贵州盘县峨眉山玄武岩系顶部凝灰岩 LA-ICP-MS 锆石 U-Pb 年龄:对峨眉山大火成岩省与生物大规模灭绝关系的约束*

朱江　张招崇**　侯通　康健丽

ZHU Jiang, ZHANG ZhaoChong**, HOU Tong and KANG JianLi

中国地质大学地质过程与矿产资源国家重点实验室,北京　100083

State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Beijing 100083, *China*

2011-05-01 收稿, 2011-07-05 改回.

Zhu J, Zhang ZC, Hou T and Kang JL. 2011. LA-ICP-MS zircon U-Pb geochronology of the tuffs on the uppermost of the Emeishan basalt succession in Panxian County, Guizhou Province: Constraints on genetic link between Emeishan large igneous province and the mass extinction. *Acta Petrologica Sinica*, 27(9):2743－2751

Abstract　In 1990s, some researchers suggested a temporal link between volcanism of the Emeishan Large Igneous Province (ELIP) and the mass extinction at the Permian-Triassic Boundary (P-TB), and were supported by the $^{40}Ar/^{39}Ar$ isotopic dating showing that the ELIP formed in the Late Permian. However, in recent years, a quantity of SHRIMP U-Pb datings suggested that the large-scale volcanism erupted at ~260Ma. Hence, the ELIP volcanism has been attributed to be the cause of the end-Guadalupian mass extinction in the Middle Permian. In contrast, the intense volcanism in Siberian traps has been considered to be the main cause of the P-T boundary great mass extinction which has been ascribed to a global environmental change due to voluminous gases and volcanic ash production. Recently, we have found a ~100m thick tuff layer in the uppermost of Emeishan basalt succession in the Panxian County, Guizhou Province, the eastern ELIP. Our new LA-ICP-MS zircon U-Pb dating on tuff from the uppermost of the Emeishan basalt succession yields an average age of 251.0±1.0Ma, coeval to those from ash or clay beds in the P-TB of the Meishan section in Zhejiang Province. Consequently, the end of the Emeishan flood volcanism is consistent with the main pulse of the P-TB Siberian large igneous province. Thus, our new dating result provides us a clue of a cause-and-effect relationship between the Emeishan large igneous province and the largest mass extinction in the earth's history (P-TB).

Key words　Tuff; Emeishan basalt succession; LA-ICP-MS U-Pb dating; Permian-Triassic Boundary; Mass extinctions; Guizhou Province

摘　要　在20世纪90年代,有学者认为峨眉山大火成岩省(Emeishan Large Igneous Province, ELIP)大规模火山活动与二叠-三叠系之交(Permian-Triassic Boundary, P-TB)的生物大灭绝事件在时间上有耦合关系,随后的$^{40}Ar/^{39}Ar$同位素测年结果也显示峨眉山大火成岩省是晚二叠世形成的。但是,近些年大量的SHRIMP U-Pb测年结果表明,ELIP大规模火山喷发约在~260Ma;因此有研究认为,ELIP火山活动与中二叠世瓜德卢普期末(end-Guadalupian)的生物灭绝事件在时间上联系更加紧密。至于P-T界线生物大灭绝,现在多数学者认为是,由于西伯利亚大火成岩省火山强烈活动释放大量气体和火山灰所造成环境变化引起的。最近,我们在ELIP东部的贵州盘县峨眉山玄武岩系剖面中发现顶部发育厚度达近百米的凝灰岩层,其LA-ICP-MS U-Pb法测年结果为251.0±1.0Ma,与浙江煤山剖面中二叠系-三叠系边界处黏土层或火山灰层的锆石U-Pb年龄接近。因此,峨眉山玄武岩喷发结束的时间应该在P-T边界,与西伯利亚大火成岩省的主体喷发时间一致。新的测年结果暗示了ELIP火山活动与地球历史上最大的一次生物灭绝事件(P-T边界)可能存在着成因联系。

---

* 本文受国家973项目(2009CB421002)、国家自然科学基金(40925006)和111计划(B07011)联合资助.

第一作者简介: 朱江,男,1986年生,硕士研究生,岩石学专业,E-mail: Zhuj206@163.com

** **通讯作者**:张招崇,男,1965年生,教授,博士生导师,主要从事火成岩岩石学以及相关金属矿床的教学和研究,E-mail: zczhang@cugb.edu.cn

关键词 凝灰岩;峨眉山玄武岩系;LA-ICP-MS U-Pb 测年;二叠-三叠系界线;生物灭绝;贵州
中图法分类号 P597.3

1 引言

地质历史上不同时期许多重大生物灭绝事件与大火成岩省在时间上存在耦合关系,所以很多学者认为是大火成岩省大规模的火山作用导致了生物的大规模灭绝(Wignall, 2001, 2005; Saunders, 2005)。其中发生于 P-T 边界的生物灭绝事件是地质历史上规模最大的一次生物灭绝事件,由于其在时间上刚好和西伯利亚大火成岩省吻合,所以很多学者将此次生物灭绝事件归因于西伯利亚大火成岩省大规模的火山作用释放大量气体和火山灰所造成的气候环境变化(Bowring *et al.*, 1998; Courtillot, 1999; Wignall, 2001; Kamo *et al.*, 2003; Mundil *et al.*, 2004; Svensen *et al.*, 2009; Saunders and Reichow, 2009)。同西伯利亚大火成岩省相比,峨眉山大火成岩省与二叠纪生物灭绝事件之间的关系更为复杂。早在 20 世纪 90 年代,就有学者认为峨眉山大火成岩省与二叠-三叠系之交生物大灭绝存在着密切的因果关系(如 Yin *et al.*, 1992; Chung and Jahn, 1995; Chung *et al.*, 1998)。随后的 $^{40}Ar/^{39}Ar$ 同位素测年结果也表明了峨眉山大火成岩省形成于晚二叠世(如 Lo *et al.*, 2002; 范蔚茗等, 2004),其时代与西伯利亚大火成岩省接近,因此也认为其与 P-T 边界的生物大规模灭绝在时间上存在耦合关系(如 Lo *et al.*, 2002)。然而,近年来大量 SHRIMP U-Pb 锆石测年结果表明,ELIP 大规模火山活动时间约为 ~260Ma(Zhou *et al.*, 2002, 2005, 2006, 2008; Wang and Zhou, 2006; Zhong and Zhu, 2006; Guo *et al.*, 2004; 陶琰等, 2008; Tao *et al.*, 2009);所以中二叠世瓜德卢普期末(end-Guadalupian)发生的生物灭绝事件被认为与 ELIP 的火山作用有关(Zhou *et al.*, 2002; Ali *et al.*, 2002; Wignall *et al.*, 2009; Bond *et al.*, 2010a, b; Xu *et al.*, 2010; He *et al.*, 2010)。

目前,尽管对于火山作用导致生物灭绝的机制还存在着不同的认识,例如,是与火山作用释放的有毒气体有关还是与释放出的气体(如 CO_2, SO_2 等)导致气候环境的变化有关?但是不论何种观点,多数学者都认为是与火山作用释放出的气体有关。以前的研究表明,由火山作用释放出到大气圈中的气体绝大多数是通过爆发作用而实现的,只有非常小的一部分气体是岩浆在流动过程中释放的,而且只有爆发作用才有可能使得气体达到平流层从而对地球的环境产生重要影响(Thordarson and Self, 2003)。然而,以前的研究表明峨眉山大火成岩省火山碎屑岩非常少(一般只有不到 1m 的厚度),加之其规模并不太大(只有约 25 ~ 30km^2),所以 ELIP 的火山作用是否能导致中二叠世瓜德卢普期末的生物大规模绝灭是令人怀疑的(Ali *et al.*, 2005)。最近,我们在 ELIP 东段的贵州盘县峨眉山玄武岩系顶部发现了厚达上百米的凝灰岩层。这一发现及其喷发时间的确定为探讨 ELIP 和生物灭绝之间的关系提供了重要物证和时间约束。

2 地质概况及峨眉山玄武岩系岩石特征

研究区位于贵州盘县境内,其大地构造位置处于上扬子准地台西南缘和华南褶皱系右江褶皱带的结合部位。区域上出露地层从老到新有泥盆系、石炭系、二叠系、三叠系、下第三系和第四系。研究区内出露地层单元主要有三叠系下统飞仙关组(T_1f)、永宁镇组(T_1yn),二叠系中统茅口组(P_2m),二叠系上统峨眉山玄武岩系($P_3\beta$)、龙潭组(P_3l)和第四系(Q)。其中峨眉山玄武岩系($P_3\beta$)假整合于茅口组之上,与上覆龙潭组呈整合接触(图 1b)。

区内岩浆岩以峨眉山玄武岩为主,零星见辉绿岩脉。峨眉山玄武岩系在本区以玄武岩、玄武质火山碎屑岩与火山碎屑岩之间互层为特征,以玄武质熔岩为主,总厚约 400 ~ 500m。根据其岩性和岩石组合特点,将本区峨眉山玄武岩系分为 4 段(图 1c)。一段($P_3\beta^1$)底部为灰至深灰火山角砾岩,角砾排列杂乱,其成分为玄武岩、凝灰岩,呈棱角及次棱角状,直径在 0.5 ~ 3.0cm 之间,胶结物质主要为泥质,呈基底式胶结;中上部是灰黄、灰白、褐黄色薄层沉凝灰岩、凝灰岩,凝灰质黏土岩夹薄层炭质黏土岩及煤线,总厚约 20m,分布不稳定,受茅口组顶部起伏不平的古剥蚀面控制。二段($P_3\beta^2$)主要为深灰色、灰色块状玄武岩,厚约 280 ~ 320m,分布稳定。三段($P_3\beta^3$)主要为灰色块状凝灰质玄武岩和凝灰岩,在中上部凝灰岩层中夹两层凝灰岩球,总厚度约 100 ~ 120m,其中凝灰岩厚约 50 ~ 60m,分布稳定。四段($P_3\beta^4$)主要为灰、紫红等杂色黏土质凝灰岩、凝灰岩、凝灰质黏土岩,中间偶夹 1 ~ 2 层薄层灰色玄武岩,厚约 40m,分布稳定。

通过在镜下观察,本次研究样品主要是玻屑凝灰岩,其次为玻屑沉凝灰岩。分别具明显的凝灰结构和沉凝灰结构,成分以刚性玻屑为主,在薄片中呈无色、灰色、淡黄、淡褐色,含量约 70% ~ 80%,粒度在 10 ~ 80μm 之间,呈尖弧状、弯弓状、不规则尖角状、浮岩状等杂乱排列,基本未变形,是原地堆积的产物,在玻屑间充填的黑褐色物质可能是极细的火山尘或褐铁矿等,约 15% ~ 25%(图 1e),玻屑沉凝灰岩中混入的正常沉积物有方解石、石英、黏土矿物等,含量约 10% ~ 15%。

需要特别说明的是,关于研究剖面的选择,我们综合考虑到剖面地层连续性、剖面出露情况、样品新鲜程度以及样品采集工作等问题。虽然本次样品采集剖面的最顶部被第四系沉积物覆盖(图 1c),但已证明该剖面的峨眉山玄武岩系无地层缺失(即顶部凝灰岩是 ELIP 火山活动的最终产物,而非某一个旋回的结束产物)。另外,我们查阅了区域相关

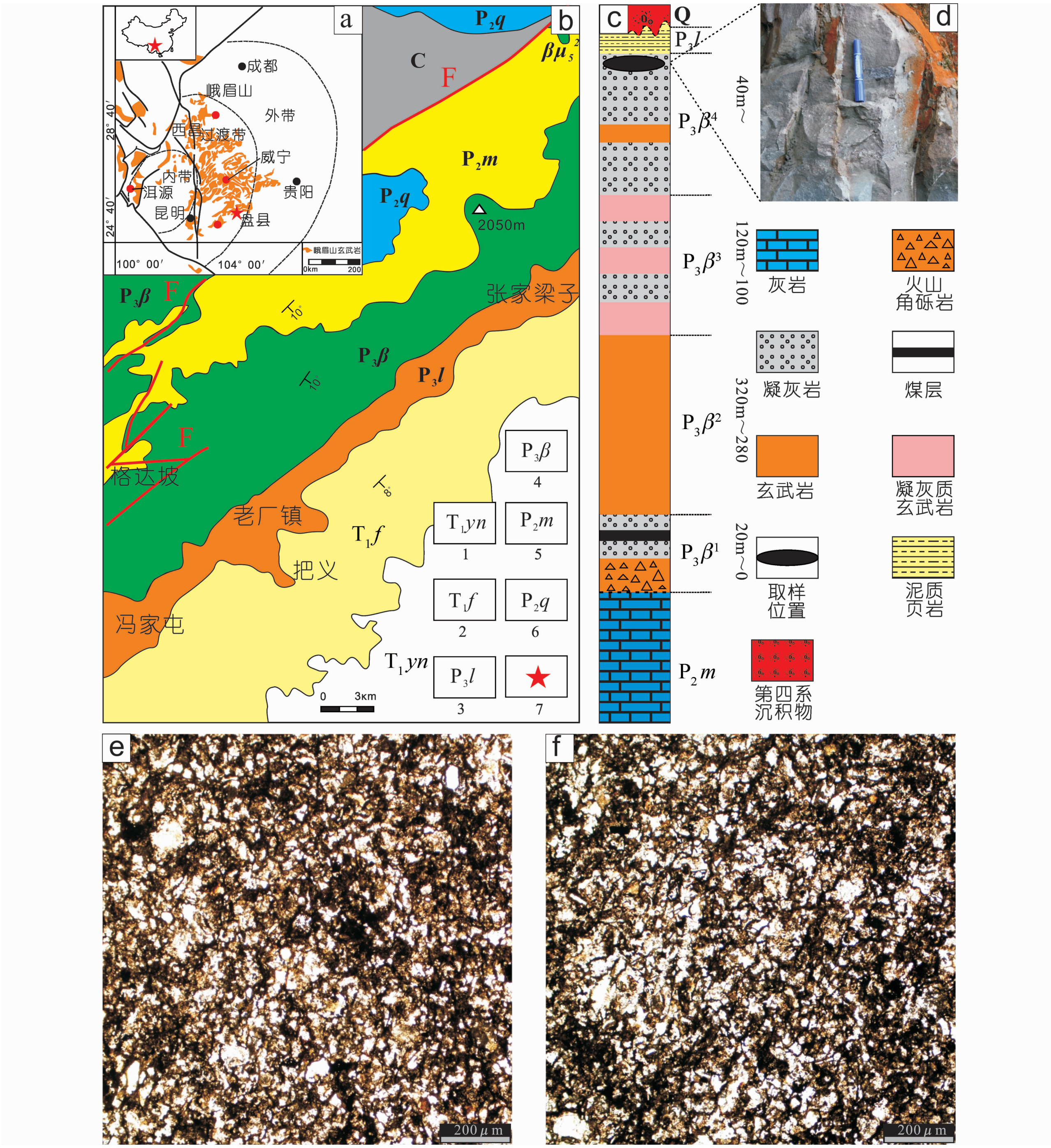

图 1　研究区地质概况、柱状及岩相学特征图

(a)-峨眉山大火成岩省地质略图(据 He *et al.*, 2007),图中的红色点为 He *et al.* (2007)的取样位置;(b)-研究区地质略图(据贵州地勘局区域地质调查研究院,1994①,1997②);(c)-研究区综合峨眉山玄武岩系地层柱状图;(d)-取样位置及野外照片;图例:1-三叠系下统永宁镇组; 2-三叠系下统飞仙关组; 3-二叠系上统龙潭组; 4-二叠系上统峨眉山玄武岩系; 5-二叠系中统茅口组; 6-二叠系中统栖霞组; 7-取样位置;(e, f)-剖面顶部玻屑凝灰岩显微特征(－)

Fig. 1　Sketch geological map of the study area, column and petrographical characteristics

(a)-sketch geological map of the Emeishan large igneous province with sampling location (modified after He *et al.*, 2007); (b)-sketch geological map of the study area; (c)-simplified stratigraphic column of the Emeishan basalt succession in the study area; (d)-photograph of the sampling location in the field. Legends: 1-Lower Triassic Yongningzhen Formation; 2-Lower Triassic Feixianguan; 3-Upper Permian Longtan Formation; 4-Upper Permian Emeishan basalts; 5-Middle Permian Maokou Formation; 6-Middle Permian Qixia Formation; 7-Sampling location; (e, f)-microscope feature of the virtric tuff from the uppermost succession (－)

① 贵州地勘局区域地质调查研究院. 1994. 贵州省老厂幅(G48E015012)1∶5 万区域地质图

② 贵州地勘局区域地质调查研究院. 1997. 贵州省普安幅(G48E014012)1∶5 万区域地质图

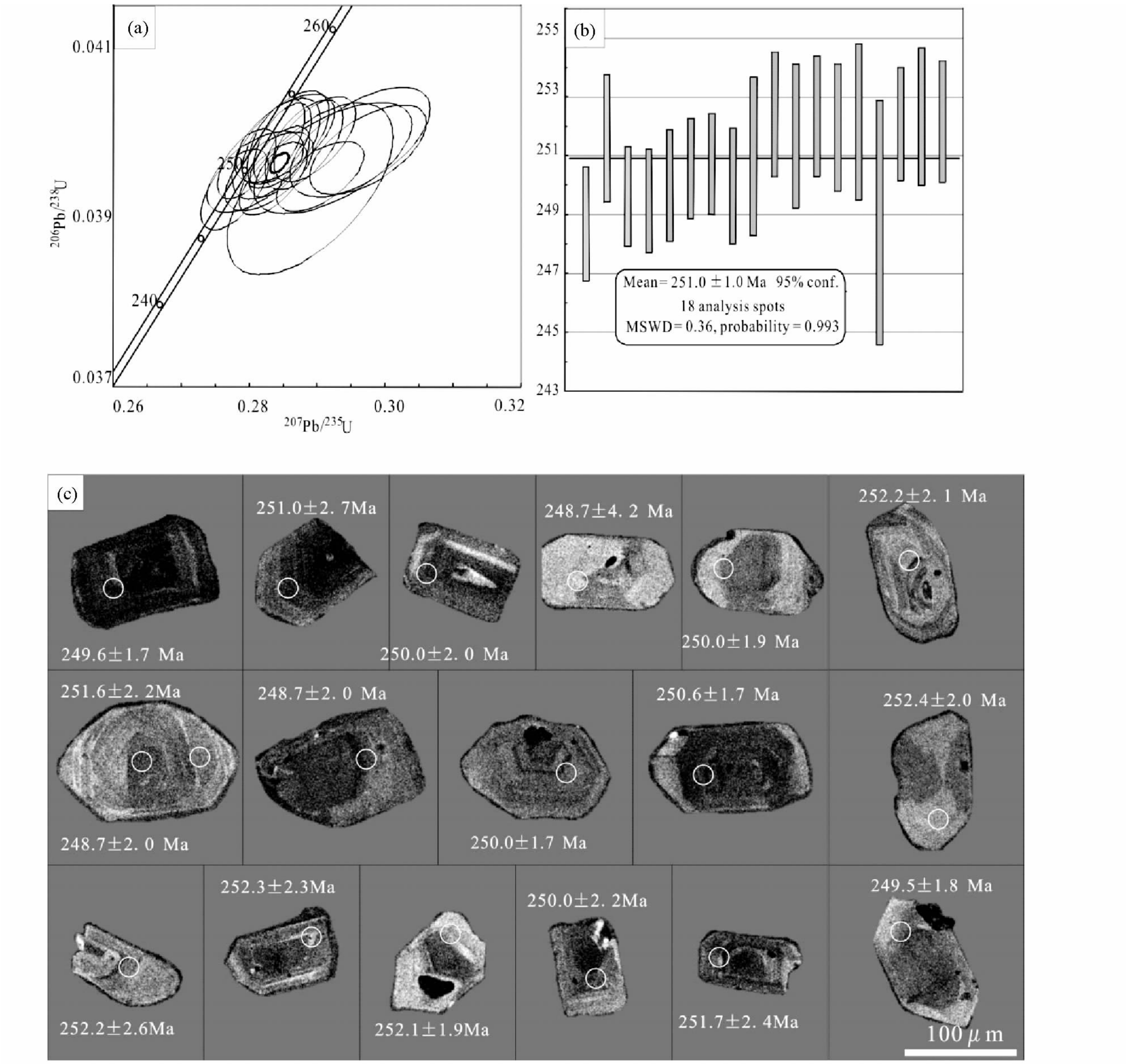

图 2 峨眉山玄武岩组顶部凝灰岩中锆石 U-Pb 谐和图(a, b)和部分锆石样品阴极发光(CL)图像(c)

Fig. 2 Zircon U-Pb concordia diagrams (a, b) and CL images of some typical zircon (c) from the tuffs on the top of the Emeishan basalts

地层资料,且又在研究区附近测了 2 条地层连续完整的辅助对比剖面,通过剖面间的标志层和厚度等一系列重要特征慎重对比后,综合分析认为,所选剖面是一套完整的峨眉山玄武岩系。然后绘制了研究区综合地层柱状图(图 1c)。

3 样品采集与实验方法

用于定年的样品采自峨眉山玄武岩系顶部的新鲜凝灰岩(约 18kg,图 1c, d)。将样品破碎,采用常规重-磁选方法,除去磁铁矿、磁黄铁矿等磁性矿物,然后在双目镜下挑选出晶形完好,透明度和色泽较好的锆石单矿物黏在双面胶上,最后用无色透明的环氧树脂固定,待环氧树脂充分固化后磨蚀露出锆石内部并抛光,具体操作流程参考锆石 SHRIMP 样品靶制作、年龄测定及有关现象的讨论(宋彪等, 2002)。

阴极发光(CL)成像和锆石 U-Pb 测年分析均在中国地质科学院矿产资源研究所 LA-ICP-MS 锆石测年实验室进行,本次实验所采用的激光束斑直径为 25μm,剥蚀深度 20 ~ 40μm,激光脉冲 10Hz。普通铅校正采用 Anderson (2002)的方法,年龄计算采用国际标准程序 Isoplot (ver3.0)。LA-ICP-MS 锆石 U-Pb 测年方法通过直接测定单颗粒锆石晶体中微区的 U-Pb 同位素组成而得出年龄,其结果以 $^{206}Pb/^{238}U$ 年龄计算,年龄误差为 1σ,加权平均年龄具 95% 的置信差。

表 1 贵州盘县峨眉山玄武岩系顶部凝灰岩中锆石 LA-ICP-MS U-Pb 的同位素测定结果

Table 1 LA-ICP-MS U-Pb isotopic data of zircons from the tuffs on the top of Emeishan basalt in Panxian County, Guizhou Province

测点号	Pb (×10⁻⁶)	Th (×10⁻⁶)	U (×10⁻⁶)	Th/U	$^{207}Pb^*/^{206}Pb$	1sigma	$^{207}Pb^*/^{235}U$	1sigma	$^{207}Pb/^{235}U$ 年龄(Ma)	$^{206}Pb^*/^{238}U$	1sigma	$^{206}Pb/^{238}U$ 年龄(Ma)	$^{208}Pb/^{232}Th$	1sigma	Concordance
plesovice	16.2	56	592	0.09	0.0533	0.0002	0.3941	0.0035	528.3 ±3.0	0.0538	0.0004	525.9 ±3.4	0.0023	0.0005	99%
DX01-1	8.5	104	195	0.53	0.0513	0.0005	0.2779	0.0033	249.0 ±2.6	0.0393	0.0003	248.7 ±2.0	0.0015	0.0003	99%
DX01-2	2.3	31	51	0.61	0.0543	0.0010	0.2975	0.0057	264.4 ±4.4	0.0398	0.0003	251.6 ±2.2	0.0045	0.0008	95%
DX01-3	3.2	96	104	0.92	0.0589	0.0010	0.3211	0.0059	282.8 ±4.5	0.0396	0.0004	250.1 ±2.2	0.0015	0.0003	87%
DX01-4	4.0	59	79	0.75	0.0534	0.0007	0.2905	0.0042	258.9 ±3.3	0.0395	0.0003	249.6 ±1.7	0.0026	0.0005	96%
DX01-5	14.2	235	152	1.54	0.0521	0.0005	0.2835	0.0033	253.4 ±2.6	0.0395	0.0003	249.5 ±1.8	0.0011	0.0002	98%
DX01-6	8.6	101	154	0.66	0.0519	0.0007	0.2829	0.0043	253.0 ±3.4	0.0395	0.0003	250.0 ±1.9	0.0019	0.0004	98%
DX01-7	12.6	182	210	0.87	0.0512	0.0004	0.2796	0.0028	250.4 ±2.3	0.0396	0.0003	250.6 ±1.7	0.0013	0.0003	99%
DX01-8	11.7	156	255	0.61	0.0520	0.0004	0.2844	0.0029	254.2 ±2.3	0.0397	0.0003	250.7 ±1.7	0.0014	0.0003	98%
DX01-9	1.8	32	63	0.51	0.0515	0.0008	0.2809	0.0047	251.4 ±3.7	0.0395	0.0003	250.0 ±2.0	0.0053	0.0013	99%
DX01-10	14.9	196	157	1.25	0.0730	0.0020	0.4101	0.0130	349.0 ±9.3	0.0402	0.0003	253.8 ±2.0	0.0015	0.0004	68%
plesovice	14.5	47	509	0.09	0.0539	0.0003	0.3994	0.0035	600.5 ±5.2	0.0536	0.0004	600.2 ±6.4	0.0042	0.001	98%
DX01-11	3.3	21	45	0.47	0.0534	0.0013	0.2923	0.0077	260.4 ±6.0	0.0397	0.0004	251.0 ±2.7	0.0079	0.0019	96%
DX01-12	4.2	98	103	0.95	0.0518	0.0008	0.2852	0.0048	254.8 ±3.8	0.0399	0.0003	252.4 ±2.1	0.0019	0.0004	99%
DX01-13	4.5	80	131	0.61	0.0518	0.0007	0.2839	0.0043	253.8 ±3.4	0.0398	0.0004	251.7 ±2.4	0.0024	0.0005	99%
DX01-14	5.5	58	112	0.52	0.0527	0.0007	0.2896	0.0040	258.3 ±3.1	0.0399	0.0003	252.4 ±2.0	0.0029	0.0006	97%
DX01-15	6.5	108	132	0.82	0.0524	0.0005	0.2880	0.0039	257.0 ±3.0	0.0399	0.0003	252.0 ±2.2	0.0019	0.0004	98%
DX01-16	2.2	17	37	0.46	0.0542	0.0012	0.2960	0.0068	263.5 ±5.3	0.0399	0.0004	252.2 ±2.6	0.0118	0.0028	95%
DX01-17	55.1	1027	696	1.48	0.0532	0.0008	0.2890	0.0081	257.7 ±6.3	0.0393	0.0007	248.7 ±4.2	0.0010	0.0002	96%
DX01-18	12.8	146	281	0.52	0.0518	0.0004	0.2849	0.0028	254.5 ±2.2	0.0399	0.0003	252.1 ±1.9	0.0017	0.0004	99%
DX01-19	4.3	67	106	0.63	0.0519	0.0006	0.2854	0.0043	254.9 ±3.3	0.0399	0.0004	252.3 ±2.3	0.0027	0.0008	98%
DX01-20	17.8	234	440	0.53	0.0517	0.0003	0.2839	0.0028	253.7 ±2.2	0.0399	0.0003	252.2 ±2.1	0.0012	0.0004	99%

注：其中编号为 plesovice 的为标样

4 分析结果

锆石无色透明,金刚光泽,晶体呈柱状,自形到半自形,粒径 40~100μm。有较清晰的生长环带,表明为典型的岩浆型锆石(图 2c)。样品共测定了 20 个数据点(表 1)。所分析的锆石的 U、Th 含量范围较大($U=36\times10^{-6}\sim931\times10^{-6}$, $Th=21\times10^{-6}\sim1027\times10^{-6}$),Th/U 比值都集中在 0.5~1.5 之间,而且 Th 和 U 之间有明显的正相关性。测试点号 DX01-3 和 DX01-10 的数据由于谐和度低于 95%,未纳入计算。锆石分析点的 $^{206}Pb/^{238}U$ 的值介于 248.7±2.0Ma 和 252.4±2.0Ma 之间,加权平均计算年龄为 251.0±1.0Ma (95% 置信度,MSWD=0.36)(图 2a, b),与 P-T 的分界线年龄 251.0±0.4Ma (章森桂等, 2009)一致。

5 讨论

5.1 峨眉山大火成岩省火山喷发结束时间的约束

目前,虽然大量研究显示,峨眉山地幔大火成岩省的火山主要喷发期在 ~260Ma (Zhou *et al.*, 2002, 2005, 2006, 2008; Wang and Zhou, 2006; Zhong and Zhu, 2006; Guo *et al.*, 2004; 陶琰等, 2008; Tao *et al.*, 2009),但火山喷发结束时间还存在着争议。He *et al.* (2007)对 ELIP 东部宣威组底部的碎屑岩及云南洱源峨眉山玄武岩系剖面顶部熔结凝灰岩测得锆石 U-Pb 年龄分别为 257±3Ma 和 263±5Ma,并因此认为该年龄代表了火山喷发的结束时间。然而需要指出的是,他们测定的年龄误差大,其 MSWD 分别达 6.5 和 7.5;且宣威组底部碎屑岩中的锆石不一定就来自于峨眉山玄武岩,其熔结凝灰岩样品也非取自于剖面的最顶部。范蔚茗等(2004)和 Lo *et al.* (2002)通过 $^{40}Ar/^{39}Ar$ 同位素测年,认为峨眉山大火成岩省的结束时间约在 ~253Ma 和 ~251Ma。但是,由于 $^{40}Ar/^{39}Ar$ 容易受后期的热蚀变事件干扰,所以他们测定的年龄结果被一些学者质疑(Ali *et al.*, 2004, 2005; He *et al.*, 2007)。许连忠等(2006)对威宁宣威组底部硅质页岩用 Rb-Sr 法测年,其年龄为 255±12Ma,显然该年龄的精度很差,无法很好地约束峨眉山玄武岩的喷发结束时间。本次研究样品采自 1 个完整剖面,地层层序连续好,测年锆石很少有残留的继承核,环带发育清晰。18 颗锆石加权平均年龄 251.0±1.0Ma 基本上代表火山喷发结束的时间,该年龄与前人 $^{40}Ar/^{39}Ar$ 法测年结果基本一致。

然而,以前认为峨眉山玄武岩喷发的结束时间为中二叠世而不可能是晚二叠世,其主要地质依据是峨眉山玄武岩被晚二叠世龙潭组地层所覆盖。但是,近年来的大量研究显示,峨眉山玄武岩系和龙潭组地层具有穿插交替关系,因而被认为可能是同时异相关系(陈景河等, 2006; Zhou *et al.*, 2000; Dai *et al.*, 2007, 2010, 2011),如陈景河等(2006)在黔西南二叠纪龙潭组地层中发现玄武质火山碎屑岩与木炭碎屑共生的直接证据,由此认为,木炭碎屑是由火山作用引发森林大火而形成的,亦即发生火山作用和沉积作用具有同时性,与加拿大北极高地 P-T 边界的煤灰层中粉煤灰颗粒的特征和形成环境十分类似,后者被认为是巨大火山喷发的直接证据(Grasby *et al.*, 2011)。综上所述,本次研究测定的年龄结果与地质事实并不矛盾。结合前人的大量同位素年龄测定结果,推测峨眉山玄武岩的喷发具有多旋回的特点,开始于中二叠世,可能结束于晚二叠世末期。另外,本次的测年结果与前人的古地磁资料吻合,即峨眉山大火成岩省火山喷发可以划分为两个阶段(Zheng *et al.*, 2010)。

5.2 ELIP 火山活动与华南地区 P-T 边界生物大灭绝的关系

目前对华南地区二叠-三叠系界线(P-TB)生物大规模灭绝的机制仍然存在争议,如火山学说(如 Yin *et al.*, 1992, 2007a)、地外碰撞学说(如 Jin *et al.*, 2000; Kaiho *et al.*, 2001; Becker *et al.*, 2001)、缺氧学说(如李玉成和周忠泽, 2002; Grice *et al.*, 2005; Shen YN *et al.*, 2011)、以及海洋酸化学说(如 Liang, 2002; 梁汉东和丁悌平, 2004)等。但是,由于在华南地区已发现晚二叠世的凝灰岩层或火山灰层较薄,因而一些学者由此认为,火山活动(火山学说)导致大规模生物灭绝的观点似乎有些牵强(如 Jin *et al.*, 2000; 张招崇, 2009)。

根据 P-T 边界普遍存在的火山物质,有学者提出华南地区二叠-三叠系界线生物灭绝与火山喷发有关的观点,如何锦文等(1987)在浙江煤山地区二叠-三叠系界线黏土岩中发现高温石英和火山玻璃等火山物质;Zhou and Kyte (1989)在四川广元上寺、浙江煤山和重庆凉风垭剖面 P-T 边界发现有火山灰层;Yin *et al.* (1989)发现华南地区多处二叠-三叠系剖面界线同样存在高温石英和火山玻璃等火山物质。

随后的许多研究也表明 P-T 界线生物大灭绝与火山活动有密切的成因联系,且对其进行了同位素年龄的约束。如 Bowring *et al.* (1998)对广西来宾和合山地区 P-T 界线黏土岩层中的锆石 SHRIMP U-Pb 测年,其年龄为 251.0±0.3Ma; Mundil *et al.* (2004)对四川广元上寺和浙江煤山剖面 P-T 边界火山灰层中的锆石 SHRIMP U-Pb 测年为 252.6±0.2Ma,认为该年龄代表了华南地区 P-T 界线生物大灭绝的时间;滇黔桂交界区域的二叠系-三叠系界线附近的黏土岩被认为可能是由于火山灰降落伴随正常沉积物沉积形成的(张素新等, 2002, 2004a, b, 2006);杨逢清等(2005)和 Yin *et al.* (2007b)在贵州威宁二叠系-三叠系界线剖面中发现了有火山成因的黏土岩,其附近上下 2 层的锆石获得的同位素年龄分别为 247.5±2.8Ma 和 252.6±2.8M。

此外,Xu *et al.* (2007)通过浙江煤山剖面 P-T 边界地层中铂族元素(PGE)与西伯利亚大火成岩省,以及峨眉山大火成岩省玄武岩中 PGE 的对比研究,发现其与这两个大火成岩省在 PGE 上具有良好的亲缘性;沈文杰等(2008)和 Shen *et al.* (2011)在浙江煤山剖面 P-T 界线地层中发现黑炭记

录，认为是强烈的火山喷发引发大量森林大火而造成了生物灭绝的残留物质，即大火事件，以上研究也支持火山活动导致晚二叠纪华南生物大灭绝的观点。

虽然上述大量的研究在一定程度上揭示了火山作用与生物灭绝之间的成因联系，但由于这些凝灰岩或火山灰厚度小，且不与峨眉山玄武岩在空间上共生，所以不能很好地证明这些凝灰岩是峨眉山大火成岩省的组成部分。本次研究表明，贵州盘县峨眉山玄武岩系中含有多层及大量的火山碎屑物，其中凝灰岩占绝对比例，厚度接近 100m，而且测年结果与前人在华南其他地区的 P-T 边界的凝灰岩、火山灰或黏土岩时间一致，说明峨眉山玄武岩发生过强烈的火山爆发，而且该次火山形成的凝灰岩可能已经遍及华南地区，从而导致了该地区的生物大规模灭绝。由此也暗示，不仅仅是西伯利亚大火成岩省火山作用产生的火山灰或气体对华南 P-T 边界生物灭绝造成影响，峨眉山大火成岩省对此次生物灭绝事件也有重要影响。

Courtillot (1999) 全面地研究了各地史时期大火成岩省，认为大火成岩省剖面中熔岩和火山碎屑的层数、厚度（即火山碎屑含量越高，表明其爆发性越强）及其持续时间制约着火山喷发造成气候变化的时空范围与幅度，即爆发性越强，其对气候环境的影响越大，并且大火成岩省的喷发物体积与生物种属灭绝的相对比例之间不存在任何相关关系 (Sepkoski, 1996)，因此认为喷发物初始体积并不是决定生物灭绝的主要因素 (Wignall, 2001)，如全球分布面积最大的 Ontong Java 洋底玄武岩喷发对气候的影响相对较微弱 (Wignall, 2001)。ELIP 虽然在 ~260Ma 发生了（中二叠瓜德卢普期末）大规模的玄武岩喷发，但主要为熔岩，火山碎屑岩占的比例极少（<1%），而且喷发主要为海相环境 (Peate and Scott, 2008, 2009)，所以 ELIP 大规模火山活动是否能对瓜德卢普期末的环境气候产生显著影响进而导致生物的大规模灭绝尚需进一步探索。尽管有研究显示其火山岩沉积夹层中的 C 同位素支持了其部分可能为火山成因 (Wignall *et al.*, 2009; Bond *et al.*, 2010a, b)；但也有研究指出瓜德卢普阶—乐平阶之间接触带是泥岩，不是酸性火山灰，因此认为 ELIP 的火山喷发与德卢普期末的生物灭绝不相吻合 (Ota and Isozaki, 2006; Isozaki, 2007; Isozaki and Ota, 2007; Isozaki *et al.*, 2007)。

6 结论

峨眉山大火成岩省东部贵州盘县峨眉山玄武岩系顶部近 100m 厚凝灰岩层 LA-ICP-MS 锆石 U-Pb 年龄为 251.0 ± 1.0Ma，代表了峨眉山大火成岩省火山喷发结束的时间，与华南地区的 P-T 分界线年龄基本相同，同时还与西伯利亚大火成岩省火山喷发的主体时间一致。说明地球历史上规模最大的生物灭绝事件可能不只是与西伯利亚大火成岩省的火山喷发有关，同时也与峨眉山大火成岩省的火山喷发有密切联系。

致谢 本次研究工作得到了中国地质大学硕士研究生孙挪亚和中科院地化所硕士研究生杜胜江，以及贵州大学顾尚义教授和硕士研究生付斌的帮助，在此谨致谢意。

References

Ali JR, Thompson GM, Song XY *et al.* 2002. Emeishan basalts (SW China) and the end-Guadalupian crisis. Journal of the Geological Society, London, 159: 21 – 29

Ali JR, Lo CH, Thompson GM *et al.* 2004. Emeishan basalt Ar-Ar overprint ages define several tectonic events that affected the western Yangtze platform in the Mesozoic and Cenozoic. Journal of Asian Earth Science, 22: 163 – 178

Ali JR, Thompson GM, Zhou MF *et al.* 2005. Emeishan large igneous province, SW China. Lithos, 79: 475 – 489

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

Becker L, Poreda RJ, Hunt AG *et al.* 2001. Impact event at the Permian-Triassic boundary: Evidence from extraterrestrial noble gases in fullerenes. Science, 291: 1530 – 1533

Bond DPG, Hilton J, Wignall PB *et al.* 2010a. The Middle Permian (Capitanian) mass extinction on land and in the oceans. Earth-Science Reviews, 102: 100 – 116

Bond DPG, Wignall PB, Wang W *et al.* 2010b. The mid-Capitanian (Middle Permian) mass extinction and carbon isotope record of South China. Palaeogeography, Palaeoclimatology, Palaeoecology, 292: 282 – 294

Bowring SA, Erwin DH, Jin YG *et al.* 1998. U/Pb zircon geochronology and tempo of the end-Permian mass extinction. Science, 280: 1039 – 1045

Chen JH, Deng YM, Wang JR *et al.* 2006. Existence of charcoal fragments in sedimentary basaltic volcanoclastic rock and its implication in geology, in the Longtan formation of Southwesten Guizhou. Guizhou Geology, 23(4): 278 – 281 (in Chinese with English abstract)

Chung SL and Jahn BM. 1955. Plume-lithosphere interaction in generation of the Emeishan flood basalts at the Permian-Triassic boundary. Geology, 23(10): 889 – 892

Chung SL, Jahn BM, Wu GY *et al.* 1998. The Emeishan Flood Basalt in SW China: A mantle plume initiation model and its connection with continental breakup and mass extinction at the Permian-Triassic boundary. In: Flower M *et al.* (eds.). Mantle Dynamics and Plate Interactions in East Asia. AGU Geodynamic Series, 27: 47 – 58

Courtillot V. 1999. Evolutionary Catastrophes: The Science of Mass Extinctions. Cambridge: Cambridge University Press, 1 – 237

Dai SF, Zhou YP, Ren DY *et al.* 2007. Geochemistry and mineralogy of the Late Permian coals from the Songzao coalfield, Chongqing, southwestern China. Science in China (Series D), 50: 678 – 688

Dai SF, Wang XB, Chen WM *et al.* 2010. A high-pyrite semianthracite of Late Permian age in the Songzao coalfield, southwestern China: Mineralogical and geochemical relations with underlying mafic tuffs. International Journal of Coal Geology, 83: 430 – 445

Dai SF, Wang XB, Zhou YP *et al.* 2011. Chemical and mineralogical compositions of silicic, mafic, and alkali tonsteins in the Late Permian coals from the Songzao coalfield, Chongqing, Southwest China. Chemical Geology, 282: 29 – 44

Fan WM, Wang YJ, Peng TP *et al.* 2004. Ar-Ar and U-Pb geochronology of Late Paleozoic basalts in western Guangxi and its constraints on the eruption age of Emeishan basalt magmatism. Chinese Science Bulletin, 20(3): 239 – 246

Grasby SE, Hamed S and Benoit B. 2011. Catastrophic dispersion of coal fly ash into oceans during the latest Permian extinction. Nature

Geoscience, 4:104 – 107
Grice K, Cao CQ, Love GD *et al*. 2005. Photic zone euxinia during the Permian-Triassic superanoxic event. Science, 307:706 – 709
Guo F, Fan WM, Wang YJ *et al*. 2004. When did the Emeishan plume activity start? Geochronological evidence from ultramafic-mafic dikes in southwestern China. International Geology Review, 46:226 – 234
He B, Xu YG, Huang LX *et al*. 2007. Age and duration of the Emeishan flood volcanism, SW China: Geochemistry and SHRIMP zircon U-Pb dating of silicic ignimbrites, post-volcanic Xuanwei Formation and clay tuff at the Chaotian section. Earth and Planetary Science Letters, 255:306 – 323
He B, Xu YG, Zhong YT *et al*. 2010. The Guadalupian-Lopingian boundary mudstones at Chaotian (SW China) are clastic rocks rather than acidic tuffs: Implication for a temporal coincidence between the end-Guadalupian mass extinction and the Emeishan volcanism. Lithos, 119:10 – 19
He JW, Rui L, Chai CF *et al*. 1987. The latest Permian and earliest Triassic volcanic activities in the Meishan area of Changxing, Zhejiang. Journal of Stratigraphy, 11:194 – 199 (in Chinese with English abstract)
Isozaki Y. 2007. Plume winter scenario for biosphere catastrophe: The Permo-Triassic boundary case. In: Yuen DA, Maruyama S, Harato S and Windley F (eds.). Superplume: Beyond Plate Tectonics. Berlin: Springer Dordrecht, 409 – 440
Isozaki Y and Ota A. 2007. Reply to comment by Ali R and Wignall PB on Ota A and Isozaki Y. 2006. Fusuline biotic turnover across the Guadalupian-Lopingian (Middle-Upper Permian) boundary in mid-oceanic carbonate buildups: Biostratigraphy of accreted limestone. Journal of Asian Earth Science, 30:201 – 203
Isozaki Y, Kawahata H and Minoshima K. 2007. The Capitanian (Permian) Kamura cooling event: The beginning of the Paleozoic-Mesozoic transition. Palaeoworld, 16:16 – 30
Jin YG, Wang Y, Wang W *et al*. 2000. Pattern of marine mass extinction near the Permian-Triassic boundary in south China. Science, 289: 432 – 436
Kaiho K, Kajiwara Y, Nakano T *et al*. 2001. End-Permian catastrophe by a bolide impact: Evidence of a gigantic release of sulfur from the mantle. Geology, 29:815 – 818
Kamo SL, Czamanske GK, Amelin Y *et al*. 2003. Rapid eruption of Siberian flood-volcanic rocks and evidence for coincidence with the Permian-Triassic boundary and mass extinction at 251Ma. Earth and Planetary Science Letters, 214:75 – 91
Li YC and Zhou ZZ. 2002. Massive dissociation of gas hydrate during oceanic anoxia as a cause of mass extinction at the end of Permian. Geology Geochemistry, 30(1):57 – 63
Liang HD. 2002. End-Permian catastrophic event of marine acidification by hydrated sulfuric: Mineralogical evidence from Meishan section of South China. Chinese Science Bulletin, 47:393 – 1397
Liang HD and Ding TP. 2004. Evidence of extremely light gypsum from the Permian/Triassic (P/T) event boundary at the Meishan section of South China. Acta Geoscientica Sinica, 25(1): 33 – 37 (in Chinese with English abstract)
Lo CH, Chung SL, Lee TY *et al*. 2002. Age of the Emeishan flood magmatism and relations to Permian-Triassic boundary events. Earth and Planetary Science Letters, 198:449 – 458
Mundil R, Ludwig KR, Metcalfe I *et al*. 2004. Age and timing of the Permian mass extinctions: U/Pb dating of closed-system zircons. Science, 305:1760 – 1763
Ota A and Isozaki Y. 2006. Fusuline biotic turnover across the Guadalupian-Lopingian (Middle-Upper Permian) boundary in mid-oceanic carbonate buildups: Biostratigraphy of accreted limestone in Japan. Journal of Asian Earth Sciences, 26:35 – 368
Peate IU and Scott EB. 2008. Re-evaluating plume-induced uplift in the Emeishan large igneous province. Nature Geoscience, 1:625 – 629
Peate IU and Scott EB. 2009. Pre-eruptive uplift in the Emeishan? reply. Nature Geoscience, 2(8):531 – 532
Saunders AD. 2005. Large igneous provinces: Origin and environmental consequences. Elements, 1:259 – 263
Saunders AD and Reichow M. 2009. The Siberian traps and the end-Permian mass extinction: A critical review. Chinese Science Bulletin, 54:20 – 37
Sepkoski JJJ. 1996. Patterns of Phanerozoic extinctions: A perspective from global data bases. In: Walliser OH (ed.). Global Events and Event stratigraphy. Berlin: Springer Verlag, 35 – 52
Shen WJ, Lin YG, Sun Y *et al*. 2008. Black carbon record across the Permian-Triassic boundary section at Meishan, Changxing County, Zhejiang Province and its significance. Acta Petrologica Sinica, 24: 2407 – 2414 (in Chinese with English abstract)
Shen WJ, Sun Y, Lin YG *et al*. 2011. Evidence for wildfire in the Meishan section and implications for Permian-Triassic events. Geochimica et Cosmochimica Acta, 75:1992 – 2006
Shen YN, James F, Zhang H *et al*. 2011. Multiple S-isotopic evidence for episodic shoaling of anoxic water during Late Permian mass extinction. Nature communications, DOI:10.1038/ncomms1217
Song B, Zhang YH, Wan YS *et al*. 2002. Mount making and procedure of the SHRIMP dating. Geological Review, 48(Suppl.):26 – 30 (in Chinese with English abstract)
Svensen H, Planke S, Polozov AG *et al*. 2009. Siberian gas venting and the end-Permian environmental crisis. Earth and Planetary Science Letters, 277:490 – 500
Tao Y, Ma YS, Miao LC *et al*. 2009. SHRIMP U-Pb zircon age of the Jinbaoshan ultramafic intrusion, Yunnan Province, SW China. Chinese Science Bulletin, 54(1):168 – 172
Thordarson T and Self S. 2003. Atmospheric and environmental effects of the 1783 – 84 Laki eruption: A review and reassessment. Journal of Geophysical Research 108 (D1): 4011, doi: 10.1029/2001JD002042
Wang CY and Zhou MF. 2006. Genesis of the Permian Baimazhai magmatic Ni-Cu-(PGE) sulfide deposit, Yunnan, SW China. Mineralium Deposita, 41:771 – 783
Wignall PB. 2001. Large igneous provinces and mass extinctions. Earth-Science Reviews, 53:1 – 33
Wignall PB. 2005. The link between large igneous province eruptions and mass extinctions. Elements, 1:193 – 297
Wignall PB, Sun YD, David PG *et al*. 2009. Volcanism, mass extinction, and carbon isotope fluctuations in the Middle Permian of China. Science, 342(29):1179 – 1182
Xu L, Lin Y, Shen WJ *et al*. 2007. Platinum-group elements of the Meishan Permian-Triassic boundary section: Evidence for flood basaltic volcanism. Chemical Geology, 246:55 – 64
Xu LZ, Zhang ZW, Zhang Q *et al*. 2006. The age of siliceous shale in the lower part of the Xuanwei Formation in Weining and its geological implication. Acta Mineralogica Sinica, 26(4): 387 – 394 (in Chinese with English abstract)
Xu YG, Chung SL, Shao H *et al*. 2010. Silicic magmas from the Emeishan large igneous province, Southwest China: Petrogenesis and their link with the end-Guadalupian biological crisis. Lithos, 119:47 – 60
Yang FQ, Yin HF, Yu JX *et al*. 2005. Study on the continental successions of Permian/Triassic boundary of the Chahe section in Weining County, Guizhou Province. Science in China (Series D), 35(6):519 – 529 (in Chinese)
Yin HF, Huang SJ, Zhang KX *et al*. 1989. Volcanism at the Permian-Triassic boundary in South China and its effects on mass extinction. Acta Geologica Sinica, 2:169 – 181
Yin HF, Huang SJ, Zhang KX *et al*. 1992. The effects of volcanism on the Permo-Triassic mass extinction in South China. In: Sweet WC, Yang ZY, Dickins JM and Yin HF (eds.). Permo-Triassic Events in the Eastern Tethys. Cambridge: Cambridge University Press, 169 – 174
Yin HF, Feng QL, Lai XL *et al*. 2007a. The protracted Permo-Triassic crisis and multi-episode extinction around the Permian-Triassic boundary. Global and Planetary, 55:1 – 20
Yin HF, Yang FQ, Yu JX *et al*. 2007b. An accurately delineated Permian-Triassic boundary in continental successions. Science in China (Series D), 35(6):1281 – 1292

Zhang SG, Zhang YB and Yan HJ. 2009. A brief introduction to the 'international stratigraphic chart' (2008). Journal of Stratigraphy, 33(1):1-10 (in Chinese with English abstract)

Zhang SX, Liu JP, Xiao SQ *et al*. 2002. Study on clay rocks of Permian/Triassic boundary from Duanshan, Guizhou Province. Journal of Earth Science, 27(Suppl.):259-264 (in Chinese with English abstract)

Zhang SX, Peng YQ, Yu JX *et al*. 2004a. Clay rocks of the terrestrial Permian-Triassic boundary of the Chahe section in Weining of western Guizhou Province, South China: Based on X-ray diffraction and scan electronicm microscope. Geological Science and Technology Information, 23(1):21-26 (in Chinese with English abstract)

Zhang SX, Yu JX, Yang FQ *et al*. 2004b. Study on clay rocks of the neritic, littoral and marine-terrigenous facies across the Permian-Triassic boundary in the eastern Yunnan and western Guizhou, South China. Journal of Mineralogy and Petrology, 24(4): 81-86 (in Chinese with English abstract)

Zhang SX, Feng QL, Gu SZ *et al*. 2006. Clay stone around deep water Permian/Triassic boundary from Guizhou and Guangxi region. Geological Science and Technology Information, 25(6):9-13 (in Chinese with English abstract)

Zhang ZC. 2009. A discussion on some important problems concerning the Emeishan large igneous province. Geology in China, 36(3):634-646 (in Chinese with English abstract)

Zheng LD, Yang ZY, Tong YB *et al*. 2010. Magnetostratigraphic constraints on two-stage eruptions of the Emeishan continental flood basalts. Geochemistry Geophysics Geosystems, doi: 10.1029/2010GC003267

Zhong H and Zhu WG. 2006. Geochronology of layered mafic intrusions from the Pan-Xi area in the Emeishan large igneous province, SW China. Mineralium Deposita, 41:599-606

Zhou L and Kyte FT. 1988. The Permian-Triassic boundary event: A geochemical study of three Chinese sections. Earth and Planetary Science Letters, 90:411-421

Zhou MF, Malpas J, Song XY *et al*. 2002. A temporal link between the Emeishan large igneous province (SW China) and the end-Guadalupian mass extinction. Earth and Planetary Science Letters, 196:113-122

Zhou MF, Robinson PT, Lesher CM *et al*. 2005. Geochemistry, petrogenesis and metallogenesis of the Panzhihua gabbroic layeredintrusion and associated Fe-Ti-V oxide deposits, Sichuan Province, SW China. Journal of Petrology, 46:2253-2280

Zhou MF, Zhao JH, Qi L *et al*. 2006. Zircon U-Pb geochronology and elemental and Sr-Nd isotope geochemistry of Permian mafic rocks in the Funing area, SW China. Contributions to Mineralogy and Petrology, 151:1-19

Zhou MF, Arndt NT, Malpas J *et al*. 2008. Two magma series and associated ore deposit types in the Permian Emeishan large igneous province, SW China. Lithos, 103:352-368

Zhou YP, Bohor BF and Ren YL. 2000. Trace element geochemistry of altered volcanic ash layers (tonsteins) in Late Permian coal-bearing formations of eastern Yunnan and western Guizhou provinces, China. International Journal of Coal Geology, 44:305-324

附中文参考文献

陈景河，邓一明，王军荣等. 2006. 黔西南地区龙潭组玄武质火山碎屑岩中木炭碎屑的存在及地质意义. 贵州地质，23(4):278-281

范蔚茗，王岳军，彭头平等. 2004. 桂西晚古生代玄武岩 Ar-Ar 和 U-Pb 年代学及其对峨眉山玄武岩省喷发时代的约束. 科学通报，49:1892-1900

何锦文，芮琳，柴之芳等. 1987. 浙江长兴煤山地区晚二叠世末、早三叠世初的火山活动. 地层学杂志，11(3):194-199

李玉成，周忠泽. 2002. 华南二叠纪末缺氧海水中有毒气体与生物集群绝灭. 地质地球化学，30(1):57-63

梁汉东，丁悌平. 2004. 中国煤山剖面二叠-三叠系事件界限地层中石膏的负硫同位素异常. 地球学报，25(1):33-37

沈文杰，林杨挺，孙永革等. 2008. 浙江省长兴县煤山剖面二叠-三叠系过渡地层中的黑碳记录及其地质意义. 岩石学报，24:2407-2414

宋彪，张云海，万渝生等. 2002. 锆石 SHRIMP 样品靶制作、年龄测定及有关现象讨论. 地质论评，48(增刊):26-30

陶琰，马言胜，苗来成等. 2008. 云南金宝山超镁铁岩体锆石 SHRIMP 年龄. 科学通报，53(22):2828-2832

许连忠，张正伟，张乾等. 2006. 威宁宣威组底部硅质页岩 Rb-Sr 古混合线年龄及其地质意义. 矿物学报，26(4):387-394

杨逢清，殷鸿福，喻建新等. 2005. 贵州威宁岔河陆相二叠系-三叠系界线地层研究. 中国科学(D 辑)，35(6):519-529

章森桂，张允白，严惠君. 2009. "国际地层表"(2008)简介. 地层学杂志，33(1):1-10

张素新，刘江平，肖少泉等. 2002. 贵州断衫 P/T 界线黏土岩研究. 地球科学，27(增刊):259-264

张素新，彭元桥，喻建新等. 2004a. 黔西威宁岔河陆相二叠系-三叠系界线黏土岩研究——基于 X 射线衍射、扫描电镜分析. 地质科技情报，23(1):81-85

张素新，喻建新，杨逢等. 2004b. 黔西滇东地区浅海、滨海及海陆交互相二叠系-三叠系界线附近黏土岩研究. 矿物岩石，24(4):81-86

张素新，冯庆来，顾松竹等. 2006. 黔桂地区深水相二叠系/三叠系界线附近黏土岩研究. 地质科技情报，25(6):9-13

张招崇. 2009. 关于峨眉山大火成岩省一些重要问题的讨论. 中国地质，36(3):634-646