

碎屑锆石 U-Pb 定年地层划分对比应用探讨

——以新元古界梵净山群“淘金河组”为例

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摘要 【目的】前寒武纪经历了多期次构造热事件、构造复杂、变形变质严重, 给地层划分对比及客观地层层序的建立带来不便与困难。【方法】以江南造山带西段新元古界梵净山群出露最老的淘金河组为研究对象, 开展碎屑锆石形态学对比、U-Pb 定年、分析该层位的物质来源及沉积大地构造背景, 并将梵净山地层进行多维定标分析对比。【结果】“淘金河组”锆石颗粒自形程度高, 代表短距离搬运, 源岩为花岗岩、辉绿岩、正长岩/二长岩和玄武岩, 碎屑锆石年龄峰值为 875 Ma、1 862 Ma 和 2 513 Ma, 经锆石地球化学数据分析, “淘金河组”沉积于汇聚背景。【结论】“淘金河组”与其上覆地层余家沟组之上的肖家河组锆石年龄图谱相似, 物源相同; 结合其他地层地质特征, 指出桃树林一带梵净山群“淘金河组”与肖家河组可能为同一地层单元。

关键词 前寒武纪; 碎屑锆石; U-Pb 定年; 梵净山群; 地层对比

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0 引言

显生宙地层划分对比方法有岩石地层、层序地层、年代地层、旋回地层、生物地层、化学地层和磁性地层等。岩石地层是地层学的基础, 是自然第一性的; 层序地层是由不整合面及其相对应的整合面划分内部相对统一且成因有关联的地层层序^[1]; 年代地层界线通过全球标准层型剖面 and 点确定; 旋回地层是识别地层中的米兰科维奇旋回信号确定各地质事件发生的时代和持续时间^[2-3]; 生物地层依据关键属种的初次或末次出现作为地层划分的依据^[4]; 化学地层是利用岩层中化学元素、化合物及元素比值的含量分布和变化规律建立地层框架^[5]; 磁性地层是基于地球磁场倒转的全球等时性建立年代地层框架^[6-7]。目前已经建立起了全球标准层型剖面, 为全球地层对比提供标准。

前寒武纪地层是地球演化历史中极为重要的组成部分,蕴藏地球历史近 90%的发展演化信息,包含最老的岩石、地层、构造演化及重要矿产资源,其沉积厚度大、无生物化石(哑地层)、形成时代久远、且地质构造复杂,一直是地质界研究较为薄弱的部分,但前寒武纪地质演化时间漫长,在地质历史中具特殊而重要的地位,因此一直是地质学家们关注与研究的重点。20 世纪 80 年代初国际地层委员会曾专门研究国际晚前寒武纪地层对比方法的有效性,然后又设计了“叠层”、“冰渍砾岩”等专题研究。然而,岩石地层因形成环境的异同、纵横向展布的差异及穿时性,加之多期构造—岩浆事件的改造,使地层记录表现为多样而复杂,导致在地层单位划分对比与地层序列建立时出现偏差甚至错误。

旋回地层在前寒武纪地层中的应用目前于初级阶段,至今尚未取得高质量的研究成果^[8]。前寒武纪地层生物化石记录异常稀少,种类低级且单一,演化替代速度慢,很难利用标准生物化石来准确界定地层单位^[9]。中新元古代化学地层的研究程度低,已有地球化学数据极少,而且已建立化学地层的区域分辨率也不高^[10]。磁性地层主要针对连续沉积的地层序列,对于经过长时间各种地质作用改造且非连续沉积的地层会有干扰^[11]。2004 年 3 月国际地层委员会确定了前寒武纪地层中唯一一个全球标准层型剖面,位于埃迪卡拉纪底部,年龄为 635 Ma^[12]。有人认为前寒武纪地层界线的标定应以全球层型剖面为依据^[13],但是全球标准层型剖面的概念和方法以生物演化记录为核心,在前寒武纪阶段基本无法满足建立标准,如果沿用原有的方法,很可能会存在巨大的缺陷和风险^[14]。上述方法均有局限性,而同位素年代学研究是目前进行前寒武纪哑地层划分对比最有效的方法。

近年来,锆石 U-Pb 定年技术被广泛应用于年代学研究中,为华南大陆前寒武纪地层提供了大量精确的年龄数据^[15-24],研究主要聚焦在火山(碎屑)岩对沉积年龄的限定,以及岩浆岩对最小沉积年龄的限定,从而对地层进行区域划分对比^[25]。由于前寒武纪地层标志层相对缺少,变形程度普遍较强,加上火山岩通常是零星出露,接触关系不明,在缺乏其他因素制约的情况下,很难做到更细致的地层划分对比与客观地层序列的建立。有研究表明,即便是酸性岩的锆石 U-Pb 年龄也有可能不能精确代表其侵位年龄^[26],针对火山灰所获得的锆石谐和年龄,也有可能得到小于地层沉积时代的特殊情况^[27]。因此,地层年代学研究应该充分建立在明晰的野外接触关系之上,而这个要求对于变质变形复杂的前寒武纪地层来说,又是较为困难的。重要的是,碎屑锆石 U-Pb 定年为前寒武纪地层年代学研究提供了另一个对比证据^[28-30],锆石年龄图谱越相似,说明经历的构造岩浆事件相似,其关系就越近^[31-35]。通过对相互接触的层位开展碎屑锆石特征及 U-Pb 年龄对比,能够充分考虑地质体的野外接

触关系和地层的形成时代；碎屑锆石研究所需的大量数据，能够有效地将定年方法中的特殊异常所稀释，为前寒武纪地层的划分对比及序列的确定提供多元信息与方法手段。

目前华南大陆江南造山带内新元古代中期地层在群的划分和横向上的对比基本无异议，均以武陵造山运动形成的区域性角度不整合面为界，结合高精度岩浆锆石 U-Pb 定年，把不整合面之下的褶皱基底和不整合面之上的沉积盖层划分为两个群，如浙西地区划分为双溪坞群和河上镇群、皖南地区划分为溪口群和历口群、赣西北地区划分为双桥山群和登山群、湘西北地区划分为冷家溪群和下江群、黔东北地区划分为梵净山群和板溪群、桂北地区划分为四堡群和丹州群^[16-17,36-42]。在褶皱基底内部的划分中，又以其中部广泛发育的钙碱性枕状熔岩^[43]作为标志层进行组级地层单位的划分。例如，桂北地区四堡群中将枕状熔岩出现的层位划分为文通组，枕状熔岩之上地层为鱼西组，其下为九小组；而相邻的湖南省和贵州省却将枕状熔岩上下的地层划分了多个组，例如黔东北地区将梵净山群枕状熔岩产出层位回香坪组划为中部序列，其上部序列划分为铜厂、洼溪和独岩塘三个组，下部序列划分为淘金河、余家沟和肖家河三个组。由于组级岩石地层单位区域性划分对比的显著标志层相对缺乏，加之岩石变形程度较强，与周围地层的接触关系也存在多种类型，导致相当的群内组、段的精细划分对比较困难，给地层序列的客观建立带来干扰甚或错误。例如，皖南地区有学者将武陵（皖南）造山运动角度不整合面之下地层划分为盆地边缘环境的上溪群和盆地中心环境的溪口群，二者在时代上可对比，属于同时异相地层，认为其物源为下伏井潭组。溪口群底部由下至上为漳前组、板桥组、木坑组和牛屋组^[44-45]；但也有学者认为溪口群底部地层应该倒置^[46]。滇东昆阳群“倒八”与“正八”及昆阳群与东川群的划分对比^[47]，湖北神龙架地区神农架群与马槽园群及内部组段的划分对比^[48]等，均存在地层划分对比的不客观与地层序列建立的错误。基于这些问题，本文选取梵净山群最古老的淘金河组砂岩作为研究对象，对淘金河组进行碎屑锆石 U-Pb 年代学研究，利用锆石的显微结构和微量元素特征对锆石的形成环境进行限定，客观解释不同地层所具有的不同年龄组合^[49]。将梵净山群不同层位的锆石年龄图谱进行对比，分析物源，限定地层格架，再通过锆石年龄图谱进行多维定标分析，实现多个样品间的定量对比，直观地表现出各层位之间的相似度，以提升地层划分对比与客观地层序列确定的客观性，为华南前寒武纪地层对比提供重要的实践案例。

1 地质概况

江南造山带位于扬子地块和华夏地块之间（图 1）^[50-51]，在 835~820 Ma^[52]碰撞形成华南大陆，经浙、皖、赣、湘、黔、桂等省，长约 1 500 km，宽约 120 km^[53]。造山带内新元

古代地层由中新元古代浅变质岩系及岩浆岩组成，被一区域性角度不整合面分开，该不整合构造事件称为武陵造山运动^[54]。下伏基底序列为双溪坞群、溪口群、双桥山群、冷家溪群、梵净山群和四堡群，形成于 870~825 Ma^[52]，以变质砂岩、粉砂岩、板岩和千枚岩为主；上覆盖层序列为河上镇群、历口群、登山群、下江群、板溪群和丹洲群^[55-60]，形成于 820~716 Ma^[61-62]，由变质砾岩、砂岩、泥灰岩和少量碳酸盐岩组成。根据新元古代火成岩的成分和分布，把江南造山带分为东北段、中段和西南段三段^[61]，东北段以变质火山岩为主，中段和西南段以变质碎屑岩为主。岩浆活动主要有基性火山岩、碱性火山岩、凝灰岩、基性—超基性侵入岩以及 I 型、S 型和 A 型花岗岩组合，这些岩石大多分布于武陵造山运动角度不整合面下的梵净山群和其上的板溪群及相当地层序列中，年龄范围约 1 000 Ma（以赣东北蛇绿岩为代表^[63-64]）至 715 Ma（以丹州群顶部凝灰岩为代表^[62]），大多数年龄集中在 850~760 Ma^[65-67]。

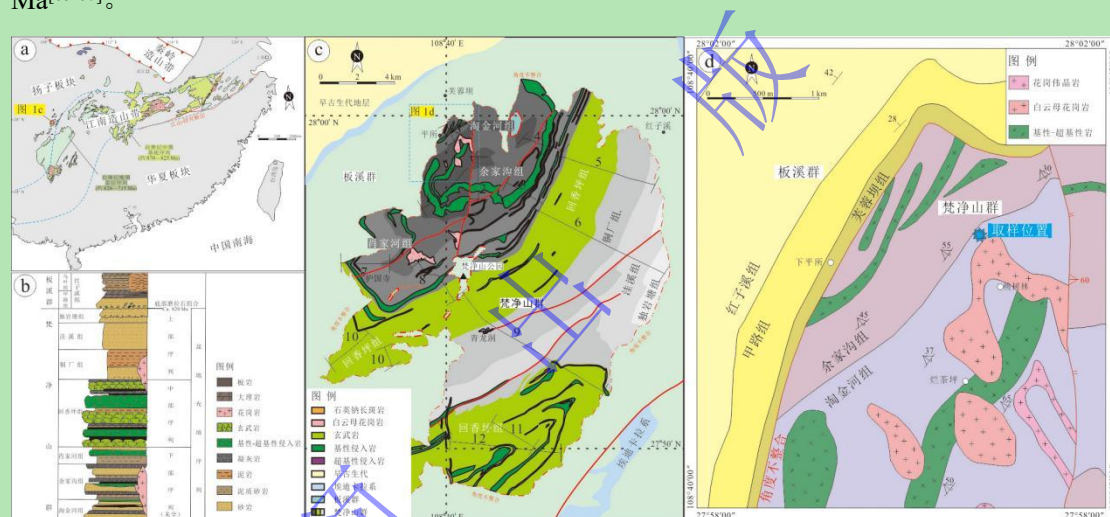


图1 (a) 华南大陆主要构造单元地质简图；(b) 梵净山群及板溪群地层柱状图；(c) 梵净山地区地质图，据文献^[65-66][50-51]修改；(d) 采样位置及岩石分布图

1. 淘金河剖面；2. 大罗剖面；3. 牛风包剖面；4. 大尖峰剖面；5. 冷家坝剖面；6. 汪溪剖面；7. 肖家河剖面；8. 太子石剖面；9. 黑湾河剖面，桑木沟剖面；10. 牛尾河剖面；11. 陈家沟剖面；12. 大转弯、盘溪沟剖面；13. 保庆堂剖面

Fig.1 (a) Geological map of the South China Continent; (b) stratigraphic histogram of the Fanjingshan and Banxi Group; (c) geological map of the Fanjingshan district, modified from references [50-51]; (d) Map of distribution of rock and sample locations

1. Taojinhe profile; 2. Daluo profile; 3. Niufengbao profile; 4. Dajianfeng profile; 5. Lengjiaba profile; 6. Waxiprofile; 7. Xiaojiahe profile; 8. Taizishi profile; 9. Heiwanhe profile, Sangmuhe profile; 10. Niuweihe profile; 11. Chenjiagou profile; 12. Dazhuanwan/Panxi profile; 13. Baoqingtang profile

梵净山群出露于新元古代江南造山带西南段的梵净山地区，面积约 270 km²，位于大型穹状背斜核部，未见底，上覆地层为板溪群，其间为武陵造山角度不整合面分隔，梵净山群为一套浅变质陆源碎屑岩夹火山岩，发育武陵构造旋回期基性—超基性岩、酸性白云母花岗岩及脉状花岗伟晶岩^[68]。在黔东北地区，20 世纪 60 年代将震旦系南沱组冰碛层（现今南

华系)以下浅变质岩系统称为板溪群,以武陵造山运动角度不整合面为界分成上板溪群和下板溪群两个亚群^[69];70年代开展梵净山区5万区调后认为部分岩层倒转产状未查明,结合湖南、广西等省(区)新的资料成果,认为上板溪群和下板溪群两套岩层应划分为梵净山群和板溪群更为合适,并将梵净山群划分为7个组、板溪群划分为4个组,沿用至今^[15-17,52,68,70-72]。因未见底的梵净山群经历了多期构造—岩浆事件,构造变形极为复杂,地层出露不连续,虽然实测了13条地层剖面(图1c),并按地层岩性特征划分对比建立了地层序列,但部分组级地层序列仍缺乏客观的建立依据,给地层及盆地演化研究带来困惑。已有资料成果将梵净山群自下而上分为:淘金河组、余家沟组、肖家河组、回香坪组、铜厂组、洼溪组、独岩塘组^[68,70],年龄在870~720 Ma^[52],划归新元古界拉伸(青白口)系。其下部四个组岩性为浅变质砂泥岩、火山碎屑岩与细碧—石英角斑岩、席状基性—超基性岩不定比互层,厚度大于6200 m;其上部三组岩性为浅变质砂泥岩夹火山碎屑岩,残留厚度大于3200 m。梵净山地区经历了武陵、广西(加里东)、印支、燕山和喜山等多期造山运动的叠加与改造影响,呈北东向构造穹窿状展布,发育南北向及北东向断裂,使地层出露不连续,局部出现地层倒转,构造形迹极为复杂(图1)^[70]。主要岩浆活动有两期,第一期为花岗岩(850 Ma)、玄武岩(840 Ma)、白云母花岗岩(834 Ma)、基性—超基性(831 Ma)演化时序,第二期是武陵运动之后的基性—超基性(814~805 Ma)岩浆活动^[15]。

2 样品与方法

2.1 样品特征

本次采集10 kg新鲜岩石样品用于岩矿鉴定及年代学研究,编号TJH,采样位置在梵净山地区桃树林一带(27.991 905° N, 108.689 145° E)。显微观察显示TJH样品为变质细粒岩屑砂岩,变余细粒砂状结构,块状构造,岩石为发生浅变质的细粒长石砂岩,主要由碎屑颗粒和填隙物组成,碎屑颗粒主要为石英、长石和岩屑,碎屑颗粒多呈次棱角至次圆状,大小一般为0.06~0.25 mm(图2),分选性一般。填隙物主要为云母、硅质和铁质,云母主要为绢云母和白云母,绢云母呈鳞片状,片径小于0.05 mm,白云母呈半自形片状,片径0.05~0.2 mm,硅质主要为微晶或隐晶的细小石英颗粒状集合体,多呈填隙状分布,铁质主要为黑色铁质,粒径0.01~0.5 mm不等,多呈不规则状,零星分布或呈填隙状分布。TJH样品中包含石英(50%~55%)、长石(2%~4%)、岩屑(5%~8%)。



图2 梵净山群淘金河组典型野外、手标本和薄片（正交偏光）照片

Pl.斜长石; Qtz.石英; Ser.绢云母

Fig.2 Representative field, hand specimen, and thin section (cross polarized light) photos of the Taojinhe Formation from the Fanjingshan Group

Pl. Plagioclase; Qtz. Quartz; Ser. Sericite

2.2 分析方法

TJH 样品的锆石制靶、透射光、反射光和阴极发光图像均在廊坊市宏信地质勘查技术服务有限公司完成, 首先机械粉碎块状样品, 进行磁选及重力分选, 然后在双目显微镜下按随机原则挑选锆石至玻璃板, 灌入环氧树脂, 制靶完成后进行透射光、反射光以及 CL 图像拍摄, U-Pb 年代学测试分析。U-Pb 年代学分析在中国科学院地球化学研究所矿床地球化学国家重点实验室进行, 激光剥蚀电感耦合等离子质谱仪 (Laser Ablation Inductively Coupled Plasma Mass Spectrometry, LA-ICP-MS) 由 Coherent 193 nm 准分子激光剥蚀系统和 Agilent7700x 电感耦合等离子质谱仪构成, 剥蚀物质载气为氦气, 空白信号 20 s、样品信号 50 s, 激光束斑直径为 32 μm , 采用 91500 作为外标进行校正, 每 10 个测点加测两次 91500。采用 ICP MS DataCal 软件对实验数据进行处理^[73], 采用 Isoplot^[74]软件完成锆石 U-Pb 年龄谐和图的绘制。在年龄选取时, 小于 1 000 Ma 的锆石采用 $^{206}\text{Pb}/^{238}\text{U}$ 的年龄; 大于 1 000 Ma 的锆石采用 $^{207}\text{Pb}/^{206}\text{Pb}$ 的年龄^[75]。

3 结果与讨论

3.1 结果

锆石长度为 70~220 μm , 形状不规则, 棱角清晰, 以自形一半自形、长—短柱状为主。在阴极发光图像中, 绝大部分锆石具密集振荡环带, 显示源自酸性火成岩锆石结构特征。结合沉积岩碎屑物特点, 推测锆石仅经历短距离搬运 (图 3)。TJH 样品共分析测试点 103 个 (图 3), 其中有 99 个测点的 U-Pb 年龄在谐和线上, 不存在明显的铅丢失现象, 锆石 Th 含量为 $43 \times 10^{-6} \sim 1\,315 \times 10^{-6}$, 平均值 259×10^{-6} ; U 含量为 $94 \times 10^{-6} \sim 2\,661 \times 10^{-6}$, 平均值 624×10^{-6} ; Th/U 比值为 0.12~1.42, 平均值 0.46, 显示岩浆锆石特征 (图 4)^[76-77]。源岩为超镁铁质、镁铁质、中性岩和含石英中性长英质岩。锆石年龄为 2 605~791 Ma, 其中, 68 颗新元古代

锆石 982~791 Ma, 占 68.7%; 6 颗中元古代锆石 1 569~1 032 Ma, 占 6.1%; 22 颗古元古代锆石 2 494~1 654 Ma, 占 22.2%; 3 颗太古代锆石 2 605~2 510 Ma, 占 3.0%。碎屑锆石 U-Pb 年龄图谱(图 5a)表现出一个主要峰值 875 Ma, 另外少部分锆石表现出 1 862 Ma 和 2 513 Ma 两个次要峰值。



图 3 TJH 样品锆石阴极发光图像及 U-Pb 年龄

Fig.3 Representative cathodoluminescence images and U-Pb ages of detrital zircons from the TJH sample

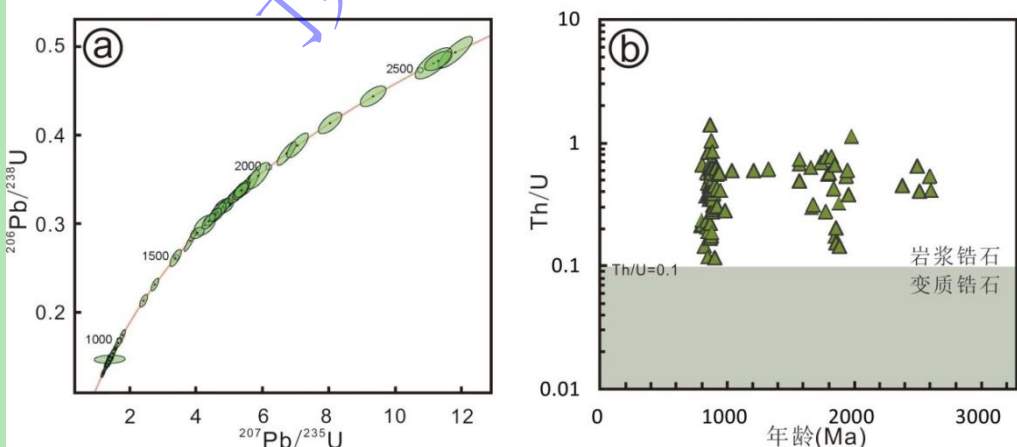


图 4 (a) TJH 样品锆石 U/Pb 年龄谐和图; (b) TJH 样品碎屑锆石 Th/U 与 U-Pb 年龄对比图

Fig.4 (a) Zircon U-Pb Concordia diagram of the TJH sample; (b) diagram of Th/U versus U-Pb ages for the detrital zircons from the TJH sample

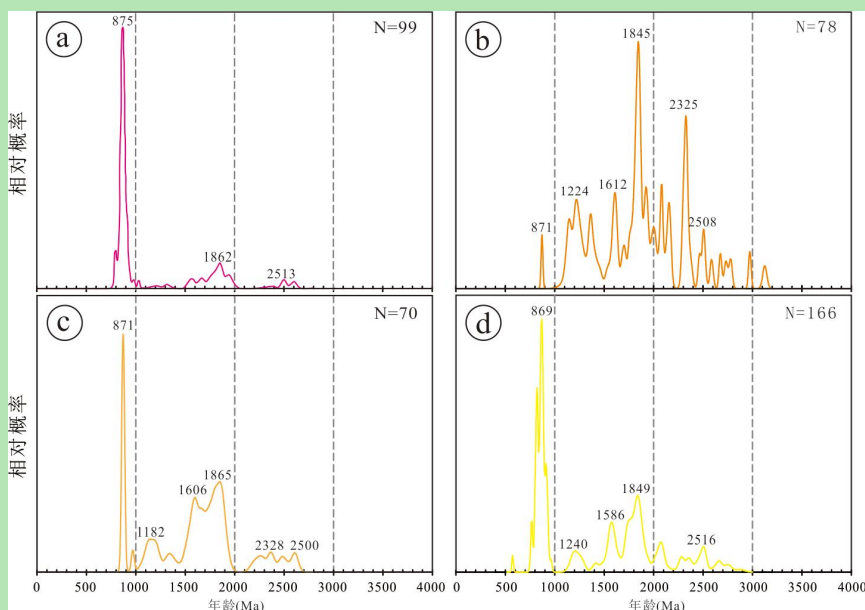


图5 碎屑锆石 U-Pb 年龄图谱

(a) TJH 样品采样于淘金河组, 本次研究; (b) 余家沟组, 数据来自文献[52]; (c) 肖家河组, 数据来自文献[78]; (d) 回香坪组, 数据来自文献[78-79]

Fig.5 U-Pb age histograms of the detrital zircons

(a) TJH sample from the Taojinhe Formation, data from this study; (b) the Yujiagou Formation, data from reference [52]; (c) the Xiaojiahe Formation, data from reference [78]; (d) the Huixiangping Formation, data from references [78-79]

3.2 讨论

3.2.1 梵净山群地层划分对比

梵净山地区经历了多期次构造运动的叠加与改造, 武陵造山运动使梵净山群褶皱断裂隆升接受剥蚀, 广西造山运动使梵净山地区又一次褶皱断裂隆升接受剥蚀, 缺失中晚志留系、泥盆系及石炭系地层, 印支运动结束研究区海相沉积历程, 燕山运动使早白垩纪地层褶皱断裂、并再一次对早期地质构造形迹进行改造与叠加, 使梵净山群反映的地质构造特征极为复杂, 故而对地层序列的客观建立带来不确定性与困难。

因多期次褶皱断裂改造与破坏, 梵净山群目前建立的地层序列由实测的 13 条主干地层剖面 (图 1c) [50-51] 结合路线、浅表工程及钻探资料, 按大致粗略的岩石地层、岩石颜色特征划分对比建立, 并确立了淘金河组为梵净山群出露最老的地层。但建立岩石地层序列所测剖面均不是连续的, 岩石层的建立仅依靠实测剖面的分析来划分对比, 由地层“标志层”相衔接, 或是根据岩性对比而得, 导致地层组、段的划分与对比缺乏客观实证的地质依据, 而可能出现偏差甚或错误。淘金河组岩性为浅变质砂泥岩、火山碎屑凝灰岩夹 3 套席状基性—超基性岩; 余家沟组下部岩性为浅变质砂泥岩夹火山碎屑凝灰岩, 上部岩性为不等比互层的席状基性—超基性岩与变质砂泥岩夹火山碎屑凝灰岩; 肖家河组岩性为浅变质砂泥岩夹火山碎

屑凝灰岩及 3~6 套席状基性—超基性岩。淘金河组与余家沟组的划分在淘金河剖面（1 号，图 1c）^[50-51]上以灰、深灰色与灰色浅变质砂岩分界，在大罗（2 号，图 1c）^[50-51]、保庆堂（13 号，图 1c）^[50-51]剖面上以深灰色粉砂质绿泥绢云板岩与灰色钙质绢云板岩分界；余家沟组与肖家河组在大尖峰剖面（4 号，图 1c）^[50-51]上以余家沟组顶部块状变质辉绿岩、肖家河组底部绢云板岩分界，在肖家河剖面（7 号，图 1c）^[50-51]上以余家沟组顶部绢云角闪石石英岩夹绢云板岩、肖家河组底部含砂质绢云板岩夹变余砂岩分界。三者岩性均为浅变质砂泥岩、火山碎屑凝灰岩与席状基性—超基性岩组合，三者的划分主要依据接触界面处颜色不同或席状辉绿岩与板岩而确立^[68,70,80-81]。本次取样于“淘金河组”的样品表现出与肖家河组相似的物源特征和构造背景^[52,72]，地层的年龄数据与已建立的地层序列不符，反映原本的地层划分对比可能有误，或者说梵净山群中出露最老的地层可能不是淘金河组而是余家沟组。

3.2.2 碎屑锆石综合对比分析

根据笔者团队之前的研究^[52,72]，梵净山群余家沟组物源为扬子板块西南缘的大红山群及相当层位，沉积余家沟组时盆地处于伸展背景。“淘金河组”作为余家沟组的下伏地层，无论是物源还是构造背景都应该表现出比上覆地层更老或者类似的特征，然而本次碎屑锆石年代学研究和地球化学数据分析得到的结果却与之矛盾，所以桃树林一带“淘金河组”并非是梵净山群最老地层。理由如下：（1）“淘金河组”锆石颗粒棱角清晰，磨圆度差（图 3），说明锆石颗粒只是经过短距离搬运，余家沟组锆石颗粒多呈椭圆形，部分呈次圆状^[52,72]，说明锆石经历了远距离搬运。（2）“淘金河组”碎屑锆石 U-Pb 年龄图谱（图 5a）表现出三个峰值：875 Ma、1 862 Ma 和 2 513 Ma，其上覆地层余家沟组（图 5b）^[52]显示出两个明显的年龄峰值 1 845 Ma 和 2 325 Ma，前者最大沉积年龄^[82]比上覆余家沟组年轻。（3）“淘金河组”锆石 U/Nb 值范围是 25~700（图 6a）^[83]，1 颗地幔源锆石，98 颗弧源锆石，用 U/Yb 值与 Hf 进行对比（图 7a）^[83]，锆石全部在陆源范围内，Sc（平均值 385.1×10^{-6} ）和 Sc/Yb 值（平均 1.1；图 6b、图 7c）^[83]同样显示出岛弧岩浆特征。另一方面，锆石表现出较高 U/Nb 值（图 6a）^[81]、Sc/Yb 值（图 6b）^[83]和 U/Yb 值（图 7b）^[83]，相对低的 Nb/Yb 值，且 $U/Nb > 20$ （图 7b）^[83]，说明锆石在俯冲环境中形成^[83-84]。也就是说“淘金河组”沉积于汇聚背景，而余家沟组沉积于伸展背景^[52,72]。（4）根据锆石微量元素源岩鉴别方式分析^[85]得出“淘金河组”碎屑锆石 57.0%来自花岗岩，41.0%来自辉绿岩，1.0%来自正长岩/二长岩，1.0%来自玄武岩（图 8b），锆石源岩与余家沟组（图 8c）不同，物质源区不同。上述证据充分证明桃树林附近地层倒转情况未查明，原本的地层划分可能有误，在梵净山桃树林一带出露最老地层可能为余家沟组。

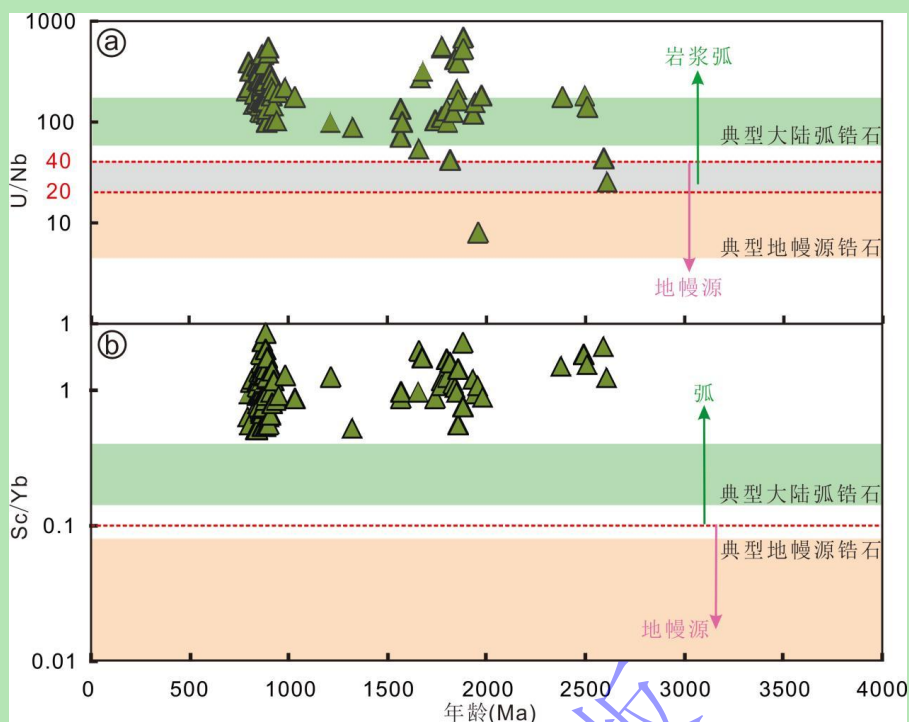


图6 (a) U/Nb 与年龄对比图, 岩浆弧锆石的 U/Nb 值 ≥ 20 , 而亏损地幔锆石的 U/Nb 值 ≤ 40 ; (b) Sc/Yb 与年龄对比图, 将 Sc/Yb=0.1 作为与弧相关以及与地幔相关背景的分界值 (红色虚线), 绿色部分为典型大陆弧的第一至第三四分位数, 橙色部分表示典型地幔源的第一至第三四分位数 (MORB 和海洋岛弧) (据文献[83]修改)

Fig.6 (a) U/Nb versus time. Zircons derived from magmatic arcs have values of U/Nb ≥ 20 and those from mantle-derived melts of U/Nb ≤ 40 ; (b) Sc/Yb versus time. Sc/Yb of 0.1 as a demarcation value between arc- and mantle-related settings (red dashed line). The green bar indicates first to third quartile of typical Phanerozoic continental arcs. The orange bar indicates first to third quartile of typical Phanerozoic depleted and relatively undepleted mantle sources (MORB and ocean islands) (modified from reference [83])

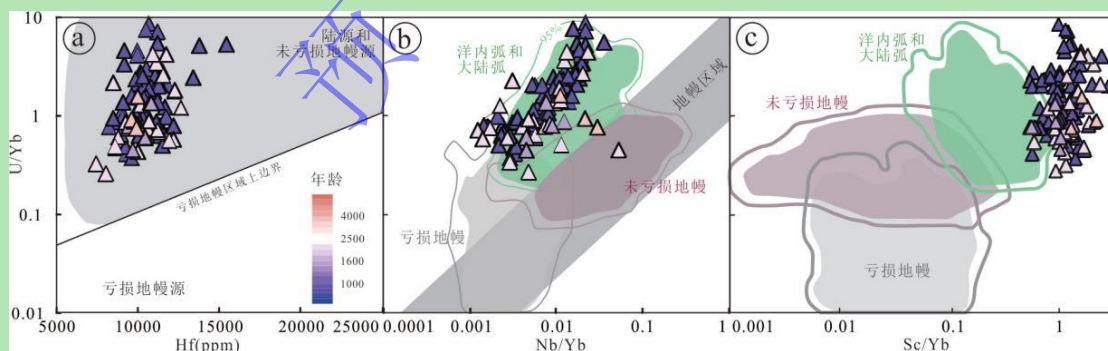


图7 微量和稀土元素图 (据文献[83]修改)

(a) 陆源锆石 U/Yb 与 Hf 判别图; (b) U/Yb 与 Nb/Yb 对比图, 亏损地幔区域上边界的 U/Nb 值为 20; (c) U/Yb 与 Sc/Yb 对比图

Fig.7 Trace and rare earth element plots (modified from reference [83])

(a) U/Yb versus Hf for zircons from the continent; (b) U/Yb versus Nb/Yb, upper boundary of the zircon mantle array roughly represents a U/Nb of ~ 20 ; (c) U/Yb versus Sc/Yb

将“淘金河组”碎屑锆石年龄图谱与梵净山群其他地层进行对比, 发现“淘金河组”与余家沟组上覆地层肖家河组相似。年龄峰值均显示由大量 870 Ma 左右的锆石与少量 1 800 Ma

和 2 500 Ma 左右的古老锆石组成 (图 5a, c) [78-79]。通过多维定标分析“淘金河组”表现出与回香坪组最为相似, 与独岩塘组为次相似, 而回香坪组与铜厂组最为相似, 与肖家河组为次相似 (图 8a)。回香坪组中赋存玄武岩, 厚可逾数百米, 延长几千米至十余千米[70,80], 但在“淘金河组” (实测剖面 1 号、2 号、4 号、13 号, 图 1c) [50-51]中没有玄武岩的记录, 根据回香坪组锆石源岩 (图 8d) 可以看出回香坪组与“淘金河组” (图 8b) 并不是来自同一物源区。铜厂组中发现有微古植物 *Protosphaeridium cf.densum* Tim, *Proleiosphaeridm* sp., *Polyporata obsolete* Sin et Liu, *Po.aff. obsolete* Sin et Liu, *Lignum?*sp., 而在“淘金河组” (实测剖面 4 号, 图 1c) [48-49]中没有植物化石存在。独岩塘组碎屑锆石呈现出约 835 Ma 的单峰值年龄[52,72], 主要源岩为辉绿岩和花岗岩 (图 8e), 与“淘金河组”的锆石峰值年龄不同, 源岩也不同。并且梵净山群铜厂组以上地层未见岩浆岩发育[70,80], 所以“淘金河组”不可能是铜厂组以上地层。由此推断“淘金河组”与回香坪组、铜厂组、独岩塘组不同, 更不会是铜厂组以上地层, 所以“淘金河组”和肖家河组可能为同一地层。

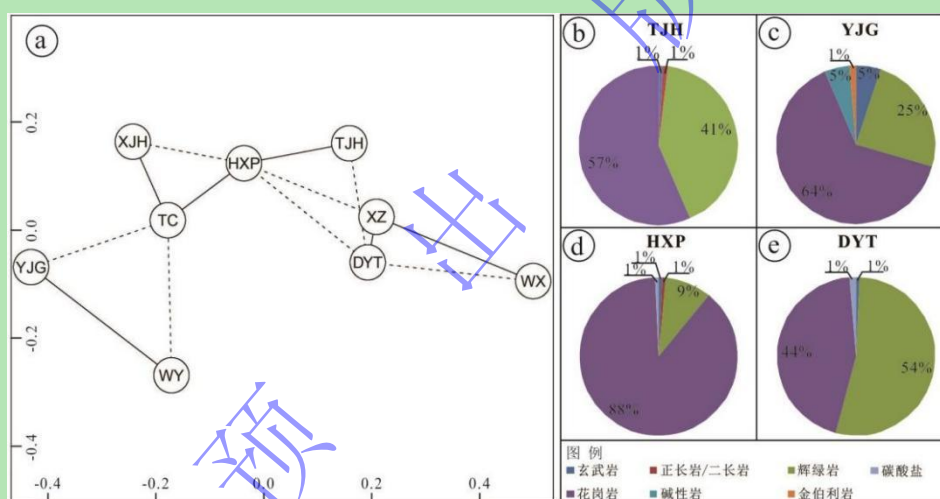


图 8 梵净山群地层多维定标分析图及锆石源岩成分比例图

实线连接的点表示最相类似, 虚线连接的点表示次相类似样品; TJH.淘金河组; YJG.余家沟组; XJH.肖家河组; HXP.回香坪组; TC.铜厂组; WX.洼溪组; DYT.独岩塘组; XZ.新寨组; WY.乌叶组

Fig.8 Multidimensional scaling and zircon source rock composition ratio plot

Solid and dashed lines indicate the closest neighbors and second closest neighbors in likeness, respectively; abbreviation of formations: TJH. Taojinhe Formation; YJG. Yujiagou Formation; XJH. Xiaojiahe Formation; HXP. Huixiangping Formation; TC. Tongchang Formation; WX. Waxi Formation; DYT. Duyantang Formation; XZ. Xinzhai Formation; WY. Wuye Formation

4 结论

(1)梵净山群“淘金河组”砂岩碎屑锆石表现出三个峰值(875 Ma、1 862 Ma 和 2 513 Ma), 上覆地层余家沟组显示出两个明显的年龄峰值 (1 845 Ma 和 2 325 Ma)。

(2)“淘金河组”沉积于汇聚背景, 碎屑锆石棱角分明, 意味着短距离搬运, 余家沟组

沉积于伸展背景, 锆石多呈椭圆形, 意味着长距离搬运, 二者源岩不同, 代表物质源区不同, “淘金河组”的最大沉积年龄比余家沟组年轻, 与区域地质调查划分的地层层序不符, 原本的地层划分可能有误, 梵净山桃树林一带出露最老地层可能为余家沟组。

(3) 梵净山群各组碎屑锆石年龄图谱对比发现, “淘金河组”年龄峰值与余家沟组上覆地层肖家河组相似, 结合多维定标分析和梵净山群各组地层地质特征, 认为“淘金河组”可能与肖家河组为同一地层单元。

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Comparative Application of Detrital Zircon U-Pb Dating for Stratigraphic Delineation: The "Taojinhe Formation" of the Neoproterozoic Fanjingshan Group as an Example

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Abstract: [Objective] Precambrian stratigraphy has undergone multiple tectonic events, complex tectonics, severe deformation, and metamorphism, making it inconvenient and difficult to compare the strata and establish an objective stratigraphic sequence. **[Methods]** This study selected the Taojinhe Formation, the oldest outcrop of the Neoproterozoic Fanjingshan Group in the western part of the Jiangnan Orogen as a research object, and we collected sandstone samples carry out comparing detrital zircon morphology, U-Pb dating, rock, and mineral identification and analysis of the material origin and sedimentary geotectonic settings of this formation, as well as for multidimensional scaling analysis and comparison of the stratigraphy of the Fanjingshan Group. **[Results]** The sample rocks are mainly composed of detrital particles and fillers; the detrital particles are mainly quartz, feldspar

and cutting and sub-angular to sub-rounded with average sortability. The fillers are mainly mica, silica, and iron, and the mica is mainly sericite and white mica. The zircon grains of the "Taojinhe Formation" are angular, representing short-distance transport, and the source rocks are granite, diabase, Syenite/Monzonite, and basalt, with detrital zircon peak ages of 875 Ma, 1 862 Ma, and 2 513 Ma. Based on the zircon geochemical data analysis, the "Taojinhe Formation" was deposited in a convergent background. U/Nb values of "Taojinhe Formation" zircon range from 25–700, with one mantle-sourced zircon and 98 arc-sourced zircons. Using U/Yb values to compare with Hf, all zircons were in the continental source range, and the Sc (average value 385.1) and Sc/Yb values (average 1.1) also show island arc magmatic features. Conversely, the zircons have high U/Nb, Sc/Yb, and U/Yb values, relatively low Nb/Yb values, and $U/Nb > 20$, suggesting that the zircons were formed in a subduction environment. In contrast, the zircons of the Yujiagou Formation are mostly elliptical, suggesting long-distance transport and deposition in a disseminated background, and the source rocks are granites, diorites, basalts, alkalites, and rarely kimberlites, with two distinct age peaks at 1845 and 2 325 Ma. **[Conclusions]** The "Taojinhe Formation" and the Yujiagou Formation have different source rocks representing different material source areas, whereas the tectonic background is also different, and the maximum depositional age of the "Taojinhe Formation" is younger than that of the overlying Yujiagou Formation, which is not consistent with the stratigraphic sequences of the regional geological survey. Therefore, the original stratigraphic division may be erroneous. Comparison of zircon age diagrams shows that the Taojinhe Formation is similar to the Xiaojiahe Formation above the overlying Yujiagou Formation and has the same material source. Combined other stratigraphic features of the Fanjingshan Group, it is suggested that the "Taojinhe Formation" and Xiaojiahe Formation in the Taoshulin area may be the same stratigraphic units.

Key words: Precambrian; detrital zircon; U-Pb dating; Fanjingshan Group; stratigraphic comparisons

