温度降低,并一直处于减弱的状态 (图 7), 因此温度也不是导致源区风化加强的原因。ENSO 频繁会导致低纬度地区降雨量的增加, EM2 的增大与 ENSO 事件频繁几乎同步开始,也进一步说明降雨量的增加可能是导致研究区水动力增强的主要原因;同时,由于降雨量的增加会加速对地表的冲刷,导致物理风化加剧,大量的雨水也会使得地表长时间湿润,导致化学风化的加剧 [56], 因此源区风化的加剧可能是由于降雨量增加导致的。这与前人的研究一致,即 4 kaBP

以来研究区降水、风化程度增加与降温趋势呈相反的变化 [57]。因此推断频繁的 ENSO 事件是研究区风化增强的主要原因。值得注意的是,对于 X2 站,重矿物组合比稀土元素对环境变化更为敏感 (图 7), 因此重矿物在环境演化的研究中具有一定的优势,在以后的环境演化中应适当关注这一指标。

5 结论

(1) 端元模拟识别出两个端元,分别代表着不同的运输机制, EM1 对应的是海洋流系搬运的细粒物质, EM2 对应的主要是近源海南岛河流输入的粗粒物质。EM2 可表征河流动力变化,受降雨量变化的影响。

(2) 物源分析表明, 7.8 kaBP 以来海南岛东南陆架陆源碎屑比较稳定,主要来源于海南岛,珠江和台湾岛的贡献相对较少。

(3) 研究区环境的改变可能是对中国 4 kaBP 以来气候转变的一个响应。频繁的 ENSO 事件导致降雨量的增加可能是研究区环境转变的主要原因。

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