黔东南新元古代下江群碎屑岩地球化学特征及其大地构造意义

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内容提要：黔东南下江群是一套具复理石特征的陆源碎屑岩夹火山碎屑岩建造，由下向上分别为甲路组、乌叶组、番昭组、清水江组、平略组和隆里组。本文研究了该套岩石的主量元素、微量元素和Nd同位素特征。结果显示：下江群各个组样品均显示出不同程度的Co、La、Ce、Nd、Y和Lu元素的富集，Ta和Ni元素亏损以及明显的Eu负异常，$\varepsilon_{Nd}(t)$表现出负异常($\varepsilon_{Nd}(t)$：-0.35～-3.36)。岩石地球化学特征显示源岩以遭受了中等程度化学风化作用(CIA：52～79)的酸性岩为主，并混有适量的基性岩。结合已有研究成果，判断物源区主要以盆地周缘的近源沉积为主，如分布在桂北一带的花岗质岩石和基性岩。构造背景判别表明盆地处于与岛弧活动相关的活动大陆边缘背景，如此的构造背景暗示，江南造山带西段在下江群沉积期可能仍存在消减作用，扬子板块与华夏板块此时还未完全拼合。综合对比江南造山带东、西两段消减—碰撞的时间，暗示扬子板块和华夏板块之间可能具有一个“东早西晚”的碰撞造山过程。

关键词：黔东南；下江群；沉积地球化学；物源；江南造山带

扬子板块东南缘的江南造山带是扬子板块与华夏板块在新元古代碰撞、拼合作用的产物(Chen Jiangfeng et al.，1991；郭令智，1996；徐夕生等，1992)。两者在新元古代时期的拼合时间是华南基础地质研究中最具争议的问题之一。一种观点认为两个板块在大约1100～900 Ma左右完成拼合，随后在820～760 Ma期间经历了超级地幔柱作用形成南华裂谷和康滇裂谷两个陆内裂谷盆地(Li Xinhua et al.，1999，2003；Li Zhengxiang et al.，2008；Wang Jian et al.，2003；李献华等，2008，2012)。另一种观点认为两个板块在820Ma左右才完成拼合，在780～720 Ma经历了大陆裂谷作用(Wang Xiaolei et al.，2006，2007，2008；周金城等，2003，2005，2009；Zhou Jincheng et al.，2004，2009；赵军红等，2015；Zhao Junhong et al.，2011；Zheng Yongfei et al.，2008；Zhou Meifu et al.，2002a，2002b)。上述两种观点均认为在江南造山带广泛分布的820 Ma左右的不整合面(四堡运动)之上的一套碎屑岩层序为陆内裂谷盆地沉积，然而近年来部分学者在研究江南造山带西段760 Ma左右的镁铁质—超镁铁质岩和四堡运动不整合面之上下江群中的同沉积碎屑锆石地球化学特征时，发现该套岩石和锆石形成于岛弧的构造背景(Lin Musen et al.，2015；覃永军，2015)，据此推测江南造山带西段在此时期的构造背景可能仍然处于弧—陆俯冲环境，扬子板块和华夏板块在四堡运动之后并未完全闭合，直至雪峰运动(720 Ma)之后华夏板块与扬子板块才完全拼贴为一体。

黔东南地区构造上位于江南造山带西段(图1a)，区内新元古代下江群是处于四堡运动和雪峰运动不整合面之间的岩石单元，是一套浅变质的陆源碎屑岩夹火山岩组合。该套碎屑岩沉积时盆地的大地构造背景受控于江南造山带西段的构造背景，因而通过对这套碎屑岩物源和沉积的构造背景的研究，能够反映该时期江南造山带西段的构造背景，对探讨扬子板块和华夏板块在西段的拼合时间具有重要的意义。本文利用碎屑骨架颗粒统计、全岩主、微量元素以及Nd同位素研究了下江群的物源和盆地的沉积背景，并结合已有的研究讨论了江南造山带西段下江期的构造背景。

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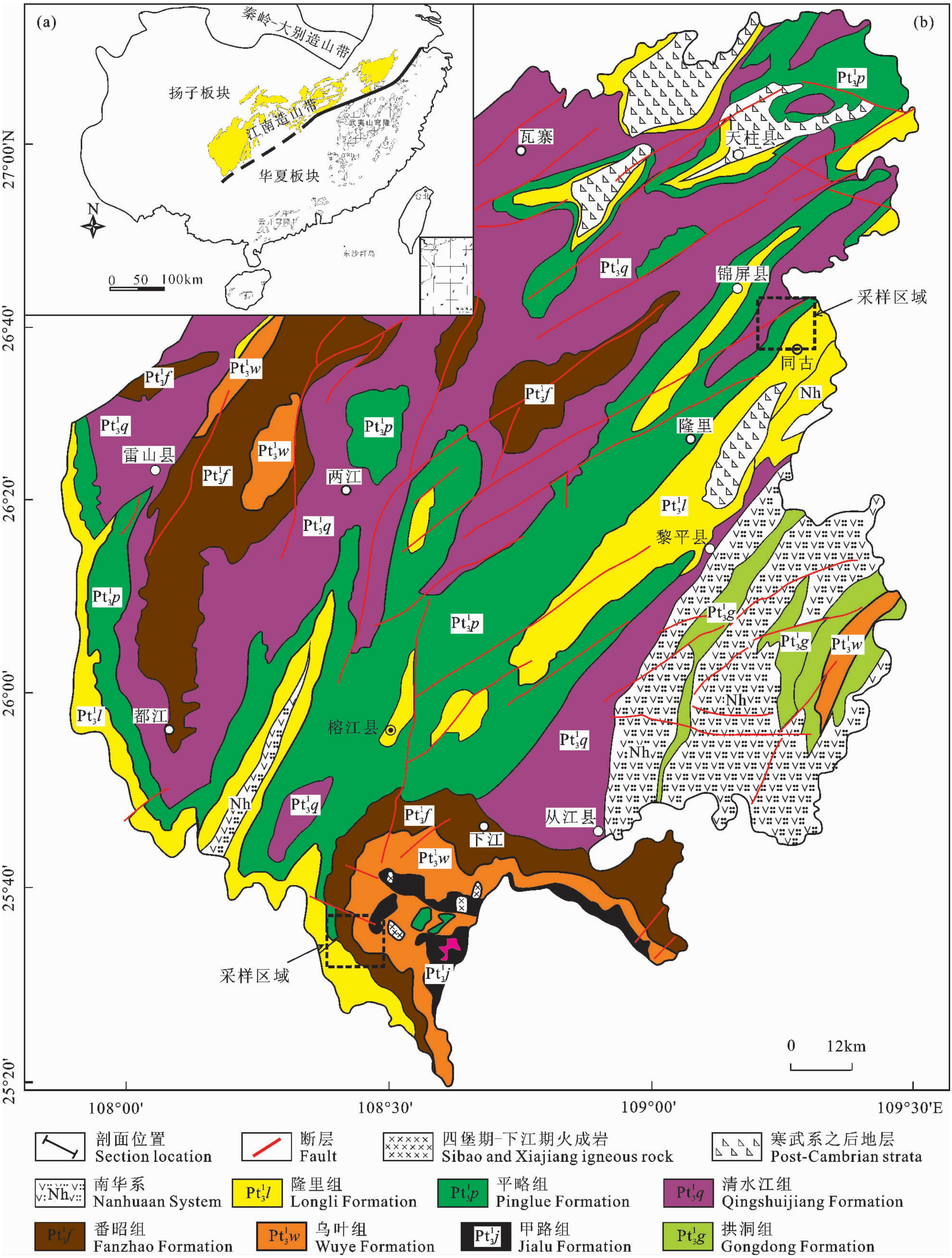

图 1 江南造山带西段大地构造位置及黔东南地区前寒武纪地层分布(据覃永军等,2015,有修改)

Fig. 1 The tectonic location of the Jiangnan orogenic belt and the Precambrian stratigraphic distribution of the Southeast Guizhou Province (modified from Qin Yongjun et al. ,2015&)

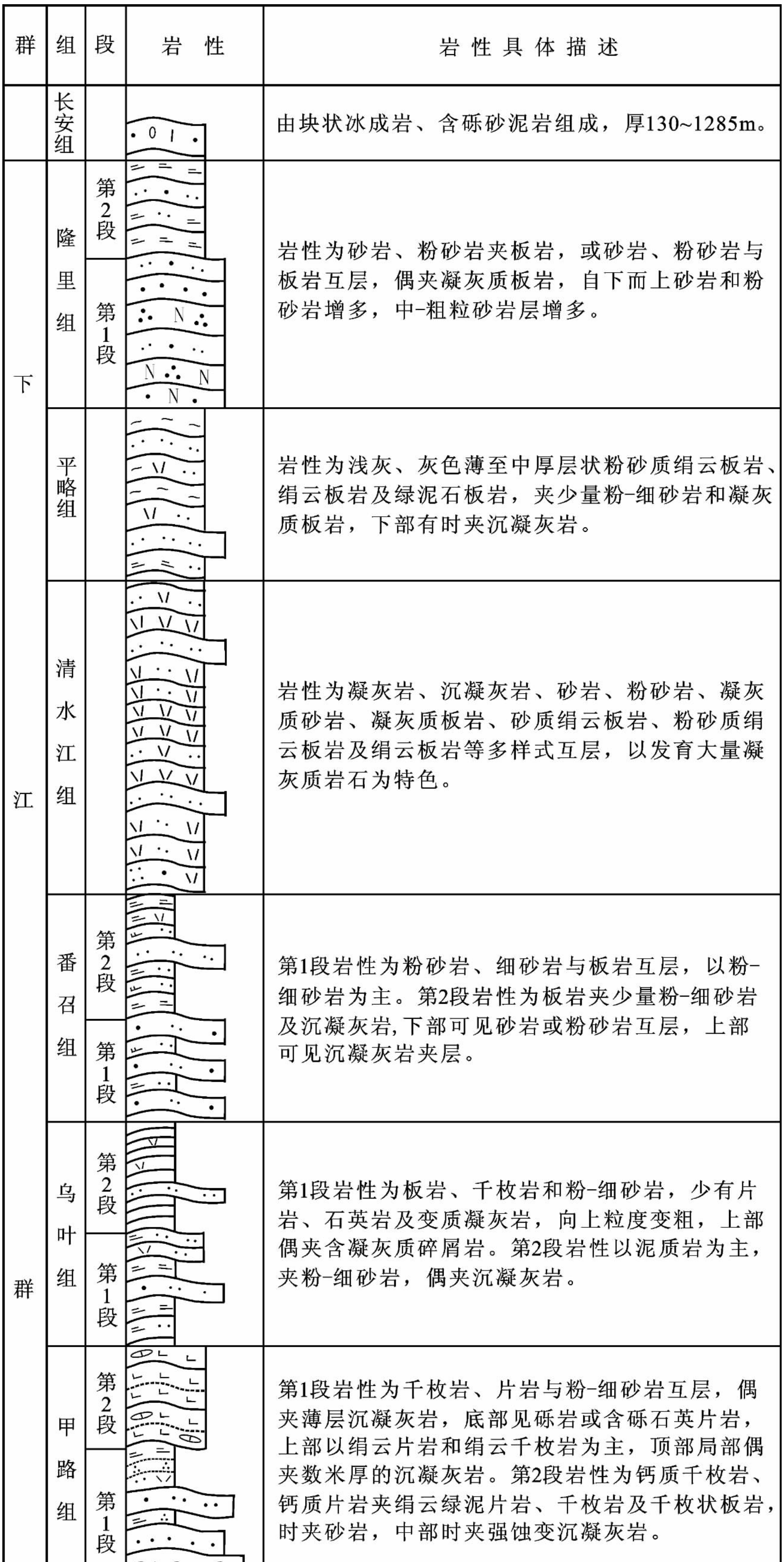

图 2 黔东南地区下江群综合柱状图
（据覃永军等,2015,有修改）
Fig. 2 Column of the Xiajiang Groups in the Southeast Guizhou (modified from Qin Yongjun et al. ,2015&)

1　区域地质概况与采样

江南造山带主要由新元古代变火山—沉积岩系、新元古代花岗岩和少量镁铁质岩组成,呈弧形从西到东跨越桂北、黔东、湘西、湘东北、赣北、皖南和浙北等地区,长约 1500 km,宽约 200 km(王剑等,2001;薛怀民等,2010;周金城等,2014)(图 1a)。这套前寒武纪地质单元被地层时代为 830 ~ 820 Ma 的四堡运动不整合面分为上、下两个构造层,下构造层变质程度较弱,一般为绿片岩相,但变形较强。上构造层变质、变形程度均较弱。上、下构造层在不同地区有不同的命名,分别是桂北四堡群/丹洲群、黔东梵净山群/下江群、湘西冷家溪群/板溪群、赣北双桥山群/登山群、皖南溪口群/历口群和浙北双溪坞群/河上镇群。下江群及其同期地层与上覆地层之间存在区域不整合面,该不整合面在区域上被称为雪峰运动(陈建书等,2016;李利阳等,2016)。

贵州新元古代下江群位于江南造山带西段,主要分布在贵州东北部梵净山至东南部从江地区,地层由老到新依次为甲路组、乌叶组、番昭组、清水江组、平略组、隆里组,各组之间呈整合接触关系(图 2)。岩性主要以粉砂质板岩、变余粉—细砂岩、凝灰质板岩、凝灰质变余粉砂岩和沉凝灰岩等为主(陈文西等,2007;覃永军等,2015;杨瑞东等,2009;张晓东等,2012)。普遍发育水平层理、平行层理、粒序层理、交错层理和透镜状层理等,属于滨海—浅海—半深海沉积体系。下江

表 1 黔东南下江群碎屑岩地球化学数据

Table 1 Geochemical data of clastic rocks from the Xiajiang Group, Southeast Guizhou Province

组名	样品	岩性	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	烧失	总量	CIA	Be	Sc	V	Cr	Co	Ni	Cu	Zn	Ga	Rb	Sr	Y	Zr
甲路组	15CJ-8	粉砂岩	62.56	0.76	18.87	7.53	0.1	1.76	0	0.2	4.39	0.05	4.15	100.37	79	2.55	22	129	113	28.2	54.5	20.7	117	25.3	219	19.1	23.2	189
甲路组	15CJ-14	细砂岩	73.87	0.75	13.49	4.72	0.04	0.88	0.03	0.12	3.65	0.02	2.88	100.45	76	2.08	15.7	85.9	219	36.2	25	13.7	56.3	17.7	203	17.9	21.4	244
乌叶组	15CJ-15	粉砂岩	65.44	1.09	19.12	4.51	0.03	1.25	0	0.41	5.21	0.01	3.27	100.34	75	2.73	24.4	142	118	21.9	20.6	19.4	67.6	26.1	264	40.1	40.1	284
乌叶组	15CJ-16	粉砂岩	62.15	0.75	19.33	6.83	0.04	1.85	0.13	1.32	4.75	0.04	3.23	100.42	72	3.19	20.2	92.4	75.6	20.4	19.1	1.04	76.3	28.4	231	63.2	70.2	246
番昭组	15CJ-17	粉砂岩	68.01	0.44	17.81	3.15	0.05	1.05	0.15	3.2	4.16	0.07	2.28	100.37	64	2.99	14.1	50.8	26.4	26	13.2	5.46	61.2	26.2	142	114	44.2	229
番昭组	15JP-4	粉砂岩	65.59	0.51	20.75	1.96	0	0.55	0	2.34	5.24	0.03	3.41	100.38	69	3.48	15	34.4	19	7.78	5.57	4.16	32.9	33.9	160	38.9	77.7	303
清水江组	15JP-11	细砂岩	77.88	0.35	10.98	1.88	0.08	0.34	1.02	3.81	1.89	0.04	2.13	100.4	52	1.35	7.62	22.5	16	50.6	6.8	3.55	50.1	12.5	52.6	85.3	31.1	197
清水江组	15JP-14	粉砂岩	71.37	0.56	15.9	2.75	0.04	0.69	0.13	4.63	2.65	0.05	1.63	100.4	60	2.18	12.2	39.7	28.5	24.2	9.42	7.69	84.4	23	75.2	145	43.3	255
平略组	15JP-23	粉砂岩	64.51	0.75	18.1	5.57	0.08	1.79	0.68	2.73	3.13	0.09	2.97	100.4	67	2.5	18.7	87.4	35.4	16.9	15.2	20	71.3	25	121	154	48.4	245
平略组	15JP-24	粉砂岩	64.08	0.71	16.66	6.33	0.14	2.01	1.64	2.08	2.47	0.11	4.13	100.36	65	1.96	16	85.6	50.5	29.8	21.8	16	116	22.7	100	178	37.3	229
隆里组	15JP-26	粉砂岩	69.56	0.58	15.55	4.8	0.08	1.85	0.14	1.55	3.34	0.05	2.94	100.44	71	2.1	13.3	52.3	31.9	22.4	13	16.8	49.8	20.3	116	91.3	37.8	257
隆里组	15JP-28	粉砂岩	68.77	0.62	15.62	3.66	0.08	1.07	1.53	3.16	2.49	0.06	3.3	100.36	59	1.9	12.1	57.7	24.4	23.8	9.08	19	49.7	20.5	83.3	303	31.8	288
PAAS		页岩	62.8	1	18.9	6.5	0.11	2.2	1.3	1.2	3.7	0.16					16		110		55			20	160	200	27	210

组名	样品	岩性	Nb	Cs	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta	Pb	Th	U	$\frac{La_N}{Yb_N}$	$\frac{Eu}{Eu^*}$	ΣREE
甲路组	15CJ-8	粉砂岩	12.7	6.73	491	31.5	21.2	7.27	27	5.23	1.16	4.3	0.7	4.18	0.83	2.53	0.45	3.18	0.49	5.17	0.87	67.5	13.5	2.49	7.11	0.73	110.02
甲路组	15CJ-14	细砂岩	14.4	6.26	281	5.61	12.3	1.44	5.7	1.26	0.29	1.73	0.4	3.03	0.72	2.34	0.41	2.8	0.42	6.46	0.9	23.1	14.1	3.08	1.44	0.60	38.45
乌叶组	15CJ-15	粉砂岩	17.6	22.4	719	42.5	87.7	10.5	40.2	7.75	1.63	6.87	1.09	6.52	1.37	4.09	0.68	4.6	0.69	7.68	1.03	7.73	17.8	3.45	6.63	0.67	216.19
乌叶组	15CJ-16	粉砂岩	15.6	25.3	1226	52.6	149	13	49.5	10.6	2	10.5	1.84	11.7	2.42	6.95	1.06	6.47	0.9	6.59	0.98	17.1	17	3.18	5.83	0.57	318.54
番昭组	15CJ-17	粉砂岩	14.4	6.53	1289	17.1	34.2	4.25	18.8	3.64	0.85	4.14	0.84	6.08	1.43	4.32	0.71	4.6	0.66	6.16	0.76	2.75	7.57	1.33	2.67	0.67	101.62
番昭组	15JP-4	粉砂岩	18.4	9.54	1568	84.5	170	20.5	80.5	16	2.68	13.8	2.12	12.5	2.61	7.79	1.28	8.2	1.21	9.18	1.04	2.25	17	3.16	7.39	0.54	423.69
清水江组	15JP-11	细砂岩	9.25	2.74	637	27.1	56.2	6.69	26.7	5.46	1.18	5.42	0.86	5.51	1.11	3.35	0.5	3.35	0.51	6.64	0.75	33.2	6.64	1.42	5.80	0.66	143.94
清水江组	15JP-14	粉砂岩	11.7	2.92	827	40.2	80.3	10.3	41.7	8.58	1.85	7.89	1.26	7.4	1.49	4.24	0.67	4.29	0.64	6.54	0.7	13	8.71	1.81	6.72	0.68	210.81
平略组	15JP-23	粉砂岩	12.1	6.27	695	46.8	96.4	11.2	43.5	8.43	1.75	7.9	1.3	8.12	1.65	4.75	0.76	4.76	0.68	6.68	0.84	3.91	11.8	2.54	7.05	0.65	238
平略组	15JP-24	粉砂岩	13	6.64	490	39	78.6	9.44	37.1	7.41	1.45	6.82	1.09	6.39	1.29	3.77	0.61	3.9	0.58	6.17	0.84	22.8	12.3	2.56	7.17	0.61	197.45
隆里组	15JP-26	粉砂岩	11.4	6.03	852	38.9	79.2	9.52	37.2	7.36	1.58	6.7	1.1	6.49	1.31	3.73	0.61	3.88	0.56	6.71	0.71	3.31	10	1.72	7.19	0.68	198.14
隆里组	15JP-28	粉砂岩	11.5	4.3	604	53.1	105	12.2	45.7	7.94	1.59	6.6	0.94	5.39	1.11	3.3	0.54	3.53	0.53	7.51	0.74	12.5	9.9	1.95	10.79	0.65	247.47
PAAS		页岩	19		650	38.2	79.6	8.83	33.9	5.55	1.08	4.66	0.77	4.68	0.99	2.85	0.41	2.82	0.43	5	1.28	20	14.6	3.1	9.72	0.63	185

注：PAAS 数据据 Mclennan，1985。主量元素单位为 %；微量元素单位为 μg/g。

表 2 黔东南下江群碎屑岩 Sm-Nd 同位素数据

Table 2 Sm-Nd isotopic data of clastic rocks from the Xiajiang Group, Southeast Guizhou Province

样品	组名	年龄(Ma)	Sm (μg/g)	Nd (μg/g)	$\frac{n(^{143}Nd)}{n(^{144}Nd)}$	2σ	$\frac{n(^{147}Sm)}{n(^{144}Nd)}$	$\left[\frac{n(^{143}Nd)}{n(^{144}Nd)}\right]_{S(t)}$	$\left[\frac{n(^{143}Nd)}{n(^{144}Nd)}\right]_{CHUR(t)}$	$\varepsilon_{Nd}(t)$	T_{DM} (Ga)
15JP-28	隆里组	725	7.94	45.7	0.512148	0.000006	0.105027	0.511649	0.511703	-1.0612	1.4050
15JP-26	隆里组	725	7.36	37.2	0.512205	0.000009	0.119600	0.511637	0.511703	-1.3008	1.5300
15JP-23	平略组	734	8.43	43.5	0.512216	0.000008	0.117148	0.511652	0.511691	-0.7662	1.4740
15JP-14	清水江组	764	8.58	41.7	0.512104	0.000007	0.124379	0.511481	0.511653	-3.3566	1.7828
15JP-11	清水江组	764	5.46	26.7	0.512191	0.000008	0.123617	0.511572	0.511653	-1.5816	1.6215
15JP-4	番昭组	775	16	80.5	0.512231	0.000007	0.120149	0.511620	0.511638	-0.3521	1.4968

注:年龄 t 取 725 Ma、734 Ma、764 Ma 和 775 Ma,据覃永军等,2015。

$$\varepsilon_{Nd}(t)=\left\{\frac{\left[\frac{n(^{143}Nd)}{n(^{144}Nd)}\right]_{S(t)}}{\left[\frac{n(^{143}Nd)}{n(^{144}Nd)}\right]_{CHUR(t)}}-1\right\}\times 10000。\qquad T_{DM}/Ga=\frac{1}{0.00654}\ln\left\{\frac{\left[0.51315-\frac{n(^{143}Nd)}{n(^{144}Nd)}\right]}{\left[0.21357-\frac{n(^{147}Sm)}{n(^{144}Nd)}\right]}+1\right\}。$$

群各岩石单元内部分选出的同沉积锆石年代学数据厘定了整个下江群的沉积时限约为 815 ~ 720 Ma(覃永军等,2015)。

本文样品的采样地点位于黔东南锦屏和从江地区(图 1b),下江群各个组均有采集,主要岩性是中砂岩、细砂岩和粉砂岩。共分析样品 21 件,对其中 9 件粒度较粗的砂岩样品进行了碎屑骨架颗粒统计,12 件粒度较细的砂岩样品进行了全岩主、微量元素测试,其中包括进行了 Nd 同位素分析的 6 件细粒砂岩样品。锦屏地区采集的样品 GPS 范围是(26°33′58″N ~ 26°41′10″N, 109°04′14″E ~ 109°21′19″E),从江地区采集的样品 GPS 范围是(25°28′48″N ~ 25°30′01"N, 108°32′26"E ~ 108°36′22"E)。主量、微量元素测试分别在中国地质大学(武汉)生物地质与环境地质国家重点实验室采用 X 荧光光谱分析和 ICP-MS 测试,分析精度均高于 5%。Nd 同位素测试在广州地球化学研究所采用 MC-ICP-MS 测试,其中 $n(^{143}Nd)/n(^{144}Nd)$ 值用 $n(^{146}Nd)/n(^{144}Nd)=0.7219$ 校正,国际标准溶液 La Jalla Nd 的 $n(^{143}Nd)/n(^{144}Nd)$ 值为 0.511862 ± 10(2σ)。在分析过程中,$n(^{146}Nd)/n(^{144}Nd)$ 比值在 95% 的置信区间内误差精度好于 0.000015。结果见表 1,表 2。

2　碎屑岩骨架颗粒统计原则及结果

碎屑岩骨架颗粒统计在偏光显微镜下采用正方网格交点法进行,每个样品的统计点数约为 300 ~ 500。按照 Dickinson 统计要求和样品特征制定了本次统计原则(Dickinson et al., 1979, 1980, 1983,

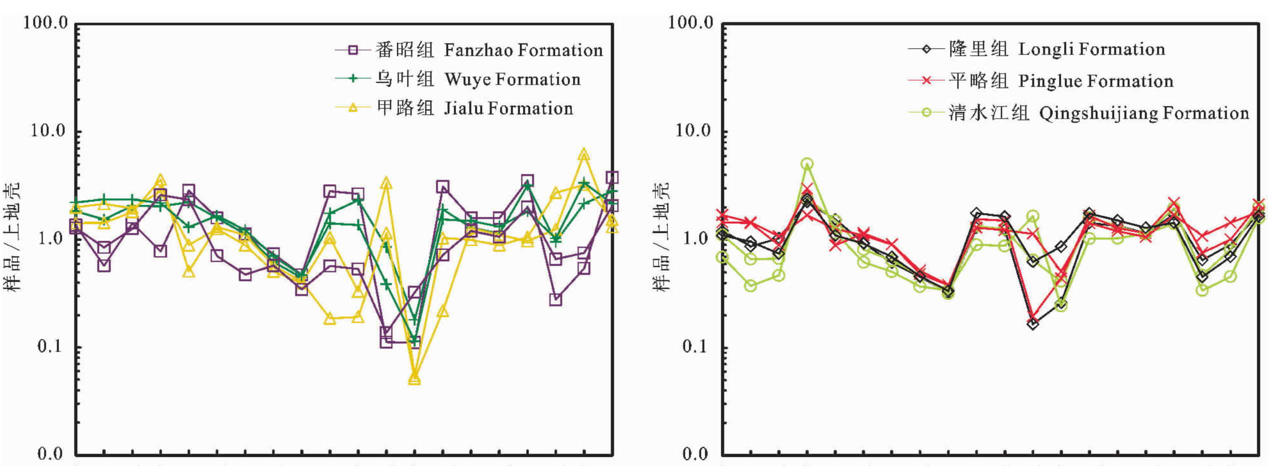

图 3 黔东南下江群碎屑岩微量元素上地壳标准化蛛网图(上地壳标准化数据据 Mclennan et al., 1993)

Fig. 3 Upper crust-normalized spider diagram of clastic rock from the Xiajiang Group, Southeast Guizhou Province (Upper crust-normalizing data from Mclennan et al., 1993)

1985)：①尽可能选取粒度较粗的砂岩，并且受到后期变质作用影响较小。②变质岩岩屑按照原岩的不同已将其分属为火山岩岩屑和沉积岩岩屑。根据上述原则，共选取了 9 件符合条件的样品，粒度为细粒及以上，9 件样品的统计结果见表 3。考虑到这 9 件样品粒度比其它样品粒度粗，因此它们仅能代表下江群部分粒度较粗的碎屑岩特征。

表 3 黔东南下江群碎屑组分统计(%)

Table 3 Detrital model of sandstones from the Xiajiang Group, Southeast Guizhou Province

样品编号	所属组名	QmFLt			QmPK		
		Qm	F	Lt	Qm	P	K
15JP-25	隆里组	74.4	10.9	14.7	87.2	12.1	0.7
15JP-27	隆里组	66.7	18.1	15.2	78.7	20.2	1.1
15JP-22	平略组	52.7	28.7	18.6	64.8	27.8	7.4
15JP-20	平略组	67.5	28.7	3.8	70.2	27.2	2.6
15JP-19	清水江组	60	14.8	25.2	80.2	17.8	2
15JP-11	清水江组	67.1	23.1	9.8	74.4	22.5	3.1
15CJ-2	番昭组	61.9	19.9	18.2	75.7	19.1	5.2
15CJ-5	甲路组	73.5	0	26.5	100	0	0
15CJ-7	甲路组	85.7	3.3	11	96.2	3.8	0

注：Qm：单晶石英；F：长石总量；Lt：岩屑和多晶石英总量；P：斜长石；K：钾长石；Qm + F + Lt = 100%，Qm + P + K = 100%。

3 地球化学特征

3.1 元素特征

主量元素中 SiO_2 含量为 62.15% ~ 77.88%，平均 67.82%。$MgO + Fe_2O_3^T$ 含量为 2.22% ~ 9.29%，平均 5.82%。K_2O/Na_2O 比值除 15CJ-8、15CJ-14 和 15CJ-15 较高外，其余样品含量较低，约为 0.50% ~ 3.60%，反映了大多数样品钾长石或含钾矿物很少而斜长石含量较多。$Al_2O_3/(CaO + Na_2O)$ 比值除 15CJ-8、15CJ-14 和 15CJ-15 很高外，其余样品含量较低，约为 2.27% ~ 13.33%。

微量元素含量总体较澳大利亚后太古宙平均页岩(PAAS)低。在上地壳标准化蛛网图中(图 3)，下江群上部的 3 个组样品均显示出不同程度的 Co、La、Ce、Nd、Y 和 Lu 元素的富集，Ta 和 Ni 元素亏损。下江群下部的 3 个组中，番昭组样品显示 La、Ce、Y 和 Lu 元素富集，Ta 和 Ni 元素亏损；乌叶组样品显示 La、Ce、Nd 和 Y 元素富集，Ta、Sr 和 Ni 元素亏损；甲路组样品显示 Co、Th、Pb 和 Cr 元素富集，Ba 和 Sr 元素亏损。

在球粒陨石标准化分配模式中(图 4)，稀土元素分配模式均显示右倾，轻稀土元素(LREE)富集，重稀土元素(HREE)较平坦(La_N/Yb_N：1.44 ~ 10.79，平均 6.32)。所有样品均显示出较明显的 Eu 负异常。

3.2 影响因素

沉积岩的化学成分一般会受到源岩属性、风化作用、沉积再循环及成岩作用等因素的影响。因此，在进行物源分析以前，需要评估上述因素对岩石样品的影响。

3.2.1 沉积分选与再循环

沉积分选与再循环一般会造成重矿物富集，从而造成一些元素富集(Mclennan et al., 1990)。Th、Sc 元素分别富集在酸性、基性岩中，Th/Sc 比值不会

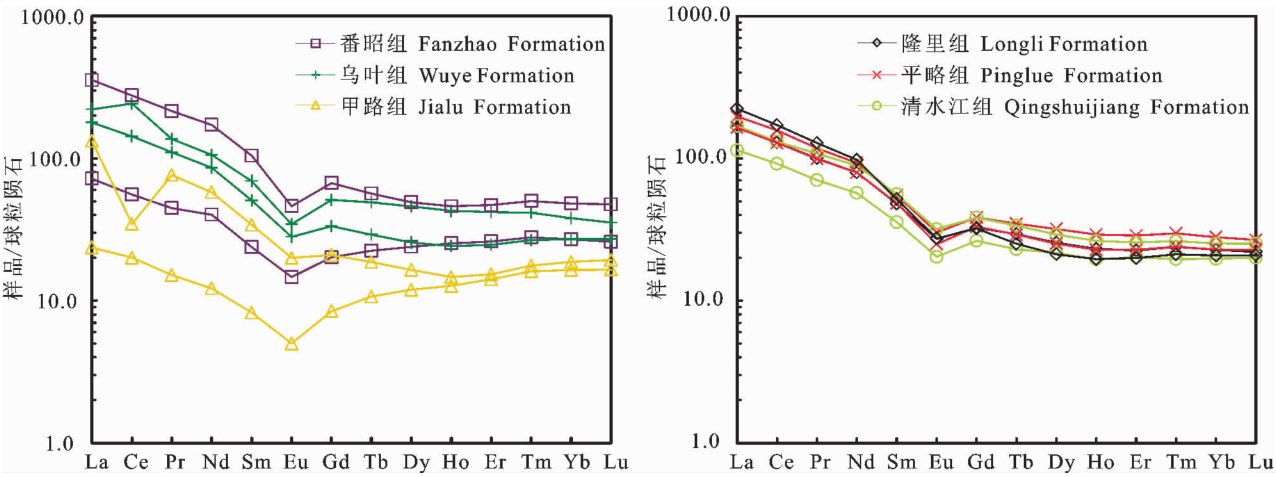

图 4 黔东南下江群碎屑岩稀土元素球粒陨石标准化分配模式(球粒陨石标准化数据据 Sun et al., 1989)

Fig. 4 Chondrite-normalized REE patterns of clastic rock from the Xiajiang Group, Southeast Guizhou Province (Chondrite-normalized data from Sun et al., 1989)

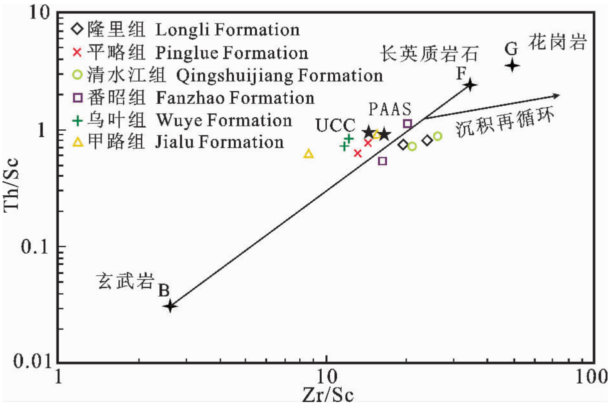

图 5 黔东南下江群碎屑岩 Zr/Sc—Th/Sc 图（据 Mclennan et al.，1993）

Fig. 5 Zr/Sc—Th/Sc diagram of clastic rocks from the Xiajiang Group, Southeast Guizhou Province (after Mclennan et al.，1993)

随着沉积再循环而发生变化；Zr 主要赋存于稳定性很强的锆石当中，会随着再循环作用在沉积物中富集，Zr/Sc 比值可以代表再循环作用的程度(Mclennan et al.，1993)。因此 Zr/Sc—Th/Sc 图解可以较好的反映沉积物的分选程度以及再循环作用的影响。在图 5 中，所有样品均靠近成分演化线(BFG)，并靠近大陆上地壳(UCC)和 PAAS，这显示出样品成分受源岩成分的控制，沉积分选和再循环作用影响不大。

3.2.2　化学风化的影响

在风化过程中，稳定的阳离子(如 Al^{3+}，Ti^{4+} 等)会保存到风化产物中，不稳定的阳离子(如 Ca^{2+}，Na^{+}，K^{+})则会流失(Fedo et al.，1995)。Nesbitt 等(1982)提出利用化学蚀变指数(*CIA*)来定量指示源区的化学风化程度。*CIA* 的表达式为：

$$CIA = \frac{n(Al_2O_3) \times 100\%}{n(Al_2O_3) + n(CaO^*) + n(Na_2O) + n(K_2O)}$$

其中 $n(CaO^*)$ 仅指硅酸盐矿物中的 $n(CaO)$。计算获得 *CIA* 值(表 1)并在 A—CN—K 三角图中投点(图 6)。*CIA* 值的范围在 52～79，平均为 67，属于中等程度的化学风化强度。这表明源区岩石经历了中等程度的化学风化作用。再结合微量元素、稀土元素均一的分配形式来看，风化作用并未影响到岩石中保存的源区信息。

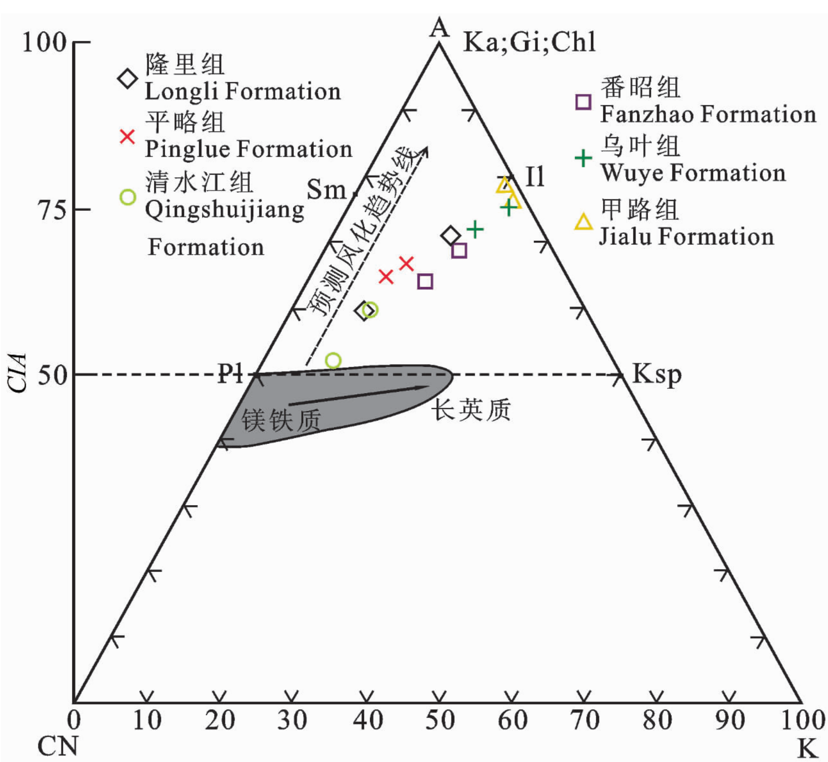

图 6 黔东南下江群碎屑岩 A—CN—K 三角图(据 Nesbitt et al.，1982)

Fig. 6 A—CN—K triangle diagram of clastic rocks from the Xiajiang Group, Southeast Guizhou Province (after Nesbitt et al.，1982)

A—$n(Al_2O_3)$；CN—$n(CaO^*) + n(Na_2O)$；K—$n(K_2O)$；Ka—高岭石；Gi—水铝矿；Chl—绿泥石；Sm—蒙脱石；Il—伊利石；Pl—斜长石；Ksp—钾长石

A—$n(Al_2O_3)$；CN—$n(CaO^*) + n(Na_2O)$；K—$n(K_2O)$；Ka—Kaolinite；Gi—Gibbsite；Chl—Chlorite；Sm—Smectite；Il—Illite；Pl—Plagioclase；Ksp—K-feldspar

4　讨论

4.1　源岩属性

一般情况下，元素 Sc、Ni、Co、Cr 和 V 倾向于在镁铁质岩中富集，元素 La、Th、Zr 和 Hf 倾向富集于长英质岩石中(Taylor et al.，1995)。此外，铁镁质岩石具有低的 LREE/HREE 比值和弱或无 Eu 异常，长英质岩石具有高的 LREE/HREE 比值和明显的负 Eu 异常(Cullers et al.，2000)。

下江群的各个组的样品中，除甲路组和清水江组各自的一件样品具有中等的 Al_2O_3/SiO_2 比值外，其余样品均具有高的 Al_2O_3/SiO_2 比值，所有样品均具有中等偏低的 $MgO + Fe_2O_3^T$ 含量。甲路组样品富集 Co、Cr 和 Th，乌叶组和番昭组样品富集 La，清水江组、平略组和隆里组样品富集 Co 和 La。LREE/HREE 比值变化大(La_N/Yb_N：1.46 ～

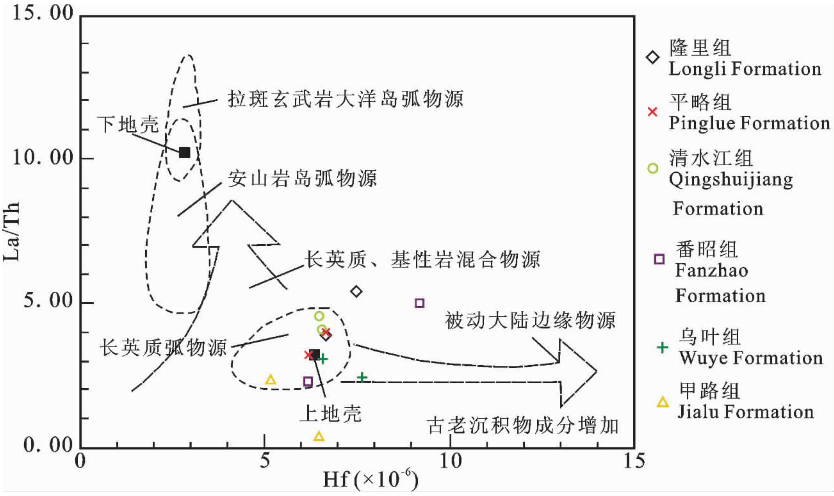

图 7 黔东南下江群碎屑岩 Hf—La/Th 图(据 Floyd et al. ,1987)

Fig. 7 Hf—La/Th diagram of clastic rocks from the Xiajiang Group,Southeast Guizhou Province (after Floyd et al. ,1987)

10.93,平均值为 6.40)。负 Eu 异常较明显。在 Zr/Sc—Th/Sc 图(图 5)和 A—CN—K 图(图 6)中,样品均落入基性岩和酸性岩演化线之间。因此推断源岩可能是长英质岩和镁铁质岩的混合产物。

稀土元素(REE)和高场强元素以及部分过渡金属元素(如 Co)通常被认为是沉积过程中最稳定的元素,因此,利用这些元素可以有效判别碎屑岩源区成分(Long Xiaoping et al. , 2008; 许德如等, 2007)。在 Hf—La/Th 图中(Floyd et al. ,1987)(图 7),多数样品落入到了长英质物源区。乌叶组和番昭组各有一件样品靠近被动大陆边缘物源区,这说明这两件样品含有一定量的来自被动边缘的古老沉积物。下江群上部的清水江组、平略组和隆里组样品都位于长英质物源区上部,隆里组的一件样品靠近长英质和基性岩的混合物源区。在 La/Sc—Co/Th 图中(Gu Xuexiang et al. ,2002)(图 8),除番昭组一件样品介于长英质火山岩和花岗岩之间,其余样品均位于长英质火山岩和玄武岩之间,清水江组样品与其它组相比更靠近玄武岩。

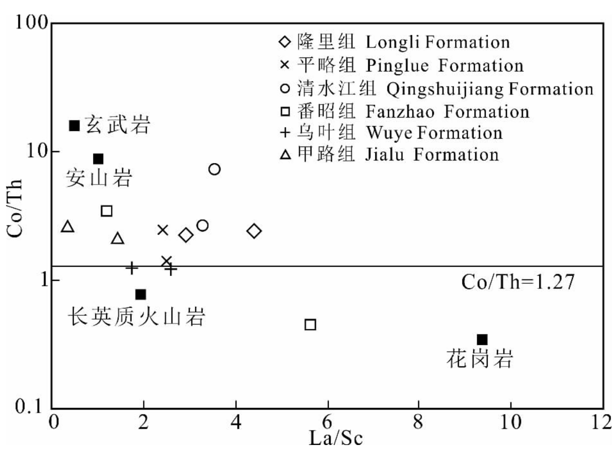

图 8 黔东南下江群碎屑岩 La/Sc—Co/Th 图(据 Gu Xuexiang et al. ,2002)

Fig. 8 La/Sc—Co/Th diagram of clastic rocks from the Xiajiang Group, Southeast Guizhou Province (after Gu Xuexiang et al. ,2002)

通常来讲,Sm-Nd 同位素体系在地质体形成之后经受的风化、蚀变与变质作用的过程中,会仍然保持封闭而不发生变化,这就使得 Nd 同位素在探讨岩石物质来源方面及不同源的混染作用等方面具有指示意义(张宏飞等,2012)。在 $\varepsilon_{Nd}(t)$—t 变异图中(沈渭洲等,1993)(图 9),$\varepsilon_{Nd}(t)$ 表现出负异常($\varepsilon_{Nd}(t)$: −0.35 ~ −3.36),除 15JP-14 落入元古代华南板块地壳区域内,其余 5 件样品靠近原始地幔演化线,说明它们的源岩是壳幔混合作用的结果。

综上所述,下江群源岩成分以酸性岩为主,并伴有一定量的基性岩,基性岩的混入主要集中在清水

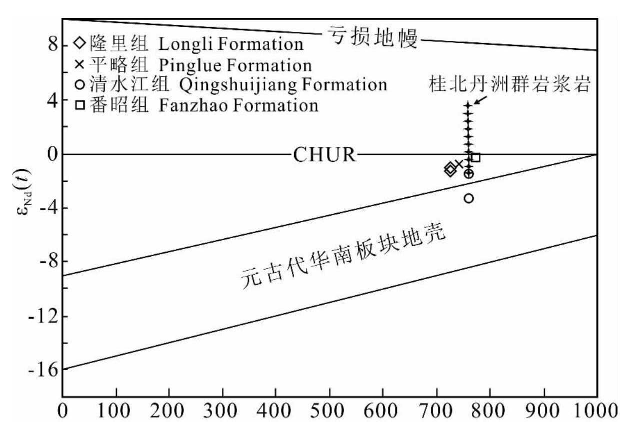

图 9 黔东南下江群碎屑岩 $\varepsilon_{Nd}(t)$—t 图(据沈渭洲等,1993;丹洲群数据据 Lin Musen et al. ,2015)

Fig. 9 $\varepsilon_{Nd}(t)$—t diagram of clastic rocks from the Xiajiang Group,Southeast Guizhou Province (after Shen Weizhou et al. ,1993&; date of Danzhou Group from Lin Musen et al. , 2015)

江组—平略组沉积时段。

4.2　源区构造背景判别

4.2.1　碎屑岩骨架颗粒统计

Dickinson 以现代海洋和陆地上已知的构造背景中获取的砂质组分为标准,提出一系列判断构造背景的三角图解(Dickinson et al. ,1979,1980,1983,1985)。在 Qm—F—Lt 三角图中(图 10a),甲路组和隆里组的样品均落到了石英旋回造山物源区,番昭组样品落到了混合物源区,清水江组样品分别落到了石英旋回造山物源区和过渡带大陆块物源区,平略组样品分别落到了混合物源区和过渡带大陆块物源区。在 Qm—P—K 三角图中(图 10b),甲路组—平略组,样品从大陆块物源区逐渐移向岩浆岛弧物源区;平略组—隆里组,样品则从岩浆岛弧物源区移向大陆块物源区。需要指出的是,这 9 件样品与其它样品相比粒度较粗且石英含量高,说明它们的源岩主要是酸性岩,采自从江的 3 件样品可能就来自附近出露的少量四堡期花岗岩,它们仅能代表下江群部分粒度较粗的碎屑岩特征。

4.2.2　主量、微量元素结果

Roser 和 Korsch(1986)在对新西兰不同物源区的砂岩和泥岩主量元素成分的基础上,结合前人研究,建立了 K_2O/Na_2O—SiO_2 二元判别图解,该图解用来区分活动大陆边缘、被动大陆边缘和岛弧三类构造背景。在图 11a 中,多数样品则落入活动大陆边缘区域,甲路组样品、乌叶组和隆里组各自的一件样品落入被动边缘区域,乌叶组的另一件样品位于被动大陆边缘和活动大陆边缘边界线上。需要说明的是,在沉积物沉积过程及随后的成岩乃至变质作用中,与源岩相比,砂岩中的 Na_2O 常显著亏损而 SiO_2 则相对富集。因此,图 11a 中的数据点会更靠近活动大陆边缘。微量元素与主量元素相比,活动性一般都很弱,能较大程度地保留源岩的信息。Bhatia 等(1986)将东澳大利亚 5 个地层杂砂岩的稀土元素特征与现代造山火山岩标准球粒陨石模型进行对比后,提出一系列微量元素判别图解。在 Ti/Zr—La/Sc 图中(图 11b),多数样品落入大陆岛弧区域,番昭组一件样品落入到被动边缘区域,隆里组一件样品落入到活动大陆边缘区域。在 La—Th—Sc 图中(图 12a),多数样品落入大陆岛弧区域,甲路组一件样品和番昭组样品落到构造区域以外。在 Th—Co—Zr/10 和 Th—Sc—Zr/10 两个图中(图 12b,c),多数样品落入大陆岛弧区域,少部分样品落入大洋岛弧区域或介于大陆岛弧与大洋岛弧区域之间。

综合上述碎屑组分和主、微量元素判别结果,黔东南地区在下江期的碎屑沉积物主要形成于活动大陆边缘环境,并且与岛弧密切相关,该特征在清水江组—平略组沉积阶段体现的最为明显。

4.3　大地构造意义

扬子板块与华夏板块最终拼合的时间一直存在争议。李献华等(2008,2012)认为拼合时间是 1100

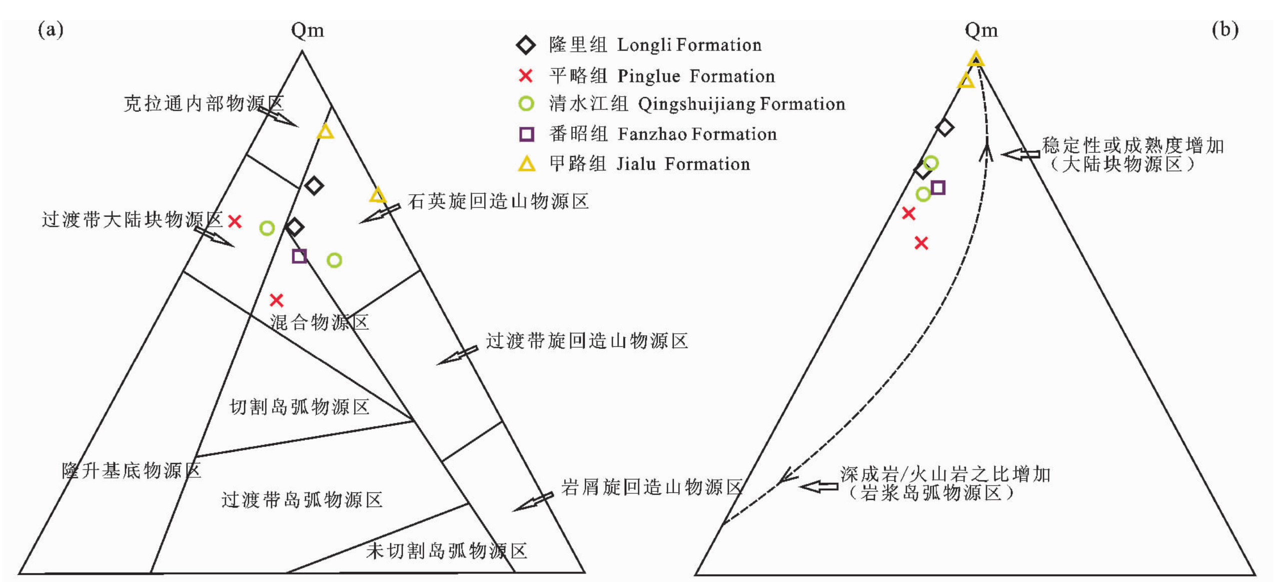

图 10 黔东南下江群碎屑岩的 Dickinson 三角图(据 Dickinson et al. ,1979,1983)

Fig. 10 Dickinson diagrams of clastic rocks from the Xiajiang Group, Southeast Guizhou Province (after Dickinson et al. ,1979,1983)

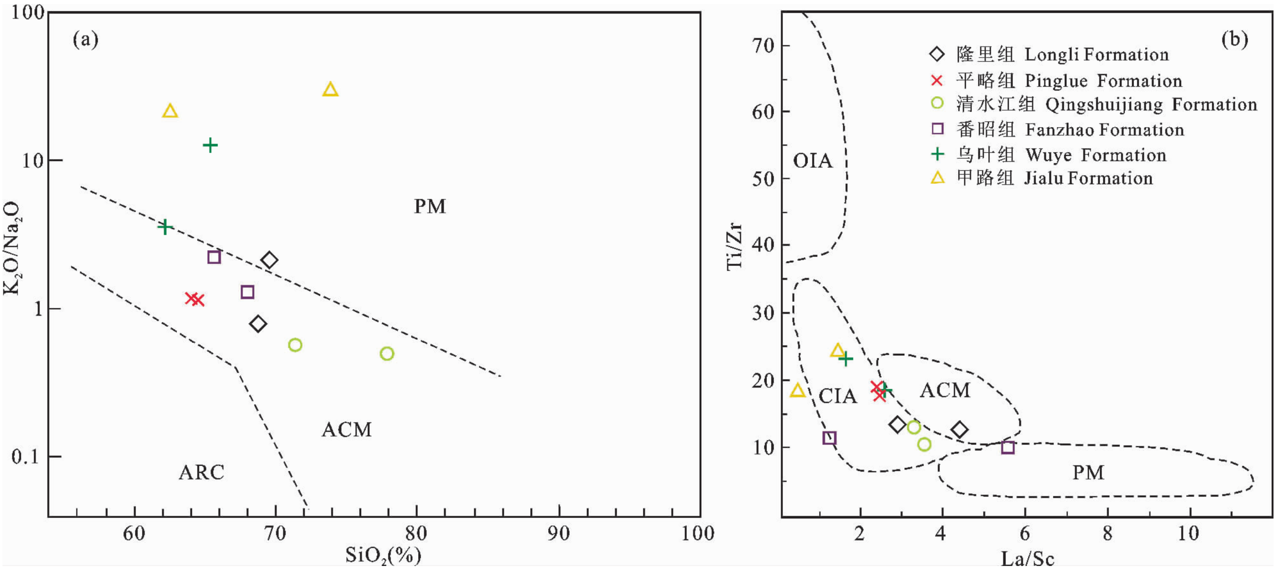

图 11 黔东南下江群碎屑岩 K_2O/Na_2O—SiO_2(a)和 Ti/Zr—La/Sc(b)构造环境判别图

(图 a 据 Roser et al. ,1986;图 b 据 Bhatia et al. ,1986)

Fig. 11 K_2O/Na_2O—SiO_2(a) and SiO_2/Al_2O_3—K_2O/Na_2O(b) tectonic discrimination of clastic rocks from the Xiajiang Group, Southeast Guizhou Province [(a) after Roser et al. ,1986; (b) after Bhatia et al. ,1986]

ARC—岛弧;ACM—活动大陆边缘;PM—被动边缘;OIA—大洋岛弧;CIA—大陆岛弧

OIA—Oceanic island arc; CIA—Continental island arc; ACM—Active continental margin; PM—Passive margin

~900 Ma,裂谷发育时间是 820 ~ 760 Ma;Zhou Jincheng 和 Wang Xiaolei (2009)、Zhao Junhong (2011)、Zheng Yongfei(2008)等认为拼合时间是在 830 ~820 Ma,裂谷发育时间是 820 ~740 Ma。尽管时间不同,但都认为四堡运动不整合面之上的地层(下江群及其相应地层)是陆内裂谷沉积,只是裂谷发育的时间不同。最近,林木森等(2016)对下江群的构造背景提出了不同观点,通过对桂北龙胜一带四堡群和丹洲群镁铁质—超镁铁质岩石的全岩主微量元素和 Sm-Nd 同位素分析以及锆石 U-Pb 定年,确定丹洲群岩石结晶年龄为 760 ±18 Ma,形成于与俯冲作用相关的活动大陆边缘,这就意味着扬子板块东南缘在 760 Ma 左右仍然存在削减作用,此时扬子板块和华夏板块并未完全拼合。

根据本文对下江群不同时期的物源分析结果,在番昭组—平略组沉积阶段,即 770 ~745Ma 前后,源岩主要形成于壳幔混合作用,与这种岩石相关的是伸展的构造背景,相关构造背景包括大陆裂谷和弧后裂谷。碎屑岩骨架颗粒统计和沉积地球化学特征显示,盆地处于与岛弧相关的活动大陆边缘。这个认识与黔东南锦屏地区番昭组和清水江组地球化学特征一致(牟军等,2015)。因此本文认为江南造山带西段在下江期仍存在岛弧活动,这就意味着扬子板块与华夏板块在下江期尚未拼合。

覃永军等(2015)对下江群不同组段进行了精确的锆石年代学研究,本文利用其获得的锆石年龄数据作出了年龄统计直方图(图 13),这些数据取自 6 件碎屑岩样品,共计 306 个锆石点,数据谐和度大于 90%,6 件样品采自乌叶组、清水江组、平略组和隆里组。从图 13 中可以看出,其年龄组主要集中在 700 ~900 Ma。黔东南周边地区出露的新元古代花岗岩集中在从江地区和桂北的三防和元宝山地区,其年龄主要集中在 840 ~770 Ma 之间(王剑,2005;Wang Xiaolei et al. ,2007;樊俊雷等,2010;陈建书等,2014)。桂北三防地区同时也出露基性—超基性岩,其年龄集中在 830 ~ 810 Ma 之间 (Wang Xiaolei et al. ,2007)。从江地区出露的基性岩年龄为 848 ±15 Ma(王劲松等,2012)。黔东北梵净山出露的基性—超基性岩年龄是 831 ~ 748 Ma (Zhou Jincheng et al. ,2009)。上述这些岩石的年代学特征与下江群碎屑锆石年龄一致。在部分地区还可观察到下江群沉积超覆在这些岩石之上(王剑,2005)。因此,下江群物源主要来自相邻的从江、桂北和黔东等地的酸性岩和基性—超基性岩。结合本文对源岩属性的分析,即下江群碎屑岩源岩主要是酸性岩,基性岩的混入集中在清水江组—平略组沉

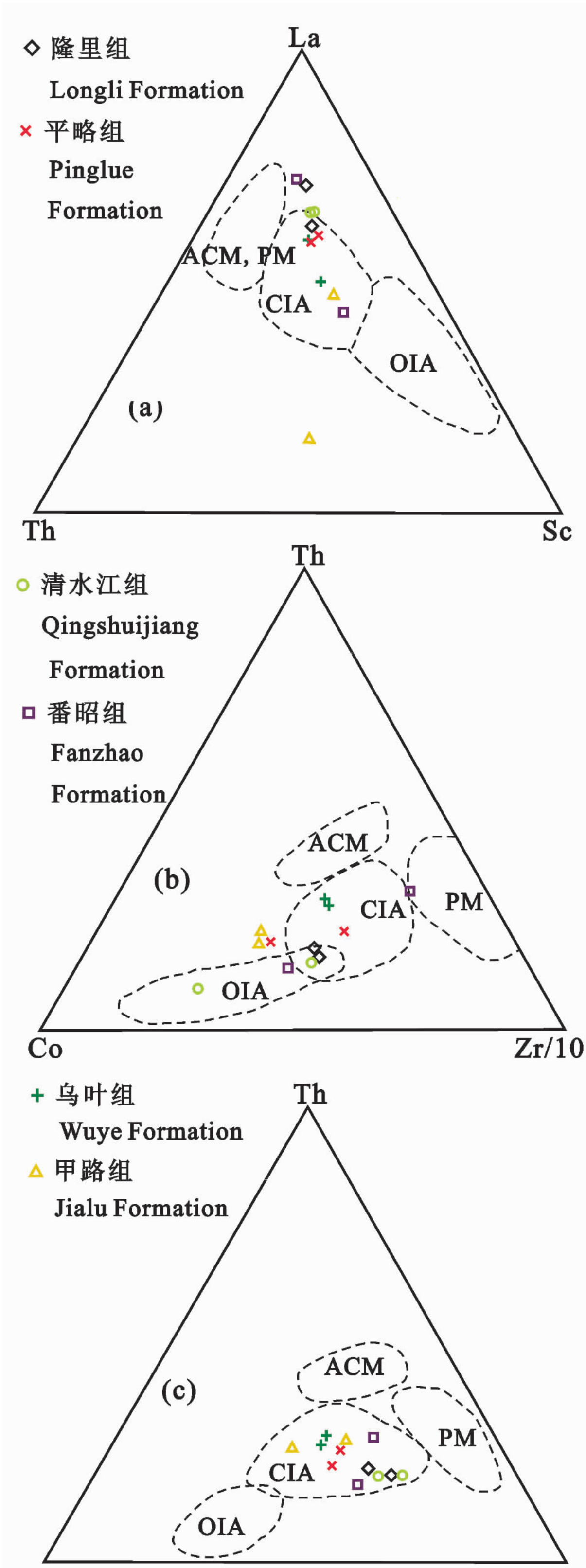

图 12 黔东南下江群碎屑岩 La—Th—Sc(a)、Th—Co—Zr/10(b)和 Th—Sc—Zr/10(c)构造环境判别图(据 Bhatia et al. ,1986)

Fig. 12 Ti/Zr—La/Sc(a)、La—Th—Sc(b)、Th—Co—Zr/10(c) and Th—Sc—Zr/10(d) tectonic discrimination of clastic rocks from the Xiajiang Group, Southeast Guizhou Province (after Bhatia et al. ,1986)

OIA—大洋岛弧;CIA—大陆岛弧;ACM—活动大陆边缘;PM—被动边缘

OIA—Oceanic island arc; CIA—Continental island arc; ACM—Active continental margin; PM—Passive margin

积阶段。可以肯定,下江群物源主要来自盆地周缘,如桂北地区。值得提及的是,覃永军(2015)对下江群同沉积碎屑锆石地化特征进行研究显示,在 815 ~770 Ma 之间的同沉积锆石的地化特征同样显示形成于岛弧相关的环境。因此,可进一步说明江南造山带西段在下江期是与岛弧密切相关的活动大陆边缘。

以往的研究已经表明,扬子板块与华夏板块的东西两端并不是同时拼合的,江南造山带西段和东段有显著区别(Wang Xiaolei et al. , 2008, 2012; Wang Wei et al. , 2013, 2016; Yao Jinlong et al. , 2013, 2015; Zhang Heng et al. , 2015; 韩瑶等, 2016)。从区域上来看,江南造山带东段双溪坞岛弧活动时间集中在 880 ~ 860 Ma,扬子板块与华夏板块在东段碰撞时间集中在 820 ~ 800 Ma(Wang Xiaolei et al. ,2012;Wang Wei et al. ,2013);西段四堡弧活动时间集中在 835 ~ 800 Ma(Lin Musen et al. ,2015)。结合本文研究,扬子板块与华夏板块的

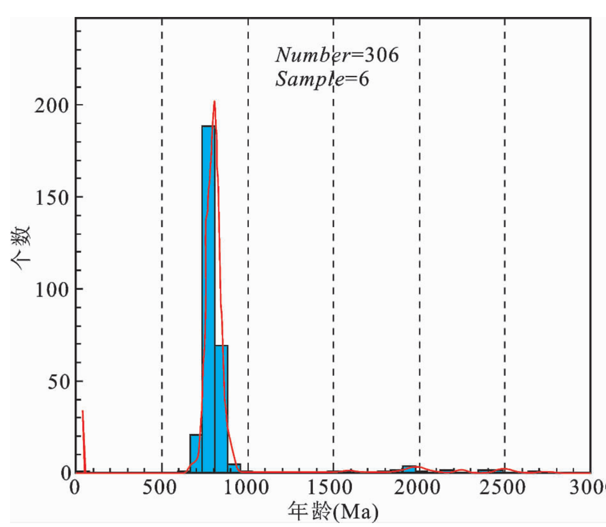

图 13 黔东南下江群碎屑岩年龄统计直方图(数据据覃永军等,2015)

Fig. 13 Histogram of clastic rocks from the Xiajiang groups in the Southeast Guizhou (date from Qin Yongjun et al. , 2015&)

碰撞时间应该在平略组沉积阶段(745 Ma)之后,因上覆隆里组与平略组之间为整合接触关系,而隆里组上部为雪峰运动不整合面,因此推断扬子板块和

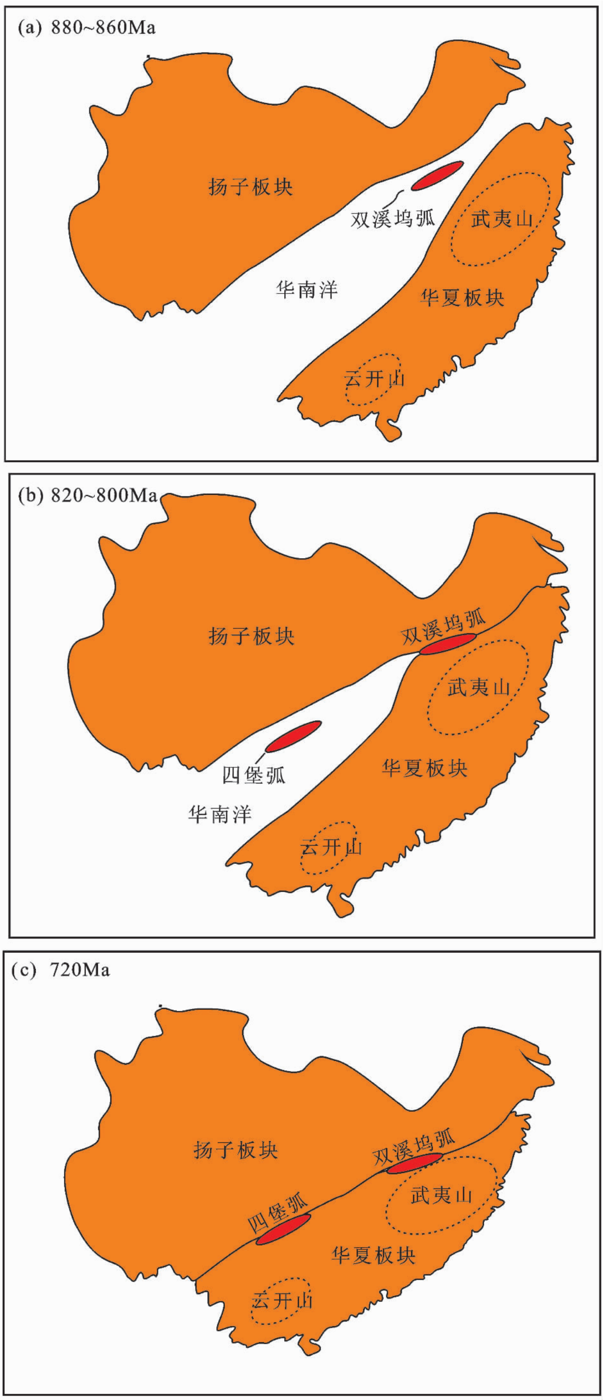

图 14 新元古代扬子板块与华夏板块拼合示意图[(a)和(b)的数据据 Wang Xiaolei et al.,2012 和 Wang Wei et al.,2013]

Fig. 14 A carton shows assembly of Yangtze and Cathaysia blocks during the Neoproterozoic [date of (a) and (b) from Wang Xiaolei et al.,2012 and Wang Wei et al.,2013]

华夏板块西段的拼合时间很可能在雪峰运动之后(720 Ma 左右)。因此,从时间来看,扬子板块与华夏板块之间洋盆的消减—碰撞可能存在东早西晚的特点。据此本文认为在新元古代早期,扬子板块与华夏板块之间的华南洋在东部首先消减(图 14a),在 800 Ma 左右,武夷山地体与扬子板块碰撞(图 14b);而西段的消减活动持续到 740 Ma,在 720 Ma 左右,经过雪峰运动,云开地体与扬子板块完成拼合(图 14c)。

5 结论

(1)黔东南地区下江群的源岩属性主要是酸性岩,基性岩在清水江组—平略组沉积阶段有适量混入。

(2)江南造山带西段在下江期是与岛弧密切相关的活动大陆边缘,扬子板块与华夏板块此时仍处于消减阶段。

(3)扬子板块与华夏板块是由东到西逐渐拼合的,即东段的武夷山地体在 800 Ma 左右与扬子板块拼合,西段的云开地体在 745 Ma 之后,经过雪峰运动,与扬子板块完成拼合。

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Geochemistry and Its Tectonic Significance of the Clastic Rock in the Neoproterozoic Xiajiang Group, Southeast Guizhou, South China

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Objectives: The Xiajiang Group in Southeast Guizhou is an assembly of siliciclastic rocks interbedded with volcanic clastic rock that show the feature of flysch. It can be divided into the Jialu, Wuye, Fanzhao, Qingshuijiang, Pinglue and Longli formations from bottom to top. This paper focused on the major, trace element and Nd isotope features of the group in order to identify the tectonic environment of western Jiangnan Orogen in Xiajiang period, and further to unravel evolution of the orogen and juxtaposition of Yangtze and Cathaysia blocks.

Methods: 21 samples have been analyzed, respectively from Jialu, Wuye, Fanzhao, Qingshuijiang, Pinglue and Longli formations. Of these, point-counting was performed on 9 coarse-grained sandstone samples from the group. Between 300 to 500 points were point counted in each thin section following the Gazzi—Dickinson method .

Major, trace and rare earth elements of 12 fine-grained sandstones were measured by XRF and ICP-MS, respectively, at the State Key Laboratory of Biogeology and Environment Geology of CUG. Both the accuracy of analysis are > 5%. And Nd isotopic analyses are measured by MC-ICP-MS at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. The mass fractionation correction for Nd isotopic ratios are based on $n(^{146}Nd)/n(^{144}Nd) = 0.7219$. The measured $n(^{143}Nd)/n(^{144}Nd)$ ratios of the La Jalla standard are 0.511862 ± 10(2σ). During the analytical process, within-run errors of precision are estimated to be better than 0.000015 for $n(^{146}Nd)/n(^{144}Nd)$ in the 95% confidence level.

Results: The results show that all the samples rich in Co, La, Ce, Nd, Y and Lu and deplete in Ta and Ni, wth obvious negative Eu anomalies. Sm-Nd isotopic analyses show negative ($\varepsilon_{Nd}(t)$ values of −0.35 to −3.36. Geochemistry features indicate the source rock are dominated by granitic rocks with the infilling of mafic rocks. And they suffered moderate chemical weathering (CIA = 52 ~ 79) before the deposition. The tectonic discrimination figures show that the basin was located in an active continental margin, which was related to island arc action.

Conclusions: This study indicates that the subduction still went on along the western part of Jiangnan Orogen during the Xiajiang period. The Yangtze Block had not collided with the Cathaysia Block at the western part of the Jiangnan Orogen untill the Xuefeng Event. Compared with the time of orogeny at the eastern part of the belt, we suggest that collision between the Yangtze and Cathaysia blocks was diachronous in the trending direction of orogen, commencing initially in the eastern part of orogen before extending to the west.

Keywords: The southeast Guizhou; The Xiajiang Group; sedimentary geochemistry; provenance; the Jiangnan Orogenic Belt

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