

# 扬子克拉通南华纪碎屑锆石 U-Pb 年龄、Hf 同位素 对华南新元古代岩浆事件的指示

谢士稳<sup>1,2</sup>, 高山<sup>1,2,3</sup>, 柳小明<sup>3</sup>, 高日胜<sup>4</sup>

1. 中国地质大学地球科学学院, 湖北武汉 430074
2. 中国地质大学地质过程与矿产资源国家重点实验室, 湖北武汉 430074
3. 西北大学地质系大陆动力学国家重点实验室, 陕西西安 710069
4. 中油国际海外中心, 北京 100083

**摘要:** 对采自宜昌三峡地区南华纪沉积岩中碎屑锆石进行了 U-Pb 定年, 新元古代锆石 U-Pb 年龄在 833 Ma、785 Ma 出现高峰, 说明此时期有两期大规模岩浆活动。结合前人的 Hf 同位素结果, 新元古代锆石 U-Pb 年龄与  $\epsilon_{\text{Hf}}(t)$  值关系图表明: 910~890 Ma 之间锆石  $\epsilon_{\text{Hf}}(t)$  值表现为高正值 ( $\approx 10$ , 接近亏损地幔演化值), 890~840 Ma 锆石  $\epsilon_{\text{Hf}}(t)$  值明显降低, 并有负值出现, 另外在 890 Ma 处有年龄峰出现。笔者认为扬子和华夏板块的拼合可能在 890 Ma 发生了由俯冲到陆-陆或陆-弧的碰撞, 之前的高  $\epsilon_{\text{Hf}}(t)$  值由洋壳俯冲造成, 之后碰撞作用陆壳物质熔融造成了  $\epsilon_{\text{Hf}}(t)$  值的降低; 840~800 Ma 的锆石  $\epsilon_{\text{Hf}}(t)$  值有正也有负, 800~780 Ma 的锆石  $\epsilon_{\text{Hf}}(t)$  值小于 0, 780~750 Ma 的锆石  $\epsilon_{\text{Hf}}(t)$  值大于 0。这些数据与 830~795 Ma、780~745 Ma 两期地幔柱事件吻合。  
**关键词:** 扬子板块; 锆石 U-Pb 定年; 地幔柱; Rodinia 超大陆; Hf 同位素。

中图分类号: P597

文章编号: 1000-2383(2009)01-0117-10

收稿日期: 2008-10-10

## U-Pb Ages and Hf Isotopes of Detrital Zircons of Nanhua Sedimentary Rocks from the Yangtze Gorges: Implications for Genesis of Neoproterozoic Magmatism in South China

XIE Shi-wen<sup>1,2</sup>, GAO Shan<sup>1,2,3</sup>, LIU Xiao-ming<sup>3</sup>, GAO Ri-sheng<sup>4</sup>

1. Faculty of Earth Sciences, China University of Geosciences, Wuhan 430074, China
2. State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan 430074, China
3. State Key Laboratory of Continental Dynamics, Department of Geology, Northwest University, Xi'an 710069, China
4. CNPC International Research Center, Beijing 100083, China

**Abstract:** This paper reports LA-ICP-MS U-Pb dates of detrital zircons from the Nanhua elastic sedimentary rocks in the Yangtze gorges. Neoproterozoic U-Pb ages show two peaks at 833 Ma and 785 Ma, assumably corresponding to two large-scale periods of magmatism.  $\epsilon_{\text{Hf}}(t)$  values for the 910–890 Ma zircons are positive ( $\approx 10$ , similar to the value of the coeval depleted mantle), while those for the 890–840 Ma zircons tend to decrease to negative values, and there shows age peaks at 890 Ma. These data allow us to infer that transformation of oceanic subduction into continental collision or continental-arc collision occurred at about 890 Ma via amalgamation of the Yangtze and Cathaysia blocks. The high  $\epsilon_{\text{Hf}}(t)$  values prior to 890 Ma resulted from the subduction of oceanic crust. The subsequent drop of  $\epsilon_{\text{Hf}}(t)$  values was caused by the crust melting and crustal collision.  $\epsilon_{\text{Hf}}(t)$  values for the 840–800 Ma zircons are either negative or positive, whereas  $\epsilon_{\text{Hf}}(t)$  values for the 800–780 Ma zircons are all negative and  $\epsilon_{\text{Hf}}(t)$  values for the 780–750 Ma zircons are mostly positive. These data are in coincidence with two stages of the mantle plume beneath the Yangtze craton at 830–795 Ma and 780–745 Ma.

**Key words:** Yangtze block; zircon U-Pb dating; mantle plume; Rodinia supercontinent; Hf isotope.

基金项目: 教育部创新团队研究计划项目 (Nos. IRT0441, 306021); 国家自然科学基金委创新研究群体科学基金项目 (No. 40521001); 高等学校学科创新引智计划 (No. B07039).

作者简介: 谢士稳 (1983-), 男, 硕士研究生在读, 岩石圈地球化学专业. E-mail: swxie210@163.com

扬子克拉通是我国重要构造单元之一,其中广泛发育新元古代岩浆事件,这些岩浆岩的年龄多分布在 830~740 Ma(Li, Z. X., *et al.*, 2003; Zheng *et al.*, 2004, 2006; Li, W. X., *et al.*, 2005; 钟玉芳等, 2005; Zhou *et al.*, 2006a, 2006b; Zhu *et al.*, 2006; Wu *et al.*, 2007; Li, X. H., *et al.*, 2008; Tang *et al.*, 2008; Wang *et al.*, 2008),随着 Rodinia 超大陆重建的进一步研究,以及华南超级地幔柱的提出(Li, Z. X., *et al.*, 1995, 1999, 2003; Li, X. H., *et al.*, 2003)扬子新元古代岩浆岩的成因已成为地质学家们研究的热点. 这些岩浆岩的成因也成为大家争论的焦点,目前已提出 3 种成因模式:(1)地幔柱成因(Li, Z. X., *et al.*, 1999, 2003; Li, X. H., *et al.*, 2003, 2006),认为这些岩浆活动是地幔柱成因,在 830~750 Ma 期间,Rodinia 超大陆下存在一个超级地幔柱,通过主要的两次地幔柱活动导致了华南大规模的地壳抬升、去顶、大陆裂谷和广泛的双峰式岩浆作用,并最终导致了 Rodinia 超大陆的裂解;(2)岛弧模式(Zhou, M. F., *et al.*, 2002a, 2002b; Zhou, J. C., *et al.*, 2004; Wang *et al.*, 2004a, 2004b, 2006)认为这些岩浆活动是洋壳俯冲消减于扬子板块下引起的岛弧岩浆,并认为新元古代时期,华南是一个被消减海洋岩石圈俯冲带包围的孤立陆块;(3)板块—裂谷模式,认为这些岩浆产物是早期弧—陆碰撞、晚期拉张垮塌和大陆裂谷的再造产物(Wu *et al.*, 2006; Zheng *et al.*, 2007). 扬子克拉通由于震旦纪及显生宙巨厚沉积物的覆盖,限制了对扬子板块新元古代岩浆事件的认识,碎屑锆石是研究岩浆事件的重要手段,可以记录源区地壳演化中的各期地质事件. 为了更全面研究华南新元古代的岩浆事件,本文报道采自宜昌黄陵地区南华纪沉积岩中碎屑锆石的 U-Pb 年龄分布和 Hf 同位素组成,以期对扬子克拉通新元古代岩浆事件提供新的研究思路.

## 1 地质概况和样品来源

黄陵穹隆是扬子克拉通太古宙岩石唯一出露的地区,该穹隆位于扬子克拉通北缘,面积约 970 km<sup>2</sup>,主要由晚太古代崆岭群高级变质地体和以黄陵花岗岩基为主的大量侵入体组成. 其中,崆岭高级变质地体主体由闪长—英云闪长—奥长花岗—花岗闪长(DTTG)质片麻岩和花岗质片麻岩组成,其次为变沉积岩和斜长角闪岩及少量基性麻粒岩等岩系组成

(Gao *et al.*, 1999),是扬子克拉通已知出露最古老的基底岩系. 盖层包括南华系—三叠系,围绕基底由老至新环状分布(图 1).

研究区位于宜昌三峡地区(图 1),该区新元古代地层由老至新可依次划分为莲沱组、古城组、大塘坡组、南沱组、陡山沱组和灯影组. 其中,莲沱组不整合覆盖在黄陵花岗岩之上,其下部为紫红色厚层含砾石英砂岩、长石石英砂岩及石英砂岩,上部以紫红色、灰绿色细屑屑砂岩,长石质砂岩和粉砂岩及流纹质晶屑屑凝灰岩组成. 古城组下部为冰碛砾岩,上部为砂砾岩和含砾砂岩及冰碛纹泥层,与下伏莲沱组呈平行不整合接触. 大塘坡组主要为黑色薄层炭质粉砂岩及砂质页岩夹含锰灰岩,是我国南方南华系重要的含锰层位之一. 南沱组主要为一套暗绿、灰绿色夹紫红色冰碛泥砾岩,下与大塘坡组呈平行不整合接触. 陡山沱与下伏南沱组呈平行不整合接触,岩性主要是中—薄层的灰、褐灰色细晶白云岩、灰白色细晶白云岩夹黑色炭质页岩,中下部常见有硅磷质结核,是我国南方重要含磷层位之一,顶部为黑色炭质页岩夹泥质白云岩. 灯影组与下伏陡山沱组为连续沉积,由巨厚白云岩和灰岩组成(湖北地质矿产局,1990;全国地层委员会,2001,2002).

样品 LT01 和 LT02 为紫红色砂岩,均采自宜



图 1 黄陵背斜地质略图

Fig. 1 Simplified geological map of Huangling antiformity

昌莲沱镇莲沱大桥附近的莲沱组底部,该处见莲沱组不整合覆盖在黄陵花岗岩之上,样品 GPS 点位为北纬  $30^{\circ}51.045'$ ,东经  $111^{\circ}9.004'$ 。样品 NT01 和 NT02 采自长阳县高家堰镇古城村锰矿采坑南约 50 m 山坡南沱组标准剖面底部冰积砾岩和冰积泥岩,样品 GPS 点位为北纬  $30^{\circ}33.048'$ ,东经  $111^{\circ}3.413'$ 。每个样品采集约 20 kg。ZG01 采自秭归九曲峡南华—震旦纪剖面, GPS 点位为北纬  $30^{\circ}53.052'$ ,东经  $110^{\circ}52.867'$ (图 1)。ZG01 是本文新采样和分析的样品,其余样品数据来自 Liu *et al.* (2008)。

## 2 样品制备与分析方法

样品 ZG01 的制备与分析方法与 Liu *et al.* (2008) 报道的其余样品制备和分析方法类似。

所采集的样品,经破碎人工分选出锆石。每个样品分选出的锆石颗粒为 500 至数千颗不等。将待测的锆石颗粒制成环氧树脂圆片,抛光后进行 CL 显微结构观察及年龄的测定。锆石阴极发光(CL)图像分析在西北大学大陆动力学国家重点实验室完成。

锆石激光剥蚀等离子体质谱(LA-ICP-MS) U-Pb 同位素分析在中国地质大学(武汉)地质过程与矿产资源国家重点实验室完成,实验采用的 ICP-MS 为美国 Agilent 公司生产的 Agilent7500a。激光剥蚀系统为德国 MicroLas 公司生产的 GeoLas2005,分析所用的激光斑束直径为  $32\ \mu\text{m}$ ,分析流程参见(Yuan *et al.*, 2004)。样品的同位素比值及元素含量计算采用 GLITTER(ver4.0, Macyuarie University)程序完成。普通 Pb 校正采用 ComPbCorr #3\_151 完成(Andersen, 2002),年龄计算及谐和图的绘制采用 Isoplot3.0 完成(Ludwig, 2003)。

对 ZG01 未分析 Hf 同位素组成,其余样品的 Hf 同位素分析方法见 Liu *et al.* (2008) 和徐平等(2004)。 $\epsilon_{\text{Hf}}(t)$  值和 Hf 模式年龄计算所采用参数见 Liu *et al.* (2008)。

## 3 结果与讨论

本次研究分析的 ZG01 结果,加上 Liu *et al.* (2008) 的分析结果,本文共获得南华纪沉积岩中 1 260 颗碎屑锆石 U-Pb 年龄值(表 1)。其中,777 颗锆石的年龄谐和度在  $100\pm 10\%$  之间。Liu *et al.*

(2008) 对其中的 251 颗锆石进行了 Hf 同位素分析。有 40% 的谐和锆石的年龄在  $730\sim 920\ \text{Ma}$  之间,对其中的 78 颗锆石进行了 Hf 同位素分析。下面笔者将讨论这些新元古代锆石的 U-Pb 年龄和 Hf 同位素组成对 Rodinia 超大陆裂解的指示意义。此阶段的碎屑锆石多具有岩浆震荡环带,多为自形,部分有后期的增生边结构, Th/U 比值除 6 颗小于 0.3 外,大多都大于 0.5(图 2),指示这些锆石为岩浆成因。锆石年龄谐和图见图 3。对 78 颗锆石的 Hf 同位素研究发现, $^{176}\text{Hf}/^{177}\text{Hf}$  分布在  $0.281\ 714\sim 0.282\ 667$  之间, $\epsilon_{\text{Hf}}(t)$  变化范围很大,从  $+12.6\sim -22$ ,其中 52 颗具有正的  $\epsilon_{\text{Hf}}(t)$  值,27 颗  $\epsilon_{\text{Hf}}(t)$  值小于 0,其  $T_{\text{DM}}^{\text{C}}$  分布在  $1.8\sim 3.0\ \text{Ga}$  之间。2/3 的锆石具有正的  $\epsilon_{\text{Hf}}(t)$  值,指示此阶段主要是大陆地壳形成的时期,并伴随有古老地壳的重熔。

从新元古代锆石年龄分布直方图(图 4)上看,笔者很明显地发现锆石年龄主要分布在  $780\sim 910\ \text{Ma}$  之间,最高的年龄峰为  $833\ \text{Ma}$ 。Li(1999)通过对华南造山后花岗岩锆石 U-Pb 定年认为,扬子与华夏板块最终聚合的时期不晚于  $820\ \text{Ma}$ 。另外, Li, Z. X., *et al.* (1999) 等测定华南地区铁镁—超铁镁质岩墙锆石的 SHRIMP 年龄为  $828\pm 7\ \text{Ma}$ ,认为在  $825\ \text{Ma}$  时,扬子克拉通有超级地幔柱的作用。 $830\ \text{Ma}$  正好是造山末期和地幔柱活动的叠加时期,笔者认为此时的拉张环境和地幔柱的烘烤更容易造成岩石圈的熔融,再加上地幔柱带来的上涌物质,因此该年龄有最高的锆石年龄峰值。 $780\sim 745\ \text{Ma}$  是第二期地幔柱活动时间(Li, Z. X., *et al.*, 2003)。因此,  $785\ \text{Ma}$  的峰值可能与第二期地幔柱的开始和活动有关,在两个峰值之间的相对低谷可能反映了第一期地幔柱的衰减和相对宁静时期的开始。扬子克拉通的此次地幔柱活动持续了近  $100\ \text{Ma}$ (Li, Z. X., *et al.*, 2003)。

从图 5 看出,锆石 U-Pb 年龄和  $\epsilon_{\text{Hf}}(t)$  值关系可分为 5 个阶段: $910\sim 890\ \text{Ma}$ 、 $890\sim 840\ \text{Ma}$ 、 $840\sim 800\ \text{Ma}$ 、 $800\sim 780\ \text{Ma}$ 、小于  $780\ \text{Ma}$ 。年龄为  $910\sim 890\ \text{Ma}$  之间的锆石  $\epsilon_{\text{Hf}}(t)$  值表现为高正值( $\approx 10$ , 接近亏损地幔演化值),可能此时期扬子和华夏板块还未发生陆—陆碰撞,仍为洋壳俯冲阶段。 $890\sim 840\ \text{Ma}$  锆石  $\epsilon_{\text{Hf}}(t)$  值明显降低,并有负值出现,  $890\ \text{Ma}$  处有个小的年龄峰值(Liu *et al.*, 2008)。Li, W. X., *et al.* (2008) 认为  $890\ \text{Ma}$  时扬子和华夏已拼合。Wang *et al.* (2007) 认为在  $870\ \text{Ma}$  时华夏板块和岛弧碰撞并发生超高压变质事件。Ye *et al.* (2007) 和 Li *et al.* (2007) 认为在  $900\ \text{Ma}$  时扬子和







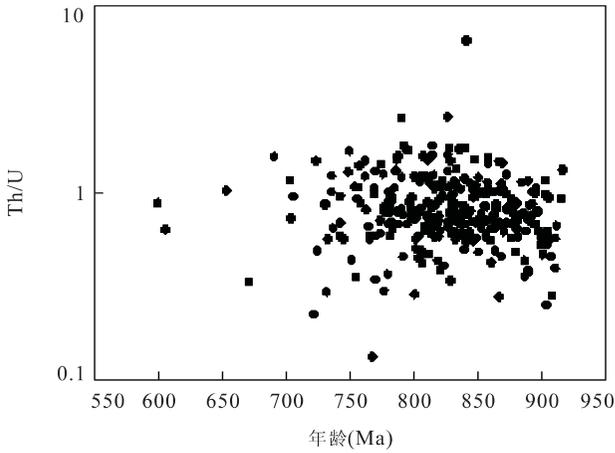


图 2 锆石 U-Pb 年龄与 Th/U 比值关系

Fig. 2 Diagram showing relationship between Th/U ratios and U-Pb ages for detrital zircons

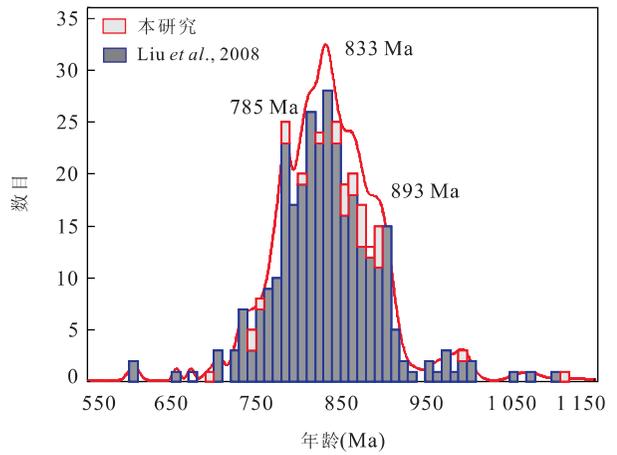


图 4 新元古代锆石 U-Pb 年龄概率分布直方图

Fig. 4 Relative probability plots of Neoproterozoic U-Pb ages for concordant detrital zircons

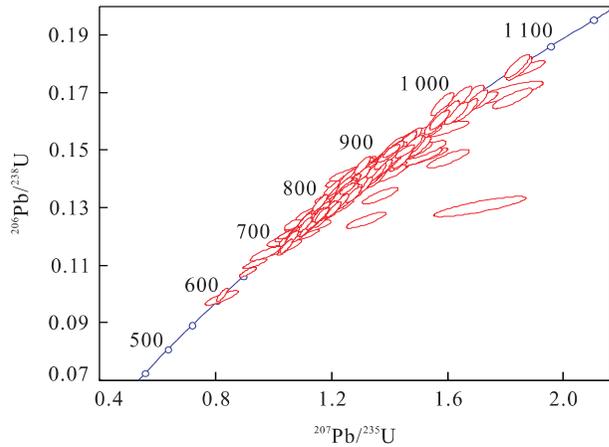


图 3 碎屑锆石 LA-ICP-MS U-Pb 年龄谐和图

Fig. 3 U-Pb concordia plots of concordant detrital zircons

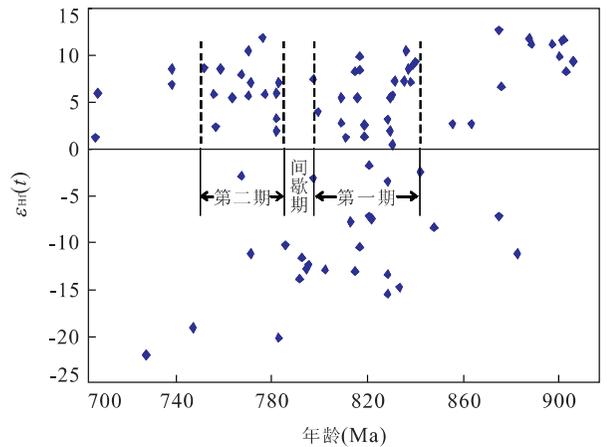


图 5 锆石 U-Pb 年龄与  $\epsilon_{\text{Hf}}(t)$  值关系

Fig. 5 Diagram showing relationship between  $\epsilon_{\text{Hf}}(t)$  values and U-Pb ages

华夏发生拼合。Li and McCulloch(1996)和 Li *et al.* (1997)通过对扬子板块中元古代—二叠纪沉积岩 Nd 同位素和安徽、江西两套蛇绿岩套的地球化学、Sm-Nd 同位素的系统研究,提出扬子和华夏板块的陆—弧—陆碰撞模式,并认为在 900~800 Ma 发生弧—陆碰撞和最终拼合,笔者认为 890 Ma 时  $\epsilon_{\text{Hf}}(t)$  值的降低可能记录了此次俯冲向碰撞的转变。840~800 Ma 有相当数目锆石  $\epsilon_{\text{Hf}}(t)$  值小于 0,但多数  $\epsilon_{\text{Hf}}(t)$  值大于 0,笔者认为正的  $\epsilon_{\text{Hf}}(t)$  值表明地幔柱的活动,而负的  $\epsilon_{\text{Hf}}(t)$  则指示地壳的熔融作用。根据 Li, Z. X., *et al.* (1999)提出的华南地幔柱模型,840~830 Ma 是地幔柱柱头上涌和有限的基性/超基性岩墙侵入时期,柱头上涌的过程中,导致岩石圈凸起,由于凸起拉伸引起压力的减小和地幔柱上涌带来的热量,引起地幔柱上部部分熔融,造成幔源岩

浆的侵入或喷发,桂北元宝山超镁铁岩形成年龄为 841 Ma,即被认为与 825 Ma 的地幔柱事件有关(周继彬等,2007)。笔者认为年龄为~840 Ma 的碎屑锆石大于 0 的  $\epsilon_{\text{Hf}}(t)$  值与此时幔源岩浆的侵入或喷发有关。825~820 Ma 是深熔花岗岩活动和侵入时期, Li, X. H., *et al.* (2003)在扬子克拉通识别出一些 825~820 Ma 的壳源花岗岩,他们认为扬子克拉通 825~820 Ma 的花岗岩是由于~825 Ma 时地幔柱烘烤地壳物质形成的,830~820 Ma 之间  $\epsilon_{\text{Hf}}(t)$  值为负值,同样表明这个时期主要为地壳物质的重熔。820~800 Ma 是地幔柱大量上涌时期,笔者认为该期大多数正的  $\epsilon_{\text{Hf}}(t)$  值与大量地幔物质上涌有关。Li, Z. X., *et al.* (2003)进一步指出,830~795 Ma 和 780~745 Ma 是两期地幔柱大规模活动时期,

800~780 Ma 介于活动期之间,处于地幔柱活动相对宁静时期。第一期地幔柱活动产生的岩浆及此时休眠的地幔柱不断地烘烤地壳物质,致使地壳重熔形成一定规模的岩浆。因此,此阶段碎屑锆石  $\epsilon_{\text{Hf}}(t)$  值表现为负值;780~750 Ma 时碎屑锆石  $\epsilon_{\text{Hf}}(t)$  值又恢复到正值,很少小于 0。Lin *et al.* (2007) 对川西康滇裂谷中康定—泸定—石棉地区广泛分布的基性岩墙群进行了 SHRIMP 锆石 U-Pb 年龄、元素和 Nd-Hf 同位素研究,结果表明这些基性岩墙群形成于 780~760 Ma,很可能是高温地幔柱部分熔融的产物。笔者认为年龄为 780~750 Ma 碎屑锆石  $\epsilon_{\text{Hf}}(t)$  值的升高可能与地幔柱的第二期活动有关。

## 4 结论

本文对采自宜昌三峡地区南华纪沉积岩中碎屑锆石的 U-Pb 定年表明,扬子和华夏板块的拼合可能在 890 Ma 发生了由俯冲到陆—陆或陆—弧的碰撞转换,之前的高  $\epsilon_{\text{Hf}}(t)$  值可能由洋壳俯冲造成,之后碰撞作用陆壳物质熔融造成了  $\epsilon_{\text{Hf}}(t)$  值的降低;碎屑锆石 U-Pb 年龄分布、Hf 同位素组成支持了前人提出的 830~795 Ma、780~745 Ma 两期地幔柱活动的认识。

## References

Andersen, T., 2002. Correction of common lead in U-Pb analyses that do not report  $^{204}\text{Pb}$ . *Chemical Geology*, 192: 59–79.

Bureau of Geology and Mineral Resources of Hubei Province, 1990. Regional geology of Hubei Province. Geological Publishing House, Beijing, 7–64 (in Chinese).

China Commission on Stratigraphy, 2001. Stratigraphic guide of China and its explanatory notes (revised edition). Geological Publishing House, Beijing, 1–59 (in Chinese).

China Commission on Stratigraphy, 2002. Explanatory notes to the regional chronostratigraphic (geochronologic) scale. Geological Publishing House, Beijing, 1–72 (in Chinese).

Gao, S., Ling, W. L., Qiu, Y. M., et al., 1999. Contrasting geochemical and Sm-Nd isotopic compositions of Archean metasediments from the Kongling high-grade terrain of the Yangtze craton; Evidence for cratonic evolution and redistribution of REE during crustal anatexis. *Geochimica et Cosmochimica Acta*, 63: 2071–2088.

Li, W. X., Li, X. H., Li, Z. X., 2005. Neoproterozoic bimodal

magmatism in the Cathaysia block of South China and its tectonic significance. *Precambrian Research*, 136(1): 51–66.

Li, W. X., Li, X. H., Li, Z. X., et al., 2008. Obduction-type granites within the NE Jiangxi ophiolite; Implications for the final amalgamation between the Yangtze and Cathaysia blocks. *Gondwana Research*, 13(3): 288–301.

Li, X. H., 1999. U-Pb zircon ages of granites from the southern margin of the Yangtze block; Timing of Neoproterozoic Jinning; Orogeny in SE China and implications for Rodinia assembly. *Precambrian Research*, 97: 43–57.

Li, X. H., McCulloch, M. T., 1996. Secular variation in the Nd isotopic composition of Neoproterozoic sediments from the southern margin of the Yangtze block; Evidence for a Proterozoic continental collision in Southeast China. *Precambrian Research*, 76: 67–76.

Li, X. H., Zhao, J. X., McCulloch, M. T., et al., 1997. Geochemical and Sm-Nd isotopic study of Neoproterozoic ophiolites from southeastern China; Petrogenesis and tectonic implications. *Precambrian Research*, 81: 129–144.

Li, X. H., Li, Z. X., Ge, W. C., et al., 2003. Neoproterozoic granitoids in South China; Crustal melting above a mantle plume at ca. 825 Ma? *Precambrian Research*, 122: 45–83.

Li, X. H., Li, Z. X., Sinclair, J. A., et al., 2006. Revisiting the “Yanbian terrane”; Implications for Neoproterozoic tectonic evolution of the western Yangtze block, South China. *Precambrian Research*, 151(1–2): 14–30.

Li, X. H., Li, W. X., Li, Z. X., et al., 2008. 850–790 Ma bimodal volcanic and intrusive rocks in northern Zhejiang, South China; A major episode of continental rift magmatism during the breakup of Rodinia. *Lithos*, 102: 341–357.

Li, Z. X., Zhang, L. H., Powell, C. M., 1995. South China in Rodinia; Part of the missing link between Australia-East Antarctica and Laurentia? *Geology*, 23(5): 407–410.

Li, Z. X., Li, X. H., Kinny, P. D., et al., 1999. The breakup of Rodinia; Did it start with a mantle plume beneath South China? *Earth and Planetary Science Letters*, 173: 171–181.

Li, Z. X., Li, X. H., Kinny, P. D., et al., 2003. Geochronology of Neoproterozoic syn-rift magmatism in the Yangtze craton, South China and correlations with other continents; Evidence for a mantle superplume that broke up Rodinia. *Precambrian Research*, 122(1–4): 85–109.

Li, Z. X., Wartho, J. A., Occhipinti, S., et al., 2007. Early

- history of the eastern Sibao orogen (South China) during the assembly of Rodinia; New mica  $^{40}\text{Ar}/^{39}\text{Ar}$  dating and SHRIMP U-Pb detrital zircon provenance constraints. *Precambrian Research*, 159(1–2): 79–94.
- Lin, G. C., Li, X. H., Li, W. X., 2007. SHRIMP U-Pb zircon age, geochemistry and Nd-Hf isotope of Neoproterozoic mafic dyke swarms in western Sichuan: Petrogenesis and tectonic significance. *Science in China (Ser. D)*, 50(1): 1–16.
- Liu, X. M., Gao, S., Diwu, C. R., et al., 2008. Precambrian crustal growth of Yangtze craton as revealed by detrital zircon studies. *Journal of American Sciences*, 308: 421–468.
- Ludwig, K. R., 2003. ISOPLOT 3: A geochronological toolkit for Microsoft excel. Geochronology Centre Special Publication, Berkeley, 4: 74.
- Tang, J., Zheng, Y. F., Wu, Y. B., et al., 2008. Zircon U-Pb age and geochemical constraints on the tectonic affinity of the Jiaodong terrane in the Sulu orogen, China. *Precambrian Research*, 161(3–4): 389–418.
- Wang, X. L., Zhou, J. C., Griffin, W. L., et al., 2007. Detrital zircon geochronology of Precambrian basement sequences in the Jiangnan orogen: Dating the assembly of the Yangtze and Cathaysia blocks. *Precambrian Research*, 159: 117–131.
- Wang, X. L., Zhou, J. C., Qiu, J. S., et al., 2004a. Comment on “Neoproterozoic granitoids in South China: Crustal melting above a mantle plume at ca. 825 Ma?” by Li, X. H., et al., [*Precambrian Res.*, 122(2003): 45–83]. *Precambrian Research*, 132: 401–403.
- Wang, X. L., Zhou, J. C., Qiu, J. S., et al., 2004b. Geochemistry of the Meso- to Neoproterozoic basic-acid rocks from Hunan Province, South China: Implications for the evolution of the western Jiangnan orogen. *Precambrian Research*, 135: 79–103.
- Wang, X. L., Zhou, J. C., Qiu, J. S., et al., 2006. LA-ICP-MS zircon geochronology of the Neoproterozoic igneous rocks from northern Guangxi, South China: Implications for tectonic evolution. *Precambrian Research*, 145: 111–130.
- Wang, X. L., Zhou, J. C., Qiu, J. S., et al., 2008. Geochronology and geochemistry of Neoproterozoic mafic rocks from western Hunan, South China: Implications for petrogenesis and post-orogenic extension. *Geological Magazine*, 145: 215–233.
- Wu, R. X., Zheng, Y. F., Wu, Y. B., et al., 2006. Reworking of juvenile crust: Element and isotope evidence from Neoproterozoic granodiorite in South China. *Precambrian Res.*, 146: 179–212.
- Wu, Y. B., Zheng, Y. F., Tang, J., et al., 2007. Zircon U-Pb dating of water-rock interaction during Neoproterozoic rift magmatism in South China. *Chemical Geology*, 246: 65–86.
- Xu, P., Wu, F. Y., Xie, L. W., et al., 2004. Hf isotopic compositions of the standard zircons for U-Pb dating. *Chinese Science Bulletin*, 49: 1403–1410 (in Chinese).
- Ye, M. F., Li, X. H., Li, W. X., et al., 2007. SHRIMP zircon U-Pb geochronological and whole-rock geochemical evidence for an early Neoproterozoic Sibaoan magmatic arc along the southeastern margin of the Yangtze block. *Gondwana Research*, 12: 144–156.
- Yuan, H. L., Gao, S., Liu, X. M., et al., 2004. Accurate U-Pb age and trace element determinations of zircon by laser ablation-inductively coupled plasma mass spectrometry. *Geostandard and Geoanalytical Research*, 28: 353–370.
- Zheng, Y. F., Wu, Y. B., Chen, F. K., et al., 2004. Zircon U-Pb and oxygen isotope evidence for a large-scale  $^{18}\text{O}$  depletion event in igneous rocks during the Neoproterozoic. *Geochimica et Cosmochimica Acta*, 68: 4145–4165.
- Zheng, Y. F., Zhang, S. B., Zhao, Z. F., et al., 2007. Contrasting zircon Hf and O isotopes in the two episodes of Neoproterozoic granitoids in South China: Implications for growth and reworking of continental crust. *Lithos*, 96: 127–150.
- Zheng, Y. F., Zhao, Z. F., Wu, Y. B., et al., 2006. Zircon U-Pb age, Hf and O isotope constraints on protolith origin of ultrahigh-pressure eclogite and gneiss in the Dabie orogen. *Chemical Geology*, 231: 135–138.
- Zhong, Y. F., Ma, C. Q., Yu, Z. B., et al., 2005. SHRIMP U-Pb zircon geochronology of the Jiuling granitic complex batholith in Jiangxi Province. *Earth Science—Journal of China University of Geosciences*, 33(6): 687–691 (in Chinese with English abstract).
- Zhou, J. B., Li, X. H., Ge, W. C., et al., 2007. Geochronology, mantle source and geological implications of Neoproterozoic ultramafic rocks from Yuanbaoshan area of northern Guangxi. *Geological Science and Technology Information*, 26(1): 11–18 (in Chinese with English abstract).
- Zhou, J. C., Wang, X. L., Qiu, J. S., et al., 2004. Geochemistry of Meso- and Neoproterozoic mafic-ultramafic rocks from northern Guangxi, China: Arc or plume magmatism? *Geochemical Journal*, 38: 139–152.
- Zhou, M. F., Kennedy, A. K., Sun, M., et al., 2002a. Neoproterozoic arc-related mafic intrusions along the northern margin of South China: Implications for the accre-

- tion of Rodinia. *Journal of Geology*, 110:611—618.
- Zhou, M. F., Yan, D. P., Kennedy, A. K., et al., 2002b. SHRIMP U-Pb zircon geochronological and geochemical evidence for Neoproterozoic arc-magmatism along the western margin of the Yangtze block, South China. *Earth and Planetary Science Letters*, 196:51—67.
- Zhou, M. F., Ma, Y. X., Yan, D. P., et al., 2006a. The Yanbian terrane (southern Sichuan Province, SW China): A Neoproterozoic arc assemblage in the western margin of the Yangtze block. *Precambrian Research*, 144:19—38.
- Zhou, M. F., Yan, D. P., Wang, C. L., et al., 2006b. Subduction-related origin of the 750 Ma Xuelongbao adakitic complex (Sichuan Province, China): Implications for the tectonic setting of the giant Neoproterozoic magmatic event in South China. *Earth and Planetary Science Letters*, 248:286—300.
- Zhu, W. G., Zhong, H., Deng, H. L., et al., 2006. SHRIMP zircon U-Pb age, geochemistry, and Nd-Sr isotopes of the Gaojiacun mafic-ultramafic intrusive complex,

Southwest China. *International Geology Review*, 48: 650—668.

### 附中文参考文献

- 湖北省地质矿产局, 1990. 湖北省区域地质志. 北京: 地质出版社, 7—64.
- 全国地层委员会, 2001. 中国地层指南及中国地层指南说明书(修订版). 北京: 地质出版社, 1—59.
- 全国地层委员会, 2002. 中国区域地层(地质年代)表说明书. 北京: 地质出版社, 1—72.
- 徐平, 吴福元, 谢烈文, 等, 2004. U-Pb 同位素定年标准锆石的 Hf 同位素. *科学通报*, 49: 1403—1410.
- 钟玉芳, 马昌前, 余振兵, 等, 2005. 江西九岭花岗岩类复式岩基锆石 SHRIMP U-Pb 年代学. *地球科学——中国地质大学学报*, 33(6): 687—691.
- 周继彬, 李献华, 葛文春, 等, 2007. 桂北元宝山地区超镁铁岩的年代、源区及其地质意义. *地质科技情报*, 26(1): 11—18.