华北、华南、塔里木三大陆块中-新元古代岩浆岩的特征及其地质对比意义*

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Abstract Meso-Neoproterozoic magmatic rocks widely occur in three Chinese blocks of China (North China, South China and Tarim blocks). Based on a large number of geochronologic data, the Meso-Neoproterozoic magmatic events in the North China Block can be divided into seven stages (1.78Ga, 1.70Ga, 1.63Ga, 1.32Ga, 1.23Ga, 0.93Ga and 0.83Ga), in which 1.78Ga and 1.32Ga magmas have a large influence range and form the large igneous provinces, respectively. The Meso-Neoproterozoic magmatic rocks in the North China Block formed in the intracontinental extensional environment indcating that North China Block was not involved in the assembly process of the Rodinia supercontinent. The Meso-Neoproterozoic magmatic events in the South China Block can be divided into eight stages (1.78Ga, 1.72Ga, 1.67Ga, 1.5Ga, 1.42Ga, 1.0Ga, 0.84Ga and 0.77Ga), the four stages of magmatic events from 1.78Ga to 1.5Ga were formed in extensional environment. The sporadic 1.4Ga magmatic rocks likely formed in an assembly setting in local area. The magmatic stages around 1.0Ga performed differently in different parts of the South China Block, indicating the different blocks have been aggregated together. Magmatic events from 0.95Ga to 0.82Ga, mainly distributed in the Jiangnan Orogen and the northern margin of the Yangtze massif, led to the coherent Yangtze massif (or Yangtze Block) and Cathaysia massif (or Cathaysia Block) into the South China Block. Subsequently, magmatic events from 0.78Ga to 0.72Ga were almost all over the South China Block, reflecting the extensional process after the formation of the entire continental block. The Meso-Neoproterozoic magmatic events in the Tarim block can be subdivided into eight stages (1.78Ga, 1.5Ga, 1.43Ga, 1.1Ga, 0.92Ga, 0.83Ga, 0.74Ga and 0.65Ga). The magmatic events of 1.78Ga and 1.5Ga are only locally distributed, and they formed in the extensional setting. 1.4Ga magmatic events performed differently in the northern and southwestern margins of the Tarim Block. Calc-alkaline magmatic rocks in the northern margin emplaced in the continental arc setting, while A2 type granites in the southwestern margin were formed in the tensional setting. During the period of 0.96 ~ 0.88Ga, the granites in the southeastern and northern margins of Tarim Block are dominated by I-type and S-type and formed in the active continental margin, while in the southwestern margin of Tarim Block, bimodal volcanic rocks in the Sailajiazitage Group formed in the intra-continental rift environment. During 0.88 ~ 0.82Ga, magmatic sequences, related to subduction and accretion, were formed in Kuruktagh area on the northern margin, while bimodal volcanic rocks related to extensional tectonic setting were formed on the southeastern margin. The difference of magmatic rock assemblages in different locations and stages of the Tarim Block denotes that the Tarim Block originally is not originally a unified block, but likey assembled by different massifs in different periods. The differential evolutions of the Meso-Neoproterozoic magmatic rocks reveal their independent processes in the North China, South China and Tarim blocks in this period.

Key words Meso-Neoproterozoic magmatism; North China Block; South China Block; Tarim Block; Differential evolution; Tectonic setting

摘 要 我国三个主要的古老陆块(华北、华南和塔里木陆块)都发育中-新元古代岩浆岩。根据大量的同位素年代学资

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料，华北陆块中-新元古代岩浆事件可以分为 7 个阶段，其中 1.78Ga 和 1.32Ga 两期影响范围较大，可以构成大火成岩省。华北陆块中-新元古代的岩浆岩均形成于大陆地壳伸展的构造背景，意味着华北并未介入 Rodinia 超大陆的聚合过程。华南陆块中-新元古代岩浆事件可以分为 8 个阶段，从 1.78Ga 到 1.5Ga 的四期岩浆事件形成于大陆地壳伸展的构造背景，1.4Ga 左右的一期岩浆-构造事件分布局限，可能形成于局部的构造拼合背景。1.0Ga 左右的岩浆事件，在华南陆块的不同部位表现形式不同，意味着发生过不同地块的拼合。从 0.95Ga 到 0.82Ga 的岩浆事件主要分布在江南造山带和扬子地块北缘，这一阶段的岩浆事件导致扬子地块和华夏地块拼接成一体，形成华南陆块。之后从 0.78Ga 到 0.72Ga 的岩浆事件几乎遍布华南陆块，反映了陆块形成后的伸展过程。塔里木陆块中-新元古代的岩浆事件可以分为 8 个阶段，1.78Ga 和 1.5Ga 的岩浆事件仅在局部有反映，它们形成于拉伸的构造背景。1.4Ga 的岩浆事件在塔里木陆块的北缘和西南缘表现形式不同，北缘钙碱性岩浆岩形成于大陆弧构造背景，而西南缘 A2 型花岗岩则形成于拉伸的构造背景。0.96～0.88Ga 期间，塔里木东南缘和北缘的花岗岩以 I 型和 S 型为特点，形成于活动大陆边缘，而在塔里木陆块的西南缘该时期则形成了塞拉加兹塔格群中双峰式火山岩，形成于陆内裂谷环境。0.88～0.82Ga 期间，在北缘的库鲁克塔格地区形成了与俯冲增生相关的岩浆岩组合，而在东南缘则形成了与拉张构造环境有关的双峰式火山岩。塔里木陆块不同部位，不同阶段岩浆岩组合的差异意味着塔里木陆块原来并不是一个统一的陆块，很可能是在不同时期由不同块体拼合而成的。华北、华南和塔里木三个陆块中-新元古代岩浆岩的差异演化，揭示了它们各自形成陆块的过程和方式及相互关系。

关键词 中-新元古代岩浆作用；华北陆块；华南陆块；塔里木陆块；差异演化；构造背景

中图法分类号 P542

1.8～0.8Ga 是地球历史上一个非常特殊的发展阶段。该阶段的初期，地球经历了哥伦比亚超大陆的裂解，晚期地球经历了罗迪尼亚超大陆的形成。但是，这一阶段大气和海洋的成分相对平稳，地球上的生物进展缓慢，所以有的学者将这一阶段称为地球中年期(Evans and Mitchell, 2011; Zhai *et al.*, 2015)、地球历史上无聊的十亿年(boring billion)(Holland, 2006; Roberts, 2013; Mukherjee *et al.*, 2018)、或最不活跃的时期(dullest period)(Young, 2013)、“哥伦比亚纪”(Van Kranendonk, 2012)。

尽管这一阶段大气和海洋的成分相对平稳，但是岩浆活动并未停止。从全球看，在中元古代早期(1.8～1.5Ga)，劳伦古陆、圣弗兰西斯科-刚果克拉通、澳大利亚北部、乌克兰地盾、印度克拉通都存在较强烈的岩浆活动，从中-基性火山岩到花岗质侵入岩，从广泛分布的基性岩墙群到斜长岩-辉长岩-纹长二长岩组合，岩石组合多样，大多形成于拉伸裂解的构造背景(Peterson *et al.*, 2015; Jackson *et al.*, 2000; Neumann *et al.*, 2006; Danderfer *et al.*, 2009, 2015; Mccourt *et al.*, 2004; Shumlyanskyy *et al.*, 2016; Shankar *et al.*, 2018; Kaur *et al.*, 2017)。中元古代晚期(1.32～1.27Ga)，华北陆块、澳大利亚等地发育大量的基性岩床，构成了大火成岩省(Zhang *et al.*, 2017; Goldberg, 2010; Pirajno and Hoatson, 2012; 张拴宏和赵越, 2018)，北美地区也广泛分布有 1.27Ga 的麦卡基岩墙群(Ernst *et al.*, 2008; Ernst, 2014)。新元古代早期，伴随罗迪尼亚超大陆的形成在很多古老大陆的边缘发育了大量的火山岩和与岛弧有关的岩浆岩(Boger *et al.*, 2000; Fitzsimons, 2000; Kelly *et al.*, 2002; Wang *et al.*, 2015a; Chen *et al.*, 2009a, b)。从我国中-新元古代岩浆岩的分布可以看出，不论是华北、华南和塔里木陆块，还是一些显生宙造山带中的老地块都存在中-新元古代的岩浆活动，其产物既有火山岩也有大量的侵入岩。从岩浆活动的角度看，1.8～0.8Ga 并不是一个无聊的十亿年。中-新元古代的岩浆岩与超大陆的裂解和聚合紧密相关，而不同陆块由于位于超大陆的不同部位，其岩浆演化受到外围环境制约，具有差异演化的特点。本文以华北陆块、华南陆块、塔里木陆块中-新元古代的岩浆岩为出发点，通过三大陆块中-新元古代岩浆岩的演化及差异探讨三大陆块的演化过程及可能的相互关系。

1 区域地质背景

中国大陆由几个古老陆块并通过年轻造山带(曾称褶皱带)拼接到一起的。其中华北、华南和塔里木是三个最重要的陆块。

1.1 华北陆块(华北克拉通)

华北陆块的变质基底主要由太古宙-古元古代片麻岩和变质地层组成，有的研究者认为太古宙的变质基底形成了一些古老的陆核，新太古代晚期的绿岩带、岩浆岩带将这些陆核结合到一起，形成了初始的华北克拉通(白瑾等, 1993; 伍家善等, 1998; Zhai, 2011)，后经过古元古代的裂解和拼合，在古元古代末完成最终的克拉通化。也有的学者认为，古元古代晚期的造山带把华北太古宙的东部陆块、西部陆块、阴山陆块拼合到一起，形成华北克拉通(Zhao *et al.*, 2002a, 2005; 赵国春, 2009)。在华北陆块早前寒武纪变质基底广泛出露，中-新元古代地层(盖层)主要出露在华北陆块南缘的熊耳裂陷槽和北部的燕辽裂陷槽，在西北缘、东部的辽东半岛及徐淮地区也有零星出露(图 1)。

华北自 1.8Ga 完成克拉通化后，开始进入全新的演化过程。在华北陆块的南缘和北缘先后形成了熊耳裂陷槽和燕辽裂陷槽(Zhai, 2013)。在熊耳裂陷槽先后沉积了熊耳群、

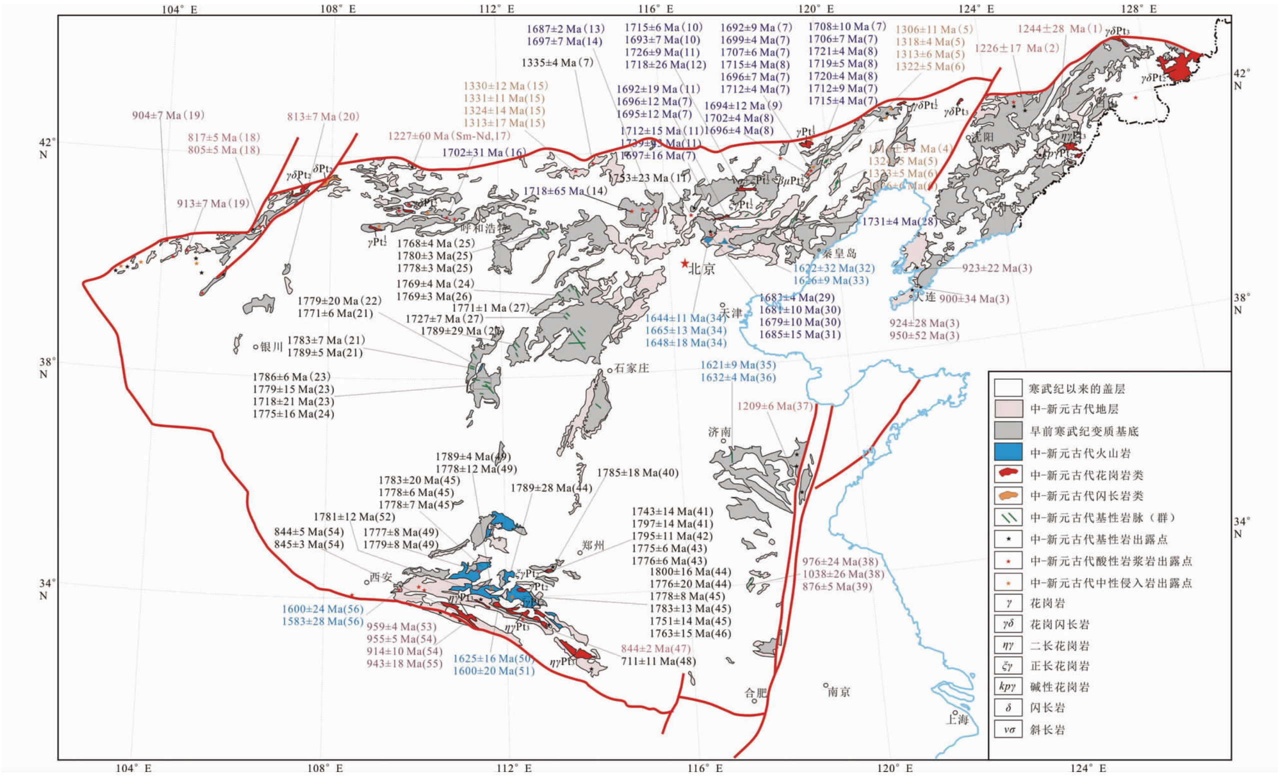

图 1 华北陆块中-新元古代地层及岩浆岩分布及年龄

图中不同颜色的年龄数据代表不同时代的岩浆岩，图中的资料来源:1-裴福萍等, 2013; 2-Wang *et al.*, 2015b; 3-Zhang *et al.*, 2016; 4-Zhang *et al.*, 2012a; 5-Zhang *et al.*, 2017; 6-Wang *et al.*, 2014a; 7-相振群, 2014; 8-Wang *et al.*, 2013; 9-Liu *et al.*, 2011; 10-赵太平等, 2004; 11-Zhang *et al.*, 2007a; 12-任康绪等, 2006; 13-郁建华等, 1996; 14-Mo *et al.*, 1997; 15-Zhang *et al.*, 2012a; 16-王惠初等, 2012; 17-Yang *et al.*, 2011; 18-彭润民等, 2010; 19-耿元生和周喜文, 2010; 20-彭澎等, 2018; 21-Yang *et al.*, 2019; 22-徐勇航等, 2007; 23-Wang *et al.*, 2014b; 24-韩宝福等, 2007; 25-王冲等, 2016; 26-李江海等, 2001; 27-Peng, 2015; 28-Peng *et al.*, 2012a; 29-Rämö *et al.*, 1995; 30-杨进辉等, 2005; 31-高维等, 2008; 32-Lu *et al.*, 2008a; 33-高林志等, 2008; 34-Wang *et al.*, 2015c; 35-陆松年等, 2008; 36-相振群等, 2012; 37-Peng *et al.*, 2013; 38-Liu *et al.*, 2006; 39-蔡逸涛等, 2018; 40-胡国辉等, 2010; 41-Zhao and Zhou, 2009a; 42-师江朋等, 2017; 43-Zhang *et al.*, 2013a; 44-Zhao *et al.*, 2004a; 45-He *et al.*, 2009; 46-Wang *et al.*, 2010; 47-Bao *et al.*, 2008; 48-Chen *et al.*, 2006; 49-崔敏利等, 2010; 50-陆松年等, 2003a; 51-包志伟等, 2009; 52-Li *et al.*, 2016a; 52-柳晓艳等, 2011; 53-王涛等, 1998; 54-陆松年等, 2003b; 55-陈志宏等, 2004; 56-邓小芹等, 2015

Fig. 1 Distribution and ages of the Meso-Neoproterozoic strata and magmatic rocks in the North China Block

The color-coded age data in the figure represent the different stages of the magmatism. Geochronologic data in the figure come from: 1-Pei *et al.*, 2013; 2-Wang *et al.*, 2015b; 3-Zhang *et al.*, 2016; 4-Zhang *et al.*, 2012a; 5-Zhang *et al.*, 2017; 6-Wang *et al.*, 2014a; 7-Xiang, 2014; 8-Wang *et al.*, 2013; 9-Liu *et al.*, 2011; 10-Zhao *et al.*, 2004; 11-Zhang *et al.*, 2007a; 12-Ren *et al.*, 2006; 13-Yu *et al.*, 1996; 14-Mo *et al.*, 1997; 15-Zhang *et al.*, 2012a; 16-Wang *et al.*, 2012; 17-Yang *et al.*, 2011; 18-Peng *et al.*, 2010; 19-Geng and Zhou, 2010; 20-Peng *et al.*, 2018; 21-Yang *et al.*, 2019; 22-Xu *et al.*, 2007; 23-Wang *et al.*, 2014b; 24-Han *et al.*, 2007; 25-Wang *et al.*, 2016; 26-Li *et al.*, 2001; 27-Peng, 2015; 28-Peng *et al.*, 2012; 29-Rämö *et al.*, 1995; 30-Yang *et al.*, 2005; 31-Gao *et al.*, 2008; 32-Lu *et al.*, 2008a; 33-Gao *et al.*, 2008; 34-Wang *et al.*, 2015c; 35-Lu *et al.*, 2008; 36-Xiang *et al.*, 2012; 37-Peng *et al.*, 2013; 38-Liu *et al.*, 2006; 39-Cai *et al.*, 2018; 40-Hu *et al.*, 2010; 41-Zhao and Zhou, 2009a; 42-Shi *et al.*, 2017; 43-Zhang *et al.*, 2013a; 44-Zhao *et al.*, 2004a; 45-He *et al.*, 2009; 46-Wang *et al.*, 2010; 47-Bao *et al.*, 2008; 48-Chen *et al.*, 2006; 49-Cui *et al.*, 2010; 50-Lu *et al.*, 2003a; 51-Bao *et al.*, 2009; 52-Li *et al.*, 2016a; 52-Liu *et al.*, 2011; 53-Wang *et al.*, 1998; 54-Lu *et al.*, 2003b; 55-Chen *et al.*, 2004; 56-Deng *et al.*, 2015

汝阳群、洛峪群等。其中熊耳群除底部少量的碎屑沉积岩之外,主要由玄武安山岩、安山岩、安山流纹岩等组成,并伴有流纹斑岩的侵入,大量的年代学研究表明熊耳群主要形成于1.8～1.75Ga(图1; Zhao *et al.*, 2002b, 2004a)。与此同时,在太行-吕梁-晋冀蒙交界地区发育了大量北西走向的基性岩墙(图1; Peng, 2015; 王冲等, 2016)。这期火山岩和基性岩墙群代表了华北克拉通化之后早期的拉张裂解作用(耿元生等, 2019)。熊耳群火山岩喷发后在熊耳裂陷槽沉积了陆缘碎屑岩和浅海碳酸盐为主的汝阳群和洛峪群。洛峪群顶部洛峪口组上部和顶部的凝灰岩中获得了1.64～1.61Ga的年龄数据(苏文博等, 2012; 李承东等, 2017; 彭楠等, 2018),可以限定熊耳群、汝阳群和洛峪群形成于1.8～1.6Ga,属于我国地层表中的长城纪。在华北南缘,1.8～1.5Ga发育了碱性花岗岩,包括～1.8Ga的摩天寨花岗岩、石

秤花岗闪长岩，1.6Ga 的麻坪正长岩、龙王疃碱性花岗岩，1.52Ga 的张家坪二长花岗岩，1.47Ga 的潘河正长岩，地球化学上它们属于 A 型花岗岩（Zhao and Zhou, 2009a; Zhao and Deng, 2016; 师江朋等, 2017），反映了从 1.8Ga 到 1.5Ga 的多期拉伸事件。

华北陆块北部的密云-承德-建平一带在 1.75～1.68Ga 期间形成了代表拉伸环境的斜长岩、纹长花岗岩、碱长花岗岩、环斑花岗岩系列（Rämö *et al.*, 1995; 杨进辉等, 2005; 任康绪等, 2006; Zhang *et al.*, 2007a; Zhao *et al.*, 2009b; Wang *et al.*, 2013），在密云-冀东和五台山北台并伴有 1.73Ga 的基性岩墙侵位（Peng *et al.*, 2012a; Peng, 2015），代表华北陆块北部早期的裂解。目前的资料表明，燕辽裂陷槽早期沉积的长城群的底界在在 1.68Ga 左右（李怀坤等, 2011; 和政军等, 2011a, b）。长城群以碎屑岩为主，上部的团山子组和大红峪组发育富钾的火山岩（图 1），形成于裂谷环境（张健等, 2015; Wang *et al.*, 2015c）。1.6～1.4Ga 在燕辽裂陷槽沉积了以碳酸盐岩、砂岩、页岩为主的蓟县群，其中夹有流纹质凝灰岩和钾质斑脱岩（Su *et al.*, 2010; 李怀坤等, 2014）。1.40～1.37Ga 在燕辽裂谷带沉积了以砂岩和页岩为主的下马岭组，1.37～1.30Ga 期间形成了大量的具有大陆玄武岩特点的基性岩床（Su *et al.*, 2008, Gao *et al.*, 2008; Zhang *et al.*, 2009a, 2012a）。之后在 1.2Ga 左右在吉林通化、山东沂水等地有基性岩脉的侵入（图 1）。到新元古代时期，在华北陆块的东北部、东南部、南部及西北部沉积有细河群、淮北群、栾川群大红口组及狼山群等地层，其中辽东半岛、徐淮地区的新元古代地层中发育大量的 0.9Ga 左右的基性岩床或岩墙（图 1）（Zhang *et al.*, 2016; Liu *et al.*, 2006; Wang *et al.*, 2012a），在南缘的栾川群大红口组中发育有 0.84Ga 左右的碱性火山岩（胡国辉等, 2019），在西北缘狼山群中发育有 0.82Ga 左右的酸性火山岩（彭润民等, 2010; Hu *et al.*, 2014）。

这些沉积岩和火成岩都显示，华北陆块从 1.78Ga 开始到新元古代经历了多期裂谷事件，一直处于拉张的构造环境（翟明国等, 2014）。

1.2 华南陆块

华南陆块是指秦岭-大别山以南、川西高原和横断山脉以东的地区。一般认为它由扬子地块、华夏古陆由江南造山带在新元古代拼贴而成（图 2）。华南陆块的演化与 Rodinia 超大陆的聚合裂解密切相关（Li *et al.*, 2002a, 2008a; Wang *et al.*, 2016a）。华南陆块的变质基底出露非常局限，仅在湖北的黄陵、浙西南的八都、扬子西北缘的后河、云南的撮科等地有零星出露。中-新元古代地层和岩浆岩主要分布在江南造山带、扬子北缘和扬子西缘，在海南岛有零星出露（图 2）。

华南陆块中元古代地层和岩浆岩主要出露在扬子西南缘的云南大红山到川西南的会理一带，在扬子北缘、海南岛抱板地区也有零星出露（图 2）。中元古代早期的岩浆事件记录在福建武夷山、云南武定和四川会理地区。在夷山地区仅零星出露。在武定和会理地区表现为双峰式的岩浆岩组合，形成时代为 1.76～1.70Ga（杨斌等, 2015; Geng *et al.*, 2020）。中元古代早期的沉积记录以云南大红山地区出露的大红山群、云南东川-武定地区出露的东川群、四川西南部河口地区出露的河口群及会理地区出露的通安组中下部为代表（耿元生等, 2017, 2019）。其中大红山群自下而上划分为老厂河组、曼岗河组、红山组、肥味河组和坡头组，属于碎屑＋火山＋碳酸盐岩建造，其中火山岩主要形成于 1.72～1.65Ga（Greentree and Li, 2008; Zhao and Zhou, 2011; 杨红等, 2012; 金廷福等, 2017）。在这一阶段，形成了大红山铁铜矿床、东川铜矿以及河口铜矿床。王伟等（Wang and Zhou, 2014; Wang *et al.*, 2014c）研究了东川群及相关岩群的沉积岩组合和沉积构造特征，把该区裂谷盆地划分为四个演化阶段，表明中元古代早期扬子西南缘处于拉伸裂解环境。中元古代中期（～1.4Ga）的变质地层和岩浆岩目前仅在海南岛有所发现，称为抱板群，自下而上划分为戈枕村组和峨文岭组（马大铨等, 1997）。是遭受中级变质的碎屑建造组合，锆石 SHRIMP U-Pb 定年结果表明戈枕村组的片麻岩（可能为变形的花岗岩）形成于 1.45～1.43Ga（Li *et al.*, 2002a; 许德如等, 2006; 张立敏等, 2017）。这期构造岩浆热事件影响的范围和形成的构造背景尚需进一步研究。

华南陆块内存在一期 1.1～0.96Ga 的岩浆事件。赣东北蛇绿混杂岩中的辉长岩获得了大量的 1.0Ga 左右的锆石 U-Pb 年龄数据（图 2, Zhang *et al.*, 2015b; 王存智等, 2015; Gao *et al.*, 2009; Wang *et al.*, 2015a）。湖北宜昌黄陵地区庙湾蛇绿岩中的辉长岩形成于 1118～974Ma 期间（图 2, Peng *et al.*, 2012b; Deng *et al.*, 2012, 2017）。扬子地块西缘石棉蛇绿岩中辉绿岩也获得了 1066Ma 和 937Ma 的年龄数据（Hu *et al.*, 2017）。这几处蛇绿岩位于华南陆块的不同构造部位（图 2），它们是否为同一构造背景下的产物尚需更深入的研究。除此之外，在扬子西南缘四川会理分布的会理群、云南元谋分布的苴林群、扬子西北缘的通木梁群中都有 1.0Ga 左右的火山岩（耿元生等, 2007a; Zhu *et al.*, 2016; Chen *et al.*, 2014, 2018; Li *et al.*, 2018）出露。在扬子西南缘还发育有 1.0Ga 左右的花岗岩（Li *et al.*, 2002a; 杨崇辉等, 2009; Chen *et al.*, 2018）。1.0Ga 左右的火山沉积岩系及相应的岩浆岩在岩石组成、地球化学特征、反映的构造环境等方面均有明显差异。

华南陆块的新元古代地层和岩浆岩出露较广，特别是在江南造山带、扬子北缘和扬子西缘有广泛的出露（图 2）。江南造山带的新元古代主要由三部分组成，新元古代早期（1.0～0.82Ga）主要由绿片岩相变质的火山沉积岩系（如广西的四堡群、贵州的梵净山群、湖南的冷家溪群、江西的双桥山群、皖南的溪口群、浙西的双溪坞群等）及相伴的 S 型花岗岩组成，新元古代中期（0.82～0.72Ga）主要由低绿片岩相变质的沉积地层（如广西的丹洲群、贵州的下江群、湖南的板溪

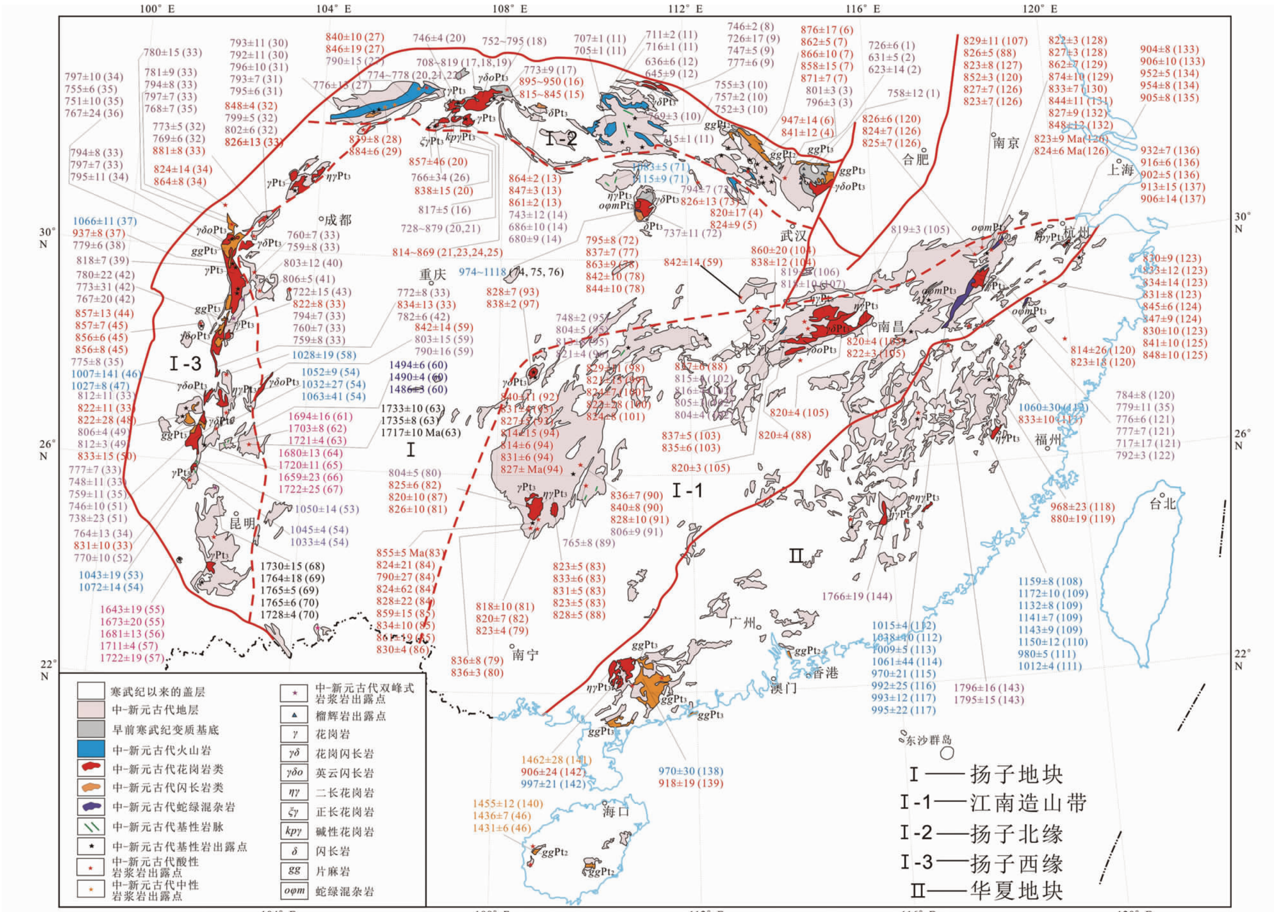

图2　华南陆块中-新元古代地层及岩浆岩分布及年龄

图中不同颜色的年龄数据代表不同时代的岩浆岩，图中的资料来源：1-刘贻灿等，2010；2-Liu *et al.*，2017；3-曹正琦等，2017；4-胡正祥等，2015；5-Deng *et al.*，2013；6-Shi *et al.*，2007；7-Xu *et al.*，2016a；8-陆松年等，2003b；9-祝禧艳等，2008；10-Ling *et al.*，2008，11-Wang *et al.*，2017a；12-邓乾忠等，2016；13-刘仁燕等，2011；14-牛宝贵等，2006；15-夏林圻等，2009；16-Ling *et al.*，2003；17-Zhou *et al.*，2002a；18-Dong *et al.*，2011；19-Zhao *et al.*，2010a；20-Dong *et al.*，2012；21-Luo *et al.*，2018；22-赵凤清等，2006；23-Zhao and Zhou，2009b；24-Wang *et al.*，2016b；25-凌文黎等，2006；26-Li，2010；27-Yan *et al.*，2004；28-赖绍聪等，2007；29-Xiao *et al.*，2007；30-裴先治等，2009；31-Li *et al.*，2018；32-Meng *et al.*，2015；33-耿元生等，2008；34-Zhou *et al.*，2002b；35-Li *et al.*，2003a；36-刘树文等，2009；37-Hu *et al.*，2017；38-Lin *et al.*，2007；39-林广春，2010；40-李献华等，2001a；41-卓皆文等，2015；42-Huang *et al.*，2008；43-Chen *et al.*，2005；44-Li *et al.*，2003b；45-Du *et al.*，2014；46-Li *et al.*，2002a；47-杨崇辉等，2009；48-杜利林等，2009；49-Zhou *et al.*，2006a；50-Li and Zhao，2018；51-Zhao and Zhou，2007；52-Li *et al.*，2009a；53-Chen *et al.*，2014；54-Chen *et al.*，2018；55-金廷福等，2017；56-Zhao and Zhou，2011；57-杨红等，2012；58-耿元生等，2007a；59-郭春丽等，2007；60-Fan *et al.*，2013；61-王冬兵等，2013；62-Lu *et al.*，2019；63-Geng *et al.*，2020；64-周家云等，2011；65-于文佳等，2017；66-耿元生等，2017；67-王冬兵等，2012；68-王子正等，2013；69-杨斌等，2015；70-郭阳等，2014；71-李怀坤等，2013；72-凌文黎等，2006；73-Zhao *et al.*，2013b；74-Peng *et al.*，2012b；75-Deng *et al.*，2012；76-Deng *et al.*，2017；77-高维和张传恒，2009；78-Wei *et al.*，2012；79-Wang *et al.*，2006；80-王孝磊等，2006；81-Li，1999；82-李献华，1999；83-Yao *et al.*，2014；84-Li *et al.*，1999；85-Lin *et al.*，2016；86-Wang *et al.*，2012b；87-李献华等，1996；88-Wang *et al.*，2014d；89-Zhou *et al.*，2007；90-孙海清等，2013；91-柏道远等，2010；92-张传恒等，2014；93-Zhao *et al.*，2011；94-Zhou *et al.*，2009；95-王敏等，2016；96-薛怀民等，2012；97-王敏等，2011；98-Zhao and Zhou，2013；99-高林志等，2012；100-Zhang *et al.*，2015a；101-马铁球等，2009；102-Xin *et al.*，2017；103-Zhang and Wang，2016；104-Zhang *et al.*，2013b；105-Xin *et al.*，2017；106-Li *et al.*，2003c；107-李献华等，2001b；108-Li *et al.*，2013；109-高林志等，2013a；110-张恒等，2015；111-Wang *et al.*，2018；112-Zhang *et al.*，2015b；113-李源等，2017；114-王存智等，2015；115-Gao *et al.*，2009；116-蒋幸福等，2017；117-Wang *et al.*，2015a；118-李献华等，1994；119-Li *et al.*，2008a；120-薛怀民等，2010；121-吴荣新等，2005；122-邓奇等，2016；123-Xia *et al.*，2015；124-Liu *et al.*，2015；125-姜杨等，2015；126-Wu *et al.*，2006；127-李献华等，2002；128-Zhang *et al.*，2013c；129-Cui *et al.*，2017；130-Yin *et al.*，2013；131-张彦杰等，2010；132-丁炳华等，2008；133-Chen *et al.*，2009a；134-陈辉等，2016；135-高林志等，2014；136-Chen *et al.*，2009b；137-Ye *et al.*，2007；138-王磊等，2015；139-Zhang *et al.*，2012b；140-许德如等，2006；141-覃小锋等，2006；142-Zhang *et al.*，2012b；143-Chen *et al.*，2017a；144-李献华等，1998

Fig. 2 Distribution and ages of the Meso-Neoproterozoic strata and magmatic rocks in the South China Block

The color-coded age data in the figure represent the different stages of the magmatism. Geochronologic data in the figure come from: 1-Liu *et al.*, 2010; 2-Liu *et al.*, 2017; 3-Cao *et al.*, 2017; 4-Hu *et al.*, 2015; 5-Deng *et al.*, 2013; 6-Shi *et al.*, 2007; 7-Xu *et al.*, 2016a; 8-Lu *et al.*, 2003b; 9-Zhu *et al.*, 2008; 10-Ling *et al.*, 2008, 11-Wang *et al.*, 2017a; 12-Deng *et al.*, 2016; 13-Liu *et al.*, 2011; 14-Niu *et al.*, 2006; 15-Xia *et al.*, 2009; 16-Ling *et al.*, 2003; 17-Zhou *et al.*, 2002a; 18-Dong *et al.*, 2011; 19-Zhao *et al.*, 2010a; 20-Dong *et al.*, 2012; 21-Luo *et al.*, 2018; 22-Zhao *et al.*, 2006; 23-Zhao and Zhou, 2009b; 24-Wang *et al.*, 2016b; 25-Ling *et al.*, 2006; 26-Li, 2010; 27-Yan *et al.*, 2004; 28-Lai *et al.*, 2007; 29-Xiao *et al.*, 2007; 30-Pei *et al.*, 2009; 31-Li *et al.*, 2018; 32-Meng *et al.*, 2015; 33-Geng *et al.*, 2008; 34-Zhou *et al.*, 2002b; 35-Li *et al.*, 2003a; 36-Liu *et al.*, 2009; 37-Hu *et al.*, 2007; 38-Lin *et al.*, 2007; 39-Lin, 2010; 40-Li *et al.*, 2001a; 41-Zhuo *et al.*, 2015; 42-Huang *et al.*, 2008; 43-Chen *et al.*, 2005; 44-Li *et al.*, 2003b; 45-Du *et al.*, 2014; 46-Li *et al.*, 2002a; 47-Yang *et al.*, 2009; 48-Du *et al.*, 2009; 49-Zhou *et al.*, 2006a; 50-Li and Zhao, 2018; 51-Zhao and Zhou, 2007; 52-Li *et al.*, 2009a; 53-Chen *et al.*, 2014; 54-Chen *et al.*, 2018; 55-Jin *et al.*, 2017; 56-Zhao and Zhou, 2011; 57-Yang *et al.*, 2012; 58-Geng *et al.*, 2007a; 59-Guo *et al.*, 2007; 60-Fan *et al.*, 2013; 61-Wang *et al.*, 2013; 62-Lu *et al.*, 2019; 63-Geng *et al.*, 2020; 64-Zhou *et al.*, 2011; 65-Yu *et al.*, 2017; 66-Geng *et al.*, 2017; 67-Wang *et al.*, 2012; 68-Wang *et al.*, 2013; 69-Yang *et al.*, 2015; 70-Guo *et al.*, 2014; 71-Li *et al.*, 2013; 72-Ling *et al.*, 2006; 73-Zhao *et al.*, 2013b; 74-Peng *et al.*, 2012b; 75-Deng *et al.*, 2012; 76-Deng *et al.*, 2017; 77-Gao and Zhang, 2009; 78-Wei *et al.*, 2012; 79-Wang *et al.*, 2006; 80-Wang *et al.*, 2006; 81-Li, 1999; 82-Li, 1999; 83-Yao *et al.*, 2014; 84-Li *et al.*, 1999; 85-Lin *et al.*, 2016; 86-Wang *et al.*, 2012b; 87-Li *et al.*, 1996; 88-Wang *et al.*, 2014d; 89-Zhou *et al.*, 2007; 90-Sun *et al.*, 2013; 91-Bai *et al.*, 2010; 92-Zhang *et al.*, 2014; 93-Zhao *et al.*, 2011; 94-Zhou *et al.*, 2009; 95-Wang *et al.*, 2016; 96-Xue *et al.*, 2012; 97-Wang *et al.*, 2011; 98-Zhao and Zhou, 2013; 99-Gao *et al.*, 2012; 100-Zhang *et al.*, 2015a; 101-Ma *et al.*, 2009; 102-Xin *et al.*, 2017; 103-Zhang and Wang, 2016; 104-Zhang *et al.*, 2013b; 105-Xin *et al.*, 2017; 106-Li *et al.*, 2003c; 107-Li *et al.*, 2001b; 108-Li *et al.*, 2013; 109-Gao *et al.*, 2013a; 110-Zhang *et al.*, 2015; 111-Wang *et al.*, 2018; 112-Zhang *et al.*, 2015b; 113-Li *et al.*, 2017; 114-Wang *et al.*, 2015; 115-Gao *et al.*, 2009; 116-Jiang *et al.*, 2017; 117-Wang *et al.*, 2015a; 118-Li *et al.*, 1994; 119-Li *et al.*, 2008a; 120-Xue *et al.*, 2010; 121-Wu *et al.*, 2005; 122-Deng *et al.*, 2016; 123-Xia *et al.*, 2015; 124-Liu *et al.*, 2015; 125-Jiang *et al.*, 2015; 126-Wu *et al.*, 2006; 127-Li *et al.*, 2002; 128-Zhang *et al.*, 2013c; 129-Cui *et al.*, 2017; 130-Yin *et al.*, 2013; 131-Zhang *et al.*, 2010; 132-Ding *et al.*, 2008; 133-Chen *et al.*, 2009a; 134-Chen *et al.*, 2016; 135-Gao *et al.*, 2014; 136-Chen *et al.*, 2009b; 137-Ye *et al.*, 2007; 138-Wang *et al.*, 2015; 139-Zhang *et al.*, 2012b; 140-Xu *et al.*, 2006; 141-Qin *et al.*, 2006; 142-Zhang *et al.*, 2012b; 143-Chen *et al.*, 2017a; 144-Li *et al.*, 1998

群、江西的修水群、皖浙赣交界的历口群、河上镇群等）和同时代的未变形花岗岩组成，新元古代晚期（0.72～0.54Ga）主要由冰水沉积的南华系和广泛海侵的碳酸盐建造为主的震旦系组成（各主要岩群的组合特征可见 Geng, 2015）。在江南造山带的中-西段早期的火山沉积岩系与中期的浅变质地层之间存在不整合接触关系。在早期的火山沉积岩系中夹有较多的火山岩层，以中基性火山岩为主，多与岛弧和弧后的构造环境有关。从新元古代中期开始，沉积地层中火山岩逐渐减少。

在扬子北缘的新元古代主要由碧口群、火地垭群和西乡群以及大量的岩浆岩组成。碧口群（本文的碧口群仅包括原碧口群中浅变质的火山岩系）主要由基性到中性熔岩和火山碎屑岩组成，包括细碧岩、玄武岩、安山岩、角斑岩、少量流纹岩及各类火山碎屑岩。碧口群形成时代大致在 0.89～0.83Ga（Yan *et al.*, 2004; Xiao *et al.*, 2007），局部的火山岩可能延续到 0.8Ga 左右（Yan *et al.*, 2004）。火地垭群自下而上分为上两组、麻窝子组和铁船山组，其中上两组和麻窝子组是变质沉积岩组合；铁船山组是火山建造，主要由红色碱性流纹岩、英安流纹岩、拉斑玄武岩、熔结凝灰岩、火山碎屑岩等组成。在铁船山组流纹岩中获得的颗粒锆石 TIMS 年龄为 817±5Ma（Ling *et al.*, 2003），形成于新元古代中期。西乡群是一套火山沉积组合，下部由低钾玄武岩和玄武安山岩组成，夹变质沉积岩；上部由钙碱性到碱性的玄武安山岩、英安岩、流纹岩组成，夹少量碱性玄武岩。其上为磨拉石建造（Ling *et al.*, 2003）。西乡群大致形成于 830～770Ma 期间（徐学义等, 2010; 夏林圻等, 2009）。在汉南地区除了新元古代的火地垭群和西乡群之外，还分布有大量的新元古代早中期的岩浆杂岩，包括碑坝基性侵入杂岩、天平河花岗闪长岩、杨家河花岗闪长岩、铁船山霓石花岗岩、望江山基性杂岩体、汉南杂岩体等，大量的同位素年代学资料表明它们主要形成于 850～750Ma 期间（图 2）。这些岩浆杂岩具有从南向北迁移的特征，南部米仓山地区与弧有关的岩浆活动发生在 870～820Ma 期间，到中部的惠家坝与弧有关的岩浆活动发生在 840～820Ma 期间，到北部的汉南地区与弧有关的岩浆活动发生在 825～706Ma 期间，这种时空上的迁移支持了扬子北缘是大陆边缘弧增生造山的构造模式（Dong *et al.*, 2012）。

扬子地块西缘新元古代早期的火山沉积岩系以盐边群为代表。其下部是以火山岩为主的荒田组，中上部的渔门组、小坪组和乍古组则主要由砂岩、各类板岩、泥灰岩、砂质灰岩、白云质灰岩等组成。侵入小坪组的关刀山花岗闪长岩的锆石 U-Pb 年龄为 857Ma（Li *et al.*, 2003b; Du *et al.*, 2014），盐边群大体形成于 877～831Ma。该地区新元古代中期的火山沉积地层以苏雄组和开建桥组为代表。苏雄组主要由巨厚的酸性火山岩组成，其中夹有少量的基性火山岩和火山碎屑岩。开建桥组主要由酸性火山碎屑岩和凝灰质砂岩组成。形成于 806～803Ma（李献华等, 2001a; 卓皆文等, 2015）。由于苏雄组酸性火山岩中夹有基性火山岩，李献华等（2001a）认为属于双峰式火山岩，形成于拉伸构造环境。在扬子地块西缘还有大量的新元古代早-中期的岩浆岩（图 2），包括辉长岩、英云闪长岩、花岗闪长岩、花岗岩等，成分变化比较大。形成于 746～864Ma，主要集中在 840～780Ma 期间（图 2）。

1.3 塔里木陆块（塔里木克拉通）

塔里木陆块位于我国的西北部，呈菱形夹持于北侧的天山造山带、西南侧的昆仑造山带和东南侧的阿尔金造山带之

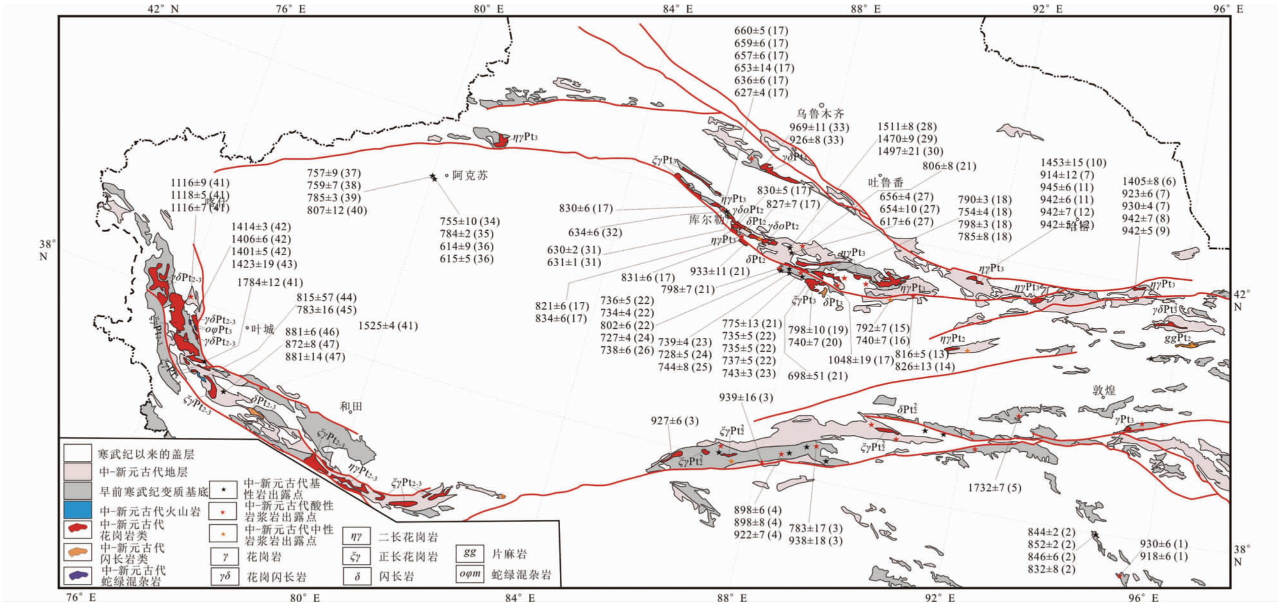

图3 塔里木陆块中-新元古代地层及岩浆岩分布及年龄

图中的资料来源:1-Fu *et al.*, 2015; 2-Xu *et al.*, 2016b; 3-张建新等, 2011; 4-Yu *et al.*, 2013; 5-王玉玺等, 2017; 6-胡霭琴等, 2006; 7-Huang *et al.*, 2015; 8-胡霭琴等, 2010; 9-Wang *et al.*, 2014e; 10-施文翔等, 2010; 11-Huang *et al.*, 2014; 12-彭明兴等, 2012; 13-Cao *et al.*, 2011; 14-Cao *et al.*, 2010; 15-徐备等, 2008; 16-Xu *et al.*, 2009; 17-Ge *et al.*, 2014; 18-Long *et al.*, 2011b; 19-罗新荣等, 2007; 20-Zhang *et al.*, 2007b; 21-Shu *et al.*, 2011; 22-Zhang *et al.*, 2012c; 23-Cao *et al.*, 2014; 24-Tang *et al.*, 2016; 25-Chen *et al.*, 2017b; 26-秦切等, 2012; 27-He *et al.*, 2014; 28-张健等, 2018; 29-Wu *et al.*, 2014; 30-Wang *et al.*, 2017c; 31-张传林等, 2014; 32-Zhu *et al.*, 2011; 33-Yang *et al.*, 2008; 34-王飞等, 2010; 35-Zhang *et al.*, 2012d; 36-Xu *et al.*, 2013; 37-张健等, 2014; 38-Zhang *et al.*, 2009b; 39-Zhan *et al.*, 2007; 40-Chen *et al.*, 2004; 41-Zhang *et al.*, 2019; 42-Ye *et al.*, 2016; 43-黄建国等, 2012; 44-张传林等, 2003; 45-Zhang *et al.*, 2006; 46-Wang *et al.*, 2015d; 47-Wang *et al.*, 2015e

Fig. 3 Distribution and ages of the Meso-Neoproterozoic strata and magmatic rocks in the Tarim Block

Geochronologic data in the figure come from: 1-Fu *et al.*, 2015; 2-Xu *et al.*, 2016b; 3-Zhang *et al.*, 2011; 4-Yu *et al.*, 2013; 5-Wang *et al.*, 2017; 6-Hu *et al.*, 2006; 7-Huang *et al.*, 2015; 8-Hu *et al.*, 2010; 9-Wang *et al.*, 2014e; 10-Shi *et al.*, 2010; 11-Huang *et al.*, 2014; 12-Peng *et al.*, 2012; 13-Cao *et al.*, 2011; 14-Cao *et al.*, 2010; 15-Xu *et al.*, 2008; 16-Xu *et al.*, 2009; 17-Ge *et al.*, 2014; 18-Long *et al.*, 2011b; 19-Luo *et al.*, 2007; 20-Zhang *et al.*, 2007b; 21-Shu *et al.*, 2011; 22-Zhang *et al.*, 2012c; 23-Cao *et al.*, 2014; 24-Tang *et al.*, 2016; 25-Chen *et al.*, 2017b; 26-Qin *et al.*, 2012; 27-He *et al.*, 2014; 28-Zhang *et al.*, 2018; 29-Wu *et al.*, 2014; 30-Wang *et al.*, 2017c; 31-Zhang *et al.*, 2014; 32-Zhu *et al.*, 2011; 33-Yang *et al.*, 2008; 34-Wang *et al.*, 2010; 35-Zhang *et al.*, 2012d; 36-Xu *et al.*, 2013; 37-Zhang *et al.*, 2014; 38-Zhang *et al.*, 2009b; 39-Zhan *et al.*, 2007; 40-Chen *et al.*, 2004; 41-Zhang *et al.*, 2019; 42-Ye *et al.*, 2016; 43-Huang *et al.*, 2012; 44-Zhang *et al.*, 2003; 45-Zhang *et al.*, 2006; 46-Wang *et al.*, 2015d; 47-Wang *et al.*, 2015e

间。由于塔克拉玛干沙漠的覆盖,塔里木陆块的前寒武纪地层和岩石主要出露于塔里木陆块的东北缘、东南缘和西南缘(图3)。另外,在天山造山带中带从星星峡经巴伦台到阿拉塔格地区存在一些前寒武纪的小地块,对于这些地块的归属尚有不同认识,本文认为它们可能来自塔里木陆块,因此将这几个地区的前寒武纪岩层归于塔里木陆块的北缘。

塔里木陆块东北缘的库鲁克塔格地区出露有太古宙-古元古代的变质基底,包括太古宙的托格拉克布拉克杂岩以及古元古代的兴地塔格群。托格拉克布拉克杂岩以TTG片麻岩为主,主要形成于新太古代(胡霭琴和韦刚健, 2006; Long *et al.*, 2010, 2011a)。古元古代的兴地塔格群,是一套含有十字石、石榴石、蓝晶石、夕线石的云母石英片岩,夹少量大理岩的变质表壳岩系,目前还缺少可靠的同位素年龄数据。同时还有一些古元古代的深成侵入体(郭召杰等, 2003; Zhang *et al.*, 2012e; Cai *et al.*, 2018)。在塔里木东南缘变质基底主要由太古宙的阿克塔什塔格杂岩和米兰岩群及古元古代的变质深成岩和具有孔兹岩特征的敦煌岩群组成(Lu *et al.*, 2008b; Long *et al.*, 2014; 辛后田等, 2011, 2013)。它们多经历了古元古代晚期的变质改造。塔里木西南缘的变质基底以赫罗斯坦杂岩为代表,其形成时代主要为古元古代(Wang *et al.*, 2014f)。

塔里木陆块东北缘出露的中元古代地层包括长城系的杨吉布拉克群、波瓦姆群和蓟县系的爱尔基干群。杨吉布拉克群主要由变质砂岩、变质长石砂岩、变质粉砂岩、绢云千枚岩等组成,属于轻微变质的浅海相碎屑岩建造。波瓦姆群主要由石英岩、绿帘黑云片岩、二云片岩及少量大理岩组成。关于这两个岩群是上下叠置关系还是相变关系还存在不同认识。蓟县系的爱尔基干群,主要由灰岩、白云岩、白云质大理岩、石英岩等组成,属于富含硅镁质的浅海相碳酸盐岩建造。塔里木陆块东北缘中元古代的岩浆岩包括侵入到古元

古代兴地塔格群兴地河组大理岩中的 1.5Ga 的辉绿岩床及中天山造山带中星星峡和阿拉塔格地区侵入到星星峡群的 1.4Ga 的变形花岗岩(图 3)。

塔里木陆块东南缘的中元古代地层包括长城系巴什库尔干群和蓟县系的塔昔达坂群。巴什库尔干群主要分布在阿尔金山北坡且末、若羌、皮山一带,以白云石英片岩、绢云绿泥石英片岩、绿泥二云石英片岩、石英砂岩为主,夹有大理岩、千枚岩。塔昔达坂群主要分布于阿尔金山的安南坝、塔昔达坂南坡及若羌一带,下部以碎屑岩为主,上部以碳酸盐岩为主。这两个群目前都缺少可靠的同位素年龄限制。该地区目前发现的中元古代的岩浆岩很少,只有位于柴达木北缘大柴旦西北鹰峰地区的环斑花岗岩,形成于中元古代的早期(Xiao *et al.*, 2004; Chen *et al.*, 2013a)。

塔里木陆块西南缘的中元古代地层主要为桑株塔格群。该群主要由碎屑岩、大理岩和少量石英岩组成,被 1.4Ga 的花岗岩所侵入,碎屑锆石的峰值在 1.5Ga 左右(Zhang *et al.*, 2019),表明其形成于中元古代。塞拉加兹塔格群也曾被认为属于中元古代,该群火山岩夹层中有 1525Ma(Zhang *et al.*, 2019)和 881Ma(Wang *et al.*, 2015d)两种年龄相差较大的锆石,其时代归属还需进一步研究。该区中元古代的岩浆岩包括侵入到侵入赫罗斯坦杂岩中 1.78Ga 的辉长岩(Zhang *et al.*, 2019)、喀拉喀什群中 1.5Ga 左右的火山岩、1.4Ga 左右的阿孜巴勒迪尔岩体(黄建国等, 2012; Ye *et al.*, 2016)以及 1.11Ga 左右侵入桑株塔格群的花岗闪长岩和淡色花岗岩等(Zhang *et al.*, 2019)。

塔里木东北缘的库鲁克塔格地区新元古代地层分布较广,属于青白口系的地层包括塞纳尔塔格组和北塞纳尔塔格组。前者以浅变质的碎屑建造为主,后者以含叠层石的碳酸盐岩建造为主。其上是库鲁克塔格群,该群自下而上包括贝义西组、照壁山组、阿勒通沟组、特瑞爱肯组、扎摩克提组、育肯沟组、水泉组和汉格尔乔克组等八个组。尽管对于这套地层的时代归属尚存异议,但多数研究者认为这套组合中包含了四个冰期的产物,即贝义西冰期大致与国际上的 Kaigas 冰期相当,阿勒通沟冰期大致与国际上的 Sturtian 冰期相当,特瑞爱肯冰期大致与国际上的 Marinoan 冰期相当,而最上部的汉格尔乔克冰期大致与国际上的 Gaskiers 冰期相当(高林志等, 2013b; 姜海健等, 2017)。贝义西组火山岩的定年表明该组形成于 740~725Ma(Xu *et al.*, 2009),表明贝义西组可以属于国际地层表中的拉伸纪。在塔里木盆地的西北缘阿克苏地区,新元古时期的地层大致可与库鲁克塔格地区的地层对比,其上部大致与扎摩克提组和育肯沟组相当的苏盖特布拉克组中火山岩夹层中获得了 615Ma 的年龄结果(Xu *et al.*, 2013),表明扎摩克提组至汉格尔乔克组属于埃迪卡拉纪。在库鲁克塔格地区新元古代岩浆岩非常发育,尤以新元古代中晚期(0.82~0.60Ga)的岩浆显著(图 3),该时期的二长花岗岩、正长花岗岩、花岗岩、基性侵入岩、基性岩脉在该区广泛分布。此外,新元古代早期(0.96~0.88Ga)片理化花岗岩在库鲁克塔格地区有零星分布(Shu *et al.*, 2011),而在北侧中天山造山带的几个小地块中则有较多分布。0.84~0.82Ga 的岩浆活动并不十分强烈,仅在库鲁克塔格分布少量的含角闪石花岗闪长岩、石榴-白云母花岗岩等。

塔里木陆块东南缘阿尔金山北坡新元古代地层仅出露有大致相当于青白口纪的索尔库里群,主要分布在巴什考贡、拉配泉、库木塔什里克等地。该岩群主要由厚层大理岩、钙质片岩、板岩、千枚岩及黑云母石英片岩等组成。该群与下伏的塔昔达坂群之间为不整合接触。该区新元古代的岩浆岩以新元古代早期(0.93~0.83Ga)的花岗岩类岩石为主(图 3)。

塔里木陆块西南缘新元古代早期地层的沉积时代一直存在争议,Zhang *et al.* (2019)认为,塞拉加兹塔格群和埃连卡特群均为新元古代早期地层。塞拉加兹塔格群主要由玄武岩、流纹岩、含凝灰质的碎屑岩、粉砂岩和少量砂岩组成,形成于 850~840Ma(Zhang *et al.*, 2019)。埃连卡特群主要由绢云绿泥片岩、粉砂岩、长石石英砂岩等组成,形成于 840~800Ma(Zhang *et al.*, 2019)。丝路群下部是厚层砾岩,上部是细粒的碎屑岩。该群不整合在埃连卡特群之上,形成时代可能为 800~750Ma(Zhang *et al.*, 2019)。恰克马克力克群主要由陆缘碎屑建造组成,其中夹有两层(波龙组、雨塘组)火山岩和冰碛砾岩、冰水沉积碎屑岩。这两套冰碛砾岩如何与库鲁克塔格地区的冰碛砾岩对比尚有不同认识,形成时代大致相当于成冰纪。其上为库尔卡克组和克孜苏胡木组,前者以粉砂岩、粉砂质页岩、页岩为主,后者以白云岩和钙质砂岩为主。大致相当于震旦系,但目前尚无精确的年龄资料约束。该区新元古代的岩浆岩主要为 880~815Ma 的火山岩和花岗岩(图 3),限于自然地理条件,该区高精度的同位素年龄资料相对较少。

总之,塔里木陆块不同地区的中-新元古代不论在沉积建造还是岩浆岩组合方面都有较明显的区别。

2 三大陆块中-新元古代的岩浆事件序列

华北、华南和塔里木陆块内中-新元古代岩浆岩发育较为广泛,但分布不均匀。图 4 为三大陆块中-新元古代岩浆岩同位素年龄(锆石 U-Pb 年龄)的统计,数据来自公开发表的文献,统计的数据多于图 1-图 3 所表示的数据。从统计结果可以看出,820~840Ma 的岩浆活动最为强烈,另外在~1780Ma、~1320Ma、~920Ma 和~640Ma 也有小的年龄峰值(图 4)。但是各期岩浆事件在不同陆块表现强度和形式并不相同,如全部数据中最突出的~830Ma 年龄峰,在华北基本没有表现,主要表现在华南和塔里木陆块(图 4)。因此,本节分别就华北、华南、塔里木三大陆块中-新元古代的岩浆事件序列进行讨论。

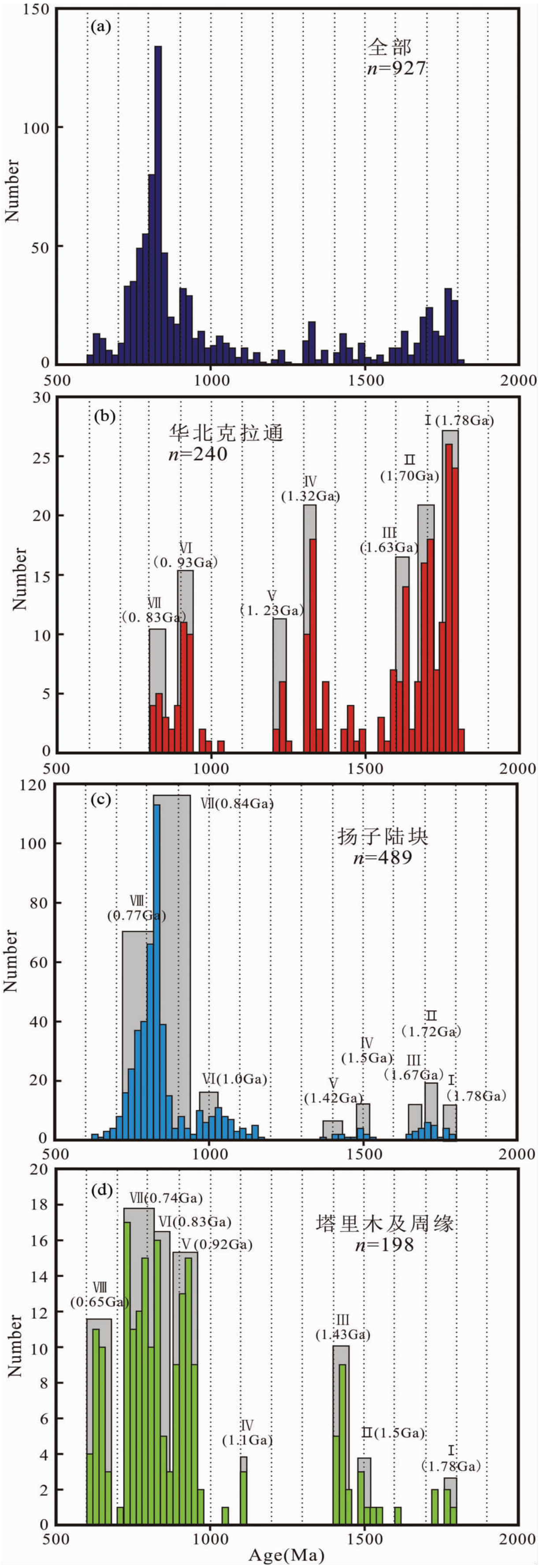

图4 华北、华南及塔里木三大陆块中-新元古代岩浆事件年龄直方图

Fig. 4 Geochronologic data histograms of Meso-Neoproterozoic magmatic events in North China, South China and Tarim blocks

2.1 华北陆块中-新元古代的岩浆事件序列

华北陆块中-新元古代的岩浆岩分布较广,但规模都较小。主体以岩体或岩墙的形式产出,仅有少量火山岩。据现有的资料,华北陆块中-新元古代岩浆事件可划分为七期。

第一期(1.80～1.75Ga)。该期岩浆岩以华北陆块南缘出露的熊耳群火山岩和太行-五台地区出露的基性岩墙群为代表。目前对于熊耳群火山岩的形成环境还有大陆边缘裂谷(Zhao *et al.*, 2002b, 2004a; Wang *et al.*, 2010; Cui *et al.*, 2011, 2013; 柳晓艳等, 2011)和大陆边缘弧(Zhao *et al.*, 2009a; He *et al.*, 2009)的争议。但考虑到华北陆块内广泛分布的放射状镁铁质岩墙与熊耳群火山岩形成时代基本一致,因此我们认为该期岩浆事件主要形成于地幔柱导致的大陆拉伸-裂谷构造环境(图5; Hou *et al.*, 2008; 耿元生等, 2019)。在华北陆块中-新元古代岩浆岩年龄直方图上,该期岩浆事件呈现出最大的年龄峰值,表明这期岩浆事件在华北陆块影响广泛,其最大峰值在1.78Ga左右(图4)。

第二期(1.72～1.67Ga)。该期岩浆岩以华北陆块北缘出露较广的AGRS组合(Anorthosite + Gabbro + Rapakivi granite + Syenite)为主,代表性岩体有承德大庙斜长岩+纹长二长岩+辉长岩,蓝营正长岩,河北建平石英正长岩+二长岩等。该期岩浆岩大体沿平泉北-大庙-汤河口-赤城-尚义一线近东西向长400km,宽约100km(王惠初等, 2012)。这套岩石组合为典型的非造山岩浆活动的产物,可与北美、格陵兰、波罗的、南美等地的AGMS(斜长岩-辉长岩-纹长二长岩-正长岩)组合和AMCG(斜长岩-纹长二长岩-紫苏花岗岩-奥长环斑花岗岩)组合对比,与陆内裂陷或初始裂谷有关(Windley, 1989; Corrigan and Hanmer, 1997; Bogdanova *et al.*, 2013)。由于该组合中有大量的斜长岩和辉长岩,它们可能来源于岩石圈地幔的部分熔融(图5)。该期岩浆事件的年龄峰较大,表明在华北陆块具有较强的响应,其年龄的峰值在1.70Ga左右(图4b)。

第三期(1.64～1.60Ga)。在燕辽裂谷的团山子组和大红峪组中发育有1.65～1.62Ga的高钾火山岩(高林志等, 2008; Lu *et al.*, 2008a; Wang *et al.*, 2015c; 张健等, 2015),除火山岩之外还有侵入串岭沟组年龄为1.62～1.63Ga的基性岩脉(张拴宏等, 2013; 张健等, 2015)。华北陆块南缘东西向近400km长碱性岩带中的龙王? 碱性花岗岩(1.60～1.63Ga)、麻坪碱性花岗岩(～1.60Ga)等(图5; 陆松年等, 2003a; 包志伟等, 2009; 邓小芹等, 2015)以及鲁西红门1.62Ga的辉绿玢岩(相振群等, 2012)等。火山岩的产出背景、侵入岩的岩石组合及地球化学等都表明这期岩浆事件发生在大陆地壳的拉伸阶段。该期岩浆事件可以从1640Ma延续到1580Ma,其峰值年龄为1630Ma(图4b)。

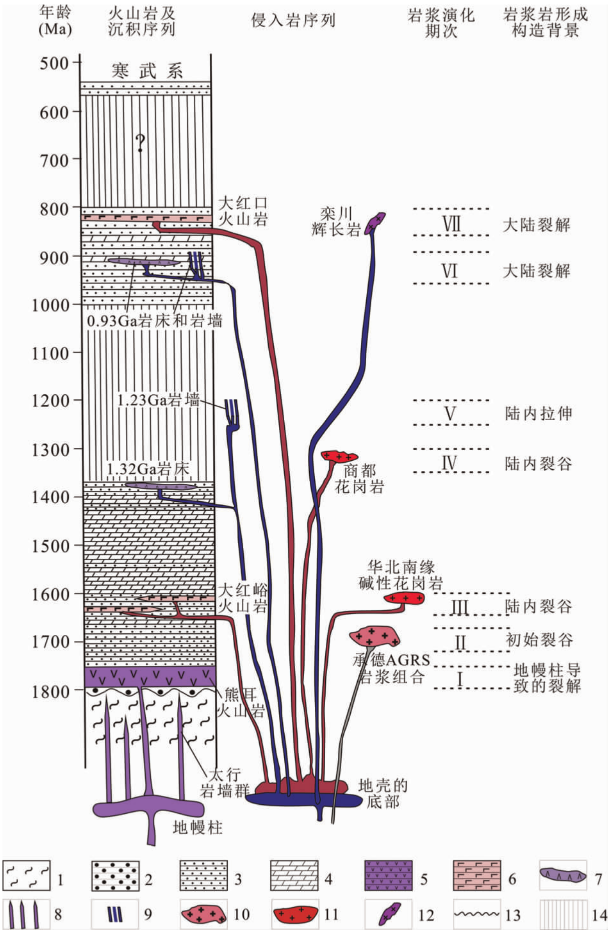

图 5　华北陆块中-新元古代岩浆演化示意图

1-太古宙-古元古代变质基底；2-砾岩；3-碎屑沉积岩；4-碳酸盐岩；5-中-基性火山岩；6-中-酸性火山岩；7-基性岩床；8-1.78Ga 的太行岩墙群；9-晚期的基性岩墙；10-大庙斜长岩＋纹长二长岩＋辉长岩组合；11-花岗岩类；12-辉长岩；13-不整合界线；14-地层缺失

Fig. 5　Schematic diagram of Meso-Neoproterozoic magmatic evolution in the North China Block

1-Archean-Paleoproterozoic metamorphic basement; 2-conglomerate; 3-clastic rocks; 4-carbonate rocks; 5-intermediate-mafic volcanic rocks; 6-intermediate-acid volcanic rocks; 7-mafic sills; 8-1.78Ga mafic dyke swarms in Taihangshan; 9-later mafic dykes; 10-anorthosite + mangerite + gabbro; 11-granitoids; 12-gabbro; 13-unconformity boundary; 14-stratigraphic break

第四期(1.33～1.30Ga)。该期的岩浆岩以燕辽裂谷带广泛发育的基性岩床和冀北出露的康保-化德二长花岗岩、花岗岩为代表。其中基性岩床(图 5)主要侵位于下马岭组、雾迷山组、高于庄组及铁岭组，在串岭沟组及团山子组内也见有少量分布，单个岩床厚从几米到近 200 米，根据 40 余条剖面的统计，不同地区辉绿岩床的累积厚度从 50m 到 1800m (Zhang *et al.*, 2017)，其分布范围超过 12 万平方千米，构成一个大火成岩省 (Zhang *et al.*, 2017；张拴宏和赵越，2018)。大量锆石和斜锆石的定年结果表明这些岩床主要形成于 1.31～1.33Ga (Zhang *et al.*, 2012a, 2017)。冀北商都花岗岩出露 20～30km²，主要由二长花岗岩和正长花岗岩所组成，形成于～1.33Ga。同时代的基性岩床和碱性花岗岩构成双峰式岩浆岩 (Zhang *et al.*, 2012a)。这期岩浆事件从 1.34Ga 延续到 1.30Ga，峰值年龄为 1.32Ga(图 4b)。

第五期(1.24～1.20Ga)。这期岩浆事件以在华北陆块零星分布的基性岩墙为代表(图 5)，如吉林南部通化地区出露的基性岩墙(裴福萍等，2013)、河北建平地区侵入到建平杂岩中的基性岩墙 (Wang *et al.*, 2015b)、山东沂水地区侵入到古老片麻岩中的基性岩墙 (Peng *et al.*, 2013)、冀东青龙和滦南司家营的基性岩墙 (Wang *et al.*, 2015b；李怀坤等，2019①)。有的研究者把这些基性岩墙联系起来，认为可以构成一个大火成岩省，与新元古代晚期的地幔柱事件有关 (Wang *et al.*, 2015b)。在华北陆块中-新元古代岩浆岩年龄直方图中只有一个较小的峰，其峰值年龄为 1.23Ga(图 4b)。

第六期(0.89～0.94Ga)。该期岩浆事件在华北陆块以辽东半岛出露的基性岩床 (Zhang *et al.*, 2016)、恒山大石沟地区出露的辉绿岩墙 (Peng *et al.*, 2011) 和徐淮地区出露的基性岩床和岩墙 (Liu *et al.*, 2006；Wang *et al.*, 2012a；蔡逸涛等，2018；Zhu *et al.*, 2019；Su *et al.*, 2020) 为代表(图 5)；在华北陆块西部阿拉善地区以强变形的花岗岩为代表(耿元生和周喜文，2010)。华北陆块东部该阶段的基性岩墙主要形成于大陆的拉张环境 (Wang *et al.*, 2012a)，阿拉善地区的花岗岩形成于拉张环境，但是，属于造山晚期的拉张还是后造山的拉张环境不明确(耿元生和周喜文，2010，2011)。这期岩浆事件从 0.94Ga 延续到 0.89Ga，峰值年龄在 0.93Ga 左右(图 4)。

第七期(0.85～0.80Ga)。该期岩浆事件在华北南缘表现为栾川群大红口组粗面岩的喷发(胡国辉等，2019)和栾川地区辉长岩的侵位 (Wang *et al.*, 2011；Ling *et al.*, 2015)；在华北陆块西北缘狼山地区表现为酸性火山岩的喷发(彭润民等，2010)以及千里山地区基性岩墙的侵位(彭澎等，2018)。一些研究者认为，高硅富钾的粗面岩与侵位的辉长岩构成双峰式火山岩，形成于大陆裂解环境(胡国辉等，2019)。狼山地区的酸性火山岩也形成于张性裂谷盆地环境(彭润民等，2010)。目前的年代学研究表明，华北陆块南缘该期的岩浆事件形成较早(849～830Ma)，而狼山地区和千里山地区的岩浆活动则稍晚(817～805Ma)。

2.2　扬子陆块中-新元古代的岩浆事件序列

扬子陆块中-新元古代的岩浆岩分布较为广泛，中元古

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① 李怀坤，张健，田辉，钟炎，刘欢，周红英，相振群，涂家润. 2019. 中国及邻区中、新元古代地层格架和大地构造研究. 中国地质调查项目研究报告，中国地质调查局天津地质调查中心 原作者 (Wu *et al.*, 2014) 采用 $^{206}Pb/^{238}U$ 加权平均年龄 1470±9Ma，考虑到中元古代的特点，本文采用 $^{207}Pb/^{206}Pb$ 的加权平均年龄

代的岩浆岩主要分布在扬子西缘和北缘,新元古代的岩浆岩分布广泛,特别是在江南造山带和扬子北缘分布较多。根据岩浆岩的形成时代,扬子陆块中-新元古代的岩浆岩可以分为八期。

第一期(1.8~1.76Ga)。该期岩浆事件只在华夏地块仅有零星出露,如福建武夷山地区侵入麻源群大金山组的片麻状花岗岩,形成年龄为 1796Ma 和 1795Ma(Chen *et al.*, 2017a);福建建宁麻源群天井坪组中的斜长角闪岩,形成年龄为 1766Ma(李献华等, 1998)。有限的资料表明,这一阶段的片麻状花岗岩属于 A 型花岗岩,形成于板内拉伸构造环境(Chen *et al.*, 2017a)。天井坪组中的斜长角闪岩的地球化学特征揭示它们类似于现代的板内玄武岩(李献华等, 1998, 1999),形成于板内的拉张环境。但是这一阶段的岩浆岩出露过于局限,其影响范围,区域构造背景还有待深入研究。

第二期(1.76~1.70Ga)。该期岩浆事件主要表现为扬子地块西南缘出露的双峰式岩浆岩。如云南武定地区出露的辉绿岩和花岗斑岩(王子正等, 2013; 郭阳等, 2014; 杨斌等, 2015)、会理皎平渡辉长岩和会东菜园子花岗岩(Geng *et al.*, 2020),以及一些基性岩脉。目前的年代学结果表明,这期岩浆事件从 1765Ma(杨斌等, 2015)一直延续到 1694Ma(王冬兵等, 2013),在华南陆块年龄直方图上在 1.72Ga 有一个小的峰值。但是作为双峰式岩浆岩似乎不应延续较长时间。值得注意的是,武定地区的同一个花岗斑岩岩株获得的年龄分别为 1764Ma(杨斌等, 2015)和 1730Ma(王子正等, 2013);皎平渡辉长岩有的作者获得的年龄为 1694Ma(王冬兵等, 2013),而笔者等获得的年龄为 1721Ma(Geng *et al.*, 2020)。因此,这次岩浆事件的准确时限还需进一步研究。这期双峰式岩浆岩形成于大陆裂解环境(图 6; 王子正等, 2013; 杨斌等, 2015; Geng *et al.*, 2020)。

第三期(1.69~1.66Ga)。该期岩浆事件以扬子地块西南缘大红山群火山岩和河口群火山岩以及东川群中的粗玄岩为代表,它们形成于 1700~1640Ma(Zhao *et al.*, 2010b; Zhao and Zhou, 2011; 杨红等, 2012; 周家云等, 2011; Chen *et al.*, 2013b; 耿元生等, 2017),由于数据有限在年龄直方图上并没有形成明显的峰值(图 4c)。这期岩浆活动形成与岩浆热液有关的铁氧化物铜金矿床(Iron-Oxide-Copper-Gold, IOCG)或层状铜矿床(Sediment-hosted Stratiform Copper, SSC)(Zhao and Zhou, 2011; 王生伟等, 2016)。根据火山岩组合及相关的沉积建造组合特征,这期火山岩形成于裂谷环境(图 6; Wang and Zhou, 2014; Wang *et al.*, 2014c)。

第四期岩浆作用(~1.5Ga)。该期岩浆活动以扬子地块西南缘会理一带的基性岩墙为代表。在四川会理通安镇的竹箐地区集中出露,在长 4km、宽 90~370m 的范围内出露有数十条基性岩墙,主要是辉长岩,一些辉长岩中含有 Fe-Ti 氧化物,局部成为矿体,这些基性岩墙主要走向北西向(300°~350°)(Fan *et al.*, 2013)。此外,在通安附近也见有该期

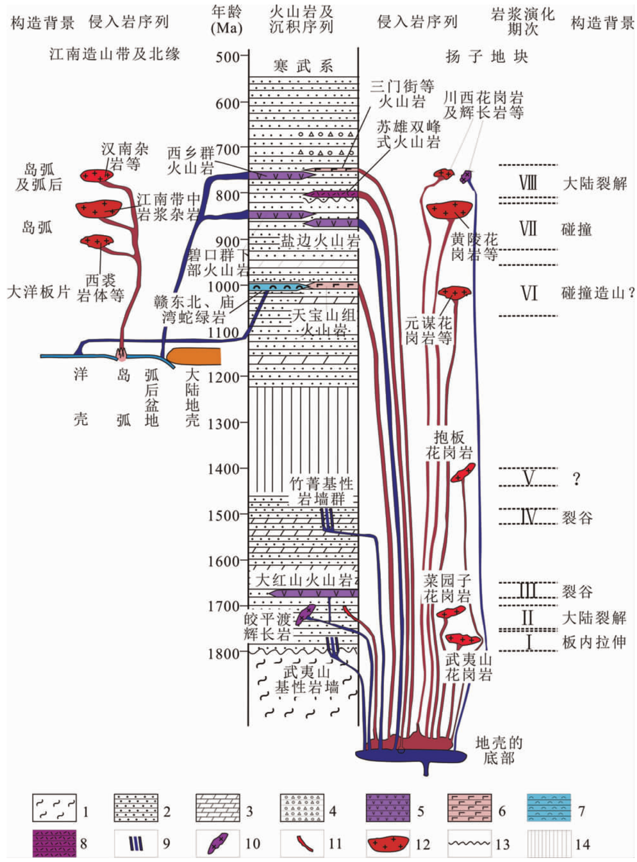

图 6 华南陆块中-新元古代岩浆演化示意图

1-太古宙-古元古代变质基底;2-碎屑沉积岩;3-碳酸盐岩;4-冰碛砾岩;5-中-基性火山岩;6-中-酸性火山岩;7-蛇绿岩组合;8-双峰式火山岩;9-基性岩墙(群);10-辉长岩类;11-花岗斑岩脉;12-花岗岩类;13-不整合界线;14-地层缺失

Fig. 6 Schematic diagram of Meso-Neoproterozoic magmatic evolution in the South China Block

1-Archean-Paleoproterozoic metamorphic basement; 2-clastic rocks; 3-carbonate rocks; 4-moraine-breccia; 5-intermediate-mafic volcanic rocks; 6-intermediate-acid volcanic rock; 7-ophiolite sequence; 8-bimodal volcanics; 9-mafic dykes; 10-gabbro; 11-granite-porphyry dykes; 12-granitoids; 13-unconformity boundary; 14-stratigraphic break

的辉长岩脉(耿元生等, 2012),这些岩墙主要侵入到通安组地层中。这期岩浆事件从 1531Ma(耿元生等, 2012)延续到 1486Ma(Fan *et al.*, 2013),在年龄直方图上在 1.5Ga 附近有一个小的峰值(图 4c)。这期岩浆岩的母岩浆为裂谷环境(图 6)下略微富集的岩石圈地幔部分熔融的产物(Fan *et al.*, 2013)。

第五期岩浆作用(~1.4Ga)。这期作用以海南岛抱板地区出露的片麻状花岗闪长岩为代表,形成年龄在 1455~1431Ma 之间,可能形成于岛弧或大陆边缘构造环境(Li *et al.*, 2002a; 许德如等, 2006; 张立敏等, 2017)。这期岩浆事件分布局限,其区域构造意义还有待进一步研究。此外,在四川西南会理地区发现有 1.37Ga 的辉长岩,可能形成于

洋壳初始俯冲背景（任光明等，2017）。由于四川会理和海南相距较远，二者的形成时代有一定差别，是否代表同一期岩浆事件尚需进一步研究。

第六期岩浆事件（1.08～0.96Ga）。这期岩浆事件在华南的不同地区表现形式有所差异。在扬子地块西南缘以川西地区会理群天宝山组中的火山岩、云南元谋地区苴林群普登组中的火山岩、云南元谋-四川会理一带出露的花岗岩及基性岩脉为代表，它们形成于 1072～1014Ma（耿元生等，2007a，2017；杨崇辉等，2009；Chen *et al.*，2014，2018；Zhu *et al.*，2016）。但对于该地区的这期岩浆事件形成的构造环境尚有不同认识，部分研究者认为这期岩浆事件形成于板块的碰撞环境，与 Grenville 期的造山事件有关（Li *et al.*，2002a；耿元生等，2007a；杨崇辉等，2009）。有的研究者认为该地区这期岩浆事件形成的花岗岩属于 A 型花岗岩，形成于陆内裂谷盆地环境（Chen *et al.*，2018）；或形成于扬子与华夏陆块碰撞初期在扬子陆块内形成的裂谷环境（Zhu *et al.*，2016）。在扬子陆块其他地区，这期岩浆事件则以赣东北蛇绿岩带、湖北黄陵西部庙湾蛇绿岩中的辉长岩等为代表。其中赣东北蛇绿岩中的辉长岩等形成于 1038～970Ma（李献华等，1994；Gao *et al.*，2009；Zhang *et al.*，2015b；Wang *et al.*，2015a；李源等，2017；蒋幸福等，2017）；庙湾蛇绿岩形成于 1096～973Ma（Peng *et al.*，2012b；Deng *et al.*，2017）。此外，四川石棉地区出露的超基性-基性岩组合（部分研究者认为属于蛇绿岩组合）中的辉长岩也曾获得 1066Ma 的锆石 SHRIMP U-Pb 年龄结果（Hu *et al.*，2017）；在扬子地块的西北缘四川青县通木梁群火山岩中堆晶辉长岩等也曾获得过 971～966Ma 的锆石 U-Pb 年龄数据（Li *et al.*，2018）。赣东北的蛇绿岩属于江南造山带的一部分，而庙湾蛇绿岩位于扬子地块的内部，石棉蛇绿岩则位于扬子地块的西缘。这些产于不同地点的蛇绿岩组合基本是同时代的产物，它们是否构成了一套西起石棉，向东经庙湾，东到赣东北蛇绿岩带是值得重视的问题。不论是岩石组合和地球化学特征，扬子西南缘云南元谋-四川会理的火山岩和花岗岩与江南造山带、扬子地块北缘的岩浆岩组合都有明显的差异，因此我们在华南中-新元古代岩浆演化示意图中将它们分别表示（图 6）。

第七期岩浆事件（0.93～0.82Ga）。在华南陆块中-新元古代年龄直方图中可以看出，从 0.95Ga 左右的低谷，到新元古代晚期是一个连续的正态分布的年龄曲线。其最大峰值在 0.84Ga 左右，之后岩浆活动的强度渐次减弱（图 4c）。我们之所以采用 0.82Ga 作为这次岩浆事件的结束时限，主要考虑以下因素：首先从广西北部，经贵州梵净山、湖南、江西北部、安徽南部、到浙江北部新元古代早期地层（也称下构造层，包括四堡群、梵净山群、冷家溪群、双桥山群和双溪坞群等）与新元古代中晚期地层（也称上构造层，包括丹州群、下江群、板溪群、修水群及河上镇群等）之间存在明显的不整合接触，造成该不整合界面的构造运动时限大体在 0.82Ga（高林志等，2011；孟庆秀等，2013）。其次，扬子地块西缘形成于裂谷环境的苏雄组双峰式火山岩形成于 806～803Ma（李献华等，2001a；卓皆文等，2015），江南造山带东段侵入许村花岗岩的混合岩墙形成于 805～804Ma，形成于裂谷环境的上墅组双峰式火山岩形成于 802～797Ma（Wang *et al.*，2012c），考虑到从碰撞造山转变为陆内的裂谷环境需要一定的时间，由此推断二者转换的时间大约在 820Ma 左右。最后，在华南中-新元古代岩浆岩年龄直方图上（图 4c）可以看出从 840Ma 的最大峰值到 810Ma 的小峰，频度有明显的下降，因此我们以 820Ma 为界。

在华南地区该阶段的岩浆岩最显著的是出露在江南造山带中的火山岩和相关的花岗岩类。在江南造山带的东段平水群、双溪坞群中的火山岩（从玄武岩到流纹岩都有出露）以及相伴的侵入岩（如西裘花岗岩套、山后岩浆杂岩等），形成时间在 950～840Ma（Li *et al.*，2009b；Chen *et al.*，2009a，b；Liu *et al.*，2015；陈辉等，2016；Lyu *et al.*，2017）。在江南造山带中段以双桥山群中的火山岩（包括玄武岩、安山岩和流纹岩）以及相关的侵入岩（如皖南的许村岩体、歙县岩体、休宁岩体、江西的九岭岩体等）为代表，它们主要形成于 840～820Ma（李献华等，2002；Li *et al.*，2003c，2016b；Wu *et al.*，2006；薛怀民等，2010；Wang *et al.*，2014d）。到江南造山带西段，该期岩浆事件以梵净山群、四堡群中的火山岩（以基性火山岩为主）和相伴的侵入岩（梵净山地区的桃树林岩体，四堡地区的三防、本洞、元宝山等岩体及辉长岩等）为代表，其主要形成于 840～818Ma（Zhou *et al.*，2009；Li *et al.*，1999；Zhao *et al.*，2011；王敏等，2011；薛怀民等，2012；张传恒等，2014；Yao *et al.*，2014；Wang *et al.*，2014d；Lin *et al.*，2016）。上述资料表明，江南造山带中该期的岩浆事件发生的时间并不完全相同，东部相对较早，西部相对较晚。它们不仅在时间上有差异，在锆石 Hf 同位素和全岩 Nd 同位素组成上也存在明显差异和分带性（Wang *et al.*，2014d），表明它们的物质来源和形成环境都有所差异。东部的火山岩和花岗岩类早期形成于岛弧环境，之后逐步过渡到弧后的前陆盆地环境，西部则形成于扬子地块和华夏地块的碰撞环境。

该期岩浆事件在扬子地块北缘和西缘也有较明显的表现。在扬子北缘的碧口群、西乡群下部的火山岩、勉略混杂岩带中的一些基性岩块，以及米仓山地块中的早期侵入体也属于这一阶段的岩浆产物，它们形成于 855～824Ma 期间（Yan *et al.*，2004；闫全人等，2007；赖绍聪等，2007；夏林圻等，2009；叶霖等，2009；Dong *et al.*，2012），这些岩浆岩主要形成于岛弧环境（Dong *et al.*，2012，2017）。

位于扬子地块内部接近北缘的黄陵花岗岩基出露面积 900km^2，其主体三斗坪英云闪长岩、黄陵庙奥长花岗岩和大老岭（二长）花岗岩也形成于这一阶段（马大铨等，2002；Zhao *et al.*，2013a，b），它们可能形成于岛弧环境（Zhao *et al.*，2013a，b）。在扬子地块西缘以盐边群中的火山岩和相

关的侵入岩为代表,盐边群中的火山岩主要为玄武岩,目前还没有可靠的年龄数据,但是侵入到盐边群的关刀山岩体已经获得856Ma的年龄(Li *et al.*, 2003b; Du *et al.*, 2014),结合碎屑锆石的年龄等资料,盐边群的火山岩大致形成于880~830Ma(Zhou *et al.*, 2006a; 杜利林等, 2013),主要形成于扬子西缘弧后盆地(Li *et al.*, 2006; 杜利林等, 2005; 2013; Sun *et al.*, 2008)。之后,有一期基性岩脉侵入到盐边群、登相营群之中(824~809Ma)(Cui *et al.*, 2015; Niu *et al.*, 2015),标志着扬子西缘这期岩浆事件的结束。

以上论述表明,该期岩浆事件在华南表现强烈。但是不同地区表现形式有所差异,很难逐个小地区进行表示。因此,考虑到江南造山带和扬子北缘的造山过程具有相似性,因此在华南中-新元古代岩浆事件演化示意图上大体分为江南造山带和扬子北缘与扬子其他地区进行表示(图6)。

第八期岩浆事件(0.82~0.72Ga)。从华南地区中-新元古代岩浆岩的年龄直方图可以看出,华南地区0.82~0.72Ga岩浆活动依然比较强烈,但显示从老到新岩浆活动的强度呈逐渐递减的趋势(图4c)。这期岩浆事件在华南不同地区表现的形式不同。在江南造山带及附近,由于0.82Ga左右的武陵运动标志造山运动的结束,所以这一地区0.82Ga以后的岩浆事件以代表拉张环境的火山岩和侵入岩为特征。如江南造山带东段802~797Ma的双峰式火山岩(Li *et al.*, 2008b; Wang *et al.*, 2012c; 吴荣新等, 2007),扬子陆块西缘806~803Ma的苏雄组双峰式火山岩(李献华等, 2001a; 卓皆文等, 2015)以及上构造层中形成于拉张环境的一些火山岩,如丹州群三门街组中的火山岩(765Ma, Zhou *et al.*, 2007)等。在江南造山带及附近这一阶段的非造山型侵入岩也比较发育,如皖南-浙北一带的莲花山花岗岩、石耳山花岗岩、白际花岗岩等(Li *et al.*, 2003a; 吴荣新等, 2005; 薛怀民等, 2010; 邓奇等, 2016),赣北的梅仙岩体(Xin *et al.*, 2017)及广西的田朋岩体等(王孝磊等, 2006)。

该阶段在扬子地块北缘的火山岩主要包括碧口群上部、武当群、西乡群、耀岭河群等中的火山岩(Yan *et al.*, 2004; Ling *et al.*, 2008; 夏林圻等, 2008, 2009; 祝禧艳等, 2008; 徐学义等, 2010; Zhu *et al.*, 2014),以及以汉南杂岩为代表的侵入岩等(凌文黎等, 2006; Zhao *et al.*, 2010a; Dong *et al.*, 2011, 2012, 2017; 杨朋涛等, 2012; 敖文昊等, 2014)。在扬子北缘(或者称勉略带)这期岩浆事件是该区0.85~0.82Ga岩浆事件的延续,0.85~0.82Ga的岩浆事件导致北侧的陡岭地体与小摩岭岛弧的拼合,大洋继续向南发展,到该阶段,在洋盆中形成了大量的火山岩,在凤凰山岛弧产生了大量的侵入岩,形成汉南杂岩(Dong *et al.*, 2017)。因此,扬子北缘该期的岩浆事件主要形成于大洋盆地和岛弧环境(图6)。

在扬子地块西缘,该阶段形成了大量的岩浆岩,包括龙门山杂岩、康定杂岩、米易杂岩、大田杂岩等,成分变化很大,有沙坝辉长岩、苏长岩、同德闪长岩、磨盘山和康定TTG岩系、摩挲营花岗岩-二长花岗岩等,这些不同成分的岩浆岩基本形成于810~740Ma期间(Zhou *et al.*, 2002b, 2006b; Li *et al.*, 2003a, 2009a; 杜利林等, 2006; 耿元生等, 2007b; 郭春丽等, 2007; Huang *et al.*, 2008; Meng *et al.*, 2015)。对于这套岩浆杂岩的形成背景目前存在不同认识,部分学者认为时期岩浆活动形成于地幔柱导致的拉伸构造环境(Li *et al.*, 2002b, 2003a, c; Zhu *et al.*, 2006);另一些学者则认为这期岩浆活动形成于与岛弧有关的构造环境(颜丹平等, 2002; Zhou *et al.*, 2002b; 沈渭洲等, 2003)。

2.3 塔里木及周缘中-新元古代的岩浆事件序列

塔里木陆块位于我国西北,由于大部分被沙漠覆盖,其前寒武纪基底只在其东北缘、东南缘及西南缘的局部出露。已有资料显示,塔里木陆块包括了太古宙、古元古代的变质基底,也出露大量的中-新元古代的地层和火成岩。在塔里木北侧的天山造山带、东南缘的阿尔金-祁连造山带中出露一些中-新元古代的地块,对于分布于(早)古生代造山带中地块的归属存在不同认识,有的认为它们可能来自不属于塔里木的外来地块,有的认为它们可能来自塔里木陆块的外来地块。本文所称塔里木及周缘,既包括塔里木陆块也包括中天山造山带及祁连造山带中的一些中-新元古代地块。根据岩浆岩的形成时代,塔里木陆块及周缘的中-新元古代岩浆事件可以分为八期。

第一期岩浆事件(1.79~1.77Ga)。目前,该期岩浆事件的产物在塔里木及周缘目前仅发现两处。一处位于塔里木西南缘叶城地区为侵入到太古宙-古元古代赫罗斯坦杂岩中的基性岩墙,岩墙宽2~10m,延长300~2000m,走向310°~330°。较宽的岩墙从边部辉绿岩到中心辉长岩,有一定变化,并发育冷凝边。其中一条较宽岩墙中辉长岩的斜锆石U-Pb年龄为1780±12Ma,可以代表基性岩墙的形成年龄(Zhang *et al.*, 2019)。这些基性岩墙从形成时代和地球化学上都可与华北该时期的基性岩墙群对比,形成于大陆的伸展环境。另一处是位于柴达木北缘大柴旦西北鹰峰地区的环斑花岗岩。鹰峰岩体呈北西-南东向延长的枣核型,出露面积20km^2,主要由粉红色环斑花岗岩和灰白色环斑花岗岩组成。该岩体侵入到达肯大坂群,并有辉长岩脉和花岗岩脉侵入其中。Xiao *et al.* (2004)曾采用锆石TIMS方法获得1776±36Ma的年龄结果,Chen *et al.* (2013a)采用锆石LA-ICPMS U-Pb法获得1794±6Ma的年龄结果。通常认为,环斑花岗岩是非造山环境的产物,是地壳伸展构造的标志之一(Windley, 1991; Rämö and Haapala, 1995)。因此,鹰峰环斑花岗岩形成于非造山的拉伸环境(图7)。从形成年代上看,鹰峰地区的环斑花岗岩较华北陆块内北京密云环斑花岗岩(1679~1685Ma)形成要早,可能意味着塔里木陆块中元古代早期裂解的深成岩浆事件略早于华北陆块,而与华北陆块中元古代早期的熊耳群火山事件和太行岩墙群事件发生的时间基本一致。由于这期岩浆事件分布零星,在年龄直方图

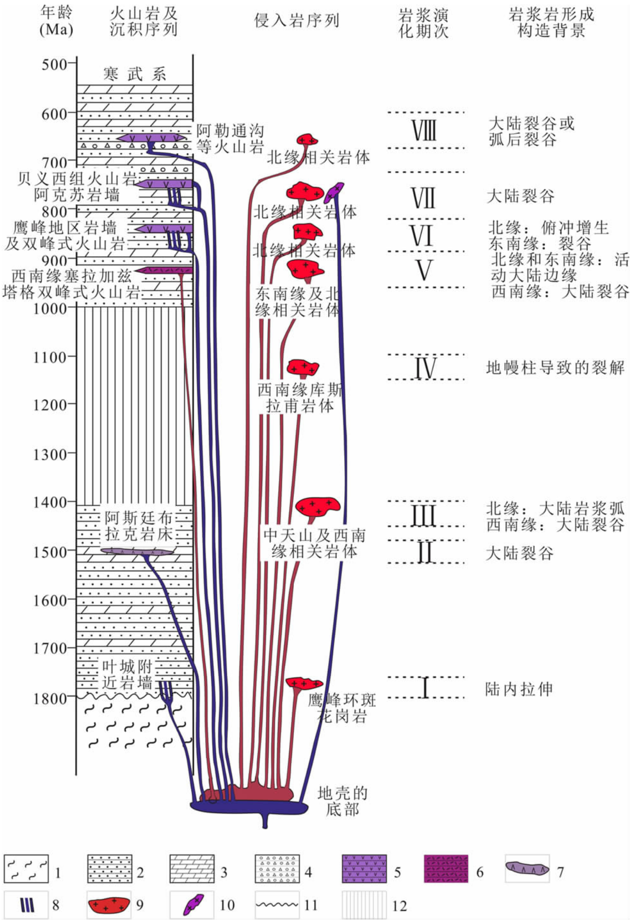

图 7　塔里木陆块及周缘中-新元古代岩浆演化示意图

1-太古宙-古元古代变质基底；2-碎屑沉积岩；3-碳酸盐岩；4-冰碛砾岩；5-中基性火山岩；6-双峰式火山岩；7-基性岩床；8-基性岩墙；9 花岗岩类；10-辉长岩类；11-不整合界线；12-地层缺失

Fig. 7　Schematic diagram of Meso-Neoproterozoic magmatic evolution in the Tarim Block

1-Archean-Paleoproterozoic metamorphic base-ment; 2-clastic rocks; 3-carbonate rocks; 4-moraine-breccia; 5-intermediate-mafic volcanic rocks; 6-bimodal volcanics; 7-mafic sills; 8-mafic dykes; 9-granitoids; 10-gabbro; 11-unconformity boundary; 12-stratigraphic break

上没有形成明显的峰(图 4d)。

第二期岩浆事件(～1.50Ga)。该期岩浆事件以塔里木北缘的库鲁克塔格的阿斯廷布拉克铁矿区内出露的基性岩床为代表。该区出露的基性岩以岩床形式为主，少量为小岩株，岩床一般长度大于 2000m，宽度 200～400m，它们侵入到兴地塔格群兴地河组下部的大理岩中。这些岩床以辉绿岩为主，主要由辉石、角闪石、斜长石组成，具有典型的辉绿结构。在局部，可以在与岩床接触的大理岩中观察到阳起石，可能是接触变质的产物(新疆维吾尔自治区地质矿产局，1993)。在辉绿岩中获得过 1491 ± 11Ma，1497 ± 21Ma 和 1551 ± 8Ma 的年龄数据(Wu *et al.*，2014；Wang *et al.*，2017c；张健等，2018)，这几个数据尚有一定差异。基性岩床的地球化学具有大陆溢流玄武岩的特点，形成于大陆裂解(裂谷)环境(图 7；Wu *et al.*，2014；张健等，2018)。在塔里木西南缘库地北，喀拉喀什群中 1525 ±4Ma 流纹岩(Zhang *et al.*，2019)可能也属于这期岩浆事件。

第三期岩浆事件(1.45～1.40Ga)。该期岩浆事件以塔里木北部天山造山带内的阿拉塔格、尾亚、星星峡等地出露的片麻状花岗闪长岩、二长花岗岩等为代表。这些变形的花岗岩体出露面积变化较大，有的仅在星星峡群片麻岩中呈大的透镜状，而在阿拉塔格地区该期的花岗岩套出露近 80km^2。岩石类型以片麻状花岗闪长岩、片麻状二长花岗岩为主，少量的片麻状英云闪长岩、片麻状闪长岩和片麻状钾长花岗岩，它们侵入到星星峡群之中，并与星星峡群一起经历了强烈的变形，普遍具有与围岩产状一致的片麻理。目前的年代学资料显示，这套岩浆杂岩主要形成于 1458～1405Ma 期间(胡霭琴等，2006；施文翔等，2010；He *et al.*，2015)，地球化学特征表明它们主要属于碱性-钙碱性系列，形成于大陆岩浆弧环境(图 7，He *et al.*，2015)。在塔里木西南缘的库斯拉甫一带出露的阿孜巴勒迪尔岩体形成时代为 1423 ± 19Ma 到 1401 ± 5Ma(黄建国等，2012；Ye *et al.*，2016)，也属于这期岩浆事件的产物。该岩体侵入到长城系的碳酸盐岩和混合岩中，地球化学成分显示该岩体属于 A2 型花岗岩，形成于大陆裂解环境(图 7，Ye *et al.*，2016)。由此可见，该期岩浆事件在塔里木北部天山造山带中的产物和塔里木西南缘的产物形成构造背景有明显差异，说明当时天山造山带中的一些中元古代地块处于碰撞造山环境，而当时塔里木西南缘的阿孜巴勒迪尔岩体则形成于大陆裂解环境。值得注意的是，天山造山带中这期岩浆事件略早，而塔里木南缘的这期岩浆事件发生的略晚，是否为同一期岩浆事件的产物尚需更深入的研究。在塔里木及周缘的年龄直方图上，1.43Ga 有一个明显的峰值(图 4d)，代表该期岩浆事件的主活动期年龄。

第四期岩浆事件(～1.12Ga)。在期岩浆事件的产物目前仅在塔里木西南缘的库斯拉甫北西一带有所发现。在该地区，花岗闪长岩、眼球状花岗岩及淡色花岗岩侵入到中元古代的桑株塔格群中，这些岩体呈北西向拉长的椭圆状，宽 2～3km，长可达 10km 左右。其中花岗闪长岩的锆石 SHRIMP U-Pb 年龄为 1118 ±5Ma，眼球状花岗岩的锆石 LA-ICPMS U-Pb 年龄为 1116 ±9Ma，淡色花岗岩的锆石 SHRIMP U-Pb 年龄为 1116 ±1Ma(Zhang *et al.*，2019)。地球化学特征显示它们具有 A2 型花岗岩特征，形成于地幔柱引发的裂解环境(Zhang *et al.*，2019)。

第五期岩浆事件(0.96～0.88Ga)。在塔里木及周缘中-新元古代岩浆事件年龄直方图上在 0.93Ga 左右有一个明显的峰值(图 4d)，是这期岩浆事件的反映。该期岩浆事件在塔里木及周缘的不同地区表现形式有所差别。在塔里木西南缘叶城以南以塞拉加兹塔格群中的火山岩为代表，这套火山岩以玄武岩为主，其次为流纹岩，缺少中性成分的安山岩，具有双峰式火山岩的特点(Wang *et al.*，2015d)。根据全岩

Rb-Sr 年龄曾将该群划分为中元古代早期(新疆维吾尔自治区地质矿产局, 1993),近年高精度锆石原位定年表明,这套火山岩形成于 896 ~ 881Ma 期间,属于新元古代早期(Wang *et al.*, 2015d, 2015e)。塞拉加兹塔格群中双峰式火山岩组合与华北陆块、西非克拉通、刚果克拉通、巴西圣弗兰西斯科克拉通等地 925 ~ 870Ma 的裂谷型火山岩可以类比,表明它们形成于裂谷环境(Wang *et al.*, 2015e)。

在塔里木东南缘,从新疆若羌向东经阿尔金、祁连到柴达木北缘造山带中都有该期岩浆岩分布,主要有片麻状花岗岩、眼球状花岗片麻岩、条带状花岗片麻岩等花岗质侵入岩。它们侵入到古-中元古代变质地层中,并与围岩一同经历了强烈的变形,其变形面理产状与围岩中的片理、片麻理产状一致。这些正片麻岩在成分上主要是花岗闪长岩、石英二长岩,少量为花岗岩,它们主要形成于 951 ~ 881Ma(Tung *et al.*, 2007; 张建新等, 2011; Song *et al.*, 2012; Yu *et al.*, 2013; Fu *et al.*, 2015)。这些岩浆片麻岩以高钾钙碱性 I 型花岗岩为主,ε_{Hf}(0.9Ga)值介于 -5.6 到 +3.9 之间,锆石 Hf 的二阶段模式年龄(t_{DM2})介于 1.9 ~ 1.4Ga,这些特征表明,塔里木东南缘该期片麻状花岗岩,是在活动大陆边缘条件下由古元古代晚期-中元古代早期基性-中性母岩部分熔融产生的(Yu *et al.*, 2013)。

在塔里木陆块北缘,该期岩浆事件的产物仅在库鲁克塔格的兴地附近有零星出露,岩性为片理化的花岗岩,形成时代为 933 ± 11Ma,并认为其可与华南等地的 Grenvillian 期造山事件相对比(Shu *et al.*, 2011)。此外,在塔里木中部塔参 1 井基底花岗闪长岩的角闪石^{40}Ar-^{39}Ar 坪年龄分别为 931.68 ± 0.73Ma 和 890.65 ± 1.94Ma(Li *et al.*, 2005),可能也属于这期岩浆事件的产物。这期岩浆事件在塔里木陆块以北的中天山造山带内则广泛分布,从西部的温泉,经中东部的阿拉塔格、尾亚,到东部的星星峡等地都有分布,主要是不同类型的片麻状花岗岩,由于它们同围岩一起经历了强烈的变形改造,以往曾将其作为地层的组成部分。近年大量的研究表明,这些花岗质片麻岩是经过强烈改造的花岗岩,属于岩浆岩的范畴。它们主要是花岗岩,少部分属于花岗闪长岩,主要形成于 969 ~ 882Ma(Yang *et al.*, 2008; 胡霭琴等, 2010; 彭兴明等, 2012; Huang *et al.*, 2014; Wang *et al.*, 2014g; Wang *et al.*, 2014e; Huang *et al.*, 2015; Gao *et al.*, 2015),岩相学、地球化学特征表明它们属于 S 型花岗岩,形成于活动大陆边缘环境(图 7; Huang *et al.*, 2015; Gao *et al.*, 2015)。

第六期岩浆事件(0.88 ~ 0.82Ga)。在塔里木陆块及周缘中-新元古代岩浆事件年龄直方图上在 0.93Ga 与 0.83Ga 两个年龄高峰之间有明显的低谷,低谷的最小年龄值在 0.88Ga 左右。另外在塔里木陆块北缘的库鲁克塔格地区有形成于裂谷拉张环境的 818 ± 11Ma 和 816 ± 15Ma 的辉长岩墙或辉绿岩墙(Zhang *et al.*, 2011; 邓兴梁等, 2008)。所以,我们把这一期岩浆事件限定在 0.88 ~ 0.82Ga(图 4d)。该期岩浆事件在塔里木陆块北缘的库鲁克塔格一带表现强烈,形成大量的含角闪石花岗闪长岩、石榴-白云母花岗岩、二云母花岗岩及混合岩中的一些淡色花岗和淡色花岗岩脉。它们主要形成于 834 ~ 824Ma 期间(Ge *et al.*, 2013, 2014)。地球化学特征表明,它们类似于现代的埃达克质岩石。锆石的 Hf 同位素等揭示,它们是在俯冲增生背景下由太古宙基性的下地壳部分熔融产生(图 7; Ge *et al.*, 2014)。库鲁克塔格东段大平梁斜长花岗岩(锆石 LA-ICPMS U-Pb 年龄 826 ± 13Ma)以及由于岩体侵位于围岩形成的矽卡岩铜矿床(辉钼矿 Re-Os 等时线年龄 830 ± 26Ma)(Cao *et al.*, 2010)也应属于这一期岩浆事件的产物。

在塔里木陆块东南缘柴北缘鹰峰地区,该期岩浆事件以粗玄岩墙和 Aolaoshan 组中的玄武岩和流纹岩为代表,这期火山岩 + 粗玄岩岩墙的组合和地球化学特征表明它们是双峰式岩浆岩组合,它们在 851 ~ 821Ma 期间(Lu *et al.*, 2008b; Xu *et al.*, 2016b)形成于地幔柱有关的拉张环境,并有可能构成大火成岩省(Xu *et al.*, 2016b)。塔里木北缘库鲁克塔格地区该期岩浆事件发生于碰撞造山环境,而塔里木东南的柴北缘鹰峰地区该期岩浆事件发生在裂谷拉张环境(图 7),二者似乎是矛盾的。一种可能就如 Xu *et al.* (2016b)所解释的,在 850Ma 之前已形成 Rodinia 超大陆,之后在华南、柴北缘、澳大利亚之间由于地幔柱的上涌形成了大火山岩省。另外一种可能就是柴北缘一带当时面对大陆,开始向外扩散裂解,而塔里木北缘则当时面向大洋,由于陆块的不断扩散,面向大洋的一侧发生了洋壳向陆块的俯冲,所以在塔里木北缘形成了与碰撞造山有关的岩浆岩。

第七期岩浆事件(0.82 ~ 0.72Ga)。该期岩浆事件在塔里木北缘的库鲁克塔格一带表现最为明显,形成大量的花岗岩类、基性侵入岩、基性岩脉、贝义西组火山岩等,这些岩石从组合到地球化学特征都表明它们形成于大陆裂谷环境(Zhang *et al.*, 2007b, 2009b, 2011; Shu *et al.*, 2011; Long *et al.*, 2011b; Cao *et al.*, 2014; Tang *et al.*, 2016)。从塔里木及邻区中-新元古代岩浆岩年龄直方图上可以看出,这期岩浆事件在 ~0.79Ga 和 ~0.73Ga 有两个峰值(图 4d)。早期峰值期间,形成了大量的花岗岩(如太阳岛花岗岩)和少量的基性岩脉(如中途站的基性-超基性岩脉)(Zhang *et al.*, 2007b, 2011; Long *et al.*, 2011b; Shu *et al.*, 2011)。从 0.77Ga 到 0.75Ga 岩浆活动相对较弱,局部形成了一些花岗岩。0.75Ga 到 0.72Ga 岩浆活动再次加强,形成了兴地附近的超-基性岩浆杂岩(如兴地Ⅰ到Ⅳ号岩体)及相关的花岗岩脉或岩株(Zhang *et al.*, 2011; Cao *et al.*, 2014; Tang *et al.*, 2016)等。该阶段在库鲁克塔格地区还形成了贝义西组火山岩(740 ~ 725Ma)(徐备等, 2008; Xu *et al.*, 2009; 高林志等, 2010)。该阶段的岩浆事件,除在库鲁克塔格地区表现强烈外,在塔里木陆块西北的阿克苏一带也有表现,如侵入到阿克苏群中的基性岩墙群(Chen *et al.*, 2004; Zhang *et al.*, 2009b; 张健等, 2014)。在塔里木西南缘这期岩浆事件

表现较弱，在库地附近的辉长岩和花岗岩构成双峰式的岩浆组合（Zhang *et al.*，2006）。在塔里木陆块内都表现为陆内拉张背景。在塔里木陆块以北的天山造山带中，这期岩浆事件也有表现，如中天山西段赛里木湖附近的辉长岩及花岗岩（Wang *et al.*，2014h），星星峡地区的花岗岩（Lei *et al.*，2013）等，它们的形成环境很可能也属于陆内的拉伸背景（Wang *et al.*，2014h；Lei *et al.*，2013）。

第八期岩浆事件（0.68～0.60Ga）。在塔里木及周缘中-新元古代岩浆岩年龄直方图中在0.68～0.60Ga期间有一个独立的峰，其峰值在0.64Ga左右（图4d）。这期岩浆事件在华北基本没有出现，在华南只有零星分布，在塔里木北缘的库尔勒-库鲁克塔格一带则比较明显的。形成了一些二长花岗岩、正长花岗岩、石英正长岩等花岗岩体（Ge *et al.*，2012，2014；何登发等，2011；张传林等，2014）外，也有辉绿岩等基性岩脉（Zhu *et al.*，2008），同时也有一些火山岩喷发，如阿勒通沟组上部的火山岩（He *et al.*，2014）、扎摩克提组上部火山岩（Xu *et al.*，2009；He *et al.*，2014）等。这期岩浆岩的组合和地球化学特征，表明它们形成于陆内的拉伸环境或者是弧后裂谷盆地环境（图7；Ge *et al.*，2012）。在塔里木陆块西北的阿克苏一带，不整合在阿克苏群之上的苏盖特布拉克组火山岩也形成于该时期较晚阶段的大陆裂谷环境，并可与库鲁克塔格地区的特瑞爱肯组及华南的南沱组成冰期相对比（Xu *et al.*，2013）。

3 三大陆块中-新元古代岩浆事件的差异演化

通过华北、华南和塔里木三大陆块中-新元古代岩浆事件的对比（表1），可以看出这三个陆块的岩浆事件序列、岩浆岩的组合、岩浆岩形成的构造背景存在一定的差异。即使在同一陆块内（如华南和塔里木），不同部位的岩浆演化也存在差异。

1.78～1.5Ga，华北、华南和塔里木陆块内岩浆事件的强度、期次、岩浆作用方式尽管不同，但是它们都形成于拉伸的构造背景。其中华北的强度较大，1.78Ga的熊耳火山岩和太行岩墙群分布比较广，可以达到大火成岩省的规模。而在华南和塔里木陆块，该时期的岩浆活动仅在局部存在，规模非常小。尽管规模上有差异，但是三大陆块都存在中元古代早期与拉伸构造背景有关的岩浆活动。如果1.8Ga之前存在一个全球的Columbia超大陆，华北、华南和塔里木陆块可能位于超大陆的不同位置，但是在这一阶段，岩浆活动的记录表明它们都参与了Columbia超大陆的裂解过程。

从表1可以看出，从1.4Ga开始华南和塔里木陆块的岩浆演化与华北有了明显的差异。1.4Ga在华南陆块的海南岛形成了与碰撞有关的片麻状花岗岩（Li *et al.*，2002a；张立敏等，2017），1.37Ga在四川南部会理一带形成了与洋壳消减碰撞有关的辉长岩（任光明等，2017），表明华南陆块在这一阶段局部已经从拉张构造体制转变为挤压构造体制。塔里木陆块北缘在1.4Ga左右形成了与碰撞造山有关的S型花岗岩，也表明该陆块的北侧已经发生了构造体制的转变。华北陆块尽管没有这一阶段的岩浆活动记录，但是，从蓟县系大红峪组火山岩到1.32Ga的燕辽沉降带中大规模的基性岩床，表明华北陆块从中元古代早期到中元古代晚期始终处于拉伸的构造背景。到新元古代早期，华南、塔里木陆块与华北陆块构造体制的差异更加明显。在华南陆块，江南造山带和扬子北缘在0.9～0.82Ga都发育了大量的与造山作用有关的火山岩和侵入岩，塔里木陆块北缘形成了大量的与造山作用有关的S型花岗岩，表明它们经历了Rodinia超大陆的汇聚过程。而华北陆块的辽东半岛、徐淮地区在0.92Ga则发育了大量的与拉伸裂解有关的基性岩床和岩墙，到0.83Ga左右在南缘发育了与拉张有关的大红口碱性火山岩，在西缘的千里山在0.81Ga发育了代表拉张环境的基性岩墙，始终处于一种拉伸状态，并没有参与Rodinia超大陆的汇聚。从1.4Ga左右开始，华南、塔里木陆块就与华北陆块经历了不同的岩浆演化，处于不同的构造背景，在全球构造演化中处于不同的位置。

从中-新元古代岩浆演化看，华北陆块从1.78Ga到新元古代中期经历了相同的岩浆演化过程，一直处于拉张的构造环境。从一个侧面说明华北陆块从古元古代末期就是一个完整的陆块，所以后期经历了相同的岩浆演化过程。但是，华南和塔里木陆块内却有不同的岩浆演化事件。在华南陆块，1.40～1.37Ga局部有与造山左右有关的岩浆事件（海南岛花岗岩和四川会理辉长岩），在1.0Ga左右在江南造山带（赣东北）、扬子地块内（湖北宜昌庙湾）以及扬子西缘石棉都发育有蛇绿岩；在扬子西南则发育有与岛弧背景有关的火山岩（四川会理群天宝山组火山岩），在云南元谋发育有板内的花岗岩。这些不同部位发育的岩浆岩表明，华南陆块不同部位经历了不同的岩浆构造事件，它们很可能是由不同的小地块在1.0Ga左右经过较广泛的岩浆构造事件拼合到一起的。塔里木陆块也有类似的岩浆演化特点。如在1.4Ga左右塔里木陆块北缘的花岗岩具有大陆岩浆弧岩浆岩的特征，而同时期在塔里木陆块西南的阿孜巴勒迪尔岩体具有A2型花岗岩特征，形成于大陆裂解环境。如0.96～0.88Ga期间，塔里木东南缘和北缘的花岗岩以I型和S型为特点，形成于活动大陆边缘。而在塔里木陆块的西南缘该时期则形成了塞拉加兹塔格群中双峰式火山岩，形成于陆内裂谷环境。再如，在0.82～0.72Ga期间塔里木陆块北缘的库鲁克塔格地区发育了大量的与拉张环境有关的花岗岩和基性岩脉，而在陆块的西北缘阿克苏地区在却发生了蓝片岩相的变质作用，形成了与洋壳俯冲有关的低温高压的蓝片岩（Chen *et al.*，2004）。同一陆块内不同部位，不同阶段岩浆岩组合的差异意味着塔里木陆块原来并不是一个统一的陆块，很可能是在不同时期由不同块体拼合而成的。Guo *et al.*（2001）根据阿尔金北缘与南缘蛇绿岩形成时代的差异，就曾提出过塔里木

表1 华北、华南和塔里木陆块中-新元古代岩浆事件对比

Table 1 Comparison of Meso-Neoproterozoic magmatic events in North China, South China and Tarim blocks

	华北	华南	塔里木
0.6 Ga			东北缘形成大量偏碱性花岗岩和基性侵入岩，形成于拉伸构造背景。
0.7 Ga			
		江南造山带以双峰式火山岩和后造山花岗岩为代表形成于拉张构造环境。扬子北缘以武当-西乡火山岩为代表，增生造山环境。	
0.8 Ga			
	以南缘大红口粗面岩、狼山火山岩和千里山岩墙为代表形成于拉张构造环境。	江南造山带以弧形火山岩和造山花岗岩为代表。北缘：碧口火山岩形成增生带西缘：，盐边群及花岗岩，形成于弧后盆地。	东北缘：花岗岩等形成于俯冲增生环境。东南缘：双峰式火山岩形成拉张构造环境。
0.9 Ga	以辽东半岛、徐淮基性岩床、岩墙为代表形成于拉张构造环境。		东北缘：S型花岗岩，活动大陆边缘。东南缘：I型花岗岩，活动大陆边缘。西南缘：双峰式火山岩，裂谷。
1.0 Ga		赣东北、庙湾蛇绿岩，大洋消减环境。西南缘天宝山火山岩及花岗岩，岛弧或弧后拉张。	
1.1 Ga			西南缘侵入三株塔格群A2型花岗岩，形成于拉张环境。
1.2 Ga	以通化、建平等地基性岩脉为代表，形成于拉张环境。		
1.3 Ga	以燕辽裂谷带中基性岩床和康保花岗岩为代表，拉张环境。		
1.4 Ga		早期海南抱板花岗岩，晚期四川会理辉长岩，碰撞造山环境	东北缘：钙碱性花岗岩等形成于大陆岩浆弧。西南缘：A2型花岗岩，拉张环境。
1.5 Ga		以四川会理基性岩墙为代表，形成于拉伸环境。	以库鲁克塔格地区基性岩床为代表，形成于拉伸环境。
1.6 Ga	以团山子组火山岩和南缘碱性岩带为代表，形成于拉伸环境。	以大红山群等火山岩为代表，形成于裂谷拉伸环境。	
1.7 Ga	以大庙AGRS岩浆岩组合为代表，形成地幔柱有关拉伸环境。	以西南缘武定-会理双峰式浆岩为代表，形成拉伸环境。	
1.8 Ga	以熊耳火山岩和太行基性岩墙群为代表，形成拉伸环境。	以武夷山基性岩和片麻状花岗岩为代表，形成拉伸环境。	以东南缘环斑花岗岩和西南缘基性岩墙为代表，拉伸环境。

陆块的基底是在不同时期由不同块体拼合而成的的认识。

4 几个有关问题的讨论

4.1 关于1.4Ga左右岩浆事件的性质

在华南和塔里木陆块零星出露一些1.43Ga左右的岩浆岩，在华南陆块包括海南岛的片麻状花岗岩、川西南1.37Ga的辉长岩，在塔里木陆块有在北缘分布的片麻状花岗闪长岩、片麻状二长花岗岩等。海南岛的花岗岩被认为形成碰撞造山环境(张立敏等, 2017)，四川会理一带的辉长岩被认为是蛇绿混杂岩的组成部分，形成于洋壳初始俯冲阶段(任光明等, 2017)，塔里木北缘的变形花岗岩类被认为形成于大陆岩浆弧环境(He *et al.*, 2015)。从地球化学特征看，这些岩浆事件都与碰撞造山环境有关。但从全球构造演化看似乎存在矛盾。Columbia超大陆在~1.8Ga形成之后，很快进入了拉伸阶段，在超大陆内部形成一些盆地，在边缘形成一些被动陆缘，但是并没有使超大陆完全裂解。通常认为，以北美麦卡基岩墙(1.27Ga)或北澳大利亚Derim-Galiwinku基性大火成岩省(1.32Ga)的出现为标志，Columbia超大陆发生

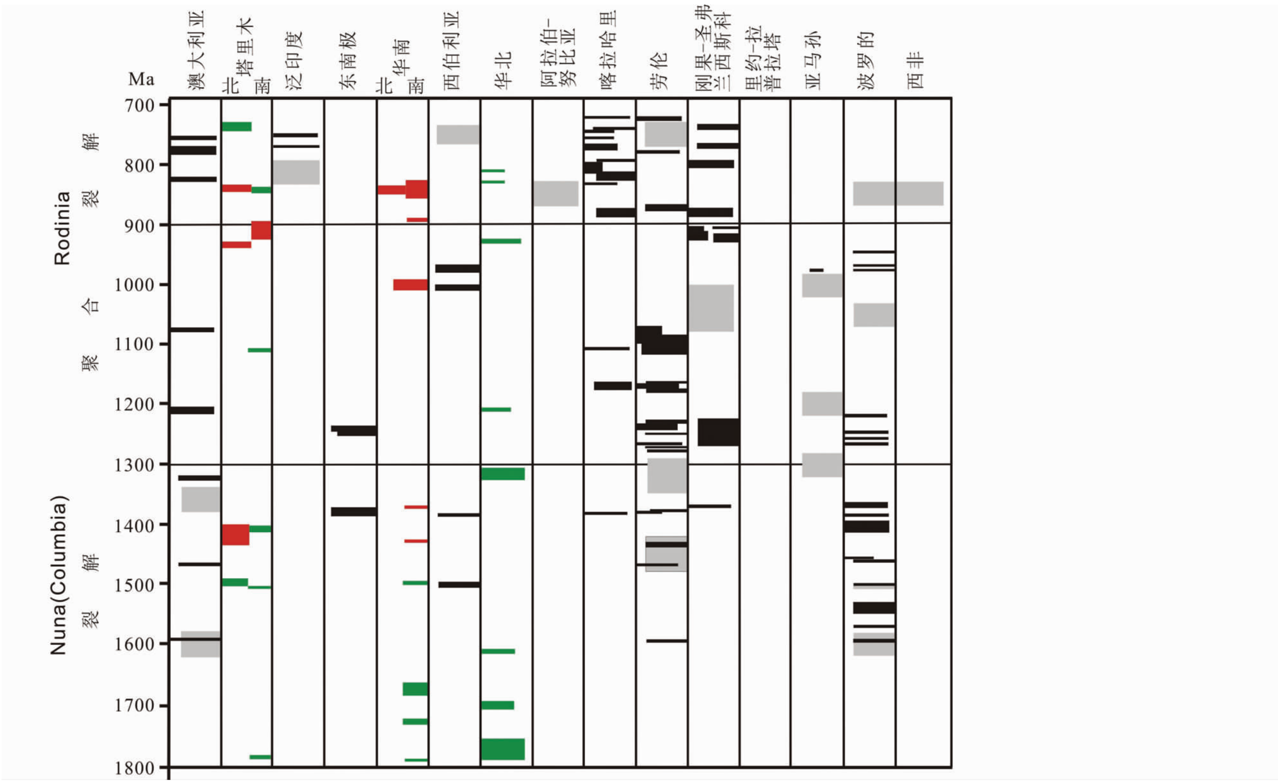

图8 全球主要陆块 1.8～0.7Ga 期间大火成岩省分布示意图(据 Ernst *et al.*, 2008 修改)

黑色和灰色引自 Ernst *et al.*, 2008,黑色为大火成岩省；灰色为被剥蚀残留的大火成岩省．绿色代表与伸展有关的岩浆事件,红色代表与挤压有关的岩浆事件

Fig. 8 Barcode diagrams showing the 1.8～0.7Ga LIPs in different cratonic blocks (modified after Ernst *et al.*, 2008)

Black and grey from Ernst *et al.*, 2008, black for LIPs; gray for LIPs (after erosion and continental breakup). Green is the magma event associated with extension, and red is the magma event associated with extrusion

了最终的裂解(Rogers and Santosh, 2002; Zhao *et al.*, 2004b; Hou *et al.*, 2008; Zhang *et al.*, 2012a)。按照这种认识,我们可以说,在 1.32～1.27Ga 之前,Columbia 超大陆仍处于完整的一体化状态。在 Columbia 超大陆在未完全裂解开之前,到裂解开之后的一段时间,全球的绝大多数陆块都处于一种拉张裂解的背景。是否存在一些小的边缘陆块较早就从超大陆裂解出去(或者始终没有与超大陆聚合)它们之间发生了局部的拼合,产生了局部的与造山有关的岩浆岩目前尚难以证实。由于华南和塔里木北缘出露的 1.43～1.37Ga 的岩浆事件非常局限,资料有限,对他们形成的构造背景还需要进行更深入的研究。除了研究局部具体的岩浆岩特征之外,还要从更大的尺度,甚至全球的尺度探讨它们形成的构造背景。同时,在超大陆格局复原时也应考虑到这期岩浆事件的作用和影响。

4.2 关于 Rodinia 超大陆聚合的时限

最初,格林威尔造山运动是指 1.19～0.98Ga 期间劳伦古陆与亚马逊地体间的"陆-陆碰撞"作用(Rivers, 1997; 周金成等,2008)。随着 Rodinia 超大陆的提出,部分学者就把导致 Rodinia 形成的地质过程称为 Grenville 期。我国的四堡运动最初是指造成上覆丹州群与下伏四堡群之间不整合的构造运动,时间在 1.0Ga 左右。一些学者提出导致扬子地块和华夏地块聚合的四堡运动与形成 Rodinia 超大陆的 Grenville 运动大致相当(Li *et al.*, 2002a, 2008a)。后来随着大量高精度同位素年龄数据的发表,该不整合界面的时限在 0.82Ga 左右。从时间上看,四堡运动与格林威尔运动有一定差异。由于超大陆的形成是一个复杂过程,于是有人提出从 Columbia 超大陆的分离到 Rodinia 超大陆的形成都属于 Rodinia 过程。Ernst *et al.* (2008) 根据大量的中-新元古代大火成岩省的资料,把 1.3～0.9Ga 作为 Rodinia 超大陆的聚合阶段,0.9～0.7Ga 作为 Rodinia 超大陆的裂解阶段(图8)。在该图中华北基本是空白,华南和塔里木只表示了 0.82～0.75Ga 与超大陆裂解有关的岩浆事件。本文根据现有的资料,将华北、华南和塔里木陆块的有关岩浆岩资料表示到该图中(由于华南和塔里木陆块内存在差异演化因此塔里木用北表示塔里木东北缘和西北缘,用南表示东南缘和西南缘;华南则用北表示扬子地块北缘及西缘,用南主要表示江南造山带),有些分布范围广,达到了属于大火山岩省(如华北 1.78Ga 的熊耳火山岩和太行基性岩墙群、华北 1.32Ga 的基性岩床等)。有些规模较小,为了与全球岩浆作用的对比也

在该图上给以了表示(图8)。

该图中 Ernst *et al.* (2008)表示了大火成岩省,并未说明这些火成岩的形成构造背景。从补充后的图中可以看出,华北陆块从1.8Ga到0.8Ga左右的岩浆活动一直是在拉张环境下形成的,由此可以判断华北陆块并没有参与Rodinia超大陆的聚合过程。华南陆块和塔里木陆块,与Rodinia超大陆聚合的岩浆事件从1.0Ga到0.82Ga左右,最终的结束事件在0.82Ga左右。所以从华南和塔里木陆块的岩浆事件演化看,Rodinia超大陆聚合的岩浆事件结束的时间应在0.82Ga左右,而不是0.9Ga。

Ernst *et al.* (2008)所确定的Rodinia超大陆开始聚合的时限1.3Ga实际是Columbia超大陆最终裂解的时限。裂解后各陆块相互间有漂移的过程。这一过程是属于Columbia超大陆的裂解过程还是属于Rodinia超大陆的聚合过程是值得探讨的。从图8中可以看出,在东南极、劳伦古陆、刚果-巴西等地都存在1.25Ga左右的大火成岩省。北美Elzevirian期(1.25 ~ 1.19Ga)是一期俯冲增生造山事件(Rivers, 1997),与这几个地区的岩浆事件在时间上可以对比。因此我们认为Rodinia超大陆的聚合期应从1.25Ga到0.82Ga。

4.3 华南陆块中1.0Ga左右岩浆事件所提出的问题

从图2可以看出,在江南造山带(赣东北)、扬子地块内(湖北宜昌庙湾)以及扬子西缘石棉都发育有在1.0Ga左右的蛇绿岩;在扬子西南则发育有与岛弧背景有关的火山岩(四川会理群天宝山组火山岩),在云南元谋发育有板内的花岗岩等。对出露在华南陆块不同部位、近同时形成岩浆岩已有较多的研究,提出了不同的认识。但是从全局上这些1.0Ga左右的岩浆岩向我们提出了一系列的问题,不同地点的蛇绿岩是同一条蛇绿岩带还是几条蛇绿岩带?这些蛇绿岩带在Rodinia超大陆形成过程中起到什么作用?1.0Ga左右的蛇绿岩与近同时代的扬子西南缘天宝山组以酸性火山岩为主的岩浆岩在构造上有没有联系?通过地球化学有人认为扬子西南缘1.0Ga左右的岩浆岩形成于类似岛弧的环境,有人认为形成于陆内裂谷环境,它们究竟是形成于同一构造背景还是形成于不同的构造背景?用于进行构造环境分析的地球化学指标的可靠性如何?等等。

Zhang *et al.* (2015b)认为,赣东北蛇绿岩是扬子地块与华夏地块之间洋中脊的产物,洋脊从北向南俯冲形成了赣东北蛇绿岩。Wang *et al.* (2015a)提出,赣东北蛇绿岩是弧后洋消减,扬子地块与怀玉岛弧碰撞的产物。Peng *et al.* (2012b)提出庙湾蛇绿岩是北侧神农架弧与扬子地块碰撞的产物。彭松柏等已经注意到庙湾蛇绿岩与赣东北蛇绿岩的关系,认为扬子北缘与澳大利亚东南缘之间的大洋在1.0Ga左右消减,神农架岛弧位于扬子地块的北侧,主消减带位于神农架弧与扬子地块之间,而赣东北蛇绿岩是主消减带东部的一个分支。Hu *et al.* (2017)认为神农架弧与扬子地块间消减带呈弧形,石棉蛇绿岩和庙湾蛇绿岩都是该弧形消减带的产物。对具体的蛇绿岩来说这些不同的模式都具有一定的合理性,但是扬子地块本身并不是一个很大的地块,因此需要从扬子地块的整体(甚至是整个Rodinia超大陆的形成过程)考虑这几处蛇绿岩的相互关系、形成的构造背景等问题。同时,扬子地块西南缘1.0Ga左右的天宝山组火山岩、相关的侵入岩与这几处蛇绿岩是基本同时形成的,它们之间是否存在内在的联系,是否处于统一的构造体制都是需要从扬子地块的整体及它们在Rodinia超大陆形成过程中的作用进行总体的考虑。

关于扬子西南缘1.0Ga左右的火山岩和侵入岩,有的研究者(Li *et al.*, 2002a; 杨崇辉等, 2009)认为它们与扬子地块、华夏地块拼合的江南造山带有关,如果这样江南造山带的地理分布就需要进行再认识。也有的研究者(Chen *et al.*, 2018)认为该期的岩浆事件形成于扬子地块西南1150 ~ 960Ma的康滇裂谷带中,有的研究者(Zhu *et al.*, 2016)认为该期岩浆事件形成于扬子和华夏碰撞初期的裂谷盆地中。这些模式都有一定的地质资料给以支持,但是缺少对这些岩浆岩与同时期蛇绿岩相互关系的研究,缺少这期岩浆事件与江南造山带广泛的0.88 ~ 0.82Ga岩浆事件相互关系的研究以及该期岩浆事件在Rodinia超大陆形成过程中所起作用的研究。

总之,1.0Ga左右蛇绿岩和岩浆岩的发现,为我们提出了一些新的问题,这些问题需要我们从华南陆块的总体或更大的范围和视角进行研究。

5 结论

(1)华北陆块中-新元古代岩浆事件可以划分为7个阶段(1.78Ga、1.70Ga、1.63Ga、1.32Ga、1.23Ga、0.93Ga 和0.83Ga),各阶段的岩浆岩均形成于大陆地壳伸展的构造背景。华南陆块中-新元古代岩浆事件可以划分为8个阶段(1.78Ga、1.72Ga、1.67Ga、1.5Ga、1.42Ga、1.0Ga、0.84Ga和0.77Ga),其中~1.4Ga左右的一期岩浆构造事构造件分布局限,可能形成于局部的构造拼合背景。1.0Ga左右的岩浆事件,在华南陆块的不同部位表现形式不同,意味着发生过不同地块的拼合。从0.95Ga到0.82Ga的岩浆事件主要分布在江南造山带和扬子地块北缘,这一阶段的岩浆事件导致扬子地块和华夏地块拼接成一体,形成华南陆块。塔里木陆块该阶段的岩浆事件可以划分为8个阶段(1.78Ga、1.5Ga、1.43Ga、1.1Ga、0.92Ga、0.83Ga、0.74Ga 和 0.65Ga),其中1.43Ga、0.96 ~0.88Ga和0.88 ~0.82Ga阶段,塔里木陆块不同部位的岩浆事件表现形式和形成背景有明显差异。

(2)华北、华南和塔里木陆块从1.8Ga到1.5Ga的岩浆事件都是在拉张构造背景下形成的,意味着它们都经历了Columbia超大陆的裂解。但是从~1.4Ga,华南和塔里木陆块都存在与碰撞有关的岩浆事件,而华北陆块缺少这一阶段的岩浆活动记录,表明三大陆块开始了各自的演化过程。华

南和塔里木陆块 0.96 ~ 0.82Ga 的岩浆活动强烈，都与 Rodinia 超大陆的聚合有关，而华北这一阶段的岩浆活动仍以拉张环境为构造背景。这种差异意味着华南和塔里木陆块卷入了 Rodinia 超大陆的聚合，而华北陆块很可能没有经历 Rodinia 超大陆的聚合过程。

（3）华南陆块的的不同部位发育的 1.0Ga 左右的蛇绿岩以及代表不同构造环境的岩浆岩和火山岩提出了一系列新的科学问题，需要我们从华南陆块的总体或更大的范围和视角进行研究和认识。

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