

蚀变洋壳玄武岩俯冲过程中含碳矿物相变质演化及脱碳作用的研究

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摘 要: 俯冲作用是连接地表系统和地球深部系统的最为关键的地质过程, 其对研究地球深部碳循环具有重要的意义。俯冲洋壳岩石圈中的碳主要存储在沉积物、蚀变洋壳玄武岩以及蛇纹岩中。俯冲变质作用过程含碳岩石的变质演化控制着其中含碳矿物相的转变及碳迁移过程。本文选取了蚀变洋壳玄武岩进行相平衡模拟, 来研究其含碳矿物相的变质演化过程。计算结果表明, 变质玄武岩体系中的碳酸盐矿物之间的转变反应除了受压力控制之外, 还受到温度和体系中铁含量的影响。随着压力的升高蚀变玄武岩中碳酸盐矿物会发生方解石/文石-白云石-菱镁矿的转变, 但在高压/超高压条件下, 温度的升高可以使菱镁矿转变成白云石。碳酸盐矿物中的铁含量受到体系中铁含量的影响, 白云石和菱镁矿中的铁含量随着体系中铁含量的增加而增加。在水不饱和条件下, 洋壳不管是沿着低温还是高温地热梯度线俯冲到岛弧深度, 蚀变玄武岩体系几乎都不发生脱碳作用。然而在水饱和条件下, 当洋壳沿着高温以及哥斯达黎加地热梯度线俯冲到岛弧深度时, 蚀变玄武岩体系中的碳几乎可以全部脱出去。蚀变玄武岩体系中水含量的增加可以促进体系的脱碳作用。

关键词: 俯冲带; 蚀变洋壳玄武岩; 深部碳循环; 地热梯度; 脱碳作用

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Metamorphic evolution and decarbonation of the carbonates in the altered oceanic basalt during the subduction process

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Abstract: Subduction is the key geological process that can link the Earth's surface system with deep Earth's interior. It plays a significant role for the study of deep carbon cycle. Carbon in the subducting lithosphere is present in sediments, altered oceanic crust and serpentinite. The evolution of the carbonate-bearing rocks during subduction metamorphism controls the transformation of the carbonate minerals and carbon transport process. In this study, phase equilibria were modeled for the altered oceanic crust to investigate the metamorphic evolution of the carbonate minerals in the metabasalt. The calculated results indicate that the transformation of carbonate minerals are also affected by temperature and iron content in the metabasalt, in addition of the controlling role of pressure. Phase equilibrium modeling demonstrates that carbonates in the subducted oceanic crust may experience calcite/aragonite-dolomite-magnesite transition with increasing pressure, but under HP/UHP conditions, magnesite can be transformed to dolomite with increasing temperature. The iron content in the carbonates is affected by the iron content in the metabasalt, where the iron content in the dolomite and magnesite will increase with the increasing iron content in

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the metabasalt. When the altered oceanic crust is under water-unsaturated conditions, almost no decarbonation will happen when the oceanic crust subducts to sub-arc depth along either low temperature or high temperature geotherm. However, under water-saturated conditions, almost all of the carbon in the metabasalt will be released when the oceanic crust subducts to sub-arc depth along high temperature or Costa Rica geotherm. The water content in the metabasalt will facilitate the decarbonation reactions.

Key words: subduction zone; altered oceanic basalt; deep carbon cycle; geotherm; decarbonation

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地球系统(万年~百万年尺度)碳和水的循环影响着气候变化,生态平衡,能源替代以及环境恢复等和人类生存息息相关的科学问题(Dasgupta, 2013; Hazen and Schiffries, 2013)。前人对全球碳循环的研究主要聚焦在大气圈、水圈以及浅层地壳等地表系统。近年来越来越多的研究发现,地球深部的碳含量可能超过地球的90%,然而相对于地表碳循环,地球深部碳循环的研究却依然非常有限(Javoy, 1997; Hilton *et al.*, 2002; Hazen and Schiffries, 2013)。俯冲带作为联系地表和地球深部系统的关键环节,被认为是深部物质循环以及能量交换的俯冲工厂(Hacker *et al.*, 2003; Tatsumi and Kogiso, 2003)。俯冲带在调节地表碳和地球深部碳储量变化方面起着重要的作用(Edmond and Huh, 2003; Johnston *et al.*, 2011; Horleston and Helffrich, 2012; Dasgupta *et al.*, 2013; Piccoli *et al.*, 2016)。

在整个地质威尔逊旋回过程中,从洋壳形成到俯冲消亡,都伴随着碳循环过程。新生洋壳在洋中脊扩张生长过程中,海水顺着构造裂隙灌入,可以使新生洋壳基性岩以及超基性岩发生水化作用和碳酸盐化作用,使海水中的 CO_2 以碳酸盐形式沉淀在被改造的洋壳蚀变玄武岩和蛇纹岩中(Alt and Teagle, 1999; Sleep and Zahnle, 2001; Kelley *et al.*, 2005; Slagle and Goldberg, 2011; Rosenbauer *et al.*, 2012)。在洋壳生长向洋中脊两边扩张过程中,洋壳火成岩部分继续发生水化和碳酸盐化。同时,由于陆壳来源的碳酸盐沉淀作用以及部分生物作用,可以在蚀变洋壳上部沉淀出含有大量碳酸盐以及少量生物碳的沉积物,使更多地表系统的碳进入俯冲洋壳循环系统(Plank and Langmuir, 1998)。俯冲板块中的碳主要赋存在沉积物、蚀变洋壳以及蛇纹岩中,然后随着板片俯冲进入地球深部。每年通过沉积物携带进入俯冲带的碳达到13~23 Mt,通过蚀变玄武岩洋壳携带进入俯冲带的碳有22~28 Mt,通过蚀变超基性

岩(蛇纹岩)携带进入俯冲带的碳含量大概为4~15 Mt(Kelemen and Manning, 2015),其中蚀变洋壳携带碳的能力最强。

进入俯冲带的含碳岩石的变质作用控制着其中含碳矿物的变质演化过程,进而控制着俯冲板片的脱碳作用过程(Bebout, 2007; Bebout *et al.*, 2013; Dasgupta, 2013)。越来越多的研究表明,进入俯冲带中的碳主要通过脱碳反应(Molina and Poli, 2000; Kerrick and Connolly, 2001; Connolly, 2005; Gorman *et al.*, 2006)、溶解脱碳作用(Frezzotti *et al.*, 2011; Ague and Nicolescu, 2014; Facq *et al.*, 2014; Sverjensky *et al.*, 2014; Kelemen and Manning, 2015)以及熔融作用(Poli, 2015; Skora *et al.*, 2015)脱出俯冲板片,然后通过火山作用或者去气作用返回地表。最近,Kelemen等(2015)结合钙质碳酸盐的高温高压溶解度实验以及碳酸盐岩矿物溶解度理论计算认为俯冲带中绝大部分含碳相在变质作用过程中,可能会被俯冲带流体溶解带出俯冲板片进入上覆地幔楔,进而返回地表。由此可见,与俯冲作用相关的地球深部碳循环对地表系统地质尺度上全球规模的气候变化起到了至关重要的控制和影响。因此,研究俯冲作用过程中各含碳相的变质演化过程对于揭示深部碳循环具有重要的意义。

本文选取了俯冲板片中含碳量最高的蚀变玄武岩洋壳部分进行相平衡模拟计算,研究了随着不同 p - t 演化轨迹,各含碳相的变质演化过程;讨论了温度和压力对脱碳反应的影响;进一步讨论了水对变质脱碳反应的影响以及铁含量对不同碳酸盐矿物相稳定域的影响。

1 相平衡模拟计算方法

蚀变洋壳中的碳主要固存在上部大约500 m范围内(Staudigel *et al.*, 1989; Alt and Teagle, 1999),

本文选取 Staudigel 等(1989)的“Super Composite”作为蚀变玄武岩洋壳的全岩组分,其氧化物的质量分数($w_B/\%$)为: $\text{SiO}_2 = 45.8$, $\text{TiO}_2 = 1.12$, $\text{Al}_2\text{O}_3 = 15.53$, $\text{FeO} = 7.77$, $\text{Fe}_2\text{O}_3 = 2.72$, $\text{MnO} = 0.17$, $\text{MgO} = 6.66$, $\text{CaO} = 12.88$, $\text{Na}_2\text{O} = 2.07$, $\text{K}_2\text{O} = 0.56$, $\text{P}_2\text{O}_5 = 0.11$, $\text{H}_2\text{O} = 2.68$, $\text{CO}_2 = 2.95$ 。考虑到 P_2O_5 主要形成磷灰石,在硅酸盐矿物中的含量很少,故忽略这个组分,选择在 $\text{Na}_2\text{O}-\text{MnO}-\text{CaO}-\text{K}_2\text{O}-\text{FeO}-\text{MgO}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{TiO}_2-\text{CO}_2-\text{H}_2\text{O}-\text{Fe}_2\text{O}_3$ (NMnCaKFMASCHO) 体系中模拟岩石的变质作用过程。计算相图采用 Perple-X-6.7.5 (Connolly, 1990, 2005) 程序以及内部一致性热力学数据库 (Holland *et al.*, 1998; Holland and Powell, 2011)。所涉及到的矿物固溶体模型为: 石榴子石 Gt (HP) (Holland and Powell, 1998), 绿辉石 Omph (GHP) (Green *et al.*, 2007), 角闪石 Amph (DPW) (Dale *et al.*, 2005), 云母 Mica (CHA) (Coggon and Holland, 2002), 绿泥石 Chl (HP) (Holland and Powell, 1998), 帘石 Ep (HP) (Holland and Powell, 1998), $\text{H}_2\text{O}-\text{CO}_2$ 流体 F (Connolly and Trommsdorff, 1991), 白云石 Do (HP) (Holland and Powell, 1998), 菱镁矿 M (HP) (Holland and Powell, 1998)。

2 p - t 视剖面图

依据“Super Composite”MORB 成分计算的 p - t 视剖面图如图 1 所示,温度压力范围分别为 $300 \sim 900^\circ\text{C}$ 和 $1 \sim 3.5$ GPa,图中含有硬柱石的组合稳定于高压低温区域,硬柱石能够稳定的最大温度随着压力的增加而增加。白云石的压力稳定域受控于温度的变化,当 $t < 610^\circ\text{C}$ 时,白云石的压力稳定域 $p < 1.7$ GPa,当压力高于 1.7 GPa 时,白云石将全部分解形成菱镁矿;然而当 $t > 610^\circ\text{C}$,白云石的压力稳定域快速升高,和温度成正比,其压力稳定域最高可以大于 3.5 GPa。这和 Kerrick 等(2001)的计算结果类似。Kerrick 等(2001)计算表明当 $t > 800^\circ\text{C}$ 时,白云石可以稳定到 $p > 6$ GPa 的深度范围。当温度进一步增加时,白云石将发生分解反应并逐渐消失,其温度稳定域和压力成正比;当 $p = 1$ GPa 时,白云石的稳定温度 $t < 650^\circ\text{C}$,当 $p = 3.5$ GPa 时,白云石的稳定温度可达 880°C 。菱镁矿的稳定域主要受温度控制,当温度 $t < 700^\circ\text{C}$ 时,菱镁矿可以稳定到上地幔深度 $p > 3.5$ GPa;等温升压过程,菱镁矿的含量几乎不发生变化,这和 Kerrick 等(2001)的计算结果相似。当 p

< 1.7 GPa,菱镁矿的温度稳定域迅速降低,小于 500°C 。 p - t 视剖面图中碳酸盐矿物的铁等值线 $X_{\text{Fe}} = \text{FeO}/(\text{FeO} + \text{MgO})$ 如图 2 所示,其中白云石中的 Dol_{Fe} 值主要受温度控制,随着温度的升高 Dol_{Fe} 值降低;菱镁矿中的 Mgs_{Fe} 值同时受到温度和压力的影响,随着温度压力的升高而升高。

图 3 所示为体系中白云石、菱镁矿、硬柱石和流体随着温度压力变化的矿物含量变化图。从中可以看出白云石和菱镁矿的含量变化存在耦合的关系,当 $t < 610^\circ\text{C}$ 时,随着压力的升高,白云石含量逐渐降低,而菱镁矿含量逐渐升高;当 $t > 610^\circ\text{C}$ 时,随着温度的升高,菱镁矿的含量逐渐降低,而白云石的含量逐渐升高,这一过程中体系中的碳含量并没有减少,只是从一种含碳矿物相转换到另一种含碳矿物相 (Molina and Poli, 2000; Li *et al.*, 2014)。然而当温度继续升高时,白云石的含量将开始减少并最终完全消失,使体系中的碳释放出去。硬柱石和体系中流体的含量也存在一定的耦合关系,在低温硬柱石稳定域,体系(水不饱和体系,详细见图 3)中几乎不含流体;随着温度的升高,硬柱石含量逐渐减少,硬柱石(含 11.5% H_2O , 质量分数)发生分解反应会使其中的水释放出来,使得体系中的流体含量增加 (Wei and Clarke, 2011; Tian and Wei, 2013) (图 3)。

3 p - $M(\text{H}_2\text{O})$ 视剖面图

p - $M(\text{H}_2\text{O})$ 视剖面图可以揭示水含量对岩石体系中各矿物组合的影响 (Guiraud *et al.*, 2001)。本文计算了 $t = 500^\circ\text{C}$ 时的 p - $M(\text{H}_2\text{O})$ 视剖面图 (图 4),其中 $M(\text{H}_2\text{O})$ 为水占体系的质量分数。从图 4 中可以看出含有流体的矿物组合不受水含量的影响。在水过饱和的情况下,含硬柱石的矿物组合稳定域受到限制,而含帘石的矿物组合稳定域增大。在水不饱和的矿物组合区域内,白云石固溶体矿物中的铁值 $X_{\text{Fe}} = \text{FeO}/(\text{FeO} + \text{MgO})$ 随着体系中水含量的增加而增加,而在水过饱和体系中,水含量的变化对白云石中的铁值 X_{Fe} 没有影响。对于菱镁矿,在水不饱和和体系内,菱镁矿中的铁值 X_{Fe} 随着水含量的增加而增大;但在含有 Chl + Ep + Lws 的矿物组合内,菱镁矿中的铁值 X_{Fe} 主要受压力控制,随着压力的增大而减小,受水含量的变化影响比较微弱。在水饱和区域,菱镁矿中的铁值 X_{Fe} 不受水含量的影响。图 5 所示为 p - $M(\text{H}_2\text{O})$ 视剖面图中白云石和菱镁矿矿物

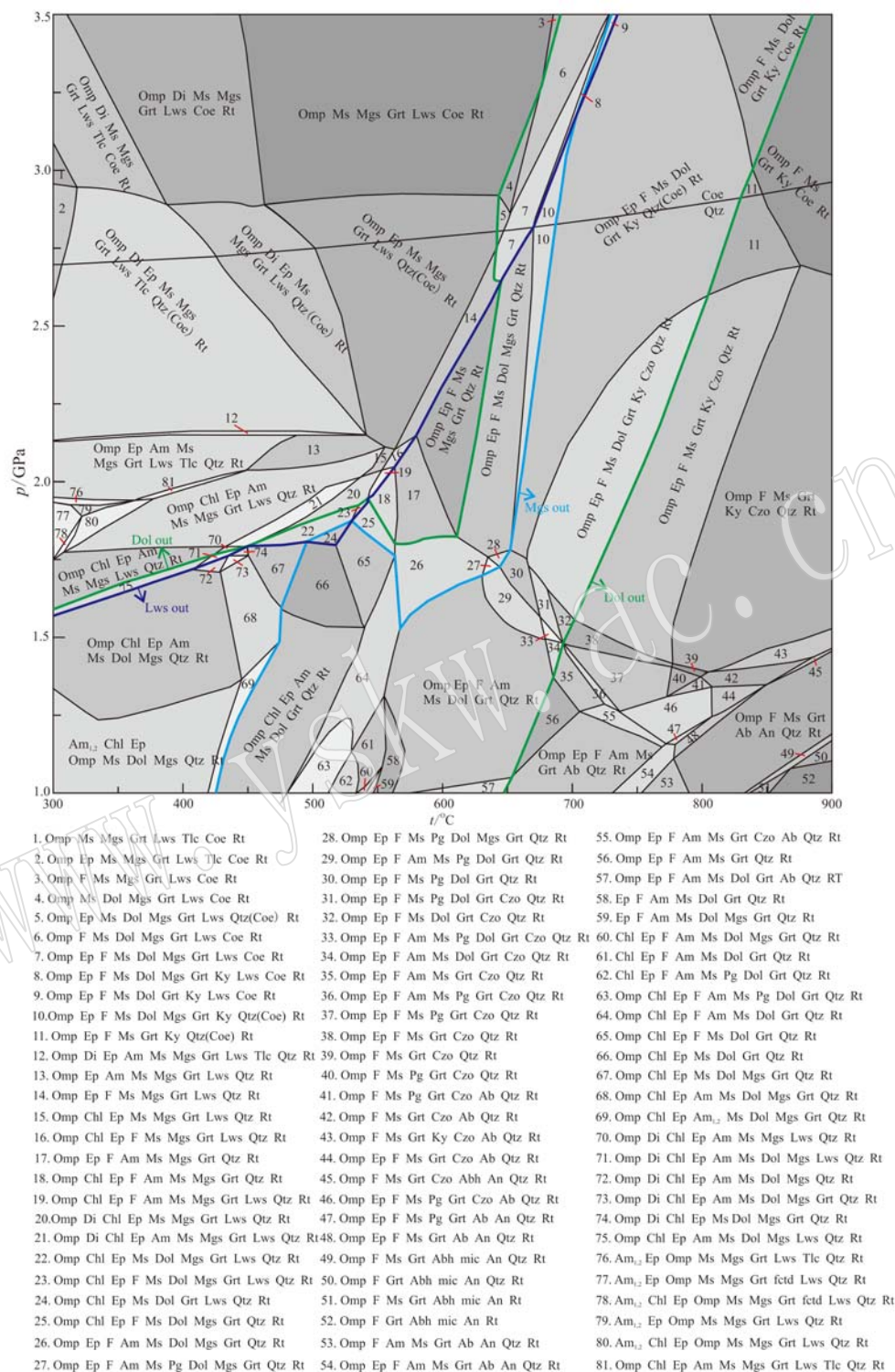


图1 “Super Composite” MORB 成分基性岩在 NMnCaKFMASrTCHO 体系中的 p - t 视剖面图

Fig. 1 p - t pseudosection in the system NMnCaKFMASrTCHO for a “Super Composite” MORB mafic composition

从三变域到六变域颜色逐渐加深, 图中深蓝色线代表硬柱石消失线, 浅蓝色线代表菱镁矿消失线, 绿色线代表白云石消失线; 矿物缩写据沈其韩(2009): Ab—钠长石; An—钙长石; Am—角闪石; Chl—绿泥石; Coe—柯石英; Czo—斜闪石; Dol—白云石; Di—透辉石; Ep—绿帘石; F—流体; Grt—石榴子石; Ky—蓝晶石; Lws—硬柱石; Mgs—菱镁矿; Ms—白云母; Omp—绿辉石; Pg—钠云母; Qtz—石英; Rt—金红石。From trivariant to hexavariant fields the color becomes gradually darkened. The dark blue line represents vanishing of lawsonite, the light blue line represents vanishing of magnesite and the green line represents vanishing of dolomite. Mineral abbreviation after Shen Qihan (2009): Ab—albite; An—anorthite; Am—amphibole; Chl—chlorite; Coe—coesite; Czo—clinzoisite; Dol—dolomite; Di—diopside; Ep—epidote; F—fluid; Grt—garnet; Ky—kyanite; Lws—lawsonite; Mgs—magnesite; Ms—muscovite; Omp—omphacite; Pg—paragonite; Qtz—quartz; Rt—rutile

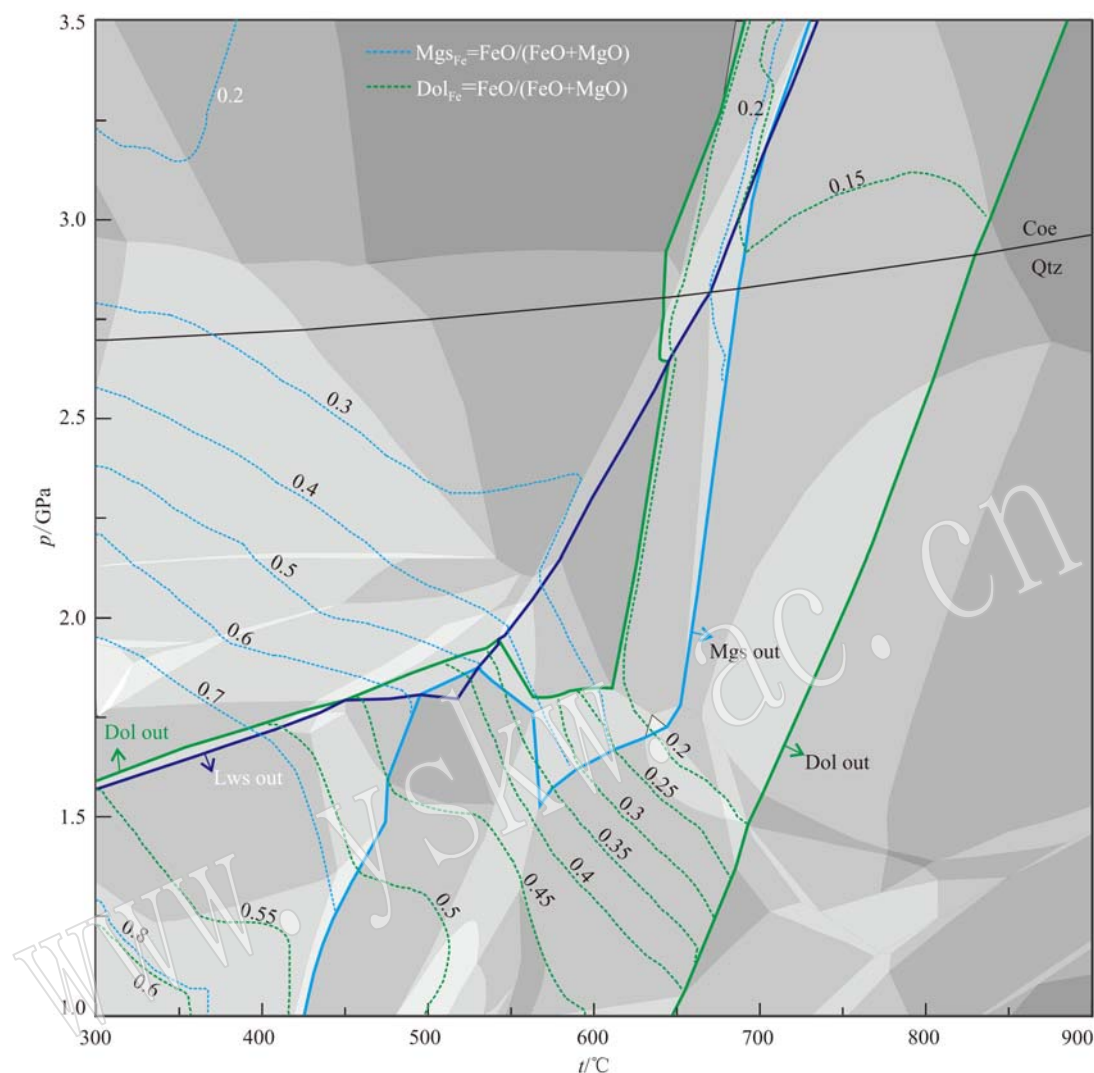


图2 碳酸盐矿物铁含量等值线

Fig. 2 Contour lines of iron content in carbonate minerals

蓝色虚线代表菱镁矿中的铁含量等值线 $Mgs_{Fe} = FeO/(FeO + MgO)$, 绿色虚线代表白云石中的铁含量等值线 $Dol_{Fe} = FeO/(FeO + MgO)$

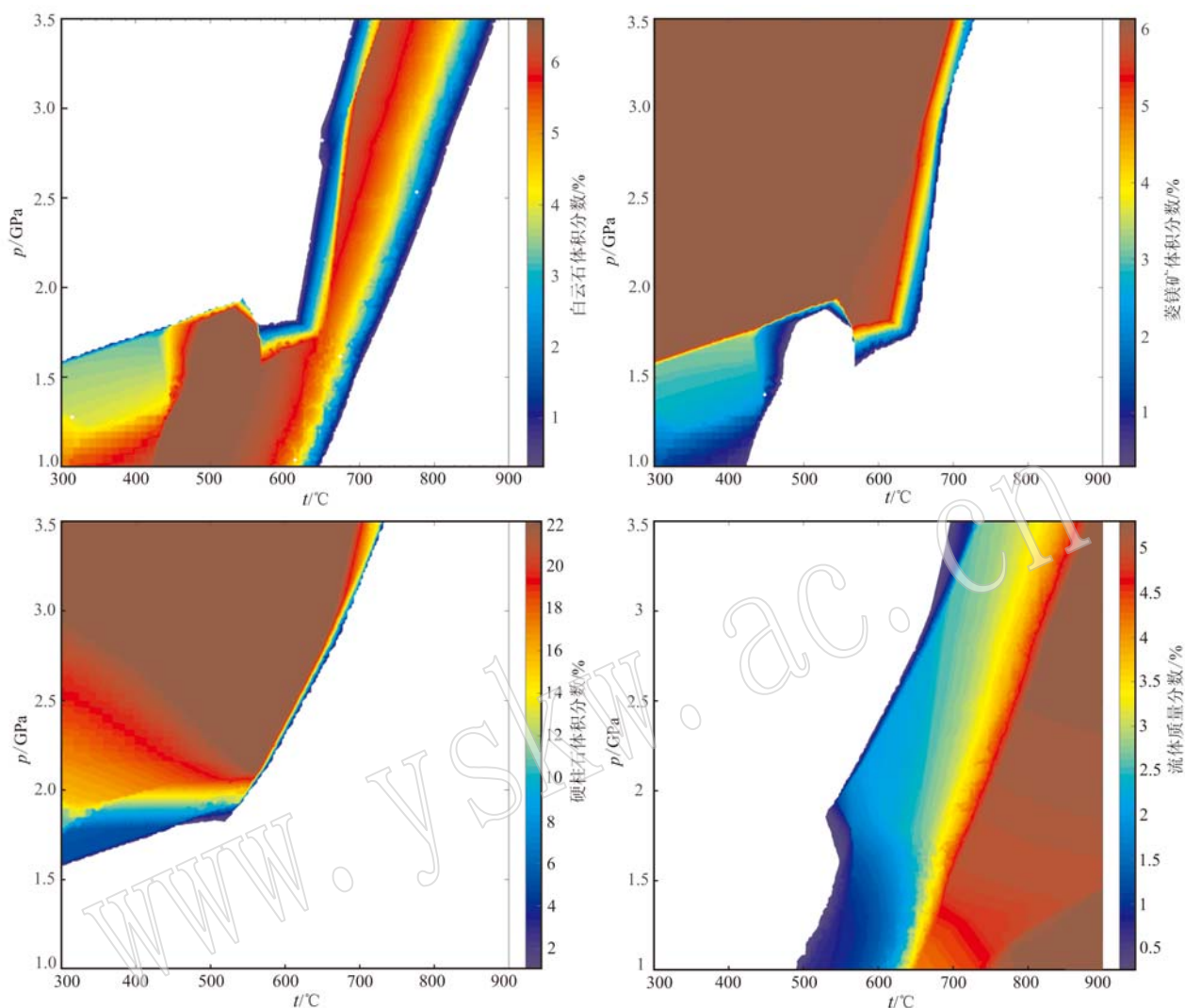
The blue dashed line represents the contour line of iron content [$Mgs_{Fe} = FeO/(FeO + MgO)$] in magnesite; the green dashed line represents the contour line of iron content [$Dol_{Fe} = FeO/(FeO + MgO)$] in dolomite

含量的变化,在不含流体的矿物组合内,体系中水含量的增加会使得白云石分解形成菱镁矿的压力升高;在水饱和情况下,水含量的增加不会影响白云石分解形成菱镁矿的压力。从图5中可以看出,水含量的增加会促进脱碳反应,使白云石和菱镁矿的含量降低。

4 p - $X(FeO)$ 视剖面图

高温高压实验研究表明,Fe可以降低含铁白云石的有序度和稳定性,因此白云石中铁含量的增加

会使得白云石分解形成菱镁矿的压力降低(Hammouda *et al.*, 2010; Franzolin *et al.*, 2012; Tao *et al.*, 2014)。本文探讨了体系中Fe含量对碳酸盐矿物中铁含量的影响以及对白云石分解压力的影响。图6所示为 $t = 500^{\circ}C$ 时的 p - $X(FeO)$ 视剖面图,从中可以看出 $t = 500^{\circ}C$ 时,白云石完全分解消失的压力大约为1.9 GPa,几乎不受体系中 $X(FeO) = FeO/(MgO + FeO)$ 值的影响。对于菱镁矿,当体系中 $X(FeO) = 0.2 \sim 0.32$ 时,菱镁矿形成的压力最低,小于1 GPa;当 $X(FeO) = 0.32 \sim 0.46$ 时,菱镁矿的形成压力随着 $X(FeO)$ 值的降低而降低;当 $X(FeO) = 0.46 \sim 0.8$ 时,菱镁矿的形成压力和 $X(FeO)$

图3 p - t 视剖面图中不同矿物含量随着温度压力变化图Fig. 3 Variation of mineral content with changing p - t conditions in the p - t pseudosection

值的大小无关, 大约为 1.8 GPa。图 6 中绿色虚线代表的是白云石中的铁等值线, 蓝色虚线代表的是菱镁矿的铁等值线。在 $\text{Omp} + \text{Chl} + \text{Ep} + \text{F} + \text{Dol} + \text{Lws}$ 矿物组合内, 白云石的铁等值线 [$\text{Dol}_{\text{Fe}} = \text{FeO}/(\text{MgO} + \text{FeO})$] 主要受压力控制, 随着压力的增加, Dol_{Fe} 值减小; 在其它矿物组合内, Dol_{Fe} 值主要受体系中铁含量的控制, 随着体系 $X(\text{FeO})$ 减小而减小。对于菱镁矿固溶体, 在 $\text{Omp} + \text{Mgs} + \text{Grt} + \text{Lws} + \text{Ep}$ 矿物组合内, 菱镁矿的铁等值线 [$\text{Mgs}_{\text{Fe}} = \text{FeO}/(\text{MgO} + \text{FeO})$] 和压力无关, 主要受体系中铁含量的控制, 随着体系 $X(\text{FeO})$ 减小而减小; 在含有滑石 (Ta) 或者含有 $\text{Chl} + \text{Grt} + \text{Lws}$ 的矿物组合内, 菱镁矿中 Mgs_{Fe} 值主要受控于压力的影响, 随着压力的增加而减小, 受体系中铁含量的影响较小; 在菱镁矿和白云石共

存区域, 菱镁矿中的 Mgs_{Fe} 值随着体系中铁含量的降低而减小。在白云石和菱镁矿共存的区域, 菱镁矿中的 Mgs_{Fe} 值要大于白云石中的 Dol_{Fe} 值, 这可能是由于白云石在分解形成菱镁矿的过程中, 铁更易进入菱镁矿固溶体中。

5 脱挥发分作用

为了追踪蚀变洋壳沿着俯冲板片上部俯冲过程中的脱挥发分作用, 选取了日本 NW 和 SE 俯冲带的地热梯度 (Peacock, 1999), 以及 Syracuse 等 (2010) 模拟的哥斯达黎加 (Costa Rica) 地热梯度, 其中日本 NW 和 SE 地热梯度分别代表俯冲带典型的低温和高温地热梯度, 哥斯达黎加地热梯度是根据全球范

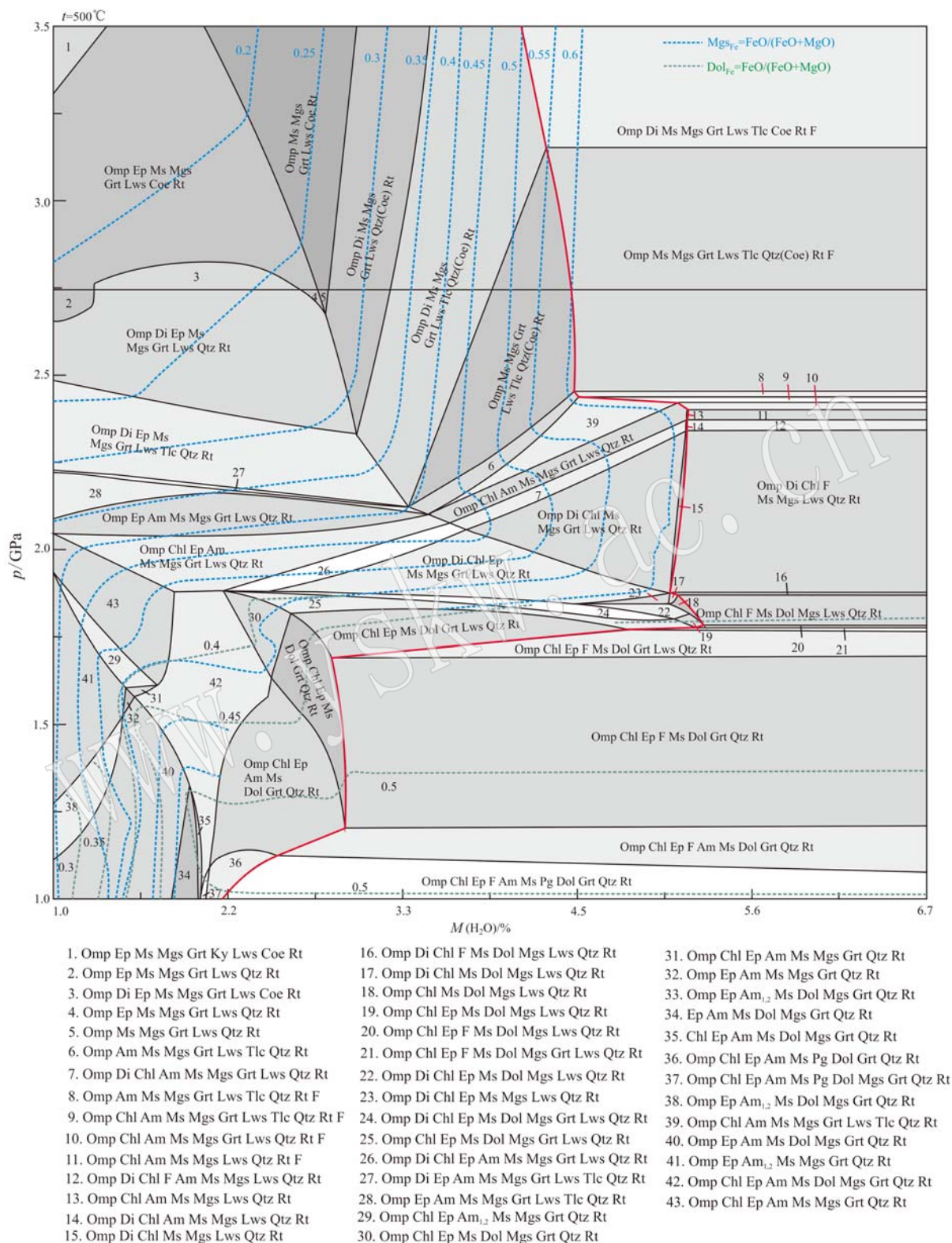


图4 $t = 500^\circ\text{C}$ 时“Super Composite” MORB成分在 NMnCaKFMASHTCHO 体系中的 p - $M(\text{H}_2\text{O})$ 视剖面图

Fig. 4 p - $M(\text{H}_2\text{O})$ pseudosection in the system NMnCaKFMASHTCHO for the “Super Composite” MORB composition calculated at 500°C

图中红色线代表水饱和线;蓝色虚线代表菱铁矿中的铁含量等值线 $\text{Mgs}_{\text{Fe}} = \text{FeO}/(\text{FeO} + \text{MgO})$,绿色虚线代表白云石中的铁含量等值线 $\text{Dol}_{\text{Fe}} = \text{FeO}/(\text{FeO} + \text{MgO})$

The red line represents the water saturation line. The blue dashed line represents the isopleth of iron content [$\text{Mgs}_{\text{Fe}} = \text{FeO}/(\text{FeO} + \text{MgO})$] in magnetite; The green dashed line represents the isopleth of iron content [$\text{Dol}_{\text{Fe}} = \text{FeO}/(\text{FeO} + \text{MgO})$] in dolomite

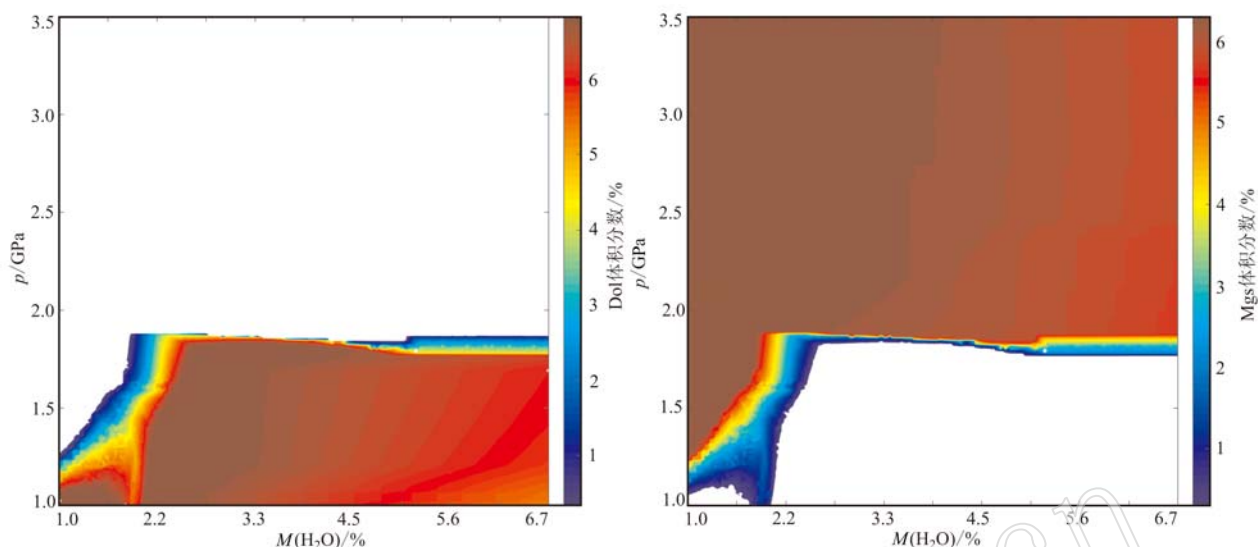


图5 p - $M(\text{H}_2\text{O})$ 视剖面图中白云石和菱镁矿矿物含量(体积分数)随着温度压力的变化图

Fig. 5 Variation of dolomite and magnesite contents with changing p - t conditions in the p - $M(\text{H}_2\text{O})$ pseudosection

围内俯冲带的地热值数据模拟的二维热流模型,可以很好地模拟俯冲带中的热流分布特征。分别计算了在水不饱和以及水饱和条件下变质玄武岩中的 H_2O 和 CO_2 含量等值线,结果如图7a和图7b所示。

在水不饱和条件下(图7a),沿着高温地热梯度线俯冲,在弧前(~ 2.25 GPa, < 80 km)深度,变质玄武岩体系中的水就可全部脱出去;在完全脱水之前,体系中几乎不发生脱碳作用,当板块继续沿着高温地热梯度线俯冲到3.5 GPa压力深度,体系中只有0.5%左右的碳脱出去,大部分碳可以保留在变质玄武岩中被带到更深地幔处。洋壳板片沿着低温地热梯度线以及中温地热梯度线俯冲时,这两条地热梯度线和 H_2O 、 CO_2 等值线平行,当板片俯冲到岛弧深度,体系几乎不发生脱水和脱碳反应。洋壳板片沿着哥斯达黎加地热梯度线(Syracuse *et al.*, 2010)俯冲时,相对于板片沿着高温地热梯度线俯冲,体系发生全部脱水的深度要更深(~ 2.6 GPa);其脱碳作用也很有限,即使俯冲到3.5 GPa压力深度,体系脱碳作用 $< 0.5\%$ 。

在水饱和条件下(图7b),变质玄武岩体系中可以携带5.5%左右的水,这和 p - $M(\text{H}_2\text{O})$ 视剖面图计算结果相似(图4)。当洋壳板片沿着高温地热梯度线俯冲,在 $p < 1$ GPa时,变质玄武岩体系便脱去了一半的水含量,当俯冲到 ~ 2.25 GPa压力深度时,体系发生全部脱水作用,这和水不饱和体系发生全部脱水的深度一致。在水饱和和体系中,当洋壳板片

俯冲到1.8 GPa压力深度便开始发生脱碳作用,当俯冲到3 GPa压力深度时,体系中的碳几乎可以全部脱出去。当洋壳板片沿着低温地热梯度线俯冲时,只发生少量的脱水作用,几乎不发生脱碳作用。当洋壳板片沿着中温地热梯度线俯冲到3.5 GPa压力深度时,体系中有一半的水可以脱出去,但几乎不发生脱碳作用。当洋壳板片沿着哥斯达黎加地热梯度线俯冲时,变质玄武岩脱水集中在2.5 GPa压力深度,脱碳作用发生在完全脱水作用之后,当俯冲到3.5 GPa压力深度,体系中的碳几乎可以全部脱出去。

6 讨论

6.1 俯冲作用过程蚀变玄武岩中碳酸盐矿物的演化

洋底热液蚀变过程可以使大量陆源以及海水的碳固定在玄武岩中(Staudigel, 2003; Coggon and Teagle, 2011)。现代大洋钻探岩芯数据表明,蚀变洋壳中的碳酸盐矿物主要为钙质碳酸盐(CaCO_3)(Staudigel and Hart, 1983; Staudigel *et al.*, 1989; Alt and Teagle, 1999; Coggon and Teagle, 2011)。相平衡模拟计算表明,在俯冲变质作用过程中,随着压力的升高,蚀变洋壳中的钙质碳酸盐会发生方解石/文石-白云石-菱镁矿的转变。Molina等(2000)模拟了玄武岩在含有 H_2O - CO_2 体系中的高温高压实验,实验结果表明在 $p < 1.4$ GPa时,碳酸盐矿物主要为方解石;当 $1.4\text{ GPa} < p < 1.8\text{ GPa}$ 时,碳酸盐矿物

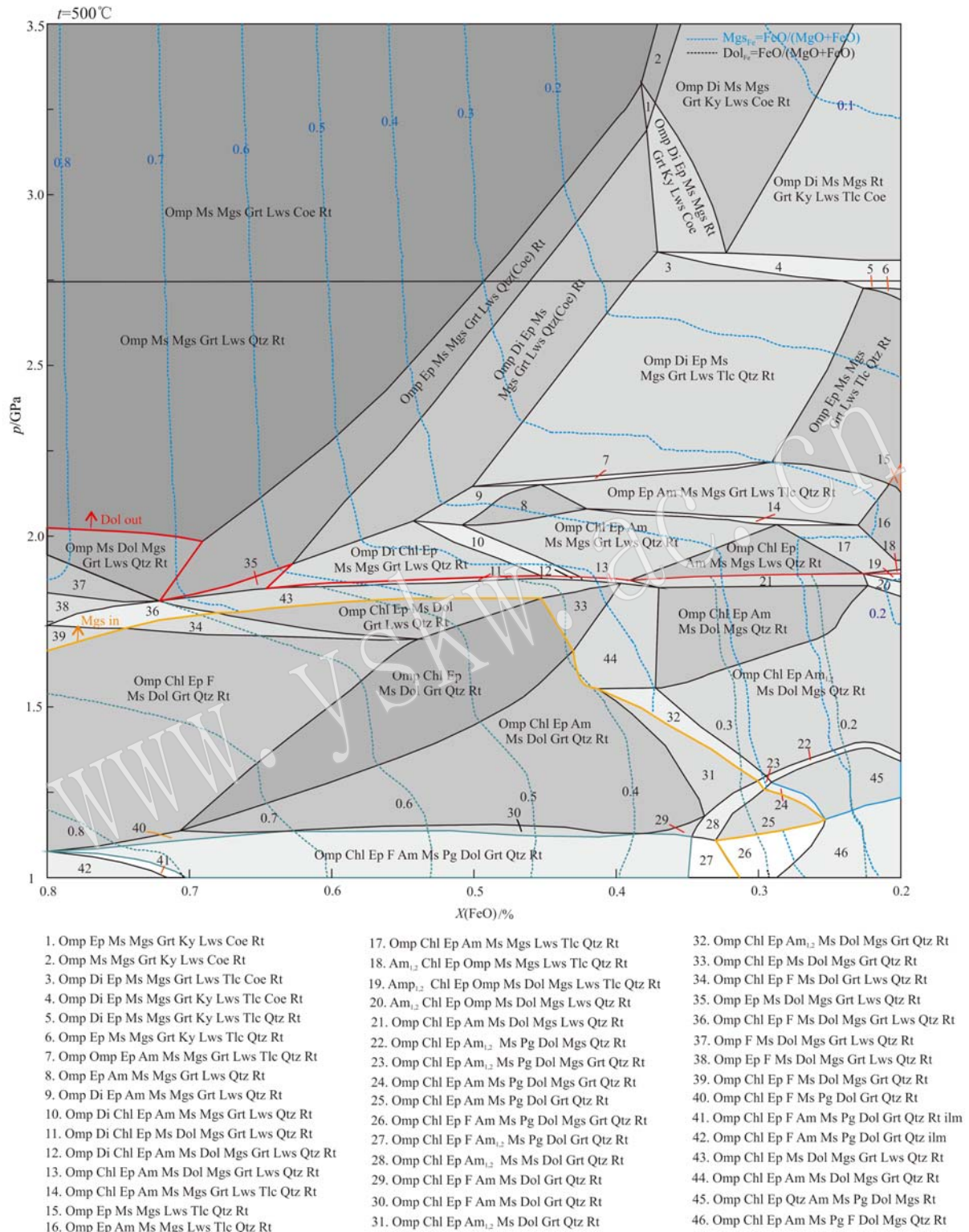
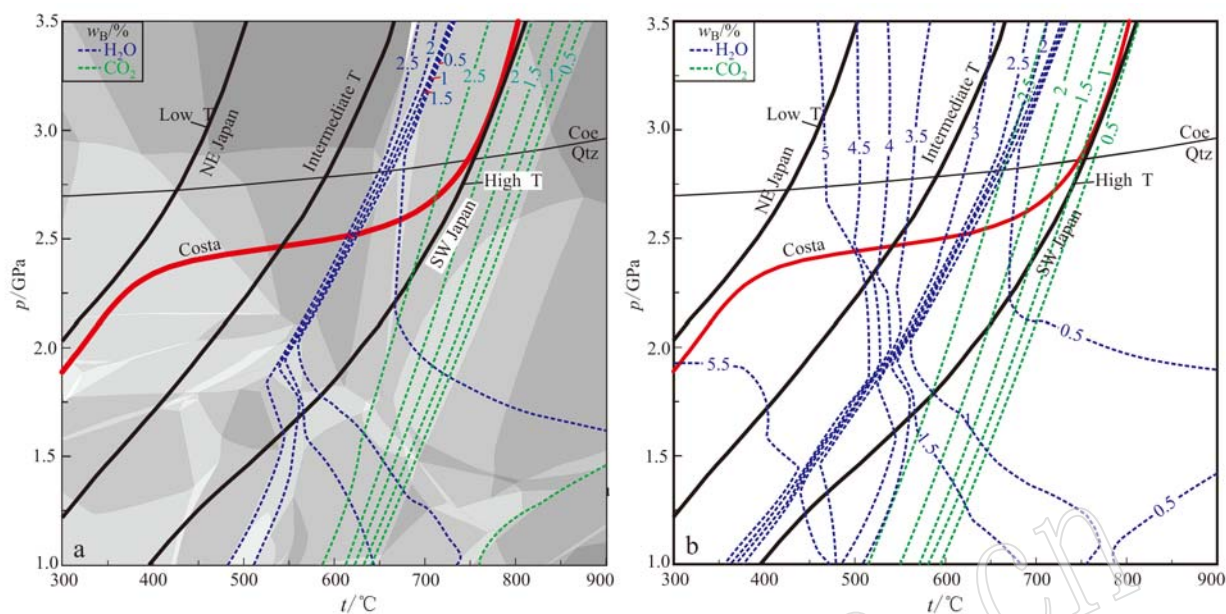


图6 $t = 500^\circ\text{C}$ 时“Super Composite”MORB成分在NMnCaKFMASHTCHO体系中的 p - $X(\text{FeO})$ 视剖面图

Fig. 6 p - $X(\text{FeO})$ pseudosection in the system NMnCaKFMASHTCHO for the “Super Composite” MORB composition calculated at 500°C

其中红色线代表白云石完全分解的压力线,黄色代表菱镁矿形成的压力线;蓝色虚线代表菱镁矿中的铁含量等值线 $\text{Mgs}_{\text{Fe}} = \text{FeO}/(\text{FeO} + \text{MgO})$,绿色虚线代表白云石中的铁含量等值线 $\text{Dol}_{\text{Fe}} = \text{FeO}/(\text{FeO} + \text{MgO})$

Red line represents the complete decomposition pressure of dolomite, yellow line represents the formation pressure of magnesite. The blue dashed line represents the isopleth of iron content [$\text{Mgs}_{\text{Fe}} = \text{FeO}/(\text{FeO} + \text{MgO})$] in magnesite; the green dashed line represents the isopleth of iron content [$\text{Dol}_{\text{Fe}} = \text{FeO}/(\text{FeO} + \text{MgO})$] in dolomite

图7 变质玄武岩体系中 CO_2 和 H_2O 含量Fig. 7 Weight percentages of CO_2 and H_2O in metabasalt

a—水不饱和变质玄武岩体系(“Super Composite”MORB)中 H_2O 和 CO_2 质量百分比,该体系中初始水含量为 2.68% (据 Staudigel *et al.*, 1989),水不饱和(据图4计算);b—水饱和变质玄武岩体系中 H_2O 和 CO_2 质量百分比,该体系中的初始水含量设定为 7%,水饱和(据图4计算);红黑粗实线为地热梯度线

a—weight percentages of CO_2 and H_2O in water unsaturated metabasalt system (“Super Composite” MORB). The initial water content of this system is 2.68% (after Staudigel *et al.*, 1989), which is water unsaturated according to the calculation in Fig. 4; b—weight percentages of CO_2 and H_2O in water saturated metabasalt system. The initial water content in this system is set at 7%, which is water saturated according to the calculation in Fig. 4;

Thick black and red curved lines are geotherms

主要为白云石;当 $p > 1.8 \text{ GPa}$ 时,白云石开始分解形成菱镁矿。本文中相平衡模拟表明,变质玄武岩体系中的碳酸盐矿物之间的转变反应除了受压力控制之外,还受到温度和体系中铁含量的影响。温度的升高可以提高白云石的压力稳定域,如图1所示,当 $t > 610^\circ\text{C}$,白云石的压力稳定域和温度成正比,其压力稳定域最高可以大于 3.5 GPa 。在高温条件下,白云石比菱镁矿稳定,压力的升高不会使白云石转变成菱镁矿;而且在超高压条件下,升高温度可以使菱镁矿转变成白云石。菱镁矿的稳定温度较低,在 $p \leq 3.5 \text{ GPa}$ 条件下,其稳定温度小于 730°C 。当 $t < 425^\circ\text{C}$ 时,菱镁矿形成的压力小于 1 GPa 。

Li 等(2014)对西南天山碳酸岩化榴辉岩中碳酸盐矿物研究表明,白云石中铁等值线和石榴子石中的端员组分等值线类似,可以反映温度压力的变化,白云石中的 X_{Fe} 值从核部到边部逐渐减小反映了进变质作用过程。这和本文在低温下的模拟结果相似,在低温条件下($t < 700^\circ\text{C}$),白云石和菱镁矿中

X_{Fe} 值随着温度压力的升高而升高(图2)。然而在高温条件下, $t > 700^\circ\text{C}$,白云石中的 X_{Fe} 值受温度影响很小。此外,碳酸盐矿物中的铁含量还受到体系中铁含量的影响,白云石和菱镁矿中的铁含量随着体系中铁含量的增加而增加(图6)。当白云石和菱镁矿共存时,体系中的铁更容易进入菱镁矿中。

6.2 俯冲带脱挥发分作用探讨

俯冲带脱挥发分作用和俯冲带岩浆活动以及地震活动之间存在成因关系(Bebout, 1996; Hacker *et al.*, 2003; Hirschmann, 2006; Grove *et al.*, 2012; Zheng *et al.*, 2016)。俯冲带变质玄武岩的脱水作用被认为是俯冲带地震的重要诱因(Peacock, 1999)。在 SW 日本俯冲带(高温地热梯度),板片内地震作用发生在 $50 \sim 65 \text{ km}$ 处;然而在 NE 日本俯冲带(低温地热梯度),板片内地震作用发生在 $125 \sim 200 \text{ km}$ 深度。这和我们的计算结果一致,对蚀变玄武岩相平衡模拟表明,不论是水不饱和体系还是水饱和体系,沿着高温地热梯度俯冲,在 $5 \sim 65 \text{ km}$ 深

度时,体系将发生大量的脱水作用,当达到 74 km (2.25 GPa)时(图7),体系中的水将会全部脱出去。然而当板片沿着低温地热梯度俯冲时,不论是水饱和体系还是水不饱和体系,俯冲到 100 km (3 GPa) (图7)时,体系也几乎不发生脱水作用,因此沿着冷俯冲地热梯度线,板片可以将水带入地幔更深处,在地幔深部脱水诱发地震。

进入俯冲带中的碳主要通过火山作用或去气作用释放返回地表(Hayes and Waldbauer, 2006; Dasgupta and Hirschmann, 2010; Bebout *et al.*, 2013; Burton *et al.*, 2013; Dasgupta, 2013)。Kerrick 等(2001)对洋壳玄武岩相平衡模拟计算表明,当洋壳板片沿着低温以及中温地热梯度线俯冲时,在岛弧深度变质玄武岩几乎不发生脱碳反应,即使沿着高温地热梯度线俯冲也只发生少量的脱碳反应。本文对蚀变洋壳玄武岩(“Super Composite”MORB, 水不饱和)相平衡模拟也表明,当洋壳板片沿着低温以及中温地热梯度线俯冲时,在岛弧深度蚀变洋壳玄武岩体系几乎不发生脱碳反应;沿着高温地热梯度线以及哥斯达黎加地热梯度线俯冲时,只有很少量的碳脱出去。在水饱和体系条件下,沿着低温及中温地热梯度线,在岛弧深度蚀变洋壳玄武岩体系仍然几乎不发生脱碳反应;但是当洋壳板片沿着哥斯达黎加以及高温地热梯度线俯冲时,在岛弧深度,洋壳玄武岩中的碳几乎可以全部脱出体系。因此,本文认为俯冲板片的脱碳作用除了受到俯冲地热梯度线控制外,还和体系的水含量有很大的关系,水含量的增加可以促进脱碳反应作用。然而,对于冷俯冲作用,即使俯冲板片体系中有大量的水,也很难促进脱碳反应的进行,因此,俯冲脱碳还受其它机制的控制,如溶解脱碳作用(Frezzotti *et al.*, 2011; Ague and Nicolescu, 2014)、熔融脱碳作用(Poli, 2015; Skora *et al.*, 2015)。体系中水含量的增加对这些脱碳作用都具有促进作用。

7 结论

(1) 随着压力的升高蚀变玄武岩中碳酸盐矿物会发生方解石/文石-白云石-菱镁矿的转变,但在高压/超高压条件下,温度的升高可以使菱镁矿转变成白云石。

(2) 碳酸盐矿物中的铁含量受到体系中铁含量的影响,白云石和菱镁矿中的铁含量随着体系中铁

含量的增加而增加。当白云石和菱镁矿共存时,体系中的铁更容易进入菱镁矿中。

(3) 在水不饱和条件下,洋壳不管是沿着低温还是高温地热梯度线俯冲到岛弧深度,蚀变玄武岩体系几乎都不发生脱碳作用。然而在水饱和条件下,当洋壳沿着高温以及哥斯达黎加地热梯度线俯冲到岛弧深度时,蚀变玄武岩体系中的碳几乎可以全部脱出去。蚀变玄武岩体系中水含量的增加可以促进体系的脱碳作用。

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