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湖南嘉禾大窝岭剖面晚二叠世吴家坪期-长兴期之交长英质火山作用记录

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摘 要: 在华南地区,中-晚二叠世之交和二叠纪-三叠纪之交的火山作用已成为地学研究的热点.相比较,地学界对晚二叠世内部的火山活动关注较少,以至对华南地区晚二叠世内部火山作用的喷发特征认识不够.湖南省嘉禾地区大窝岭剖面大隆组中下部,即吴家坪阶-长兴阶界线附近沉积了3层粘土岩,自下而上分别为HD08、HD12和HD20.对这3层粘土岩进行全岩地球化学,锆石U-Pb年代学、微量元素和Lu-Hf同位素测试工作表明,这些粘土岩源自蚀变的火山灰,代表吴家坪阶-长兴阶之交的三期火山作用.全岩和锆石微量元素特征显示火山灰来源于流纹质或流纹英安质火山作用,具有钙碱系列的亲属性,形成于汇聚大陆边缘的后碰撞构造环境.其中,HD08和HD20的$\varepsilon_{Hf}(t)$值为-6.4~7.1,范围变化较大,岩浆源于峨眉山/新元古代新生地壳物质和古老地壳物质的混合;HD12的$\varepsilon_{Hf}(t)$值为-12.0~-3.5,岩浆主要来源于古老地壳物质.这3层火山灰层的发现丰富了华南地区乐平统地层中火山作用的记录,综合前人研究成果,进一步证实了华南地块周边地区在晚二叠世中期发生强烈的、与Pangea超大陆汇聚有关的长英质火山作用.

关键词: 晚二叠世;Pangea超大陆;火山作用;地球化学;锆石微量元素;锆石Lu-Hf同位素.
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Felsic Volcanisms across the Wuchiapingian-Changhsingian Boundary (Late Permian) in the Dawoling Section, Jiahe Area, Hunan Province

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Abstract: The volcanisms of the Guadalupian-Lopingian (also middle-late Permian) and Permian-Triassic boundaries in South China have attracted increasing attentions from geologists. In contrast, less studies concerned the volcanisms between the two. Here, we report geochemical studies on volcanisms near the Wuchiapingian - Changhsingian boundary within the late Permian from the Dawoling section of Jiahe Area, Hunan Province, South China, in which three layers of claystones, named as HD08, HD12 and HD20, are pronounced in the Wuchiapingian-Changhsingian boundary beds that are calibrated to the lower and middle Dalong Formation. The integrated analyses of whole-rock geochemistry, zircon U-Pb chronology, trace elements and Lu-Hf isotopes reveal that these three claystones originated from altered volcanic ashes, representing three episodes volcanism across the Wuchiapingian-Changhsingian boundary. The whole-rock and zircon trace element signatures indicate that the volcanic ashes originated from rhyolitic or rhyodacitic volcanism, with calc-alkaline affinities, and formed in post-collisional tectonic settings in the convergent continental margins. Among them, $\varepsilon_{Hf}(t)$ values of HD08 and HD20 are −6.4 to 7.1, with a wide range of variability, and the magma originates from the mixing of Emeishan/Neoproterozoic neogenic crustal materials of and ancient crustal materials; $\varepsilon_{Hf}(t)$ values of HD12 are −12.0 to −3.5, and the magma mainly originates from ancient crustal materials. These three volcanic ash layers, together with previous researches, further confirm the occurrence of intense felsic volcanisms related to the convergence of the Pangea supercontinent in the areas around the South China block during the middle of the Lopingian (late Permian).

Key words: Lopingian; pangea supercontinent; volcanism; geochemistry; zircon trace elements; zircon Lu-Hf isotopes.

中－晚二叠世之交和二叠纪－三叠纪之交发生了两次引人注目的生物大绝灭事件和两个大火成岩省强烈喷发事件,分别为约260 Ma的峨眉山大火成岩省和约252 Ma的西伯利亚大火成岩省(Renne *et al*., 1995; Xu *et al*., 2004; Yin *et al*., 2007; Shellnutt, 2014; Chen *et al*., 2015; Lai *et al*., 2018; Shen *et al*., 2019a; Davydov, 2021; Zhu *et al*., 2021).与此伴生的酸性火山作用也强烈喷发,且频率密集(Gao *et al*., 2013; Zhao *et al*., 2016, 2019; Huang *et al*., 2018; Pei *et al*., 2019; Wang *et al*., 2019a; Bailie and Leetz, 2021; Liu *et al*., 2021).西伯利亚大火成岩省主要表现为沉积地层中的汞含量和同位素出现特别的异常值(Shen *et al*., 2019a, 2019b; Wang *et al*., 2019b);峨眉山大火成岩省和酸性火山作用主要表现为地层序列中记录明显的火山灰层.其中,火山灰层在生物大灭绝附近地层中特别发育,譬如,二叠纪－三叠纪界线粘土层就是典型的例子,该粘土层源自蚀变的火山灰,与生物大灭绝事件共生,稳定地遍布华南地区各省,成为华南地区二叠纪－三叠纪界线和生物大灭绝最理想的标志层(盛金章等, 1983; Yin *et al*., 2001; Chen *et al*., 2015).研究显示,二叠纪－三叠纪界线附近的火山灰层主要来源于汇聚大陆边缘相关的长英质火山作用(Gao *et al*., 2013; Wang *et al*., 2019a; Zhao *et al*., 2019; Liu *et al*., 2021).中－晚二叠世界线附近的火山灰层的来源有峨眉山大火成岩省相关的镁铁质火山作用,也有汇聚大陆边缘相关的长英质火山作用(Zhong *et al*., 2013; Zhao *et al*., 2016; Huang *et al*., 2018).相比较,很少研究关注晚二叠世最早和最晚两次火山喷发密集期之间的火山作用,因此,晚二叠世内部的火山作用是否也与两次大灭绝时期的火山活动那样强烈尚不得而知.

我们在湖南省嘉禾地区的大窝岭剖面二叠纪大隆组中下部吴家坪阶－长兴阶界线附近地层中发现3层灰白色粘土岩,颜色纯净、组分均一,显示为蚀变的火山灰层.本文对这3层粘土岩开展了全岩地球化学,锆石U-Pb年代学、微量元素及Lu-Hf同位素分析,揭示这些粘土岩来源的火山作用性质和形成的大地构造背景,以及与两次大绝灭事件同期的火山作用的异同之处.

1　区域地质背景与样品采集

研究区位于湖南省郴州市嘉禾县.嘉禾县东部发育有一个SN走向的小向斜,即袁家向斜(图1),乐平统地层主要发育在此向斜的两侧.研究区内乐平统地层从老到新可分为斗岭组、小元冲组和大隆组,斗岭组岩性为深灰色泥岩夹泥质灰岩透镜体;小元冲组岩性主要为黑色、黑褐色硅质泥岩、硅质灰岩和硅质岩;大隆组则主要由硅质岩、硅质灰岩

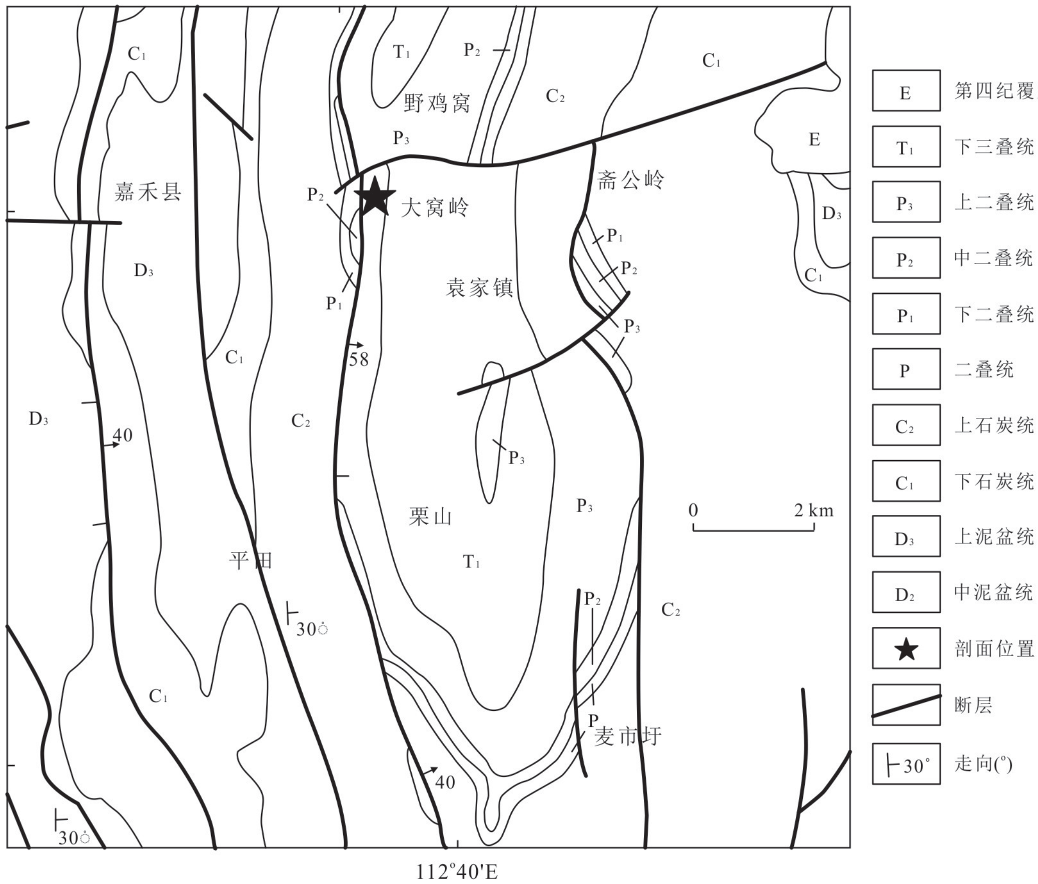

图1　湖南嘉禾大窝岭剖面区域地质

Fig.1　Geological map of the Jiahe aera, Hunan Province, showing the location of the Dawoling section

和页岩等组成（张志沛等，1993）. 大窝岭剖面位于袁家向斜西部的大窝岭村附近，主要出露乐平统大隆组. 剖面描述见叶茜和江海水（2016）.

大隆组下部地层主要为黄褐色—黄色泥岩、灰黑色硅质岩（夹硅质灰岩）、灰白色灰岩互层，发育3层灰白色粘土岩（图2）；上部地层主要为灰褐色—灰黑色灰岩与泥岩互层. 地层中产出*C. wangi*、*C. deflecta*、*C.* sp.3种牙形石，以*C. wangi*的首现，暂将吴家坪阶—长兴阶界线置于第11层的底部（叶茜和江海水，2016；郝少波等，2021；吴奎等，2022）.

3层粘土岩，厚5～7 cm，自下而上分别为HD08、HD12和HD20，颜色、组分均匀，与已报道的蚀变火山灰层特征一致（Gao *et al.*, 2013），推测为火山灰蚀变成因.

2　测试技术与数据处理方法

项目组对3个样品开展了全岩地球化学，锆石U-Pb年代学、微量元素和Lu-Hf同位素分析测试工作. 样品分两部分进行处理. 一部分磨碎至200目，准备进行全岩主量元素和微量元素分析. 另一部分利用重液和重磁分选进行重矿物分离，然后在双目镜下挑选出锆石颗粒. 利用双面胶和环氧树脂将锆石颗粒制成靶圈，然后将靶圈磨平、抛光. 在分析之前，对所有的靶圈在透射光和反射光下拍照. 锆石阴极发光（CL）分析在Macquarie大学GEMOC ARC实验中心Zeiss EVO MA15扫描电镜上完成. 利用锆石光学照片和CL照片进行锆石颗粒大小、外形、内部结构和包裹体的鉴别，以选择合适的锆石颗粒进行U-Pb年代学、微量元素和Lu-Hf同位素分析.

2.1　全岩地球化学分析

全岩主量元素分析在中国地质大学（武汉）生物地质与环境地质国家重点实验室完成，测试仪器为XRF-1800. 首先将样品置于烘箱中，于105 ℃烘干2 h. 烘过的样品在1 000 ℃下熔融制玻璃熔片，并进行烧失量的测定，然后在XRF-1800进行主量元素氧化物含量的测定. XRF-1800的X光管靶材为Rh靶，测试功率为2 500 W，光栏为30 mm. 测试标

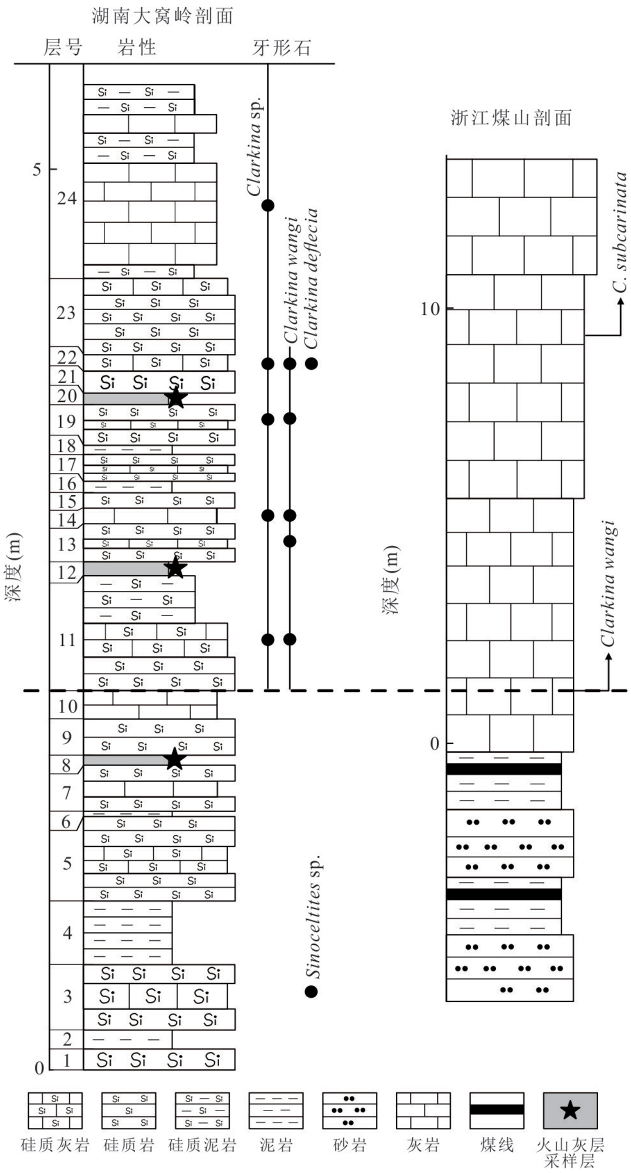

图2　湖南大窝岭剖面生物岩石地层柱状图

Fig.2　Lithostratigraphy and biostratigraphy of late Permian in the Dawoling section

据叶茜和江海水(2016)

准物质为GBW07105和GBW07109，分析过程中，每10个样品做一次重复样．标准物质和重复样的测试结果显示：含量大于5%的氧化物的测试误差多在1%以内，含量在5.0%～0.5%的氧化物的测试误差多在3%以内，含量在0.5%～0.1%的氧化物的测试误差多在9%以内．

全岩微量元素测定在贵州拓谱资源环境分析检测中心完成，使用仪器为Bruker Aurora M90 ICP-MS．具体操作手续参照(Qi *et al.*, 2000)：准确称取0.050 0 g样品于Teflon杯中，加入1 mL HF、1 mL HNO_3，密封，于185 ℃分解30～36 h，取出，冷却，于160 ℃电热板上蒸干，加入500 ng Rh内标溶液，加入2 mL HNO_3、4 mL水，再密封，于135 ℃密封溶解5 h，冷却．取出Teflon杯，取0.4 mL溶液于15 mL离心管中，稀释至10 mL，待测．

应用普通灵敏度模式，仪器灵敏度调整为1 ng mL^{-1} ^{115}In 400 000 cps，1 ng mL^{-1} ^{232}Th 150 000 cps．标样AMH-1(andesite)和OU-6(slate)结果与推荐值(Potts and Kane, 2005)基本一致，大部分元素结果相对误差为±(5%～10%)．

2.2　锆石U-Pb年代学和微量元素分析

锆石U-Pb同位素定年和微量元素含量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(GPMR)利用LA-ICP-MS同时分析完成．激光剥蚀系统为GeoLas 2005，ICP-MS为Agilent 7500a．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，二者在进入ICP之前通过一个T型接头混合．在等离子体中心气流(Ar+He)中加入了少量氮气，以提高仪器灵敏度、降低检出限和改善分析精密度(Hu *et al.*, 2008)．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(包括对样品和空白信号的选择、仪器灵敏度漂移校正、元素含量及U-Th-Pb同位素比值和年龄计算)采用软件ICPMSDataCal(Liu *et al.*, 2010)完成．详细的仪器操作条件和数据处理方法同Liu *et al.*(2010)．

U-Pb同位素定年中采用锆石标准91500作外标进行同位素分馏校正，每分析5个样品点，分析2次91500．对于与分析时间有关的U-Th-Pb同位素比值漂移，利用91500的变化采用线性内插的方式进行了校正(Liu *et al.*, 2010)．锆石标准91500的U-Th-Pb同位素比值推荐值据Wiedenbeck *et al.*(1995)．锆石样品的U-Pb年龄谐和图绘制和年龄权重平均计算均采用Isoplot/Ex_ver4 (Ludwig, 2003)完成．监控标样GJ-1的$^{206}Pb/^{238}U$加权平均年龄为601.7±2.3 Ma(N=28，1σ，MSWD=0.86)，与推荐值(Jackson *et al.*, 2004)在误差范围内一致．

锆石微量元素含量利用多个USGS参考玻璃(BCR-2G，BIR-1G)作为多外标、Si作内标的方法进行定量计算(Liu *et al.*, 2010)．这些USGS玻璃中元素含量的推荐值据GeoReM数据库(http://georem.mpch-mainz.gwdg.de/)．测试误差在10%以内．

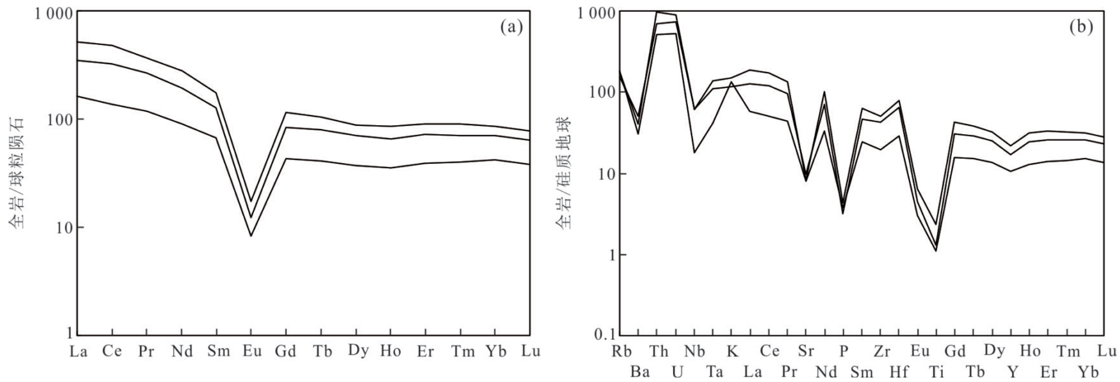

图 3　稀土元素和微量元素蛛网图

Fig.3　Rare earth elements and trace elements spider diagrams

表 1　大窝岭剖面火山灰层全岩主量元素和微量元素数据表

Table 1　Major and trace-element compositions of whole rocks from the Dawoling ash beds

样品	HD08	HD12	HD20	样品	HD08	HD12	HD20
SiO_2	53.37	55.69	61.51	Y	93.6	45.8	72.8
TiO_2	0.42	0.2	0.24	Zr	534	208	449
Al_2O_3	27.37	25.92	22.77	Nb	40.4	11.9	40
Fe_2O_3	1.62	1.48	1.42	Cs	8.31	5.58	4.82
MnO	0.02	0.01	0	Ba	268	202	329
MgO	1.81	1.79	1.54	La	122	38	82.9
CaO	1.06	1.03	0.79	Ce	292	84.4	199
Na_2O	0.47	1	1.01	Pr	34.2	11	24.7
K_2O	3.96	3.52	3.11	Nd	128	41.3	88.9
P_2O_5	0.08	0.07	0.06	Sm	25.7	9.96	18.8
LOI	10	8.8	7.37	Eu	0.97	0.47	0.68
Total	100.18	99.51	99.82	Gd	23.05	8.56	16.61
里特曼指数(σ)	1.9	1.6	0.9	Tb	3.76	1.49	2.86
Li	12.4	8.05	11.3	Dy	21.6	9.1	17.1
Be	5.2	2.18	3.04	Ho	4.62	1.91	3.59
V	32.1	16.2	9.29	Er	14.4	6.16	11.4
Cr	26.5	13.8	13.9	Tm	2.2	0.99	1.74
Co	6.27	2.72	3.46	Yb	13.9	6.72	11.4
Ni	17.1	9.46	12	Lu	1.89	0.93	1.55
Cu	18.2	9.18	11.6	Hf	22.6	8.11	18.2
Zn	105.8	64.2	92.0	Ta	5.12	1.52	4.13
Ga	45.3	26.9	36.3	Pb	50	31.5	21.8
Ge	1.49	0.86	1.2	Th	77.6	40.9	55.9
Rb	107	108	93.5	U	18.4	10.7	15
Sr	163	159	193				

2.3　锆石 Lu-Hf 同位素分析

锆石 Lu-Hf 同位素测试工作在中国地质大学(武汉)地质过程与矿产资源国家重点实验室完成.仪器由一个 GeoLas 2005 激光剥蚀系统和一个 Neptune Plus MC-ICP-MS 组成.具体的仪器参数和实验条件参考 Hu *et al*.(2012).测试采用单点剥蚀模式,激光输出能量密度为 5.3 J/cm^2,斑束直径为 44 μm.对于 ^{176}Yb 对 ^{176}Hf 的干扰,实验室采用锆石样品自身的 β_{Yb} 进行干扰校正.利用 ^{179}Hf/^{177}Hf=0.732 5 和 ^{173}Yb/^{171}Yb=1.130 17(Segal *et al*., 2003)来计算 Hf 和 Yb 的质量分馏系数 β_{Hf} 和 β_{Yb},利用 ^{179}Hf/^{177}Hf 和 ^{173}Yb/^{171}Yb 的比值来计算 Hf (β_{Hf}) 和 Yb (β_{Yb}) 的

质量偏差，然后使用$^{176}Yb/^{173}Yb$＝0.793 81（Segal *et al.*，2003）来扣除^{176}Yb对^{176}Hf的干扰．对于^{176}Lu对^{176}Hf的干扰，使用$^{176}Lu/^{175}Lu$＝0.026 56（Blichert-Toft *et al.*，1997）来进行校正．同时，由于Yb和Lu具有相似的物理化学属性，实验室采用Yb的质量分馏系数β_{Yb}来校正Lu的质量分馏行为．分析数据的信号选择和同位素质量分馏校正等采用软件ICPMSDataCal（Liu *et al.*，2010）完成．

测试的监控标样为锆石Temora，其校正的$^{176}Hf/^{177}Hf$加权平均值为0.282 687±0.000 007（N＝19）；与推荐值在误差范围内一致（Woodhead and Hergt，2005）．

3　测试结果

3.1　全岩主量和微量元素特征

3个样品（HD08、HD12、HD20）的SiO_2含量为53.37%～61.51%，呈依次升高趋势（表1）；Al_2O_3含量为27.37%～22.77%，呈依次降低趋势；Fe_2O_3和MgO含量较低，均在2%以下；Na_2O+K_2O含量为4.12%～4.52%；岩石的里特曼指数（σ）为0.9～1.9，为钙碱性系列．岩石的烧失量（LOI）较高（7.37%～

图4　锆石阴极发光图像

Fig.4　Cathodoluminescence images of zircon grains

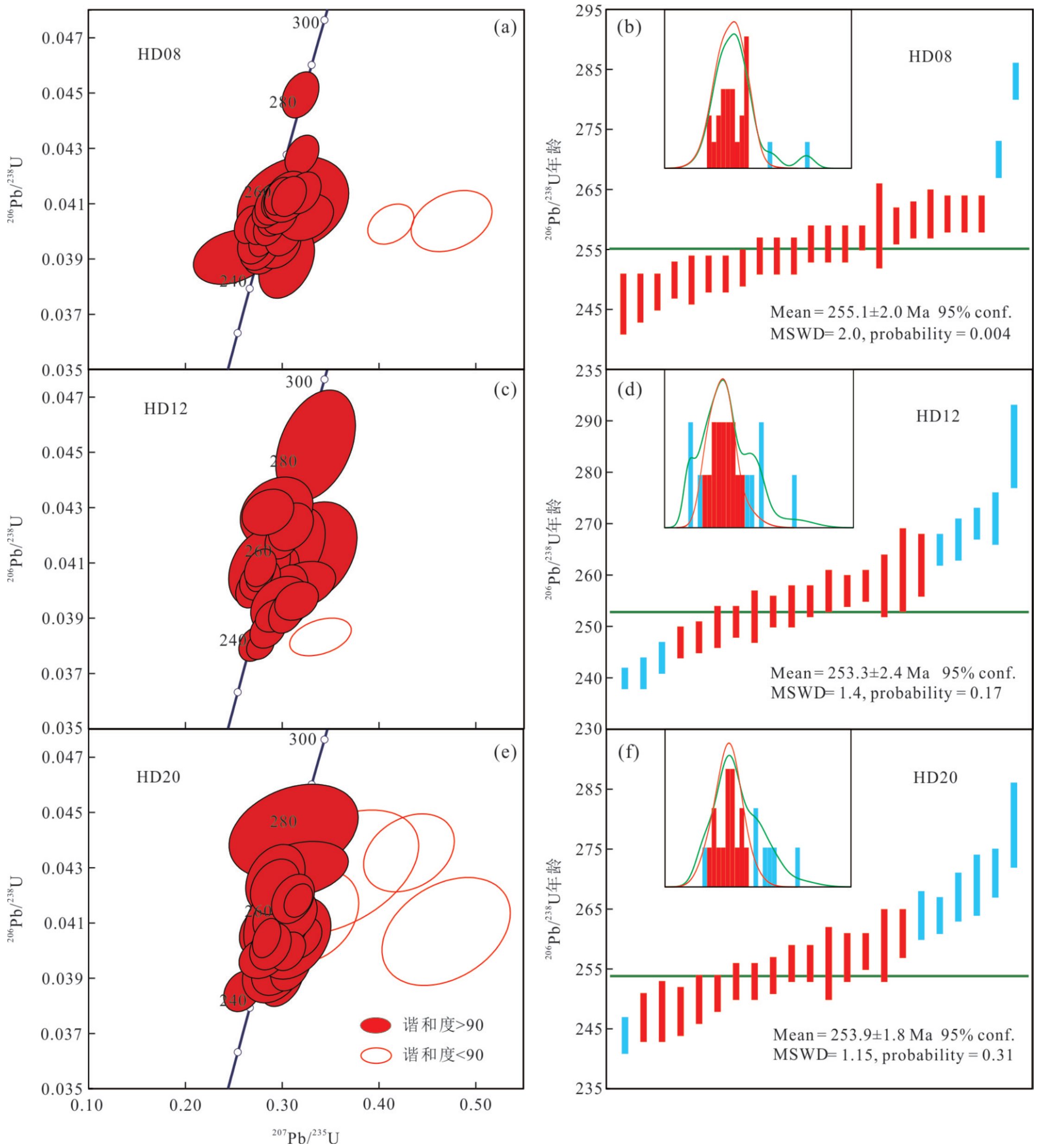

图 5　锆石 U-Pb 年龄谐和图和加权平均年龄

Fig.5　U-Pb age concordia diagrams and weighted ages of zircon grains

a，c，e. U-Pb 年龄谐和图；b，d，f. 加权平均年龄 b，d，f 中，红色标记数据为参与加权平均计算的数据；蓝色标记数据为未参与加权平均计算的数据；嵌入小图为 $^{206}Pb/^{238}U$ 年龄频数和频率分布图，绿色曲线为全部谐和数据的频率分布，红色曲线为参与加权平均计算的数据的频率分布．所有图中数据误差均为 1σ

10.0%），说明后期蚀变对主量元素影响较大．

相比主量元素，微量元素稳定性高很多．岩石稀土元素显示轻稀土富集、重稀土亏损的分布特征，具有明显的 Eu 负异常（图 3a）．微量元素蛛网图显示明显的 Th、U 正异常和 Ti、P、Sr、Nb、Ba 负异常（图 3b）．

3.2　锆石 U-Pb 年龄

锆石颗粒均为柱状外形，具有均一或震荡环带的内部结构，显示岩浆锆石的特征（图 4）．对 76 个锆石颗粒进行了锆石 U-Pb 年代学分析，获得了 68 个谐和年龄．所有谐和年龄的 $^{206}Pb/^{238}U$ 年龄均处于 240～285 Ma 范围内．

样品 HD08 获得 24 个谐和数据，排除 2 个较老年龄，计算加权平均年龄为 255.1±2.0 Ma（表 2，图 5）．HD12 和 HD20 均获得 22 个谐和数据，排除可能因为 Pb 丢失导致的较年轻年龄和岩浆中结晶较早

的较老年龄数据,计算加权平均年龄分别为253.3±2.4 Ma和253.9±1.8 Ma(表2,图5).3个样品的加权平均年龄在误差范围内一致,且与吴家坪阶—长兴阶界线年龄(254.14±0.07 Ma,国际地质年代表2 021.05)一致.综合3层粘土岩的产出层位和颜色、组分特征,认为3层粘土岩为火山灰蚀变成因,代表了吴家坪阶—长兴阶之交的3期火山作用.

3.3 锆石微量元素特征

所有颗粒均具有重稀土(HREE)富集的REE配分模式(图6),典型的岩浆锆石特征.REE元素含量在(618~5 109)×10^{-6}范围内变化(表2).正Ce异常(δCe)变化较大(1.4~108),负Eu异常(δEu)多小于0.3. Y含量从881×10^{-6}变化到9 701×10^{-6},Hf含量为(6 057~13 872)×10^{-6},Ti含量为(1.25~51.70)×10^{-6}. Th含量在(66~895)×10^{-6}范围内变化,U含量为(84~922)×10^{-6}. U/Yb比值为0.22~1.35,Nb/Ta比值为1.35~6.42. Yb/Y比值为0.20~0.41,Yb/Nb比值为31.9~744.9,Hf/Yb比值为3.5~37.0. $(Yb/Gd)_N$比值为9.4~31.1,Th/U比值为0.36~1.48.所有元素含量和比值都与岩浆锆石一致.

3.4 锆石Lu-Hf同位素特征

HD08获得23个Lu-Hf同位素数据,其$\varepsilon_{Hf}(t)$在−5.0~4.6范围内变化,平均值为1.4,计算的二阶段模式年龄(T_{crust})为0.99~1.61 Ga;HD12获得20个Lu-Hf同位素数据,其$\varepsilon_{Hf}(t)$在−12.0~−3.5范围内变化,平均值为−5.7,计算的二阶段模式年龄(T_{crust})为1.51~2.04 Ga;HD20获得21个Lu-Hf同位素数据,其$\varepsilon_{Hf}(t)$在−6.4~7.1范围内变化,平均值为2.7,计算的二阶段模式年龄(T_{crust})为0.83~1.68 Ga(表2). HD08和HD20具有相对亏损的Hf同位素组成,HD12具有相对富集的Hf同位素组成(图7).

HD08和HD20大的Hf同位素变化范围暗示火山作用来源于混合的岩浆源区.最年轻的(0.83 Ga)和最老的(2.04 Ga)T_{crust}模式年龄可能分别代表了新生地壳端元的最大值和古老地壳物质端元的最小值. HD12相对富集的Hf同位素组成暗示火山作用的岩浆主要来自古老地壳物质的熔融.

4 讨论

4.1 火山作用岩石学性质

由于蚀变作用对全岩主量元素影响较大,这里

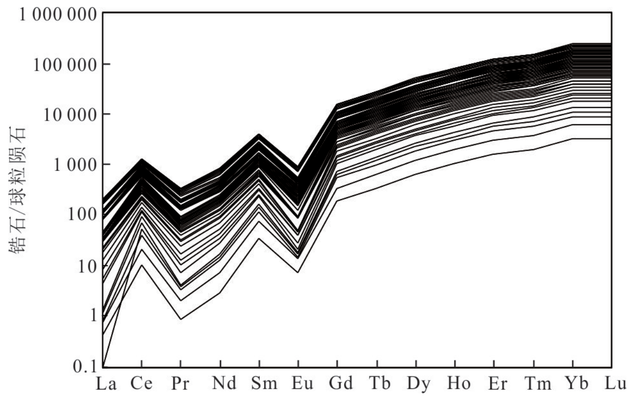

图6 锆石稀土元素配分图

Fig.6 REE patterns of zircon grains

球粒陨石(CI)标准值引自McDonough and Sun (1995)

主要利用相对稳定的全岩微量元素和锆石微量元素来探讨火山灰层来源的火山作用的岩石学性质(图8和图9).利用相对惰性的微量元素Nb、Y、Zr、Ti对岩石类型进行判断,3个样品落在了流纹岩和流纹英安岩区域(图8).其锆石的平均Y、Hf含量均投在含石英的中酸性岩石范围内(图9a).在锆石Y_2O_3和HfO_2图(图9b)中,HD08和HD12均显示钙碱性中酸性岩石的特征,而HD20中锆石HfO_2含量变化较大,部分颗粒具有钙碱性岩石特征,部分则显示碱性岩石的特征,可能是岩浆房中不同端元物质没有完全混合所致.因此,全岩微量元素和锆石微量元素组成共同显示火山灰层来源于流纹质或流纹英安质火山作用,HD08和HD12两期火山作用具有钙碱性亲属性,HD20火山作用显示碱性—钙碱性亲属性.

4.2 火山喷发的构造背景

晚二叠—早三叠时,Pangea超大陆边缘广泛存在泛古洋地壳的俯冲.晚二叠时沿着俯冲带,长英质火山作用非常活跃,产生了大量的长英质火山岩,形成了硅质大火成岩省和广泛分布的凝灰岩,如:南美的Choiyoi岩浆岩省(Bastias-Mercado *et al.*, 2020),南美Paraná盆地(Rocha-Campos *et al.*, 2011)、南非Karoo盆地(Fildani *et al.*, 2007)、澳大利亚Bowen盆地和Sydney盆地的凝灰岩(Kramer *et al.*, 2001; Grevenitz *et al.*, 2003).这些火山作用在成分上都是流纹/英安质的,具有钙碱性和弧相关火山作用的亲属性(Kramer *et al.*, 2001; Fildani *et al.*, 2007; Rocha-Campos *et al.*, 2011; Bastias-Mercado *et al.*, 2020).

古特提斯洋向东向华南和印支板块下面的俯

表 2　大窝岭剖面火山灰层锆石 U-Pb 测年、Lu-Hf 同位素和微量元素数据汇总表

Table 2　Summary of U-Pb, Hf-isotope ratios and trace-element compositions of zircon grains from the Dawoling ash beds

层号	$^{206}Pb/^{238}U$ 年龄 (Ma)	加权平均年龄 (Ma)	$\varepsilon_{Hf}(t)$	平均 $\varepsilon_{Hf}(t)$	T_{crust} 年龄 (Ga)	REE (10^{-6})	$(Yb/Gd)_N$	Eu 异常[a]	Ce 异常[a]	Y (10^{-6})	平均 Y (10^{-6})	Hf (10^{-6})	平均 Hf (10^{-6})
HD20	244～279	253.9±1.8	−6.4～7.1	2.7	0.83～1.68	801～5 109	9.4～25.5	0.00～0.27	1.5～108	1 171～9 701	2 672	6 057～13 252	8 513
HD12	240～285	253.3±2.4	−12.0～−3.5	−5.7	1.51～2.04	619～3 530	11.6～31.1	0.07～0.24	1.4～34.7	881～5 970	1 824	8 737～13 872	10 528
HD08	246～283	255.1±2.0	−5.0～4.6	1.4	0.99～1.61	730～1 719	11.1～29.4	0.01～0.32	2.5～102.4	1 014～2 795	1 826	8 029～13 836	10 037

层号	Y_2O_3 (10^{-6})	HfO_2 (10^{-6})	Ti (10^{-6})	Th (10^{-6})	U (10^{-6})	Th/U	U/Yb	Nb/Ta	Yb/Y	Yb/Nb	Hf/Yb
HD20	1 488～12 320	7 143～15 627	1.25～51.7	100～794	100～693	0.36～1.48	0.22～1.35	2.23～6.42	0.20～0.31	31.9～466.5	3.5～30.7
HD12	1 119～7 582	10 303～16 359	1.4～9.2	66～895	151～922	0.36～1.10	0.33～1.35	1.58～3.70	0.24～0.33	121.4～744.9	6.2～37.0
HD08	1 288～3 550	9 468～16 317	3.4～24.3	104～366	84～569	0.36～1.24	0.22～1.27	1.35～3.27	0.25～0.41	49.2～509.2	12.3～30.4

注：[a] Eu 异常和 Ce 异常计算公式：δEu=[Eu]/SQRT([Sm]×[Gd])；δCe=[Ce]/SQRT([La]×[Pr]).REE 标准化数据引自 McDoungh and Sun (1995).

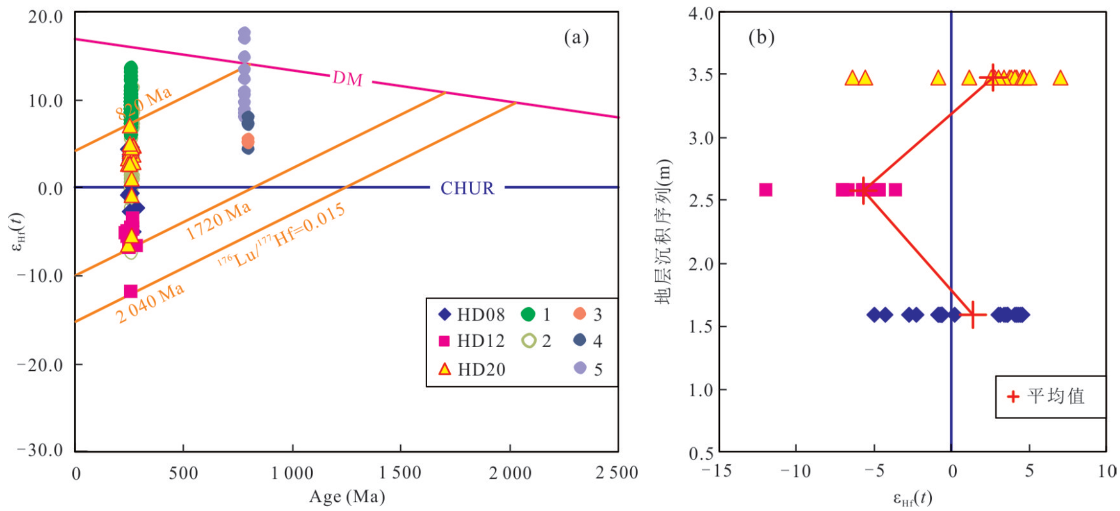

图 7 锆石 Hf 同位素组成图

Fig.7 Hf-isotope compositons of zircon grains

a. $\varepsilon_{Hf}(t)$值对年龄分布图；b. 地层沉积序列对$\varepsilon_{Hf}(t)$值分布图；图 a 中：1. 峨眉山 A 型花岗岩(Xu *et al.*, 2008; Shellnutt *et al.*, 2009)；2. 峨眉山正长岩和闪长岩(Xu *et al.*, 2008)；3、4. 新元古代裂谷环境形成的双峰式火山岩(全岩 Hf 同位素)(Li *et al.*, 2005)，3. 流纹岩，4. 玄武岩；5. 新元古代裂谷环境形成的镁铁质岩墙(全岩 Hf 同位素)(Lin *et al.*, 2007)

冲，以及华南和印支板块之间的碰撞也发生在晚二叠—早三叠(Zi *et al.*, 2012; Liu *et al.*, 2020; 许王等, 2021). 沿着 Song Ma、哀牢山、金沙江等碰撞带，长英质钙碱性岩浆作用非常活跃(Hoa *et al.*, 2008; Halpin *et al.*, 2016; 田梦宇等, 2021). 同时，还存在巨大体积的玄武质火山作用，即～260 Ma 峨眉山大火成岩省(Xu *et al.*, 2004; Shellnutt, 2014)，其中的高钛玄武岩具有 OIB 亲属性(Xiao *et al.*, 2004)，与地幔柱形成的大陆溢流玄武岩特征一致(Xu *et al.*, 2004)；大火成岩省相关的长英质火山作用和硅质侵入作用中有大量地壳物质的加入(Xu *et al.*, 2008; Tran *et al.*, 2015).

锆石 U/Yb 比值和 Y 含量特征显示大窝岭剖面记录的三期火山作用可能形成于后碰撞或大陆弧背景(图 10a). Yb/Y 比值则排除了大陆弧背景的可能性，数据落在了后碰撞背景范围内(图 10b)，同时，HD08 和 HD20 部分颗粒具有相对低的 Yb/Nb 比值(图 10b)，显示陆内裂谷环境的亲属性. 综合锆石 Hf 同位素组成(图 7)，认为 3 期火山作用主要形成于后碰撞环境，与大陆汇聚有关；HD12 的岩浆主要来源于古老地壳物质，HD08 和 HD20 来源于峨眉山/新元古代新生地壳物质和古老地壳物质的混合，部分锆石显示出陆内裂谷环境的亲属性.

4.3 华南记录的中-晚二叠世长英质火山作用

华南地块的周边地区在中二叠世至早三叠世时期火山作用异常频繁. 一方面，峨眉山大火成岩

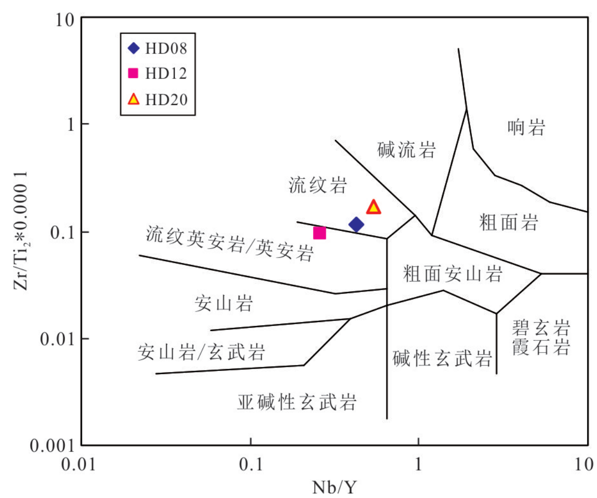

图 8 全岩 Nb/Y 比值-Zr/TiO_2比值判别岩石类型图

Fig.8 Whole-rock Nb/Y-Zr/TiO_2 diagram, showing discrimination of rock types

省于～260 Ma 发生强烈喷发(Xu *et al.*, 2004; Shellnutt, 2014)；另一方面，与 Pangea 超大陆汇聚相关的火山作用，包括古特提斯洋向华南和印支板块下面的俯冲，以及华南和印支板块之间的碰撞(Zi *et al.*, 2012; Liu *et al.*, 2020; 许王等, 2021)，沿着 Song Ma、哀牢山、金沙江等碰撞带，岩浆作用非常活跃(Hoa *et al.*, 2008; Halpin *et al.*, 2016; 田梦宇等, 2021). 这些火山作用在华南地层剖面上均有记录. 之前的研究主要集中在生物绝灭界线附近(中—晚二叠世之交和二叠纪—三叠纪之交). 在两

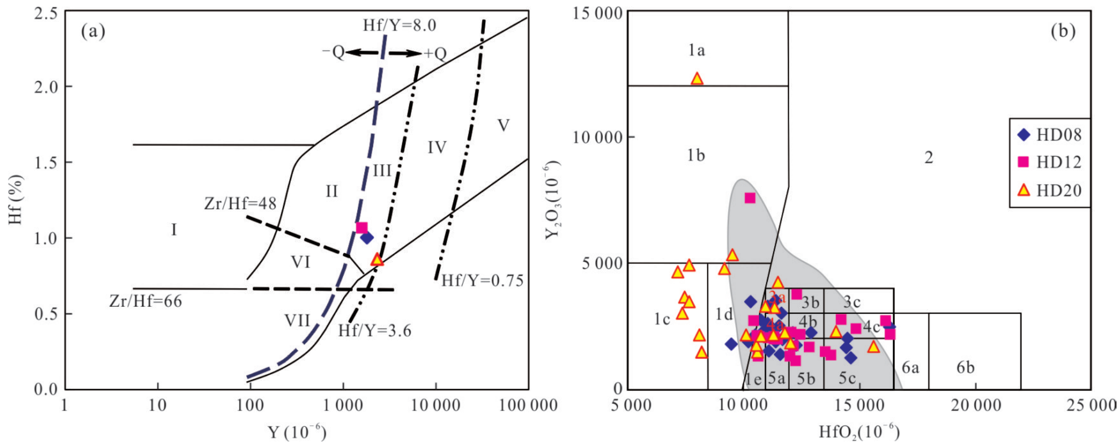

图 9　锆石微量元素判别岩石类型图

Fig.9　Zircon trace element diagrams, showing discrimination of rock types

图 a 中：Ⅰ. 金伯利岩；Ⅱ. 超镁铁质、镁铁质和中性岩石；Ⅲ. 含石英的中酸性岩石；Ⅳ. 具有高 SiO_2 含量的酸性岩石；Ⅴ. 云英岩；Ⅵ. 碱性杂岩中的碱性岩和碱性交代岩；Ⅶ. 碳酸岩. 图 b 中：拉斑质斜长花岗岩-1a；固溶线上碱性花岗岩/流纹岩-1b-c-d-e；碱性/过碱性正长岩/粗面岩-1c-d-e；夏威夷岩和碱性玄武岩-1c；固溶线下碱性花岗岩/流纹岩-1e, 2, 3a-b-c, 4a-b-c；中基性钙碱性岩石（辉长岩，闪长岩，英云闪长岩，石英闪长岩，安山岩-英安岩）-4a-b-c, 5a-b-c, 6a-b；钙碱性花岗岩/流纹岩-5a-b-c；高钾钙碱性或 Mg-K 花岗岩/流纹岩-4a-b, 5a-b-c；亚碱性或 Fe-K 花岗岩/流纹岩-4c, 5a-b-c；过铝质斑状花岗岩/流纹岩-3b-c, 4b-c, 5b-c, 6a-b；过铝质淡色花岗岩-3c, 4c, 5c, 6a；原地产生的过铝质花岗岩和混合岩-3c, 4c, 5c, 6a；图中灰色区域代表钙碱性中性岩石（闪长岩—英云闪长岩/安山岩—英安岩）中的锆石；a. Hf vs Y (Belousova *et al.*, 2002)；b. Y_2O_3 *vs* HfO_2 (Pupin, 2000)

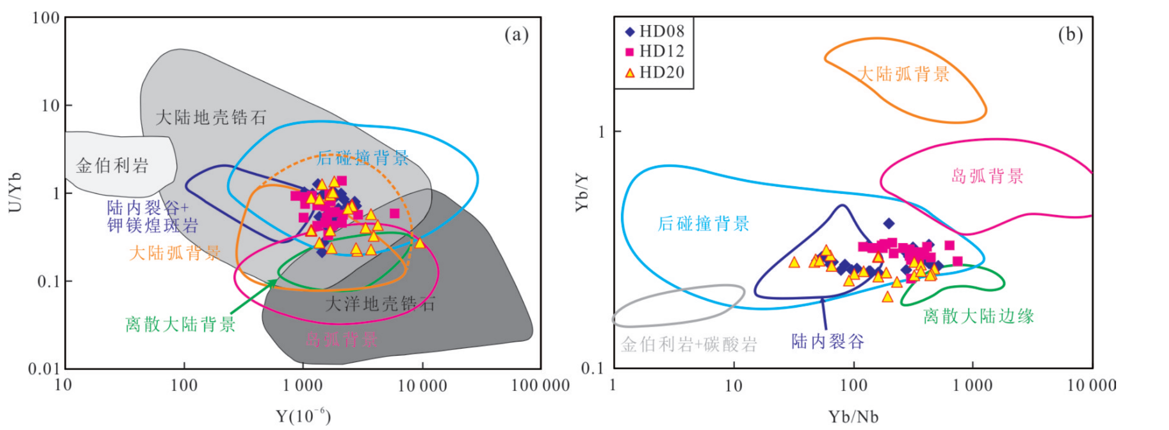

图 10　锆石微量元素判别构造背景图

Fig.10　Zircon trace element diagrams, distinguishing the possible tectonic setting of the volcanism that produced the zircons

底图引自高秋灵(2013)

个界线附近，发育有大量的火山灰层（Gao *et al.*, 2013; Zhong *et al.*, 2013; Huang *et al.*, 2018; Zhao *et al.*, 2019; Liu *et al.*, 2021）. 中—晚二叠世界线附近的火山灰层既有峨眉山大火成岩省相关的镁铁质火山作用，也有汇聚大陆边缘相关的长英质火山作用（Zhong *et al.*, 2013; Zhao *et al.*, 2016; Huang *et al.*, 2018）；二叠纪—三叠纪界线附近的火山灰层主要来源于汇聚大陆边缘的长英质火山作用（Gao *et al.*, 2013; Wang *et al.*, 2019a; Zhao *et al.*, 2019; Liu *et al.*, 2021）.

本次研究报道的乐平统内部的长英质火山作用补充了华南晚二叠世内部火山作用的记录，进一步证实了华南地块周边地区晚二叠世时期持续、广泛存在与 Pangea 超大陆汇聚有关的长英质火山作用. 这些持续且广泛的火山喷发导致了晚二叠世生态环境的持续恶化，可能是引起二叠纪—三叠纪之交生物大绝灭的前兆（Zhang *et al.*, 2021）.

5　结论

大窝岭剖面吴家坪阶—长兴阶界线附近地层

中发育的三层灰白色粘土岩(HD08、HD12和HD20),为火山灰蚀变成因.火山灰来源于流纹质或流纹英安质火山作用,具有钙碱性亲属性,形成于Pangea超大陆汇聚相关的构造背景.其中,HD08和HD20样品具有变化较大的Hf同位素组成范围[$\varepsilon_{Hf}(t)$值:−6.4~7.1],岩浆来源于峨眉山/新元古代新生地壳物质和古老地壳物质的混合;HD12样品具有相对富集的Hf同位素组成范围[$\varepsilon_{Hf}(t)$值:−12.0~−3.5],岩浆主要来源于古老地壳物质.3层火山灰层的发现丰富了华南晚二叠世地层中火山作用的记录,揭示了华南地块周边地区在乐平世最早期和末期两个火山强烈喷发密集期之间火山作用也非常强烈,至少在吴家坪期—长兴期之交发生强烈的、与Pangea超大陆汇聚相关的长英质火山作用.

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