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云南大关新地2井奥陶—志留纪之交钾质斑脱岩岩石地球化学特征分析

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摘要:扬子地台内晚奥陶世末—早志留世初五峰—龙马溪组内沉积了多层钾质斑脱岩,但对于该时期扬子地台西缘钾质斑脱岩的研究报道相对较少。本文旨在通过对云南大关地区新地2井五峰—龙马溪组内沉积的钾质斑脱岩进行矿物学及地球化学分析,进一步确定扬子西缘该时期钾质斑脱岩原始岩浆类型及其所产生的构造环境。矿物学特征表明,钾质斑脱岩主要由黏土矿物和非黏土矿物组成,其中黏土矿物由伊利石和伊蒙混层组成,非黏土矿物以石英、长石、方解石、白云石和黄铁矿等为主。钾质斑脱岩主量元素以高K_2O,低TiO_2为特征,微量元素特征表现为富集Rb、Ba、Th、U等元素,Ti、P元素相对亏损,Ti/Th值指示了酸性火山灰的性质;ΣREE在$(49.86\sim209.43)\times10^{-6}$;与球粒陨石相比,轻稀土轻微富集、具Eu负异常,无Ce异常;在Nb/Y−Zr/TiO_2图解中,数据点主要落在安山岩和粗面英安岩之间,表明钾质斑脱岩源岩浆性质为中酸性岩浆;依据微量元素特征和构造环境判别结果,初步认为原始岩浆可能形成于岛弧环境,其火山灰来源可能与扬子北缘早古生代秦岭洋闭合过程中的板块碰撞有关。

关 键 词:新地2井;钾质斑脱岩;奥陶—志留纪之交;地球化学;源岩浆;构造背景;大关地区;云南

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Petrology and geochemistry of the K−bentonites at the Ordovician−Silurian transition in XD2 well, Daguan, Yunnan Province

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Abstract: Many K−bentonites have been recognized from the Wufeng−Longmaxi Formations (Upper Ordovician−Lower Silurian) in the Yangtze Block, but only a few of them on the western margin of the Yangtze Block are reported. The mineralogical and

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geochemical studies of K−bentonites in the Wufeng−Longmaxi Formations through Xindi 2 well in Daguan area of Yunnan province were carried out to confirm the original magma type and its tectonic setting. The mineralogical characteristics show that the potassium bentonite is mainly composed of clay minerals and non−clay minerals, in which the clay minerals are composed of illite and illite−montmorillonite mixed beds. The non−clay minerals are mainly quartz, feldspar, calcite, dolomite and pyrite. It is geochemically characterized by high K_2O and low TiO_2, relative enrichment of Rb, Ba, Th and U and depletion of Ti and P elements. The Ti /Th values indicates acidic volcanic ash character. Compared with the chondrite, the total rare earth elements is (49.86−209.43)×10^{-6} with slight rich LREE and negative Eu amomaly, without Ce abnormity. In Nb/Y−Zr/TiO_2 diagram, the data dots are mainly plotted in the andesite and trachy andesite range, which shows that the volcanic ash is mostly from middle−acid rocks. Various chemical discrimination diagrams and trace elements imply that K−bentonites were possibly derived from an island arc environment, and the volcanic ash was probably related to the subduction and closure of the Qinling Ocean on the northern border of Yangtze Plate in the Early Paleozoic.

Key words: XD2 well; K−bentonite; Ordovician−Silurian transition; geochemistry; source magma; tectonic setting; Daguan; Yunnan Province

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1 引 言

钾质斑脱岩，由火山喷发产生的火山灰物质在海相环境中经沉积、成岩和蚀变作用而形成，它的存在多与地质历史时期的火山活动有关。奥陶—志留纪时期钾质斑脱岩全球广布，在北美、南美、中欧、北欧以及中国华南地区均有发育。国外对于该时期斑脱岩的研究相对久远，以Huff, Bergström和Kolata等为代表，他们在年代地层、古大陆再造、地层对比和构造背景分析方面取得了很大的成果（Kolata et al.,1987,1996；Huff et al.,1992，1993，1996，1997，1998，2000，2014；Bergström et al.,1997，1998, 2004，2016；Huff, 2008，2016；Harvey, 2014；Kiipli et al., 2014，2015；Heintz et al., 2015；Türkmenoğlu et al., 2015；Siir et al., 2015；Jones et al., 2017；Rakociński et al., 2018；Trela et al., 2018）。

中国对于钾质斑脱岩的研究起步相对较晚，始于20世纪80年代且多集中于前寒武系和二叠—三叠系钾质斑脱岩的研究（万斌等，2013；Zhou et al., 2014；Cui and Kump，2015；廖志伟等，2016；Wang et al., 2018；Hong et al., 2019；Zheng et al., 2020a）。近些年随着华南地区奥陶—志留系钾质斑脱岩不断地被发现和证实，Su et al.（2003，2007，2009）、苏文博等（2002，2006，2007）、Hu et al.（2008）、胡艳华等（2008，2009a，2009b，2012）、汪隆武等（2015）、谢尚克等（2012）、罗华等（2016，2017）、Zheng et al (2020b)开始对华南东部地区（尤其湖北宜昌王家湾北和贵州桐梓南坝子剖面）晚奥陶世末—早志留世初沉积的钾质斑脱岩开展同位素年龄、岩石矿物学和地球化学等研究工作，指出钾质斑脱岩所指示的火山活动与构造板块活动（华南地区扬子陆块和华夏陆块的碰撞拼接）有着密切联系。该时期扬子地台西缘同样也沉积了多层钾质斑脱岩，但对于该地区钾质斑脱岩的相关研究报道相对较少。上奥陶统五峰组—下志留统龙马溪组黑色页岩广泛分布于上扬子地区，是近些年来上扬子地区早古生代页岩气研究的重要层位，中石油，中石化等单位也相继在四川盆地及其周缘地区开展钻井及地表剖面调查工作（Yan et al., 2015；Luo et al., 2016；王玉满等，2017；Yang et al., 2017；李斌等，2017；熊晓辉等，2018；陈孝红等，2018；宋腾等，2018；姜生玲等，2018；Ge et al., 2019；杨平等，2019；冯伟明等，2021），钻井岩心资料为我们提供了很多丰富新鲜的黑色泥页岩及钾质斑脱岩样品。新地2井位于云南省昭通市大关县木杆镇（图1），其岩心内上奥陶统—下志留统发育多层钾质斑脱岩，笔者通过扫描电镜（SEM））和X射线衍射仪对该岩心内钾质斑脱岩进行矿物岩石学分析，以X荧光光谱仪和ICP−MS等离子体质谱仪对所发现的钾质斑脱岩进行主量元素、微量元素地球化学分析，尝试利用钾质斑脱岩的某些不活泼元素的地球化学特征，进行源岩浆性质和构造环境的判别，以丰富华南地区

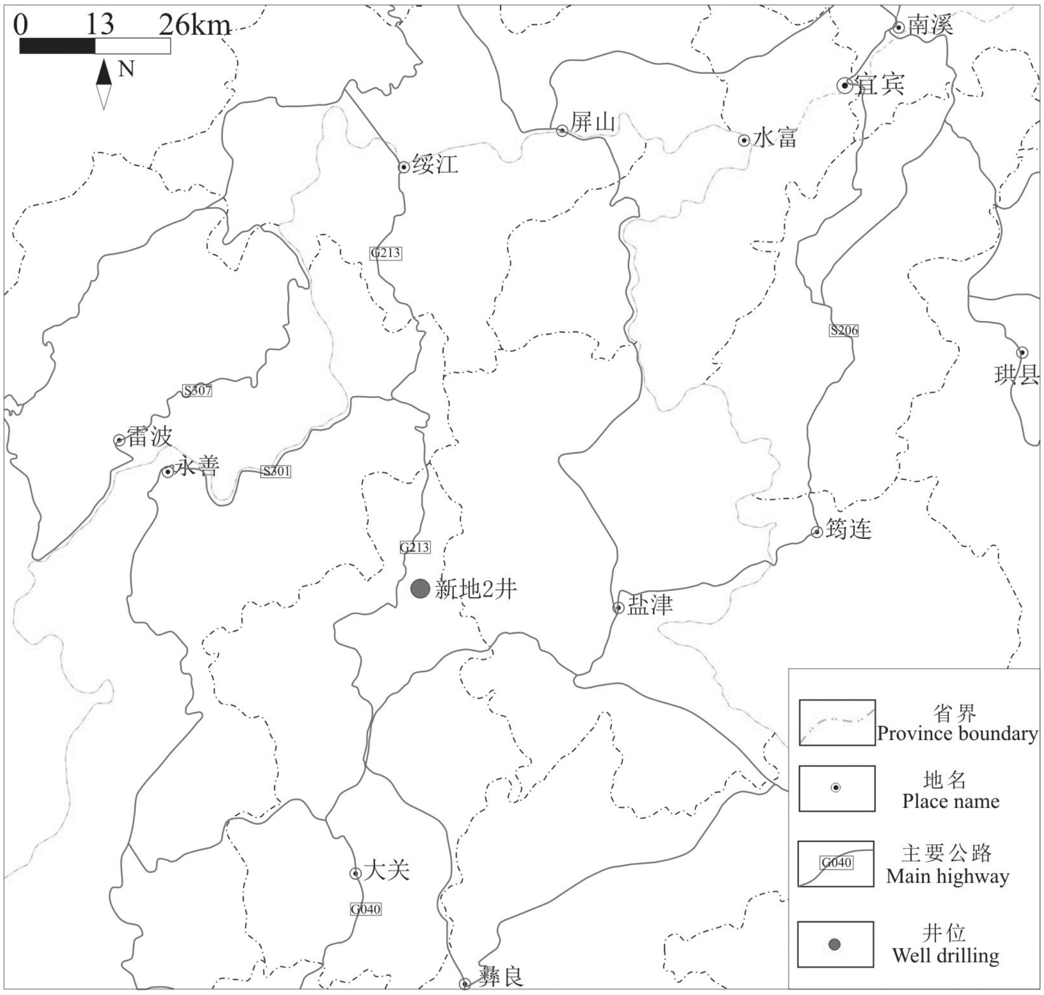

图1 新地2井位置图
Fig.1 Location of XD2 well

奥陶—志留系钾质斑脱岩的研究。

2 样品采集及分析方法

本研究样品均采自新地2井岩心，具体采样层位见图2。将采集到的样品在室内进行风干，剔除明显不属于钾质斑脱岩的杂质，以备后续的岩石学和地球化学分析测试。

样品的扫描电镜分析在核工业北京地质研究院利用Nova Nano SEM450型扫描电子显微镜完成。X衍射分析在四川省科源工程技术测试中心完成，测试过程使用X pertPowder型X射线衍射仪，仪器采用Ni滤波Cu靶辐射，工作电压为30 kV，工作电流为25 mA，发射狭缝与散射狭缝均为1°，接受狭缝0.3 mm，扫描方式为步进扫描，扫描速度采用2°（2θ）/min，采样步宽为0.02°（2θ）数据分析采用软件High Score。样品的主量和微量元素分析测试均在国家地质实验测试中心完成，主量元素采用X荧光光谱仪（PW4400）分析，其中Al_2O_3、CaO、Fe_2O_3、K_2O、MgO、MnO、Na_2O、P_2O_5、SiO_2、TiO_2遵循GB/T 14506.28−2010，FeO遵循GB/T14506.14−2010，分析精度优于5%，微量元素采用ICP−MS等离子质谱仪(PE300D)分析，实验依据DZ /T0223−2001 电感耦合等离子体质谱(ICP−MS) 方法，分析精度优于10%。

3 钾质斑脱岩岩石学特征

新地2井岩心内五峰—龙马溪组沉积的钾质斑脱岩颜色相对单一，通常呈现灰色和灰白色，单层厚度在1~4 cm(图3)，且钾质斑脱岩内通常含有黄铁矿条带或结核。姜尧发等（2006)曾指出大量黄铁矿的出现，可能与当时由于火山作用喷发出大量含

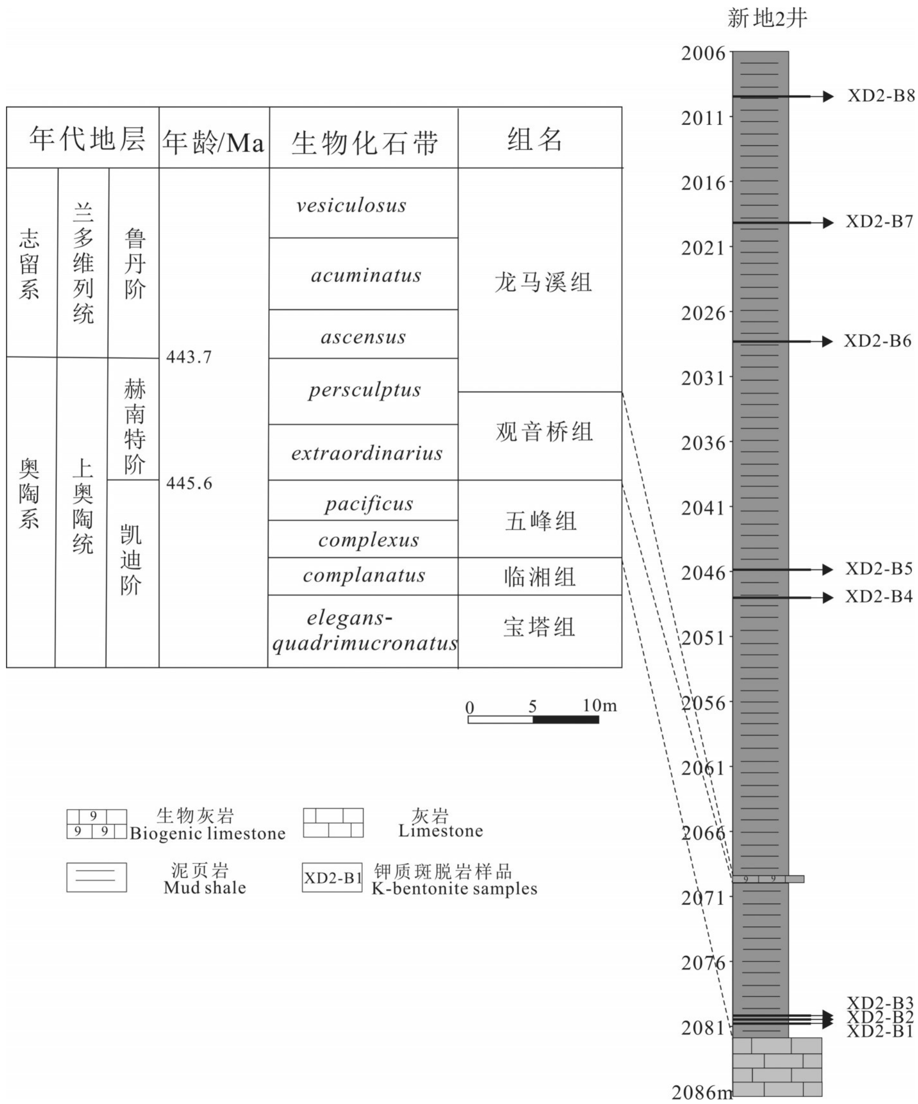

图2 新地2井柱状图和样品采样位置图(生物化石带据Chen et al., 2006)

Fig.2 Lithological column and sampling location of XD2 well (Chronostratigraphic subdivision after Chen et al., 2006)

硫化物火山物质有关，这些富硫矿物为钾质斑脱岩在后期沉积过程中黄铁矿的形成提供了物质基础。由于钾质斑脱岩厚度均相对较薄(小于4 cm)，加之相对疏松，未能成功制作成岩石薄片进行镜下观察，其矿物组成主要通过X衍射分析和扫描电镜进行确定。

X衍射分析结果表明所研究的钾质斑脱岩主要由黏土矿物和非黏土矿物组成(表1，图4)，黏土矿物主要为伊利石和伊蒙混层，其中伊利石含量55%~84%，伊蒙混层13%~37%；非黏土矿物主要有石英、长石、方解石、白云石以及黄铁矿等。其中样品XD2−B4、B5、B6中可能因混入了较多的黄铁矿结核成分而导致其矿物成分中黄铁矿含量高达38%~66%，从而导致上述样品中所测的其他矿物成分含量相对不准确。除XD2−B4，B5，B6之外，钾质斑脱岩样品的黏土矿物含量普遍大于50%，非黏土矿物中石英和钠长石存在于所有样品中，含量分别为2%~8%和5%~20%，方解石和白云石在样品分别为3%~7%和4%~6%，另外黄铁矿含量在8%~30%。

4 钾质斑脱岩地球化学特征

4.1 主量元素特征

由所有样品的主量元素含量分析结果(表2)可见，样品XD2−B4−B6中具低SiO_2(9.31%~25.63%)和高Fe_2O_3(31.11%~51.6%)含量，而且灼失量也较高(19.68%~28.83%)，以上均说明这三层钾质斑脱岩

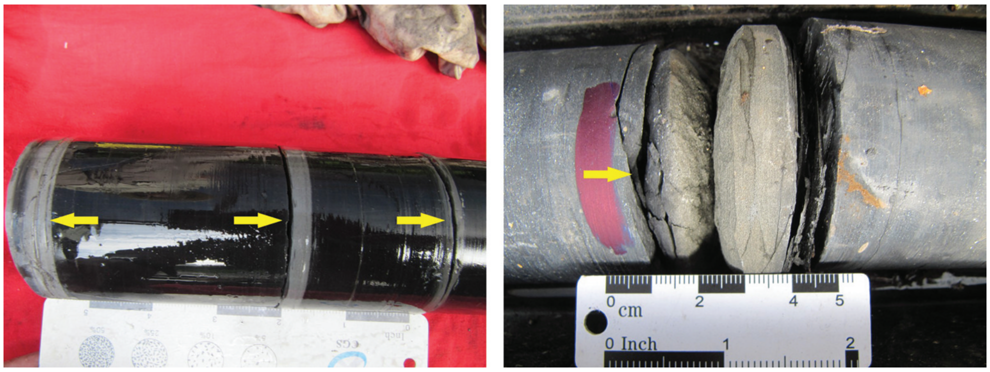

图3 新地2井岩心五峰—龙马溪组钾质斑脱岩照片
Fig.3 Photos of K−bentonite from the Wufeng−Longmaxi Formations in XD2 well

样品可能因混入了围岩成分而导致样品的不纯,因此后面的讨论中均不包含这3个样品。

其余4个钾质斑脱岩样品中SiO_2含量38.37%~48.75%,平均44.90%,Al_2O_3含量在16.71%~25.76%,平均22.17%。4件钾质斑脱岩样品均表现为K_2O>Na_2O,其中K_2O含量在4.45%~6.99%,平均5.93%,Na_2O含量较低,介于0.77%~1.51%,平均0.99%,显示了其钾质斑脱岩的特征;Fe_2O_3含量变化也相对较大,从2.95%~15.42%不等,FeO含量相对较稳定,在0.93%~2.55%,平均1.41%。MgO、CaO、MnO、TiO_2含量均较低,其中MgO介于2.5%~2.65%,平均2.57%,CaO分布在1.33%~3.06%,MnO不超过0.13%,TiO_2最大值2.32%。

与NASC和PAAS相比,这些钾质斑脱岩具有低SiO_2,高Al_2O_3,高K_2O等特征,其SiO_2含量普遍低于NASC(64.8%)和PAAS(62.8%),但其平均Al_2O_3含量22.17%,高于NASC(16.90%)和PAAS(18.90%),K_2O最低值4.45%都明显高于NASC和PAAS的K_2O含量(3.99%,3.70%),充分显示了其富钾质的特征(周明忠等,2007)。

4.2 微量元素特征

所有样品的微量元素特征分析结果示于表3。微量元素原始地幔标准化蛛网图(图5,除去样品XD2−B4、B5、B6)表明其微量元素总体特征表现为富集Rb、Ba、Th、U等元素,Ti、P元素相对亏损。大离子亲石元素Sr、K呈现较为强烈的负异常,高场强元素Nd、Hf表现出一定程度的正异常。其中Ti/Th比值可以初步指示钾质斑脱岩源岩浆的性质,酸性火山灰物源的Ti/Th比值为30~400,中性火山灰物源为400~1000,基性火山灰物源为2500~3500(冯宝华,1989),4个钾质斑脱岩样品的Ti/Th比值介于31.34~100.55,提示其酸性火山灰物源。

4.3 稀土元素特征

所有钾质斑脱岩样品的稀土元素结果见表4,Eu异常采用Rollinson(1993)提出的计算方法($\delta Eu=Eu/Eu^*=(Eu_N)/[(Sm_N\times Gd_N)^{1/2}]$)进行计算,其中下标N

表1 新地2井五峰—龙马溪组内钾质斑脱岩矿物成分(X衍射分析))
Table 1 Mineral compositions of K−bentonite samples from the Wufeng-Longmaxi Formations in XD2 well (XRD)

序号	样品	黏土矿物相对含量/%								全岩分析/%					
		K	C	I	S	I/S	C/S	I/S%		黏土	石英	钠长石	黄铁矿	方解石	白云石
								S%	I%						
1	XD2-B1	0	1	62	0	37	0	5	95	61	2	7	17	7	6
2	XD2-B2	0	1	73	0	26	0	5	95	59	8	16	8	5	4
3	XD2-B3	0	5	59	0	36	0	10	90	58	5	20	17	0	0
4	XD2-B4	0	0	63	0	37	0	15	85	50	12	0	38	0	0
5	XD2-B5	0	3	84	0	13	0	10	90	32	5	8	55	0	0
6	XD2-B6	0	0	72	0	28	0	5	95	26	7	1	66	0	0
7	XD2-B7	2	8	55	0	35	0	5	95	51	6	5	30	3	5

注:K为高岭石;C为绿泥石;I为伊利石;S为蒙脱石;I/S为伊蒙混层;I/S%为 伊蒙混层比。

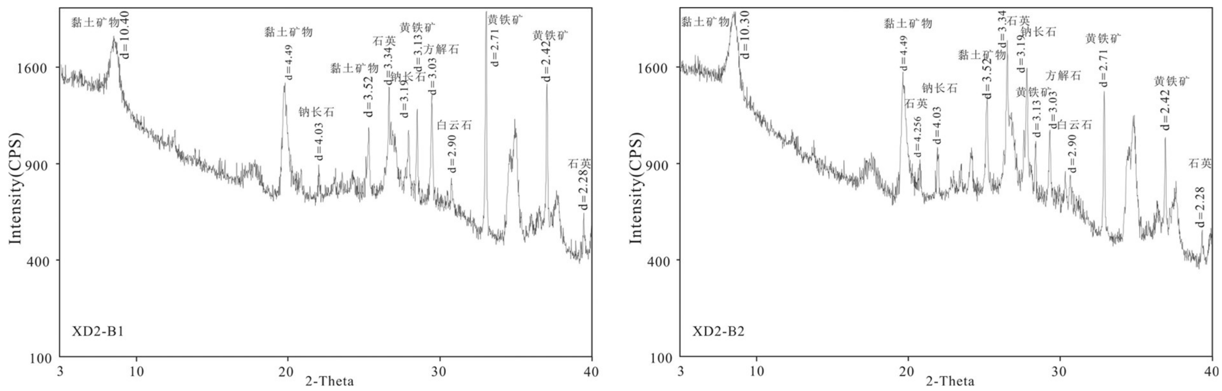

图4 新地2井五峰—龙马溪组内钾质斑脱岩样品的X衍射图谱

Fig.4 X−ray diffraction of the K−bentonite from Wufeng−Longmaxi Formations in XD2 well

指示元素相对于球粒陨石的标准化值(Taylor and McLenann, 1985)。从表4可以看出所研究的钾质斑脱岩样品稀土总量∑REE 含量变化较大，其范围（除 XD2−B4、B5、B6 样品外）介于 49.86 10^{-6}~209.43×10^{-6}，相对富集 LREE，贫 HREE，LREE/HREE 比值为 1.44~3.58，平均值为 2.36；La_N/Yb_N 比值为 0.67~2.57，δEu 值为 0.60~0.95。从稀土元素球粒陨石标准化模式图(图6)显示，整体上曲线展布特征大体一致，其中样品 XD2−B3 和 B7 标准化配分图呈弱的右倾型，轻稀土弱富集，重稀土相对亏损，Eu 轻度亏损，无明显的 Ce 异常，样品 XD2−B1 和 B2 标准化配分图上呈近乎平坦型，Eu 负异常。周明忠等(2007)指出 Eu 负异常形成的原因有两种可能，一是继承了母岩浆 Eu 负异常，另外一种可能是钾质斑脱岩沉降后期成岩作用的结果。从4个钾质斑脱岩样品的稀土元素的配分模式来看，其无明显的 Ce 异常说明钾质斑脱岩未受到海水蚀变作用的影响，火山灰沉降后受海水成岩作用影响较小，其 Eu 负异常可能是继承了母岩浆 Eu 负异常特征。

5 源岩浆性质及源火山构造背景讨论

5.1 源岩浆性质

TiO_2 以及 Nb、Zr、Y、Ta、Hf 等微量元素被认为在大部分的成岩过程和低级变质作用过程中是不活泼的，因而它们能够有效地保存相应的原始岩浆信息(Huff et al., 1997；苏文博等，2006；胡艳华等，

表2 新地2井岩心内五峰—龙马溪组钾质斑脱岩及参考样品主量元素含量(%)

Table 2 Analytical data of major elements(%) of K−bentonite from the Wufeng−Longmaxi Formations in XD2 well and reference samples

测试项目	样号								
	XD2-B1	XD2-B2	XD2-B3	XD2-B4	XD2-B5	XD2-B6	XD2-B7	NASC	PAAS
SiO_2	44.26	48.75	48.23	22.24	25.63	9.31	38.37	64.80	62.80
Al_2O_3	22.52	23.69	25.76	10.3	12.26	4.73	16.71	16.90	18.90
CaO	3.06	1.78	1.33	0.62	0.66	0.18	1.79	3.56	1.30
Fe_2O_3	6.17	2.95	3.08	36.37	31.11	51.6	15.42	-	7.20
FeO	0.97	1.19	0.93	2.01	2.95	2.3	2.55	5.70	-
K_2O	6.08	6.2	6.99	2.68	2.86	1.08	4.45	3.99	3.70
MgO	2.65	2.6	2.53	1.39	1.83	0.8	2.5	2.85	-
MnO	0.13	0.05	0.03	0.01	0.01	0.01	0.04	0.06	2.20
Na_2O	0.91	1.51	0.77	0.32	0.74	0.26	0.76	1.15	1.20
P_2O_5	0.12	0.08	0.77	0.02	0.13	0.05	0.11	0.11	0.16
TiO_2	1.68	2.29	2.32	0.26	0.39	0.17	0.79	0.78	1.00
LOI	9.02	6.89	6.64	22.29	19.68	28.83	13.04	-	-
TOTAL	97.57	97.98	99.38	98.51	98.25	99.32	96.53	-	-

注：NASC为北美页岩 (Gromet et al.,1984)；PAAS为澳大利亚后太古宙页岩(Taylor and McLennan, 1985)；−表示未检测到。

表3 新地2井岩心内五峰-龙马溪组钾质斑脱岩微量元素含量(10^{-6})

Table 3 Analytical data of trace elements (10^{-6}) of K-bentonite samples from the Wufeng-Longmaxi Formations in XD2 well

测试项目	样号						
	XD2-B1	XD2-B2	XD2-B3	XD2-B4	XD2-B5	XD2-B6	XD2-B7
V	165	215	252	29.5	32	13.8	86.9
Cr	9.25	10.2	5.99	7.17	8.64	5.97	32.1
Co	57	56.4	23.2	14.7	22.5	22.5	45.4
Ni	102	93.7	60.3	68	118	113	192
Cu	30.5	53.4	31.1	71.6	165	332	91.5
Zn	878	795	503	70.2	301	478	5023
Ga	22.3	23.4	25.8	10.9	11.9	4.66	19.3
Rb	198	178	210	94.1	98.2	34.4	171
Sr	141	72.4	67.4	31	30.8	10.9	73.4
Nb	21.2	28.3	20.5	6.78	6.07	3.8	57
Cs	18.1	17.8	20.4	7.81	8.91	2.38	11.7
Ba	3732	3826	4333	2674	3059	1633	6905
Ta	2.43	2.69	2.11	0.98	1.82	1.51	9.71
Pb	105	176	175	64.1	49.1	67.9	75
Th	36.7	34.8	29.6	16.1	24.5	26.1	35.3
U	7.04	6.87	8.28	5.81	5.23	4.35	20.9
Zr	407	402	398	121	177	145	479
Hf	17.6	17.4	14.6	4.28	6.52	6.4	15.9
Sc	22.5	20.9	27.2	4.16	4.21	2.25	10.7
Y	32.2	28.8	63.6	12.8	14.3	7.73	42.1
Ti/Th	31.34	34.01	56.65	42.68	35.00	38.28	100.55

表4 新地2井岩心内五峰-龙马溪组钾质斑脱岩稀土元素含量(10^{-6})

Table 4 Analytical data of REE(10^{-6}) of K-bentonite samples from the Wufeng-Longmaxi Formations in XD2 well

测试项目	样号							
	XD2-B1	XD2-B2	XD2-B3	XD2-B4	XD2-B5	XD2-B6	XD2-B7	NASC
La	4.9	5.38	20.2	16.6	20.8	2.3	17.9	98.1
Ce	12.9	11.3	68.5	31.6	44.4	5.21	37.1	207
Pr	2.06	1.81	10.6	4.16	6.07	0.79	5.09	22.8
Nd	10.5	8.03	48.4	15.9	23.3	3.7	20.8	80.8
Sm	3.45	2.28	13.3	3.08	4.69	1.12	5.01	17.1
Eu	0.84	0.62	2.74	0.47	0.63	0.28	1.45	3.03
Gd	3.88	2.73	14.7	2.73	4.15	1.2	4.39	17.5
Tb	0.76	0.62	2.27	0.41	0.56	0.22	0.85	2.16
Dy	5.62	5	12.4	2.57	3.13	1.5	6.78	11.6
Ho	1.33	1.23	2.28	0.52	0.6	0.33	1.7	2.2
Er	4.91	4.53	6.62	1.78	1.89	1.19	6.54	6.9
Tm	0.78	0.72	0.88	0.26	0.27	0.19	1.04	0.94
Yb	5.21	4.88	5.71	1.75	1.75	1.35	7.38	6.17
Lu	0.81	0.73	0.83	0.25	0.26	0.2	1.12	0.9
∑REE	57.95	49.86	209.43	82.08	112.50	19.58	117.15	477.2
LREE	34.65	29.42	163.74	71.81	99.89	13.40	87.35	428.83
HREE	23.30	20.44	45.69	10.27	12.61	6.18	29.80	48.37
LREE/HREE	1.49	1.44	3.58	6.99	7.92	2.17	2.93	8.87
La_N/Yb_N	0.67	0.79	2.54	6.80	8.53	1.22	1.74	11.40
Eu/Eu*	0.70	0.76	0.60	0.50	0.44	0.74	0.95	0.54

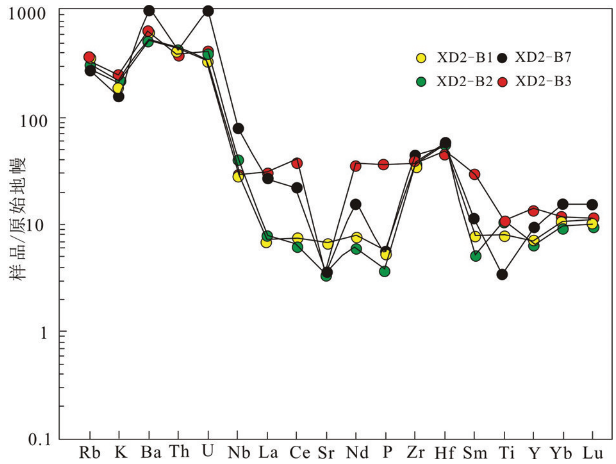

图5 新地2井五峰—龙马溪组内钾质斑脱岩微量元素原始地幔标准化珠形网

Fig.5 Primitive mantle-normalized trace elements spider of K-bentonite from Wufeng-Longmaxi Formations in XD2 well

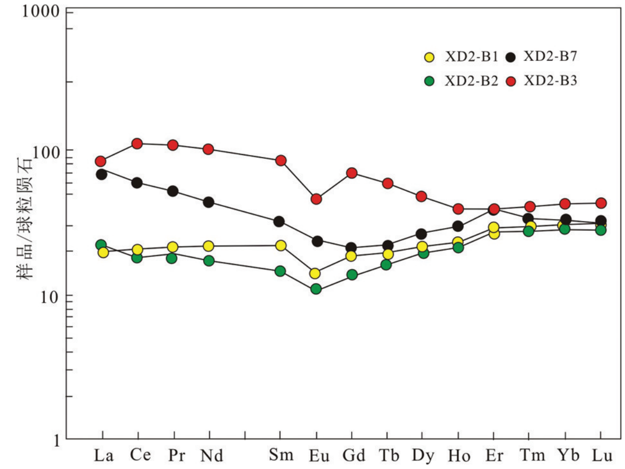

图6 新地2井五峰—龙马溪组钾质斑脱岩稀土元素配分模式

Fig.6 Chondrite-normalized REE distribution patterns of K-bentonite from the Wufeng-Longmaxi Formations in XD2 well

2009a）。对于钾质斑脱岩的原始岩浆性质恢复，通常采用的是Winchester 和 Floyd (1977) 的Nb/Y-Zr/TiO_2图解。将新地2井岩心的4个钾质斑脱岩样品(XD2-B4，B5，B6除外）投入Nb/Y- Zr /TiO_2判别图中（图7a）。结果表明其中1个钾质斑脱岩样品落入粗面英安岩类，1个落入碱性玄武岩类，2个落入安山岩类范围内，该结果与胡艳华等(2009)宜昌王家湾剖面以及Su et al.(2009)湖南桃源、新化、江苏句容等地奥陶—志留系钾质斑脱岩大体一致，仅一个样品落在碱性玄武岩范围，其余多数样品落在安山岩、粗面岩和流纹岩范围内，反映所研究的钾质斑脱岩的原始岩浆性质可能为中酸性成分。

5.2 源火山构造背景分析

钾质斑脱岩中一些稳定的微量和稀土元素除了可以反映原始岩浆成分之外，还可以有效指示源火山喷发的构造背景(Teale and Spears, 1986; Roberts and Merriman, 1990; Huff et al., 1997)。最初Pearce et al.(1973)根据化学成分来限定岩浆起源的大地构造背景，区别产生于不同大地构造背景的玄武岩，并建立了构造岩浆判别图解，被广泛应用的有Th-Hf-Ta图解、(Nb+Y)-Rb 图解、Y-Nb图解等，尔后Pearce et al.(1984)又将该判别方法发展到花岗岩质岩石领域，并有更多的研究者提出了许多新的基于化学成分判断岩浆源区大地构造背景的判别图解(Wood, 1980; Mullen, 1983; Cabanis and Lecolle, 1989)。对于钾质斑脱岩而言，判别其构造背景应用最多的是Nb-Y，(Y+Nb)-Rb，Zr-TiO_2，Nb/Yb-Th/Yb等。

将新地2井岩心中4个钾质斑脱岩(XD2-B4，B5，B6除外）投入以上判别图解中，Y-Nb图（图7b）显示，4个样品均落在板内花岗岩一侧，该结果与Su et al.(2009)湖南、江苏等地的奥陶—志留系钾质斑脱岩结果基本一致，但与胡艳华等(2009)有较大的不同，他们的结果在岛弧、同碰撞、洋脊和板内花岗岩均有落入。(Y+Nb)-Rb图解（图7c）中，判别结果与胡艳华等(2009)一致，4个样品均落在岛弧型花岗岩和板内花岗岩的交界线上以及接近板内花岗岩一侧。在Nb/Yb-Th/Yb图解（图7e）中，4个样品均落入大陆弧和大洋弧的重合处，在Zr-TiO_2图解（图7f）中，4个样品均落在板内岩浆范围内，但在Hf/3-Th-Ta 三角图解中(Wood, 1980; 图7d)，其中除1个样品未落入相关定义区域内外，其余3个数据点均落入火山弧玄武岩区内。此外近期研究表明，曾经被认为是不活泼的Zr、Hf、Nb、Ta、Ti等元素在有水条件下的化学风化过程中，也表现出一定的活动性(Nesbitt et al., 1996; Nesbitt and Markovics, 1997; Ma et al., 2007)，因此以这些非活动性元素的含量作为变量的判别图可能也会存在一定的误差，胡艳华(2009a，b)指出化学性质比较接近的元素在风化作用过程中受到的影响相当，因此可以利用元素之间的比值来消除风化作用的影响，可以说利用元素的比值作为变量的判别图解可能

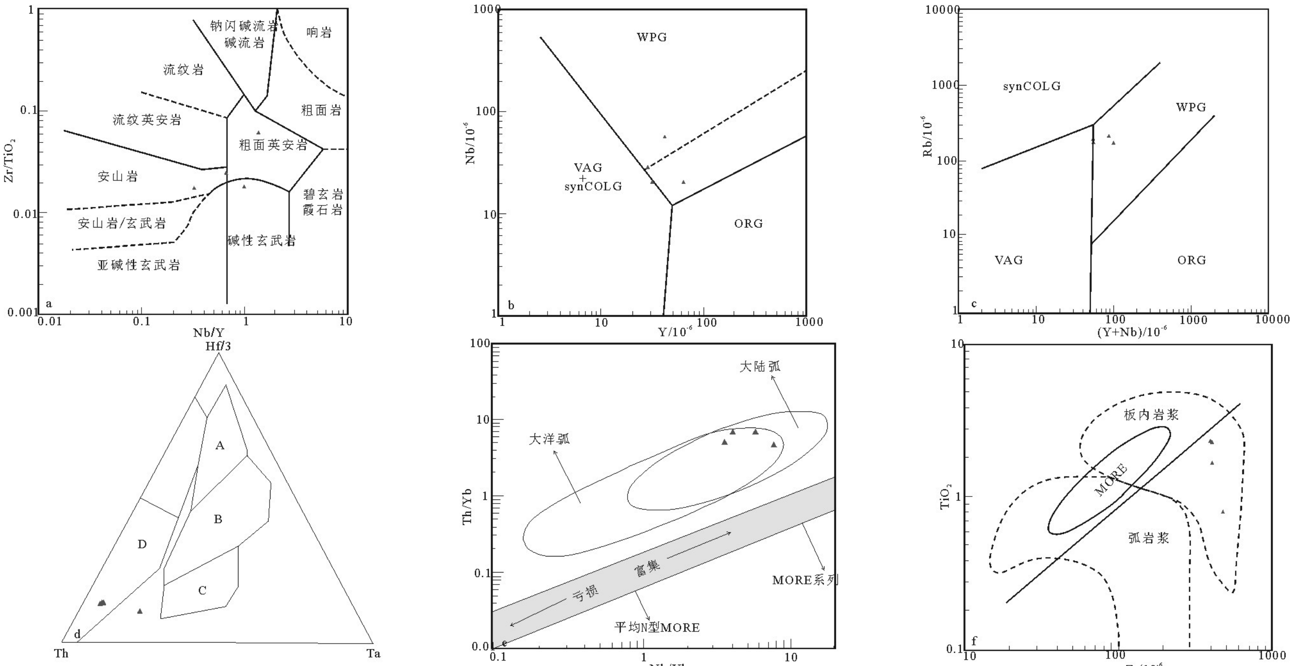

图7 新地2井五峰—龙马溪组内钾质斑脱岩原始岩浆及构造背景判别图解

(a底图据Winchester and Floyd, 1977;b、c底图据Pearce et al.,1984;d底图据Wood, 1980;e底图据Pearce and Peat,1995;f底图据Pearce and Peat, 1979)

WPG—板内花岗岩；VAG—火山弧花岗岩；ORG—洋中脊花岗岩；syn COLG—同碰撞花岗岩；A—N型MORE；B—E型MORE和板内拉斑玄武岩；C—碱性板内玄武岩；D-火山弧玄武岩

Fig.7 Source magma and tectonic environment discrimination diagrams of K−bentonite samples from the Wufeng−Longmaxi Formations in XD2 well

(a−Bulk rock ratios of Nb/Y and Zr/TiO_2 from dashed lines indicate source fields defined by Winchester & Floyd (1977); b−Nb−Y and (c−Rb−Y + Ta plots of K−bentonites defined by Pearce et al.(1984); d−Hf/3−Th−Ta,e−Th/Yb−Nb/Yb and f−TiO_2−Zr plots of K−bentonites defined by Wood (1980); Pearce and Peat (1995,1979) respectively. WPG−within plate granite; VAG− volcanic arc granite; ORG− ocean ridge granite, syn COLG− syn−collision granite; A−N−MORE; B−E−MORE and within plate tholeiitic basalt；C−within palte alkaline basalt；D−volcanic arc basalt

更加准确，而基于不活泼元素比值的Nb/Yb−Th/Yb图解（Pearce and Peate，1995）和Hf/3−Th−Ta三角图解（Wood，1980）的判定结果可能更具信服力，故本文笔者更倾向于认为新地2井上奥陶统—下志留统五峰—龙马溪组内发育的钾质斑脱岩其源火山构造背景可能多源于岛弧环境。

钾质斑脱岩原为火山灰沉降后经海水蚀变作用形成，属火山成因，这些火山灰来源于哪里呢？钾质斑脱岩的地球化学信息指示其源火山构造背景为岛弧环境，晚奥陶世—早志留世初，扬子地台北缘早古生代秦岭洋闭合过程中板块俯冲发育岛弧岩浆活动，杨颖（2011）从湖北宜昌黄花场和桐梓南坝子两条剖面五峰—龙马溪组内的斑脱岩中分选出的锆石具典型的环带结构，属岩浆成因锆石，锆石U−Pb年龄结果也在440 Ma左右，黄花场剖面锆石Hf同位素$\varepsilon_{Hf}(t)$值为正，同南秦岭陕西省旬阳县早泥盆世西岔河组杂砂岩中的碎屑锆石年龄及$\varepsilon_{Hf}(t)$值特征一致，以上均反映火山灰的来源可能与扬子北缘秦岭洋的闭合的板块俯冲活动有关。

另外有学者指出这些火山灰来源与扬子和华夏地块的汇聚有关，但是现阶段针对扬子与华夏地块在早古生代是否为板块间俯冲还是板内碰撞挤压仍未有定论（刘宝珺等，1994；陈旭等，1995；殷鸿福等，1999；舒良树，2006；张国伟等，2013），华夏板块附近也未见有早古生代岛弧活动的迹象，苏文博等（2006）、Su et al.(2009)指出扬子板块的东南缘外侧可能存在一个“华夏陆块”，这个“华夏陆块”的范围可能包括了现今中国东南部海岸线，东海以及其他相邻地区，正是由于以上两陆块的拼合碰撞产生相应的火山岛弧活动，为华南晚奥陶世—早志留世

初钾质斑脱岩的沉积提供相应的火山灰来源。笔者可能更倾向于认为华南地区五峰—龙马溪组黑色页岩内沉积的钾质斑脱岩的火山灰来源可能与扬子北缘秦岭洋闭合的板块俯冲活动有关。

6 结 论

（1）新地2井五峰—龙马溪组内斑脱岩矿物成分以黏土矿物（伊蒙混层和伊利石）为主，同时含有石英、长石、黄铁矿、方解石、白云石等矿物，且所有样品均为$K_2O > Na_2O$，K_2O平均含量大于3.5%，显示了其富钾质特征，野外和室内特征都符合钾质斑脱岩的定义。

（2）斑脱岩样品具有相似的地球化学组成及相应的配分模式，主量元素以高K_2O，低CaO、低TiO_2为特征，其中微量元素总体特征表现富集Rb、Ba、Th、U等元素，Ti、P元素相对亏损。大离子亲石元素Sr、K呈现较为强烈的负异常，高场强元素Nd、Hf表现出一定程度的正异常。稀土元素ΣREE在$(49.86\sim209.43)\times10^{-6}$；与球粒陨石相比，轻稀土轻微富集、具Eu负异常，无Ce异常。

（3）Nb/Y−Zr/TiO_2岩浆判别图表明这些钾质斑脱岩的原始岩浆具中酸性特征，依据微量元素特征和构造环境判别图（Y−Nb，（Y+Nb）−Rb，Zr−TiO_2，Nb/Yb−Th/Yb，Hf/3−Th−Ta三角图解）等，初步认为其源火山构造背景可能多源于岛弧环境，火山灰来源可能与扬子北缘早古生代秦岭洋闭合过程中的板块俯冲有关。

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