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末次冰期山东黄土物源研究：来自碎屑锆石U-Pb年龄的约束

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摘　要：胶东半岛北部海滨和山东中部山区北麓沉积了典型的风尘黄土，详细记录了晚更新世以来的气候变化，然而有关这些黄土究竟来自哪里，目前仍处于争议之中．锆石是黄土中常见的副矿物，其U-Pb年龄谱对比被广泛用于黄土的物源示踪研究．基于此，利用激光剥蚀电感耦合等离子质谱仪（LA-ICP-MS）对上述地区晚更新世典型的黄土剖面开展碎屑锆石（n=420）微区原位U-Pb年龄分析，结合Kolmogorov-Smirnov统计方法的多维判别图和前人已经发表的研究结果，发现胶东半岛北部海岸和山东中部山地北麓东段的晚更新世黄土主要来自渤海裸露的大陆架和华北平原的碎屑物质，受中国西北内陆干旱区的影响较小，但由于地理位置的差异，山东中部山地北麓西段的晚更新世黄土具有黄河下游和黄土高原的物质信号，而与晚更新世渤海末次冰期裸露在海底的沉积物的物源关系较弱．

关键词：胶东半岛；山东中部山区；黄土；锆石U-Pb年龄；第四纪；地层学．

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Provenance of the Loess in Shandong Province (Eastern China) during the Last Ice Age: Constraints from the U-Pb Age of Detrital Zircons

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Abstract: The thick loess-palaeosol sequences in the Jiaodong Peninsula and Central Shandong mountains provide high-resolution records of Late Quaternary climate change of the Shandong Province. However, it is still controversial as to where they came from. This study presents systematically the detrital zircon U-Pb age (n=420) and multi-dimensional discrimination diagram results of statistical method. It is shown that the North China Plain and Bohai shelf material served as a major dust supply for the loess in the Jiaodong Peninsula and eastern parts of the Central Shandong mountains during the Late Pleistocene. By contrast, the major dust source for the loess in the western parts of the Central Shandong mountains is mainly derived from the sediments exposed on the floodplain of the lower reaches of the Yellow River and the Loess Plateau during the Late Pleistocene. They have no provenance relationship with the sediments exposed on the sea floor in the Bohai Sea at the same time.
Key words: Jiaodong Peninsula; Central Shandong Mountains; loess; zircon U-Pb age; Quaternary; stratigraphy.

0　引言

中国西北分布着大面积的沙漠、戈壁以及黄土，是世界上主要风尘物质来源区之一(Ding *et al.*, 1999; Chen *et al.*, 2007; Sun *et al.*, 2007; 曾方明等, 2014; Nie *et al.*, 2014; Wang *et al.*, 2014; Lu *et al.*, 2019).对风尘物质开展物源示踪研究，有助于了解风化、剥蚀、搬运、沉积等地球不同圈层相互作用的地质过程(Sun, 2002; Wang *et al.*, 2016; Zheng, 2016; Liu *et al.*, 2018; Zhao *et al.*, 2019)，对认识大气中尘埃的运移和重建过去气候变化同样具有重要意义(Sun *et al.*, 2008; Stevens *et al.*, 2010; Peng *et al.*, 2011, 2016; Wang *et al.*, 2020).黄土沉积作为风尘沉积的重要载体之一，对其开展物源示踪研究，是重建第四纪气候变化的一条重要途径(曹家欣等, 1994; 彭淑贞等, 2007, 2010; Kang *et al.*, 2013; Xu *et al.*, 2015, 2018; Xie *et al.*, 2019).以往的研究主要集中在黄土高原，但最近对黄土高原外围的黄土开展物源示踪研究也逐渐兴起(Kang *et al.*, 2013; Peng *et al.*, 2016; 徐树建等, 2016; Ding *et al.*, 2017; Shang *et al.*, 2018; Wang *et al.*, 2018; Xie *et al.*, 2019; 张玉芬等, 2020).

在胶东半岛北部沿海和山东中部山区北麓地区也广泛分布着黄土沉积(图 1)，由于处于海陆交汇位置，其对区域内海平面变化、东亚冬季风时空变化的反映比内陆黄土更为灵敏，详细保存了晚更新世剧烈的气候变化信息(彭淑贞等, 2007; 牛洪燕等, 2009; 徐树建和王涛, 2011; Ding *et al.*, 2018; 黎武标等, 2019a, 2019b; Tian *et al.*, 2019; Li *et al.*, 2020b).因此，众多学者对上述区域的黄土开展物源示踪研究.例如有学者认为晚更新世裸露的渤海陆架物质和黄河下游的河漫滩物质是山东黄土的主要物源(曹家欣等, 1987; 刘乐军等, 2000; 彭淑贞等, 2010; 牛洪燕等, 2010; Ding *et al.*, 2017; 郑力, 2018; 徐建国等, 2019)，也有研究者认为山东黄土主要来自黄土高原(丁新潮等, 2015)，以及部分来自中国内陆沙漠和戈壁(Tian *et al.*, 2019; Li *et al.* 2020b).由于上述研究或是对山东黄土的某一个剖面进行物源示踪，或是对其中的几个剖面进行物源示踪，选择的潜在物源区对比数量少，导致有关山东黄土物源区的具体分布位置并未达成一致.因而，对山东黄土典型黄土剖面进行系统的物源示踪研究，详细地对比其潜在物源区有助于解决上述分歧.

将沉积区(汇)与潜在物源区(源)进行比较，是开展风尘沉积物物源示踪研究的基本思路(Sun, 2002; 李高军等, 2017; Lu *et al.*, 2019).碎屑锆石是风尘沉积物中广泛存在的副矿物，其U-Pb年龄谱对比已被普遍应用于黄土物源示踪研究(Pullen *et al.*, 2011; Xiao *et al.*, 2012; Xie *et al.*, 2012; Che and Li, 2013; Bird *et al.*, 2015; Pan *et al.*, 2016; Rittner *et al.*, 2016; Zhang *et al.*, 2016, 2018; Fan *et al.*, 2018; Shang *et al.*, 2018; Wang *et al.*, 2018; Xiong *et al.*, 2021).所以，基于上述研究存在的问题和解决的可能性，本文对胶东半岛的烟台芝罘岛、蓬莱林格庄以及山东中部山地北麓的潍坊朱里、青州张家崖顶、章丘埠西和平阴这些有良好研究基础的典型黄土剖面，开展碎屑锆石U-Pb年代学分析，与中国西北和蒙古的沙漠、戈壁和我国黄土高原、青藏高原东北缘的河流冲积扇，以及华北平原的河流和渤海钻孔的碎屑锆石U-Pb年龄

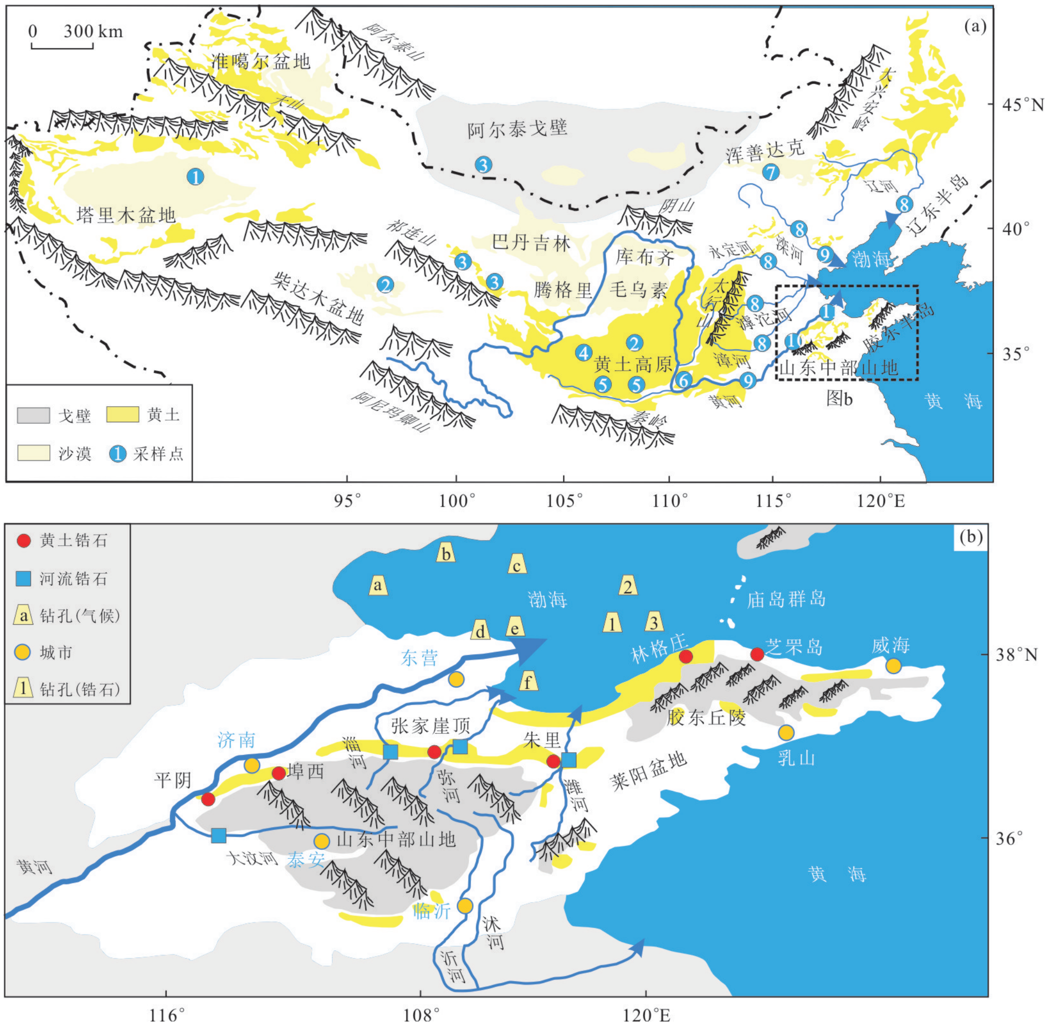

图1　中国主要沙漠、戈壁和黄土位置分布(a),山东黄土位置分布(b)

Fig.1　Location distribution of major deserts, gobi and loess in China (a); distribution diagram of loess locations in Shandong Province (b)

底图a修改自Sun *et al.* (2008)、Nie *et al.* (2014)和Li *et al.* (2020b),图中数字1~7(1: Xie and Ding, 2007, Rittner *et al.*, 2016; 2: Pullen *et al.*, 2011; 3: Zhang *et al.*, 2016; 4: Stevens *et al.*, 2010, Nie *et al.*, 2014; 5: Gong *et al.*,2017; 6: Xiong *et al.*, 2021; 7: Stevens *et al.*, 2010)代表沙漠、戈壁、黄土碎屑锆石采集地,8~11(8: 林旭等, 2020; 9: Yang *et al.*, 2009; 10: Yang *et al.*, 2009, Nie *et al.*, 2015; 11: Nie *et al.*, 2015)为华北克拉通河流碎屑锆石采样位置;图b中1~3为渤海钻孔锆石数据(1和2: Huang *et al.*, 2020; 3: Sun *et al.*, 2020),a~f为渤海钻孔气候数据(Yao *et al.*, 2014, 岳保静等, 2020)

进行对比,结合前人在区域内的研究结果,系统判别山东黄土的物源区,为山东黄土物源示踪研究提供新的地球化学证据.

1　研究区概况

1.1　胶东半岛

胶东半岛位于渤海和黄海之间,在构造上可将半岛分为两部分:北部的胶北地体和东部的胶东地体(Yang *et al.*, 2014).胶北地体具有华北克拉通的属性,其前寒武基底主要为太古代、古元古代,以及新元古代地层(Zhao *et al.*, 2018).胶东地体具有扬子克拉通苏鲁超高压的属性,其前寒武基底主要为新元古代花岗质片麻岩,锆石年龄集中在600~800 Ma (Tang *et al.*, 2008).锆石U-Pb年代学结果表明,晚侏罗世(160 Ma)和早白垩世(115~130 Ma)花岗质侵入岩体在胶北和胶东地体广泛分布(Tang *et al.*, 2008; Yang *et al.*, 2014).

1.2　山东中部山地

山东中部山地位于黄河以南,胶东半岛以西,东西长约200 km,南北宽约50 km,由泰山、鲁山、沂山、尼山等山脉组成,海拔多在1 500 m

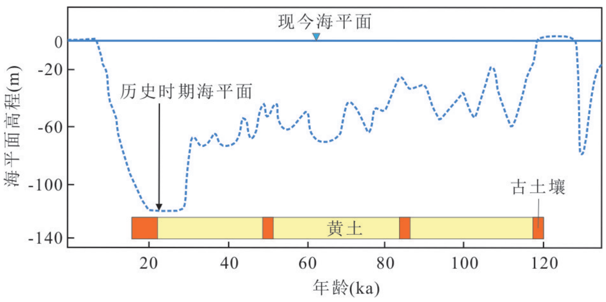

图 2　晚更新世以来黄海及其邻近地区海平面变化曲线

Fig.2　Curve of sea-level changes of Yellow Sea and adjacent areas since 120 ka

图修改自赵希涛等(1979)、岳保静等(2020)

到 1 000 m 左右.该区主要由早前寒武纪结晶基底、新元古代-古生代沉积盖层和中新生代陆相盆地沉积组成,少量中生代侵入岩体(宋明春等, 2020).鲁中山区的岩浆岩期次单一,主要以太古代时期最强烈,锆石 U-Pb 年龄集中在:2 750～2 500 Ma(Wan *et al.*, 2012).

1.3　海洋和河流

渤海位于胶东和辽东半岛的西部,面积 77 000 km^2,是一个封闭的陆架浅海,平均水深 18 m.第四纪初期,海水从南部侵入渤海湾盆地,古渤海初步形成(Yao *et al.*, 2012; Yi *et al.*, 2016).渤海第四系(平原组)分布稳定,厚度变化不大,一般在 300～400 m,往沉积中心有加厚的趋势,岩性主要以灰黄色-土黄色粘土、砂质粘土与粉砂层、泥质砂层为主(林旭等, 2021).晚更新世以来,渤海的海平面发生多次波动变化,最大降幅超过 120 m(赵希涛等, 1979; 岳保静等, 2020).汇入渤海的河流,从北到南主要有辽河、滦河、永定河、滹沱河、漳河、黄河等(图 2).辽河每年向渤海输入大约 3.5×10^7 t 碎屑物质(Milliman and Farnsworth, 2013).滦河每年向渤海输入大约 2.67×10^7 t 碎屑物质.永定河、滹沱河和漳河等发源于太行山的河流每年向渤海提供大约 1.8×10^8 t 碎屑物质.黄河是世界上泥沙含量最高的河流,每年平均向渤海输入超过 1×10^9 t 泥沙(Li *et al.*, 2020a).

2　样品来源及分析方法

2.1　样品来源

2020 年 6 月笔者对胶东半岛的烟台市芝罘岛(N121°21′55″,E37°37′7″)、蓬莱市林格庄镇(N120°41′21″,E37°48′2″)以及山东中部山区北麓的潍坊市朱里镇(N119°23′22″,E36°45′5″)、青州市张家崖顶村(N118°23′45″,E36°39′7″)、章丘区埠西村(N117°28′48″,E36°37′11″)和平阴县(N116°21′27″, E36°

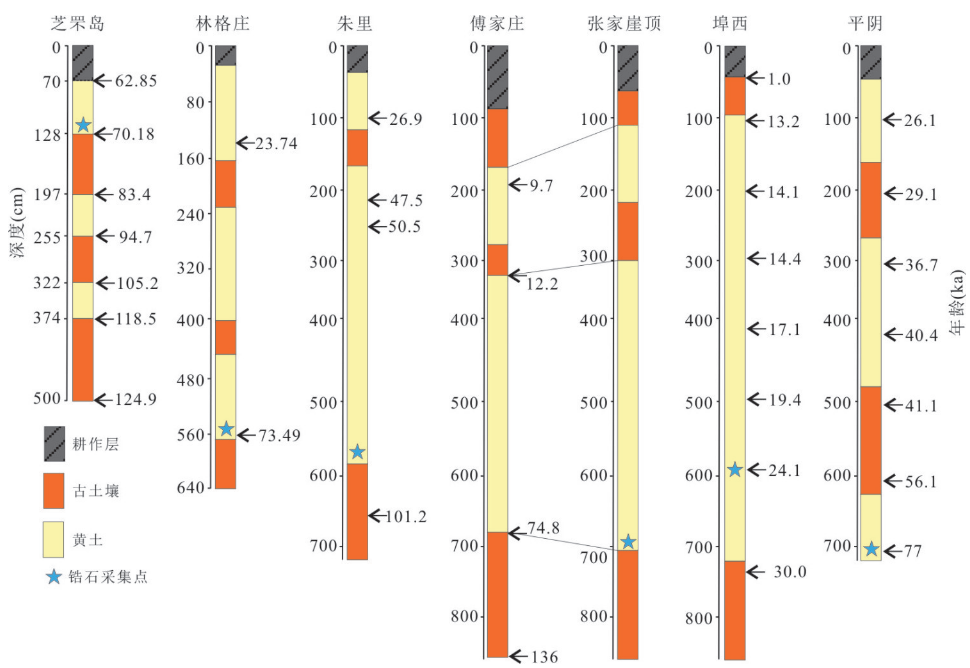

图 3　晚更新世山东黄土及其年龄分布柱状图

Fig.3　Histogram of Shangdong loess in the Late Pleistocene and its age distribution.

芝罘岛结果据黎武标等(2019a);林格庄结果据徐树建和王涛(2011);朱里结果据李强(2014);傅家庄结果据彭淑贞等(2010);埠西结果据徐树建等(2014);平阴结果据徐树建等(2016).张家崖顶剖面采样点年龄通过与其邻近傅家庄剖面进行对比,限定在晚更新世

17′31″)的晚更新世黄土剖面进行碎屑锆石样品采集,每个点大约采集3～5 kg样品(图3).芝罘岛剖面的年龄结果引用黎武标等(2019a)的结果,林格庄剖面的年龄结果来自徐树建和王涛(2011),朱里剖面的年龄采用李强(2014)发表的数据,张家崖顶剖面的年龄通过与邻近傅家庄剖面对比获得(彭淑贞等, 2010).埠西剖面的年龄来自徐树建等(2014)的结果,平阴剖面的年龄引用自徐树建等(2016)的结果.此次采集的样品均为黄土层,地层年龄分布范围集中在晚更新世末次间冰期以来,由于芝罘岛剖面靠近海边,其顶部的黄土层已被侵蚀掉;林格庄、傅家庄、张家崖顶、埠西和平阴剖面发育较弱的古土壤层.由于受地形等因素的影响,导致上述剖面的同期沉积厚度有所差异.每一个剖面笔者采集一个样品.

2.2 实验方法

将野外采集回来的黄土样品经重砂分析、磁性分选等一系列过程,将锆石颗粒分离出来,并在双目显微镜下进行人工挑选提纯.每个样品挑选出来的锆石颗粒均在1 000粒以上,随机挑选大于300颗制成环氧树脂靶,并对靶片进行表面抛光处理.然后对所有样品进行阴极发光(CL)图像拍摄,了解样品的外部(如矿物裂纹、矿物蚀变和夹杂物)和内部结构,避开包裹体和裂隙部位,选择某一颗粒的分析位置,提高分析精度.

锆石U-Pb同位素定年在南京宏创地质勘查技术服务有限公司微区分析实验室,使用激光剥蚀-电感耦合等离子体质谱仪(LA-ICPMS)完成.激光剥蚀平台采用Resolution SE型193 nm深紫外激光剥蚀进样系统(Applied Spectra,美国),配备S155型双体积样品池.质谱仪采用Agilent 7900型电感耦合等离子体质谱仪(Agilent,美国).详细的调谐参数见Thompson *et al.* (2018),锆石样品固定在环氧树脂靶上,抛光后在超纯水中超声清洗,分析前用分析级甲醇擦拭样品表面.采用5个激光脉冲对每个剥蚀区域进行预剥蚀(剥蚀深度约0.3 μm),以去除样品表面可能的污染.在束斑直径30 μm、剥蚀频率5 Hz、能量密度2 J/cm^{2}的激光条件下分析样品.数据处理采用Iolite程序(Paton *et al.*, 2010),锆石91500作为校正标样,GJ-1作为监测标样,每隔10～12个样品点分析2个91500标样及一个GJ-1标样.通常采集20 s的气体空白,35～40 s的信号区间进行数据处理,按指数方程进行深度分馏校正(Paton *et al.*, 2010).以NIST 610作为外标,^{91}Zr作为内标计算微量元素含量.本次实验过程中测定的91500(1 061.5±3.2 Ma, 2σ)、GJ-1 (604±6 Ma, 2σ)年龄在不确定范围内与推荐值一致.选择^{206}Pb/^{238}U(年龄小于1 000 Ma)与^{207}Pb/^{235}U或^{207}Pb/^{206}Pb(年龄大于1 000 Ma)谐和度在90%～99%之间的结果.锆石样品的U-Pb年龄计算采用Isoplot/Ex_ver3完成.基于Kolmogorov-Smirnov(K-S)统计方法的多维判别图(MDS)用于辅助判别样品年龄的远近关系(Vermeesch *et al.*, 2016).

3 实验结果

此次共分析430颗锆石颗粒,共420颗锆石年龄合格.所分析样品中的锆石呈圆状和次圆状以及棱角状,如果忽略棱角状锆石的断裂面,其他部分仍然显示出圆形-次圆形.细颗粒(<50 μm)锆石占大部分,以粉砂和粘土为主,属于典型的远源风成沉积.另外,图4中不少颗粒>50 μm,甚至大于100 μm的现象,强烈暗示这些颗粒的近端起源.锆石粒径大小出现明显差异,具有振荡环带的锆石居多,此次分析的大部分锆石的Th/U比值>0.1(图5),代表岩浆成因,同时也有6颗变质锆石.

芝罘岛剖面的黄土锆石年龄出现多个峰值,主要集中在131 Ma、301 Ma、451 Ma、1 882 Ma和2 494 Ma,同时出现本次分析的最年轻峰值年龄:47 Ma(图6a).相比芝罘岛,林格庄的黄土样品缺乏新太古代和古元古代峰值年龄,出现中生代和古生代峰值年龄:131 Ma,255 Ma和443 Ma (图6b).朱里剖面的黄土锆石U-Pb年龄具有新太古代(2 532 Ma)和古元古代(1 888 Ma)峰值年龄,同时具有132 Ma、264 Ma和423 Ma的峰值(图6c).在张家崖顶的样品中,同时出现多个锆石U-Pb峰值年龄:131 Ma、263 Ma、436 Ma、749 Ma、788 Ma和2 520 Ma(图6d).埠西剖面的黄土锆石中生代峰值年龄集中在230 Ma,古生代峰值年龄集中在255 Ma和428 Ma,并出现728 Ma和968 Ma两个新元古代峰值年龄,同时具有1 877 Ma和2 536 Ma的古元古代和新太古代峰值年龄(图6e).平阴黄土除了出现中生代峰值(229 Ma)以外,晚古生代峰值年龄为450 Ma (图6f),新元古代峰值为758 Ma,并具有古元古代(1 817 Ma)和新太古代(2 523 Ma)峰值年龄(图6j).

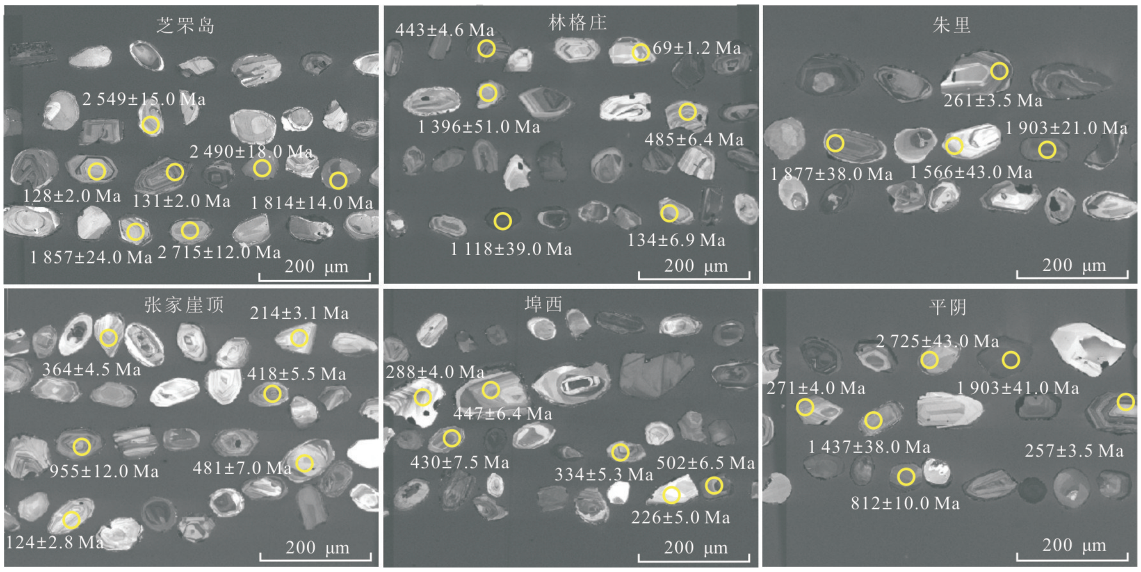

图4　山东黄土锆石CL图像

Fig.4　CL images of zircon grains from the loess of Shandong Province

图中圆圈代表分析点位置

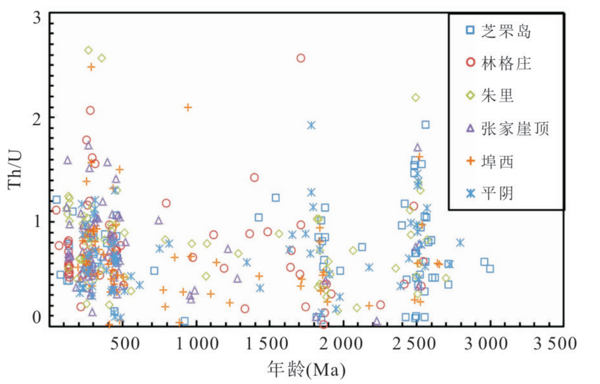

图5　山东黄土碎屑锆石U-Pb年龄与Th/U比二维散点图

Fig.5　Two-dimensional scatter plots of U-Pb age and Th/U ratio of detrital zircons from Shandong Province

4　讨论

将胶东半岛北部滨海和山东中部山地北麓黄土的碎屑锆石U-Pb年龄峰值组成与潜在物源区进行对比(图7)，结合MDS图综合判别(图8)，可以很清楚地判别这些晚更新世黄土的物质来源．从图7a和图7b中对比后可以清楚地看到，虽然芝罘岛黄土的碎屑锆石U-Pb峰值年龄与所在地芝罘岛存在明显差异，具体表现在芝罘岛基岩锆石不存在古生代和新生代U-Pb年龄，但二者同时具有古元古代、新太古代和中太古代峰值年龄，并且分布形态高度相似，在MDS判断图中同样可以看到二者的相关性．结合芝罘岛黄土中出现的棱角状砾石与当地芝罘岛基岩的岩性高度吻合(牛洪燕等，2010)，说明芝罘岛基岩风化后的碎屑物质成为芝罘岛黄土的物质来源之一，而芝罘岛黄土其他锆石主要来自外部源区．渤海湾盆地在始新世进入陆内裂谷的高潮(Li *et al.*，2012)，盆地内出现大量同期的岩浆锆石年龄(Sun *et al.*，2020)，在后期经历多期沉积再循环过程暴露于晚更新世渤海海底，同时对比其他主要潜在的物源区，都缺乏这部分锆石年龄，因而芝罘岛黄土内出现的新生代锆石年龄(47 Ma)很可能来自渤海湾盆地内部(图7c)．芝罘岛黄土的碎屑锆石U-Pb峰值年龄组成与胶北基岩(图7e)也存在明显差异，这主要体现在后者古元古代和新太古代峰值不明显(图7e)．芝罘岛黄土与渤海中部晚更新世钻孔的碎屑锆石U-Pb峰值年龄组成最显著的差别在于前者具有新生代峰值年龄(47 Ma)．芝罘岛黄土新元古代锆石峰值年龄不显著，因而据此判定莱阳盆地(图7g)、黄河下游(图7p)、塔里木盆地(图7r)、黄土高原(图7u)、青藏高原东北缘(图7v)和柴达木盆地(图7w)与芝罘岛之间没有紧密的物源联系．芝罘岛黄土与阿尔泰戈壁(图7t)的锆石U-Pb年龄峰值同样存在显著差异，主要因为后者同时缺乏古元古代、新太古代和中太古代峰值年龄．而与浑善达克沙漠(图7s)相比，芝罘岛黄土同时具有新生代、古元古代、新太古代和中太古代峰值，因而可以判定上述区域并不是芝罘岛黄土的物源区．此外，可以清晰看到芝罘岛黄土与华北平原(图7q)的锆石

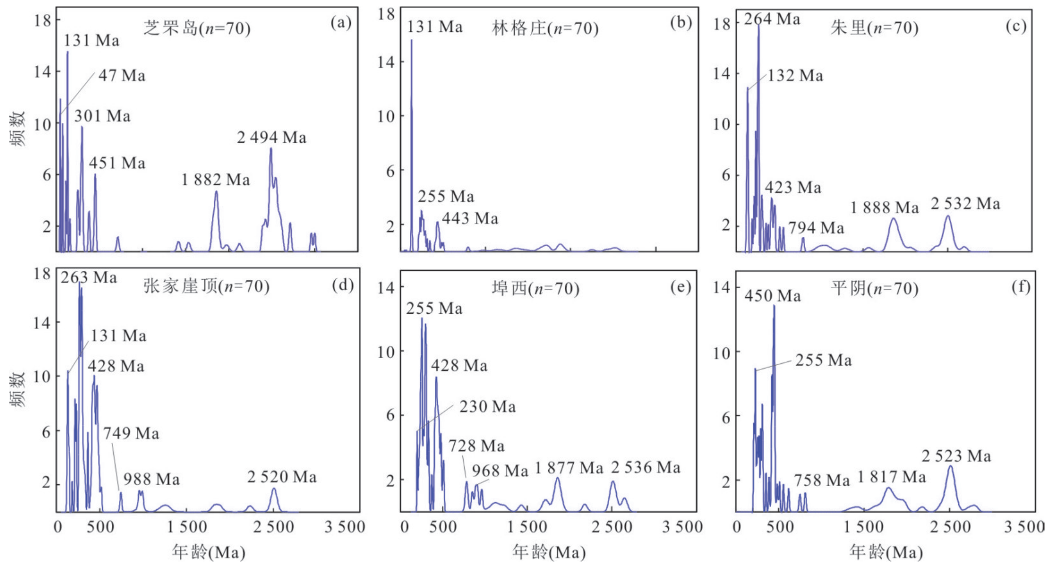

图6 山东黄土碎屑锆石U-Pb年龄频率分布

Fig.6 U-Pb age frequency distribution map of loess zircons from Shandong Province

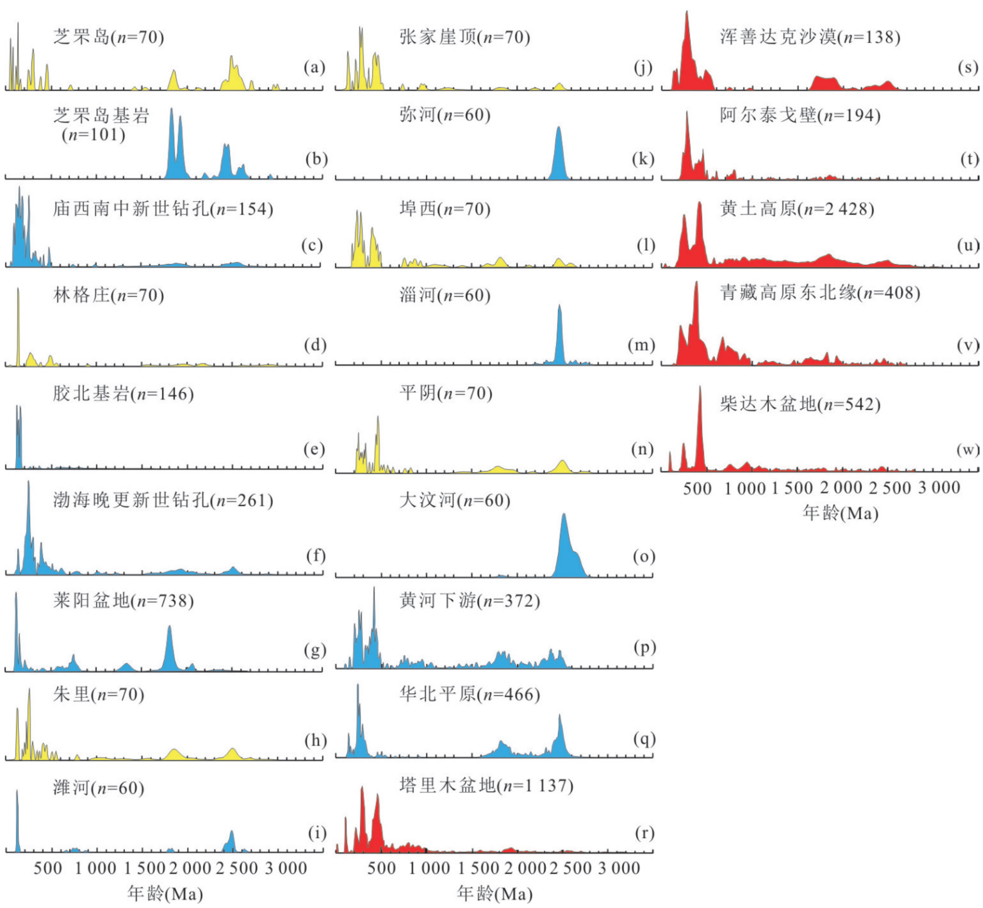

图7 山东黄土和潜在物源区的锆石U-Pb年龄频率分布

Fig.7 U-Pb age frequency distribution of zircons from the loess and potential provenance regions of the Shandong Province

a、d、h、j、l、n. 本次研究；b. Liu *et al.* (2013)；c. Sun *et al.* (2020)；e. 张田和张岳桥 (2008)；f. Huang *et al.* (2020)；g. Zhang *et al.* (2019)；i、k、m、o. 林旭未发表数据；p. Yang *et al.* (2009)、Nie *et al.* (2015)；q. Yang *et al.* (2009)、林旭等 (2020)；r. Xie and Ding (2007)、Rittner *et al.* (2016)；s. Stevens *et al.* (2010)；t. Zhang *et al.* (2016)；u. Stevens *et al.* (2010)；Nie *et al.* (2014)、Gong *et al.* (2017)、Xiong *et al.* (2021)；v. Zhang *et al.* (2016)；w. Pullen *et al.* (2011). 图中黄色、蓝色和红色分别代表黄土剖面、近源区、远源区

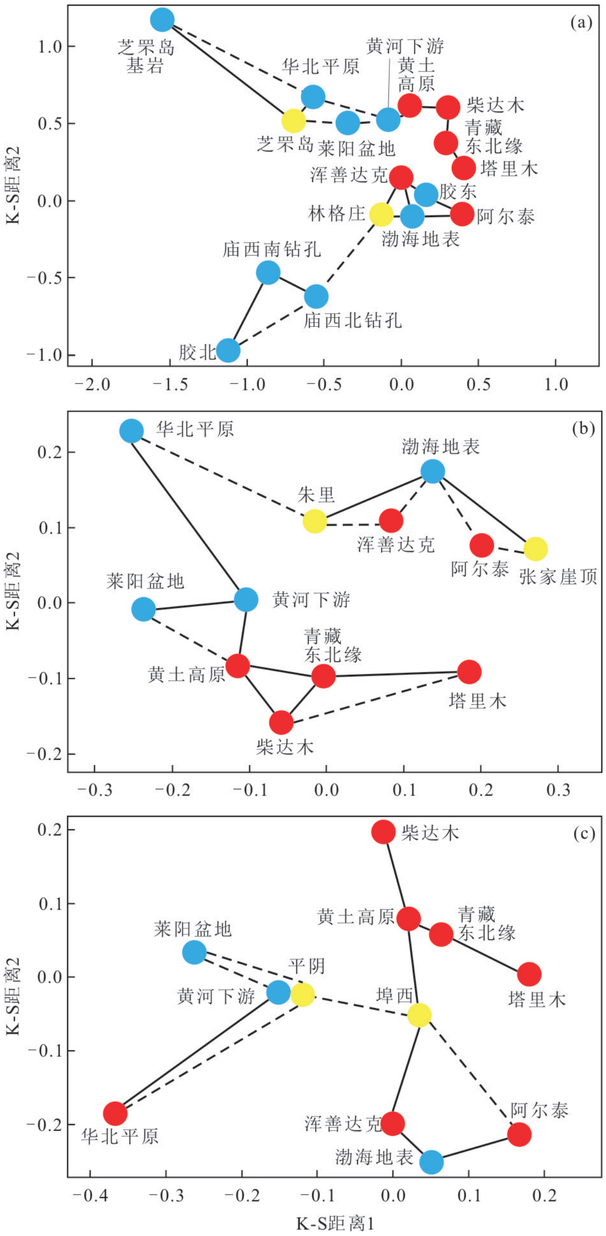

图8　山东黄土锆石U-Pb年龄之间的K-S距离MDS图

Fig.8　MDS plot showing the K-S distances between the zircon U-Pb ages of Shandong Province

图中黄色、蓝色和红色分别代表黄土剖面、近源区、远源区

U-Pb年龄组成和分布形态高度相似,这也进一步体现在MDS判断结果中(图8a).综合来看,芝罘岛黄土主要来自芝罘岛基岩风化剥蚀和华北平原的碎屑物质.这与牛洪燕等(2009, 2010)对芝罘岛南岸的晚更新世黄土进行的重矿物和粒度物源示踪结果,揭示其具有多源性和近源性的结论一致.

蓬莱林格庄黄土锆石U-Pb峰值年龄(图7d)与胶北地体(图7e)的碎屑锆石U-Pb峰值年龄组成存在明显不同,这主要体现在胶北基岩的古生代峰值年龄不显著,因而说明二者不具有物源联系.此外,蓬莱林格庄黄土不具有新元古代峰值年龄,与莱阳盆地(图7g)、黄河下游(图7p)、塔里木盆地(图7r)、黄土高原(图7u)、青藏高原东北缘(图7v)和柴达木盆地(图7w)相比,锆石峰值年龄组成和分布形态都存在差异.在与浑善达克沙漠(图7s)以及阿尔泰戈壁(图7t)的锆石U-Pb年龄谱对比中,蓬莱林格庄黄土的中生代锆石U-Pb年龄集中在一个峰值(131 Ma),组成相对单一,而上述沙漠和戈壁地区的晚中生代峰值年龄缺乏,而其与渤海晚更新世钻孔结果十分吻合(132 Ma; Huang *et al.*, 2020; 图7f).另外,蓬莱林格庄黄土的古生代锆石U-Pb年龄出现两个典型峰值:255 Ma和443 Ma(图6b),这同样主要和渤海晚更新世钻孔结果一致.此外,结合MDS图判断结果(图8a),进一步说明蓬莱林格庄黄土主要来自晚更新世渤海海底表面裸露的碎屑物质.晚更新世,渤海的碎屑物质主要来自黄河(Huang *et al.*, 2020),除此以外发源于燕山和太行山的大河则是渤海同期另外重要的碎屑物质来源(Xu *et al.*, 2017; 林旭等, 2020),在晚更新世海平面下降时暴露于地表,因而渤海陆架物质自身碎屑物质组成存在多样性,因而经过强劲的东亚冬季风的搬运,来自不同区域的碎屑物质各自成为芝罘岛与蓬莱林格庄黄土的物质供给,导致这两个地区的黄土在物源上存在一定差异.这与庙岛群岛(曹家欣, 1987; 倪志超, 2015)和蓬莱沿海(Tian *et al.*, 2019)多个剖面的黄土物源示踪结果吻合.因而,胶东半岛北部海岸末次冰期的黄土主要以近源物质为主.

潍坊朱里(图7h)和青州张家崖顶(图7j)黄土锆石U-Pb峰值年龄组成相似,它们最主要的特征就是中生代和古生代峰值年龄组成复杂,与其附近的潍河(图7i)和弥河(图7k)的碎屑锆石U-Pb峰值年龄组成截然不同,可以判定山东中部山地并不是这些黄土的物源区.同时,其与莱阳盆地(图7g)、黄河下游(图7p)、塔里木盆地(图7r)、黄土高原(图7u)、青藏高原东北缘(图7v)和柴达木盆地(图7w)相比,又缺乏新太古代峰值年龄,说明它们之间不存在物源关系.在MDS图中(图8b),可以看到潍坊朱里和青州张家崖顶的黄土锆石U-Pb年龄组成分别与浑善达克(图7s)和阿尔泰戈壁(图7t)的相近,但在锆石U-Pb峰值年龄组成中,前者都具有显著的晚中生代(131~132 Ma)峰值;同时考虑到渤海

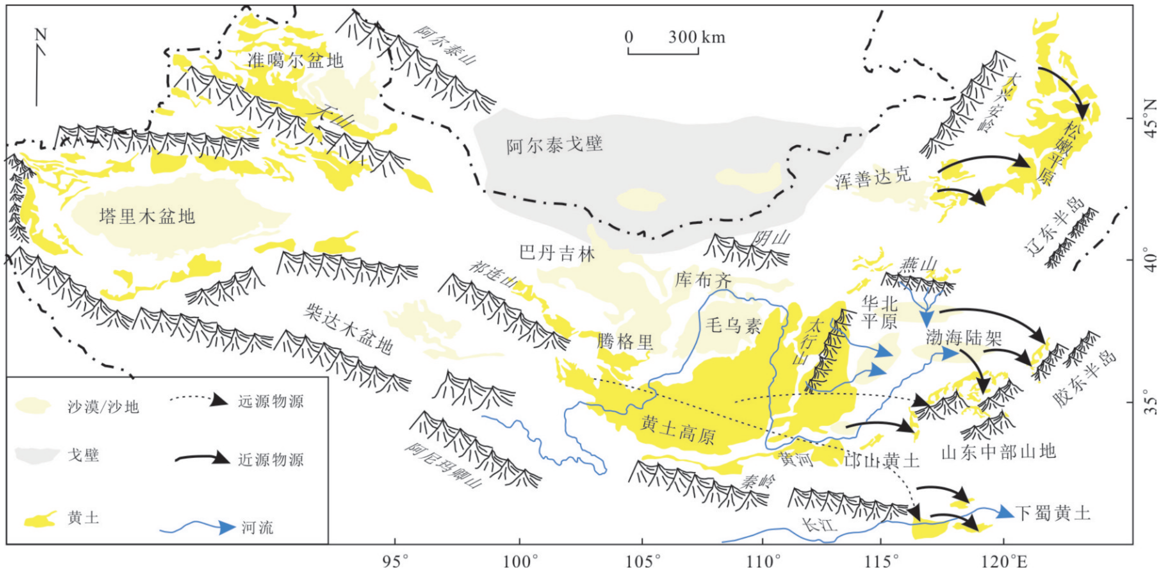

图 9　晚更新世山东黄土物源区分布示意

Fig.9　Schematic diagram of source area distribution of Late Pleistocene loess in Shandong Province

晚更新世钻孔(图 7f)具有明显的晚中生代年龄峰值(132 Ma),进一步结合所有的年龄分布特征和二者都与渤海晚更新世钻孔物质的MDS判断距离相近(图 8b),据此认为山东中部山地东段的这些黄土来自渤海晚更新世暴露的陆架物质,中国西部内陆沙漠和戈壁碎屑物质的影响较小.李强(2014)对潍坊朱里镇黄土剖面开展的粒度测试,结果表明其与黄土高原存在明显差异,他推断朱里剖面黄土物质来自末次冰期出露的渤海陆架物质,这与青州傅家庄黄土的粘土矿物(彭淑贞等,2010;王亚男,2013)、细粒物质的 $^{234}U/^{238}U$ 比值(李高军等,2017)、粒度和全岩主量元素(Peng *et al.*,2016)物源示踪结果一致.所以,山东中部山区北麓东段的黄土主要以近源物质为主.

将山东中部山区北麓西段的章丘埠西(图 7l)和平阴(图 7n)黄土的碎屑锆石U-Pb年龄组成与东段的朱里和张家崖顶进行对比后,可以看到其共同的特征是都具有多个峰值,但差异在于西段黄土不具有晚中生代锆石峰值(131~132 Ma),在MDS图中埠西、平阴黄土和渤海晚更新世钻孔距离较远(图 8c),说明它们与渤海晚更新世物质不存在物源关系.与此同时,区域内的淄河(图 7m)和大汶河(图 7o)的锆石U-Pb年龄组成相对单一,主要以新太古代峰值年龄为主,因而山东中部山地与埠西和平阴黄土也不存在物源关系.将华北平原(图 7q)锆石U-Pb峰值年龄组成与埠西黄土进行比较,前者不具有新元古代峰值年龄;埠西黄土与黄河下游(图 7p)碎屑锆石U-Pb峰值年龄组成最主要的差异体现在,前者不具有新元古代晚期的峰值年龄;与阿尔泰戈壁(图 7t)相比,埠西黄土同时具有古元古代和新太古代峰值年龄,因此上述区域应该不是埠西黄土的主要物源区.通过对比可以发现,埠西黄土与黄土高原(图 7u)的锆石U-Pb峰值组成相似性高,在MDS判断中二者距离最近,结合埠西黄土的常量元素和粒度物源示踪结果,表明其与黄土高原具有紧密的物源属性关联(丁新潮,2016);因而,埠西黄土的物源区主要来自黄土高原.平阴黄土与华北平原(图 7q)相比,具有新元古代峰值年龄;和塔里木盆地(图 7r)、阿尔泰戈壁(图 7t)相比,平阴黄土同时具有古元古代和新太古代峰值年龄,因而上述区域均不是平阴黄土的物源区.通过对比可见,平阴黄土在锆石U-Pb年龄组成和MDS距离分布上,主要与黄河下游(图 7p)碎屑物质相近.这主要因为华北平原主要是黄河形成的冲积平原,位于研究区的上风向,而且考虑到黄河经常性的泛滥和移动,其含有丰富碎屑的河床和洪泛平原必将是一个重要的物源区.平阴晚更新世黄土的稀土元素(丁新潮,2016)、全岩Sr和Nd同位素物源示踪结果(付信花,2014),表明其物源主要来自华北平原.Ding *et al.*(2018)根据全岩主量元素物源示踪的结果认为平阴晚更新世黄土的物源主要以黄河下游的河漫滩物质为主.郑州西北部的邙山黄土碎屑锆石U-Pb年龄物源示踪结果表明,其物质主要来自黄河下游的河漫滩物质(Shang *et al.*,2018).因而,黄河下游

河漫滩的碎屑物质对平阴黄土的物源具有重要影响.受到区域地理位置的影响,山东中部山地北麓西段(埠西和平阴)和其东段(朱里和张家崖顶),以及胶东半岛北部海岸黄土的物源区存在差异.

进入晚更新世以来,受末次冰期的影响,渤海发生大规模的海退(赵希涛等,1979;岳保静等,2020),大陆架面积较之间冰期明显增加,大量碎屑物质暴露地表,同时华北平原北部和西部发源于燕山和太行山的大河以及西南部的黄河,将大量碎屑物质搬运到华北平原,这些碎屑物质在强劲的东亚冬季风的吹拂下,就近分别搬运到胶东半岛和山东中部山地北麓东段以及西段堆积(图9).与此同时,位于东亚冬季风运动路径的中国西北内陆的戈壁以及黄土高原的粘土-粉砂级的碎屑物质被吹离原地,受到距离衰减以及山东中部山地的阻挡,这些远源搬运的碎屑物质落入山东中部山地北麓西段沉积(图9).此外,碎屑锆石U-Pb年龄和全岩主量元素地球化学物源示踪结果表明,长江下游分布广泛的下蜀黄土主要以长江下游的河流、湖泊和山麓物质为主(图9),而西北内陆沙漠和黄土远源碎屑物质的贡献占据次要位置(Wang *et al.*, 2018).重矿物、全岩主微量元素和Sr-Nd同位素分析表明,松嫩平原的黄土主要来自松嫩平原和其附近的沙地(Kang *et al.*, 2013; Xie *et al.*, 2019;图9).因此,在黄土高原以外中国东部沉积的黄土主要以近源物质为主,远源物质输入为辅.

5　结论

通过对山东胶东半岛北部沿海和山东中部山区北部山麓的晚更新世黄土进行碎屑锆石U-Pb年龄分析,结合MDS图结果,与上述地区的近源地区和远源潜在物源区进行对比,笔者获得如下结果:

(1)胶东半岛北部海岸和山东中部山地北麓东段的晚更新世黄土,主要来自渤海裸露的大陆架和华北平原,受中国西北内陆干旱区的影响小.

(2)由于地理位置的差异,山东中部山地北麓西段的晚更新世黄土具有黄土高原和黄河下游的物质信号,而与晚更新世渤海末次冰期裸露在海底的沉积物的物源关系较弱.

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