

# 东天山大草滩蛇纹岩中铬铁矿特征及其构造意义

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**摘要:** 东天山大草滩蛇纹岩中发育副矿物铬铁矿, 部分铬铁矿具环带结构, 核部为铝铬铁矿, 富 Al 贫 Fe,  $\text{Cr}_2\text{O}_3$  为 39.27% ~ 42.65%,  $\text{Al}_2\text{O}_3$  为 24.58% ~ 26.21%,  $\text{TiO}_2$  含量很低 (< 0.20%), FeO 为 12.18% ~ 18.14%, 而  $\text{Fe}_2\text{O}_3$  含量为 0.33% ~ 7.30%,  $\text{Cr}^\#$  为 50.6 ~ 53.5,  $\text{Mg}^\#$  为 53.3 ~ 68.2,  $\text{Fe}^{2+\#}$  为 31.8 ~ 46.7。核部铝铬铁矿结晶温度平均约为 1385°C, 结晶压力平均为 2.77 GPa, 推断其形成深度约为 86 km, 相当于软流圈位置; 相对于 FMQ 缓冲剂的地幔氧逸度为  $\text{FMQ} - 4.38 \sim \text{FMQ} + 0.63$  log 单位, 平均值为  $\text{FMQ} - 1.15$  log 单位; 地幔熔融程度  $F$  为 21.04% ~ 21.28%。推测大草滩蛇纹岩的原岩橄榄岩单元源区为石榴石二辉橄榄岩, 形成于亏损的软流圈地幔, 可能产自俯冲带环境中的岛弧环境。大草滩铬铁矿的环带结构特征表明其经历了温度由高到低、氧逸度由低到高的过程, 反映了大草滩蛇纹岩由最初的高温高压地幔环境被推覆到地壳, 随后经历了低温低压的浅程度区域变质作用。

**关键词:** 铬铁矿; 蛇绿岩; 蛇纹岩; 构造环境; 大草滩; 东天山

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## Characteristics and tectonic significance of chromites from Dacatan serpentinite of East Tianshan Mountains

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**Abstract:** The disseminated and banded chromites in the serpentinized ultrabasic rocks of the Dacatan area, East Tianshan Mountains, are helpful to clarifying the characteristics and evolutionary process of the rocks. Some chromites have zoned texture, with rich Al but poor Fe in the core. The geochemical characteristics of the core of chromites, with the data  $\text{Cr}_2\text{O}_3$  39.27% ~ 42.65%,  $\text{Al}_2\text{O}_3$  24.58% ~ 26.21%,  $\text{TiO}_2$  less than 0.20%, FeO 12.18% ~ 18.14%,  $\text{Fe}_2\text{O}_3$  0.33% ~ 7.30%,  $\text{Cr}^\#$  50.6 ~ 53.5,  $\text{Mg}^\#$  53.3 ~ 68.2, and  $\text{Fe}^{2+\#}$  31.8 ~ 46.7, are in accord with the features of ophiolites serpentinite and may be a member of ophiolites. Moreover, the crystallization temperature and pressure of the chromite are estimated to be 1385°C and 2.77 GPa on average, respectively, with a formation depth of about 86 km, which is similar to features of the asthenosphere. The oxygen fugacity relative to FMQ buffer is  $\text{FMQ} - 4.38 \sim \text{FMQ} + 0.63$  log units,  $\text{FMQ} - 1.15$  log units on average. Furthermore, the degree of partial melting of the mantle is estimated to be in the range of 21.04% ~ 21.28%, 21.18% on average, in the light of its relationship with  $\text{Cr}^\#$ . These parameters provide some clues to the physicochemical conditions: these peridotites were derived from garnet lherzolites located in the asthenosphere of the upper mantle, and Dacatan serpentinite was formed in the depleted island-arc setting of supra-subduction zone. The compositional zoning suggests that the peridotites have undergone a thermal path of decreasing temperature and increasing oxygen fugacity. It can be inferred that the mantle peridotites experienced the process from the stage of high temperature and high pressure mantle with lower oxygen fugacity to the thrusting slice stage to reach the crustal surface, where they were subjected to

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regional metamorphism with higher oxygen fugacity.

**Key words:** chromite; ophiolite; serpentinite; tectonic setting; Dacaoatan; East Tianshan Mountains

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橄榄岩中存在的副矿物铬铁矿对其形成时的壳幔环境具有重要指示作用 (Barnes and Roeder, 2001), 原生铬铁矿对于判断寄主岩石成因及地幔特征具有重要意义 (Dick and Bullen, 1984; Kamenetsky *et al.*, 2001)。Arai (1992) 提出, 可以利用铬铁矿  $Cr^{\#}$ 、 $Mg^{\#}$ 、 $Fe^{3+ \#}$  和  $Fe^{2+ \#}$  等特征值来探讨铬铁矿形成时的物化条件和部分熔融程度等, 进而对铬铁矿形成时的构造环境进行探讨。蛇绿岩作为古洋壳残余, 加强其研究, 对区域大地构造单元格局的划分与拟定具有重要意义。目前通过利用铬铁矿成

分特征分析判断其寄主岩体是否属于蛇绿岩的方法已经较为成熟 (Suita and Streider, 1996; 兰朝利, 2005)。

大草滩地区位于吐-哈盆地南侧 (图 1), 多认为形成于岛弧环境 (周济元等, 2001; Xiao *et al.*, 2013), 目前尚无蛇绿岩的报道。本文对大草滩蛇纹岩中铝铬铁矿进行了化学成分分析, 判断其寄主岩石的蛇绿岩特性, 估算其产出物化条件, 探讨源区构造环境, 以为造山带的演化研究提供地球化学方面的限定。

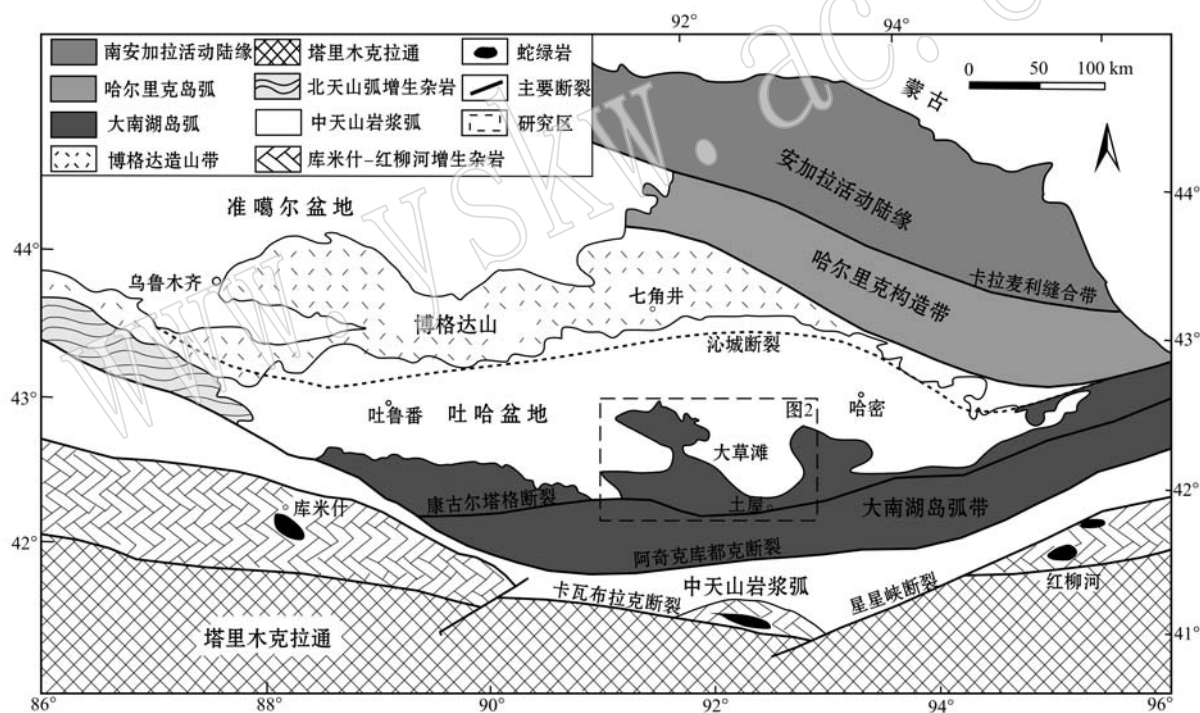


图 1 东天山及邻区构造地质简图 (据 Xiao *et al.*, 2013)

Fig. 1 Structural geological sketch map of the Eastern Tianshan Mountains and adjacent area (after Xiao *et al.*, 2013)

## 1 地质背景及岩石学特征

研究区构造主要以南部的近东西向的大草滩断裂和康古尔塔格断裂为主 (图 2)。地层出露较连续, 志留系-新生界均有出露。侵入岩主要为晚古生代酸性侵入岩。大草滩地区超基性岩分布面积小, 抗风化能力较弱, 产于山沟等负地形中, 出露零星,

多被第四系风成砂所覆盖, 为探槽工程揭露; 超基性岩蚀变强烈, 基本已蚀变为蛇纹岩, 与正常沉积的下泥盆统大南湖组 ( $D_1d$ ) 细-中粒碎屑岩呈构造接触 (李玮等, 2016)。

蛇纹岩呈深灰绿色-黑绿色, 鳞片变晶结构、网脉状变晶结构, 块状构造 (图 3a), 主要由蛇纹石 (90%) 和残余橄榄石 (5%) 组成 (图 3b)。残余橄榄石多呈粒状, 粒度 0.4 ~ 2.0 mm。橄榄石颗粒间隙

均由网脉状蛇纹石填充。副矿物为磁铁矿(3%)和铬铁矿(2%)。磁铁矿粒径 0.03 ~ 2.00 mm, 呈他

形散布于蛇纹石矿物间; 铬铁矿粒径 0.03 ~ 2.00 mm, 他形, 部分具环带结构(图 3c、3d)。

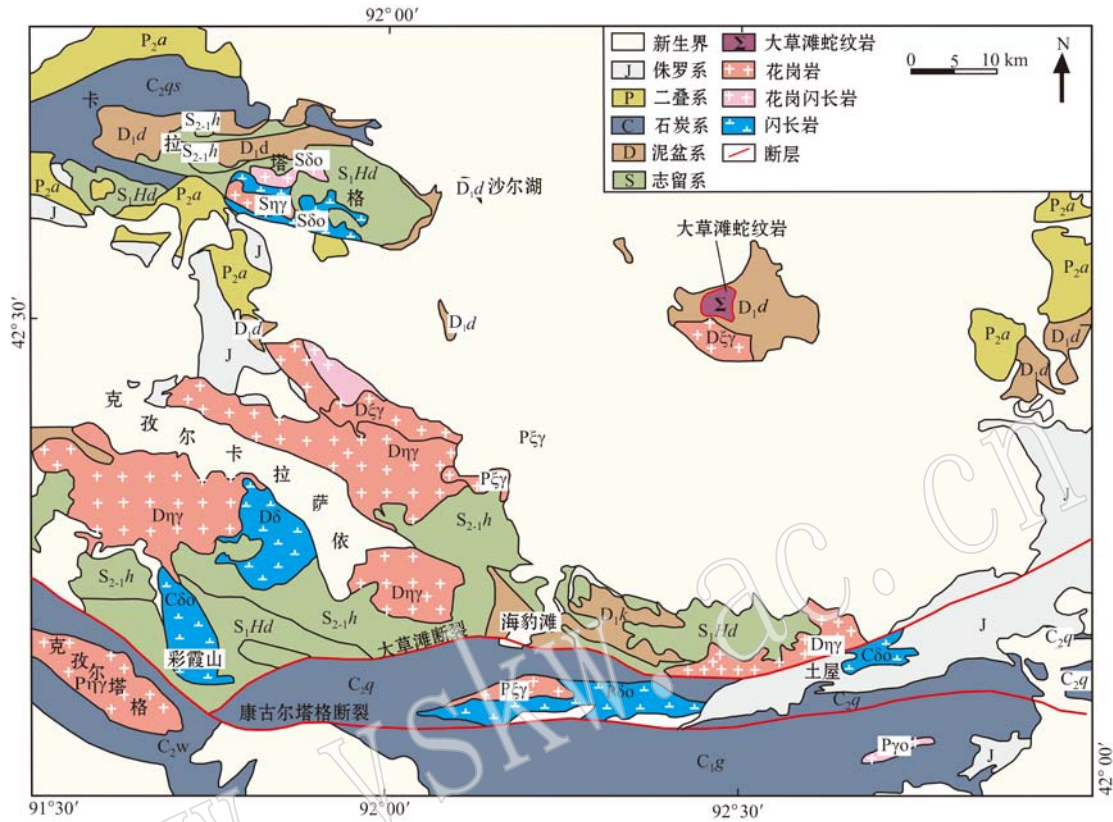


图2 东天山大草滩地区地质简图(据李玮等,2016)

Fig. 2 Regional geological sketch map of the Dacota area in east Tianshan Mountains(after Li Wei et al. , 2016)

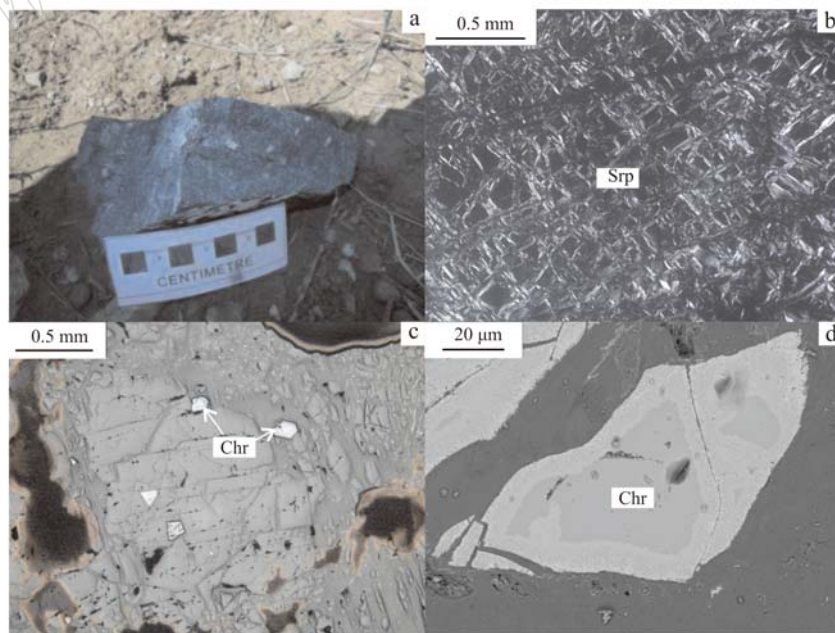


图3 野外及显微照片

Fig. 3 Photographs of outcrops and microphotographs of serpentinite  
a—野外蛇纹岩; b—蛇纹岩(正交偏光); c—副矿物铬铁矿(背散射); d—环带状铬铁矿(背散射); Srp—蛇纹石; Chr—铬铁矿  
a—serpentinite of outcrops; b—serpentinite (crossed nicols); c—accessory mineral chromite (back-scattered electron);  
d—zoned texture chromite (back-scattered electron); Srp—serpentine; Chr—chromite

## 2 岩石矿物地球化学特征

### 2.1 分析方法

铬铁矿的电子探针分析工作在新疆矿产实验研究所实验室完成,仪器型号为JXA-8230,工作加速电压20 kV,电流 $1.00 \times 10^{-8}$  A,束斑 $1 \sim 5 \mu\text{m}$ 。Fe价态对于下文铝铬铁矿温度、压力、氧逸度等物化条件的计算至关重要,需将电子探针数据中FeO折算成FeO和 $\text{Fe}_2\text{O}_3$ ,本文利用化学式( $\text{AB}_2\text{O}_4$ )和电价平衡计算出 $\text{Fe}^{2+}$ 和 $\text{Fe}^{3+}$ 含量,再以4个氧原子为基础,计算求得全部样品的阳离子数。分析和计算结果见表1。

### 2.2 铬铁矿地球化学特征

核部 $\text{Cr}_2\text{O}_3$ 含量为39.27%~42.65%, $\text{Al}_2\text{O}_3$ 含量为24.58%~26.21%,FeO含量为12.18%~18.14%,而 $\text{Fe}_2\text{O}_3$ 含量为0.33%~7.30%, $\text{FeO}^{\text{T}}$ 含量为18.45%~19.50%,具核部低Cr、高Al、低Fe的特点,属铝铬铁矿(图4a);幔部 $\text{Cr}_2\text{O}_3$ 含量为54.93%~60.79%, $\text{Al}_2\text{O}_3$ 含量为8.53%~12.62%,FeO含量为20.52%~24.56%,而 $\text{Fe}_2\text{O}_3$ 含量为0.72%~3.61%,属于铬铁矿;边部 $\text{Cr}_2\text{O}_3$ 含量为40.19%~52.06%, $\text{Al}_2\text{O}_3$ 含量为4.31%~16.96%,FeO含量为13.23%~20.16%,而 $\text{Fe}_2\text{O}_3$ 含量为8.74%~28.43%,高 $\text{FeO}^{\text{T}}$ (22.67%~41.44%),归属于高铁铬铁矿。

按照由内到外核部-幔部-边部的顺序, $\text{Cr}^{\#}$ 值逐渐变大, $\text{Mg}^{\#}$ 含量显著上升, $\text{FeO}^{\text{T}}$ 明显升高, $\text{TiO}_2$ 含量略有升高, $\text{Fe}^{2+\#}$ 值在幔部和边部铬铁矿中的含量明显高于核部铝铬铁矿。边部铬铁矿 $\text{Cr}^{\#}$ 、 $\text{Mg}^{\#}$ 、 $\text{Fe}^{2+\#}$ 、Yfe等指标值普遍高于幔部铬铁矿和核部铝铬铁矿。

## 3 讨论

铬铁矿的成因具有多样性,岩浆熔离作用多以堆晶结构的出现为特征,反映在铬铁矿的产出上,则多表现为层状铬铁矿的出现,而大草滩铬铁矿主要作为浸染状的副矿物出现,产出数量也很少,没有表现出岩浆熔离的特征,因此排除岩浆熔离作用成因的可能。熔岩反应产生铬铁矿的观点也不适用于大草滩铬铁矿:首先,野外观察结果显示大草滩超基性

岩蛇纹石化严重,由于复杂的构造地质作用,导致其与围岩呈构造接触关系,未见有熔岩反应边界(冷凝边或烘烤边)的存在;其次,大草滩铬铁矿作为浸染状的副矿物存在,既不具有豆荚状形态特征,也不具有成矿的可能,不符合多数学者应用熔岩反应解释SSZ上地幔中形成豆荚状铬铁矿的认识。因此,本文认为应用熔融残留来解释大草滩铬铁矿的成因更加合理。

### 3.1 原岩性质判定

根据显微观察及化学成分分析认为核部铝铬铁矿代表原始铬铁矿残留,而边缘高铁铬铁矿则是在原始铬铁矿遭受变质作用之后形成的,其化学成分已经发生了相应的变化,不能代表原始的铬铁矿(Barnes, 2000; Barnes and Roeder, 2001; 李犇, 2010; 张炜斌等, 2011; 冯惠彬等, 2015)。探针数据显示核部的铝铬铁矿成分基本稳定且较均匀,颗粒间无明显变化,表明各颗粒核部处于平衡状态(Barnes 2000),所以本文所做计算和分析都是以核部铝铬铁矿数据为基础的(李犇, 2010; 张炜斌等, 2011; 冯惠彬等, 2015)。

大草滩铝铬铁矿 $\text{TiO}_2$ 含量低,除个别外大多数 $\text{TiO}_2$ 含量为0.17%~0.20%(表1),符合蛇绿岩的特征;在铝铬铁矿 $\text{Cr}^{\#}-\text{Mg}^{\#}$ 图解(王希斌等, 2009)(图4b)中,大多数铝铬铁矿落入中国蛇绿岩地幔橄榄岩铬尖晶石成分区域内;在 $\text{Cr}-\text{Al}-\text{Fe}^{3+}+2\text{Ti}$ 图解(Kepezhinskas *et al.*, 1993)(图5a)和 $\text{Cr}^{\#}-\text{Fe}^{2+\#}$ 图(Su *et al.*, 2012)(图5b)中均落入蛇绿岩区域中,同层状杂岩和阿拉斯加型杂岩区别明显。由此认为大草滩蛇纹岩的原岩应属于蛇绿岩组成部分。

### 3.2 地幔源区性质

在 $\text{Cr}^{\#}-\text{TiO}_2$ 关系图解(O'Neill, 1981)(图6a)中,铝铬铁矿主体位于亏损地幔橄榄岩与洋中脊过渡区域内,表明大草滩蛇绿岩形成于亏损地幔环境,并逐渐向亏损程度降低的方向发展(Pal and Mitra, 2004)。 $\text{Cr}^{\#}-\text{Mg}^{\#}$ 构造环境判别图解(图6b)中,大草滩铝铬铁矿落入俯冲带(SSZ)类蛇绿岩、弧前橄榄岩区域及阿尔卑斯型地幔橄榄岩的重合区域。大草滩铝铬铁矿具 $\text{Cr}^{\#}=51 \sim 53$ 和 $\text{Mg}^{\#}=53 \sim 68$ 的特征,与典型的大洋上地幔物质和标准的大陆上地幔区别较大,而与纽芬兰岛湾蛇绿岩、阿曼赛迈尔蛇绿岩相似(Dick and Bullen, 1984; 孔凡梅等, 2011)。



$w_B/\%$

表 1 铬铁矿电子探针分析结果  
Table 1 Composition of Al-chromites from Dacotian serpentinite

矿物 测点号	铝铬铁矿								铬铁矿								高铁铬铁矿			
	P8-1	P8-2	P9-1	P9-2	P3-1	P3-2	P4-1	P4-2	P7-1	P7-2	P10-1	P1-1	P2-1	P8-3	P8-4					
FeO <sup>†</sup>	18.75	18.45	19.50	18.90	25.70	25.69	25.05	25.21	23.77	24.27	26.21	22.67	27.41	41.44	28.03					
FeO	12.18	18.14	16.66	15.25	23.99	23.83	24.38	24.56	20.52	22.51	23.34	13.23	16.66	15.85	20.16					
Fe <sub>2</sub> O <sub>3</sub>	7.30	0.33	3.16	4.06	1.90	2.06	0.74	0.72	3.61	1.96	3.18	10.48	11.94	28.43	8.74					
TiO <sub>2</sub>	0.20	0.35	0.18	0.17	0.21	0.08	0.36	0.06	0.13	0.03	0.05	0.38	0.24	0.21	0.14					
SiO <sub>2</sub>	0.00	0.05	0.03	0.13	0.05	0.02	0.00	0.03	0.02	0.00	0.00	0.53	2.19	0.16	2.76					
MgO	14.65	11.64	12.28	12.90	5.93	6.00	5.70	5.61	8.33	6.84	6.30	12.56	10.04	7.20	8.48					
Al <sub>2</sub> O <sub>3</sub>	25.75	26.21	25.32	24.58	8.84	8.85	8.53	8.60	12.59	12.62	9.55	16.96	5.96	4.98	4.31					
Cr <sub>2</sub> O <sub>3</sub>	39.27	42.65	42.50	42.07	59.25	59.57	60.12	60.79	54.93	54.90	58.28	42.75	48.98	40.19	52.06					
MnO	0.27	0.29	0.21	0.26	0.42	0.39	0.48	0.43	0.47	0.49	0.38	0.58	0.95	0.82	0.95					
CoO	0.01	0.09	0.08	0.06	0.10	0.07	0.19	0.10	0.08	0.12	0.09	0.06	0.07	0.08	0.13					
NiO	0.12	0.16	0.18	0.14	0.05	0.05	0.00	0.04	0.00	0.02	0.01	0.17	0.10	0.05	0.09					
Total	99.01	99.88	100.28	99.20	100.55	100.72	100.43	100.87	100.31	99.28	100.87	97.70	97.13	97.97	97.81					
以 4 个氧原子为基础																				
Fe <sup>2+</sup>	0.316 5	0.464 7	0.429 2	0.397 3	0.687 9	0.682 3	0.698 9	0.701 1	0.573 7	0.638 0	0.666 8	0.373 3	0.507 3	0.541 7	0.610 6					
Fe <sup>3+</sup>	0.085 2	0.003 8	0.036 6	0.047 5	0.024 4	0.026 5	0.009 5	0.009 3	0.045 4	0.025 0	0.040 9	0.132 9	0.163 4	0.436 8	0.119 0					
Ti	0.004 7	0.008 0	0.004 2	0.003 9	0.005 3	0.002 0	0.009 3	0.001 6	0.003 2	0.000 8	0.001 2	0.009 5	0.006 5	0.006 4	0.003 9					
Si	0.000 0	0.001 5	0.000 8	0.003 9	0.001 8	0.000 8	0.000 0	0.001 0	0.000 8	0.000 0	0.000 0	0.017 8	0.079 6	0.006 6	0.099 8					
Mg	0.677 9	0.531 0	0.563 7	0.598 8	0.302 8	0.306 0	0.291 1	0.285 4	0.414 9	0.345 1	0.320 6	0.631 3	0.544 6	0.438 4	0.457 6					
Al	0.941 7	0.945 2	0.918 6	0.901 3	0.356 8	0.356 8	0.344 1	0.345 8	0.495 5	0.503 4	0.384 1	0.673 4	0.255 3	0.239 6	0.183 8					
Cr	0.963 7	1.031 9	1.034 8	1.035 5	1.604 6	1.611 0	1.627 8	1.639 7	1.451 1	1.470 0	1.572 6	1.139 0	1.408 9	1.297 7	1.489 7					
Mn	0.007 2	0.007 4	0.005 6	0.006 8	0.012 3	0.011 2	0.014 0	0.012 5	0.013 2	0.014 0	0.011 0	0.016 6	0.029 3	0.028 4	0.029 2					
Co	0.000 2	0.002 3	0.002 1	0.001 5	0.002 6	0.002 0	0.005 3	0.002 6	0.002 1	0.003 3	0.002 5	0.001 6	0.002 0	0.002 7	0.003 6					
Ni	0.002 9	0.004 0	0.004 6	0.003 4	0.001 5	0.001 4	0.000 0	0.001 0	0.000 0	0.000 4	0.000 4	0.004 6	0.003 0	0.001 7	0.002 6					
Cr <sup>#</sup>	50.6	52.2	53.0	53.5	81.8	81.9	82.5	82.6	74.5	74.5	80.4	62.8	84.7	84.4	89.0					
Mg <sup>#</sup>	68.2	53.3	56.8	60.1	30.6	31.0	29.4	28.9	42.0	35.1	32.5	62.8	51.8	44.7	42.8					
Yfe	4.3	0.2	1.8	2.4	1.2	1.3	0.5	0.5	2.3	1.3	2.0	6.8	8.9	22.1	6.6					
Fe <sup>2+#</sup>	31.8	46.7	43.2	39.9	69.4	69.0	70.6	71.1	58.0	64.9	67.5	37.2	48.2	55.3	57.2					

注: Cr<sup>#</sup> = 100 Cr/(Cr + Al), Mg = 100 Mg/(Mg + Fe<sup>2+</sup>), Yfe = 100 Fe<sup>3+</sup>/(Fe<sup>3+</sup> + Al + Cr), Fe<sup>2+#</sup> = 100 Fe<sup>2+</sup>/(Fe<sup>2+</sup> + Mg); 利用化学式(AB<sub>2</sub>O<sub>4</sub>)和电价平衡计算出 Fe<sup>2+</sup> 和 Fe<sup>3+</sup> 含量。

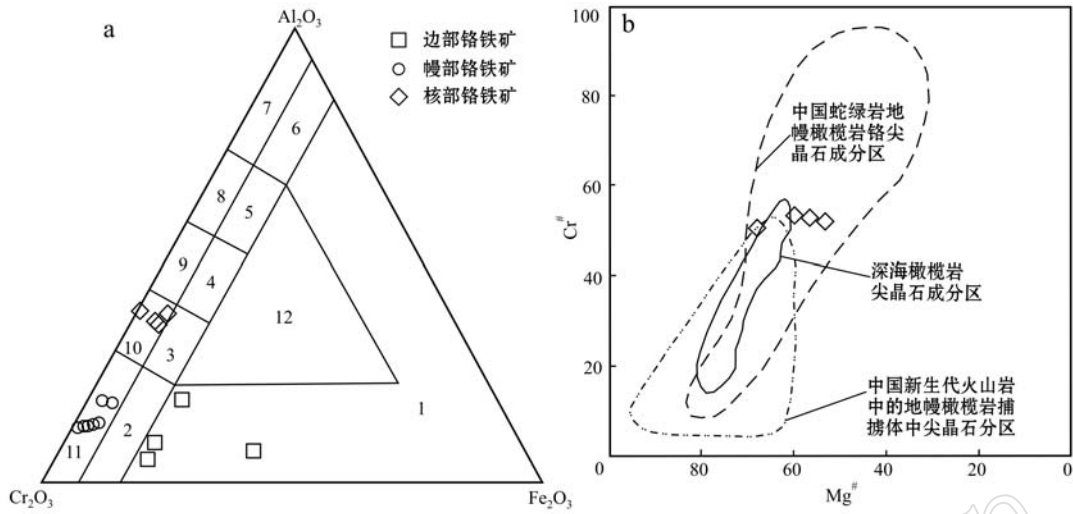


图 4 铬铁矿分类图(索科洛夫,1985)和 Cr<sup>#</sup>-Mg<sup>#</sup>图解(王希斌等,2009)

Fig. 4 Classification of chromites (after Sokolov,1958) and Cr<sup>#</sup>-Mg<sup>#</sup> diagram (after Wang Xibin *et al.*, 2009) of alurchromite from Dacaotan

- 1—高铁铬铁矿; 2—富铁铬铁矿; 3—富镁铝铬铁矿; 4—富铁富铬尖晶石; 5—富铁铝富铬尖晶石; 6—富铁铝尖晶石; 7—铬尖晶石;  
 8—富铝铬尖晶石; 9—富铬尖晶石; 10—铝铬铁矿; 11—铬铁矿; 12—高铁富铬尖晶石  
 1—ferri-chromite; 2—ferro-chromite; 3—micro-alumochromite; 4—ferro-chromopicotite; 5—ferro-alumopicotite; 6—ferropicotite;  
 7—picotite; 8—alumopicotite; 9—chromopicotite; 10—alumo-chromite; 11—chromite; 12—ferri-chromopicotite

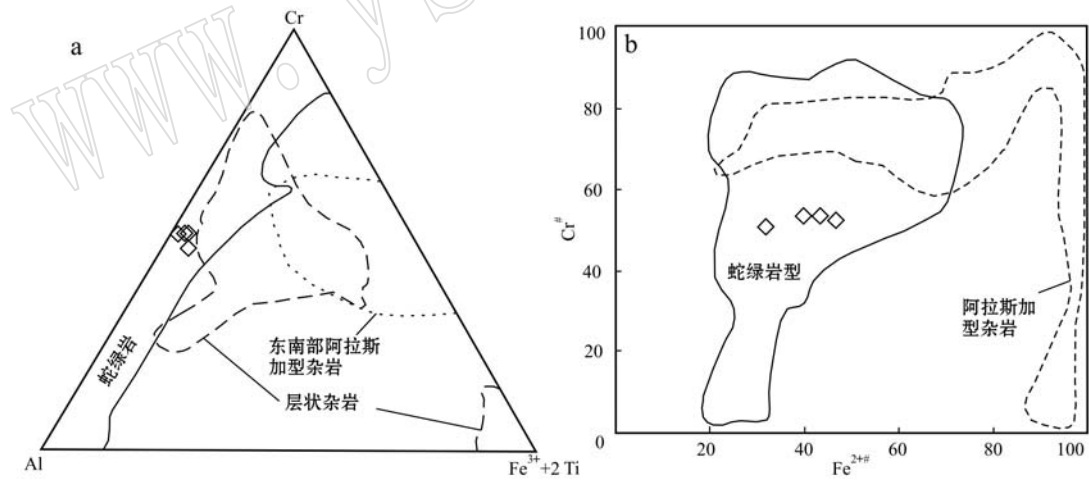


图 5 铝铬铁矿 Cr-Al-Fe<sup>3+</sup>+2Ti 判别图(据 Kepezhinskas *et al.*, 1993)和 Cr<sup>#</sup>-Fe<sup>2+#</sup>图解(据 Su *et al.*, 2012)

Fig. 5 Diagrams of Cr-Al-Fe<sup>3+</sup>+2Ti (after Kepezhinskas, 1993) and Cr<sup>#</sup>-Fe<sup>2+#</sup> of alurchromite from Dacaotan (after Su *et al.*, 2012)

根据 O'Neill (1981) 总结出的压力公式计算得出铬铁矿核部结晶压力为 2.75 ~ 2.83 GPa, 平均值为 2.77 GPa, 推测其形成深度约为 86 km; 根据 Fabries (1979) 的温度公式计算得出铬铁矿核部结晶温

度为 1 382 ~ 1 392 °C, 平均值为 1 385 °C (表 2), 与软流圈温度 (约为 1 280 ~ 1 350 °C)、压力 (约为 3.0 GPa) (McKenzie and Bickle, 1988) 很接近, 因此推测铬铁矿寄主岩石形成于软流圈, 位于石榴石二辉橄

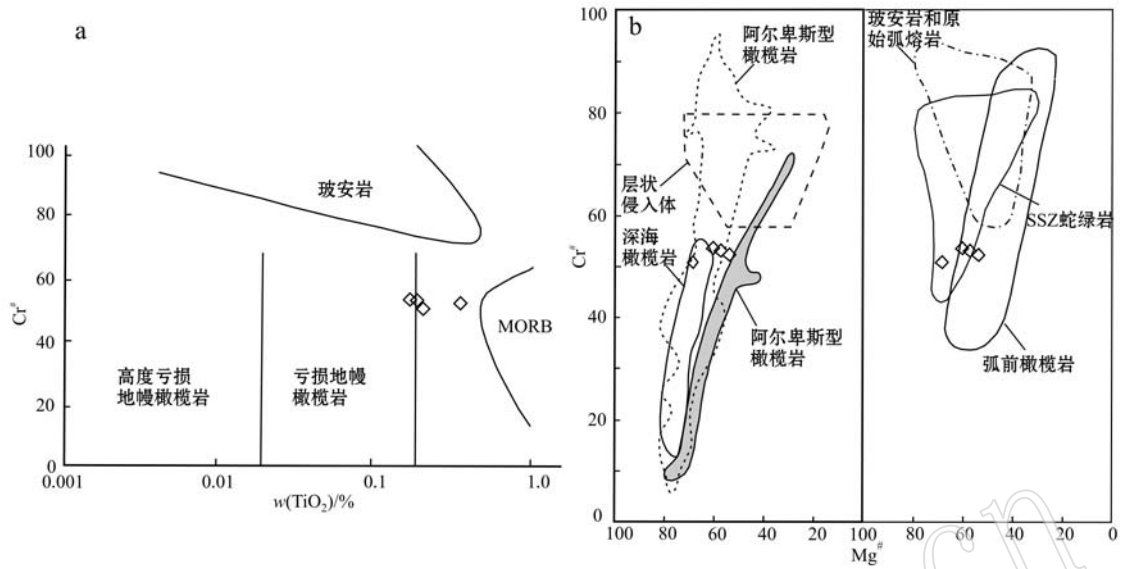


图6 铝铬铁矿 Cr<sup>#</sup>-TiO<sub>2</sub> 亏损程度判别图(据 O'Neill, 1981)和 Cr<sup>#</sup>-Mg<sup>#</sup>形成环境判别图(据 Dick and Bullen, 1984; 孔凡梅等, 2011)

Fig. 6 Discriminant diagram of Cr<sup>#</sup>-TiO<sub>2</sub>(after O'Neill, 1981) and Cr<sup>#</sup>-Mg<sup>#</sup> of aluminous olivine from Daccaotan (after Dick and Bullen, 1984; Kong Fanmei *et al.*, 2011)

榄岩的稳定相区内(O'Neill, 1981; 张招崇, 2004)(图7), 认为铬尖晶石的寄主橄榄岩原岩为石榴石二辉橄榄岩。

氧逸度的估算主要依赖于岩浆岩中贫铁矿物的 Fe<sup>2+</sup> 与 Fe<sup>3+</sup> 含量关系(Sack *et al.*, 1980)。所求  $\Delta \log(f_{O_2})_{FMQ}$  为相对氧逸度, 氧缓冲剂为 FMQ, 即铁橄榄石-磁铁矿-石英氧缓冲剂。通过氧逸度计算公式(Irvine, 1965; Fabries, 1979; Ballhaus *et al.*, 1991), 求得相对氧逸度为 FMQ - 4.38 ~ FMQ + 0.63 log 单位, 平均值为 FMQ - 1.15 log 单位(表2)。通过 Hellebrand 等(2001)提出的地幔熔融程度

估算公式, 得到部分熔融程度  $F$  为 21.04% ~ 21.28%(表2), 平均值为 21.18%。

表2 铝铬铁矿物物理化学条件计算结果

Table 2 Physical and chemical conditions of aluminous olivine from Daccaotan

特征参数	P8-1	P8-2	P9-1	P9-2	平均值
结晶温度( $t/^\circ\text{C}$ )	1 392	1 382	1 382	1 382	1 385
结晶压力( $p/\text{GPa}$ )	2.83	2.75	2.76	2.75	2.77
形成深度( $H/\text{km}$ )	87.6	85.3	85.5	85.3	85.9
氧逸度( $\Delta \log f_{O_2}$ )	0.63	-4.38	-0.63	-0.2	-1.15
部分熔融程度( $F/\%$ )	21.04	21.18	21.24	21.28	21.19

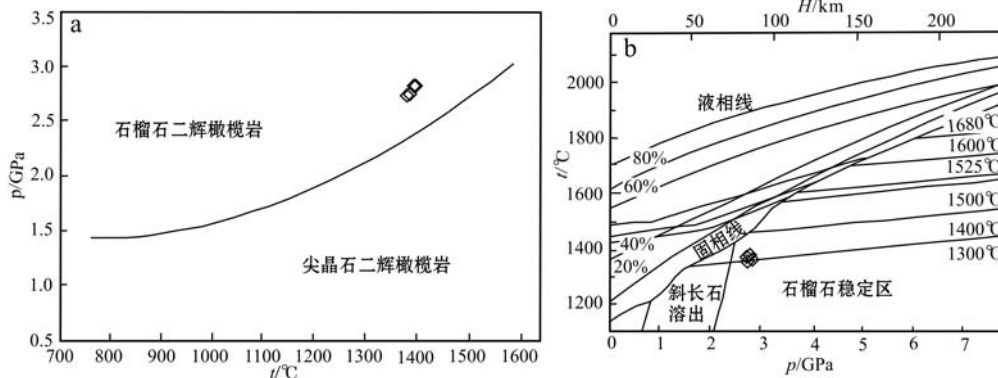


图7 石榴石二辉橄榄岩与尖晶石二辉橄榄岩相转变图(据 O'Neill, 1981)和无水地幔温度压力图解(据张招崇等, 2004)

Fig. 7 Transition from garnet lherzolite to spinel lherzolite in the CMAS system (after O'Neill, 1981) and pressure-temperature diagram for the melting of anhydrous mantle lherzolite( after Zhang Zhaochong *et al.*, 2004)

### 3.3 构造环境讨论

研究区位于东天山北缘的哈尔里克-大南湖岛弧带上,该岛弧带为一复杂的增生复合体(Xiao *et al.*, 2004),多由奥陶纪、泥盆纪-石炭纪的火山岩、志留纪-二叠纪的侵入岩、火山碎屑岩和浊积岩、玄武岩、硅质岩以及超基性岩组成。带内主要发育志留纪-二叠纪岩浆侵入作用(陈富文等,2005;李文铅等,2006;王银宏等,2014)。志留纪-石炭纪为俯冲碰撞的岛弧环境(陈富文等,2005),二叠纪则进入造山后的陆内伸展期(王银宏等,2014)。吐哈盆地南缘火山岩时空分布上从北向南时代依次变新,北部为一套钙碱性系列为主的中酸性火山岩,南部为一套拉斑玄武岩系列为主的基性火山岩,是古亚洲洋在早古生代向北俯冲、不同时代岛弧带依次向南增生的结果(陈富文等,2005;李锦铁等,2006)。

在  $\text{TiO}_2 - \text{Al}_2\text{O}_3$  图解中(Kamenetsky *et al.*, 2001)(图8a),样品落入岛弧区域外,主要落在俯冲带橄榄岩(SSZP)和大洋中脊橄榄岩(MORP)的重叠区域,更加靠近 SSZP 区域的中心部位。 $\text{Fe}^{2+}/\text{Fe}^{3+} - \text{Al}_2\text{O}_3$  图解(Khalil and El-Makky, 2009)(图8b)中,核部铝铬铁矿绝大多数落入 SSZ 橄榄岩区域。核部铝铬铁矿的  $\text{Fe}^{3+}/\text{Fe}^{2+}$  (0.01 ~ 0.27) < 0.5, 具备地幔橄榄岩、洋中脊玄武岩、与岛弧有关的火山岩等岩石类型的特征(郭荣华等,2012);绝大部分铝铬铁矿的  $\text{TiO}_2$  (0.17% ~ 0.20%) < 0.20%, 显示出地幔橄榄岩(包括俯冲带橄榄岩 SSZP 和洋中脊橄榄岩 MORP)、玻安岩、岛弧拉斑玄武岩的特征; $\text{TiO}_2$  和  $\text{Al}_2\text{O}_3$  负相关关系不明显,同来自 MORB 的铬尖晶石(Blanco *et al.*, 2009)区别较大。综合推断大草滩蛇纹岩形成于俯冲带岛弧环境。

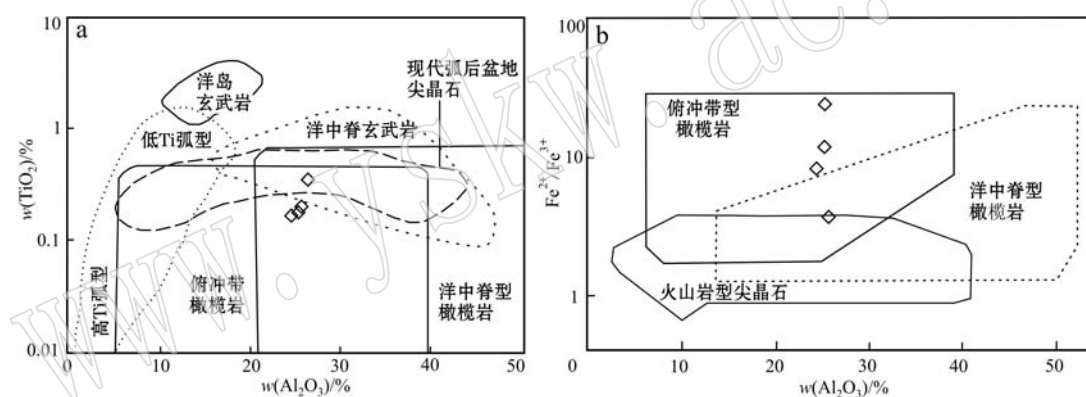


图8 铝铬铁矿  $\text{TiO}_2 - \text{Al}_2\text{O}_3$  构造环境判别图(据 Kamenetsky *et al.*, 2001)和  $\text{Fe}^{2+}/\text{Fe}^{3+} - \text{Al}_2\text{O}_3$  图解(据 Khalil and El-Makky, 2009)

Fig. 8 Discriminant diagram of  $\text{TiO}_2 - \text{Al}_2\text{O}_3$  (after Kamenetsky *et al.*, 2001) and  $\text{Fe}^{2+}/\text{Fe}^{3+} - \text{Al}_2\text{O}_3$  (after Khalil and El-Makky, 2009) of aluminous chromite from Daccaotan

### 3.4 矿物成分分带形成机制探讨

铬尖晶石核部贫 Fe, 而富 Cr、Mg 和 Al, 边部特征与之截然相反, 为富 Fe 而贫 Cr、Mg 和 Al。这种边缘富 Fe 而贫 Mg 的特征是铬尖晶石经受了由温度降低导致的亚固相平衡作用的结果(Ozawa, 1983)。当温度降低时, 橄榄石或辉石中的 Fe 向邻近的铬尖晶石中扩散, 而 Mg 则从铬尖晶石中向橄榄石或辉石中扩散。而  $\text{Cr}^{3+}$  的晶体场稳定能要高于  $\text{Fe}^{3+}$ , 在矿物结晶早期,  $\text{Cr}^{3+}$  比  $\text{Fe}^{3+}$  更易于占据铬尖晶石晶体空隙(张炜斌等, 2011)。

岩浆结晶分异形成的铬尖晶石, 从核部到边部

通常具备  $\text{Cr}^\#$  降低、 $\text{Mg}^\#$  升高的特征(张炜斌等, 2011)。而大草滩蛇纹岩铬铁矿从核部到边部, 具  $\text{Cr}^\#$  增高、 $\text{Mg}^\#$  降低的趋势, 故环带的形成不能归为岩浆成因, 而是超基性岩经变质作用、不同物质组成对应不同变质相的结果(Barnes and Roeder, 2001)。图9a 中部高铁铬铁矿同时具备绿片岩相和低角闪岩相的特征, 幔部铬铁矿全部落入绿片岩相, 从铬铁矿内部到外部, 变质相程度有加深的趋势。图9b 中部铬铁矿的温度多低于  $500^\circ\text{C}$ , 幔部铬铁矿部分低于  $500^\circ\text{C}$ , 部分为  $500 \sim 550^\circ\text{C}$ , 而核部铬铁矿明显高于  $600^\circ\text{C}$ , 表明铬铁矿从内到外温度逐渐降低。

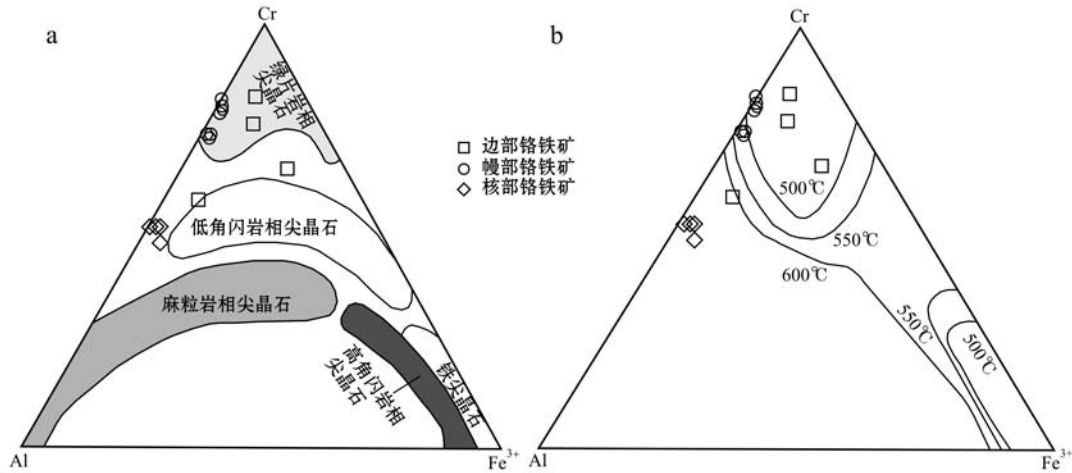


图 9 铬尖晶石成分对应的变质相图(据张建等,2009)和与 Fo90 橄榄石平衡的铬尖晶石稳定性判别图(据 Barnes, 2000)

Fig. 9 Spinel compositions corresponding to different metamorphic facies (after Zhang Jian *et al.*, 2009) and spinel stability distinguished by spinel inequilibrium with Fo90 olivine (after Barnes, 2000)

岩石在遭受蛇纹石化的过程中会产生含 Fe 流体,该流体交代铬尖晶石,在高氧逸度的情况下,流体中的 Fe 置换铬尖晶石中的 Al 和 Cr,使铬尖晶石边部更加贫 Al、Cr 而富 Fe。在变质作用(同橄榄石或辉石发生反应)过程中,铬尖晶石中 Al 比 Cr 更容易被置换,于是表现出铬铁矿中 Cr<sup>#</sup>从核部到边部铬铁矿逐渐升高的趋势,这与张炜斌等(2011)的研究结果一致。

上述讨论表明,大草滩铬铁矿经历了温度由高到低、氧逸度由低到高的过程。这表明大草滩蛇纹岩由最初的高温高压地幔环境,被推覆到地壳,随后经历了低温低压的浅程度区域变质作用。

## 4 结论

(1) 大草滩铬铁矿蚀变程度较强,从核部到边部对应的矿物分别是铝铬铁矿-铬铁矿-高铁铬铁矿。核部铝铬铁矿相对富 Al 贫 Fe,边缘高铁铬铁矿富 Fe 贫 Al。

(2) 大草滩蛇纹岩具有蛇绿岩特性,与层状杂岩和阿拉斯加型杂岩区别明显,应属于蛇绿岩成员。

(3) 大草滩铬铁矿为熔残残留成因,核部铝铬铁矿的结晶温度为 1 382 ~ 1 392℃,平均值为 1 385℃;铝铬铁矿的结晶压力为 2.75 ~ 2.83 GPa,平均值为 2.77 GPa,形成深度约为 86 km,所处的地幔氧逸度为 FMQ - 4.38 ~ FMQ + 0.63 log 单位,平均值为 FMQ - 1.15 log 单位;地幔熔融程度 *F* 为

21.04% ~ 21.28%, 平均值为 21.18%。

(4) 大草滩蛇纹原岩为石榴石二辉橄榄岩,形成于亏损软流圈位置,对应 SSZ 中岛弧环境。

(5) 大草滩铬铁矿经历了温度由高到低、氧逸度由低到高的过程,反映了大草滩蛇纹岩由最初的高温高压地幔环境被推覆到地壳,随后经历了低温低压的浅程度区域变质作用。

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