黄河中新世末进入渤海湾盆地：来自碎屑锆石 U-Pb 年龄的约束

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内容提要：黄河是中国北方最大河流，其发育和形成对中国北部三大地势阶梯的建立具有重要指示意义。但到目前为止，有关黄河的形成时代存在较大争议。基于此，本文对鲁中山区的河流进行碎屑锆石 U-Pb 年龄分析（n=240），与流入渤海湾盆地的辽河、滦河、永定河、滹沱河、漳河和黄河的锆石 U-Pb 年龄进行对比，从而确定黄河因具有显著的新元古代峰值年龄（1000～700 Ma）成为渤海湾盆地的特征河流。本文将黄河下游的碎屑锆石 U-Pb 峰值年龄与渤海湾盆地中新统钻孔的锆石 U-Pb 峰值年龄进行对比，结合多维判别图（MDS），结果表明黄河在中新世末进入渤海湾盆地。

关键词：渤海湾盆地；黄河演化；锆石；U-Pb 年龄；物源示踪

随着印度板块和太平洋板块向欧亚大陆俯冲，塑造了世界海拔最高的青藏高原（Liu Zengjing et al.，2008；Li Jijun et al.，2014；Wang Chengshan et al.，2014）和东亚地区面积广阔的边缘海系统（Ren Jianye et al.，2002；Wang Pinxian，2004）。在大河的串联下（黄河和长江）青藏高原与中国东部陆架海组成了规模宏大的源-汇沉积系统（Yang Shouye et al.，2016；Pang Hongli et al.，2018；Lin Xu et al.，2020）。认识这一源-汇系统的发展过程，不仅为探索东亚地区海陆交互作用提供基础支撑，也能提供这些大河的演化信息，对中国三大地势阶梯的建立具有重要指示意义，也是探索青藏高原构造-气候-沉积系统科学研究的重要组成部分。其中尤以中国北部最大河流，发源于青藏高原东北部，流经积石山、鄂尔多斯盆地、华北平原，最终流入渤海的黄河最受关注（Pan Baotian，1991；图 1）。因而，国内外研究者通过地层对比、河流阶地时代、钻孔物源示踪对其源汇过程开展了广泛研究，目前有关黄河形成时代集中在＞34 Ma（Lin Aimin et al.，2001）、8 Ma（Bao Guodong et al.，2020；Liu Yunming，2020）、5.2～4.5 Ma（Li Weidong et al.，2020；Zhao Xitao et al.，2020；Zhang Hanzhi et al.，2021）、3.6～3.3 Ma（Nie Junsheng et al.，2015；Guo Benhong et al.，2018；Zhao Xitao et al.，2018；Wang Zhao et al.，2019）、2.8～2.5 Ma（Jia Liyun et al.，2017；Li Xuemei et al.，2020）、1.8～1.2 Ma（Pan Baotian et al.，2009；Hu Xiaofei et al.，2011；Kong Ping et al.，2014；Zhang Huiping et al.，2014；Hu Zhenbo et al.，2016；Li Zhongyuan et al.，2020；Xiao Guoqiao et al.，2020）、0.9～0.8 Ma（Yao Zhengquan et al.，2017；Shang Yuan et al.，2018；Zhang Jin et al.，2019）、0.6～0.5 Ma（Craddock et al.，2010；Su Qi et al.，2020）、0.15～0.01 Ma（Fu Jianli et al.，2013；Wang Shubing et al.，2013）。因而，可以明显看出，目前有关黄河的形成时代存在较大争议。

河流的发育过程对区域构造活动、气候变化反应灵敏，是追溯地球深部过程与地表圈层相互作用的有效对象，更是重塑区域内地貌演化的重要载体（Yang Shouye et al.，2001；Zheng Hongbo，2015；

注：本文为国家自然科学基金项目（编号 41972212）资助的成果。
收稿日期：2020-04-06；改回日期：2020-08-24；网络发表时间：2021-11-08；责任编委：张永双；责任编辑：潘静。
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引用本文：林旭，刘海金，刘静，陈济鑫，李玲玲．2022．黄河中新世末进入渤海湾盆地：来自碎屑锆石 U-Pb 年龄的约束．地质学报，96（7）：2506～2518，doi：10.19762/j.cnki.dizhixuebao.2022004．
Lin Xu，Liu Haijin，Liu Jing，Chen Jixin，Li Lingling．2022．The Yellow River did not enter the Bohai Bay basin during the Miocene：constraints from detrital zircon U-Pb ages．Acta Geologica Sinica，96(7)：2506～2518．

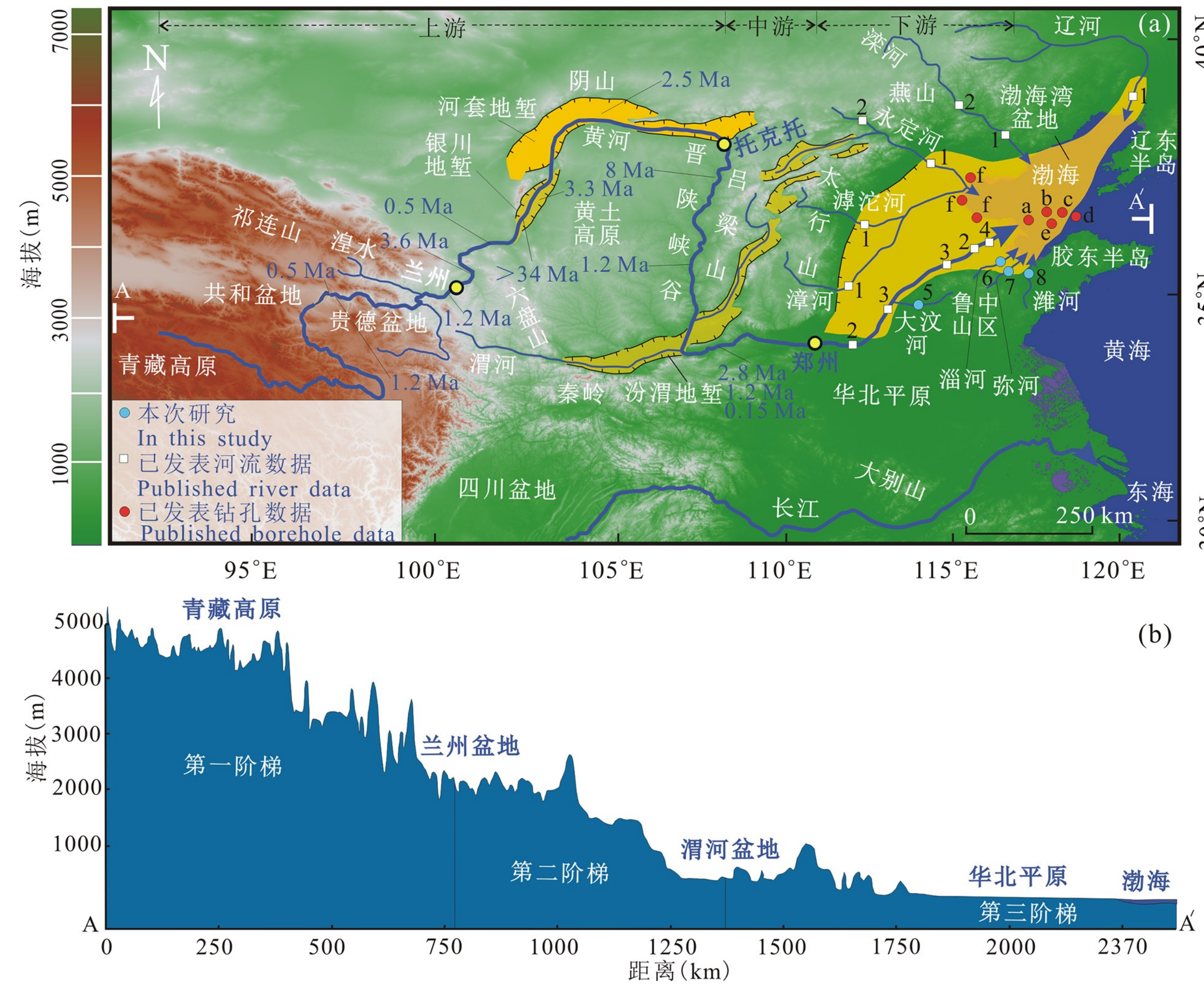

图 1　黄河流域和渤海湾盆地位置分布图(a)和黄河流域纵剖面(b)(与图 1a 中的 A—A′位置一致)

Fig. 1　Location map of the Yellow River basin and the Bohai Bay basin (a) and longitudinal section of the Yellow River basin (b)(corresponding to the A—A′ position in Fig. 1a)

图中数字 1～4 为渤海湾盆地已发表河流锆石数据:1 据 Lin Xu et al.,2021a;2 据 Yang Jie et al.,2009;3 据 Nie Junsheng et al.,2015;4 据 Zheng Ping et al.,2013;5～8 为此次分析的鲁中山区河流碎屑锆石;a～e 为渤海湾盆地渤中凹陷钻孔锆石数据:a 据 Liu Tao, 2020;b～c 据 Zhao Meng et al.,2019a, 2019b;d 据 Sun Zhongheng et al.,2020;e 据 Li Mengyun, 2018;f 据 Xiao Guoqiao et al.,2020

1～4 in the figure are published river zircon data of the Bohai Bay basin:1 after Lin Xu et al.,2021a; 2 after Yang Jie et al.,2009; 3 after Nie Junsheng et al.,2015; 4 after Zheng Ping et al.,2013; 5～8 are the detrital zircons from rivers in the central mountainous area of Shandong Province; a～e are zircon data from borehole in Bozhong sag, Bohai Bay basin: a after Liu Tao, 2020; b～c after Zhao Meng et al.,2019a, 2019b; d after Sun Zhongheng et al.,2020; e after Li Mengyun, 2018; f after Xiao Guoqiao et al.,2020

Lin Xu et al., 2017; Liu Jing et al., 2018)。来源于河流下游卸载盆地的碎屑沉积物,系统保存了河流自身的发育过程(汇),通过将其与潜在物源区(源)进行对比,结合沉积地层的年代,是开展大河形成时代研究的有效方法(Zhang Yufen et al., 2008; Fu Xiaowei et al., 2021)。碎屑锆石是河流沉积物和沉积盆地中广泛存在的副矿物,是进行 U-Pb 年龄测定的理想矿物(Belousova et al., 2002; Huang Xiangtong et al., 2020),通过与潜在源区的岩浆或变质成因锆石及主要构造事件的 U-Pb 年代进行对比,被广泛应用于沉积源区分析和古地理重建(Yang Jie et al., 2009; Lin Xu et al., 2021a, 2021b)。进入新近纪,随着青藏高持续隆升阻隔了来自印度洋和太平洋的湿润空气深入中国西北内陆,在增加其干旱化的同时(Guo Zhengtang et al., 2004; Miao Yunfa et al., 2012),也加大了海陆热力性差异(Lu Huayu et al., 2019),进而驱动稳定的东亚季风开始出现(An Zhisheng et al., 2001; Guo Zhengtang et al., 2002)。那么在此背景下,贯通的黄河水系是否在中新世出现?渤中坳陷夹于辽

东半岛和胶东半岛之间(图 2),位于渤海湾盆地的中央部位,是渤海物质进入黄海的必经之地,同时保留最厚的中新统地层(Zhu Xia et al., 1990),因而对其开展物源示踪研究,能提供黄河是否在此时出现在渤海湾盆地至关重要的判断信息。然而,以往的研究主要关注油气资源评价方面(Li Mengyun, 2018; Zhao Meng et al., 2019a, 2019b; Liu Tao, 2020; Sun Zhongheng et al., 2020),未对这些钻孔记录的河流演化信息进行解译。因此,为厘定上述黄河形成时代研究存在的争议,并验证我们此次提出的科学假设,本文对渤海湾盆地南缘鲁中山区的河流开展碎屑锆石 U-Pb 年龄研究(源),综合渤海湾盆地主要汇入河流辽河、滦河、永定河、漳河、滹沱河(Lin Xu et al., 2021a)和黄河下游(Yang Jie et al., 2009; Zheng Ping et al., 2013; Nie Junsheng et al., 2015)的河流碎屑锆石 U-Pb 年龄(源),将其与渤海湾盆地(汇)渤中坳陷的中新统钻孔的碎屑锆石 U-Pb 年龄进行对比,系统判别黄河在中新世是否进入渤海湾盆地,从而为渤海湾盆地的盆山耦合以及黄河水系的形成过程提供对比数据。

1 地质背景

1.1 渤海湾盆地地层特征

渤海湾盆地是在华北克拉通基底上发育的中—新生代断陷、坳陷叠合盆地(Qi Jiafu et al., 2010; Li Sanzhong et al., 2012)。渤海湾盆地由坳陷和隆起组成。其中较大的坳陷分别为:辽河、渤中、黄骅、冀中、临清和济阳(Qiu Yan et al., 2016; 图 2)。

燕山运动后华北克拉通东部受西太平洋板块俯冲的影响较大(Li Sanzhong et al., 2012),导致其内岩石圈减薄,出现拉张-断陷,形成渤海湾盆地的雏形,同时堆积了含煤沉积、暗色砂泥岩、红色砂泥岩和中—酸性火山岩,最大厚度可达 4000 m (Zhu Xia et al., 1990)。孔店组(E_1k)在盆地内的沉积厚度接近 200 m,与下伏白垩系不整合接触,岩性以泥岩为主,局部含砂和粉砂岩(图 3a)。沙河街组(E_2s)堆积时期,渤海湾盆地发生强烈断陷,并奠定盆地的形成基础,堆积灰色砂岩、含砾砂岩、杂色砾岩夹深灰色泥岩,在地层底部往往有玄武岩层出现,在顶部常出现钙质页岩、泥灰岩、白云质灰岩、生物碎屑灰岩。始新统以陆相河、湖相沉积为主(Qiu Yan et al., 2016; 图 3b),厚度变化较大,最大可达 5000 m。东营组(E_3d)在渤海湾盆地内广泛分布,在陆域厚度较小,约 500~800 m,在海区分布厚度可达 1000~1800 m,在渤中坳陷可达 2000 m 以上。岩性较稳定,以河湖相暗色泥岩、灰色泥岩及砂泥岩互层为主,与始新统地层为连续沉积,经历了从深湖-半深湖-三角洲填充直至河流相完整的沉积演化过程,呈现"下细上粗"的沉积特征。渐新世是渤海湾盆地的主要形成时期,这时所有的断陷全部形成,主要接受近缘的燕山、太行山、鲁中山区和胶东半岛的碎屑物质(Tan Mingxuan et al., 2018; Chen

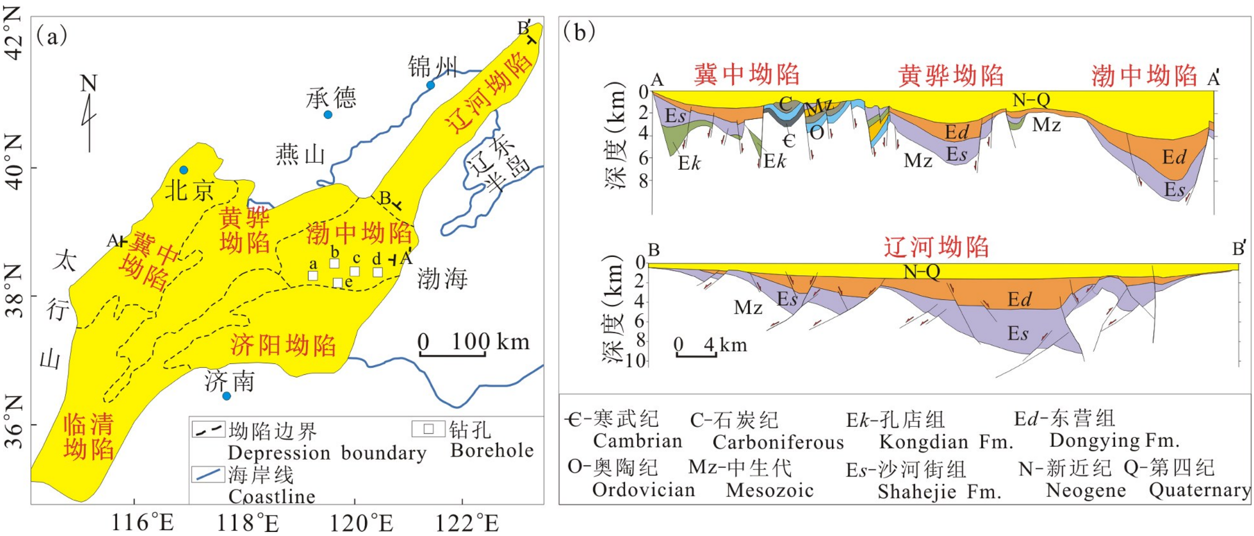

图 2 渤海湾盆主要坳陷位置图(a);剖面 A—A′和 B—B′地震反射剖面图(b)
(据 Qi Jiafu et al.,2010;与(a)图中位置相对应,a~e 同图 1)
Fig. 2 Location map of major depressions in Bohai Bay basin (a); A—A′ and B—B′ seismic reflection profiles (b) correspond to positions in Fig. 2a (after Qi Jiafu et al.,2010; a~e the same as Fig. 1)

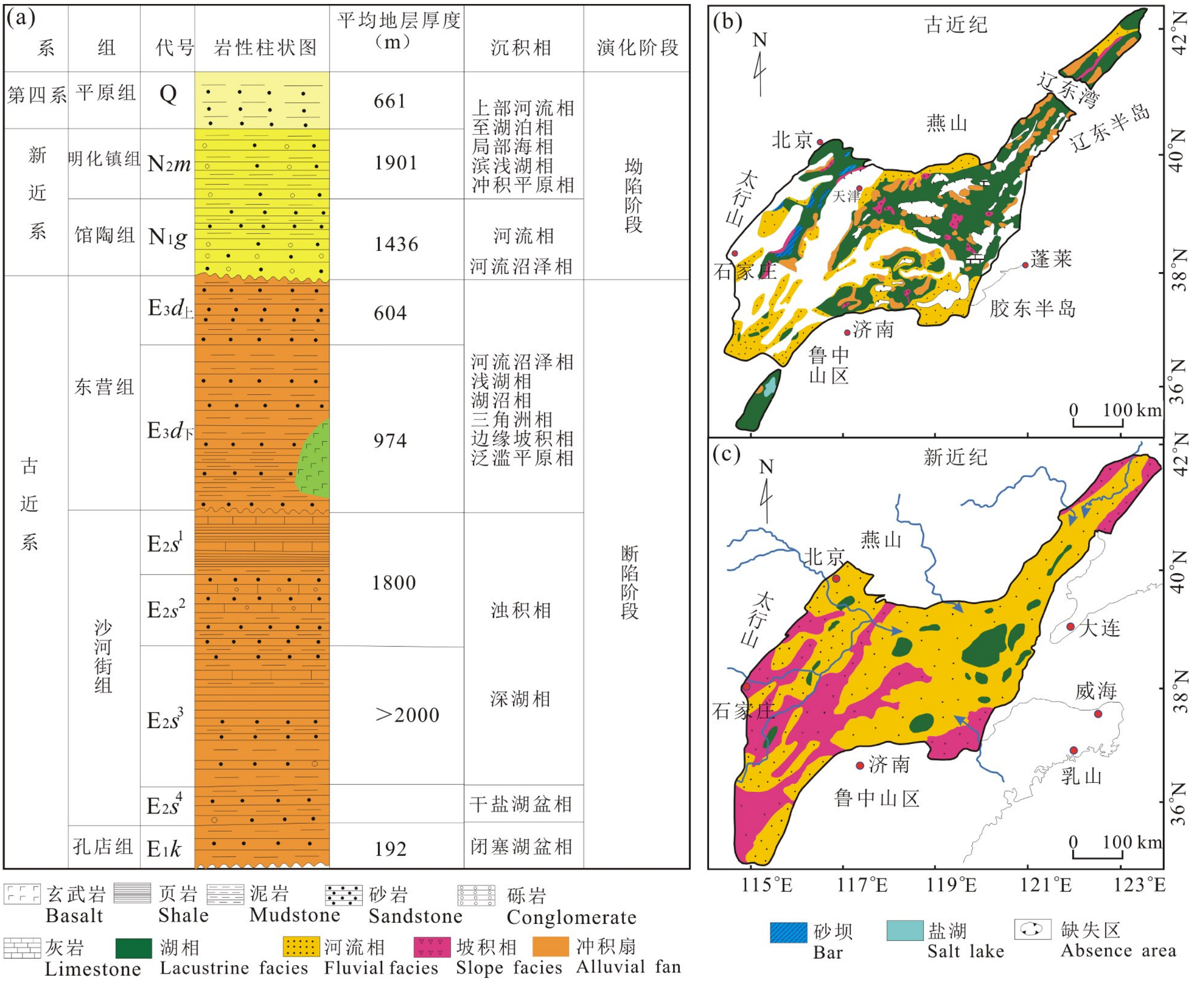

图 3　渤海湾盆地区域地层综合柱状图(a)(据 Qiu Yan et al.，2016)；渤海湾盆地古近系(b)和新近系沉积相分布图(c)(据 Qiu Yan et al.，2016)

Fig. 3　Comprehensive histogram of regional stratigraphy in Bohai Bay basin (a) (after Qiu Yan et al.，2016); sedimentary facies distribution maps of Paleogene (b) and Neogene in Bohai Bay basin (c) (after Qiu Yan et al.，2016)

Hehe et al.，2020；Sun Zhongheng et al.，2020)。馆陶组(N_1g)沉积期间，盆地内的断块活动基本终止，盆地开始整体沉降，其周围山脉相对上升。馆陶组在盆地内分布广泛，一般厚度在 1000 m 左右，但最大沉降中心在渤海湾盆地中部，厚度达到 2000 m，主要以河流、沼泽相灰白色厚层块状砂砾岩夹棕红色泥岩为主。明华镇组(N_2m)厚度比较稳定，一般为 1000～1500 m，在辽东湾岩性主要以河流相含砾砂岩为主，在渤中和渤西地区则以砂岩和泥岩为主(图 3c)。平原组(Q)地层分布稳定，厚度变化不大，一般 300～400 m，往沉积中心有加厚的趋势，岩性主要以灰黄色-土黄色黏土、砂质黏土与粉砂层、泥质砂层，多含钙质团块。

1.2　渤海湾盆地河流

汇入渤海的河流，从北到南主要有辽河、滦河、海河(永定河、滹沱河、漳河)、黄河、淄河、弥河和潍河等(图 1)。辽河全长 1390 km，是渤海东部最大河流。滦河全长 833 km，是渤海北部最大河流。永定河全长 747 km，滹沱河全长 587 km，漳河长 412 km，其在天津附近汇合形成海河水系。根据河流阶地和渤海钻孔的物源示踪结果(Wu Chen，2008；Qiu Yan et al.，2016；Chen Hehe et al.，2020；Tan Mingxuan et al.，2020)，辽河、滦河和海河在古近纪已开始发育，到新近纪逐渐向燕山和太行山内部延伸(图 3c)。黄河全长 5464 km，是世界上泥沙含量最高的河流(Li Li et al.，2020)。淄河长 155.1 km，弥河长 206 km，潍河长 233 km，大汶河长 239 km，这些河流是鲁中山区的主要河流。

2　样品来源及分析方法

2.1　样品来源

2017 年 10 月和 2020 年 5 月，笔者对大汶河、

表 1 碎屑锆石样品采样位置及采样信息

Table 1 Sampling locations and information of detrital zircon samples

样品编号	采样位置	经度(°E)	纬度(°N)	采样信息	沉积时代
1	辽河	122.804	41.751	边滩中细砂	现代
1	滦河	118.820	39.851	边滩中细砂	现代
1	永定河	116.053	38.983	河漫滩细砂	现代
1	滹沱河	115.079	38.172	边滩细砂	现代
1	漳河	114.141	36.530	河床细砂	现代
2	滦河	118.759	39.729	边滩中细砂	现代
2	永定河	116.234	39.764	边滩细砂	现代
2	黄河	113.663	34.906	边滩细砂	现代
2	黄河	118.392	37.610	边滩细砂	现代
3	黄河	115.110	35.430	边滩细砂	现代
3	黄河	119.160	37.760	边滩细砂	现代
4	黄河	119.097	37.852	边滩细砂	现代
5	大汶河	117.090	35.940	边滩中粗砂	现代
6	淄河	118.217	36.636	河床中粗砂	现代
7	弥河	118.541	36.355	河床中细砂	现代
8	潍河	119.375	36.684	河漫滩细砂	现代
a(BZ26-A)	渤中坳陷钻孔	119.361	38.094	砂岩	馆陶组
b(KL6-6-A)	渤中坳陷钻孔	120.101	37.846	砂岩	馆陶组
c(PL-15-2-12d)	渤中坳陷钻孔	120.685	38.446	砂岩	馆陶组
d(PL7)	渤中坳陷钻孔	120.007	38.614	砂岩	馆陶组
d(PL15)	渤中坳陷钻孔	120.409	38.614	砂岩	馆陶组
d(PL19-A)	渤中坳陷钻孔	120.105	38.402	砂岩	馆陶组
d(PL31)	渤中坳陷钻孔	120.054	38.117	砂岩	馆陶组
d(PL20)	渤中坳陷钻孔	120.271	38.341	砂岩	馆陶组
e(PL14)	渤中坳陷钻孔	120.320	38.518	砂岩	馆陶组
e(PL19-B)	渤中坳陷钻孔	120.080	38.366	砂岩	馆陶组
e(PL19-C)	渤中坳陷钻孔	120.103	38.357	砂岩	馆陶组
e(PL19-D)	渤中坳陷钻孔	120.103	38.315	砂岩	馆陶组

淄河、弥河和潍河河边滩开展样品采集工作，具体位置见表 1。此外，表 1 列举文中所引用的渤海湾盆地已发表的河流和沉积钻孔碎屑锆石 U-Pb 年龄采样点的基本信息，样品编号与图 1 中的位置对应。

2.2 实验方法

将野外采集回来的碎屑样品经重砂、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。每个样品随机挑选＞30 颗锆石制成环氧树脂靶，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，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。锆石样品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～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，91Zr 作为内标计算微量元素含量。本次实验过程中测定的 91500 (1061.5 ± 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＜1000 Ma) 与 $^{207}Pb/^{235}U$ 或 $^{207}Pb/^{206}Pb$ (年龄＞1000 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。

非矩阵多维标度 MDS (Multi-dimensional Scaling)统计分析是基于 K-S 统计方法(Vermeesch et al., 2016)，利用数据之间的相似性对数据进行成分分析，这种相似性分析已被广泛应用到碎屑锆石 U-Pb 年龄分析中。因此，本文采用该方法进行环渤海湾盆地河流与中新世钻孔的碎屑锆石 U-Pb 年龄组成相似/向异性分析，从而辅助判断黄河何时

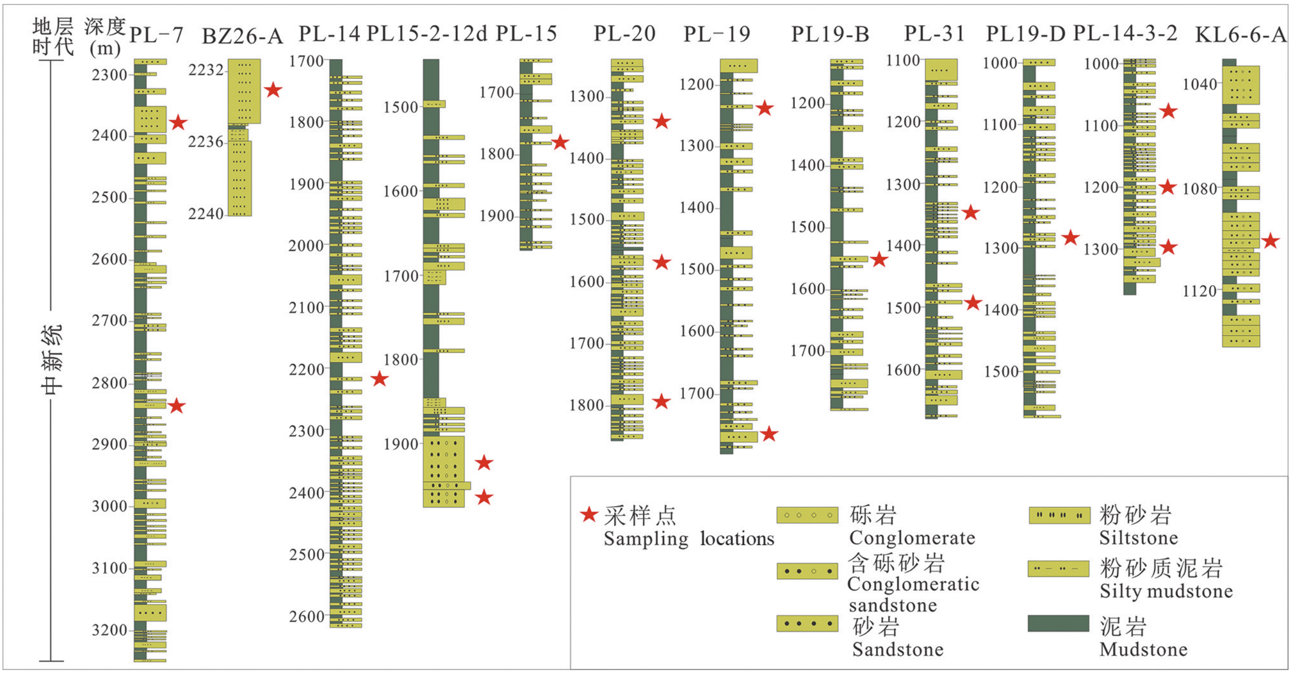

图 4　渤海湾盆地钻孔柱状图(图中编号与表 1 对应，位置标记在图 1 中)

Fig. 4　Stratigraphic column diagram of boreholes in the Bohai Bay basin (numbers in the figure are corresponding to those in Table 1, and locations are marked in Fig. 1)

与中新世钻孔建立物源关系。

3　实验结果

本次研究共获得有效锆石年龄数据 240 颗，具体实验数据结果见附表 1(http://www.geojournals.cn/dzxb/ch/reader/view_abstract.aspx? file_no = 202200797&flag=1)。据阴极发光(CL)图像观察(图 5)，本次分析的锆石具有非常明显的环带特征，说明主要以岩浆成因为主。计算 Th/U 比值发现除去 3 颗锆石的 Th/U<0.1 以外，其他锆石的 Th/U 比值均大于 0.1(图 6)。因而，本次分析的锆石以岩浆锆石为主。

大汶河沉积物中碎屑锆石 U-Pb 年龄主要集中于新太古代(图 7a)，其年龄峰值为 2536 Ma。淄河碎屑锆石的 U-Pb 年龄峰值为 2518 Ma(图 7b)，属于新太古代。弥河的碎屑锆石 U-Pb 年龄峰值为 132 Ma、255 Ma、494 Ma 以及 2532 Ma(图 7c)，主要集中在新太古代。潍河沉积物中碎屑锆石的 U-Pb 年龄集中于中生代和新太古代(图 7d)，其主要峰值年龄为 123 Ma 和 2536 Ma。

4　讨论

4.1　黄河是渤海湾盆地物源示踪的特征河流

根据从源到汇的大河研究思路(Chen Yi et

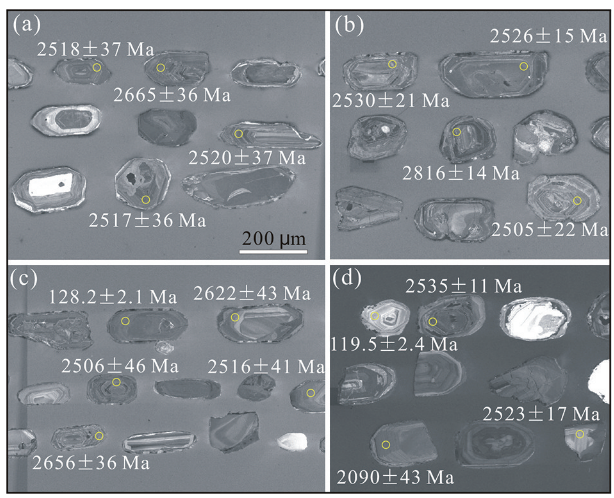

图 5　鲁中山区河流碎屑锆石阴极发光图像

Fig. 5　Cathodoluminescence images of detrital zircons from rivers in central Shandong

(a)—大汶河；(b)—淄河；(c)—弥河；(d)—潍河；图中圆圈代表分析点位置

(a)—Dawen River; (b)—Zi River; (c)—Mi River; (d)—Wei River; circles in the figure representing the locations of the analysis points

al., 2017; Wang Ce et al., 2019)，利用碎屑锆石 U-Pb 年龄进行河流物源示踪研究的基础是汇入沉积盆地的大河的碎屑锆石 U-Pb 年龄组成存在明显差异(源)，进而可以根据这一差异和沉积盆地中的碎屑锆石 U-Pb 年龄进行对比(汇)，从而判别碎屑

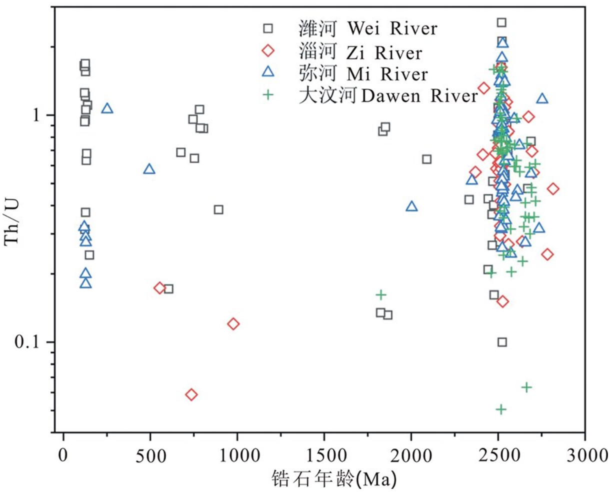

图 6 鲁中山区河流碎屑锆石 U-Pb 年龄和 Th/U 比值散点图

Fig. 6 Scatter plot of U-Pb ages and Th/U ratios of detrital zircons from rivers in central Shandong

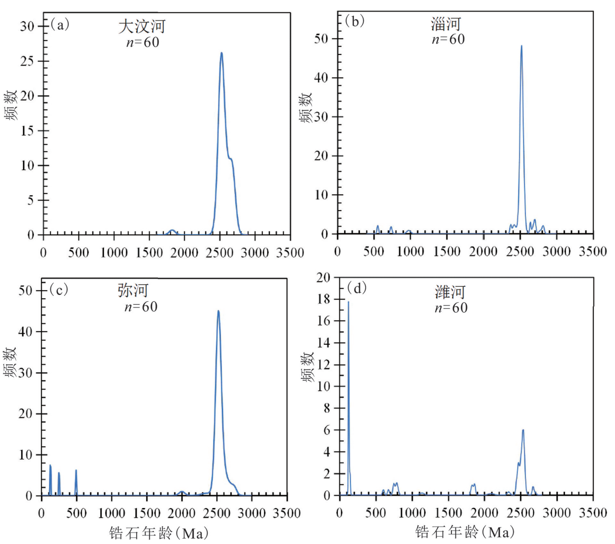

图 7 鲁中山区碎屑锆石 U-Pb 年龄频率分布图

Fig. 7 U-Pb age frequency distribution of detrital zircons in central Shandong

(a)—大汶河;(b)—淄河;(c)—弥河;(d)—潍河

(a)—Dawen River; (b)—Zi River; (c)—Mi River; (d)—Wei River

物质的来源(Lin Xu et al., 2021a),结合沉积地层的时代,可以重建地质历史时期的河流形成过程(Fu Xiaowei et al., 2021)。此次分析的大汶河(图 8a)、淄河(图 8b)、弥河(图 8c)和潍河(图 8d)与环渤海湾盆地主要汇入河流(图 8e~j)的碎屑锆石 U-Pb 年龄组成相比,前者主要以新太古代峰值年龄为主,这和鲁中山区南部最大河流沂河的碎屑锆石 U-Pb 年龄组成相似(Lin Xu et al., 2021a),也与鲁中山区基岩锆石 U-Pb 年龄组成一致(Wan Yusheng et al., 2012),因而其主要代表了鲁中山区的锆石 U-Pb 年龄物源信息。所以,大汶河、淄河、弥河和潍河这四条河流的锆石 U-Pb 峰值年龄组成与辽河、滦河、永定河、滹沱河、漳河和黄河明显不同;黄河是渤海湾盆地唯一远缘注入河流,通过对比可以发现,其锆石 U-Pb 峰值年龄与上述渤海湾盆地近缘河流最大不同在于,黄河存在典型的新元古代峰值(1000~700 Ma;图 8j),而这一峰值在华北克拉通内部的河流并不显著(Yang Jie et al., 2009; Yue Baojing et al., 2016; Lin Xu et al., 2021a),因而,利用碎屑锆石 U-Pb 年龄能很好区分来自近缘的燕山、太行山、鲁中山区和远缘黄河的碎屑物质,这使其成为环渤海湾盆地钻孔物源示踪研究的基础。

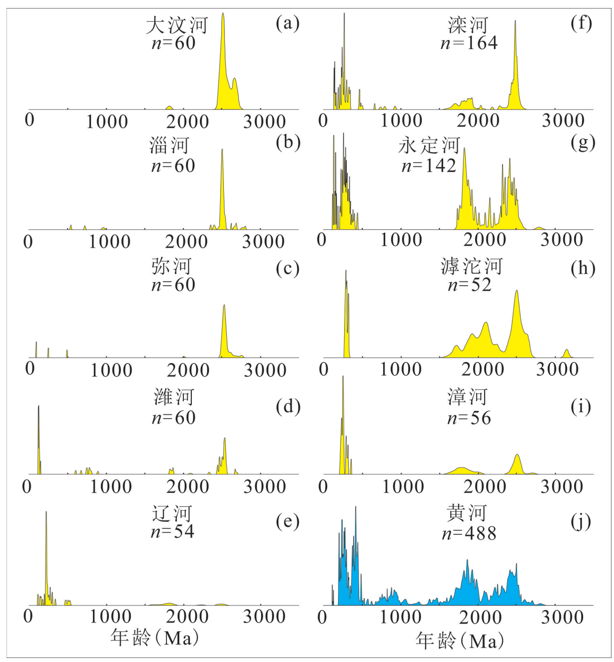

图 8 渤海湾盆地主要汇入河流碎屑锆石 U-Pb 年龄组成分布图

Fig. 8 U-Pb age distribution of detrital zircons from major inflow rivers in the Bohai Bay basin

(a)—大汶河;(b)—淄河;(c)—弥河;(d)—潍河;(e)—辽河;(f)—滦河;(g)—永定河;(h)—滹沱河;(i)—漳河;(j)—黄河

(a)—Dawen River; (b)—Zi River; (c)—Mi River; (d)—Wei River; (e)—Liao River; (f)—Luan River; (g)—Yongding River; (h)—Hutuo River; (i)—Zhang River; (j)—Yellow River

4.2 黄河中新世未进入渤海湾盆地

进入新近纪,渤海湾盆地由断陷阶段进入坳陷阶段(图 3c),盆地内部结束了古近纪时期多个沉积中心分隔的地貌特征(Qiu Yan et al., 2016),开始出现以河流沉积为主的演化阶段。本文将黄河下游的碎屑锆石 U-Pb 峰值年龄与渤中坳陷 12 个中新

统沉积钻孔进行对比,发现这些钻孔的新元古代峰值年龄并不明显(图 9a～l),结合 MDS 判断图(图 10)进一步说明这些钻孔此时并未出现黄河的物质信号。而此时渤中坳陷的物质主要以辽东半岛和胶东半岛的近源物质为主(Li Mengyun, 2018; Zhao Meng et al., 2019a, 2019b; Liu Tao, 2020; Sun Zhongheng et al., 2020)。同样,在黄骅坳陷的中新统钻孔也没有出现黄河物质(Xiao Guoqiao et al., 2020),此时其碎屑物质主要来自燕山山脉(Wu Chen, 2008; Tan Mingxuan et al., 2020; Yang Jilong et al., 2020),是对燕山山脉快速隆升的响应(Wu Zhonghai et al., 2003; Xu Qinmian et al., 2019)。此外,受印度-欧亚板块碰撞远程效应的影响,祁连山在晚中新世(Lin Xu et al., 2015, 2019; Hu Xiaofei et al., 2019)处于地貌重组阶段(Li Jijun et al., 2014; Fang Xiaomin et al., 2019),黄河上游受此影响处于演化初始阶段(Wang Xianyan et al., 2012; Bao Guodong et al., 2020; Meng Kai et al., 2020);鄂尔多斯地块周围发育规模宏大的地堑系统(Zhang Yueqiao et al., 2003; Clinkscales et al., 2020; Su Peng et al., 2021),这些地堑深度超过几千千米,逐渐发展为区域汇水中心(Chen Fahu et al., 2008; Wang Bin et al., 2013; An Zhisheng et al., 2020)。碎屑锆石 U-Pb 年龄和重矿物物源示踪结果表明,晚中新世黄河出现在银川盆地(Liang Hao et al., 2013; Bao Guodong et al., 2020)和河套盆地(Li Weidong et al., 2020; Zhao Xitao et al., 2020);晋陕峡谷在 8～5 Ma 时出现区域性大河(Liu Yunming, 2020; Zhang Hanzhi et al., 2021),并注入汾渭地堑。汾渭地堑是黄河穿过二、三级阶梯东流入海的必经之地,物源示踪(Kong Ping et al., 2014)、构造分析(Liu Jin et al., 2019)、河流阶地(Hu Zhenbo et al., 2017, 2019)研究结果表明,贯通汾渭地堑并连接晋陕峡谷和华北平原的黄河在 1.3～1.0 Ma 稳定出现。除黄河外,渭河是汾渭地堑主要的物质输送河流之一,其碎屑物质主要来自北秦岭(Zhang Xiaoyu et al., 2018),具有典型的新元古代峰值年龄(1000～700 Ma, 图 9n),通过对比可以发现,渭河物质在中新世也未出现在渤中坳陷中。然而,贯通三门峡东流入海的黄河进入华北平原后其河道频繁发生摆动(Wu Chen et al., 2008),时而进入渤海(Yao Zhengquan et al., 2017),时而进入黄海(Zhang Jin et al., 2019; Huang Xiangtong et al., 2021)。因而,中新世时黄河的演化信息是否保存于南黄海盆地或苏北盆地,仍需要继续开展相关工作

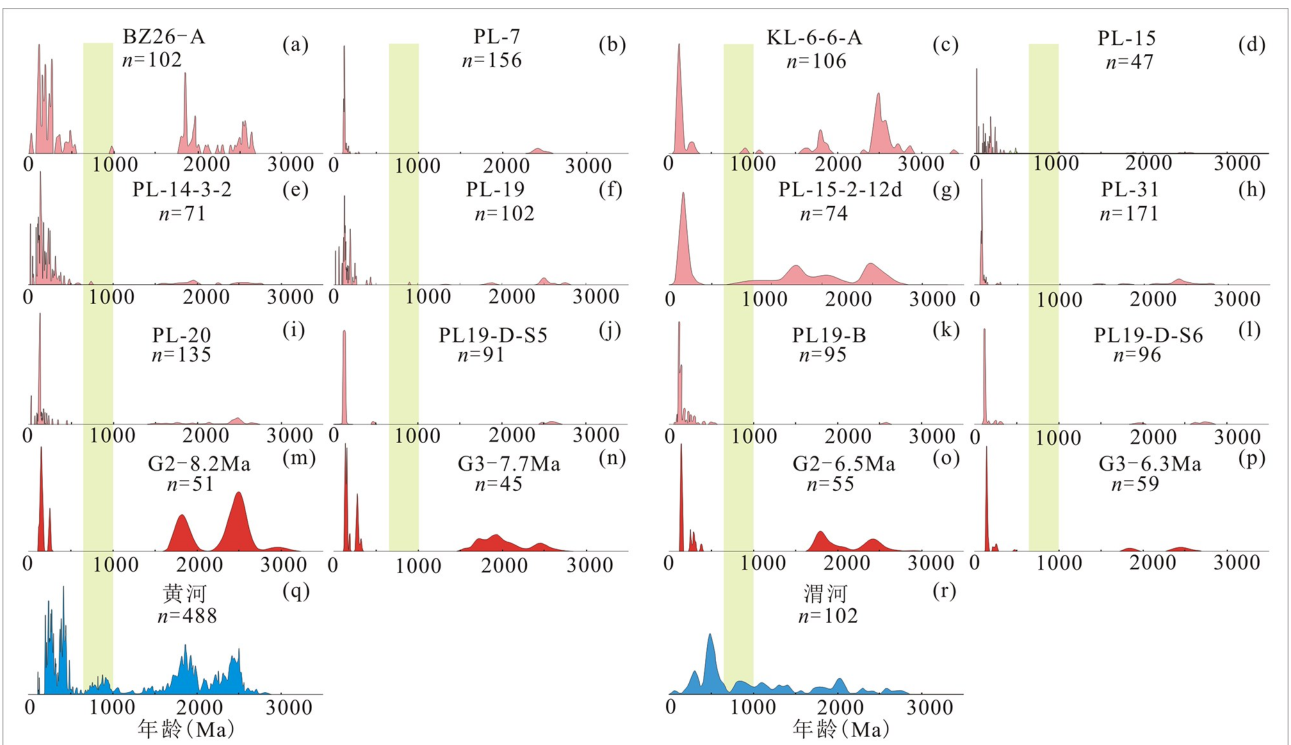

图 9　渤海湾盆地渤中坳陷(a～p)和黄河(q)、渭河(r) 锆石 U-Pb 年龄对比关系图

Fig. 9　Correlation of zircon U-Pb ages between the Bozhong sag (a～p) and Yellow River (q) and Wei River (r)

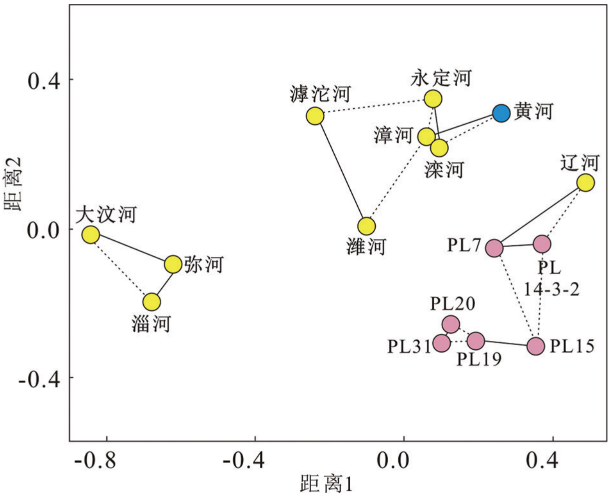

图 10 渤海湾盆地河流与钻孔碎屑锆石 U-Pb 年龄 MDS 判断图

Fig. 10 MDS map of rivers and boreholesof detrital zircon U-Pb ages in the Bohai Bay basin

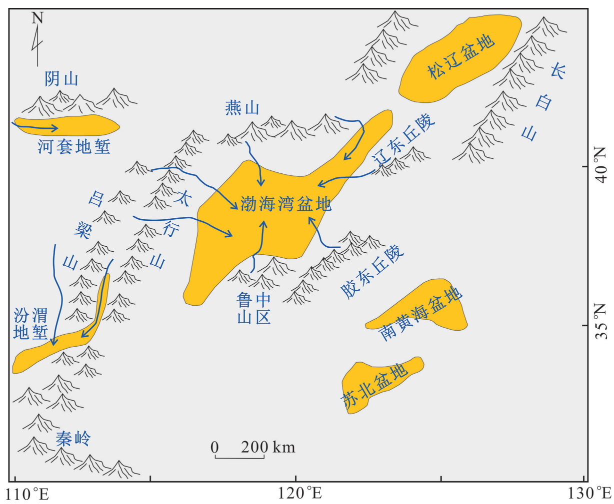

图 11 中新世渤海湾盆地河流演化模式图

Fig. 11 River evolution model of the Bohai Bay basin during the Miocene

进行厘定。

5 结论

通过对鲁中山区的大汶河、淄河、弥河和潍河进行碎屑锆石 U-Pb 年龄进行分析，与流入渤海湾盆地的辽河、滦河、永定河、滹沱河、漳河和黄河，以及渤海湾盆地沉积钻孔的锆石 U-Pb 年龄进行对比，得到如下结论：

（1）发源于鲁中山区的大汶河、淄河、弥河和潍河的锆石 U-Pb 峰值年龄组成单一，主要以新太古代峰值年龄为主。

（2）黄河具有显著的新元古代锆石 U-Pb 峰值年龄（1000～700 Ma），这在辽河、滦河和海河水系中均没有出现，使其成为渤海湾盆地的特征河流。

（3）黄河在中新世末进入渤海湾盆地。

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The Yellow River did not enter the Bohai Bay basin during the Miocene: constraints from detrital zircon U-Pb ages

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Abstract

The development and formation of the Yellow River, the largest river in North China, is of great significance to the establishment of the three terrains in North China. But so far, there is a great controversy about the formation age of the Yellow River. In this case, we have carried out the analysis of detrital zircon U-Pb ages ($n=240$) of the rivers derived from the Central Luzhong Shan, and compared them with those of the Liao River, the Luan River, the Yongding River, the Hutuo River, the Zhang River and the Yellow River flowing into the Bohai Bay basin. The results show that the Yellow River is the characteristic river of the Bohai Bay basin due to its significant Neoproterozoic peak ages (1000～700 Ma). The systematic evolution information of big river is preserved in the clastic sediments deposited in the downstream of river; therefore, we compared the detrital zircon U-Pb peak age of the lower reaches of the Yellow River with the drilling cores within the Bohai Bay basin. Combining multi-dimensional discrimination diagram (MDS) results, it shows that the Yellow River did not flow into the Bohai Bay basin during the Miocene.

Key words: Bohai Bay basin; Yellow River evolution; zircon; U-Pb age; provenance tracing