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河南桐柏麻粒岩相变质作用的 *p*- *t* 条件

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摘 要: 地处华北板块南缘的桐柏麻粒岩区, 主要以长英质麻粒岩为主。通过矿物化学及矿物组合特征的研究, 结合温压计计算得出桐柏麻粒岩变质条件为 700~ 840 ℃、0. 61~ 0. 85 GPa, 属于典型中压麻粒岩, 地温梯度大致为 28~ 31 ℃/ km。桐柏麻粒岩相变质作用可能发生于早古生代晚期。

关键词: 麻粒岩; *p*- *t* 条件; 桐柏地区
中图分类号: P588. 125; P584 **文献标识码**: A

The *p*- *t* conditions of granulite_facies metamorphism in Tongbai area, Henan Province

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Abstract: There are mainly felsic granulites in Tongbai area located at southern fringe of the North China plates. A study of the mineral chemistry and the features of the mineral paragenesis and the calculation with thermobarometers revealed that the granulites in Tongbai area were formed under the *p*- *t* conditions of 700~ 840 ℃ and 0. 61~ 0. 85 GPa, belonging to typical medium_pressure type, and the geothermal gradient is approximately from 28 to 31 ℃/km. The granulite facies metamorphism probably occurred at the late stage of Early Palaeozoic.

Key words: granulites; *p*- *t* conditions; Tongbai area

不同的学者对桐柏麻粒岩变质条件有不同认识。翟淳等(1990) 认为桐柏麻粒岩形成温度为 700~ 900 ℃, 压力值范围为 0. 6~ 1. 0 GPa; 翟淳等(1997, 1999) 指出豫南角闪麻粒岩经历过 $t >$ 987 ±50 ℃、$p \geqslant$ 2. 0~ 1. 6 GPa 和 $t >$ 700 ℃、$p =$ 1. 4 GPa 等多阶段近等温减压变质作用; Kröner 等(1993) 计算桐柏麻粒岩变质条件为 827~ 840 ℃、0. 95~ 0. 98 GPa。Zhai Xiaoming(1996, 1998) 算得麻粒岩的温度范围为 600~ 700 ℃, 压力 0. 55~ 0. 70 GPa, 温压明显低于前人工作成果, 认为桐柏麻粒岩形成于高角闪岩相- 低麻粒岩相。

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1　区域地质概况

桐柏地区以松扒断裂为界(可能为商丹断裂的东沿部分)划分为北桐柏和南桐柏,对应于秦岭山区的北秦岭和南秦岭。南桐柏地区包括含榴辉岩的高压变质岩系、角闪岩相片麻岩和蓝片岩- 绿片岩系等。北桐柏区包括秦岭群、宽坪群和分布于其中的二郎坪群。宽坪群主要由云母石英片岩、石英岩、大理岩及少量的斜长角闪岩组成。二郎坪群为一套含碎屑岩和大理岩的细碧- 角斑岩建造。秦岭群(图 1)由 3 套岩石组成: 雁岭沟(蔡家凹)组大理岩、郭庄组上段和中段的片麻岩及郭庄组下段的麻粒岩。以前很多学者(翟淳, 1990; 张宏飞, 1995; Zhai Xiaoming, 1996))认为这一地区的麻粒岩呈大小不等的透镜体分布于大面积的片麻岩中,但我们经过详细研究发现,这些透镜体之间的所谓片麻岩实际为经过强烈变形和退变质作用的麻粒岩。因此,在本区麻粒岩构成一个约 0.5~ 2.0 km 宽的变质带。根据现有资料,麻粒岩相变质作用的时代为 410~ 350 Ma(Xu Bei *et al.*, 2000)。

本区麻粒岩相岩石可分为 3 类: 长英质麻粒岩、基性麻粒岩和夕线石片麻岩。基性麻粒岩分布较少(图 1),其暗色矿物一般大于 50%,不含或含少量石英。新鲜麻粒岩一般呈透镜状,长轴约为 0.4~ 3.0 m,短轴一般为 0.2~ 1.5 m。其主要矿物组合为: Opx(斜方辉石) + Cpx(单斜辉石) + Pl(斜长石) + / - Gar(石榴石) + / - Hb(角闪石)。长英质麻粒岩广泛分

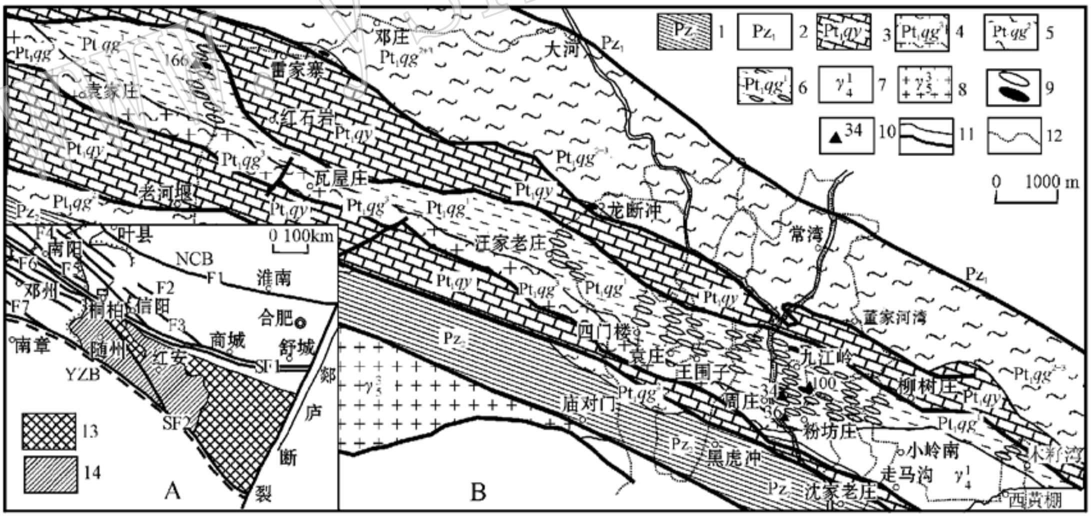

图 1　大别- 桐柏造山带(A)及桐柏地区麻粒岩分布(B)地质略图

Fig. 1　Geological sketch map of the Tongbai_Dabie orogenic belt and geological sketch map showing the distribution of granulite_facies metamorphic rocks in Tongbai area

A(Zhang Guowei *et al.*, 1996): NCB—华北板块南缘; YZB—扬子板块北缘; SF1—商丹缝合带; SF2—勉略缝合带; 13—秦岭造山带结晶基底岩块; 14—秦岭造山带过渡性基底岩块; B: 1—信阳群: 二云石英片岩、斜长角闪片岩、黑云斜长片岩; 2—二郎坪群: 斜长角闪片岩夹白云斜长变粒岩、大理岩、云母片岩; 3—秦岭群雁岭沟组: 大理岩; 4—秦岭群郭庄组上段: 花岗质片麻岩; 5—秦岭群郭庄组中段: 斜长角闪片麻岩、斜长角闪岩为主; 6—秦岭群郭庄组下段: 退变质麻粒岩夹新鲜麻粒岩透镜体为主; 7—走马沟片麻状花岗岩; 8—老湾花岗岩; 9—长英质及基性麻粒岩; 10—采样位置及样品编号; 11—地层界线及断层; 12—野外路线

布(约占 95% 以上),其主要矿物组合为: Opx+ Gar+ Bit(黑云母)+ Pl+ Qz(石英),一般暗色矿物含量 20%~ 30%,石英大于 10%。新鲜麻粒岩一般呈透镜状、似层状,东部及中部体积通常不大,透镜状长轴约为 0.4~ 1.5 m,短轴一般为 0.2~ 0.8 m,有的体积较大。夕线石片麻岩在本区分布不广,呈似薄层状、小透镜状,长轴为 0.3~ 0.6 m,短轴 0.15~ 0.3 m,其主要矿物组合为: Gar+ Pl+ Kfs(钾长石)+ Bit+ Qz+ Sil(矽线石)。

2　主要矿物特征

桐柏麻粒岩主要矿物为石榴石、斜方辉石、斜长石、黑云母,少部分基性麻粒岩中有单斜辉石和角闪石。麻粒岩相中代表性矿物成分见表 1。

表 1　麻粒岩相中代表性矿物成分(w_B/ %)及相关参数

Table 1　Representative mineral composition and related parameters of granulite facies

样号	T99- 100				T99- 34				T99- 36				T99- 166
矿物	Pl	Cpx	Opx	Gar	Opx	Gar	Bit	Pl	Pl	Kfs	Bit	Gar	Hb
SiO_2	53.35	50.04	50.86	38.58	52.06	38.07	38.10	58.75	62.41	65.50	37.84	39.11	42.64
TiO_2	0.00	0.26	0.00	0.00	0.00	0.00	6.16	0.00	0.00	0.21	5.32	0.00	2.10
Al_2O_3	27.43	2.95	1.34	20.53	2.35	21.15	15.17	26.24	24.06	19.33	15.69	21.78	11.64
FeO	0.24	12.74	30.05	28.51	26.97	29.66	14.54	0.00	0.00	0.23	10.85	27.11	16.89
MnO	0.00	0.46	0.67	1.65	0.17	0.77	0.00	0.00	0.00	0.00	0.00	0.32	0.25
MgO	0.00	10.52	16.50	4.39	18.55	6.82	12.35	0.00	0.00	0.00	15.93	10.21	8.94
CaO	10.91	21.25	0.90	7.23	0.19	2.98	0.00	8.58	5.64	0.96	0.14	1.19	11.79
Na_2O	7.38	0.72	0.00	0.00	0.00	0.00	0.00	6.07	7.87	3.50	0.00	0.33	1.59
K_2O	0.19	0.14	0.00		0.00		9.48	0.14	0.17	10.22	9.18		1.54
Total	99.50	99.08	100.32	100.89	100.29	99.45	95.80	99.78	100.15	99.95	94.95	100.05	97.38
O	32	6	6	12	6	12	22	32	32	32	22	12	23
Si	9.791	1.910	1.962	3.017	1.976	2.992	5.629	10.499	11.025	11.867	5.540	2.984	6.476
Al	5.928	0.133	0.061	1.891	0.105	1.957	2.639	5.522	5.005	4.124	2.705	1.958	2.082
Ti	0.000	0.007	0.000	0.000	0.000	0.000	0.685	0.000	0.000	0.029	0.586	0.000	0.24
Fe	0.037	0.407	0.969	1.865	0.856	1.950	1.796	0.000	0.000	0.035	1.329	1.730	2.145
Mg	0.000	0.599	0.947	0.512	1.050	0.799	0.000	0.000	0.000	0.000	0.000	1.161	2.024
Mn	0.000	0.015	0.022	0.109	0.005	0.051	2.720	0.000	0.000	0.000	3.477	0.021	0.032
Ca	2.145	0.869	0.037	0.606	0.008	0.251	0.000	1.643	1.067	0.186	0.022	0.097	1.919
Na	2.626	0.053	0.000	0.000	0.000	0.000	0.000	2.103	2.696	1.230	0.000	0.049	0.468
K	0.044	0.007	0.000		0.000		1.787	0.032	0.038	2.362	1.715		0.298
X_{Mg}		0.655	0.499	0.222	0.551	0.296	0.602				0.723	0.419	
Fe^{3+}/Fe^{2+}				0.038		0.028						0.073	
Ab	54.50		Alm	58.298	Alm	53.717	Ab	55.70	70.90	32.60	Alm	55.769	
An	44.50		And	3.503	And	3.329	An	43.50	28.10	4.90	And	3.363	
Or	0.90		Gross	17.088	Gross	7.217	Or	0.80	1.00	62.50	Gross	0.000	
			Pyr	17.396	Pyr	33.582					Pyr	40.153	
			Spess	3.715	Spess	2.154					Spess	0.715	

T99- 100、166 为基性麻粒岩; T99- 34 为长英质麻粒岩; T99- 36 为麻粒岩相富铝片麻岩; 由北京大学电子 X 射线显微分析仪(EPM- 810Q)测试,分析条件: 15 kV 加速电压,20 nA 电子束。

(1) 石榴石　见于各种麻粒岩和夕线石片麻岩中,一般粒度 0.5~ 1.0 mm,少数达到 2

mm, 常见斜长石、石英、辉石等包体。电子探针分析石榴石中铁铝榴石 53.7%～63.3%, 镁铝榴石 16.2%～33.6%, 钙铝榴石 7.2%～22.1%。其中基性麻粒岩中的钙铝榴石较高, 长英质麻粒岩中钙铝榴石较低, 但镁铝榴石较高。夕线石片麻岩中铁铝榴石 55.7%～61.4%, 钙铝榴石 0%～2.2%, 镁铝榴石 34.7%～40.2%。本区石榴石没有明显的成分环带, 说明它们在麻粒岩相变质作用时达到了平衡。与世界各地低压、中压及高压麻粒岩中石榴石成分相比(图 2), 桐柏麻粒岩中石榴石端员组分的特点是介于高压与低压麻粒岩之间。

(2) 辉石　斜方辉石见于基性和长英质麻粒岩中, 其成分相当于紫苏辉石和铁紫苏辉石(图 3), Al_2O_3 为 1.06%～2.94%, CaO 为 0.19%～0.90%, X_{Mg} 为 0.470～0.628, 基性麻粒岩中的斜方辉石中 Al_2O_3 较低, 主要在 1.06%～1.78% 之间, X_{Mg} 为 0.470～0.588。长英质麻粒岩中的斜方辉石有以下特点: 成分分布较集中, 均为紫苏辉石; CaO 含量较低, 大部分在 0.19%～0.40% 之间; X_{Mg} 为 0.551～0.628; Al_2O_3 较基性麻粒岩中高, 且大部分集中在 1.79%～2.94% 之间。单斜辉石仅见于基性麻粒岩中, 其成分相当于透辉石、普通辉石(图 3), Al_2O_3 为 1.46%～3.49%, Na_2O 为 0.57%～0.79%, X_{Mg} 为 0.655～0.692。

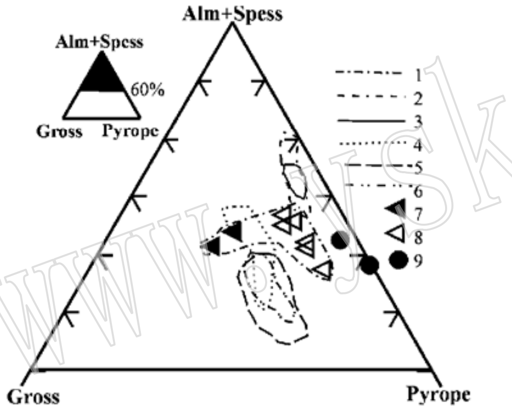

图 2　石榴石的 Alm+Spe-Pyr-Grs 图解

Fig. 2　Alm+Spe-Grs-Pyr diagram of garnets

1—桐柏麻粒岩中石榴石; 2—中澳大利亚 Reynolds Rang 低压麻粒岩(Buick *et al.*, 1998); 3—两广交界地区的中低压麻粒岩(杜杨松等, 1999); 4—纽约 Adirondack 高原中压麻粒岩(Frank *et al.*, 1997); 5—东坦桑尼亚 Pan-African 带高压麻粒岩(Appel *et al.*, 1998); 6—华北太古宙桑干构造带高压麻粒岩(Guo jinghui *et al.*, 1996); 7—基性麻粒岩; 8—长英质麻粒岩; 9—麻粒岩相富铝片麻岩

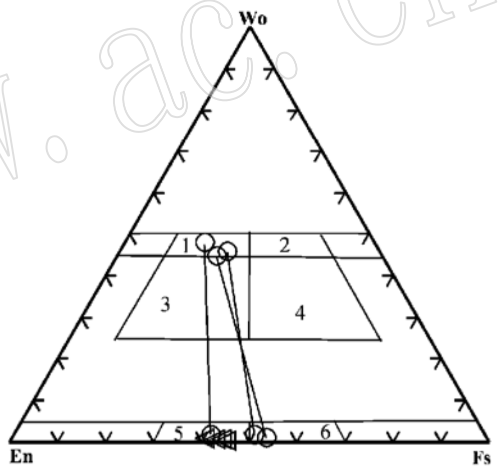

图 3　麻粒岩中辉石 Wo-En-Fs 图

(据 Dahl, 1980)

Fig. 3　Wo-En-Fs diagram of pyroxene from granulites

连线表示共生的斜方辉石与单斜辉石; 1—次透辉石; 2—铁次透辉石; 3—普通辉石; 4—铁普通辉石; 5—紫苏辉石; 6—铁紫苏辉石; 圆圈为基性麻粒岩; 三角形为长英质麻粒岩

(3) 角闪石　主要见于基性麻粒岩中, 薄片中呈绿色、黄绿色及棕褐色。其成分相当于含亚铁菲闪石、含亚铁菲闪角闪石等, 一般与紫苏辉石共生, 极少与石榴石共生。Al(Ⅳ) 1.52～1.79, Al(Ⅵ) 0.332～0.558, Ti 0.24～0.562, Na 0.369～0.468, K 0.298～0.505。具有麻粒岩相角闪石的特点(Закрутин, 1968)。角闪石为峰期变质产物。

(4) 黑云母 见于麻粒岩和夕线石片麻岩中。原生黑云母呈浅红褐色或深红褐色,富钛,TiO_2(w_B/%) 5.43~ 6.75, X_{Mg}为0.485~ 0.662。不同岩石中黑云母成分变化不大。

(5) 长石 斜长石分布广泛,斜长石An为36.9%~ 57.1%, Ab为42.3%~ 61.9%。桐柏麻粒岩中斜长石绝大部分属于中长石范围。基性麻粒岩An为36.9%~ 44.5%, Ab为53.2%~ 61.9%;长英质麻粒岩An为38.8%~ 57.1%, Ab为42.3%~ 59.6%。钾长石主要存在于矽线石片麻岩中, Or为62.5%, Ab为32.6%

3 麻粒岩相变质作用的温压条件

选择不同岩石类型(基性、长英质麻粒岩及麻粒岩相富铝片麻岩)中的代表性样品,利用传统地质温压计、TWQ程序进行温压计算,其结果见表2、3、图4。

表2 温度计算表 ℃

Table 2 Calculations of temperature

代入压力 GPa	基性麻粒岩(T99- 100)					长英质麻粒岩(T99- 34)				石榴矽线片麻岩
	Gar- Opx	Gar- Cpx			Cpx- Opx	Gar- Opx		Gar- Bit	Opx	Gar- Bit
0.65	804	706	811	727	763	770	708	708	715	720
0.75	804	709	814	733	763	770	713	714	719	725
0.85	804	712	816	739	763	770	719	719	723	730
来源	1	2	3	1	4	1	5	6	7	6

1—Dahl(1980); 2—Ellis & green (1979); 3—Granguly (1979); 4—Wood & Banno(1973); 5—Harley(1984); 6—Dasgupta *et al* (1991); 7—Brey & Kohler(1990)。

表3 压力计算表 GPa

Table 3 Calculations of pressure

代入温度 ℃	基性麻粒岩(T99- 100)		长英质麻粒岩(T99- 34)				石榴矽线片麻岩 (T99- 36)
	Gar- Cpx - Pl- Qz	Gar- Cpx - Opx- Pl - Qz	Gar- Opx- Pl- Qz		Gar- Opx		GASP
700	0.671	0.645	0.789	0.624	0.615	0.703	0.619
800	0.742	0.688	0.838	0.701	0.752	0.703	0.782
850	0.777	0.714	0.862	0.739	0.821	0.703	0.873
来源	Perkins & Newton (1982)	Paria *et al* (1988)	Perkins & Newton (1982)	Perkins & Chipera (1985) Mg	Perkins & Chipera (1985) Fe	Brey *et al* (1986)	Koziol & Newton (1988)

前面用3种典型麻粒岩标本计算了桐柏麻粒岩的峰期变质温度压力条件:长英质麻粒岩(T99- 34)用传统温压计得出t= 708~ 770℃, p= 0.615~ 0.838 GPa,据此绘出的图(图4A)交点显示的温压范围为t= 705~ 770℃, p= 0.63~ 0.82 GPa,用TWQ计算结果t= 700~ 840℃, p= 0.61~ 0.83 GPa;基性麻粒岩(T99- 100)用传统温压计得出t= 706~ 816℃, p= 0.645~ 0.777 GPa,图4B交点显示的温压范围为t= 705~ 815℃, p= 0.65~ 0.74 GPa,用TWQ计算结果t= 735~ 760℃, p= 0.78~ 0.85GPa(在该范围内所交反应线最多);麻粒岩相泥质变质岩黑云石榴矽线片麻岩(T99- 36)用传统温压计绘出图4C的交

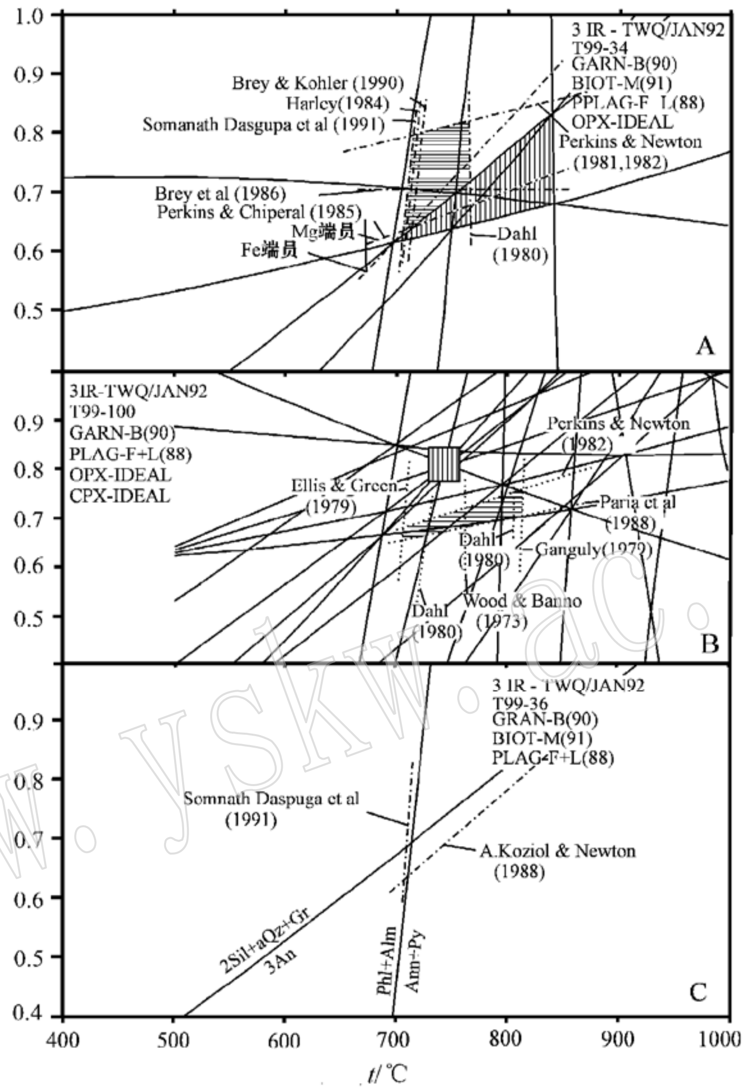

图 4　桐柏麻粒岩温压计算结果

Fig. 4　$p-t$ diagram based on calculation of the granulites in Tongbai area

A —长英质麻粒岩(T99- 34) ; B —基性麻粒岩(T99- 100) ; C —麻粒岩相富铝片麻岩(T99- 36) ; 虚线为用传统温压计计算结果, 虚线框为其标定范围; 实线为用 TWQ 程序计算结果, 实线框为其标定范围

点 $t=705$ ℃, $p=0.63$ GPa, 用 TWQ 计算结果 $t=712$ ℃, $p=0.69$ GPa。综合以上计算结果, 得出桐柏麻粒岩的变质条件为 $t=700\sim840$ ℃, $p=0.61\sim0.85$ GPa。

4　讨　论

翟淳等(1990, 1997, 1999) 与 Kröner 等(1993) 算得桐柏麻粒岩的温压条件较高, 其原因主要是没有从矿物组合特征上分析, 而仅仅用单一的传统温压计确定其形成条件。Zhai Xiaoming(1996, 1998) 得出较低的温压条件, 其主要原因是以不确定性基本否定了传统温压

计计算结果的可靠性, 也没有从麻粒岩区的矿物组合特征分析麻粒岩的温压条件, 仅仅从单一岩石类型(角闪麻粒岩)及单一计算方法(TWQ 程序)结果作为桐柏麻粒岩变质的条件。另外, 从笔者的填图结果来看, Zhai Xiaoming(1996)所圈定的麻粒岩分布范围包括整个秦岭群, 这实质上是扩大了麻粒岩的分布区, 包括了角闪岩相区部分, 自然得出麻粒岩具较低的温度条件, 即其所说的高角闪岩相变质。

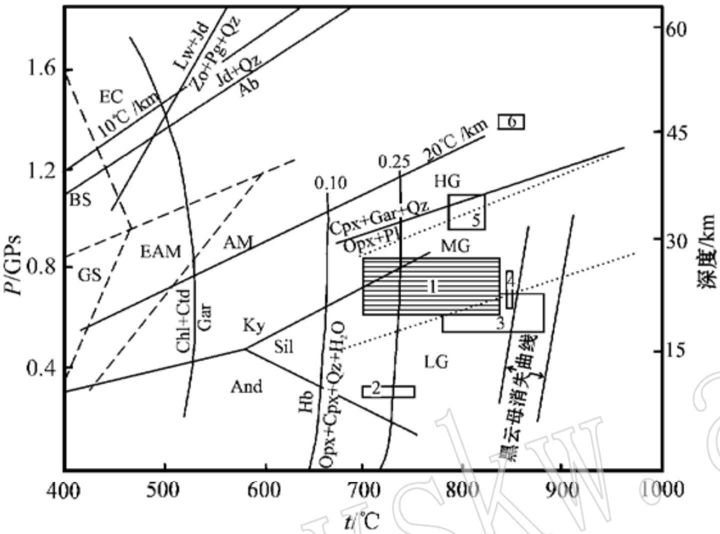

图 5 麻粒岩 p－t 图

Fig. 5 p－t diagram of granulite facies metamorphism

1—桐柏麻粒岩; 2—中澳大利亚Reynolds Rang低压麻粒岩(Buick *et al*., 1998); 3—两广交界中低压麻粒岩(杜杨松等, 1999); 4—纽约Adirondack高原中压麻粒岩(Frank *et al*., 1997); 5—东坦桑尼亚Pan－African带高压麻粒岩(Appel *et al*., 1998); 6—华北太古宙桑干构造带高压麻粒岩(Guo jinghui *et al*., 1996); 短实虚线的变质相界引自Ernst(1988); GS—绿片岩相; EAM—绿帘角闪岩相; AM—角闪岩相; EC—榴辉岩相; 点虚线的高中低压麻粒岩界限引自Harley(1989); LG—低压麻粒岩; MG—中压麻粒岩; HG—高压麻粒岩; 硬柱石(Lw)+硬玉(Jd)=黝帘石(Zo)+钠云母(Pg)+Qz引自Holland(1979); 钠长石(Ab)=Jd+Qz引自Holland(1979); 蓝晶(Ky), 石Sil和红柱石(And)三相转变和绿泥石(Chl)+硬绿泥石(Ctd)=Gar引自Powell & Holland(1990); Cpx+Gar+Qz=Opx+Pl引自Green & Ringwood(1967); Hb=Cpx+Opx+H_2O引自Lamb(1988); 黑云母消逝的边界范围引自Vielzeuf & Montel(1994), Patiao Douce & Beard(1995, 1996), Montel & Vielzeuf(1997), Stevens *et al*(1997)

从前面的计算中, 可发现麻粒岩相中3类典型岩石温压结果略有不同, 这很可能是在峰期变质时, 由于局部流体及其他条件不绝对一致造成的。由桐柏麻粒岩中共生的斜方辉石－单斜辉石连线(图3)可知麻粒岩中共生的二辉石温度不超过850℃。从图2中可看出, 桐柏麻粒岩石榴石不同于世界其他地方的低压麻粒岩及高压麻粒岩, 基本上介于高压与低压麻粒岩之间。

从麻粒岩的矿物组合来看, 变质反应Cpx+Gar+Qz=Opx+Pl控制了桐柏麻粒岩的压力上限, 即桐柏麻粒岩不属于高压麻粒岩; 桐柏麻粒岩中黑云母是常见矿物, 由此可推知桐柏麻粒岩的温度上限不超过黑云母消失线, 即温度不超过820～850℃; 角闪石分解曲线受水活度影响较大, 因此角闪石在温度大于700℃时仍可出现(图5)。

通过以上讨论可知桐柏麻粒岩变质条件为700～840℃, 0.61～0.85 GPa, 属于典型的中压麻粒岩, 地温梯度较高, 大致为28～31℃/km。

References

Appel P, Moller A, Schenk V. 1998. High_pressure granulite facies metamorphism in the Pan－African belt of eastern

Tanzania: $P-T-t$ evidence against granulite formation by continent collision[J]. Journal of Metamorphic Geology, 16(4): 491~510.

Brey G T, Kohler T. 1990. Geothermobarometry in four phase lherzolites, part Ⅱ: new thermobarometers, and practical assessment of existing thermobarometers [J]. Journal of Petrology, 31: 1 353~1 378.

Brey G P, Nickel K G, Kogarko L. 1986. Garnet-pyroxene equilibriain the system CaO-MgO-Al_2O_3-SiO_2(CMAS): prospects for simplilified (T_independent) lherzolite barometry and an eclogite-barometer [J]. Contributions to Mineralogy and Petrology, 92: 448~455.

Buick I S, Cartwright I, Harley S L. 1998. The retrograde $P-T-t$ path for low_pressure granulites from the Reynolds Rang, central Australia: petrological constraints and implications for low_P/high_T metamorphism [J]. Journal of Metamorphic Geology, 16(4): 511~529.

Dahl P S. 1980. The thermal_compositional dependence of Fe^{2+}-Mg distributions between coexisting garnet and pyroxene: applications to geothermometry [J]. American Mineralogist, 65: 854~866.

Dasgupta S, Sengupta P, Guha D, *et al*. 1991. A refined garnet-biotite Fe-Mg exchange geothermometer and its application in amphibolites and granulites[J]. Contributions to Mineralogy and Petralogy, 109: 130~137.

Du Yangsong, Collerson K D, Zhao jianxin, *et al*. 1999. Characteristics and petrogenesis of granulite enclaves in S_type granites in the junction of Guangdong and Guangxi provinces [J]. Acta Petrologica Sinica, 15(2): 309~314 (in Chinese with English abstract).

Ellis D J, Green D H. 1979. An experimental study of the effect of Ca upon garnet-clinopyroxene Fe-Mg exchange equilibria [J]. Contributions to Mineralogy and Petralogy, 71: 13~22.

Ernst W G. 1988. Tectonic history of subduction zones inferred from retrograde blueschist $P-T$ path [J]. Geology, 16: 1 081~1 084.

Frank S S, Jeffrey C M. 1997. Mineral Zoning, $P-T-X-M$ phase relations, and metamorphic evolution of some Adirondack granulites, New York [J]. Journal of Petrology, 38(6): 757~783.

Ganguly J. 1979. Garnet and clinopyroxene solid solutions, and geothermometry based on Fe-Mg distribution coefficient [J]. Geochimica et Cosmochimica Acta, 43: 1 021~1 029.

Green D H, Ringwood A E. 1967. An experiment investigation of the gabbro to eclogite transformation and its petrologic applications [J]. Geochimca et Conmochimica Acta, 31: 767~833.

Guo Jinghui, Bian Aiguo, Shi Yin. 1996. High_pressure granulite, retrograde eclogite and granite Early Precambrican Sanggan structure belt [A]. Zhai mingguo, *et al*. Granulites and Lower Continental Crust in North China Archaean Craton [C]. Beijing: Seismological Press, 21~54.

Harley S L. 1984. An experimental study of the partitioning of Fe and Mg between garnet and orthopyroxene [J]. Contributions to Mineralogy and Petralogy, 86: 359~373.

Harley S L. 1989. Origins of granulites: a metamorphic perspective [J]. Geological Magazine, 126(3): 215~331.

Holland T J B. 1979. Experimental determination of the reaction paragonite= jadeite+ kyanite+ water, internally consistent thermodynamic data for part of the system Na_2O-Al_2O_3-SiO_2-H_2O, with applications to eclogites and blueschists [J]. Contributions to Mineralogy and Petralogy, 68: 293~301.

Kröner A, Zhang G W, Y Sun. 1993. Granulites in the Tongbai area, Qingling belt, China: geochemistry, petrology, single zircon geochronology, and implications for the tectonic evolution of eastern Asia [J]. Tectonics, 12(1): 245~255.

Lamb W M. 1988. Granulite facies amphibole and biotite equilibria, and calculated peak metamorphism water activitives [J]. Contributions to Mineralogy and Petralogy, 100: 349~360.

Montel J M, Vielzeuf D. 1997. Partial melting of metagreywackes, Part II. Compositions of minerals and melts [J]. Contributions to Mineralogy and Petralogy, 128: 176~196.

Newton R C, Perkins D III. 1982. Thermodynamic calibration of geobarometers based on the assemblages garnet-plagioclase-orthopyroxene (clinopyroxene)-quartz [J]. American Mineralogist, 67: 203~222.

Paria P, Bhattacharya A, Sen S K. 1988. The reaction garnet+ clinopyroxene+ quartz= 2 orthopyroxene+ anorthite: a potential geobarometer for granulites [J]. Contributions to Mineralogy and Petrology, 99: 126~133.

Patino Dounce A E, Beard J S. 1995. Dehydration_melting of biotite geniss and quartz amphibolite from 3 to 15 kbar [J]. Journal of Petrology. 36: 707~ 738.

Patino Dounce A E, Beard J S. 1996. Effects of P, $f(O_2)$ and Mg/Fe ratio on dehydration melting of model metagreywacks [J]. Journal of Petrology, 37: 999~ 1024.

Perkins D III, Chipera S J. 1985. Garnet- orthopyroxene- plagioclase- quartz geobarometry: refinements and application to the English River subprovince and the Minnesota River Valley [J]. Contributions to Mineralogy and Petrology, 89: 69~ 80.

Powell R, Holland T J B. 1990. Calculated mineral equilibrium in the pelite system, KFMASH [J]. American Mineralogist, 75: 129~ 134.

Stevens G, Clemens J D, Droop G T R. 1997. Melt production during granulite_facies anatexis: experimental data from "primitive" metasedimentary protoliths[J], Contributions to Mineralogy and petrology, 128: 352~ 370.

Vielzeuf D, Montel J M. 1994. Partial melting of metagreywackes. part I. Fluid_absent experiments and phase relationships [J]. Contributions to Mineralogy and Petrology. 117: 375~ 379.

Wood B J, Banno S. 1973. Garnet- orthopyroxene and orthopyroxene- clinopyroxene relationships in simple and complex systems [J]. Contributions to Mineralogy and Petrology, 42: 109~ 124.

Xu Bei, Grove M, Wang Changqiu, *et al*. 2000. $^{40}Ar/^{39}Ar$ thermochronology from the northwestern Dabie Shan: constraints on the evolution of Qinling- Dabie orogenic belt, east_central China [J]. Tectonophysics. 322: 279~ 301.

Zhai Xiaoming, Day H W, Hacker B R, *et al*. 1998. Paleozoic metamorphism in Qinling orogen, Tongbai Mountains, Central China[J]. Geology, 26(4): 371~ 374.

Zhai Xiaoming. 1996. Metamorphic petrology and geochronology of the north Tongbai Mountains, central China [D]. America: University of California, 105, 222.

Zhai Chun, Lin jinhui, Gong Xiasheng. 1999. Origin and significance of Ti_rich amphiboles in high_pressure granulites from southern Henan province, China [J]. Acta Mineralogica Sina. 19(1): 63~ 69 (in Chinese with English abstract).

Zhai Chun, Wang Jiangzhen. 1990. Pressure and temperature conditions of for formation of the Tongbai high_grade metamorphic block [A]. Liu Guohui, Zhang Shouguang. Geological Memoirs of the Qinling- Daba Mountains (1) Metamorphic Geology[C]. Beijng: Beijing Scientific and Technical Publishing House, 111~ 122 (in Chinese with English abstract).

Zhai Chun, Zhang Qinghua, Wang Guozhi, *et al*. 1997. Preliminary study of high_pressure mafic granulites in southern Henan province [J]. Journal of Mineral Petrology 17(2): 1~ 7 (in Chinese with English abstract).

Zhang Guowei, Guo Anlin, Liu Fulai, *et al*. 1996. Three_dimentional architecture and dynamic analysis of the Qinling Orogenic Belt [J]. Science in China (series D), 39(supp.): 1~ 9.

Zhang Hongfei, Zhangli, Gao Shan, *et al*. 1999. Pb isotopic compositions of metamorphic rocks and their geological implication [J]. Earth science, 24(3): 309~ 314 (in Chinese with English abstract).

Закруткин В В. 1968. Обэволюций амфиболов при метаморфизм. ЗВМО. и. 97. вып. 1.

附中文参考文献

张宏飞, 张 利, 高 山, 等. 1999. 桐柏地区变质杂岩和侵入岩内 Pb 同位素特征及其地质意义[J]. 地球科学. 24(3): 309~ 314.

杜杨松, Ken D C, 赵建新, 等. 1999. 两广交界地区 S 型花岗岩中麻粒岩包体的特征和成因[J]. 岩石学报, 15(2): 309 ~ 314.

翟 淳, 王奖臻. 1990. 桐柏高级块体形成的温压条件[A]. 刘国惠, 张寿广. 秦岭- 大巴山地质论文集(一) 变质地质[C]. 北京: 北京科学技术出版社, 111~ 122.

翟 淳, 林金辉, 龚夏生. 1999. 豫南高压麻粒岩中富钛角闪石类的成因和意义[J]. 矿物学报, 19(1): 63~ 69.

翟 淳, 张清华, 王奖臻, 等. 1997. 豫南高压镁铁质麻粒岩的初步研究[J]. 矿物岩石, 17(2): 1~ 7.