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赣东北蛇绿岩地幔橄榄岩岩石成因及其地质意义

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提要：赣东北蛇绿岩作为华南少有的前寒武纪蛇绿岩长期都是华南大地构造研究中的热点。该蛇绿岩地幔橄榄岩以方辉橄榄岩为主，稀土总量为0.83×10^{-6}~2.62×10^{-6}，远低于原始地幔的含量，而MgO含量高于原始地幔。稀土元素表现为LREE相对富集，微量元素表现为大离子亲石元素（LILE）富集，高场强元素Nb明显亏损的特征，这表明赣东北地幔橄榄岩具有亏损地幔源区特征，同时也有不同程度的俯冲带流体的交代特征。HREE模拟的部分熔融程度为10%~30%；同时，赣东北蛇绿岩地幔橄榄岩中同时包含$Cr^{\#}>60$和$Cr^{\#}<60$两种不同成因的铬尖晶石，说明其经历了MOR（mid−ocean ridge）和SSZ（supra−subduction zone）两种构造环境。结合前人资料，笔者推测赣东北蛇绿岩早先可能形成于洋中脊环境（约1060 Ma），随后在洋内俯冲作用下（约970 Ma），位于俯冲带上部的地幔橄榄岩受到了来自俯冲带的流体/熔体的交代，经历了SSZ环境的改造。

关　键　词：地幔橄榄岩；尖晶石；赣东北蛇绿岩；MOR；SSZ

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The origin of the mantle peridotite from ophiolitite in northeast Jiangxi and its geological implications

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Abstract: The ophiolite in northeast Jiangxi is one of rare Precambrian ophiolites in Jiangnan orogenic belt and also a hot topic for the tectonics of South China. The mantle peridotite mainly consists of harzburgite. Compared with primitive mantle, the peridotites have lower total REE values varying from 0.83×10^{-6} to 2.62×10^{-6} and higher MgO content. On the chondrite−normalized REE patterns, the rocks display enriched LREE patterns. When normalized to primitive mantle, all samples show variable enrichment of LILEs and are characterized by significant Nb negative anomalies. These features imply a depleted mantle source, which was overlapped by fluid alteration in a subduction zone. On the HREE patterns, the calculation shows that the harzburgites exhibit the residues of 10%−30% partial melting of the mantle source. Meanwhile, the spinels from mantle peridotites in northeast Jiangxi can be divided into two types which are $Cr^{\#}>60$ and $Cr^{\#}<60$ in the light of their chemical compositions. It is thus concluded that the

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spinels are of characteristics of both MOR and SSZ setting. In combination with previous researches, the authors infer that ophiolites in northeast Jiangxi originated in a MOR setting at ca. 1060 Ma, and was modified by melts and fluids in a SSZ mantle wedge at ca. 970 Ma.

Key words: mantle peridotite; spinel; ophiolite in northeast Jiangxi MOR; SSZ

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造山带中的蛇绿岩可以为大洋岩石圈的岩浆事件、变质事件、构造作用以及古洋盆演化的过程提供重要的信息[1]。赣东北蛇绿岩位于江南造山带东段(图1-a),是华南目前公认的少数前寒武纪蛇绿岩之一[2],蕴含了有关江南造山带乃至华南前寒武纪大地构造演化的重要信息,一直以来都是华南前寒武纪研究的热点而备受关注[3-14]。

前人对赣东北蛇绿岩的形成环境的研究,多集中在火山岩的地球化学和同位素方面,且较为一致的认为其为SSZ型蛇绿岩,形成于岛弧环境或弧后盆地环境中[6,12,15-17]。而对于蛇绿岩中的地幔橄榄岩的研究工作,尚比较薄弱。蛇绿岩中的橄榄岩可为地幔熔融过程,岩石-流/熔体反应提供重要的信息,进而为蛇绿岩形成的构造背景的研究提供重要线索[18]。

本文对赣东北蛇绿岩中地幔橄榄岩进行了系统研究,为赣东北蛇绿岩的性质和演化过程提供了新的制约。

1 区域地质概况

赣东北断裂带是扬子东南缘一条重要的地体构造边界,即江南东段九岭地体和怀玉地体的分界线[8,19-21]。沿该断裂带广泛分布中—新元古代基性-超基性岩块,构成NNE向展布的赣东北蛇绿岩带。赣东北蛇绿岩带南起弋阳樟树墩,北至德兴中村,全长约80 km,呈NNE方向展布(图1-b)。它们由一系列基性-超基性岩块组成,包括樟树墩、西湾、饶二和茅桥等超基性岩块,构造侵位在张村岩群浅变质火山-沉积岩中[4,12,15]。赣东北蛇绿岩的原始层序已经被构造肢解,岩性复杂,主要岩石类型为变质橄榄岩、堆晶辉长岩、辉石岩、辉绿岩、闪长岩、浅色花岗岩、玄武岩和硅质岩[5]。地幔橄榄岩出露面积最大,普遍强烈蛇纹石化。辉长岩和辉绿岩规模较小。浅色花岗岩出露在西湾变质橄榄岩中,呈团块状散布,出露面积很小。这些浅色花岗岩可分为2类:一类为俯冲型的钠长花岗岩,年龄约为970 Ma[9,14];另一类为代表仰冲型的黑云母花岗岩,年龄约为880 Ma[13]。变质火山岩主要为变质玄武岩和细碧岩[17]。与赣东北蛇绿岩套共生的沉积岩则出现大量的白云质大理岩和条带状大理岩,是典型的深海沉积岩[7]。在西湾变质橄榄岩与千枚岩之间的断层接触带上,前人还报道见有高压变质岩,由蓝闪石片岩、硬玉钠长石片岩与千枚岩混杂组成,并获得高压变质矿物(蓝闪石/青铝闪石)K-Ar年龄为866 Ma左右[8]。赣东北蛇绿岩内的这些岩石单元普遍经历了低绿片岩相变质,并强烈地构造变形,与围岩呈明显的构造接触,在接触带上存在明显的挤压破碎带。

2 分析方法

在详细野外观察基础上,系统采集樟树墩和西湾等地地幔橄榄岩样品,显微镜下开展详细岩相学研究,选择较为新鲜的样品进行全岩地球化学分析。全岩主量分析在南京地质矿产研究所实验室完成,主量元素用原子荧光光谱仪(AFS-2202a)分析,微量元素采用电感耦合等离子体质谱仪(ELMENT2)分析,分析精度相对误差符合DZ/T0130-2006行业标准。分析结果见表1。

选择代表性矿物进行电子探针成分分析及背散射图像分析(BSE)。所有分析均在中国冶金地质总局山东测试中心用JOEL JXA 8230型电子探针完成。选用15 kV加速电压,20 nA电子束电流,5 μm电子束直径。标准样品选用硬玉 (Si、Na)、橄榄石(Mg)、铁铝榴石 (Fe、Al)、透辉石 (Ca)、钾长石 (K)、氧化铬 (Cr)、金红石 (Ti)、硅化镍 (Ni)、金属钴 (Co)、蔷薇辉石 (Mn) 、磷灰石(P)。Ni、Co、F、Mn的测试

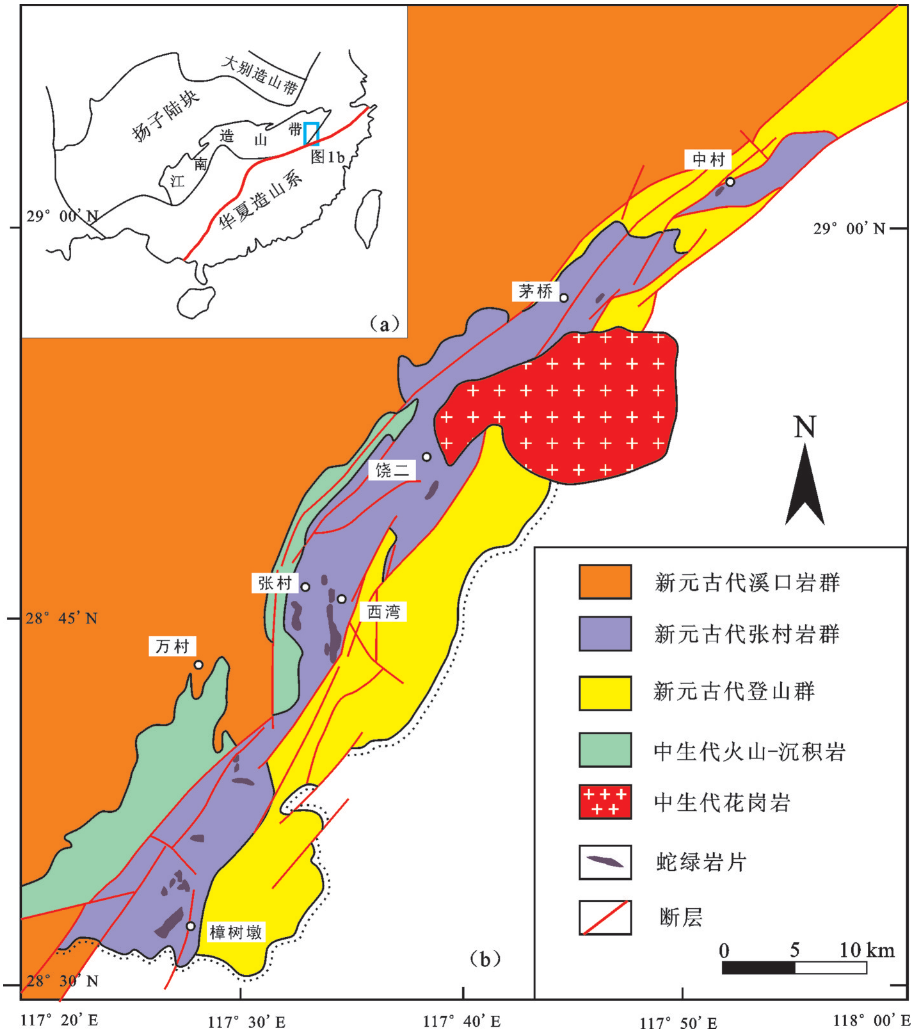

图1 赣东北蛇绿岩带大地构造位置(a)及区域地质简图(b,据Li et al., 2008[13]修改)

Fig.1 Schematic tectonic map of South China showing the location of the northeast Jiangxi ophiolite (a), Geological map of the northeast Jiangxi ophiolite (modified after Li et al., 2008[13]) (b)

时间为30 s,其他的元素的测试时间为10 s。详细的分析误差及分析方法见[22]。分析结果见表3。

3 岩石地球化学特征

赣东北蛇绿岩中的地幔橄榄岩呈灰黑色,块状构造,强烈蛇纹石化成蛇纹岩(图2-a)。矿物组成主要有蛇纹石、碳酸盐类、尖晶石及少量磁铁矿。蛇纹石多为叶蛇纹石,呈叶片状(图2-b),仍保留有橄榄石假象,含量约为70%;碳酸盐矿物主要为菱镁矿,约占15%;尖晶石镜下仅在矿物边缘微透光,呈现红褐色、黄褐色色调,具不等粒粒状结构,发育不规则网脉状裂纹,粒径0~1.5 mm,约占10%;磁铁矿及其他不透明矿物约占5%(图2-c)。

尽管岩石受到了一定的蚀变,但对于这种蛇纹石化的岩石进行CIPW标准矿物的计算仍然可以帮助我们判断原岩的矿物组成。从CIPW标准矿物计算结果中可以看出,赣东北蛇绿岩中蛇纹石化的地幔橄榄岩的原岩除一个样品落在纯橄岩区域外,大多为方辉橄榄岩(图3)。

樟树墩和西湾蛇蛇纹石化地幔橄榄岩强烈亏损易容元素Al_2O_3(0.60%~1.71%)、CaO(0.04%~1.09%)、Na_2O(<0.04%)和TiO_2(0.01%~0.03%),含量均明显低于原始地幔的平均值[23]。过渡元素Ni和Cr富集,Ni为1600×10^{-6}~1990×10^{-6},Cr为1030×

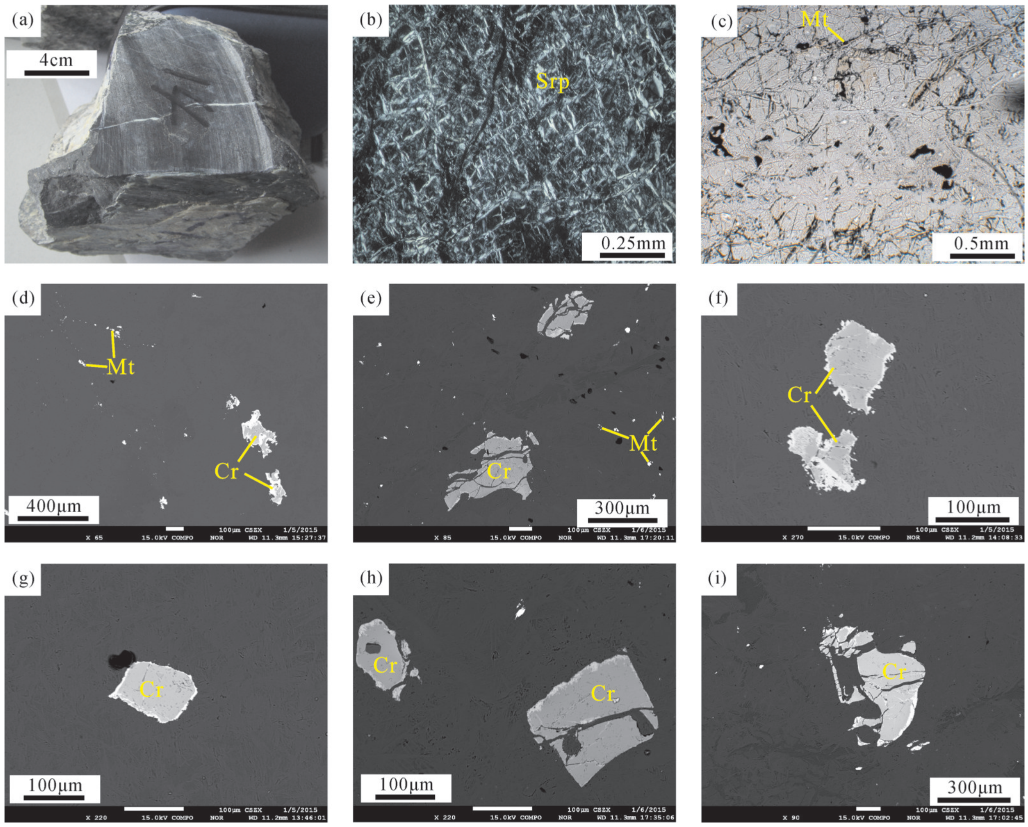

图2 赣东北蛇绿岩地幔橄榄岩照片和背散射图像

a—蛇纹石化方辉橄榄岩手标本;b—蛇纹岩主要由叶蛇纹石组成;c—蛇纹石化过程形成的磁铁矿条带;d~i—蛇纹岩中自形和半自形的铬尖晶石;Srp—蛇纹石;Cr—铬尖晶石;Mt—磁铁矿

Fig. 2 Photographs and back-scattered electron (BSE) images of the peridotites from the northeast Jiangxi ophiolites

a- Hand specimen of the serpentinized harzburgite; b- Serpentinite mainly composed of serpentine; c- Magnetite band formed during serpentinization; d-i-Euhedral Cr-spinel and subhedral Cr-spinel within serpentinite; Srp-Serpentine; Cr-Chrome spinel; Mt-Magnetite

10^{-6}~1510×10^{-6},Mg#值较高(变化于91~94)(表1),反映了地幔残留岩石的特征。

赣东北地幔橄榄岩REE丰度较低,∑REE为0.83×10^{-6}~2.62×10^{-6},远低于原始地幔(∑REE=7.430×10^{-6})和亏损地幔(∑REE=4.245×10^{-6}),指示了地幔橄榄岩岩石经历了较高程度的部分熔融作用。LREE/HREE=3.29~5.31,$(La/Yb)_N$和$(La/Sm)_N$分别变化于3.75~13.14和2.44~10.22。虽然REE含量略有变化,但分布模式却较为一致。在球粒陨石标准化稀土元素图解中(图4-a),表现出略呈“U”型的配分型式。LREE均富集,富集程度略有差异。研究表明,地幔橄榄岩的LREE在蛇纹石化的过程中保持稳定,LREE的富集主要受流体/熔体与地幔橄榄岩之间的反应控制[24-25]。樟树墩和西湾地幔橄榄岩的LREE相对富集的特征,表明岩石受到了后期流体/熔体的改造。Niu[24]对采自现代洋脊的深海橄榄岩的研究显示,地幔橄榄岩的全岩HREE含量主要受岩石中单斜辉石含量的控制,而在后期蛇纹石化及地幔交代作用中基本保持稳定,认为可以用HREE来定量模拟地幔橄榄岩的部分熔融程度。樟树墩和西湾地幔橄榄岩利用HREE模拟的部分熔融程度为10%~30%(图4-a)。

在地幔橄榄岩微量元素原始地幔标准化图中(图4-b),显示一个向右倾斜的特征。其中大离子亲石元素(LILE)富集,指示俯冲带流体作用;高场强元素Nb明显亏损,可能是受到了后期分异熔体交代作用造成的[26]。总体显示后期流体/熔体的交代改造特点。

4 矿物化学成分

在地幔橄榄岩中,尖晶石是一种非常重要的副矿物,虽然含量较低,但它非常稳定,在后期地质作

表1 赣东北蛇绿岩中地幔橄榄岩主量(%)、微量和稀土元素(10^{-6})组成

Table 1 Major (%), trace and rare earth (10^{-6}) elements compositions of the mantle peridotites from northeast Jiangxi ophiolites

分析项目	PMZSD-0-1	PMZSD-0-2	PMZSD-0-3	PMZSD-0-4	1001-1	1002-1	1003-1
	樟树墩				西湾		
SiO_2	36.88	37.84	39.89	34.42	40.50	40.60	39.50
TiO_2	0.01	0.03	0.02	0.03	0.01	0.01	0.01
Al_2O_3	0.77	0.74	0.60	0.87	0.98	1.07	0.71
Fe_2O_3	5.87	8.39	6.84	9.38	6.89	7.15	7.87
MnO	0.12	0.06	0.06	0.07	0.08	0.09	0.10
MgO	40.72	40.24	40.67	39.00	37.20	37.30	39.30
CaO	1.09	0.04	0.14	0.96	0.07	0.05	0.90
NaO_2	0.04	<0.01	<0.01	<0.01	<0.01	0.02	0.01
K_2O	0.01	0.02	0.02	0.02	0.01	<0.01	<0.01
P_2O_5	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
LOI	13.81	12.86	12.00	15.51	13.12	12.41	12.42
Total	99.38	100.23	100.24	100.27	98.86	98.70	100.82
$Mg^{\#}$	94	92	93	91	93	92	92
La	0.42	0.46	0.56	0.68	0.18	0.16	0.13
Ce	0.45	0.49	0.38	0.63	0.25	0.22	0.32
Pr	0.09	0.13	0.06	0.08	0.05	0.04	0.03
Nd	0.34	0.45	0.22	0.55	0.11	0.14	0.15
Sm	0.07	0.09	0.06	0.07	0.03	0.07	0.06
Eu	0.02	0.05	0.04	0.05	0.02	0.03	0.05
Gd	0.08	0.10	0.07	0.14	0.03	0.03	0.05
Tb	0.01	0.02	0.01	0.03	0.01	0.01	0.01
Dy	0.06	0.11	0.09	0.15	0.04	0.04	0.05
Ho	0.01	0.02	0.02	0.03	0.01	0.01	0.01
Er	0.04	0.07	0.06	0.09	0.04	0.04	0.03
Tm	0.01	0.01	0.01	0.01	0.01	0.01	0.00
Yb	0.04	0.08	0.06	0.10	0.05	0.05	0.03
Lu	0.01	0.02	0.01	0.02	0.01	0.01	0.01
Y	0.44	0.69	0.52	0.82	0.38	0.46	0.28
Rb	0.29	0.51	0.45	0.45	0.50	0.30	0.20
Ba	9.39	7.80	8.20	8.68	5.45	8.13	6.78
Th	0.12	0.16	0.12	0.11	0.02	0.02	0.05
U	0.06	0.05	0.04	0.04	0.02	0.02	0.02
Ta	0.04	0.03	0.04	0.14	0.02	0.02	0.03
Nb	0.21	0.12	0.18	0.23	0.16	0.13	0.09
Pb	0.21	1.20	0.58	0.31	0.10	0.15	0.45
Sr	22.90	6.00	33.10	17.90	4.22	3.08	35.80
Zr	0.54	0.64	0.65	0.72	0.44	0.41	0.83
Hf	0.08	0.02	0.02	0.02	0.01	0.01	0.02
Cu	1.7	9.91	1.93	1.89	3.46	5.65	4.95
Zn	33.6	18.1	13.6	16	41.5	49.8	46
V	34.5	65.1	49.9	66.2	36.8	40.7	23.4
Ni	1792	2162	1586	1904	1990	1940	1700
Co	82.6	108	94.4	108	101	98.1	79.4
Cr	2594	2394	1612	2061	1500	1720	1310
Li	0.59	0.72	2.99	0.73	1.94	2.02	4.14
W	0.31	0.21	0.16	0.14	0.12	0.06	0.24
Bi	0.06	0.20	0.06	0.09	0.02	0.01	0.07

用过程中，不容易发生蚀变，因此可以作为其寄主岩石地幔橄榄岩的成因指示剂[27-29]。在高度蛇纹石化蚀变的样品中，尖晶石具有氧化边，因此，本项研究中分析的都是尖晶石新鲜的核部。

镜下观察显示，在樟树墩和西湾地幔橄榄岩中的尖晶石出现在蛇纹石化的橄榄石颗粒之间（图2-d、e）。大多数尖晶石颗粒在50~100 μm，在矿物边缘的亮度与中心明显不一致，形成一圈氧化边（图2-f、g）。在薄片中，还见到磁铁矿围绕蛇纹石化的橄榄石边缘分布（图2-f~i）。从所有尖晶石的分析结果（表3）可以看出，尖晶石具有高的Cr_2O_3、FeO和Al_2O_3含量，MgO含量变化大，但Na_2O、K_2O、

表2 赣东北蛇绿岩中地幔橄榄岩全岩CIPW标准矿物计算的矿物成分

Table 2 Mineral composition of the mantle peridotites from northeast Jiangxi ophiolites calculated by CIPW method

样品	1210ZSD-1	1210ZSD-2	1210ZSD-3	PMZSD-0-4	1001-1	1002-1	1003-1
Pl	2.26	0.13	0.69	2.34	0.35	0.42	2
Or	0	0.12	0.12	0.12	0.06	0	0
C	0	0.68	0.32	0	0.85	0.96	0
Di	2.72	0	0	1.95	0	0	2.04
Hy	8.34	17.34	24.03	1.63	35.68	35.38	20.51
Ol	71.28	67.8	62.04	77.28	47.79	48.47	62.68
Ilm	0.02	0.06	0.04	0.06	0.02	0.02	0.02
Ap	0.02	0.02	0	0	0	0	0
Mt	0.86	1.23	1	1.38	1.22	1.04	1.15

注：Pl—斜长石；Or—正长石；C—刚玉；Di—透长石；Hy—紫苏辉石；Ol—橄榄岩；Ilm—钛铁矿；Ap—磷灰石；Mt—磁铁矿。

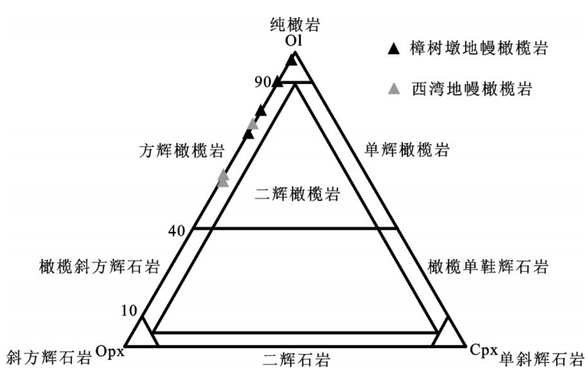

图3 赣东北蛇纹岩原岩成分恢复图解

Fig.3 Discrimination diagram for restoration of orignal composition of the serpentinites from northeast Jiangxi ophiolite

NiO、SiO_2 和 TiO_2 含量低。CaO 和 K_2O 含量大部分在检出限以下。所有测试结果表明，这些原生尖晶石为铬尖晶石，$Cr^{\#}$ 值（100×Cr/(Cr+Al)）在 52~70。这种变化可能是由于岩浆抽取或后期的蚀变导致[30]。从尖晶石表面结构分析，在地幔橄榄岩就位前，发生过部分熔融事件。

5 讨 论

5.1 地幔橄榄岩成因

赣东北地幔橄榄岩中易熔元素和稀土总量远低于原始地幔的含量，而MgO含量高于原始地幔，表明该地幔橄榄岩为一套高亏损的原始地幔熔融残留物。从稀土元素配分模式来看，赣东北蛇绿岩地幔橄榄岩配分模式基本相似，均表现为略具“U”型，LREE相对富集，微量元素中Cr和Ni含量较高。大离子亲石元素富集，高场强元素Nb明显亏损，表明赣东北地幔橄榄岩既具有亏损地幔源区的特征，也有不同程度的俯冲带流体的交代特征。

同时，我们的研究表明，地幔橄榄中的尖晶石属于Cr尖晶石。Cr尖晶石在蛇绿岩的研究中，是一种比较稳定的标型矿物，它在一般的后期蚀变中不

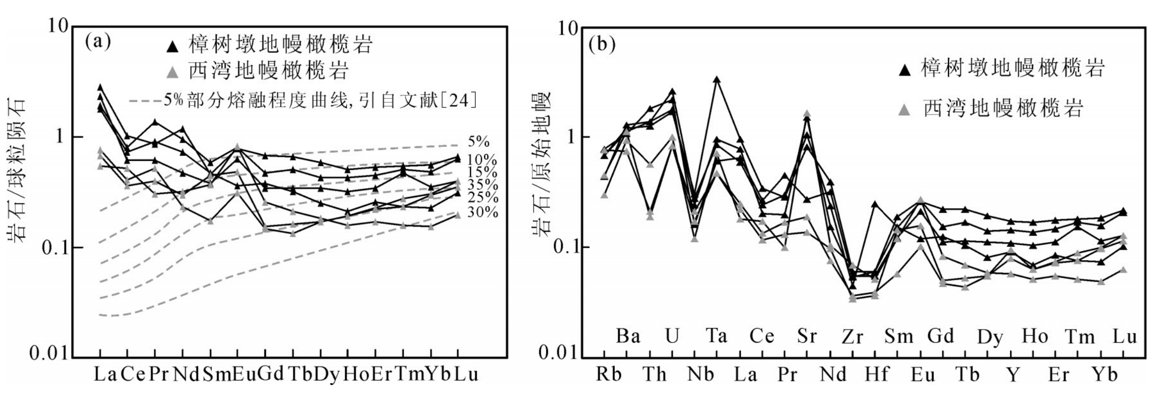

图4 赣东北蛇绿岩地幔橄榄岩稀土元素配分模式图（a）和微量元素蛛网图（b）（球粒陨石和原始地幔的值据文献[23]）

Fig.4 Chondrite-normalized REE patterns (a) and primitive mantle-normalized spider diagram (b) of the mantle peridotite from northeast Jiangxi ophiolites (normalization values after reference[23])

会改变成分[30,34−36]。含Cr尖晶石的地幔橄榄岩在部分熔融过程中，Cr尖晶石是部分熔融程度的标型矿物[27,37]。随着部分熔融程度的增加，Cr尖晶石的Cr#值会随之增高[38]。从赣东北蛇绿岩地幔橄榄岩的尖晶石化学成分看，在Al_2O_3−Cr_2O_3图解中（图5−a），所有测试点位于地幔演化区域内，和韩国地区Bibong蛇绿岩相当[30]。随着Cr#的增加，$Fe^{2+\#}$[TFe^{2+}/($Mg+TFe^{2+}$)]也随之增加，部分落入MORB区域，暗

表3 赣东北蛇绿岩地幔橄榄岩中尖晶石电子探针分析结果(%)

Table 3 Electron microprobe analyses of spinel in mantle peridotites from northeast Jiangxi ophiolites

测点号	地点	Na_2O	MgO	Al_2O_3	SiO_2	NiO	FeO	MnO	K_2O	CaO	Cr_2O_3	TiO_2	Total	Mg#	Cr#
1		0.081	10.982	24.166	0.032	0.082	20.559	0.366	0.019	0	44.279	0.022	100.588	53	55
2		0.056	10.687	21.189	0.045	0.046	20.554	0.351	0	0	47.404	0.002	100.334	52	60
3		0.16	10.278	21.246	0.032	0.021	20.673	0.334	0.011	0.021	45.799	0.021	98.596	51	59
4		0.005	9.691	19.632	0.002	0	21.73	0.328	0.008	0	48.375	0.012	99.783	48	62
5		0.011	10.753	21.297	0.049	0.047	19.732	0.27	0	0	46.904	0.017	99.08	53	60
6		0.074	11.738	22.332	0.026	0.039	19.887	0.254	0.031	0	47.152	0.02	101.553	55	59
7		0.007	11.928	24.619	0.022	0.081	19.245	0.255	0.017	0	43.729	0.013	99.916	57	54
8		0.415	11.384	21.401	0.025	0.022	19.733	0.254	0.012	0.023	46.984	0	100.253	55	60
9		0.032	11.274	23.846	0.02	0.006	20.053	0.243	0	0	43.612	0.046	99.132	54	55
10		0.097	11.37	24.086	0.024	0.054	20.144	0.317	0.032	0	44.08	0.007	100.211	54	55
11		0.377	10.49	23.415	0.032	0.062	20.831	0.339	0.008	0	43.779	0	99.333	51	56
12	樟	0.093	9.214	21.43	0.043	0	22.486	0.331	0.023	0	44.81	0	98.43	46	58
13	树	0.115	9.326	18.913	0.039	0.074	23.805	0.358	0.013	0.004	46.027	0.003	98.677	45	62
14	墩	0.073	9.11	18.298	0.02	0.087	23.895	0.296	0.01	0.001	47.051	0.037	98.881	44	63
15		0.017	7.208	17.881	0.02	0.017	26.441	0.487	0	0	46.086	0.013	98.184	36	63
16		0.394	7.994	15.961	0.067	0.057	25.147	0.369	0.046	0.049	48.302	0.022	98.442	40	67
17		0.008	6.749	18.275	0.018	0.023	27.583	0.463	0	0	45.159	0.029	98.314	34	62
18		0.021	8.655	17.442	0.039	0.03	24.514	0.396	0	0	47.971	0	99.068	43	65
19		0.029	7.189	14.688	0.029	0.008	26.005	0.428	0	0	50.313	0	98.726	37	70
20		0.022	8.451	17.725	0.04	0.064	25.496	0.384	0	0	47.996	0.011	100.189	41	64
21		0	8.813	20.614	0.026	0.018	24.532	0.463	0	0.007	44.284	0.006	98.822	43	59
22		0.075	9.132	17.521	0	0.039	23.398	0.379	0.018	0	48.28	0	98.842	45	65
23		0.002	7.566	20.756	0.054	0.026	26.631	0.425	0	0	44.003	0.003	99.466	37	59
24		0	10.231	21.268	0.004	0.041	22.699	0.291	0.007	0	45.454	0	100.002	49	59
25		0.116	10.221	21.55	0.008	0.055	22.714	0.329	0	0.028	44.496	0.012	99.557	49	58
26		0.087	5.091	22.863	0.165	0.04	25.57	0.524	0.019	0.012	41.908	0.054	98.166	29	55
27		0.092	5.155	23.082	0.116	0.019	26.228	0.546	0.021	0.031	41.697	0.09	98.946	29	55
28	西	0.114	7.155	23.971	0.083	0.007	23.599	0.732	0.004	0.016	42.892	0.073	100.569	39	55
29		0.066	5.489	23.688	0.037	0.022	25.278	0.539	0	0	41.654	0.074	98.487	31	54
30	湾	0.058	9.015	25.523	0.027	0.031	21.021	0.722	0	0.011	41.956	0.115	100.241	47	52
31		0.062	6.234	24.107	0.001	0.031	24.934	0.67	0.023	0	41.488	0.074	99.505	34	54
32		0.073	4.708	24.264	0.023	0.008	27.335	0.488	0	0.012	41.276	0.065	100.15	27	53

注：$Mg^{\#}=Mg^{2+}/(Mg^{2+}+Fe^{2+})\times100$；$Cr^{\#}=Cr^{3+}/(Cr^{3+}+Al^{3+})\times100$。

示着其与大洋洋中脊之间的成因联系(图5−b)。在$Mg^{\#}$−$Cr^{\#}$的图解中，两者基本呈负相关关系，除个别点落入深海地幔橄榄岩之外，几乎所有测试点位于弧前地幔橄榄岩的区域(图5−c)。除了$Cr^{\#}$值之外，尖晶石中TiO_2也可作为地幔橄榄岩形成的构造环境的指示剂[35]。从表3可以看到，赣东北地幔橄榄岩铬尖晶石TiO_2含量较低，变化于0~0.115%，平均为0.03%，小于0.1%。在TiO_2−Al_2O_3关系图中(图5−d)，一部分尖晶石落入大洋洋中脊(MOR)地幔橄榄岩区，一部分尖晶石落入SSZ型地幔橄榄岩区，显示了该区地幔橄榄岩成因上具有同时具有MOR和SSZ地幔橄榄岩的特点。

5.2 构造意义

自蛇绿岩的概念提出以来，对于蛇绿岩的成因及构造环境有了较多的研究，其中以Pearce et al.[39]将蛇绿岩分为MOR型和SSZ型最为经典和适用。随着研究的不断深入，研究发现在造山带中出露的蛇绿岩产出环境往往很复杂，并非具单一的某种形式[27]。但地幔橄榄岩仍然是一个重要的判别标志。MOR型蛇绿岩地幔橄榄岩一般为二辉橄榄岩型[40]，副矿物尖晶石$Cr^{\#}$值低于60[27]；SSZ型蛇绿岩地幔橄榄岩为方辉橄榄岩，尖晶石$Cr^{\#}$值较高，常大于60[32]。

而对于在一个地幔橄榄岩中同时出现$Cr^{\#}$值大于60和$Cr^{\#}$值小于60的尖晶石，有学者认为是与地幔橄榄岩的部分熔融程度、原岩亏损程度及岩浆性质有关[41]；也有人认为是地幔岩在形成过程中经历了从洋中脊到岛弧环境的变化所致[42]；Liu et al.[43]则认为这可能是在MOR和SSZ环境分别形成低$Cr^{\#}$和高$Cr^{\#}$的地幔橄榄岩，由于后期构造运动而使两者结合在一起。同时越来越多的学者证明同一蛇绿岩可以同时存在俯冲带上和深海橄榄岩2种不同特征，反映蛇绿岩在不同构造环境下经历多期演化[44−51]。

赣东北地幔橄榄岩中尖晶石$Cr^{\#}$值变化于52~70，表明其具有复杂的熔融历史，其形成过程可能经历了2种构造环境的转变。最近对赣东北蛇绿岩樟树墩辉长岩的研究表明，赣东北蛇绿岩可能为形

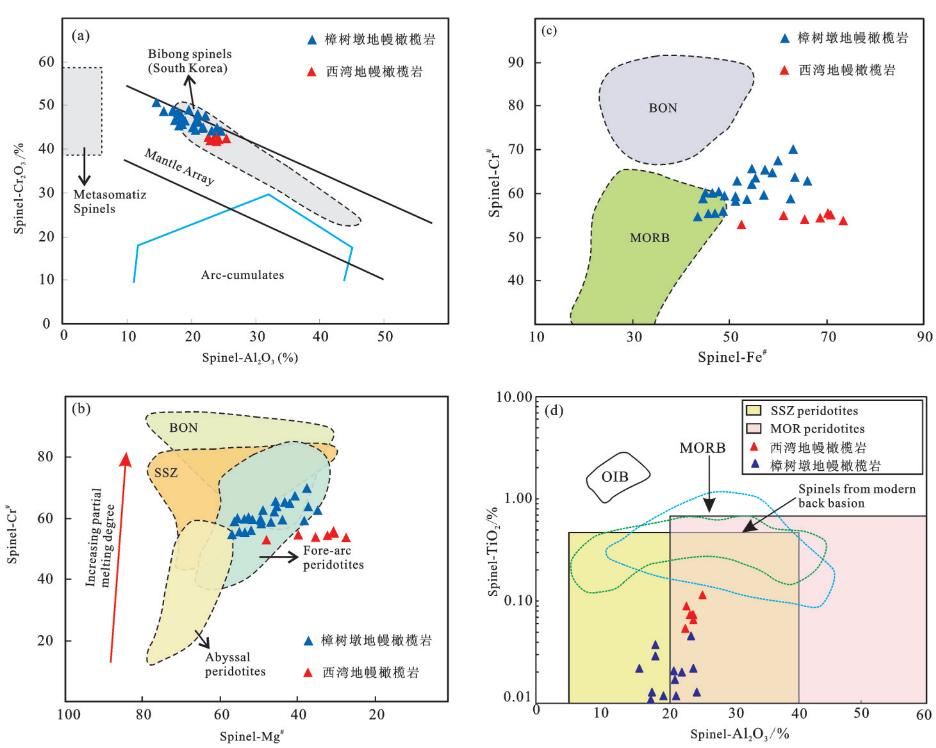

图5 赣东北地幔橄榄岩铬尖晶石特征图解

a—Cr_2O_3−Al_2O_3图解 (据文献 [31])；b—$Cr^{\#}$−$Mg^{\#}$图解(据文献[33])；c—$Cr^{\#}$−$Fe^{\#}$图解 (据文献[28, 32])；d—TiO_2−Al_2O_3图解 (据文献[33])

Fig.5 Plot of chromian spinels on discrimination diagrams

a−Al_2O_3 versus Cr_2O_3(wt.%) diagram (after rererence[31]); b−Mg/(Mg+Fe^{2+}) versus Cr/(Cr+Al) diagram (after rererence[33]); c−TFe^{2+}/(Mg+TFe^{2+}) versus Cr/(Cr+Al) diagram (after rererence[28, 32]); d−Al_2O_3 versus TiO_2 (wt.%) diagram (after rererence[33])

成于1061 Ma的初始裂解的洋中脊环境[52],形成具有MOR性质的低熔橄榄岩(尖晶石Cr#值小于60);同时样品具有弧前地幔橄榄岩的特征(图5-c),表明赣东北一带可能曾发生洋内俯冲作用,这也得到了赣东北蛇绿岩西湾约970 Ma的埃达克质斜长花岗岩的证据支持[12,14,53],俯冲作用使早先形成的MOR型低熔橄榄岩进入岛弧环境。由于流体的作用,处于岛弧之下的地幔楔可以发生较高程度的熔融,从而形成含高Cr#值尖晶石的SSZ型橄榄岩。

6 结 论

(1)赣东北蛇绿岩地幔橄榄岩以方辉橄榄岩为主,稀土总量远低于原始地幔的含量,而MgO含量高于原始地幔。LREE和LILE相对富集,高场强元素Nb明显亏损,表明赣东北地幔橄榄岩具有亏损地幔源区特征,同时也有不同程度的俯冲带流体的交代特征。HREE模拟的部分熔融程度为10%~30%。

(2)赣东北蛇绿岩地幔橄榄岩中尖晶石可分为Cr#值大于60和小于60两种不同成因类型,说明其可能经历了MOR和SSZ两种构造环境。

(3)推测赣东北蛇绿岩早先可能形成于洋中脊环境(约1060 Ma),随后在洋内俯冲作用下(约970 Ma),位于俯冲带上部的地幔橄榄岩受到了来自俯冲带的流体/熔体的交代,经历了SSZ环境的改造。

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