

<https://doi.org/10.3799/dqkx.2025.027>



华南主要大河新生代演化： 南海北缘沉积学记录的制约

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摘要: 印度-欧亚大陆碰撞和青藏高原隆升, 深刻地改变了亚洲地形及气候格局, 引发了大河水系的重大调整. 近年来, 南海北缘大河演化成为地学研究的前沿和热点问题. 近海油气勘探和国际大洋钻探计划(IODP)的实施, 为重建华南主要大河演化提供了连续且年代精确的沉积记录. 梳理了近 20 年来南海北缘新生代盆地的沉积物源研究, 讨论了华南主要大河演化(包括红河和珠江等)的沉积学研究进展. 莺歌海盆地物源研究显示, 晚始新世以来红河是该盆地主要物源供给者; 并且莺歌海盆地与青藏高原东南缘其他大河(包括怒江、澜沧江和长江等)的物源信号差异较大(如碎屑锆石 U-Pb 年龄和钾长石 Pb 同位素等), 表明晚始新世以来这些大河并未汇入莺歌海盆地, 即青藏高原东南缘并不存在巨型古红河. 珠江口盆地在始新世-早渐新世主要由华南南缘供给沉积物, 指示古珠江流域范围较小; 晚渐新世在南海打开的驱动下, 古珠江向西扩展至青藏东南缘. 台湾新生代地层的物源区在晚渐新世由华南沿海转变为武夷山, 暗示着古闽江向西扩展. 华南沿海主要大河(包括珠江和闽江等)在晚渐新世均经历了由中小型水系向内陆拓展的过程, 与南海打开时限基本吻合, 表明南海打开控制了这些大河的演化.

关键词: 南海; 珠江; 红河; 物源示踪; 大河演化; 沉积学; 海洋地质学.

中图分类号: P67

文章编号: 1000-2383(2025)07-2775-16

收稿日期: 2024-05-24

Cenozoic Evolution of Large Rivers in South China: Constraints from Sedimentary Archive in Northern South China Sea

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Abstract: The India-Eurasia collision and the uplift of the Tibetan Plateau have profoundly changed the topography and climate patterns of Asia, triggering reorganization of large river systems. Recently, the evolution of large rivers on the northern South China Sea has become a frontier and hot issue in geoscience research. Offshore oil and gas exploration and the implementation of the International Ocean Drilling Program (IODP) have provided continuous and accurately dated sedimentary records for

基金项目: 国家自然科学基金项目(Nos. 42271008, 42171008); 南方海洋科学与工程广东省实验室(珠海)自主科研项目(No. SML2021SP315).

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引用格式: 张增杰, 田云涛, 孙习林, 闫义, 2025. 华南主要大河新生代演化: 南海北缘沉积学记录的制约. 地球科学, 50(7): 2775-2790.

Citation: Zhang Zengjie, Tian Yuntao, Sun Xilin, Yan Yi, 2025. Cenozoic Evolution of Large Rivers in South China: Constraints from Sedimentary Archive in Northern South China Sea. *Earth Science*, 50(7): 2775-2790.

reconstructing the evolution of major rivers in South China. This paper reviews the sedimentary provenance investigations of the Cenozoic basins in the northern South China Sea in the past two decades, and discusses the progress in the evolution of major rivers in South China, such as the Red and Pearl Rivers. Provenance research in the Yinggehai Basin shows that the Red River has been the main supplier since the Late Eocene; and there are differences in provenance signals between the Yinggehai and large rivers of the Tibet Plateau (including the Nujiang, the Lancang and the Yangtze Rivers, indicating that they have not flowed into the Yinggehai Basin since the Late Eocene. During the Eocene to Early Oligocene, the Pearl River Mouth Basin was mainly supplied by the South China, indicating that the Pearl River was relatively small. Driven by the opening of the South China Sea in the Late Oligocene, the Pearl River expanded westward to the southeastern Tibetan Plateau. Cenozoic stratigraphy in Taiwan records that the ancient Minjiang River expanded westward to the Wuyi Mountain in the Late Oligocene. This evidence shows that the opening of the South China Sea controlled the evolution of the large rivers in South China.

Key words: South China Sea; Pearl River; Red River; sedimentary provenance; large river evolution; sedimentology; marine geology.

0 引言

印度-欧亚大陆碰撞引发的青藏高原隆升,对亚洲地貌格局及气候产生了巨大的影响(An *et al.*, 2001).宏观地貌格局的革命性转变,必然导致水系分布的重大调整(Brookfield, 1998, 2008; Clark *et al.*, 2004; Zhang *et al.*, 2019).青藏高原东南缘发育了多条世界级大河且具有特殊的水系结构,如金沙江、澜沧江和怒江的“三江并流”和石鼓“长江第一湾”等(图 1),是研究构造-地貌-气候耦合作用的天然实验室(Nie *et al.*, 2018).大河塑造着高原地貌形态,如青藏东南缘的高海拔低起伏面与深切峡谷并存地貌,是水系重组和河流下切共同作用的产物(Yang *et al.*, 2015; Cao *et*

al., 2018).同时,青藏东南部的大型河流搬运大量物质入海,直接影响着亚洲边缘海的沉积速率、物质组成及化学通量变化等(汪品先, 2005; Liu *et al.*, 2016).因此,大河演化研究对理解青藏高原隆升、地貌演化及边缘海沉积过程具有重要意义.

20 世纪 30 年代,李春昱等根据地貌调查和盆地演化分析,推断雅砻江和大渡河等曾沿南北向断裂带汇入红河或澜沧江(Lee, 1934).通过沉积学及水系形式研究,Clark *et al.*(2004)认为在中新世中期之前存在一个类似于密西西比河的巨型古红河水系将青藏高原东南缘和(古)南海相连(图 1).近年来,很多学者对古红河演化开展了大量研究,取得了丰硕的成果(Yan *et al.*, 2012; Lei *et al.*, 2015; Wei *et al.*, 2016; Chen *et al.*, 2017).然而,新生代

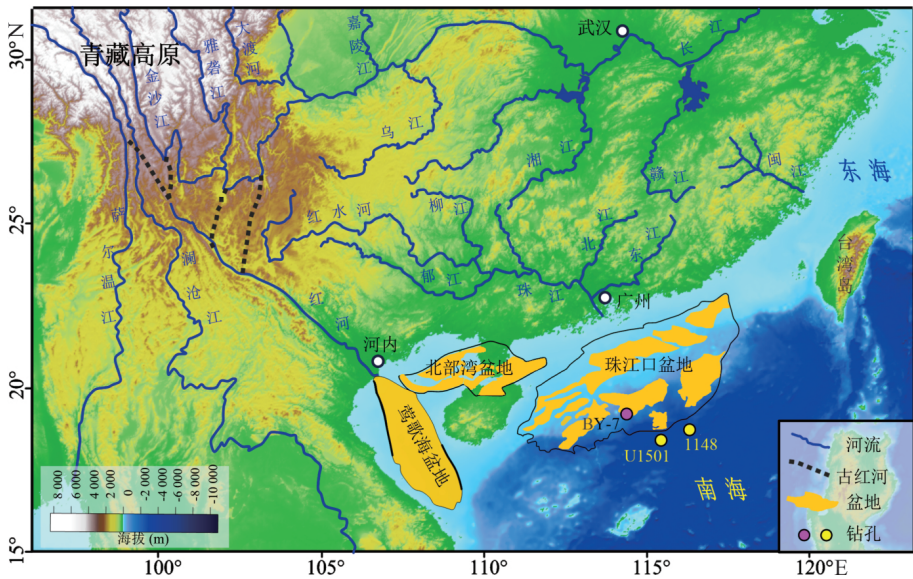


图 1 南海北缘主要大河及新生代盆地分布

Fig.1 Sketch map showing the large rivers and Cenozoic basins in the northern South China Sea

初期青藏东南缘是否存在巨型古红河?它何时解体?目前学术界对这些问题存在很大分歧.由于客观条件的限制,前期研究多聚焦于河流地貌和陆相盆地(任美镠等,1959;杨达源等,2008;Kong *et al.*, 2012; Yan *et al.*, 2012),但陆相地层易遭受后期构造活动的变形和破坏,难以保存连续的长时间尺度沉积层序.这些因素限制了对青藏东南缘水系演化等基础地貌问题的认识,对古红河变迁的一些关键问题还存在较大争议.

在新生代东亚强烈的地貌反转过程中,古珠江如何响应青藏高原隆升及南海的张裂?它与长江和红河等水系变迁之间存在着怎样的联系?其中珠江何时达到现今的规模是解决上述争议的关键,归纳起来有两种相对立的观点:(1)早渐新世珠江拓展至现今的水系规模(Jin *et al.*, 2022);(2)珠江水系格局在晚渐新世-早中新世基本定型(Cao *et al.*, 2018).不同学者得到的珠江形成年龄存在较大差异,主要源于物源示踪方法的不同,如Jin *et al.* (2022)利用全岩Nd同位素开展物源研究,而持晚渐新世-早中新世观点的学者则通过碎屑锆石U-Pb年龄示踪.闽江等水系自西向东流经华夏地体,汇入西太平洋边缘海(图1),其形成演化与华南地貌变迁紧密相关.由于对沉积物输送模式认识的差异,这条河流的演化历史有以下两种观点:(1)古闽江曾拓展至长江中下游流域:根据南海北部新生代沉积物源分析,Yan *et al.* (2018)认为湘江和赣江等长江支流在早中新世经古珠江、古闽江汇入南海,中中新世(~ 12 Ma)之后华南现代水系格局才形成;也有学者推断受南海打开影响,古闽江在早中新世向西拓展至扬子克拉通,袭夺了赣江上游,直到晚中新世赣江才成为长江支流(Lan *et al.*, 2014, 2016).(2)东南沿海水系格局在早中新世基本定型:东海陆架盆地碎屑锆石U-Pb年龄物源研究显示晚渐新世东海陆架盆地的“源-汇”与现今类似,扬子及华北克拉通物质可被搬运至大陆边缘,并能够随沿岸流输送至台湾地区(Deng *et al.*, 2017; Zhang *et al.*, 2017).

伴随着青藏高原隆升和大河的形成,大量陆源碎屑被搬运至边缘海盆地,使其成为重要的“沉积汇”(如莺歌海盆地、珠江口盆地和东海陆架盆地等).它们沉积了巨厚新生代地层,是详细解析华南沿海地貌及水系变迁的理想载体(庞雄等,2007;邵磊等,2008, 2013; Cao *et al.*, 2018).本文梳理了近

20年来南海北缘新生代盆地的物源数据,包括碎屑锆石U-Pb年龄、钾长石Pb同位素和全岩Nd同位素等.碎屑锆石U-Pb年龄是一种重要的示踪工具,被广泛运用于华南大河演化研究,取得了大量研究成果(Lan *et al.*, 2016; Cao *et al.*, 2018; Liu *et al.*, 2022).但存在以下不足:(1)锆石的沉积再旋回难以准确示踪直接物源区(Garzanti *et al.*, 2013);(2)物源区矿物丰度差异使得部分物源区的贡献被低估(Malusà *et al.*, 2016; Caracciolo, 2020).与稳定矿物(如锆石)相比,钾长石作为地壳中最主要造岩矿物,其抗风化能力弱,不太可能经历沉积再旋回(Tyrrell *et al.*, 2007; Flowerdew *et al.*, 2012),能示踪沉积物的直接物源区.并且作为砂岩骨架矿物,钾长石含量高($\sim 10\%$),更能代表物源区特征.本文通过对比分析南海北缘新生代盆地已发表的物源数据及水系演化模型,并结合区域构造活动和气候事件阐述华南主要大河的演化历史.

1 地质背景

1.1 莺歌海盆地

莺歌海盆地位于海南岛与越南之间的莺歌海海域,面积超过 $11 \times 10^4 \text{ km}^2$,由莺歌海凹陷和河内凹陷组成,二者被临高凸起分隔.受印度-欧亚板块碰撞的影响,印支地块发生南东方向逃逸,红河断裂带及莺歌海盆地一号断裂构成印支地块逃逸的东部边界,并将南海及其周缘地区划分为“俯冲拖曳构造区”和“挤出逃逸构造区”(任建业和雷超,2011).莺歌海盆地是在“挤出逃逸构造区”内由走滑断层所形成的沉积盆地.莺歌海盆地基底为前新生代变质岩、海相地层和陆相碎屑岩等,盆地内发育了完整的新生代地层,主要由裂陷期(始新统、渐新统崖城组和陵水组)和坳陷期(中新统三亚组、梅山组和黄流组)两套沉积层序组成(图2;雷超,2012;任建业,2018).始新统为河湖相和三角洲相沉积,主要由泥岩、砂岩和砂砾岩等组成.下渐新统崖城组为海陆过渡沉积,发育棕红色砂砾岩、白色砂岩和深灰色薄层泥岩.上渐新统陵水组为滨海-半封闭浅海沉积,主要由灰-浅灰色砾岩和砂岩组成,并且常夹有深灰色泥岩,局部可见生物灰岩.中新统三亚组、梅山组和黄流组主要发育滨浅海-半深海沉积,由灰-深灰色泥岩、灰白色砂岩和砂砾岩互层组成(谢玉洪,2009).

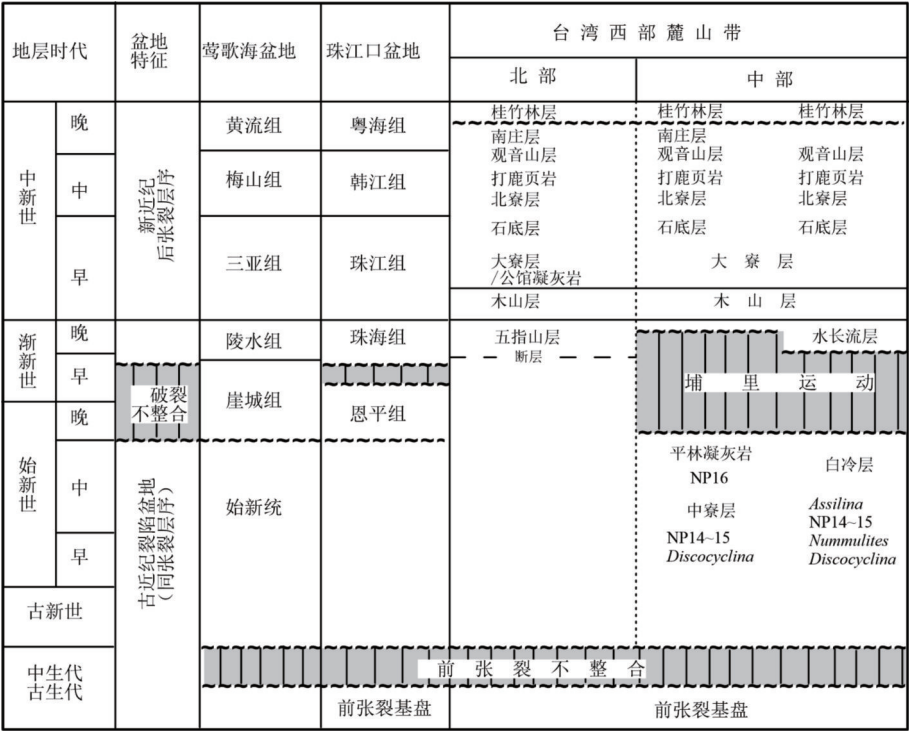


图2 莺歌海盆地、珠江口盆地及台湾西部麓山带新生代地层

Fig.2 Cenozoic stratal sequences correlation of the eastern Asian offshore basins, including the Yinggehai Basin, Pearl River Mouth Basin, and Taiwan

1.2 珠江口盆地

珠江口盆地新生界可划分为裂陷层序和裂后期层序,二者以破裂不整合接触(陈长民等,2003).裂陷期层序以河湖相为主,包括古新统神狐组、始新统文昌组和下渐新统恩平组(赵中贤等,2009);神狐组主要为杂色及棕红色粗碎屑岩,代表了盆地断陷初期形成的河流相快速堆积.始新统文昌组主要为半深湖相的暗色泥岩、页岩.渐新统恩平组底部发育厚层的砂岩与砂砾岩沉积,中上部为泥岩与砂岩互层.裂后期层序主要为浅海相沉积,包括上渐新统珠海组、中新统珠江组、韩江组和粤海组(陈长民等,2003).珠海组为厚层砂岩夹薄层砂岩沉积,它与下伏恩平组之间的不整合界面,指示了南海洋中脊打开(王永凤等,2015).中新统珠江组底部砂岩较发育,向上泥岩含量逐渐增加,表现为下粗上细的正旋回特征;珠江组和珠海组之间的不整合面受控于洋中脊向南跃迁(王永凤等,2015).韩江组砂岩发育程度降低,沉积物粒度变细,以厚层泥岩夹薄层砂岩、粉砂岩为主.粤海组整体上沉积物的粒度偏细,以厚层泥岩夹薄层砂岩为特征.晚渐新世以来,珠江口盆地沉积物由富砂为特征转变为以泥为主,被认为指示了珠江由近源性河流拓展为远源河

流(邵磊等,2013).庞雄等(2007)将珠江口盆地渐新统-中新统(~23.8 Ma)界面的地质事件称为“白云运动”,涉及南海扩张和珠江水系形成等重大构造事件;并认为其影响和改变了南海北部沉积物的组成、沉积作用、海平面变化和油气成藏特点等.

1.3 台湾西部麓山带

自中中新世开始,南海洋壳沿马尼拉海沟向东俯冲于菲律宾海板块之下(Shao *et al.*, 2015);同时菲律宾海板块持续向西北运动,导致北吕宋岛弧与亚洲大陆发生弧-陆碰撞,使得华南大陆边缘的新生代地层变形、抬升,最后出露形成台湾岛(Huang *et al.*, 2012).南海北坡及东海陆架盆地南端的新生代地层几乎完整出露,因此台湾就相当于“出露的边缘海”,这使台湾成为研究华南地貌及水系变迁的天然地质窗口(Lan *et al.*, 2014, 2016; Deng *et al.*, 2017).

台湾西部麓山带发育完整的新生代沉积,且生物地层研究程度高,沉积年代约束精确(Huang *et al.*, 2012; 图2).西部麓山带新生界可划分为裂陷层序和裂后期层序,二者以破裂不整合接触,其代表的地质事件称为“埔里运动”,对应南海洋壳的打开(Lan *et al.*, 2014);裂陷层序以河湖相沉积为主,包

括始新统西村层、白冷层和中寮层(图2);西村层为厚层砂岩夹薄层页岩,其上为四棱层,二者均指示辫状河流-沼泽相的沉积环境。白冷层为中粗砂岩和页岩互层沉积,具有交错层理,含植物根化石,指示为辫状河-沼泽环境。裂后层序主要为浅海相沉积,包括渐新统水长流层和五指山层;中新统木山层、大寮层、石底层、北寮层、打鹿层和观音山层等(Huang *et al.*, 2012; 图2)。水长流层由暗灰色-黑色致密页岩夹少量的石英砂岩组成,含海绿石及鲨鱼牙齿、珊瑚和有孔虫化石等海相化石;五指山层主要由厚层细粒砂岩夹砾岩及深灰色页岩组成;木山层为厚层砂岩、粉砂岩夹页岩组成,具有交错层理,含大量有孔虫化石;观音山砂岩主要由厚层砂岩及粉砂岩组成,夹有含大量化石的碳酸盐岩层。

2 南海北缘主要新生代盆地物源研究

2.1 莺歌海盆地物源研究

河流水系型式分析和沉积学研究表明,青藏高原东南缘在中中新世之前存在着一个类似于现今密西西比河的巨型古红河水系(Clark *et al.*, 2004),包含了金沙江及长江川江段、湄公河、怒江和雅鲁藏布江等。伴随着青藏高原的隆升,这些支流相继脱离古红河,巨型古红河水系解体。莺歌海盆地是红河的沉积汇(图1),保存了厚约万米的

新生代地层,是探究红河演化最为关键的沉积记录。莺歌海北部河内盆地的全岩Nd同位素物源研究显示,始新统Nd同位素极其负偏(图3),与古老陆壳如扬子克拉通的Nd同位素类似,由此推断长江中游及流经松潘-甘孜地体的古河流曾经倒流,作为古红河的一部分注入古南海(Clift *et al.*, 2006)。但亚洲东部Nd同位素填图并不支持这一结论(Yan *et al.*, 2018)。Nd同位素数据显示,大别造山带是扬子克拉通周缘Nd同位素唯一负偏的区域(Yan *et al.*, 2018),然而新生代以来大别山剥蚀下来的碎屑物主要堆积在邻近的江汉盆地,很难跨越江汉盆地及四川盆地等多个内陆盆地汇入古红河。如果河内盆地始新统不是由扬子克拉通供给,那么它的源区是哪里?越南北部部分区域呈Nd同位素负异常(Yan *et al.*, 2018),很可能是河内盆地始新统重要的物源供给者。

Van Hoang *et al.* (2009)通过河内盆地中新统碎屑锆石U-Pb年龄研究,表明中新世以来红河就已达到现今的水系规模(图4),也注意到红河沉积物很大一部分碎屑锆石再旋回自红河流域内的中生代砂岩。Lei *et al.* (2019)对琼东南盆地中央谷地和谷坡裂陷期渐新统碎屑锆石物源的研究,显示晚渐新世一条类似于现代红河的大河开始向琼东南盆地供给碎屑物质,这一物源突变与河内盆地记录的Nd同位素负偏相一致(Clift *et al.*, 2006),很可能代表了现代红河的诞生。

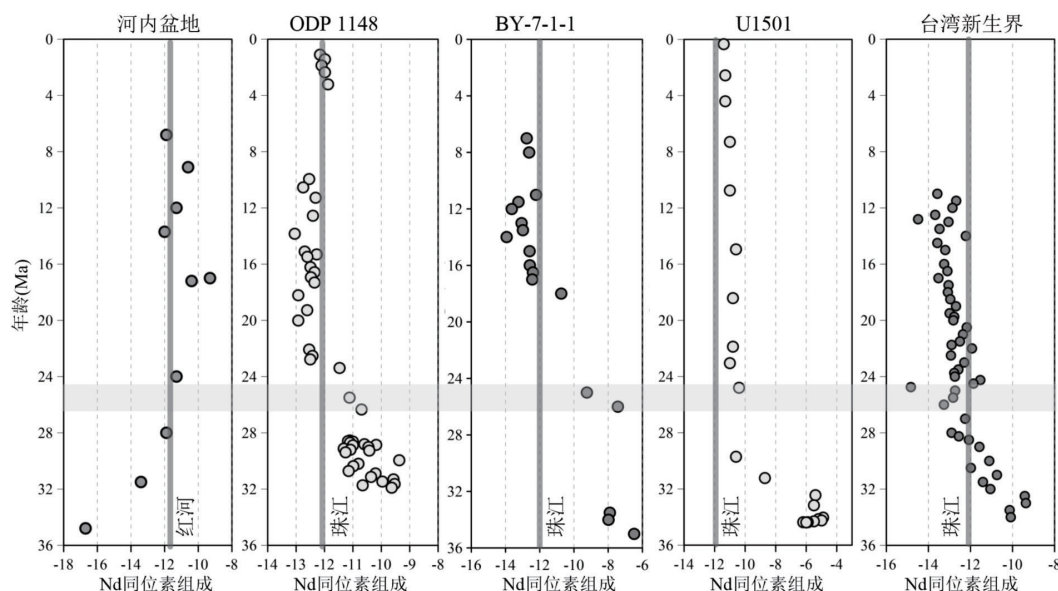


图3 南海北部新生代地层Nd同位素组成

Fig.3 The variations of Nd isotopic composition in northern South China Sea

引自 Clift *et al.*, 2006; Jin *et al.*, 2022; Lan *et al.*, 2016; Li *et al.*, 2003; Yan *et al.*, 2018。灰色线条代表了红河和珠江的Nd同位素比值

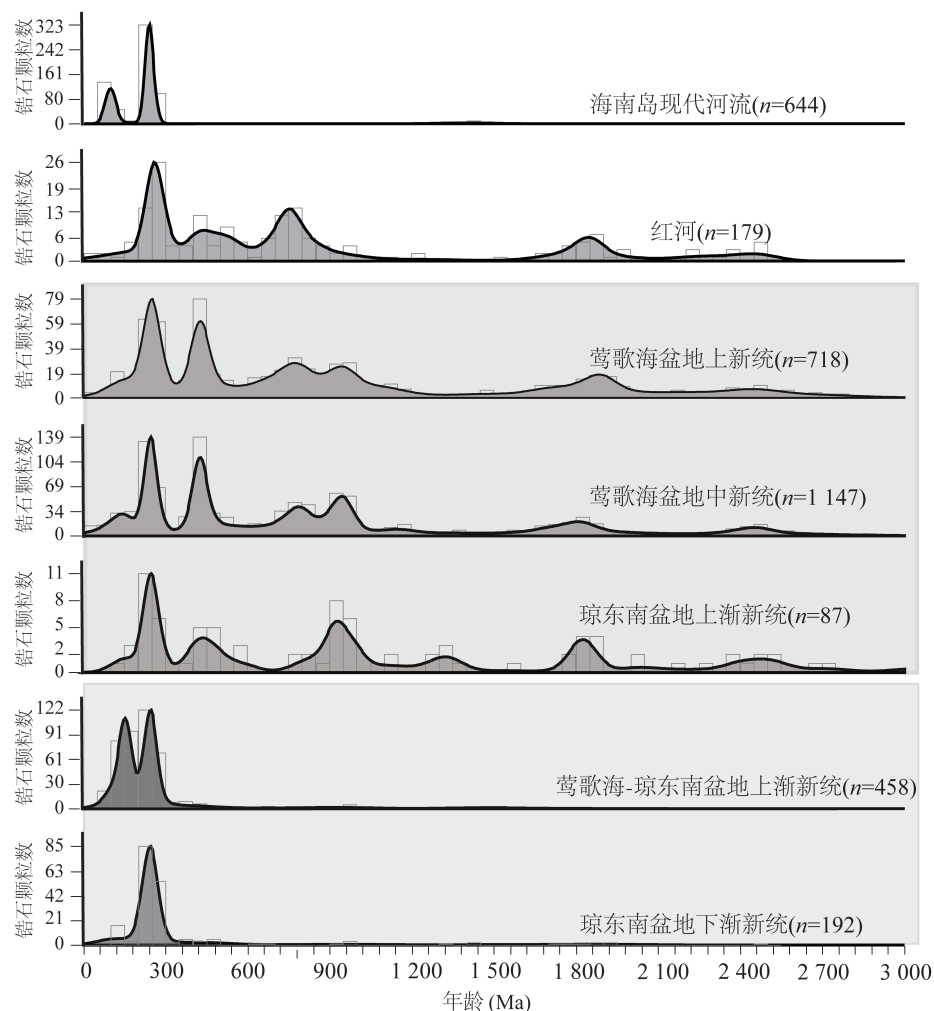


图4 莺歌海盆地新生代地层碎屑锆石 U-Pb 年龄分布

Fig.4 Compilation of detrital zircon U-Pb ages from the Yinggehai Basin, Red and Hainan Rivers

下部和上部浅灰色区域分别代表了莺歌海盆地的近源供给和远源供给. 数据来源: 下渐新统 (Lei *et al.*, 2019; Shao *et al.*, 2016); 上渐新统 (Lei *et al.*, 2019; Yan *et al.*, 2011); 中新统和上新统 (Cao *et al.*, 2015; Jiang *et al.*, 2015; Wang *et al.*, 2014, 2016, 2018); 红河 (Clift *et al.*, 2006; Van Hoang *et al.*, 2009); 海南岛河流 (Wang *et al.*, 2015)

Clift *et al.* (2008) 在河内盆地始新统中检测出低放射性成因 Pb 钾长石颗粒, 它们主要来自于扬子克拉通, 由此推断长江中游曾作为古红河的主要支流. Wang *et al.* (2019) 对莺歌海盆地临高凸起的研究显示, 渐新世之前大部分碎屑物质来自扬子克拉通, 即长江上游支流曾经汇入莺歌海盆地. 前人已通过不同方法测定了青藏东缘主要河流的长石 Pb 同位素组成 (如澜沧江、怒江、红河和金沙江), 结果显示这些河流以高放射性 Pb 同位素组成为主 ($^{206}\text{Pb}/^{204}\text{Pb}$ 大于 18.2) (Bodet and Schärer, 2001; Clift *et al.*, 2008). 与这些水系相比, 流经松潘-甘孜的岷江和大渡河沉积物中含有大量低放射性成因 Pb 长石颗粒 ($^{206}\text{Pb}/^{204}\text{Pb}$ 小于 17.5), 并且这些低放

射性颗粒在与长江干流汇合后, 甚至搬运至长江三峡出口处时 (Zhang *et al.*, 2014), 依然是一个非常稳定的物源信号. 它们与红河、澜沧江和怒江截然不同的 Pb 同位素物源信号, 如果雅砻江、岷江或是流经扬子克拉通的嘉陵江在地质历史时期曾南流入古红河, 则可以应用 Pb-in-K-feldspar 这一物源工具来判别不同水系的沉积物供给.

前人的古红河演化模型主要根据零星分布的基岩同位素数据 (Clift *et al.*, 2008), 河流沉积物碎屑钾长石 Pb 同位素组成常与流域内基岩有一定程度上的偏离, 尤其是在松潘-甘孜板块. 因此, 仅依据基岩 Pb 同位素重建水系演化存在很大的不确定性. 钾长石 Pb 同位素数据显示, 松潘-甘孜地体在始

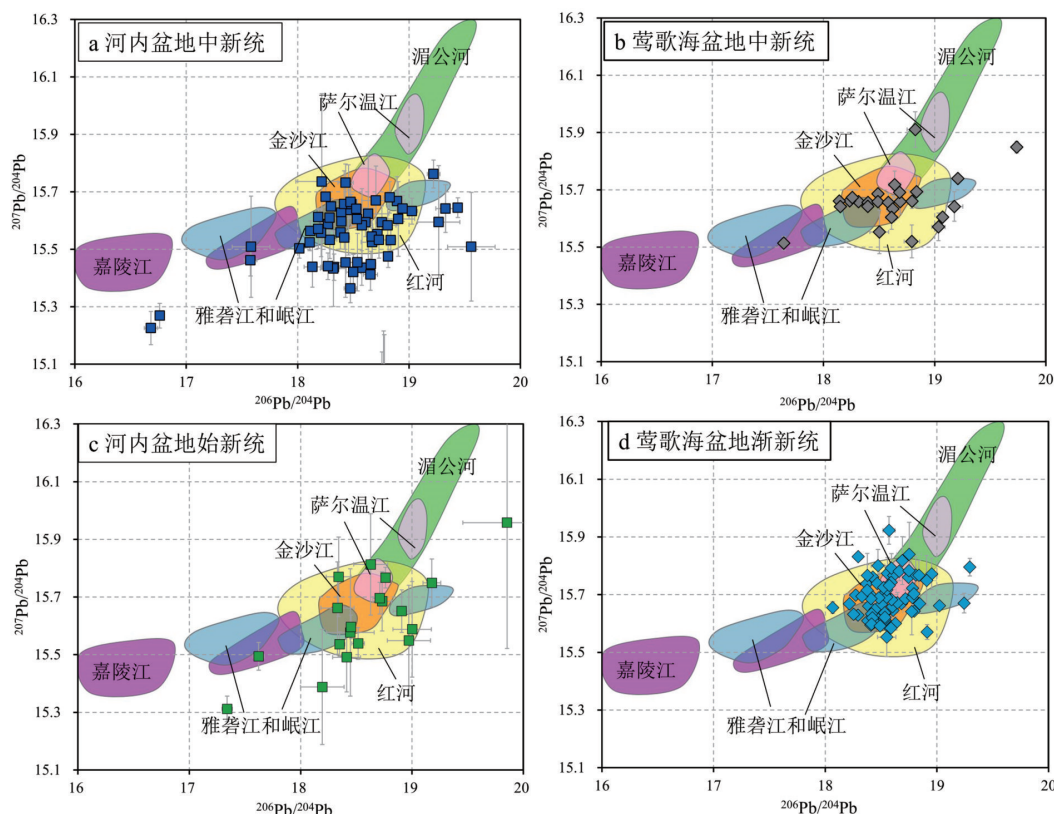


图5 莺歌海盆地钾长石 Pb 同位素组成及与潜在源区的对比 (Clift *et al.*, 2008; Zhang *et al.*, 2021)

Fig.5 Compiled Pb isotopic data of detrital K-feldspar of the Yinggehai Basin, compared with potential sources (Clift *et al.*, 2008; Zhang *et al.*, 2021)

新世是河内盆地重要的物源区 (Clift *et al.*, 2008). 然而, 在重新厘定青藏高原东缘潜在源区的 Pb 同位素组成后, 发现河内盆地的沉积物几乎没有松潘—甘孜地体的特征性钾长石颗粒 (图 5). 对此现象的一个可能的解释是, 相对于现今的红河流域而言, 青藏高原东缘距离古红河入海口较远, 这些低放射性成因 Pb 长石颗粒在搬运过程中发生“丢失”. 然而长江沉积物长石 Pb 同位素研究表明, 青藏高原东缘的特征长石颗粒可以被搬运至三峡出口处, 并且在长江沉积物中的含量很高 (Zhang *et al.*, 2014). 如若存在一条巨大的古红河, 其规模应与长江类似, 青藏东缘的物质可以被输送到河内盆地的. 据此, 本文推断发源于松潘—甘孜的 (古) 雅砻江和岷江很可能不是古红河的一部分.

2.2 珠江口盆地物源研究

全岩 Nd 同位素能很好地约束细粒组分的物源, 已被广泛应用于珠江演化研究 (Yan *et al.*, 2018; Jin *et al.*, 2022). Jin *et al.* (2022) 对 IODP 367-368 航次 U1501 站位开展了全岩 Nd 同位素和黏土矿物分析, 显示早渐新世以来 (~30 Ma), 南

海北缘沉积物 Nd 同位素组成与现代珠江一致 (图 3), 推断珠江在早渐新世就已形成, 与青藏高原的隆升相关. Pang *et al.* (2009) 认为珠江口盆地晚渐新世 Nd 同位素突变与南海北部一次重要的构造事件——白云运动相关. Li *et al.* (2003) 则认为南海北缘晚渐新世物源转变与伴随着南海打开、物源区由南海南部婆罗洲向华南陆缘转变相关.

Cao *et al.* (2018) 对珠江口盆地渐—中新统开展了碎屑锆石 U-Pb 年龄分析, 通过对潜在物源区的详细定义、对锆石年代学数据的定量分析, 结合地球化学成果, 验证了南海北部在晚渐新世时期的重要物源转折事件, 表现为伴随 Nd 同位素的显著负偏 (图 3), 古生代锆石明显增多 (图 6); 此次物源转折代表了珠江流域面积明显扩张的过程, 从早渐新世局限在华南沿岸的小型河流演化至早中新世的大型河流. IO-DP U1501 站位的物源分析显示伴随着南海打开, 早渐新世东江和北江等逐渐形成, Liu *et al.* (2022) 认为南海的张裂为沿海河流向内陆拓展提供了动力.

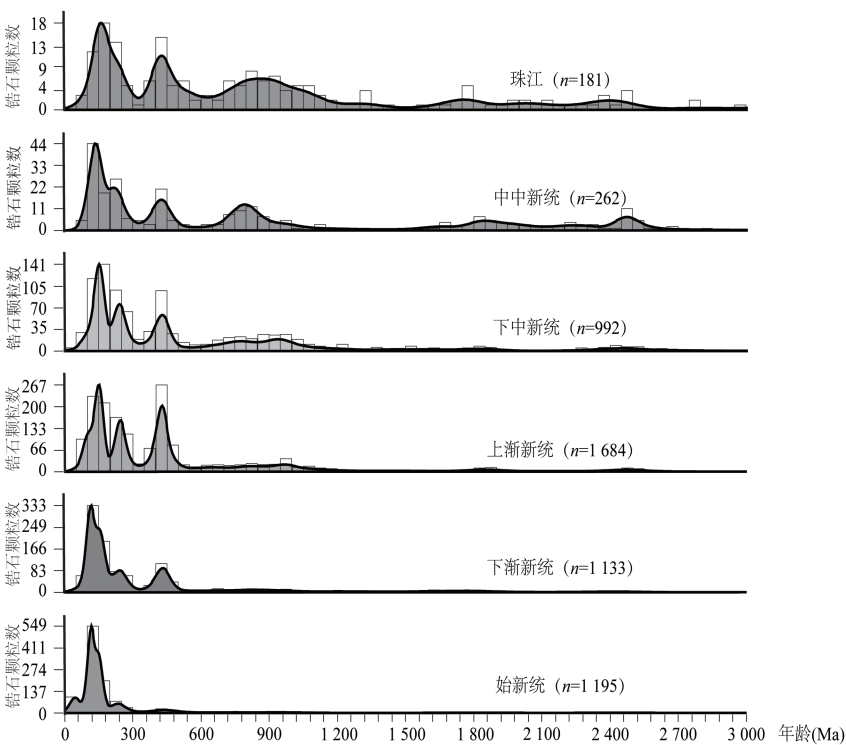


图 6 珠江口盆地新生界碎屑锆石 U-Pb 年龄组成

Fig.6 Compilation of detrital zircon U-Pb ages from the Pearl River Mouth Basin

数据来源: Cao *et al.*, 2018; Shao *et al.*, 2016; Yan *et al.*, 2018; Zeng *et al.*, 2019; 阙晓铭等, 2024

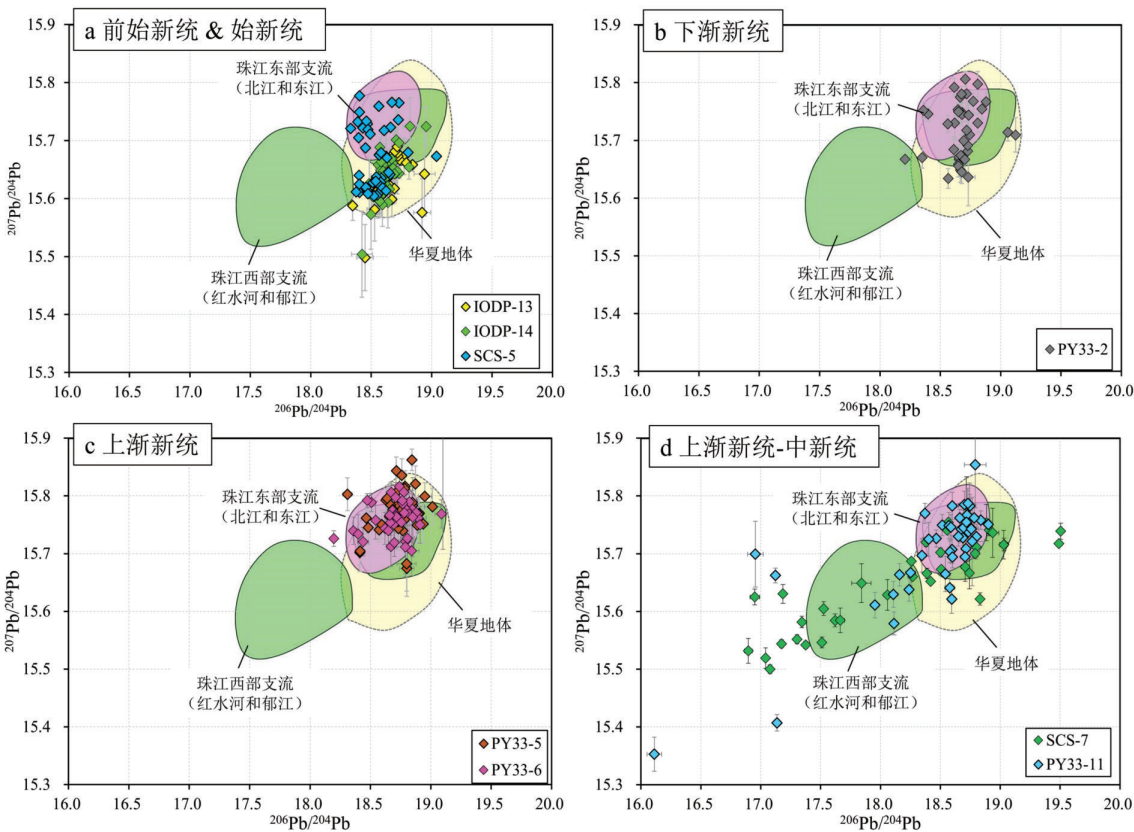


图 7 珠江口盆地新生代地层钾长石 Pb 同位素组成 (Zhang *et al.*, 2023)

Fig.7 Pb isotopic data of detrital K-feldspar of the Pearl River Mouth Basin (Zhang *et al.*, 2023)

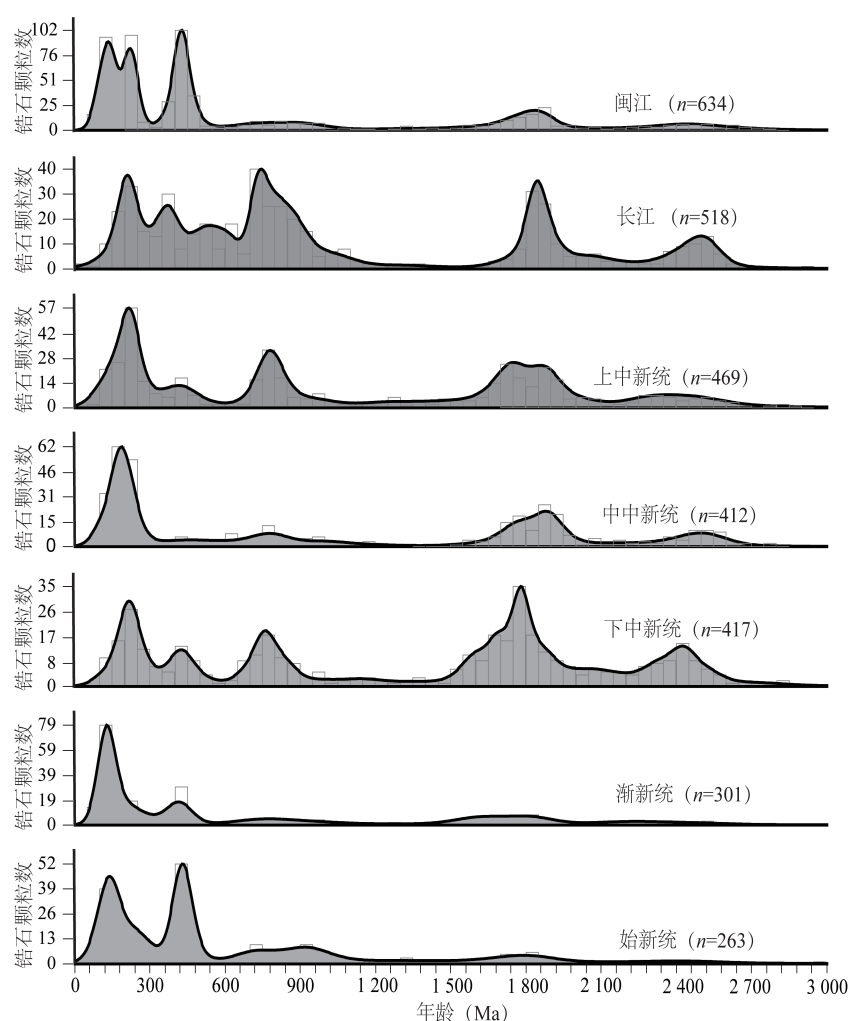


图8 台湾碎屑锆石 U-Pb 年龄分布

Fig.8 Compilation of detrital zircon U-Pb ages from Taiwan

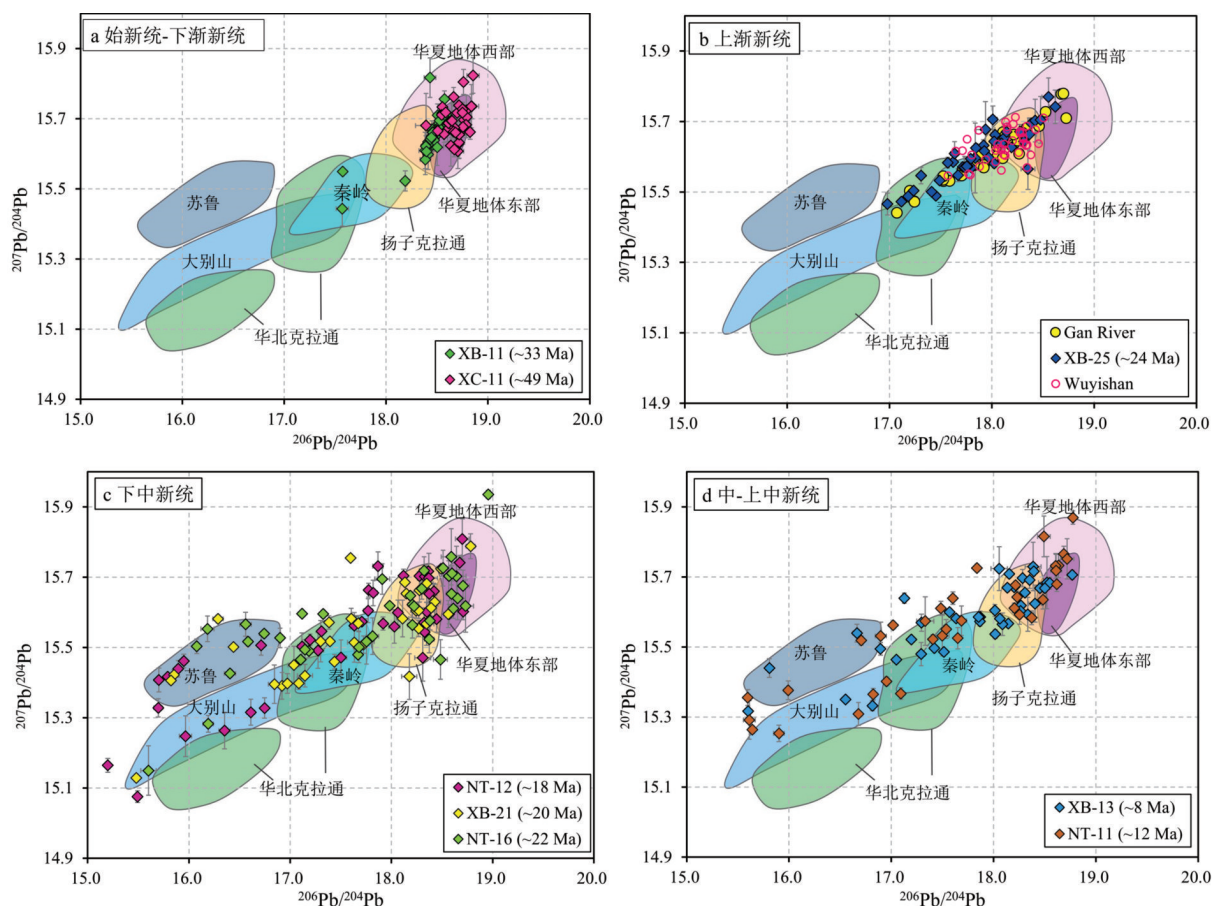
数据来源: He *et al.*, 2013; Lan *et al.*, 2016; Xu *et al.*, 2016; Yang *et al.*, 2012; Zhang *et al.*, 2017

Zhang *et al.* (2023) 对南海北缘新生界开展了详细的钾长石 Pb 同位素研究, 显示流经华夏地体的东江和北江等珠江东部以放射性成因 Pb 为主, 而发源于云贵高原的西江则富含低放射性成因 Pb 长石 (图 7)。珠江口盆地始新统以高放射性成因 Pb 钾长石为主, 且各个凹陷物质组成明显不同, 表明此时珠江口盆地的各凹陷之间并不连通。早渐新世时, 珠江口盆地的物质组成与东部支流类似, 表明北江和东江等已经形成。晚渐新世以来, 珠江口盆地出现大量的低放射性成因 Pb 长石颗粒, 即红水河已成为主要供给者, 表明珠江已经拓展至云贵高原。

2.3 台湾新生界物源研究

台湾西部麓山带新生代地层地球化学及 ϵ_{Nd} 值在 25~31 Ma 期间均发生了突变 (图 3)。

碎屑锆石 U-Pb 年龄谱及 $\epsilon_{\text{Hf}}(t)$ 值范围也显示台湾古近系与新近系物源存在明显差别 (图 8)。台湾古近系碎屑锆石 U-Pb 年龄组成与闽江沉积物一致; 而中新统则与下扬子地区和长江碎屑锆石 U-Pb 年龄谱很相似, 与闽江则差别较大 (图 8)。碎屑独居石 U-Th-Pb 年代学物源研究显示台湾新生界富含年龄为 ~1.8 Ga 的独居石颗粒, 而在中国大陆沿海河流 (包括珠江、闽江和长江等) 普遍缺乏这个年龄峰值的独居石, 因此 Chen *et al.* (2019) 推断台湾西部麓山带的沉积物并不是由中国大陆供给。但渐新世-中新世早期东海陆架盆地构造反转可能为中国大陆东部沉积物向台湾的输送创造了有利条件 (Suo *et al.*, 2015; Zhang *et al.*, 2016)。东海陆架现代沉积物输送过程研究表明, 长江沉

图9 台湾新生界碎屑钾长石 Pb 同位素组成 (Zhang *et al.*, 2022)Fig.9 Pb isotopic data of detrital K-feldspar of Cenozoic deposits in Taiwan (Zhang *et al.*, 2022)

积物可通过沿岸流从长江口向南输送约 800 km 到达台湾海峡 (Liu *et al.*, 2006, 2007)。

铅同位素分布图显示东亚主要构造单元的 Pb 同位素存在明显差异 (张理刚, 1995)。与华夏地体相比, 扬子克拉通的铅同位素比值略低, 而华北克拉通和桐柏-大别山等则以低放射性成因 Pb 为特征 (图 9), 因此通过分析台湾新生代地层的钾长石 Pb 同位素组成, 并与中国东部主要构造单元的 Pb 同位素进行综合分析, 能够准确示踪沉积物的直接输送路径。始新统西村层所含钾长石均以高放射性成因 Pb 为主 ($^{206}\text{Pb}/^{204}\text{Pb} > 18.4$), 与华夏地体的 Pb 同位素特征极为类似 (图 9), 与扬子克拉通、桐柏-大别山、华北克拉通和长江等有很大差别。始新世-渐新世过渡层的钾长石 Pb 同位素组成与始新统西村层的一致 ($^{206}\text{Pb}/^{204}\text{Pb} > 18.4$) (图 9), 这表明在裂陷期主要由发源于华夏地体的水系 (如古闽江、九龙江和瓯江等) 提供碎屑物质。与前人碎屑锆石 U-Pb 年代学和同位素地球化学得到的物源示踪结果一致 (Lan *et al.*, 2014, 2016)。

与始新统-下渐新统相比, 上渐新统五指山层有更多的中放射性成因 Pb 长石颗粒 ($17.0 < ^{206}\text{Pb}/^{204}\text{Pb} < 18.0$, 图 9), 表明自晚渐新世开始, 台湾的物源区发生了一定的转变。通过与扬子克拉通、华夏地体、秦岭、桐柏-大别山和现代水系 (赣江) 对比, 发现上渐新统长石 Pb 同位素与赣江的基本一致 (图 9), 表明在晚渐新世赣江上游流域曾为台湾的重要物源区。与裂陷期地层相比, 中新统样品含有大量低放射性成因 Pb 颗粒 ($^{206}\text{Pb}/^{204}\text{Pb} < 17$), 它们在扬子克拉通和华夏地体均较为少见, 与秦岭、桐柏-大别山的低放射性成因 Pb 特征类似 (图 9)。这些证据显示, 中新世时台湾的物源区已经拓展至中国大陆东部的大部分地区。

3 华南主要大河新生代演化及动力机制

前期研究均强调青藏高原隆升在东亚地形反转和大规模水系重组中起到的主导作用, 如多数学

者认为古红河解体和长江诞生的控制因素是青藏高原隆升(Clark *et al.*, 2004; Zheng *et al.*, 2013). 根据经典地貌学理论,除源区隆升之外,侵蚀基准面的急剧下降也能诱发大规模水系重组,然而这一因素在东亚主要大河演化研究中并未引起足够的关注. 在中生代末期-新生代早期,太平洋板块后撤式俯冲,岩浆上涌引起区域性的伸展拉张,华南陆缘发生正断层断陷,形成珠江口盆地及古台湾盆地等(索艳慧等, 2012; Ren *et al.*, 2002),它们在裂陷期以河湖相填充为主;渐新世起,被动大陆边缘因大陆地壳持续拉张减薄,最后基性岩浆冒出,形成南海洋壳及洋中脊(Li *et al.*, 2014; Larsen *et al.*, 2018). 南海打开这一重大构造事件,必然导致区域侵蚀基准面大规模的下降,为华南边缘的中小型水系向内陆溯源提供较强的动力. 此外,气候变迁在华南大河演化中也扮演着重要角色;新生代早期中国东部主要由行星风系控制,存在一个宽阔的由西向东贯穿的干旱带(Guo *et al.*, 2008),不利于大型河流发育. 晚始新世以来,青藏高原东南缘及华南气候格局基本定型(Sun and Wang, 2005; Wu *et al.*, 2022),以湿热型气候为主,有利于沿海河流向内陆拓展.

台湾新生界多种物源指标清晰地指示,在始新世-早渐新世区域破裂不整合事件之后(古)闽江曾向内陆侵蚀(Lan *et al.*, 2014; Zhang *et al.*, 2022). 早中新世之后,随着中国东部区域整体沉降之后,东亚东倾地形基本形成,大量碎屑物质被古长江和古黄河等搬运至东海陆架盆地. 珠江口盆地新生代地层也记录了类似的水系拓展事件,在始新世-渐新世早期,珠江口盆地主要由近源的华南大陆南缘供给沉积物,暗示此时古珠江流域范围较为局限(Shao *et al.*, 2015, 2016; Yan *et al.*, 2018). 渐新世晚期以后,珠江口盆地沉积物的供给模式与现代珠江基本类似,表明珠江水系已向西扩展至青藏高原东南缘(Cao *et al.*, 2018). 这些证据表明,珠江的扩展与南海打开紧密相关.

4 结论及展望

莺歌海盆地物源研究显示,始-早渐新世该盆地主要由近源河流供给,晚渐新世以来红河是主要物源供给者;莺歌海盆地新生代沉积物与青藏高原东南缘其他大河(如长江、怒江和澜沧江等)的物源信号差异较大,表明它们在晚始新世以来并未汇入

莺歌海盆地,即青藏高原东南缘并不存在南流的巨型古红河. 始新世-早渐新世,台湾主要物源区为临近的华夏地体;晚渐新世之后,随着南海的打开,古闽江逐渐拓展至下扬子地区. 早中新世以后,扬子克拉通及秦岭-大别造山带等成为华南大陆边缘的主要物源区,表明中国大陆东倾地貌格局已基本形成. 结合珠江口盆地沉积记录,显示珠江在晚渐新世向西拓展,其流域范围已覆盖青藏高原东南缘. 考虑东亚季风气候在晚始新世已基本定型(Wu *et al.*, 2022),这表明渐新世边缘海的打开是晚渐新世华南沿海水系向内陆拓展的主要驱动力,这一构造事件在东亚主要水系演化中的角色不亚于青藏隆升. 华南主要大河是东亚新生代构造活动(南海打开)、气候变迁(亚洲季风形成)和地貌演化(东亚地形反转)相互作用的产物. 因此,利用精确年代学控制的沉积记录,结合有效的物源示踪工具,在充分考虑区域构造演化和气候变迁的前提下,才能更准确地刻画华南主要大河的演化过程. 目前大多数学者利用单矿物示踪工具(如锆石)研究华南水系演化,常忽略了以下两种因素的影响:(1)物源区矿物丰度的不均一;(2)沉积再旋回效应等(Malusà *et al.*, 2016). 未来研究中,在详细的砂岩岩相学研究基础上,将稳定性较弱的单矿物(如钾长石和磷灰石等)与极稳定重矿物(如锆石 U-Pb 测年)结合,校正沉积再旋回效应和矿物丰度差异的影响,准确示踪沉积物的直接物源区,能较好地约束水系的演化过程.

致谢:感谢香港大学秦咏辉博士和南京大学郭汝军博士在数据收集提供的帮助!

References

- An, Z. S., Kutzbach, J. E., Prell, W. L., et al., 2001. Evolution of Asian Monsoons and Phased Uplift of the Himalaya-Tibetan Plateau since Late Miocene Times. *Nature*, 411(6833): 62–66. <https://doi.org/10.1038/35075035>
- Bodet, F., Schärer, U., 2001. Pb Isotope Systematics and Time-Integrated Th/U of SE-Asian Continental Crust Recorded by Single K-Feldspar Grains in Large Rivers. *Chemical Geology*, 177(3–4): 265–285. [https://doi.org/10.1016/S0009-2541\(00\)00413-7](https://doi.org/10.1016/S0009-2541(00)00413-7)
- Brookfield, M. E., 1998. The Evolution of the Great River Systems of Southern Asia during the Cenozoic India-Asia Collision: Rivers Draining Southwards. *Geomorphology*, 22(3–4): 285–312. [https://doi.org/10.1016/S0169-555X\(97\)00082-2](https://doi.org/10.1016/S0169-555X(97)00082-2)

- Brookfield, M. E., 2008. Evolution of the Great River Systems of Southern Asia during the Cenozoic India-Asia Collision: Rivers Draining North from the Pamir Syntaxis. *Geomorphology*, 100(3–4): 296–311. <https://doi.org/10.1016/j.geomorph.2008.01.003>
- Cao, L. C., Jiang, T., Wang, Z. F., et al., 2015. Provenance of Upper Miocene Sediments in the Yinggehai and Qiongdongnan Basins, Northwestern South China Sea: Evidence from REE, Heavy Minerals and Zircon U-Pb Ages. *Marine Geology*, 361: 136–146. <https://doi.org/10.1016/j.margeo.2015.01.007>
- Cao, L. C., Shao, L., Qiao, P. J., et al., 2018. Early Miocene Birth of Modern Pearl River Recorded Low-Relief, High-Elevation Surface Formation of SE Tibetan Plateau. *Earth and Planetary Science Letters*, 496: 120–131. <https://doi.org/10.1016/j.epsl.2018.05.039>
- Caracciolo, L., 2020. Sediment Generation and Sediment Routing Systems from a Quantitative Provenance Analysis Perspective: Review, Application and Future Development. *Earth-Science Reviews*, 209: 103226. <https://doi.org/10.1016/j.earscirev.2020.103226>
- Chen, C. H., Lee, C. Y., Lin, J. W., et al., 2019. Provenance of Sediments in Western Foothills and Hsuehsan Range (Taiwan): A New View Based on the EMP Monazite versus LA-ICPMS Zircon Geochronology of Detrital Grains. *Earth - Science Reviews*, 190: 224–246. <https://doi.org/10.1016/j.earscirev.2018.12.015>
- Chen, C.M., Shi, H.S., Xu, S.C., et al., 2003. Formation Conditions of Tertiary Oil and Gas Reservoirs in the Eastern Pearl River Mouth Basin. Geological Publishing House, Beijing (in Chinese).
- Chen, Y., Yan, M. D., Fang, X. M., et al., 2017. Detrital Zircon U - Pb Geochronological and Sedimentological Study of the Simao Basin, Yunnan: Implications for the Early Cenozoic Evolution of the Red River. *Earth and Planetary Science Letters*, 476: 22–33. <https://doi.org/10.1016/j.epsl.2017.07.025>
- Clark, M. K., Schoenbohm, L. M., Royden, L. H., et al., 2004. Surface Uplift, Tectonics, and Erosion of Eastern Tibet from Large-Scale Drainage Patterns. *Tectonics*, 23(1): TC1006. <https://doi.org/10.1029/2002tc001402>
- Clift, P. D., Blusztajn, J., Nguyen, A. D., 2006. Large-Scale Drainage Capture and Surface Uplift in Eastern Tibet-SW China before 24 Ma Inferred from Sediments of the Hanoi Basin, Vietnam. *Geophysical Research Letters*, 33(19): L19403. <https://doi.org/10.1029/2006gl027772>
- Clift, P. D., Long, H. V., Hinton, R., et al., 2008. Evolving East Asian River Systems Reconstructed by Trace Element and Pb and Nd Isotope Variations in Modern and Ancient Red River-Song Hong Sediments. *Geochemistry, Geophysics, Geosystems*, 9(4): Q04039. <https://doi.org/10.1029/2007GC001867>
- Deng, K., Yang, S. Y., Li, C., et al., 2017. Detrital Zircon Geochronology of River Sands from Taiwan: Implications for Sedimentary Provenance of Taiwan and Its Source Link with the East China Mainland. *Earth - Science Reviews*, 164: 31–47. <https://doi.org/10.1016/j.earscirev.2016.10.015>
- Flowerdew, M. J., Tyrrell, S., Riley, T. R., et al., 2012. Distinguishing East and West Antarctic Sediment Sources Using the Pb Isotope Composition of Detrital K - Feldspar. *Chemical Geology*, 292–293: 88–102. <https://doi.org/10.1016/j.chemgeo.2011.11.006>
- Garzanti, E., Vermeesch, P., Andò, S., et al., 2013. Provenance and Recycling of Arabian Desert Sand. *Earth - Science Reviews*, 120: 1–19. <https://doi.org/10.1016/j.earscirev.2013.01.005>
- Guo, Z. T., Sun, B., Zhang, Z. S., et al., 2008. A Major Reorganization of Asian Climate by the Early Miocene. *Climate of the Past*, 4(3): 153–174. <https://doi.org/10.5194/cp-4-153-2008>
- He, M. Y., Zheng, H. B., Clift, P. D., 2013. Zircon U-Pb Geochronology and Hf Isotope Data from the Yangtze River Sands: Implications for Major Magmatic Events and Crustal Evolution in Central China. *Chemical Geology*, 360–361: 186–203. <https://doi.org/10.1016/j.chemgeo.2013.10.020>
- Huang, C. Y., Yen, Y., Zhao, Q. H., et al., 2012. Cenozoic Stratigraphy of Taiwan: Window into Rifting, Stratigraphy and Paleoceanography of South China Sea. *Chinese Science Bulletin*, 57(24): 3130–3149. <https://doi.org/10.1007/s11434-012-5349-y>
- Jiang, T., Cao, L. C., Xie, X. N., et al., 2015. Insights from Heavy Minerals and Zircon U - Pb Ages into the Middle Miocene-Pliocene Provenance Evolution of the Yinggehai Basin, Northwestern South China Sea. *Sedimentary Geology*, 327: 32–42. <https://doi.org/10.1016/j.sedgeo.2015.07.011>
- Jin, H. L., Wan, S. M., Clift, P. D., et al., 2022. Birth of the Pearl River at 30 Ma: Evidence from Sedimentary Records in the Northern South China Sea. *Earth and Planetary Science Letters*, 600: 117872. <https://doi.org/10.1016/j.epsl.2022.117872>
- Kong, P., Zheng, Y., Caffee, M. W., 2012. Provenance and Time Constraints on the Formation of the First

- Bend of the Yangtze River. *Geochemistry, Geophysics, Geosystems*, 13(6): Q06017. <https://doi.org/10.1029/2012gc004140>
- Lan, Q., Yan, Y., Huang, C. Y., et al., 2014. Tectonics, Topography, and River System Transition in East Tibet: Insights from the Sedimentary Record in Taiwan. *Geochemistry, Geophysics, Geosystems*, 15(9): 3658—3674. <https://doi.org/10.1002/2014gc005310>
- Lan, Q., Yan, Y., Huang, C. Y., et al., 2016. Topographic Architecture and Drainage Reorganization in South East China: Zircon U-Pb Chronology and Hf Isotope Evidence from Taiwan. *Gondwana Research*, 36: 376—389. <https://doi.org/10.1016/j.gr.2015.07.008>
- Larsen, H. C., Mohn, G., Nirrengarten, M., et al., 2018. Rapid Transition from Continental Breakup to Igneous Oceanic Crust in the South China Sea. *Nature Geoscience*, 11(10): 782—789. <https://doi.org/10.1038/s41561-018-0198-1>
- Lee, C. Y., 1934. The Development of the Upper Yangtze Valley. *Bulletin of the Geological Society of China*, 13 (1): 107—118. <https://doi.org/10.1111/j.1755-6724.1934.mp13001006.x>
- Lei, C., 2012. Analysis of Cenozoic Tectonic Deformation Pattern and Its Evolution Process in Yinggehai - Qiongdongnan Basin in the Northern South China Sea (Dissertation). China University of Geosciences, Wuhan (in Chinese with English abstract).
- Lei, C., Clift, P. D., Ren, J. Y., et al., 2019. A Rapid Shift in the Sediment Routing System of Lower-Upper Oligocene Strata in the Qiongdongnnan Basin (Xisha Trough), Northwest South China Sea. *Marine and Petroleum Geology*, 104: 249—258. <https://doi.org/10.1016/j.marpetgeo.2019.03.012>
- Lei, C., Ren, J. Y., Sternai, P., et al., 2015. Structure and Sediment Budget of Yinggehai-Song Hong Basin, South China Sea: Implications for Cenozoic Tectonics and River Basin Reorganization in Southeast Asia. *Tectonophysics*, 655(2): 177—190. <https://doi.org/10.1016/j.tecto.2015.05.024>
- Li, C. F., Xu, X., Lin, J., et al., 2014. Ages and Magnetic Structures of the South China Sea Constrained by Deep Tow Magnetic Surveys and IODP Expedition 349. *Geochemistry, Geophysics, Geosystems*, 15(12): 4958—4983. <https://doi.org/10.1002/2014gc005567>
- Li, X. H., Wei, G. J., Shao, L., et al., 2003. Geochemical and Nd Isotopic Variations in Sediments of the South China Sea: A Response to Cenozoic Tectonism in SE Asia. *Earth and Planetary Science Letters*, 211 (3—4): 207—220. [https://doi.org/10.1016/S0012-821X\(03\)00229-2](https://doi.org/10.1016/S0012-821X(03)00229-2)
- Liu, C., Stockli, D. F., Clift, P. D., et al., 2022. Geochronological and Geochemical Characterization of Paleorivers Deposits during Rifting of the South China Sea. *Earth and Planetary Science Letters*, 584: 117427. <https://doi.org/10.1016/j.epsl.2022.117427>
- Liu, J. P., Li, A. C., Xu, K. H., et al., 2006. Sedimentary Features of the Yangtze River-Derived Along-Shelf Clinoform Deposit in the East China Sea. *Continental Shelf Research*, 26(17—18): 2141—2156. <https://doi.org/10.1016/j.csr.2006.07.013>
- Liu, J. P., Xu, K. H., Li, A. C., et al., 2007. Flux and Fate of Yangtze River Sediment Delivered to the East China Sea. *Geomorphology*, 85(3—4): 208—224. <https://doi.org/10.1016/j.geomorph.2006.03.023>
- Liu, Z. F., Zhao, Y. L., Colin, C., et al., 2016. Source-to-Sink Transport Processes of Fluvial Sediments in the South China Sea. *Earth-Science Reviews*, 153: 238—273. <https://doi.org/10.1016/j.earscirev.2015.08.005>
- Malusà, M. G., Resentini, A., Garzanti, E., 2016. Hydraulic Sorting and Mineral Fertility Bias in Detrital Geochronology. *Gondwana Research*, 31: 1—19. <https://doi.org/10.1016/j.gr.2015.09.002>
- Nie, J. S., Ruetenik, G., Gallagher, K., et al., 2018. Rapid Incision of the Mekong River in the Middle Miocene Linked to Monsoonal Precipitation. *Nature Geoscience*, 11(12): 944—948. <https://doi.org/10.1038/s41561-018-0244-z>
- Pang, X., Chen, C. M., Shao, L., et al., 2007. Baiyun Movement, a Great Tectonic Event on the Oligocene-Miocene Boundary in the Northern South China Sea and Its Implications. *Geological Review*, 53(2): 145—151 (in Chinese with English abstract).
- Pang, X., Chen, C. M., Zhu, M., et al., 2009. Baiyun Movement: A Significant Tectonic Event on Oligocene/Miocene Boundary in the Northern South China Sea and Its Regional Implications. *Journal of Earth Science*, 20(1): 49—56. <https://doi.org/10.1007/s12583-009-0005-4>
- Que, X. M., Shu, Y., Wang, X. D., et al., 2024. Provenance Characteristics and Sedimentary Evolution of Zhu I Depression in Paleogene: Indications from Detrital Zircon Ages. *Earth Science*, 49(7): 2373—2387 (in Chinese with English abstract).
- Ren, J. Y., 2018. Genetic Dynamics of China Offshore Cenozoic Basins. *Earth Science*, 43(10): 3337—3361 (in Chinese with English abstract).

- Ren, J. Y., Lei, C., 2011. Tectonic Stratigraphic Framework of Yinggehai-Qiongdongnan Basins and Its Implication for Tectonic Province Division in South China Sea. *Chinese Journal of Geophysics*, 54(12): 3303–3314 (in Chinese with English abstract).
- Ren, J. Y., Tamaki, K., Li, S. T., et al., 2002. Late Mesozoic and Cenozoic Rifting and Its Dynamic Setting in Eastern China and Adjacent Areas. *Tectonophysics*, 344 (3–4): 175–205. [https://doi.org/10.1016/S0040-1951\(01\)00271-2](https://doi.org/10.1016/S0040-1951(01)00271-2)
- Ren, M. E., Bao, H. S., Han, T. C., et al., 1959. Geomorphology and River Capture in Jinsha River Valley in Northwest Yunnan. *Acta Geographica Sinica*, 25(2): 135–155 (in Chinese with English abstract).
- Shao, L., Cao, L. C., Pang, X., et al., 2016. Detrital Zircon Provenance of the Paleogene Syn-Rift Sediments in the Northern South China Sea. *Geochemistry, Geophysics, Geosystems*, 17(2): 255–269. <https://doi.org/10.1002/2015gc006113>
- Shao, L., Pang, X., Qiao, P. J., et al., 2008. Sedimentary Filling of the Pearl River Mouth Basin and Its Response to the Evolution of the Pearl River. *Acta Sedimentologica Sinica*, 26(2): 179–185 (in Chinese with English abstract).
- Shao, L., Qiao, P. J., Zhao, M., et al., 2016. Depositional Characteristics of the Northern South China Sea in Response to the Evolution of the Pearl River. *Geological Society, London, Special Publications*, 429(1): 31–44. <https://doi.org/10.1144/SP429.2>
- Shao, L., Zhao, M., Qiao, P. J., et al., 2013. The Characteristics of the Sediment in Northern South China Sea and Its Response to the Evolution of the Pearl River. *Quaternary Sciences*, 33(4): 760–770 (in Chinese with English abstract).
- Shao, W. Y., Chung, S. L., Chen, W. S., et al., 2015. Old Continental Zircons from a Young Oceanic Arc, Eastern Taiwan: Implications for Luzon Subduction Initiation and Asian Accretionary Orogeny. *Geology*, 43(6): 479–482. <https://doi.org/10.1130/g36499.1>
- Sun, X. J., Wang, P. X., 2005. How Old is the Asian Monsoon System? —Palaeobotanical Records from China. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 222(3–4): 181–222. <https://doi.org/10.1016/j.palaeo.2005.03.005>
- Suo, Y. H., Li, S. Z., Zhao, S. J., et al., 2015. Continental Margin Basins in East Asia: Tectonic Implications of the Meso-Cenozoic East China Sea Pull-Apart Basins. *Geological Journal*, 50(2): 139–156. <https://doi.org/10.1002/gj.2535>
- Suo, Y. H., Li, S. Z., Dai, L. M., et al., 2012. Cenozoic Tectonic Migration and Basin Evolution in East Asia and Its Continental Margins. *Acta Petrologica Sinica*, 28(8): 2602–2618 (in Chinese with English abstract).
- Tyrrell, S., Haughton, P. D. W., Daly, J. S., 2007. Drainage Reorganization during Breakup of Pangea Revealed by In-Situ Pb Isotopic Analysis of Detrital K-Feldspar. *Geology*, 35(11): 971–974. <https://doi.org/10.1130/g4123a.1>
- Van Hoang, L., Wu, F. Y., Clift, P. D., et al., 2009. Evaluating the Evolution of the Red River System Based on In Situ U-Pb Dating and Hf Isotope Analysis of Zircons. *Geochemistry, Geophysics, Geosystems*, 10(11): Q11008. <https://doi.org/10.1029/2009gc002819>
- Wang, C., Liang, X. Q., Foster, D. A., et al., 2016. Zircon U-Pb Geochronology and Heavy Mineral Composition Constraints on the Provenance of the Middle Miocene Deep-Water Reservoir Sedimentary Rocks in the Yinggehai-Song Hong Basin, South China Sea. *Marine and Petroleum Geology*, 77: 819–834. <https://doi.org/10.1016/j.marpetgeo.2016.05.009>
- Wang, C., Liang, X. Q., Foster, D. A., et al., 2019. Linking Source and Sink: Detrital Zircon Provenance Record of Drainage Systems in Vietnam and the Yinggehai-Song Hong Basin, South China Sea. *GSA Bulletin*, 131 (1–2): 191–204. <https://doi.org/10.1130/b32007.1>
- Wang, C., Liang, X. Q., Foster, D. A., et al., 2019. Provenance and Drainage Evolution of the Red River Revealed by Pb Isotopic Analysis of Detrital K-Feldspar. *Geophysical Research Letters*, 46(12): 6415–6424. <https://doi.org/10.1029/2019gl083000>
- Wang, C., Liang, X. Q., Xie, Y. H., et al., 2014. Provenance of Upper Miocene to Quaternary Sediments in the Yinggehai-Song Hong Basin, South China Sea: Evidence from Detrital Zircon U-Pb Ages. *Marine Geology*, 355: 202–217. <https://doi.org/10.1016/j.marpetgeo.2014.06.004>
- Wang, P. X., 2005. Cenozoic Deformation and History of Sea-Land Interactions in Asia. *Earth Science*, 30(1): 1–18 (in Chinese with English abstract).
- Wang, W., Bidgoli, T., Yang, X. H., et al., 2018. Source-to-Sink Links between East Asia and Taiwan from Detrital Zircon Geochronology of the Oligocene Huagang Formation in the East China Sea Shelf Basin. *Geochemistry, Geophysics, Geosystems*, 19(10): 3673–3688. <https://doi.org/10.1029/2018gc007576>
- Wang, Y. F., Li, D., Wang, Y. M., et al., 2015. Major Un-

- conformities and Sedimentary System Evolution in Pearl River Mouth Basin. *Acta Sedimentologica Sinica*, 33 (3): 587—594 (in Chinese with English abstract).
- Wei, H. H., Wang, E., Wu, G. L., et al., 2016. No Sedimentary Records Indicating Southerly Flow of the Paleoupper Yangtze River from the First Bend in Southeastern Tibet. *Gondwana Research*, 32: 93—104. <https://doi.org/10.1016/j.gr.2015.02.006>
- Wu, F. L., Fang, X. M., Yang, Y. B., et al., 2022. Reorganization of Asian Climate in Relation to Tibetan Plateau Uplift. *Nature Reviews Earth & Environment*, 3(10): 684—700. <https://doi.org/10.1038/s43017-022-00331-7>
- Xie, Y. H., 2009. Sequence Stratigraphy and Natural Gas Accumulation Models in Tectonically Active Basins: A Case Study of the Yinggehai Basin. Geological Publishing House, Beijing (in Chinese).
- Xu, Y. H., Wang, C. Y., Zhao, T. P., 2016. Using Detrital Zircons from River Sands to Constrain Major Tectonothermal Events of the Cathaysia Block, SE China. *Journal of Asian Earth Sciences*, 124: 1—13. <https://doi.org/10.1016/j.jseaes.2016.04.012>
- Yan, Y., Carter, A., Huang, C. Y., et al., 2012. Constraints on Cenozoic Regional Drainage Evolution of SW China from the Provenance of the Jianchuan Basin. *Geochemistry, Geophysics, Geosystems*, 13(3): Q03001. <https://doi.org/10.1029/2011GC003803>
- Yan, Y., Carter, A., Palk, C., et al., 2011. Understanding Sedimentation in the Song Hong - Yinggehai Basin, South China Sea. *Geochemistry, Geophysics, Geosystems*, 12(6): Q06014. <https://doi.org/10.1029/2011GC003533>
- Yan, Y., Yao, D., Tian, Z. X., et al., 2018. Tectonic Topography Changes in Cenozoic East Asia: A Landscape Erosion-Sediment Archive in the South China Sea. *Geochemistry, Geophysics, Geosystems*, 19(6): 1731—1750. <https://doi.org/10.1029/2017gc007356>
- Yang, D. Y., Han, Z. Y., Ge, Z. S., et al., 2008. Geomorphic Process of the Formation and Incision of the Section from Shigu to Yibin of the Jinshajiang River. *Quaternary Sciences*, 28(4): 564—568 (in Chinese with English abstract).
- Yang, R., Willett, S. D., Goren, L., 2015. In Situ Low-Relief Landscape Formation as a Result of River Network Disruption. *Nature*, 520(7548): 526—529. <https://doi.org/10.1038/nature14354>
- Yang, S. Y., Zhang, F., Wang, Z. B., 2012. Grain Size Distribution and Age Population of Detrital Zircons from the Changjiang (Yangtze) River System, China. *Chemical Geology*, 296: 26—38. <https://doi.org/10.1016/j.chemgeo.2011.12.016>
- Zeng, Z. W., Zhu, H. T., Yang, X. H., et al., 2019. Using Seismic Geomorphology and Detrital Zircon Geochronology to Constrain Provenance Evolution and Its Response of Paleogene Enping Formation in the Baiyun Sag, Pearl River Mouth Basin, South China Sea: Implications for Paleo-Pearl River Drainage Evolution. *Journal of Petroleum Science and Engineering*, 177: 663—680. <https://doi.org/10.1016/j.petrol.2019.02.051>
- Zhang, G. H., Li, S. Z., Suo, Y. H., et al., 2016. Cenozoic Positive Inversion Tectonics and Its Migration in the East China Sea Shelf Basin. *Geological Journal*, 51 (S1): 176—187. <https://doi.org/10.1002/gj.2809>
- Zhang, L. G., 1995. Block - Geology of Asia Lithosphere: Isotope Geochemistry and Dynamics of Upper Mantle, Basement and Granite. Science Press, Beijing, 252 (in Chinese).
- Zhang, P., Najman, Y., Mei, L. F., et al., 2019. Palaeodrainage Evolution of the Large Rivers of East Asia, and Himalayan - Tibet Tectonics. *Earth - Science Reviews*, 192: 601—630. <https://doi.org/10.1016/j.earsci-rev.2019.02.003>
- Zhang, X. C., Huang, C. Y., Wang, Y. J., et al., 2017. Evolving Yangtze River Reconstructed by Detrital Zircon U-Pb Dating and Petrographic Analysis of Miocene Marginal Sea Sedimentary Rocks of the Western Foot-hills and Hengchun Peninsula, Taiwan. *Tectonics*, 36 (4): 634—651. <https://doi.org/10.1002/2016TC004357>
- Zhang, Z. J., Daly, J. S., Tian, Y. T., et al., 2023. Late Oligocene Formation of the Pearl River Triggered by the Opening of the South China Sea. *Geophysical Research Letters*, 50(8): e2023GL103049. <https://doi.org/10.1029/2023gl103049>
- Zhang, Z. J., Daly, J. S., Yan, Y., et al., 2021. No Connection between the Yangtze and Red Rivers since the Late Eocene. *Marine and Petroleum Geology*, 129: 105115. <https://doi.org/10.1016/j.marpetgeo.2021.105115>
- Zhang, Z. J., Daly, J. S., Yan, Y., et al., 2022. Cenozoic Reorganization of Fluvial Systems in Eastern China: Sedimentary Provenance of Detrital K - Feldspar in Taiwan. *Chemical Geology*, 592: 120740. <https://doi.org/10.1016/j.chemgeo.2022.120740>
- Zhang, Z. J., Tyrrell, S., Li, C. A., et al., 2014. Pb Isotope Compositions of Detrital K-Feldspar Grains in the Upper-Middle Yangtze River System: Implications for Sediment Provenance and Drainage Evolution. *Geo-*

chemistry, Geophysics, Geosystems, 15(7): 2765–2779.
<https://doi.org/10.1002/2014GC005391>

- Zhao, Z.X., Zhou, D., Liao, J., 2009. Tertiary Paleogeography and Depositional Evolution in the Pearl River Mouth Basin of the Northern South China Sea. *Journal of Tropical Oceanography*, 28(6): 52–60 (in Chinese with English abstract).
- Zheng, H., Clift, P. D., Wang, P., et al., 2013. Pre-Miocene Birth of the Yangtze River. *Proceedings of the National Academy of Sciences*, 110(19): 7556–7561.
<https://doi.org/10.1073/pnas.1216241110>

中文参考文献

- 陈长民, 施和生, 许仕策, 等, 2003. 珠江口盆地(东部)第三系油气藏形成条件. 北京: 科学出版社.
- 雷超, 2012. 南海北部莺歌海-琼东南盆地新生代构造变形格局及其演化过程分析(博士学位论文). 武汉: 中国地质大学.
- 庞雄, 陈长民, 邵磊, 等, 2007. 白云运动: 南海北部渐新统一中新统重大地质事件及其意义. *地质论评*, 53(2): 145–151.
- 阙晓铭, 舒誉, 汪旭东, 等, 2024. 珠一坳陷古近纪物源特征及其沉积演化: 来自碎屑锆石年龄的指示. *地球科学*, 49(7): 2373–2387.
- 任建业, 2018. 中国近海海域新生代成盆动力机制分析. *地球科学*, 43(10): 3337–3361.

- 任建业, 雷超, 2011. 莺歌海-琼东南盆地构造-地层格架及南海动力变形分区. *地球物理学报*, 54(12): 3303–3314.
- 任美镔, 包浩生, 韩同春, 等, 1959. 云南西北部金沙江河谷地貌与河流袭夺问题. *地理学报*, 25(2): 135–155.
- 邵磊, 庞雄, 乔培军, 等, 2008. 珠江口盆地的沉积充填与珠江的形成演变. *沉积学报*, 26(2): 179–185.
- 邵磊, 赵梦, 乔培军, 等, 2013. 南海北部沉积物特征及其对珠江演变的响应. *第四纪研究*, 33(4): 760–770.
- 索艳慧, 李三忠, 戴黎明, 等, 2012. 东亚及其大陆边缘新生代构造迁移与盆地演化. *岩石学报*, 28(8): 2602–2618.
- 汪品先, 2005. 新生代亚洲形变与海陆相互作用. *地球科学*, 30(1): 1–18.
- 王永凤, 李冬, 王英民, 等, 2015. 珠江口盆地重要不整合界面与珠江沉积体系演化分析. *沉积学报*, 33(3): 587–594.
- 谢玉洪, 2009. 构造活动型盆地层序地层分析及天然气成藏模式: 以莺歌海盆地为例. 北京: 地质出版社.
- 杨达源, 韩志勇, 葛兆帅, 等, 2008. 金沙江石鼓-宜宾河段的贯通与深切地貌过程的研究. *第四纪研究*, 28(4): 564–568.
- 张理刚, 1995. 东亚岩石圈块体地质: 上地幔、基底和花岗岩同位素地球化学及其动力学. 北京: 科学出版社, 252.
- 赵中贤, 周蒂, 廖杰, 2009. 珠江口盆地第三纪古地理及沉积演化. *热带海洋学报*, 28(6): 52–60.