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黔西北下三叠统碎屑岩对峨眉山大火成岩省的响应

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摘 要 【目的】晚二叠世—早三叠世早期，华南西部的峨眉山大火成岩省遭受了强烈的剥蚀，为相邻的右江盆地提供了大量的碎屑沉积物质。这些碎屑沉积物质不仅记录了峨眉山大火成岩省被剥蚀的火山岩岩石类型和组分特征，也揭示了峨眉山大火成岩省晚期火山序列可能存在的岩浆演化趋势。因此，黔西北地区下三叠统碎屑岩对于系统认识剥蚀序列及岩浆演化的变化特征具有重要的意义。【方法】为进一步明确早三叠世的侵蚀变化，以威宁地区下三叠统飞仙关组碎屑沉积岩为研究对象，通过碎屑岩的岩相学、地球化学和碎屑锆石U-Pb年代学及微量元素开展了详细的物源分析，探讨了峨眉山大火成岩省的风化侵蚀和晚期的岩浆过程。【结果】飞仙关组碎屑岩主要由石英、长石、方解石、火山岩屑和黏土矿物组成。火山岩屑结构反映其源岩为玄武质和长英质的火山岩。粉砂岩中具有较高的ICV值，反映了威宁地区飞仙关组碎屑岩来源于第一次循环碎屑。粉砂岩中含有较高的Fe_2O_3和MgO，Al_2O_3/TiO_2值略高于峨眉山高Ti玄武岩，暗示了峨眉山高Ti玄武岩为主要源岩。碎屑锆石U-Pb年龄分布以~260 Ma的主要年龄组和>300 Ma的次要年龄组为特征，与右江盆地及其周缘晚二叠世碎屑沉积物的碎屑锆石U-Pb年龄组成一致，均指示峨眉山大火成岩省为主要碎屑沉积物源区。与下伏的上二叠统龙潭组相比，威宁地区下三叠统飞仙关组具有更多>300 Ma 的老锆石，且该组~260 Ma的锆石颗粒具有更高的Th/Nb值和U/Yb值，它们在垂向上表现为系统的变化。【结论】在右江盆地与峨眉山大火成岩省构成的源—汇沉积系统中，早三叠世和晚二叠世碎屑沉积物的锆石地球化学特征很可能代表了剥蚀的火山序列固有特征，共同且连续记录了峨眉山大火成岩省晚期的岩浆活动，即晚期岩浆活动中伴随了逐渐减弱的地壳混染作用。

关键词 贵州；早三叠世；物源分析；峨眉山大火成岩省；岩浆演化

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0 引言

峨眉山大火成岩省广泛分布于华南板块西南缘[1-3]，主要由玄武质熔岩和少量苦橄岩、火山碎屑岩及酸性火山岩组成[1-2,4]，伴生有大量的镁铁质、超镁铁质和长英质侵入岩[5-13]。生物地层学、磁性地层学和同位素年代学限定了峨眉山大火成岩省火山作用的喷发期为255~262 Ma[13-20]。峨眉山大火成岩省在喷发后遭受了强烈的陆表风化剥蚀，并产生了大量的火山碎屑物质[2,14,21-23]，这些碎屑物质被保存于右江盆地及其周缘地区上二叠统—下三叠统印度阶的陆相—海陆交互相(或滨海相)—海相地层中。碎屑锆石年代学研究显示，贵州哲觉[14]、普安[23]和四大寨[22]地区上二叠统碎屑锆石的U-Pb峰值年龄均集中在257~261 Ma，云南会泽地区下三叠统飞仙关组碎屑锆石U-Pb年龄主要为248~272 Ma，其峰值年龄为257 Ma[24]，而贵州贞丰地区下三叠统也报道了大量~260 Ma 的碎屑锆石[25]。它们与峨眉山大火成岩省的喷发期一致。由此可见，右江盆地与峨眉山大火成岩省构成了一个独特的“源—汇”沉积系统[14,21-34]。基于此源—汇沉积系统之间的内在物质联系，晚二叠世—早三叠世印度期的碎屑沉积记录也对认识区域

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沉积古地理演变、峨眉山大火成岩省的剥蚀序列、源—汇沉积系统的搬运—沉积过程和陆表风化作用与古气候之间关系等具有重要意义。

晚二叠世—早三叠世的碎屑沉积物质不仅记录了峨眉山大火成岩省顶部被剥蚀的火山岩岩石类型和组分特征，也揭示了峨眉山大火成岩省晚期火山序列可能存在的岩浆演化趋势。岩相学、全岩地球化学和同位素年代学的研究表明，华南西南地区晚二叠世—早三叠世印度期的碎屑沉积物主要来源于峨眉山大火成岩省高Ti玄武岩的风化剥蚀，有少量酸性火山岩的贡献[14,22-23,25,28,31,35]。晚二叠世碎屑锆石U-Pb年龄、微量元素和Hf同位素的研究表明，峨眉山大火成岩省晚期岩浆演化经历了逐渐衰弱的地壳混染[22-23]。周寅生等[25]在黔西南贞丰地区，利用下三叠统夜郎组上部的碎屑沉积物揭示了更加强烈的地壳混染作用。然而，相对于晚二叠世的风化侵蚀研究，早三叠世的相关研究还不深入，特别是缺少早三叠世印度早期的研究，使得该时期剥蚀的火山序列组成及其记录的岩浆演化的变化特征仍不清楚。

本文对贵州威宁地区下三叠统飞仙关组开展了系统而详细的沉积物源分析，通过对比分析同一源—汇沉积系统晚二叠世和早三叠世沉积物的全岩地球化学、碎屑锆石年代学及微量元素数据，揭示了峨眉山大火成岩省在晚二叠世—早三叠世连续剥蚀的火山序列，探讨其可能的岩浆演化趋势。

1 区域地质概况

中元古代，扬子地块与华夏地块碰撞拼贴形成了华南板块[36-37]。泥盆纪，在拉张裂陷作用下，华南板块的西南地区形成了具有明显沉积分异的裂谷盆地，即右江盆地[38]。早石炭世—早三叠世，该盆地转换为被动大陆边缘，并在中三叠世形成前陆盆地[39]。晚古生代，华南西南缘呈现北西高、南东低的古地貌，右江盆地及其周缘的晚古生代沉积物主要由碎屑岩、硅质岩和碳酸盐岩组成[21]。中—晚二叠世之交，峨眉山大火成岩省喷出事件与全球大规模海退事件[14,40]改变了早、中二叠世华南西南缘均为海域的单一古地理格局。晚二叠世—早三叠世印度期，峨眉山大火成岩省遭受大量的风化和剥蚀，为右江盆地及其周缘提供了大量火山碎屑物质，分别沉积保存在上二叠统的陆相宣威组、海陆交互相龙潭组、海相晒瓦组和领薅组[14,21-23,30,33]及下三叠统陆相青天堡组和台地相夜郎组中[25,31]。早三叠世巢湖期，华南进入了稳定的海相碳酸盐岩沉积阶段[41]，弧相关/造山带型火山碎屑岩的出现[27,42-44]也意味着晚二叠世—早三叠世印度期的源—汇沉积系统的落幕。

贵州西南部地区位于右江盆地及其北西缘，毗邻峨眉山大火成岩省，出露古生代和中生代地层，其中以二叠系和三叠系分布最为广泛。根据沉积相的不同，下三叠统由北西至南东可划分为东川组、飞仙关组、夜郎组、大冶组、罗楼组和乐康组，分别代表了陆相、海陆交互相、局限台地相、开阔台地相、台地边缘—斜坡相和深水盆地相的沉积，向南东具有灰岩逐渐增多和碎屑岩逐渐减少的分布特征[45]。本次取样钻孔位于贵州省威宁县新发乡(图1a)，取样地层为下三叠统飞仙关组，为一套紫红色、灰绿色粉砂岩、细砂岩、钙质粉砂岩和泥岩的沉积，中上部偶夹鲕粒灰岩和泥晶灰岩。发育水平层理、小型交错层理、透镜状层理、脉状层理和双黏土层等沉积构造，受潮汐作用影响明显(图2a，b)。

2 样品采集和分析方法

在威宁县新发乡钻孔J806的飞仙关组粉砂岩和细砂岩中共采集5件碎屑锆石样品，其中飞仙关组下部2件(J806-2g和J806-3g)、中部1件(J806-4g)、上部2件(J806-5g和J806-6g)。在飞仙关组中共采集9件粉砂岩的全岩地球化学样品(图1b)。

采集的9件粉砂岩样品均在澳实分析检测(广州)有限公司完成。样品采用PREP-31法进行样品细粉碎(<200目)，随后采用ME-XRF26方法，试样中加入含硝酸锂的硼酸锂—硝酸锂熔融助熔剂，充分混合后高温熔融，熔融物倒入铂金模子形成扁平玻璃片后，再利用X射线荧光光谱仪(PW2424)分析主量元素含量。微量元素采用ME-MS61r方法，试样用高氯酸、硝酸、氢氟酸和盐酸消解后，用稀盐酸定容，再利用电感耦合等离子发射光谱(Agilent 5110)进行分析，若Bi/Hg/Mo/Ag/W较高，需要做相应稀释，再利用电感耦合等离子质谱(Agilent 7900)分析。稀土元素采用ME-MS81方法，往试样中加入硼酸锂熔剂，混合均匀后在1 025 ℃下熔融，待熔融液冷却后用硝酸、盐酸和氢氟酸消解并定容，然后利用电感耦合等离子质谱(Agilent 7900)分析。

采集的5件粉砂岩和细砂岩样品利用淘洗和重

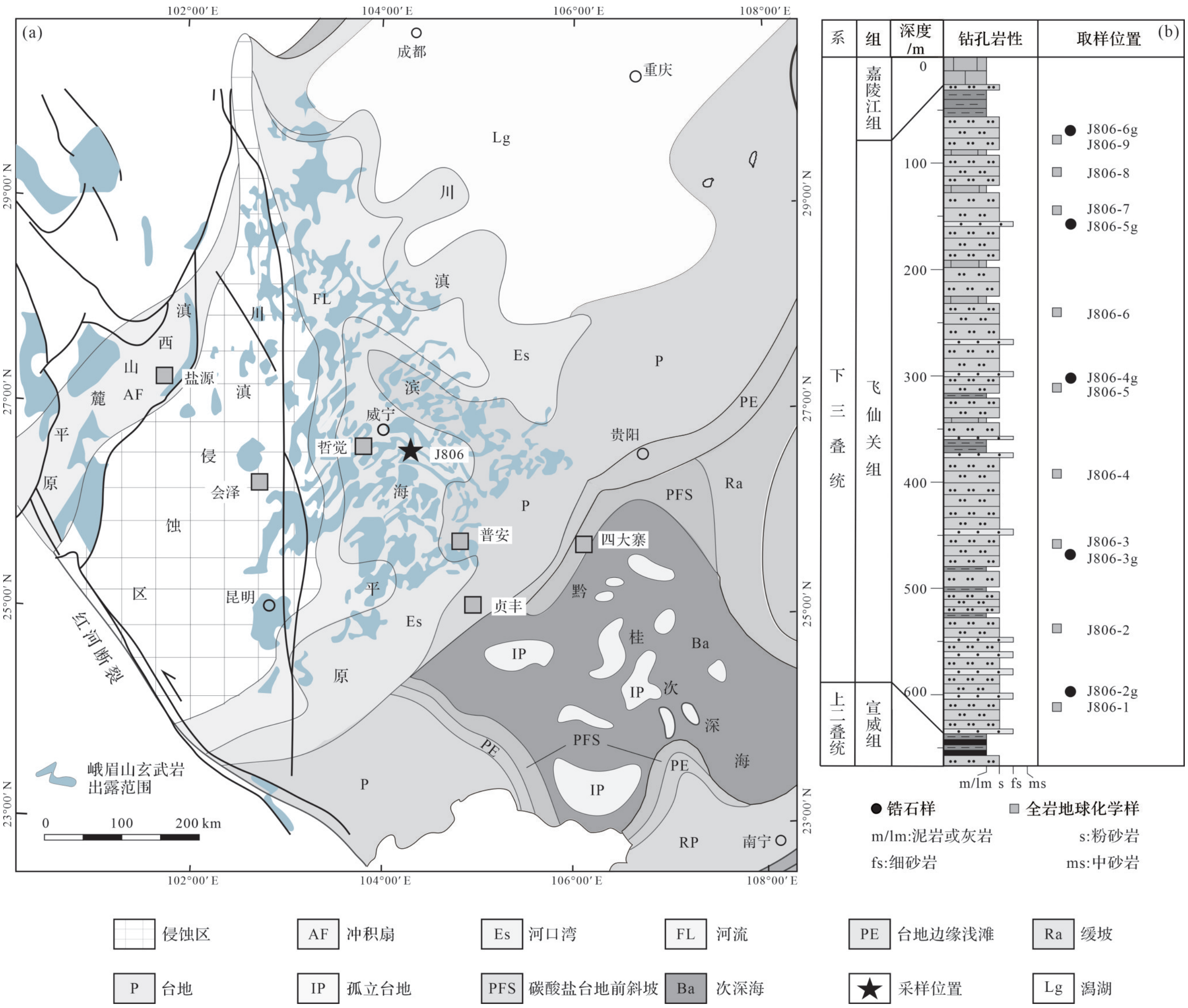

图1　(a)峨眉山玄武岩分布范围及华南西南部早三叠世印度期古地理图[3,41]；(b)钻孔岩心取样柱状图

Fig.1　(a) Schematic of the distribution of the Emeishan basalt and Early Triassic Induan paleogeographic map of South China[3,41]; (b) stratigraphy of sampled section

液分选矿物，在双目镜下挑选碎屑锆石颗粒。碎屑锆石颗粒经制靶和抛光后，使用阴极发光观察以明确其内部结构特征，指导测试点位置的选择。锆石U-Pb同位素测年及微量元素含量测定在武汉上谱分析科技有限责任公司利用激光剥蚀等离子体质谱仪(LA-ICP-MS)分析完成。激光剥蚀系统由COMPexPro102 Arf 193 nm准分子激光器和MicroLas光学系统组成，ICP-MS型号为Agilent 7900，束斑直径32 μm。激光剥蚀过程中采用氦气作载气、氩气为补偿气以调节灵敏度。U-Pb同位素年龄和微量元素含量处理中采用锆石标准91500和玻璃标准物质NIST610作为外标分别进行同位素和微量元素分馏校正。每个时间分辨分析数据包括大约20~30 s的空白信号和50 s的样品信号。对分析数据的离线处理采用软件ICPMS DataCal完成。更加详细的仪器操作条件和数据处理方法参见Liu *et al.*[46]。锆石样品的U-Pb年龄谐和图绘制和加权平均年龄计算均采用Isoplot/Ex_ver 3[47]完成。在获得的U-Pb年龄数据中，小于1 000 Ma的锆石年龄按照$^{206}Pb/^{238}U$比值计算，而大于1 000 Ma的锆石年龄按照$^{207}Pb/^{206}Pb$比值计算。

3　分析结果

3.1　砂岩的岩相学

显微镜下鉴定显示，本次采集的贵州威宁地区

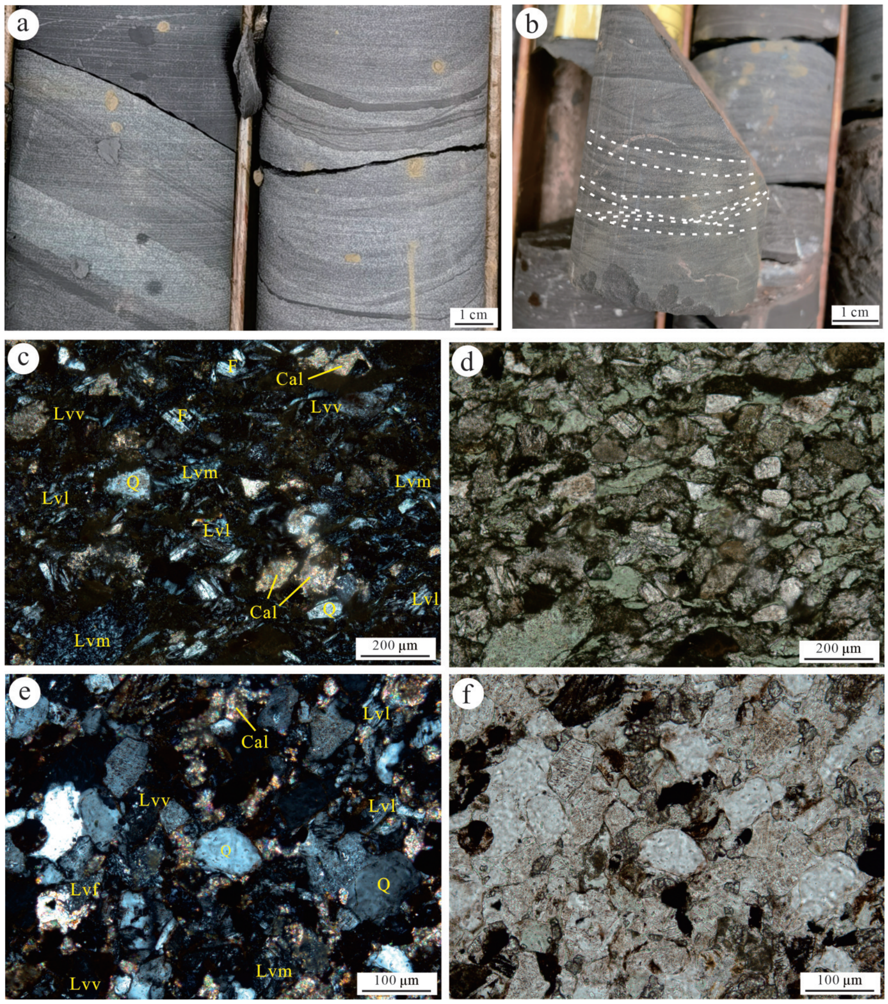

图2 威宁地区下三叠统飞仙关组岩心和砂岩显微照片

(a,b)飞仙关组岩心照片;(c,e)飞仙关组J806-2g和J806-5g显微照片,正交偏光;(d,f)飞仙关组J806-2g和J806-5g显微照片,单偏光;Q.石英;F.长石;Cal.方解石;Lvl、Lvm、Lvf和Lvv分别为板条状、微晶质、长英质和玻璃质结构的火山岩屑

Fig.2 Representative photographs of sedimentary structures and microphotographs of sandstones in the Lower Triassic Feixianguan Formation, Weining area

(a,b) photographs of the Feixianguan Formation from drill core; (c,e) microphotographs of sample J806-2g and J806-5g, in cross-polarized light (XPL); (d,f) microphotographs of sample J806-2g and J806-5g, in plane-polarized light (PPL); Q. quartz; F. feldspar; Cal. calcite; the Lvl., Lvm., Lvf., and Lvv. represent the vacanic rock fragments of lath-work, microlitic, felsic and vitric textures

下三叠统飞仙关组样品为岩屑粉砂岩和岩屑细砂岩,主要由石英、长石、方解石、火山岩屑和黏土矿物组成(图2c~f)。火山岩屑为棱角状—次圆状,大小通常小于0.1 mm,按结构可将其分为板条状、微晶状和霏细晶状、玻璃质,它们分别指示基性和酸性火山源岩[48-50]。其中板条状和微晶状岩屑较多,霏细晶和玻璃质岩屑较少。石英和长石颗粒分别以次棱角状—次圆状和棱角状—次棱角状为主,大小为0.05~0.25 mm。单晶石英内部可见矿物或者流体包裹体。在飞仙关组沉积序列上,石英含量由下至上有略微增多的趋势。长石以斜长石为主,呈长条状或板条状,发育聚片双晶。

3.2 砂岩全岩地球化学

威宁地区下三叠统飞仙关组9件粉砂岩样品具有较低的SiO_2含量(48.14%~51.39%),而TiO_2、Fe_2O_3和MgO的含量较高,其中TiO_2含量介于2.34%~3.20%,Fe_2O_3介于11.45%~15.48%,MgO介于3.62%~6.83%。Na_2O和K_2O含量分别介于0.89%~4.52%和2.02%~3.38%(表1)。粉砂岩样品中的Al_2O_3含量稳定(14.12%~14.96%),Al_2O_3/TiO_2值变化范围窄,集中在4.43~6.11(图3),明显低于平均后太古代页岩(18.9)[61]和平均大陆上地壳(30.4)[62]。

表1 威宁地区下三叠统飞仙关组粉砂岩主量元素含量(%)

Table1 Major elemental contents (%) for the siltstones of the Lower Triassic Feixianguan Formation at Weining area

样品编号	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	MnO	P_2O_5	LOI	ICV
J806-1	51.39	14.43	13.26	2.40	5.78	0.89	2.02	3.15	0.17	0.42	6.17	1.92
J806-2	48.14	14.16	13.87	4.01	5.55	4.52	2.03	3.20	0.17	0.44	3.63	2.36
J806-3	48.27	14.12	15.48	4.03	3.62	4.06	2.57	2.92	0.15	0.43	3.42	2.33
J806-4	50.56	14.58	12.63	3.75	4.73	3.65	2.99	2.62	0.16	0.41	3.90	2.09
J806-5	49.30	14.96	13.12	3.94	4.83	3.09	2.94	2.88	0.14	0.41	4.35	2.07
J806-6	49.92	14.90	11.45	3.84	6.19	2.79	3.38	2.87	0.18	0.47	4.22	2.06
J806-7	49.51	14.13	12.18	3.82	6.83	2.85	2.81	2.51	0.16	0.45	4.55	2.21
J806-8	49.48	14.30	12.44	4.04	6.58	2.44	2.92	2.34	0.15	0.40	5.20	2.16
J806-9	50.09	14.65	12.48	3.43	6.06	2.33	2.87	2.47	0.13	0.42	4.74	2.03

注:$ICV=w(Fe_2O_3+K_2O+Na_2O+CaO+MgO+MnO+TiO_2)/ w(Al_2O_3)$[51]。

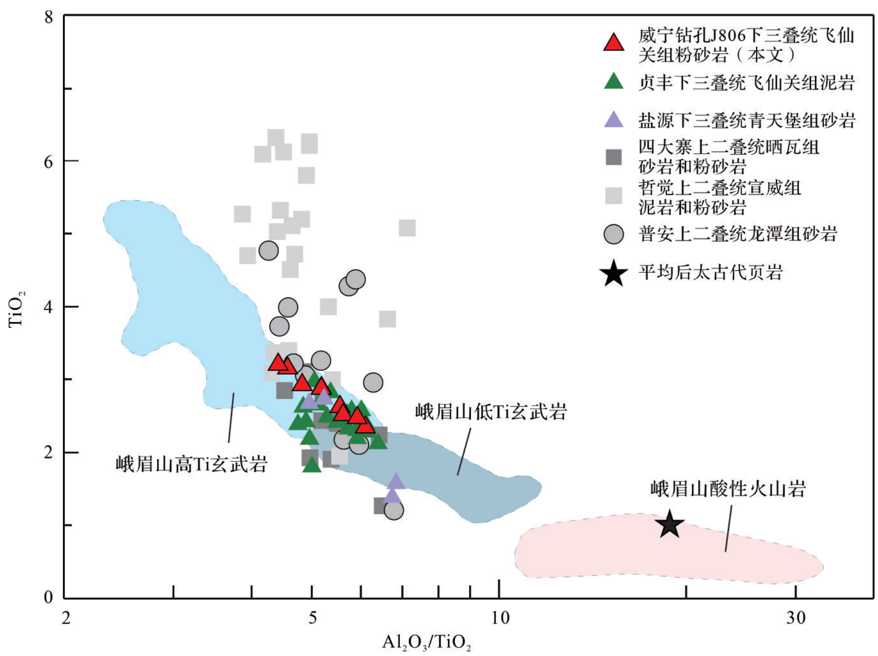

图3 威宁地区下三叠统飞仙关组粉砂岩 Al_2O_3/TiO_2-TiO_2 图解

数据来源:贞丰下三叠统飞仙关组泥岩[25];盐源下三叠统青天堡组砂岩[31];普安上二叠统龙潭组砂岩[23];四大寨上二叠统晒瓦组砂岩和粉砂岩[22];哲觉上二叠统宣威组泥岩和粉砂岩[14];峨眉山高Ti玄武岩[2,52-57];峨眉山低Ti玄武岩[2,52,54];峨眉山酸性火山岩[4,11,58-60];平均后太古代页岩[61]

Fig.3 Al_2O_3/TiO_2 vs. TiO_2 plot for the siltstones of the Feixianguan Formation at Weining area

Data sources: the mudstones from the Yelang Formation in Zhenfeng drill core[25]; the sandstones from the Tianqingbao Formation in Yanyuan[31]; the sandstones from the Longtan Formation in the Pu'an drill core[23]; the sandstones and siltstones from the Shaiwa Formation in the Sidazhai[22]; the mudstones and siltstones from the Xuanwei Formation in Zhejiao[14]; the high-Ti basalts[2,52-57], low-Ti basalts[2,52,54] and silicic volcanic rocks[4,11,58-60] in the Emeishan large igneous province; the average post-Archean shale[61]

3.3 碎屑锆石U-Pb年龄及微量元素

飞仙关组碎屑锆石多为无色或淡黄色,磨圆度差,呈棱角状—次棱角状,在CL图像上大部分锆石颗粒显示出振荡环带(图4),个别颗粒整体较亮,内部成分显示均一。在5件样品的388个分析点中,有6个分析点的Th/U值小于0.1,45个分析点的Th/U值介于0.11~0.39,2个点的Th/U值分别为13.82和41.68,其余分析点的Th/U值均介于0.40~3.52。大部分锆石颗粒表现为岩浆锆石的形态结构[63]和Th/U值特征[64-65]。

对388个锆石颗粒进行LA-ICP-MS分析,获得388个U-Pb年龄数据,其中358年龄数据谐和度≥90%(图5)。飞仙关组的5件样品均具有相对一致的碎屑锆石U-Pb年龄分布,主要年龄组介于280~238 Ma,其峰值年龄在256.5±1.9 Ma~251.3±1.8 Ma之间变化(图6)。除飞仙关组顶部1件样品具有571±

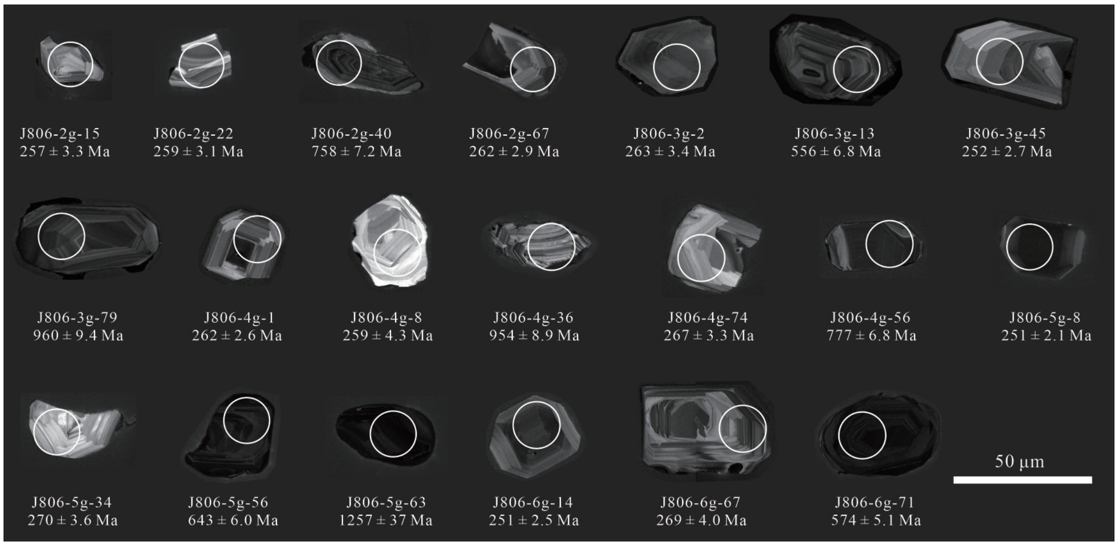

图4 威宁地区下三叠统飞仙关组砂岩中碎屑锆石阴极发光图像

Fig.4 Cathodoluminescence images of detrital zircons from the Lower Triassic Feixianguan Formation at Weining area

26 Ma和954±14 Ma的次要峰值年龄外，其余锆石颗粒的年龄均零散分布在频率直方图上，介于153~238 Ma和458~2 762 Ma。

威宁地区下三叠统飞仙关组5件样品的锆石微量元素变化范围均较宽，在获得较高谐和率的锆石颗粒中，大部分~260 Ma锆石都具有高Th/Nb(>10)和U/Yb值(>0.5)。在飞仙关组下部、中部和上部样品中，~260 Ma锆石颗粒的Th/Nb和U/Yb值分别为3.42~219.15和0.10~2.43、9.03~169.14和0.31~1.68、11.14~752.40和0.19~1.39。在飞仙关组地层序列上，由下至上Th/Nb和U/Yb值具有逐渐升高的趋势。而年龄>300 Ma的锆石颗粒整体上则具有更高的Th/Nb和U/Yb值。

4 讨论

4.1 飞仙关组的物源分析

贵州威宁地区下三叠统飞仙关组砂岩主要由石英、长石和岩屑组成，大部分岩屑、石英和副矿物(如锆石)磨圆度一般，为次棱角状—次圆状，表现出一定距离的搬运特征。火山岩岩屑结构对于识别源岩类型具有指示意义。飞仙关组砂岩中的火山岩屑以板条状和微晶状为主，它们与黔西南地区上二叠统龙潭组[23]和晒瓦组[22]砂岩中火山岩屑具有相似的结构组成，说明了其源岩主要为玄武质的火山岩，含少量长英质火山岩[48-50]。

年轻沉积物与古老沉积物中氧化物含量具有差异性，Cox *et al.*[51]认为成分变异指数(ICV)可用于反映泥岩的成分成熟度。岩石ICV值与黏土矿物的含量和第一次循环碎屑的输入量相关，第一次循环碎屑输入量较高的岩石，其黏土矿物含量较低，岩石ICV值一般大于1，其物质来源多为火成岩。而黏土矿物含量较高的岩石多形成于稳定区域，其物质来源很可能经历过多次风化—沉积成岩的过程。飞仙关组粉砂岩均具有较高的ICV值(1.92~2.36，表1)，说明威宁地区飞仙关组碎屑岩来源于第一次循环碎屑，而非稳定区域的再循环碎屑。

威宁地区下三叠统飞仙关组粉砂岩中含有较高的Fe_2O_3和MgO，表明其源岩可能为富Fe和Mg的基性火成岩。在火成岩中，Al大部分赋存于长石中，而Ti则赋存于镁铁质矿物中。因此，火成岩中的Al/Ti比值通常会随SiO_2含量的增加而增加。镁铁质火山岩、中性火山岩、酸性火山岩的Al_2O_3/TiO_2比值分别介于3~8、8~21和21~70[66]。此外，在风化、搬运、沉积和成岩过程中，源岩中的Al_2O_3/TiO_2比值不会受到明显的改变。因此，沉积岩中的Al_2O_3/TiO_2比值可以作为示踪的指标[14,66]。威宁地区下三叠统飞仙关组粉砂岩样品的Al_2O_3/TiO_2值略高于峨眉山高Ti玄武岩[2,52-57]，而与峨眉山低Ti玄武岩相比[2,52,54]，则具有更低的Al_2O_3/TiO_2值，远低于峨眉山酸性火山岩[4,11,58-60]和后太古代页岩(18.9)[61]。它们也与贵州哲觉[14]、普安[23]、四大寨[22]上二叠统和四川盐源[31]、贵州贞丰[25]下三叠统的碎屑沉积物具有相似的Al_2O_3/TiO_2值范围(图3)。在峨眉山大火成岩省的火山序列中，绝大部

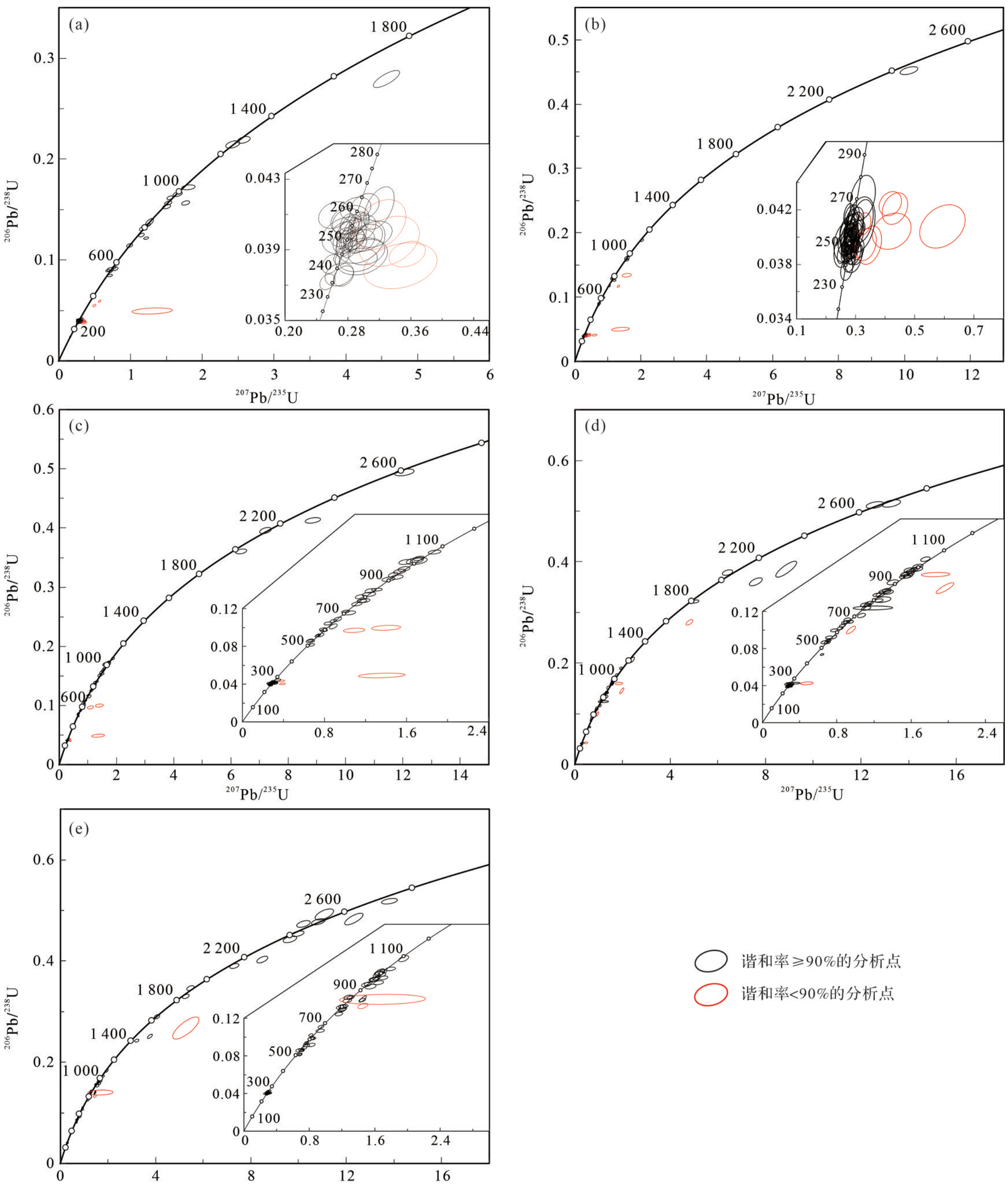

图5　威宁地区下三叠统飞仙关组碎屑锆石U-Pb年龄谐和图

(a)J806-2g,*n*=68;(b)J806-3g,*n*=80;(c)J806-4g,*n*=80;(d)J806-5g,*n*=80;(e)J806-6g,*n*=80

Fig.5　Concordant diagram of detrital zircon U-Pb ages from sandstone in the Lower Triassic Feixianguan Formation at Weining area

分地区的高Ti玄武岩都覆盖在低Ti玄武岩之上[2],低Ti玄武岩不可能作为源岩。而在金平地区,低Ti玄武岩直接暴露地表被认为是晚白垩世—早古近纪的构造破坏所致[67]。此外,低Ti玄武岩中通常具有较多的斜辉石[2],而本次研究的样品中并未发现该矿物。由此可见,威宁地区下三叠统的碎屑岩很可能也主要来源于峨眉山高Ti玄武岩的风化剥蚀。

贵州威宁地区下三叠统飞仙关组砂岩中锆石具有较为统一的U-Pb峰值年龄,与峨眉山大火成岩省的主要喷发时限相一致(~260 Ma)[13-20]。在锆石微量元素的Th/Nb-Hf/Th与U/Yb-Nb/Yb图解中[22,68],这些~260 Ma碎屑锆石颗粒大部分位于或靠近板内/非造山构造背景中,与洋岛型的锆石颗粒更具地球化学亲和性(图7)。这也进一步反映了这些碎屑物质的

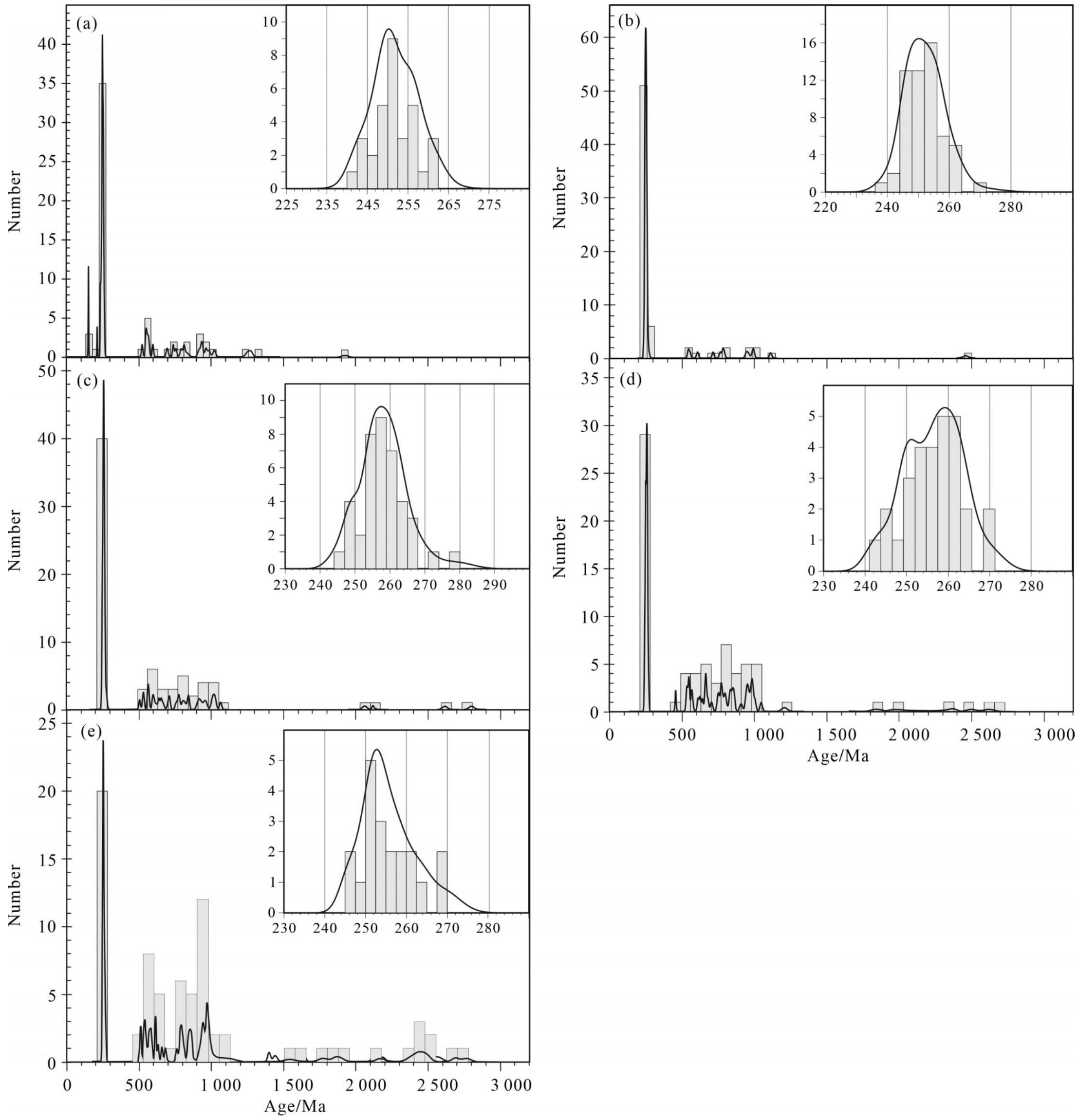

图6 威宁地区下三叠统飞仙关组砂岩中碎屑锆石的U-Pb年龄频率直方图

(a)J806-2g (n=32/61);251.3±1.8 Ma;MSWD=3.7;(b)J806-3g (n=57/70);251.5±1.4 Ma;MSWD=3.0;(c)J806-4g (n=40/75);256.5±1.9 Ma;MSWD=4.8;(d)J806-5g (n=29/75);255.7±2.5 Ma;MSWD=5.5;(e)J806-6g (n=20/77);254.4±2.7 Ma;MSWD=4.2

Fig.6 Frequency distribution of detrital zircon U-Pb ages from sandstone in the Lower Triassic Feixianguan Formation at Weining area

主要源区为峨眉山大火成岩省。而部分~260 Ma碎屑锆石颗粒投在弧相关/造山带和大陆弧区域内,与那些大于300 Ma的锆石相比,它们更靠近板内/非造山和地幔锆石矩阵。这很可能是地壳物质的混染导致峨眉山幔源岩浆具有一些陆壳的地球化学特征[70]。华南与印支地块之间的火成岩也具有相似的年龄(~248~300 Ma)[71-72]。然而,这些岛弧物质的输入将导致全岩地球化学组分的变化,与威宁地区飞仙关组全岩地球化学特征不符。综上分析,威宁地区下三叠统飞仙关组碎屑物质主要来源于峨眉山大火成岩省的风化剥蚀。这与前人关于扬子西南缘的早三叠世碎屑沉积物物质来源的认识相一致[24-25,31]。

除了~260 Ma碎屑锆石外,威宁地区飞仙关组砂岩中还含有较多U-Pb年龄>300 Ma的老锆石。它们与滇黔桂地区基底的锆石U-Pb年龄谱(~430 Ma、~520 Ma、~770 Ma、~860 Ma、~960 Ma、~1 100 Ma、~2 500 Ma等七组峰值年龄)具有较高的相似性[73]。然而,再循环沉积物或前寒武系的基底物质将产生高Al_2O_3/TiO_2值、低ICV值的碎屑物质和少量沉积/变质岩屑。飞仙关组样品中未发现有变质岩屑,且具

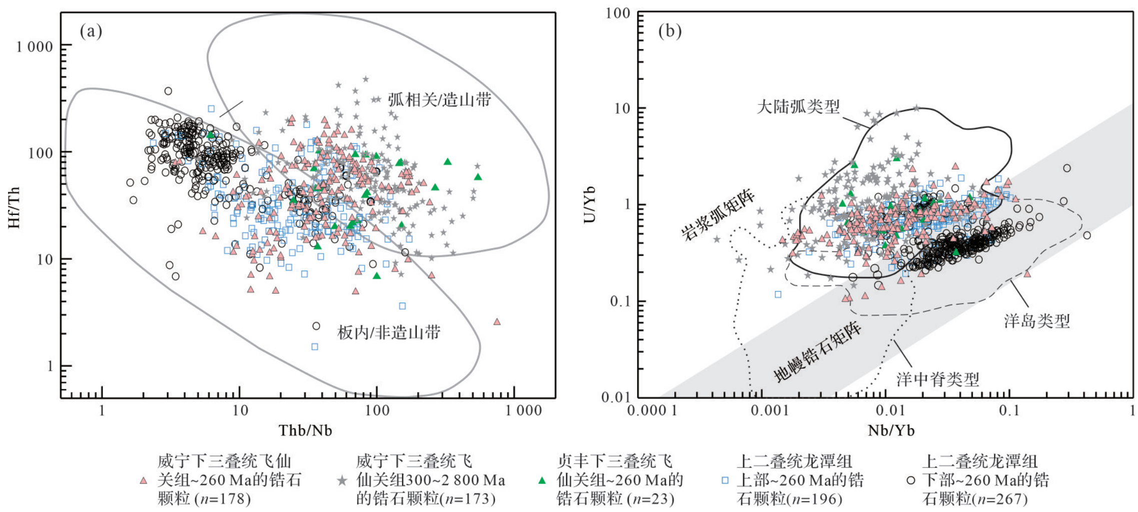

图7　威宁地区下三叠统碎屑锆石Th/Nb-Hf/Th与Nb/Yb-U/Yb图解(底图据文献[22,69])

数据来源:贞丰地区下三叠统夜郎组锆石[25];普安地区上二叠统龙潭组锆石[23])

Fig.7　Th/Nb vs. Hf/Th and Nb/Yb vs. U/Yb diagrams for detrital zircons from the Lower Triassic Feixianguan Formation at Weining area (base map from references [22,69])

Data sources: zircons from the Lower Triassic Yelang Formation at Zhenfeng[25]; zircons from the upper Permian Longtan Formation at Pu'an[23]

有低Al_2O_3/TiO_2值和较高ICV值的特征,而大量再循环物质的加入将导致全岩组分的明显变化。飞仙关组碎屑岩中的石英含量及老锆石的占比由下至上具有增多的趋势,考虑到这些石英颗粒圆度与再循环碎屑有所差异,且在晚二叠世的宣威组和龙潭组等砂岩中也观察到棱角状的石英颗粒,这些沉积物基本不含有>300 Ma的老锆石[22-23,33],很可能不是来源于再旋回沉积物。因此,再循环碎屑不太可能作为老锆石主要物质来源。更为重要的是,峨眉山高Ti玄武岩之下仍有低Ti玄武岩,而华南西南缘在早—中二叠世未缺失碳酸盐岩沉积[41],峨眉山大火成岩省在早三叠世的剥蚀不可能下切至基底。而川滇侵蚀区以西的区域则逐渐过渡为海相沉积,在晚二叠世—早三叠世不可能为研究区及其周缘提供基底的碎屑物质来源,且飞仙关组中石英颗粒的圆度也未表现出长距离搬运的特征。此外,华南板块东南缘的同期沉积岩中可见大量石英,含少量火山岩屑,甚至不含火山岩屑,且具有多组峰值的碎屑锆石年龄谱[74]。北西高和南东低的岩相古地理格局进一步说明了华南东南缘不可能成为威宁地区的下三叠统沉积物提供碎屑物质输入。事实上,前人在峨眉山大火成岩省的侵入岩和喷出岩中报道过很多年龄>300 Ma的锆石[75-78]。综合考虑上述几个方面,认为飞仙关组中的老锆石很可能来源于峨眉山大火成岩省岩浆的捕获晶或围岩。这与相同源—汇沉积系统中老锆石来源的认识相一致[22-23,25],符合构造背景判别图中部分~260 Ma锆石颗粒偏移的解释。

4.2　对峨眉山大火成岩省剥蚀序列的响应

前人研究显示,在右江盆地北西缘的晚二叠世海陆交互相和海相碎屑沉积物岩石学和地球化学特征在沉积序列上无明显的差异,而碎屑锆石U-Pb年龄及微量元素在沉积序列上则具有明显的变化特征。晚二叠世下部沉积序列中,~260 Ma的锆石颗粒具有较低的U/Yb(大部分小于0.5)和Th/Nb(大部分小于10)值,几乎不含老锆石(>300 Ma)。而上部序列的锆石颗粒具有更高的U/Yb(大部分大于0.5)和Th/Nb(大部分大于10)值,老锆石逐渐增多[22-23]。与上二叠统碎屑锆石相比,在本文研究的早三叠世印度期沉积序列中,~260 Ma锆石颗粒具有更高的Th/Nb值、U/Yb值和老锆石比重,在垂向序列上表现为系统的变化趋势(图8)。考虑到这些~260 Ma的锆石主要来源于峨眉山大火成岩省顶部火山序列的剥蚀,它们与下二叠统的碎屑锆石地球化学变化特征很可能代表了右江盆地与峨眉山大火成岩省构成的源—汇沉积系统中碎屑沉积物的一种固有特征,即剥蚀的火山序列特征。

岩浆锆石Th/Nb和U/Yb值对母岩浆化学组成和演化具有一定的指示作用,如幔源岩浆的锆石具有低的Th/Nb和U/Yb值,而地壳物质的输入则会使岩浆锆石具有更高的Th/Nb和U/Yb值[68-69,79]。普安地区

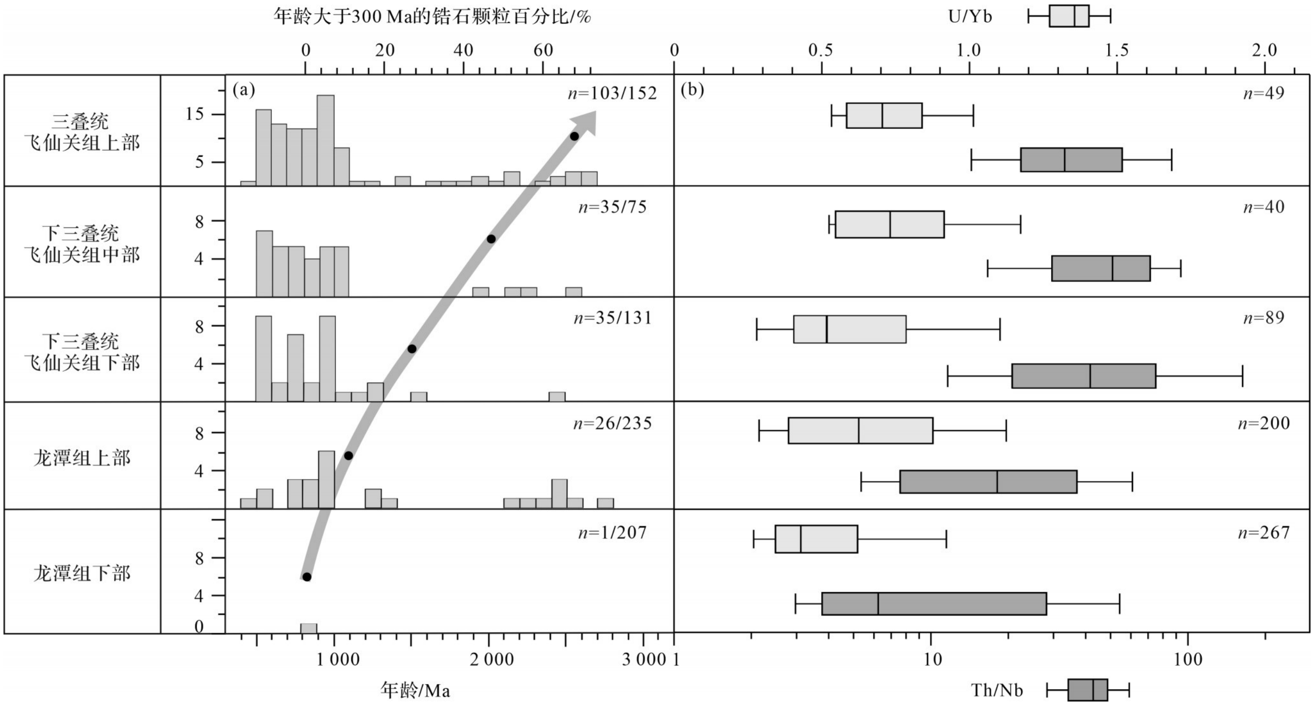

图8 右江盆地北西缘上二叠统龙潭组—下三叠世飞仙关组碎屑锆石地球化学特征变化图

(a)>300 Ma碎屑锆石年龄分布图;(b)~260 Ma碎屑锆石微量元素箱状图;箭头线为>300 Ma碎屑锆石所占百分比变化趋势线;箱状图的左右边界分别为25%和75%,其中黑线代表中位值;龙潭组数据来源于Deng *et al.*[23]

Fig.8 Geochemical characteristics of detrital zircons from the Lower Triassic Feixianguan Formation and the Upper Permian Longtan Formation in northwestern Youjiang Basin

(a) U-Pb age distributions for detrital zircon with ages of >300 Ma; (b) box plots of Th/Nb and U/Yb ratios for the ~260 Ma zircons; arrow is the percentages of the detrital zircon with ages of >300 Ma in all detrital zircons; left and right boundaries of the boxes are set at 25% and 75%; black lines in the box represent the median values; zircon U-Pb ages and trace element data for the Late Permian Longtan Formation are from Deng *et al.*[23]

龙潭组中锆石地球化学和Hf同位素的研究显示,副矿物的分异、锆石在熔体中的分异系数和岩浆的温度及氧化状态等因素对锆石中Th/Nb和U/Yb值未产生明显的影响。因此,锆石微量元素中的Th/Nb、U/Yb值可用来揭示锆石结晶期间峨眉山晚期岩浆活动[80]。右江盆地北西缘的晚二叠世碎屑沉积物揭示了峨眉山大火成岩省晚期岩浆活动过程中伴随地壳混染作用的不断减弱[22-23]。在沉积序列上,威宁地区下三叠统飞仙关组中锆石Th/Nb值和U/Yb值均表现出由下至上逐渐变大的趋势,且大部分锆石具有Th/Nb值大于10和U/Yb值大于0.5的特征,反映了峨眉山大火成岩省晚期的早期阶段经历了更为强烈且逐渐减弱的地壳混染作用。来源于峨眉山大火成岩省岩浆的捕获晶或围岩的老锆石颗粒(>300 Ma),在沉积序列上也具有其比重逐渐增多的趋势,进一步支持上述认识。右江盆地北西缘早三叠世和晚二叠世碎屑的沉积物共同且连续地记录了峨眉山大火成岩省顶部剥蚀火山序列所经历的岩浆活动。

5 结论

(1) 威宁地区下三叠统飞仙关组的碎屑沉积物主要来源于峨眉山大火成岩省高Ti玄武岩的风化剥蚀,酸性火山岩可能有少量贡献。

(2) 威宁地区下三叠统飞仙关组具有更多>300 Ma的岩浆捕获锆石,其中~260 Ma的锆石颗粒具有更高Th/Nb值和U/Yb值。在右江盆地与峨眉山大火成岩省构成的源—汇沉积系统中,早三叠世和晚二叠世碎屑沉积物的锆石地球化学特征在垂向序列上具有系统的变化趋势,很可能代表了剥蚀的火山序列固有特征。

(3) 威宁地区早三叠世印度期的碎屑沉积物与右江盆地北西缘的晚二叠世碎屑沉积物共同且连续记录了峨眉山大火成岩省晚期的岩浆活动,即晚期岩浆活动在分异结晶作用下,伴随了逐渐减弱的地壳混染作用。

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Response of the Lower Triassic Clastic Rocks in Northwestern Guizhou to the Emeishan Large Igneous Province

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Abstract: [**Objective**] The Emeishan large igneous province (ELIP), located in southwest China, experienced extensive post-eruption erosion resulting in the accumulation of voluminous volcanic detritus in the adjacent Youjiang Basin during the Late Permian to Early Triassic. These clastic sediments not only record the types and composition characteristics of the denuded volcanic rocks at the top of the ELIP, but also reveal the possible magmatic evolution trend of the denuded volcanic sequence in the ELIP. Therefore, the Lower Triassic clastic rocks in northwest Guizhou are of great significance for the systematic understanding of the denudation sequence and magmatic evolution. [**Methods**] To further clarify the Early Triassic erosion evolution, we analyzed the provenance of the Lower Triassic Feixianguan Formation in the Weining area, southwestern Guizhou province, and discussed the erosion and magmatic process in the late stage of the ELIP. [**Results**] The mudstones of the Feixianguan Formation are composed of quartz, feldspar, calcite, volcanic lithic fragments, and clay minerals. The structures of volcanic lithic fragments indicate a basaltic and felsic volcanic source. The mudstones have high ICV (the Index of Compositional Variability) values, which reflects that the clastic rocks of the Fexianguan Formation in Weining area are derived from the first cyclic clastic rocks. The mudstone, which of Al_2O_3/TiO_2 ratio are slightly higher than the high-Ti basalt of the ELIP, is characterized by high Fe_2O_3 and MgO contents. It indicates a dominant source from the Emeishan high-Ti basalt. Detrital zircons from the Fexianguan Formation have an age peak of ca. 260 Ma, which support the ELIP as the main provenance. This is consistent with the provenance of the Late Permian clastic sediments in the Youjiang Basin. Compared with the underlying Longtan Formation in the Upper Permian, the Lower Triassic Fexianguan Formation in Weining area, of which ~260 Ma zircons have higher Th/Nb and U/Yb ratios, have more zircons with ages of >300 Ma. Such features show a systematic variation in sedimentary sequence. [**Conclusions**] In the source-sink sedimentary system composed of the Youjiang Basin and ELIP, the zircon geochemical characteristics of detrital sediments preserved in the Late Permian and Early Triassic Induan likely represent the inherent characteristics of the denuded volcanic sequence. Such zircon geochemical characteristics reflect a magmatic evolution process with diminishing crustal assimilation in the late-stage of the ELIP.

Key words: Guizhou; Early Triassic; provenance analysis; Emeishan large igneous province; magma evolution