热烈庆祝中国地质学会成立100周年
1922～2022
www.
geojournals.cn/georev

Mg同位素示踪中国东部中生代深部碳循环

段先哲[1,2)]，牛苏娟[1)]，李赛[1)]，李南[2)]，孙浩然[1)]，郭聪[1)]，
肖文舟[1,2)]，隋清霖[1,2)]，冯鹏[1,2)]，贺海洋[1,2)]

1)南华大学资源环境与安全工程学院，湖南衡阳，421001；
2)稀有金属矿产开发与废物地质处置技术湖南省重点实验室，湖南衡阳，421001

内容提要：地球深部碳循环对全球气候变化、生命探索和岩石圈演化的研究具有重要意义。中国东部岩石圈是地球深部碳循环的重要场所，其减薄和破坏与深部碳循环密切相关。中生代太平洋板块俯冲是制约中国东部岩石圈减薄和破坏的关键，对华北克拉通和华南板块的大规模金属成矿作用具有重要作用。笔者等系统阐述了Mg示踪地球深部碳循环原理，例举了镁同位素示踪中国东部深部碳循环的实例，论述了中生代俯冲的古太平洋板块所释放的碳酸盐熔体/流体与地幔相互作用，是造成中国东部地幔具有普遍的轻Mg同位素组成的重要原因。此外，指出轻镁同位素的多解性，提出多同位素联合示踪是未来研究地球深部碳循环的趋势。

关键词：深部碳循环；中生代；中国东部岩石圈；Mg同位素；岩石圈减薄与破坏；古太平洋板块俯冲

碳循环分为大气圈、水圈、生物圈和土壤圈之间的短周期地球表层碳循环和表层—深部系统之间的长周期碳循环。地球表层碳约占地球总碳量的10%，主要赋存于沉积碳酸盐、硅质页岩及油页岩中(Falkowski et al.，2000)，而地球深部碳储量占地球总碳量的90%以上(Dasgupta and Hirschmann，2010；Yang Wei et al.，2012)，强烈影响着深部地幔的组成和结构。

地表碳(包含有机碳和无机碳)通过板片深俯冲作用进入地球深部系统，其中部分碳伴随着岛弧火山脱气作用携至地表，其他大部分残余碳稳定地滞留在深部地幔中，这一过程构成了深部碳循环(Zhang and Liou，1994；Zhu Yongfeng and Ogasawara，2002；Dasgupta et al.，2004；Yaxley and Brey，2004；Kawamoto，2006；Poli et al.，2009；Keshav and Gudfinnsson，2010；张立飞等，2017；Plank et al.，2019；Hilton et al.，2020；Wu Hailin et al.，2022)。地球深部碳循环的研究对全球气候变化、生命探索和地幔演化机制具有重要意义(Hoffman and Nehrkorn，2009；Hyde et al.，2000；Hoffman and Schrag，2002；Armstrong et al.，2019；Manthilake et al.，2021)。

中国东部岩石圈自古生代以来发生了减薄和破坏，从太古代厚的(>200 km)、冷的、难熔型的古老地幔转变为新生代薄的(<80 km)、热的、饱满型的新生地幔，中生代是其减薄和破坏的关键时期；中国东部岩石圈这种减薄和破坏机制可能与华北和华南中生代众多大规模金属矿床的形成有着密切的联系，因而受到了国内外学者的广泛关注(Fan Weiming and Menzies，1992；Griffin et al.，1998；Xu Yigang et al.，2002；Wu Fuyuan et al.，2003；Zhang Hongfu et al.，2003；Rudnick et al.，2004；Zheng Jianping et al.，2004；Niu Yaoling，2005；Liu Yongsheng et al.，2005；李曙光，2015，2017；Li Shuguang and Wang Yang，2018；Liu Jin et al.，2020；Duan Xianzhe et al.，2020；Chang Zeguang et al.，2021；Ji Zheng et al.，2021；Wang Chen et al.，2021；Sun Pu et al.，2021)。

中国东部岩石圈是深部碳循环的重要场所，它的减薄和破坏与地球深部碳循环密切相关，反映了

注：本文为国家自然科学基金资助项目(编号：42102060，42003028)、创新项目(编号：202110555075)和南华大学人才资助项目(编号：2018XQD22)的成果。
收稿日期：2022-01-22；改回日期：2022-05-02；网络首发：2022-06-20；责任编辑：刘志强。Doi：10.16509/j.georeview.2022.06.001
作者简介：段先哲，男，1985年生，博士，副教授，主要从事岩石/矿床地球化学等方面研究；Email：duanxianzhe@126.com。

深部碳循环的地球动力学效应(Huang Jian et al., 2015a; Li Shuguang et al., 2017;李曙光和汪洋, 2018)。因此,研究中国东部中生代深部碳循环对于制约中国东部岩石圈减薄和破坏机制有着重要意义。然而,对于中国东部岩石圈破坏机制和减薄机理、深部碳的赋存形式和储量、板块俯冲作用的参与程度、岩石圈破坏的范围和程度等仍然存在较大的争议(Follett et al., 2014; Liu Dong et al., 2015; Tappe et al., 2017; 陈春飞, 2018; 刘勇胜等, 2019; 沈骥等, 2019; 汤艳杰和张宏福, 2019)。

近年来,岩石地球化学和同位素示踪研究在识别中国东部岩石圈物质组成方面取得了重大进展(Huang Fang et al., 2011; 李曙光, 2015, 2017; Huang Jian et al., 2016a, d; Li Shuguang et al., 2017; 宗克清和刘勇胜,2018; Tian Hengci et al., 2018; Wang Xiaojun et al., 2018)。前人依次通过模拟计算、实验及两者结合的方式得到一些研究成果。随着非传统稳定金属同位素的发展,发现其示踪碳酸盐金属离子与地幔存在明显差异,这对研究深部碳循环有重要意义。Mg 同位素是理想的示踪深部碳循环工具,其分馏作用在早期太阳系演化、变质岩和地幔岩的平衡温度、大陆风化、植物生长、酶合成和古气候演变等诸多科学问题上发挥了制约作用。笔者等系统阐述了镁同位素示踪再循环碳酸盐对中国东部中生代深部碳循环形成制约,论述了中国东部岩石圈减薄和破坏与深部碳循环的动力学效应及中国东部岩石圈 Mg 同位素研究进展,以期为中国东部岩石圈减薄与破坏机制的进一步研究提供参考和依据。

1 同位素示踪

地表和深部“碳的命运”是关注的热点课题。近年来,众多学者通过同位素示踪的方法对俯冲碳的循环进行研究。

1.1 C/Ca 同位素

碳同位素被广泛应用于研究深碳循环,碳同位素可以有效区分有机碳 OC(δ^{13}C 值小于−15‰)和无机碳 IC(δ^{13}C 值大于−10‰; Deines, 2002; Cartigny, 2005),约 95%的火山作用释放的大部分都是无机碳(例如壳源碳、板块俯冲再循环碳酸盐和地幔原生碳),而碳同位素示踪无机碳无效,并且在岩浆去气过程中会发生显著分馏(Javoy et al., 1982;Mattey, 1991; Graham et al., 2018)。前人提出二价金属同位素(Ca, Mg)受去气分馏作用影响较小,Ca 同位素在示踪过程中也显示出极大潜力(Huang Shichun et al., 2010, 2011; Kang Jinting et al., 2016; Zhao Xinmiao et al., 2017; Zhu Hongli et al., 2018)。例如,Huang Shichun 等(2011)观察到一些夏威夷玄武岩的 $\delta^{44/40}$Ca 与 ^{87}Sr/^{86}Sr 成负相关,认为地幔遭受了古老沉积碳酸盐的俯冲。而 Ionov 等(2019)认为 $\delta^{44/40}$Ca 值并不能简单归因于再循环碳酸盐,西伯利亚克拉通含交代方解石的地幔包体研究发现其与饱满地幔同位素组成几乎没有差别($\delta^{44/40}$Ca = 0.81‰~0.83‰)。在高精度同位素测试方面,质谱测量过程中^{40}Ar 强烈干扰且^{40}Ca 和^{42}Ca(或^{44}Ca)同位素丰度存在很大差异,因此 Ca 同位素示踪对象要有选择性。目前采用的同位素示踪方法的有 Ca、Zn、Mg、Li 等同位素结合示踪,也取得了相关成果,本文主要叙述关于 Mg 同位素的相关内容。

1.2 Mg 同位素

镁是宇宙中第九丰富和地球上第四丰富的元素,广泛分布于碳酸盐和硅酸盐矿物中。>99.9%镁分布在地幔橄榄石和辉石中,0.031%主要赋存在地壳辉石和橄榄石中,总体上从地幔到洋壳,镁的含量是逐渐降低的,水圈中镁<0.001‰(Liu Fang et al., 2017a)。镁作为主量元素,有^{24}Mg、^{25}Mg 和^{26}Mg 3 个稳定同位素,在自然界中丰度分别是 78.99%、10.00%和 11.01%,^{24}Mg 和^{26}Mg 之间的相对质量差高达 8%,巨大的质量差使其足以在地质过程中发生显著的质量分馏,这也是镁同位素成为理想地质示踪剂的条件之一。相比 Ca 同位素而言,海相碳酸盐岩和地幔之间的 Mg 同位素组成差值可达 5‰,同位素测试方法更加简洁、高效。因此,Mg 同位素是迄今深部碳循环应用最广泛的示踪剂。

δ^{26}Mg、δ^{25}Mg 计算公式(Galy et al., 2001)如下:

$$\delta^{26}\mathrm{Mg}=\left\{\frac{[n(^{26}\mathrm{Mg})/n(^{24}\mathrm{Mg})]_{\mathrm{sample}}}{[n(^{26}\mathrm{Mg})/n(^{24}\mathrm{Mg})]_{\mathrm{DSM\text{-}3}}}-1\right\}\times1000‰$$

$$\delta^{25}\mathrm{Mg}=\left\{\frac{[n(^{25}\mathrm{Mg})/n(^{24}\mathrm{Mg})]_{\mathrm{sample}}}{[n(^{25}\mathrm{Mg})/n(^{24}\mathrm{Mg})]_{\mathrm{DSM\text{-}3}}}-1\right\}\times1000‰$$

DSM-3 为标样。

1.3 表生过程中的 Mg 同位素组成

表生圈层(水圈、洋/陆壳)Mg 同位素组成差异明显(δ^{26}Mg= −5.5‰ ~ +1.8‰)(Teng Fangzhen, 2017)。Teng Fangzhen 等(2010b)对美国南卡的辉绿岩岩墙的风化剖面进行了研究,发现随着剖面深度越接近地表岩石,其风化程度越强,风化残余物越

富集重 Mg 同位素组成，轻 Mg 同位素优先释放到了海洋中。海水有均一的镁同位素组成，其 δ^{26}Mg 平均值为 −0.83‰ ± 0.07‰（2SD，n = 25）（Ling Mingxing et al.，2011；孙剑等，2012）。大部分海水是由流经地表经大陆风化作用的河水和洋壳经海水蚀变溶解的（Tipper et al.，2006b；Brenot et al.，2008），不同经纬度和深度的海水与其盐度和温度无关（Foster et al.，2010；Ling Mingxing et al.，2011）。河流水作为海水的一个主要来源，其 δ^{26}Mg 平均值是−1.1‰，具有比海水更轻的镁同位素组成（Tipper et al.，2006a；何学贤等，2008）。控制河流水的镁同位素组成因素之一是基岩种类，流经硅酸岩河水相比原始硅酸岩更富集轻 Mg 同位素（Tipper，2006a；高庭，2016），而流经碳酸盐河流水（δ^{26}Mg = −1.7‰ ~ −1.37‰）比流经硅酸盐河流水（δ^{26}Mg = −1.1‰ ~ −0.77‰）具有更低的 δ^{26}Mg 值（Brenot et al.，2008），这与碳酸盐 δ^{26}Mg 值较低是相一致的。Teng Fangzhen 等（2016）对海洋沉积物（Site 144 和 Site 543）的 Mg 同位素组成（δ^{26}Mg = −0.76‰~ +0.52‰）开展研究，发现富含碳酸盐岩（Site 144）有更轻的镁同位素组成。Wang Shuijiong 等（2015a）对英国湖区开展研究，发现含碳酸盐岩的南部的 Mg 同位素组成低于不含碳酸盐岩的北部，有残留相的南部湖区和北部有一致的 Mg 同位素组成（较重 Mg 同位素），若玄武岩源区中有再循环碳酸盐混入，δ^{26}Mg 值与 Mg/Al、CaO/Al_2O_3 和 CaO/TiO_2 呈负相关性（Wang Shuijiong et al.，2015a）。

1.4　地幔中的 Mg 同位素组成

地幔具有均一的 Mg 同位素组成（δ^{26}Mg ≈ −0.25‰，平均值与球粒陨石（δ^{26}Mg = −0.28 ± 0.06‰）相似（Teng Fangzhen et al.，2010a）。全球分布的洋中脊玄武岩（MORB）、洋岛玄武岩（OIB）和大陆玄武岩的 Mg 同位素组成有均一性（δ^{26}Mg = −0.23±0.19‰，柯珊等，2011）。

地幔 Mg 同位素组成（δ^{26}Mg ≈ −0.25±0.07‰，Teng Fangzhen et al.，2010a）与沉积碳酸盐岩的 Mg 同位素组成（δ^{26}Mg = −5.31‰ ~ −1.09‰，Young and Galy，2004；Tipper et al.，2006a；Brenot et al.，2008；Hippler et al.，2009）存在明显差异，因而幔源岩浆岩的轻镁同位素特征可以指示沉积碳酸盐。例如，中国东部白垩纪到第四纪时期的玄武岩具有轻 Mg 同位素和低 ^{87}Sr/^{86}Sr 值，表明是沉积碳酸盐岩与地幔相互作用的结果（Yang Wei et al.，2012）。

1.5　板块俯冲过程中的 Mg 同位素组成

俯冲沉积物中的沉积碳酸盐是碳主要的存在形式。大洋板块从形成到运送至俯冲带期间与海水相互作用产生沉积物，新鲜的大洋玄武岩和橄榄岩发生蚀变，蚀变洋壳中大部分碳酸盐并不会在俯冲脱水过程中被释放，而是被携带到地幔深部，从而显著改变地幔的物理化学性质（如固相线，地震波速，密度等）（Alt and Teagle，1999；Thomson et al.，2016）。

Wang Shuijiong 等（2012）和 Wang Xuance 等（2015b）报道了南非和西非克拉通金伯利岩中榴辉岩（CO_2 含量并不高）具有低 δ^{26}Mg 值（可到 −1.38‰），认为这些俯冲进入地幔的榴辉岩的低 δ^{26}Mg 值特征可能继承了蚀变洋壳的特征，也可能是在俯冲过程中与沉积碳酸盐岩发生同位素交换反应的结果；Huang Jian 等（2016a）同样在榴辉岩的研究中也认为板块俯冲变质脱水过程不导致显著的 Mg 活动和分馏；Wang Shuijiong 等（2014a）研究了新元古代扬子板块北缘和大别山造山带不同变质程度（变质程度由浅到深分别为绿片岩、斜长角闪岩和榴辉岩）和原岩（玄武质变质岩），得出随着变质程度的加深，MgO 和 Mg 同位素含量无变化，岩石含水量下降，板块俯冲变质脱水过程不发生显著的 Mg 同位素分馏；Wang Shuijiong 等（2014b）考察研究了苏鲁超高压变质带的荣成 UHP 大理岩及其包裹的碳酸盐化榴辉岩，发现普通榴辉岩与其原岩的 δ^{26}Mg 与地幔值（δ^{26}Mg = −0.25 ± 0.07‰）一致，但包裹在大理岩中的碳酸盐化榴辉岩有更低的 δ^{26}Mg 值（δ^{26}Mg = −0.6 ~ −1.9‰）。Huang Jian 等（2015b）发现东太平洋洋脊钻探 1256D 岩芯样品与地幔有相似的 Mg 同位素组成，表明蚀变玄武岩与新鲜玄武岩有相似的 Mg 同位素组成。

值得指出的是，深海橄榄岩发生蛇纹石化蚀变（t=200℃），其 Mg 同位素为一般地幔组成。当深海橄榄岩发生更低温的海底风化作用时，轻 Mg 同位素被海水带走，导致深海橄榄岩富集较重的 Mg 同位素组成（Liu Xin et al.，2017b）。蚀变深海橄榄岩脱水可产生富 MgO 和具有较重的 Mg 同位素组成流体（Teng Fangzhen et al.，2016）。

1.6　地幔部分熔融和岩浆过程中的 Mg 同位素组成

碳酸盐岩被俯冲到地幔深处并且在俯冲过程中可能经历了脱气反应或者部分熔融过程（Wyllie，1989；Wallace and Green，1998；Hammouda，2003；

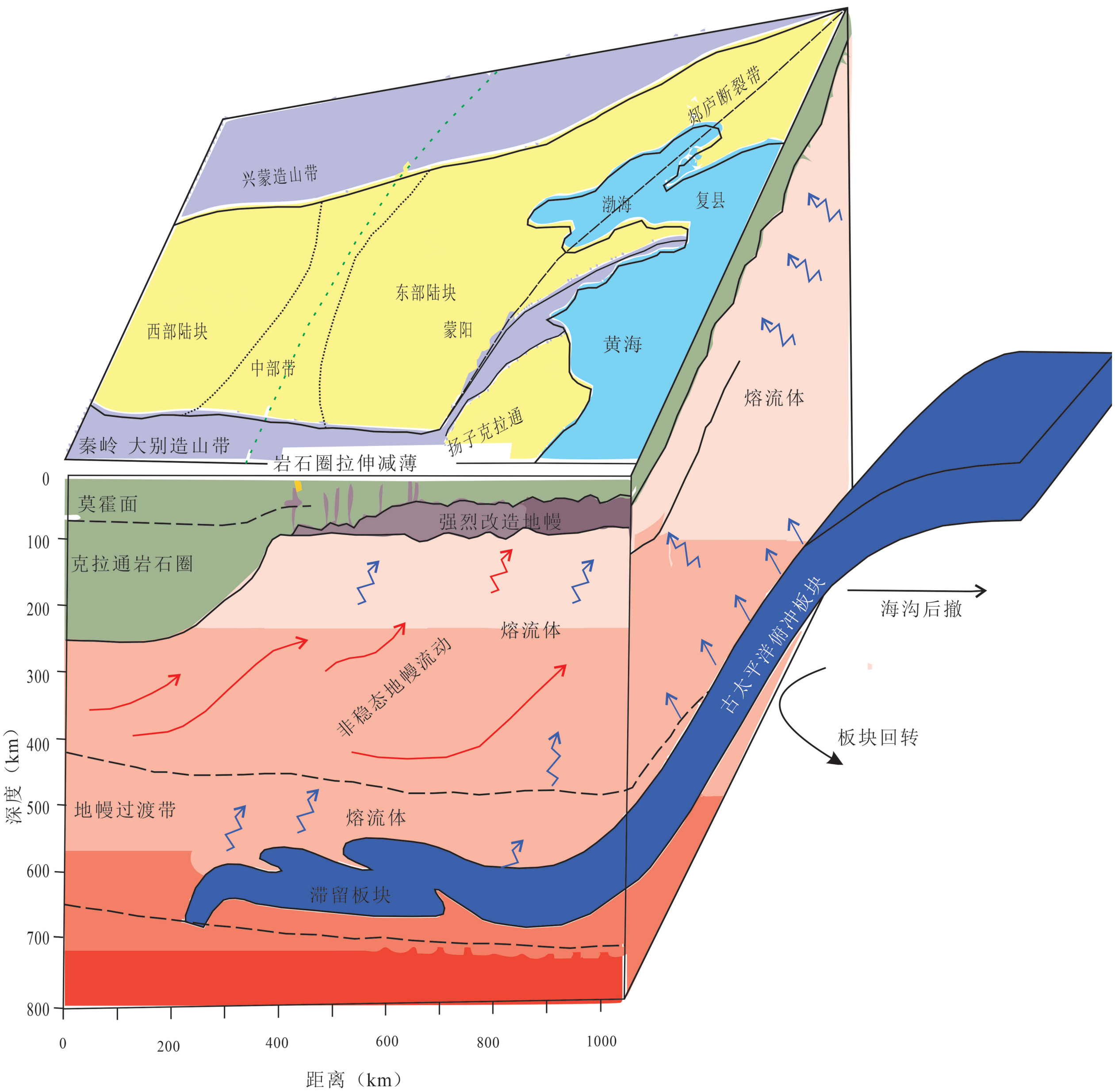

图 1 中生代中国东部岩石圈地幔改造与古太平洋板块俯冲示意图(改自汤艳杰,2021)

Fig. 1 Schematic diagram of the transformation of the lithospheric mantle beneath Eastern China and the subduction of the paleo-Pacific Plate in the Mesozoic(modified from Tang Yanjie, 2021&)

Ducea et al., 2005; Doucelance et al., 2014; Collins et al., 2015; Zhong Yuan et al., 2017; 陈春飞, 2018)。在地幔部分熔融、中—基性岩浆分异和变质过程中 Mg 同位素几乎不分馏(Teng Fangzhen et al., 2007;朱祥坤等,2013),未遭受陆壳混染的玄武质岩浆同位素组成可直接代表其地幔源区的同位素组成(Teng Fangzhen et al., 2007; Handler et al., 2009; Bourdon et al., 2010; Liu Sheng'ao et al., 2010; Teng Fangzhen et al., 2010b; Huang Fang, 2011; Philip et al., 2011; Yang Wei et al., 2012)。

中国东部岩石圈在遭受板块俯冲过程中会发生部分熔融,中高温的深部地幔会向较低温的浅部上涌减压产生玄武质岩浆,但并不产生显著的 Mg 同位素分馏。玄武岩和地幔橄榄岩(δ^{26}Mg ≈ −0.25‰)的 Mg 同位素组成有均一性和相似性,接近球粒陨石的平均值(δ^{26}Mg = −0.28 ± 0.06‰; Teng Fangzhen et al., 2010a)。Liu Sheng'ao 等(2011)发现花岗岩全岩和单矿物的 Mg 同位素组成

(δ^{26}Mg = −0.21 ± 0.07‰)与地幔在误差范围内一致,富 Mg 矿物的分离结晶作用也不会导致显著 Mg 同位素分馏(Liu Sheng'ao et al., 2011; 柯珊等, 2011)。

2　中国东部岩石圈减薄与深部碳循环

中国东部主要由华南板块、华北克拉通和中国东北(即兴蒙地块)组成,其性质和厚度发生了强烈改变,是国内外学者研究的热门课题(图 1)。古生代,华北克拉通有典型的克拉通型岩石圈地幔特征,主要成分是难熔的方辉橄榄岩,岩石圈厚度为 200 km(郑建平和路凤香, 1999; Zheng Jianping et al., 2001; Zhang Hongfu et al., 2008; 吴福元等, 2008; Tang Yanjie et al., 2013)。中生代,华北克拉通和华南板块发生了大范围的岩浆活动和地壳形变,其稳定性遭受了不同程度破坏(郭锋等, 1997, 1998; Fan Weiming et al., 2000; Zheng Jianping et al., 2001; Li Xianhua et al., 2004; Wang Yuejun et al., 2008; 朱日祥等, 2012; Liu Chuanzhou et al., 2012)。新生代,华北克拉通和华南板块岩石圈厚度是 60 ~ 80 km,岩石圈地幔在物质组成和性质上具有类似大洋型较年轻的地幔特征,由主量元素饱满、Sr—Nd 同位素组成亏损的二辉橄榄岩组成(Fan Weiming and Menzies, 1992; Menzies et al., 1993; 汤艳杰等, 2019; Fan Weiming et al., 2000)。

关于减薄峰期大体分两个阶段,第一个减薄峰期是中生代中—晚期,这一阶段华北克拉通与整个东部岩石圈的剧烈破坏一致(Gao Shan et al., 2008; Meng Fanxue et al., 2015)。另一个减薄高峰是新生代晚期(25 Ma 后),岩石圈厚度继续减薄到至今约 70 km(Xu Yigang et al., 2004; Zhang Hongfu, 2005; Zheng Jianping et al., 2007)。对于减薄,李曙光(2015)认为应该要把再循环碳酸盐对地幔固相线的影响作为一个考虑因素。

中国东部岩石圈物理化学性质的强烈改变可能诱发了燕山期广泛的多金属矿化,形成了大规模的有色、稀有等多金属矿床(赵振华等, 1998, 2000; 黄诚和李晓峰, 2013; 毛建仁等, 2014)。因此,中生代对于研究华北和华南板块的成矿规律有重要意义。

众多学者研究了中国东部晚白垩世—新生代地幔橄榄岩包体含水量(Xia Qunke et al., 2013; Hao Yantao et al., 2012, 2016a, b; Li Yanqing et al., 2015; 徐义刚等, 2018),发现岩石圈减薄有不均一性特征。典型和非典型克拉通岩石圈地幔的水含量分别为(119 ± 54)×10^{-6} 和(78 ± 45)×10^{-6},华北(34 ± 34)×10^{-6} 和东北(47 ± 32)×10^{-6} 岩石圈地幔的水含量低于该标准,表明其都发生了岩石圈减薄。华北克拉通岩石圈中西部水含量低于软流圈地幔,这与华北克拉通中西部受后期减薄影响小相一致,其厚度大约是~ 200 km。而其东部含水量远高于软流圈地幔,这显示出华北克拉通岩石圈显著减薄发生在最东部(新生的岩石圈地幔),其厚度 80 ~ 120 km(渤海地区厚度 60~70 km; Zheng Tianyu et al., 2006; Chen Bin et al., 2009; Chen Ling et al., 2014)。华南岩石圈含水量在中、新生代两个时代差别不大,水含量都较高为(90 ± 45) ×10^{-6},与岩石圈减薄发生在晚中生代特征相一致。

一些学者(如 Jiang Yaohui et al., 2009; Wang Xuance et al., 2011)认为华北克拉通的破坏和减薄是中—晚中生代太平洋板块俯冲所导致的。在板块俯冲过程中,大部分样品经历了地壳混染作用,无法鉴别其是否真的经历了再循环过程,因此几乎无法直接从地幔中找到再循环碳的可靠证据。

3　俯冲碳的证据

3.1　实验模拟

Wyllie 等(1975)模拟了地幔橄榄岩的部分熔融,采用 CO_2—CMS(CaO—MgO—SiO_2)体系在>70 km 处模拟出了富碳酸盐的岩浆。Dalton 等(1998)在相同系统下模拟并发现 3~7 GPa 压力下碳酸盐化二辉橄榄岩的固相线熔体成分相当于碳酸岩。Grassi 等(2010, 2011)模拟了碳酸盐化泥质岩固相线与俯冲温压的关系,发现伴随着固相线温度的降低产生了富钾的碳酸盐(Ca—Fe—Mg)熔体(6 ~ 9 Gpa 是第一个熔融区)。众多实验研究测定了部分熔融过程中碳酸盐种属固相转化 P—T 界限(Sato and Katsura, 2001; Morlidge et al., 2006; Tao Renbiao et al., 2014),这一结果与 Mg—Sr 同位素制约玄武岩源区的碳酸盐种属(菱镁矿主要+白云石少量)相一致。Dasgupta 等(2007, 2013),朱日祥和郑天愉(2009),Huang Jian 和 Xiao Yilin(2016d),Li Shuguang 等(2017),李曙光和汪洋(2018)用数值方法和实验模拟中国东部碳酸盐熔体(高 T—P),认为大多数的碳酸盐在太平洋板块俯冲过程中留存下来并进入了深部地幔。

3.2　计算模拟

Yang Wei 等(2012)通过计算模拟发现纯硅酸

盐熔体交代难以形成低 $\delta^{26}Mg$ 的地幔源区，必须少量的碳酸岩熔体才能形成，从而认为华北克拉通中、新生代玄武岩的低 $\delta^{26}Mg$ 值很可能源自再循环碳酸盐对玄武岩源区的交代作用。Huang Jian 和 Xiao Yilin（2016d）和 Li Shuguang 等（2017）通过计算模拟和同位素相结合的方法研究了中国东部岩石圈自白垩世之后的碱性玄武岩，得出玄武岩的地幔源区碳酸岩种属主要是白云石+菱镁矿，地幔源区混入<10%的再循环碳酸盐就能产生中国东部<110 Ma 玄武岩的轻 Mg 同位素组成（Huang Jian and Xiao Yilin，2016d；田恒次等，2017），但其忽略了俯冲蚀变洋壳和泥质沉积物这一影响因素。因此仅靠简单的模拟计算方法可能会造成结果单一的特点，若要全面反映俯冲过程中的深部碳循环，探究深部碳循环过程还需要借助其他手段。

3.3 计算模拟—实验相结合

柯珊等（2011）分别用 DAR 模型、AF 模型模拟计算和实验相结合验证 Mg 同位素的分馏，得到分馏结果不一致，认为可能是模拟或实际观测的 Mg 同位素分馏未达到平衡或者白云岩实际形成与理论过程不同（甯濛等，2018）。因而，通过实验和计算模拟结合可能不太准确表达出地质历史过程，甚至可能有错误引导性，需要结合非传统性同位素才能反演出更准确的深部碳循环过程。

3.4 碳酸盐熔—流体交代岩石圈地幔

碳酸盐熔体是一种重要的地幔交代介质和深部碳循环作用的指示物，长期的碳酸岩熔体交代作用可能是碳储库形成的因素之一，也是造成中国东部岩石圈地幔组成和性质改变的重要因素（Dai Baozhang et al.，2008；Jiang Yaohui et al.，2009；Wang Xuance et al.，2011；Li Xiyao et al.，2014；Huang Jian et al.，2015a；杨金豹等，2015）。深部碳循环过程中大量地表的碳酸盐（或者 CO_2）或者碳酸盐流体被俯冲进入地幔，极大降低地幔熔融的固相线，从而诱发深部地幔部分熔融，中国东部岩石圈的减薄与破坏被碳酸盐交代作用和部分熔融过程所制约。Li Shuguang 等（2017）发现中国东部碱性玄武岩有典型的碳酸盐熔体特征，如高 CaO/Al_2O_3 比值、低 FeO/MnO 值和显著的 K、Pb、Hf、Ti 等微量元素负异常，证实了岩石圈地幔大多数发生了周边俯冲板块的含碳酸盐熔流体的交代作用。中生代，初始的碳酸盐熔体交代—熔融作用弱化了岩石圈地幔的强度，为中国东部岩石圈的最终破坏提供了关键前提条件。不同比例碳酸盐熔体改造了岩石圈的再循环地壳物质，大规模的碳酸盐化交代—部分熔融造成了岩石圈的减薄与破坏。

碳酸盐化洋壳部分熔融产生碳酸盐熔体在地幔过渡带 410 ~ 660 km，具有低 Gd_N/Yb_N 值，LREE 富集和 HREE 亏损特征，其向上渗透并交代底部岩石圈地幔可形成碳酸盐化橄榄岩，随着太平洋板块的俯冲和东部岩石圈的减薄与破坏，碳酸盐交代熔融深度<130 km 和逐渐靠近 70 km（Huang Jian et al.，2015b）。

4 中国东部岩石圈轻 Mg 同位素组成

中国东部是环太平洋火山带的边缘组成部分，是目前世界上最活跃的构造—岩浆区域之一（Zhou Xinghua and Armstrong，1982），也存在一条巨大的 Mg 同位素异常区，与滞留在地幔过渡带中的太平洋俯冲板片范围一致（Fukao et al.，1992；Huang Jinli and Zhao Dapeng，2006）。中国东部地震层析成像表明中—晚中生代，太平洋板块已经开始俯冲至中国东部（Huang Jinin and Zhao Dapeng，2006；Zheng Yongfei，2012）。大量幔源火山岩的镁同位素研究表明，俯冲板块携带的碳酸盐被折返至上地幔，在地幔过渡带形成碳酸化橄榄岩，成为各种玄武岩的来源，可能揭示出中国东部是一个巨大的再循环碳库。

玄武岩的 Mg 同位素分馏为探索中国东部深部碳循环提供了约束。Yang Wei 等（2012）最先研究了华北克拉通中—新生代玄武岩的 Mg 同位素组成，发现辽西义县>120 Ma 的玄武岩具有地幔类似的 Mg 同位素组成（$\delta^{26}Mg$ = −0.31‰ ~ −0.25‰），而阜新和太行山<110 Ma 的玄武岩 $\delta^{26}Mg$ 值（$\delta^{26}Mg$ = −0.60‰ ~ −0.42‰）低于地幔，其地球化学特征表现为 MORB 型的 Sr—Nd—Pb 同位素、高的 Ce/Pb 和 Nb/U 比值和类似地幔 HIMU 端元的高 U/Pb 和 Th/Pb 值，因此认为低 $\delta^{26}Mg$ 值可能与俯冲洋壳的含碳酸岩熔体交代地幔有关。Huang Jian 等（2015b）报道了华南新生代碱性玄武岩表现出典型碳酸盐熔体特征（如 K、Pb、Hf、Ti 负异常），具有轻镁同位素组成特征（$\delta^{26}Mg$= −0.60 ‰ ~ −0.35‰），认为再循环碳酸盐熔体交代地幔造成了玄武岩的轻 Mg 同位素组成。李曙光（2015）认为中国东部地幔部分熔融产生的岩浆 Mg 同位素组成要轻于地幔，很可能是由于碳酸盐的交代作用造成。Tian Hengci 等（2016）对中国东北五大连池和二克山玄武岩展开研究（$\delta^{26}Mg$= −0.57‰ ~ −0.46‰），其富集 EM-I 型 Sr—Nd—Pb 同位素，如高 CaO/Al_2O_3，Ba/Rb 等

有典型碳酸盐岩交代特征。Hu Yan 等(2016)报道了华北汉诺坝石榴子石辉石岩有低 Ti/Eu 和轻的 Mg 同位素组成(δ^{26}Mg = −1.37‰ ~ −1.47‰),认为是再循环碳酸盐熔体与橄榄岩反应的结果。Li Shuguang 等(2017)认为太平洋板片携带大量沉积碳酸盐俯冲到了软流圈地幔,造成了中国东部晚白垩纪和新生代玄武岩的低 δ^{26}Mg 值特征。因此,上述研究表明中国东部大陆玄武岩的低 δ^{26}Mg 值很可能是地幔源区卷入再循环碳酸盐的结果(图 2)。

综合地震层析影像资料和前人对 Mg 同位素研究表明,俯冲至中国东部岩石圈并滞留在地幔过渡带的太平洋板块,其释放的碳酸盐熔体与地幔相互作用,很可能是造成东部地幔 Mg 同位素组成偏轻的重要原因(Xiao Yan et al., 2013; Huang Jian et al., 2015b)。因此,俯冲的太平洋板块在中国东部岩石圈减薄与破坏过程中发挥着重要作用。

除中国东部的"轻镁同位素异常",世界各地均发现轻镁同位素的幔源岩浆岩并将其解释为与地幔源区中再循环碳酸盐有关(Liu Dong et al., 2015; Liu Fang et al., 2017a; Wang Shuijiong et al., 2016b; Wang Xiaojun et al., 2018; Ke Shan et al., 2016; Dai Liqun et al., 2017; Tian Hengci et al., 2018; Hoang et al., 2018; Kim et al., 2019)。例如,Wang Shuijiong 等(2016b)报道了具有 HIMU 特征的新西兰板内玄武岩的 Mg 同位素组成(−0.47‰ ~ −0.06‰),认为低 δ^{26}Mg 异常是再循环的碳酸盐洋壳(榴辉岩)加入地幔源区的结果。Tian Hengci 等(2018)研究了较轻 Mg 同位素组成的腾冲玄武岩(−0.51‰ ~ −0.45‰),将低 δ^{26}Mg 值异常归因于超临界流体溶解白云石的结果。Hong 等(2018)报道了越南中部和南部板内晚新生代玄武岩的轻 Mg 同位素组成(−0.62‰ ~ −0.28‰),认为其源区为橄榄岩和再循环碳酸盐化榴辉岩的混合源区。Wang Xiaojun 等(2018)发现属于 EM1 端元的经典 Pitcairn 群岛地区玄武岩具有低 δ^{26}Mg 值异常,认为其源区来自俯冲含碳酸盐沉积物改造的深部地幔。

值得指出的是,近年来研究发现低 δ^{26}Mg 值存在多解性。除再循环碳酸盐外,部分榴辉岩和碳酸盐化榴辉岩也具有低的 δ^{26}Mg 值(Wang Shuijiong et al., 2012; Wang Xuance et al., 2015b)。月岩高 Ti 玄武岩的钛铁矿堆晶作用也同样显示出低 δ^{26}Mg 值(Sedaghatpoura et al., 2013)。另一方面,成因与俯冲板块有关的岛弧火山岩却有着与地幔相似的轻 Mg 同位素组成(Teng Fangzhen et al., 2016; Li

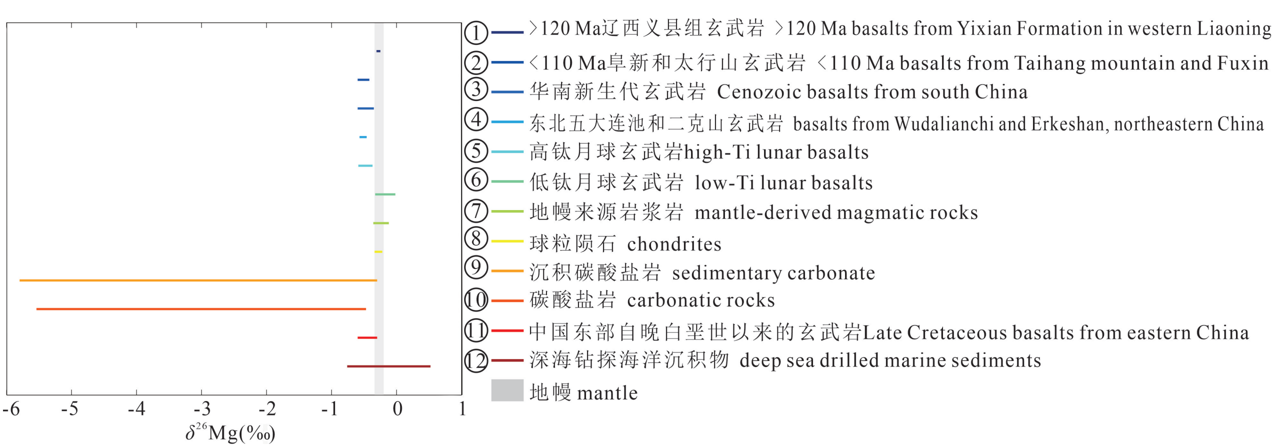

图 2 部分储库镁同位素组成

Fig. 2 Part of the reservoir magnesium isotope composition

①②据 Zhang Hongfu and Zheng Jianping, 2003; Tang Yanjie et al., 2006; Yang Wei and Li Shuguang, 2008; ③据 Huang Jian et al., 2015a; ④据 Tian Hengci et al., 2016; ⑤据 Sedaghatpoura et al., 2013; ⑥据 Huang Jian et al., 2015a; ⑦据 Teng Fangzhen et al., 2010a; ⑧据 Sun and McDonough, 1989; ⑨据 Tian Hengci et al., 2016; ⑩据 Huang Jian et al., 2015a; ⑪据 Galy et al., 2002; Young and Galy, 2004; Tipper et al., 2006a; Pogge et al., 2008; Higgins and Schrag, 2010; Jacobson et al., 2010; Pokrovsky et al., 2011; Wombacher et al., 2011; ⑫据 Teng Fangzhen et al., 2016

①② from Zhang Hongfu and Zheng Jianping, 2003; Tang Yanjie et al., 2006; Yang Wei and Li Shuguang, 2008; ③ from Huang Jian et al., 2015a; ④from Tian Hengci et al., 2016; ⑤from Sedaghatpoura et al., 2013; ⑥from Huang Jian et al., 2015a; ⑦from Teng Fangzhen et al., 2010a; ⑧from Sun and McDonough, 1989; ⑨from Tian Hengci et al., 2016; ⑩from Huang Jian et al., 2015a; ⑪ from Galy et al., 2002; Young and Galy, 2004; Tipper et al., 2006a; Pogge et al., 2008; Higgins and Schrag, 2010; Jacobson et al., 2010; Pokrovsky et al., 2011; Wombacher et al., 2011; ⑫ from Teng Fangzhen et al., 2016

Shuguang et al., 2017)。

5 低 δ^{26}Mg 值的多解性

5.1 岛弧火山岩的低 δ^{26}Mg 值

Teng Fangzhen 等(2016)和 Li Shuguang 等(2017)对环太平洋和 Martinique 岛弧火山岩进行系统的 Mg 同位素组成研究,结果表明岛弧火山岩具有与地幔相似的 Mg 同位素组成。这原因之一可能是俯冲板片携带的再循环沉积碳酸盐岩在岛弧下发生板片脱水,主要溶解的是富 Ca 的方解石,因此产生的流体含很少量的 Mg,因此,不会明显的改变岛弧玄武岩的 Mg 同位素组成。另一个原因是来自蚀变洋壳和蚀变深海橄榄岩的流体,可能具有比地幔重的 Mg 同位素组成。低 δ^{26}Mg 玄武岩是由大洋板块俯冲释放碳酸盐所致,还是同位素轻钛铁矿在其地幔源中积累所致,一直存在争议。

5.2 碳酸盐化榴辉岩的低 δ^{26}Mg 值

碳酸盐化榴辉岩和沉积碳酸盐具有类似的轻 Mg 同位素组成(Wang Shuijiong et al., 2012, 2014a, 2015a; Huang Kangjun et al., 2016b),蚀变洋壳经历高温高压变质可以形成榴辉岩,碳酸盐化榴辉岩和再循环沉积碳酸盐交代产生的熔体表现出低 δ^{26}Mg 值,用 Mg 同位素示踪深部碳循环可能会产生多解(Wang Shuijiong et al., 2016b; Tian Hengci et al., 2018)。Wang Shuijiong 等(2014b)发现苏鲁超高压变质带的荣成 UHP 大理岩和其包裹的榴辉岩块,独立的榴辉岩的 Mg 同位素组成与原岩一致(δ^{26}Mg≈ −0.25 ± 0.07‰),而包裹的碳酸盐化榴辉岩块有较轻的 Mg 同位素组成(δ^{26}Mg ≈ −0.6 ± 1.9‰),该文指出碳酸盐化榴辉岩的极低 δ^{26}Mg 值异常是由榴辉岩变质所致。Wang Shuijiong 等(2014b)将不同的 Mg 同位素组成归结于板块俯冲过程中榴辉岩和大理岩之间发生了同位素交换反应,认为再循环进入深部地幔的低 δ^{26}Mg 值物质有两类:再循环碳酸盐的 δ^{26}Mg 值不可能低于−2.5‰;再循环碳酸盐化榴辉岩(含碳量不高),其 δ^{26}Mg 值可低至−1.9‰。Huang Jinxian 等(2016c)在南非金伯利岩榴辉岩中再次验证了确实存在轻镁同位素组成,解释为继承了蚀变洋壳的特点,可能是板块俯冲过程中和沉积碳酸盐岩发生同位素交换所造成的结果。Liu Pingping 等(2016b)认为碳酸盐化榴辉岩部分熔融形成的熔体富集 SiO_2,Na_2O 和 K_2O,亏损 TiO_2,并与地幔橄榄岩反应形成辉石岩;然而,玄武岩的 δ^{26}Mg 值并没有与$(Gd/Yb)_N$ 和 Fe/Mn 存在相关性,以此排除混入碳酸盐化榴辉岩,得出源区并没有混入碳酸盐化榴辉岩的结论,同时指出 Zn 同位素可以区分再循环碳酸岩和再循环榴辉岩。

5.3 钛铁矿堆晶的低 δ^{26}Mg 值

除此之外,钛铁矿堆晶作用也可造成低 δ^{26}Mg 值,Sedaghatpoura 等(2013)发现高钛和低钛月岩玄武岩表现出显著的 Mg 同位素分馏(δ^{26}Mg = −0.61‰ ~ −0.02‰),但是月球不存在板块俯冲作用,与碳酸盐交代作用无关,认为钛铁矿堆晶作用可能与高 Ti 月岩玄武岩低 δ^{26}Mg 值(δ^{26}Mg = −0.6‰)有关。另外,地幔岩浆上升时因温度不同,扩散引起的同位素动力学分馏程度十分显著(Richter et al., 2008),由于热扩撒和化学扩散的发生,造成玄武岩轻 Mg 同位素组成异常(Liu Sheng'ao and Li Shuguang, 2019),这一问题一度引来争议。前人提出了排除源区钛铁矿堆晶作用的方法,认为若存在钛铁矿堆晶,TiO_2 会与 Nb/Ta 和 δ^{26}Mg 形成负相关关系(Huang Jian et al., 2015a, Tian Hengci et al., 2016)。

6 结论与展望

地球深部碳循环对全球气候变化、生命探索和岩石圈演化的研究具有重要意义,Mg 同位素是其有效的示踪工作。笔者等系统阐述了镁同位素示踪深部碳循环的原理,例举了镁同位素示踪中国东部深部碳循环的实例,论述了中生代俯冲的古太平洋板块所释放的碳酸盐熔体/流体与地幔相互作用,是造成中国东部地幔具有普遍的轻 Mg 同位素组成的重要原因。中国东部岩石圈的减薄与破坏体现了中国东部中生代深部碳循环的地球动力学效应。因此,研究中国东部中生代深部碳循环有助于制约中国东部岩石圈减薄和破坏机制。

然而,轻镁同位素组成存在多解性。除了再循环碳酸盐外,岛弧火山岩、榴辉岩、钛铁矿堆晶均具有轻镁同位素组成,因此,需要研究探索不同同位素和(或)主微量元素特征联合示踪。例如,Liu Sheng'ao 等(2016a)研究了中国东部玄武岩 Zn 同位素组成,发现 δ^{66}Zn 与 δ^{26}Mg 具有负相关性,可以采用 Zn—Mg 同位素联合示踪地球深部碳循环。另一方面,地幔深部碳循环机理和深部碳循环如何贡献地幔不均一性等科学问题仍未解决,有待进一步开展研究。

致谢:感谢田恒次博士给予的帮助,同时感谢刘

志强高级工程师和评审专家对本文修改提出的宝贵意见！

参 考 文 献 / References

(The literature whose publishing year followed by a "&" is in Chinese with English abstract; The literature whose publishing year followed by a "#" is in Chinese without English abstract)

陈春飞. 2018. 古亚洲洋俯冲引起的深部碳循环及其对华北克拉通岩石圈活化的贡献. 导师：刘勇胜; Stephen F F. 武汉：中国地质大学博士学位论文：1～203.

高庭. 2016. Mg 同位素的高精度测定及其在大陆风化过程中的地球化学行为. 导师：滕方振、柯珊. 北京：中国地质大学硕士学位论文：1～90.

郭锋，范蔚茗，林舸. 1998. 湘南中生代玄武岩浆成因与岩石圈—软流圈相互作用. 矿物岩石地球化学通报，17(1)：1～4.

郭锋，范蔚茗，林舰，林源贤. 1997. 湘南道县辉长岩包体的年代学研究及成因探讨. 科学通报，42(15)：1661～1663.

何学贤，李世珍，唐索寒. 2008. Mg 同位素应用研究进展. 岩石矿物学杂志，27(5)：472 ～ 476.

黄诚，李晓峰. 2013. 湖南黄沙坪多金属矿床流体演化及其特征. 矿物学报，33(S2)：451～452.

柯珊，刘盛遨，李王晔，杨蔚，滕方振. 2011. 镁同位素地球化学研究新进展及其应用. 岩石学报，27(2)：383～397.

李曙光，汪洋. 2018. 中国东部大地幔楔形成时代和华北克拉通岩石圈减薄新机制——深部再循环碳的地球动力学效应. 中国科学:地球科学，48(7):809～824.

李曙光. 2015. 深部碳循环的 Mg 同位素示踪. 地学前缘，22(5)：143～159.

李曙光. 2017. 深部碳循环的 Mg 同位素示踪：2015～2016 的进展与问题. 矿物岩石地球化学报，36(2)：197～203+183.

刘勇胜，陈春飞，何德涛，陈唯. 2019. 俯冲带地球深部碳循环作用. 中国科学：地球科学，49(12)：1982～2003.

毛建仁，厉子龙，叶海敏. 2014. 华南中生代构造—岩浆活动研究：现状与前景. 中国科学：地球科学，44(12)：2593～2617.

甯濛，黄康俊，沈冰. 2018. 镁同位素在"白云岩问题"研究中的应用及进展. 岩石学报，34(12)：3690～3708.

沈骥，李王晔，李曙光，肖益林. 2019. 俯冲隧道内不同深度的壳幔相互作用：地幔楔超镁铁质岩的镁同位素记录. 地球科学，44(12)：4102～4111.

孙剑，房楠，李世珍，陈岳龙，朱祥坤. 2012. 白云鄂博矿床成因的 Mg 同位素制约. 岩石学报，28(9)：2890 ～ 2902.

汤艳杰，英基丰，赵月鹏，许欣然. 2021. 华北克拉通岩石圈地幔特征与演化过程. 中国科学:地球科学，51(9)：1489～1503.

汤艳杰，张宏福. 2019. 华北克拉通岩石圈地幔的锂同位素特征与熔体改造作用. 矿物岩石地球化学通报，38(2)：217～223+444～445.

田恒次，杨蔚，李曙光，魏海泉，柯珊. 2017. Mg 同位素组成揭示长白山火山岩内部演化过程. 中国矿物岩石地球化学学会第九次全国会员代表大会暨第 16 届学术年会文集，286.

吴福元，徐义刚，高山，郑建平. 2008. 华北岩石圈减薄与克拉通破坏研究的主要学术争论. 岩石学报，24(6)：1145～1174.

徐义刚，李洪颜，洪路兵，马亮，马强，孙明道. 2018. 东亚大地幔楔与中国东部新生代板内玄武岩成因. 中国科学：地球科学，48(7)：825～843.

杨金豹，赵志丹，莫宣学，盛丹，丁聪，王丽丽，侯青叶，李红进. 2015. 湖南道县虎子岩碱性玄武岩及其基性捕虏体成因和地质意义. 岩石学报，31(5)：1421～1432.

张立飞，陶仁彪，朱建江. 2017. 俯冲带深部碳循环：问题与探讨. 矿物岩石地球化学通报，36(2)：185～196.

赵振华，包志伟，张伯友，熊小林. 2000. 柿竹园超大型钨多金属矿床形成的壳幔相互作用背景. 中国科学：地球科学，30(S1)：161～168.

赵振华，包志伟，张伯友. 1998. 湘南中生代玄武岩类地球化学特征. 中国科学：地球科学，(S2)：7～14.

郑建平，路凤香. 1999. 胶辽半岛金伯利岩中地幔捕虏体岩石学特征：古生代岩石圈地幔及其不均一性. 岩石学报，15(1)：65～74.

朱日祥，郑天愉. 2009. 华北克拉通破坏机制与古元古代板块构造体系. 科学通报，54(1)：1950～1961.

朱日祥，徐义刚，朱光，张宏福，夏群科，郑天愉. 2012. 华北克拉通破坏. 中国科学，42(8)：1135～1159.

朱祥坤，王跃，闫斌，李津，董爱国，李志红，孙剑. 2013. 非传统稳定同位素地球化学的创建与发展. 矿物岩石地球化学通报，32(6)：651～688.

宗克清，刘勇胜. 2018. 华北克拉通东部岩石圈地幔碳酸盐熔体交代作用与克拉通破坏. 中国科学：地球科学，48(6)：732～752.

Alt J C, Teagle D A H. 1999. The uptake of carbon during alteration of ocean crust. Geochimica et Cosmochimica Acta, 63(10): 1527～1535.

Armstrong K, Frost D J, Cammon M, Catherine A, Rubie D C, Boffa B T. 2019. Deep magma ocean formation set the oxidation state of Earth's mantle. Science, 365(6456): 903～906.

Bourdon B, Tipper E T, Fitoussi C, Stracke A. 2010. Chondritic Mg isotope composition of the Earth. Geochimica et Cosmochimica Acta, 74 (17): 5069～5083.

Brenot A, Nicole B, Emmanuelle P G, Philippe N. 2008. Interaction between different water bodies in a small catchment in the Paris basin (Brevilles, France): Tracing of multiple Sr sources through Sr isotopes coupled with Mg/Sr and Ca/Sr ratios. Applied Geochemistry, 23(1): 58～75.

Cartigny P. 2005. Stable isotopes and the origin of diamond. Elements, 1(2): 79～84.

Chang Zeguang, Dong Guochen, Scott J M. 2021. Early Cretaceous basalts record the modification of the North China Craton lithospheric mantle: implications for lithospheric thinning. International Geology Review, 64(9): 1～17.

Chen Bin, Jahn B M, Tian Wei. 2009. Evolution of the Solonker suture zone: Constraints from zircon U-Pb ages, Hf isotopic ratios and whole-rock Nd—Sr isotope compositions of subduction- and collision-related magmas and forearc sediments. Journal of Asian Earth Sciences, 34(3): 245～257.

Chen Chunfei. 2018&. Deep carbon cycle induced by Paleo-Asian oceanic slab subduction and its contribution to lithospheric refertilization under the North China Craton. Supervisor: Liu Yongsheng; Stephen F F. Doctoral Dissertation of China University of Geosciences (Wuhan), 64: 1～ 203.

Chen Ling, Jiang Mingming, Yang Jinhui, Wei Zigen, Liu Chuanzhou, Ling Yuan. 2014. Presence of an intralithospheric discontinuity in the central and western North China Craton: Implications for destruction of the craton. Geology, 42(3): 223～226.

Collins C N, Bebout E G, Angiboust S, Agard P, Scambelluri M, Crispini L, John T. 2015. Subduction zone metamorphic pathway for deep carbon cycling: II. Evidence from HP/UHP metabasaltic rocks and ophicarbonates. Chemical Geology, 412(1): 132～150.

Dai Baozhang, Jiang Shaoyong, Jiang Yaohui, Zhao Kuidong, Liu Dunyi. 2008. Geochronology, geochemistry and Hf—Sr—Nd isotopic compositions of Huziyan mafic xenoliths, southern Hunan Province, South China: Petrogenesis and implications for lower crust evolution. Lithos, 102(1): 65～87.

Dai Liqun, Zhao Zifu, Zheng Yongfei, An Yajun, Zheng Fei. 2017.

Geochemical distinction between carbonate and silicate metasomatism in generating the mantle sources of Alkali basalts. Journal of Petrology, 58(5): 863~884.

Dalton J, Presnall D. 1998. Carbonatitic melts along the solidus of model lherzolite in the system CaO—MgO—Al_2O_3—SiO_2—CO_2 from 3 to 7 GPa. Contrib Mineral Petrol, 131(2): 123~135.

Dasgupta R, Hirschmann M M, Smith N D. 2007. Partial melting experiments of peridotite + CO_2 at 3 GPa and genesis of Alkalic Ocean Island Basalts. J. Petrol., 48(11): 2093~2124.

Dasgupta R, Hirschmann M M, Withers A C. 2004. Deep global cycling of carbon constrained by the solidus of anhydrous, carbonated eclogite under upper mantle conditions. Earth and Planetary Science Letters, 227(1~2): 73~85.

Dasgupta R, Hirschmann M M. 2010. The deep carbon cycle and melting in Earth's interior. Earth and Planetary Science Letters, 298 (1~2): 1~13.

Dasgupta R. 2013. Ingassing, storage, and outgassing of terrestrial carbon through geologic time. Rev. Mineral. Geochem., 75(1): 183~229.

Deines P. 2002. The carbon isotope geochemistry of mantle xenoliths. Earth-Science Review, 58(3~4):247~278.

Doucelance R, Bellot N, Boyet M, Hammouda T, Bosq C. 2014. What coupled cerium and neodymium isotopes tell us about the deep source of oceanic carbonatites. Earth and Planetary Science Letters, 407(3): 175~186.

Duan Xianzhe, Zhang Hongfu, Santosh M, Tian Hengci, Sun He, Tan Kaixuan, Han Shili, Xiao Yilin, Hou Zhenhuiand Zhang Yanqun. 2020. The transformation of the lithospheric mantle beneath South China Block (SCB): constraints from petrological and geochemical studies of Daoxian and Ningyuan basalts and their melt inclusions. International Geology Review, 62(4): 479~502.

Ducea M N, Saleeby J, Morrison J, Valencia V A. 2005. Subducted carbonates, metasomatism of mantle wedges, and possible connections to diamond formation: An example from California. American Mineralogist, 90(5): 864~870.

Falkowski P, Schloles R J, Boyle E, Canadell J, Cafield D, Elser J, Gruber N, Hibbard K, HÖgberg P, Linder S, Mackenzie F T, Moore III B, Pedersen T, Rosenthal Y, Seitzinger S, Smetacek V and Steffen W. 2000. The global carbon cycle: a test of our knowledge of earth as a system. Science, 290(5490): 291~296.

Fan Weiming, Menzies M A. 1992. Destruction of aged lower lithosphere and accretion of asthenosphere mantle beneath eastern China. Geotectonica et Metallogenia, 16(2): 171~180.

Fan Weiming, Zhang Hongfu, Baker J, Jarvis K E, Mason P R D, Menzies M A. 2000. On and off the north China craton: Where is the Archaean keel? Journal of Petrology, 41(7): 933~950.

Follett C L, Repeta D J, Rothman D H, Xu L, Santinelli C. 2014. Hidden cycle of dissolved organic carbon in the deep ocean. Proceedings of the National Academy of Sciences, 111(47): 16706~16711.

Foster G L, Pogge von Strandmann P A E, Rae J W B. 2010. Boron and magnesium isotopic composition of seawater. Geochemistry Geophysics Geosystems, 11(8): 1~10.

Fukao Y, Obayashi M, Inoue H, Nenbai M. 1992. Subducting slab stagnant in the mantle transition zone. Journal of Geophysical Research, 97(B4): 4809~4822.

Galy A, Bar-Matthews M, Halicz L, O'Nions R K. 2002. Mg isotopic composition of carbonate: insight from speleothemformation. Earth and Planetary Science Letters, 201(1): 105~115.

Galy A, Belshaw S N, Halicz L, O'Nions R K. 2001. High-precision measurement of magnesium isotopes by multiple-collector inductively coupled plasma mass spectrometry. International Journal of Mass Spectrometry, 208(1~3): 89~98.

Gao Ting. 2016&. High precision determination of Mg isotopes and their geochemical behavior during continental weathering. Supervisor: Teng Fangzhen; Ke Shan. Master Dissertation of China University of Geosciences (Beijing): 1~90.

Graham D W, Michael P J, Rubin K H. 2018. An investigation of mid-ocean ridge degassing using He, CO_2, and $\delta^{13}C$ variations during the 2005~06 eruption at 9° 50′ N on the East Pacific Rise. Earth and Planetary Science Letters, 504(2): 84~93.

Grassi D, Schmidt M W. 2010. Melting of carbonated pelites at 8~13 GPa generating K-rich carbonatites for mantle metasomatism. Contrib. Mineral. Petrol., 162(1): 169~191.

Grassi D, Schmidt M W. 2011. The melting of carbonated pelites from 70 to 700 km depth. Journal of Petrology, 52(4): 765~789.

Griffin W L, Zhang A D, O'reilly S Y, Ryan C G. 1998. Phanerozoic evolution of the lithosphere beneath the Sino—Korean Craton. Mantle Dynamics and Plate Interactions in East Asia, 27(4): 107~126.

Guo Feng, Fan Weiming, Lin Ge, Lin Yuanxian. 1997 #. Geochronological study and genesis of gabbro xenoliths in Daoxian County, southern Hunan Province. Chinese Science Bulletin, 42 (15): 1661~1663.

Guo Feng, Fan Weiming, Lin Ge. 1998#. Genesis of Mesozoic basaltic magma and lithosphere—asthenosphere interaction in southern Hunan. Bulletin of Mineralogy, Petrology and Geochemistry, 17 (1): 1~4.

Gao Shan, Rudnick R L, Xu Wenliang, Yuan Honglin, Liu Yongsheng, Walker R J, Puchtel I S, Liu Xiaomin, Huang Hua, Wang Xiaorui, Yang Jie. 2008. Recycling deep cratonic lithosphere and generation of intraplate magmatism in the North China Craton. Earth Planet Sci. Lett., 270(1~2): 41~53.

Hammouda T. 2003. High-pressure melting of carbonated eclogite and experimental constraints on carbon recycling and storage in the mantle. Earth and Planetary Science Letters, 214(1~2): 357~368.

Handler M R, Baker J A, Schiller M, Bennett V C, Yaxley G M. 2009. Magnesium stable isotope composition of Earth's upper mantle. Earth and Planetary Science Letters, 282(1~4): 306~313.

Hao Yantao, Xia Qunke, Jia Zubing, Zhao Qichao, Li Pei, Feng Min, Liu Shaochen. 2016b. Regional heterogeneity in the water content of the Cenozoic lithospheric mantle of Eastern China. Geophys. Res. ——Solid Earth, 121(2): 517~537.

Hao Yantao, Xia Qunke, Liu Shaochen, Feng Min, Zhang Yaping. 2012. Recognizingjuvenile and relict lithospheric mantle beneath the North China Craton: Combined analysis of H_2O, major and trace elements and Sr—Nd isotope compositions of clinopyroxenes. Lithos, 149(1): 136~145.

Hao Yantao, Xia Qunke, Tian Zhenzhen, Liu Jia. 2016a. Mantle metasomatism did not modify the initial H_2O content in peridotite xenoliths from the Tianchang basalts of eastern China. Lithos, 260 (3): 315~327.

He Xuexian, Lishizhen, Tang Suohan. 2008&. Advances in the study of Mg isotopes application. Acta Petrologica et Mineralogica, 27(5): 472~476.

Higgins J A, Schrag D P. 2010. Constraining magnesium cycling in marine sediments using magnesium isotopes. Geochim. Cosmochim. Acta, 74(17): 5039~5053.

Hilton R G, West A J. 2020. Mountains, erosion and the carbon cycle. Nat. Rev. Earth Environ., 1(6): 284~299.

Hippler D, Buhl D, Witbaard R, Richter D, Immenhauser A. 2009. Towards a better understanding of magnesium-isotope ratios from marine skeletal carbonates. Geochimica et Cosmochimica Acta: 73 (20): 6134~6146.

Hoang T H A, Sung H C, Yongjae Y, Trung H P, Kim H N, Jong-Sik R. 2018. Geochemical constraints on the spatial distribution of recycled oceanic crust in the mantle source of late Cenozoic basalts, Vietnam. Lithos, 296(2): 382~395.

Hoffman P F, Schrag D P. 2002. The snowball Earth hypothesis: Testing the limits of global change: Terra Nova, 14(3): 129~155.

Hoffman R N, Nehrkorn T. 2009. A simulation test of three-dimensional temperature retrievals. Monthly Weather Review, 117(3): 473~494.

Hong A, Sung H C, Yongjae Y, Pham T H. 2018. Geochemical constraints on the evolution of the lithospheric mantle beneath central and southern Vietnam. Geosciences Journal, 25(4):433~451.

Hu Yan, Teng Fangzhen, Zhang Hongfu, Xiao Yan, Su Benxun. 2016. Metasomatism-induced mantle magnesium isotopic heterogeneity: Evidence from pyroxenites. Geochim Cosmochim Acta, 185(2): 88~111.

Huang Cheng, Li Xiaofeng. 2013#. Fluid evolution and characteristics of Huangshaping polymetallic deposit, Hunan Province. Acta Mineralogica Sinica, 33(S2): 451~452.

Huang Fang. 2011. Non-traditional stable isotope fractionation at high temperatures. Acta Petrologica Sinica, 27(2): 365~382.

Huang Fang, Zhang Zhaofeng, Lundstrom C C, Zhi Xiachen. 2011. Iron and magnesium isotopic compositions of peridotite xenoliths from Eastern China. Geochimica et Cosmochimica Acta, 75(12): 3318~3334.

Huang Jian, Ke Shan, Gao Yongjun, Xiao Yilin, Li Shuguang. 2015b. Magnesium isotopic compositions of altered oceanic basalts and gabbros from IODP Site 1256 at the East Pacific Rise. Lithos, 231 (1): 53~61.

Huang Jian, Li Shuguang, Xiao Yilin, Ke Shan, Li Wangye, Tian Yefan. 2015a. Origin of low δ^{26}Mg Cenozoic basalts from South China Block and their geodynamic implications. Geochimica et Cosmochimica Acta, 164(3): 298~317.

Huang Jian, Liu Sheng'ao, Gao Yongjun, Xiao Yilin, Chen Sha. 2016a. Copper and zinc isotope systematics of altered oceanic crust at IODP site 1256 in the eastern equatorial Pacific. Journal of Geophysical Research. Solid Earth, 121(10): 7086~7100.

Huang Jian, Xiao Yilin, Li Wangyi, Ke Shan, Li Shuguang, Andreas P, Tian Ye. 2014#. Recycled sedimentary carbonates exist in the upper mantle of eastern China: Mg and O isotopic constraints of basalts. Annual meeting of China Geoscience Association of 2014, 38 (Theory, analysis and application of unconventional stable isotopes): 9~10.

Huang Jian, Xiao Yilin. 2016d. Mg—Sr isotopes of low-δ^{26}Mg basalts tracing recycled carbonate species: Implication for the initial melting depth of the carbonated mantle in Eastern China. International Geology Review, 58(11): 1350~1362.

Huang Jinli, Zhao Daping. 2006. High-resolution mantle tomography of China and surrounding regions. Journal of Geophysical Research, 111(B9): 305.

Huang Jinxiang, Xiang Yuanxin, An Yajun, Griffin L W, Greau Y, Xie Liewen, Norman J P, Yu Huimin, O´Reilly Y S. 2016c. Magnesium and oxygen isotopes in Roberts Victor eclogites. Chemical Geology, 438(5): 73~83.

Huang Kangjun, Teng Fangzhen, Plank T, Staudige H, Hu Yan, Bao ZhengYu. 2016b. Magnesium isotopic composition of the altered oceanic crust: Implications for the magnesium geochemical cycle. Geochimica et Cosmochimica Acta, 238 (2): 357~373.

Huang Kangjun, Teng Fangzhen, Terry P, Hubert S, Hu Yan, Bao Zhengyu. 2017#. Mg isotopic behavior during low temperature alteration of oceanic crust and its indication to global mg cycle. Proceedings of the 9th National Congress and the 16th Annual Academic Meeting of the Chinese society of mineral and rock geochemistry: 487.

Huang Kangjun. 2013&. Study on magnesium isotope behavior in the process of low temperature water rock interaction. Supervisor: Bao Zhengyu; Teng Fangzhen. Doctoral Dissertation of China University of Geosciences (Wuhan): 1~115.

Huang Shichun, Farka J, Jacobsen B S. 2011. Stable calcium isotopic compositions of Hawaiian shield lavas: Evidence for recycling of ancient marine carbonates into the mantle. Geochimica et Cosmochimica Acta, 75(17): 4987~4997.

Huang Shichun, Juraj F, Jacobsen S B. 2010. Calcium isotopic fractionation between clinopyroxene and orthopyroxene from mantle peridotites. Earth and Planetary Science Letters, 292(3~4): 337~344.

Hyde W T, Crowley T J, Baum S K, Peltier W R. 2000. Neoproterozoic "snowball Earth" simulations with a coupled climate—ice—sheet model. Nature, 405(1): 425~429.

Ionov D A, Kang Jinting, Alexander V, Zheng Wang, Ariel D A, Zhang Zhaofeng, Huang Fang. 2019. Calcium isotopic signatures of carbonatite and silicate metasomatism, melt percolation and crustal recycling in the lithospheric mantle. Geochim Cosmochim Acta, 248 (1): 1~13.

Jacobson A D, Zhang Zhaofeng, Lundstrom C, Huang Fang. 2010. Behavior of Mg isotopes during dedolomitization in the Madison Aqirfer, South Dakota. Earth and Planet Science Letters, 297(3~4): 446~452.

Javoy M, Pineau F, Allegre C J. 1982. Carbon Geodynamic Cycle. Nature, 300(2): 171~173.

Ji Zheng, Zhang Yanlong, Wan Chuanbiao, Ge Wenchun, Yang Han, Dong Yu, Yan Jing. 2021. Recycling of crustal materials and implications for lithospheric thinning: Evidence from Mesozoic volcanic rocks in the Hailar—Tamtsag Basin, NE China. Geoscience Frontiers, 12(5): 101~184.

Jiang Yaohui, Jiang Shaoyong, Dai Baozhang, Liao Shiyong, Zhao Kuidong, Ling Hongfei. 2009. Middle to late Jurassic felsic and mafic magmatism in southern Hunan province, southeast China: Implications for a continental arc to rifting. Lithos, 107(3~4): 185~204.

Kang Jinting, Zhu Hongli, Liu Yufei, Liu Fang, Wu Fei, Hao Yantao, Zhi Xiachen, Zhang Zhaofeng, Huang Fang. 2016. Calcium isotopic composition of mantle xenoliths and minerals from Eastern China. Geochimica et Cosmochimica Acta, 17((1) 335~344.

Kawamoto T. 2006. Hydrous phases and water transport in the subducting slab. Reviews in Mineralogy and Geochemistry, 62(1): 273~289.

Ke Shan, Liu Sheng´ao, Li Wangye, Yang Wei, Teng Fangzhen. 2011&. Advances and application in magnesium isotope geochemistry. Acta Petrologica Sinica, 27(2): 383~ 397.

Ke Shan, Teng Fangzhen, Li Shuguang, Gao Ting, Liu Shengyao, He Yongsheng, Mo Xuanxue. 2016. Mg, Sr and O isotope geochemistry of syenites from northwest Xinjiang, China: Tracing carbonate recycling during Tethyan oceanic subduction. Chemical Geology, 437(2): 109~119.

Keshav S, Gudfinnsson G H. 2010. Experimentally dictated stability of carbonated oceanic crust to moderately great depths in the Earth: Results from the solidus determination in the system CaO—MgO—Al_2O_3—SiO_2—CO_2. Journal of Geophysical Research, 115, (B5): 205.

Kim J, Choi S H, Gi W K, Jun B P, Jong S R. 2019. Petrogenesis and mantle source characteristics of volcanic rocks on Jeju Island, South Korea. Lithos, 326~327(1): 476~490.

Li Shuguang, Wang Yang. 2018&. Formation time of the big mantle wedge beneath eastern China and a new lithospheric thinning mechanism of the North China craton—Geodynamic effects of deep recycled carbon. Science China (Earth Sciences), 61(7): 853~868.

Li Shuguang, Yang Wei, Ke Shan, Meng Xunan, Tian Hengci, Xu Lijuan, He Yongsheng, Huang Jian, Wang Xuance, Xia Qunke, Sun Weidong, Yang Xiaoyong, Ren Zhongyuan, Wei Haiqun, Liu Yongsheng, Meng Fancong, Yan Jun. 2017. Deep carbon cycles constrained by a large-scale mantle Mg isotope anomaly in eastern China. National Science Review, 4(1): 111~120.

Li Shuguang. 2015&. Tracing deep carbon recycling by Mg isotopes. Geoscience Frontiers, 22(5): 143~ 159.

Li Shuguang. 2017&. A review of tracing deep carbon recycling researches by using Mg isotopes during 2015~2016: progresses and questions. Bulletin of Mineralogy, Petrology and Geochemistry, 36 (2): 197~203+183.

Li Xianhua, Chung Sunlin, Zhou Hanwen, Lo Chinghua, Liu Ying, Chen Changhwa. 2004. Jurassic intraplate magmatism in southern Hunan—eastern Guangxi: $^{40}Ar/Ar$ dating, geochemistry, Sr—Nd isotopes and implications for the tectonic evolution of SE China, Geological Society. London, Special Publications, 226(1): 193~215.

Li Xiyao, Zheng Jianping, Ma Qiang, Xiong Qing, Griffin W L, Lu Jianggu. 2014. From enriched to depleted mantle: Evidence from Cretaceous lamprophyres and Paleogene basaltic rocks in eastern and central Guangxi Province, western Cathaysia block of South China. Lithos, 184~187(1): 300~313.

Li Yanqing, Ma Changqian, Robinson P, Zhou Qin, Liu Mngliang. 2015. Recycling of oceanic crust from a stagnant slab in the mantle transition zone: Evidence from Cenozoic continental basalts in Zhejiang Province, SE China. Lithos, 230(2): 146~165.

Ling Mingxing, Fatemeh S, Teng Fangzhen, Phillip D H, Josiah S, Sun Weidong. 2011. Homogeneous magnesium isotopic composition of seawater: An excellent geostandard for Mg isotope analysis, Rapid Commun. Mass Spectrom, 25(19): 2828~2836.

Liu Chuanzhou, Liu Zhichao, Wu Fuyuan, Chu Zhuyin. 2012. Mesozoic accretion of juvenile sub-continental lithospheric mantle beneath South China and its implications: Geochemical and Re-Os isotopic results from Ningyuan mantle xenoliths. Chemical Geology, 291 (2): 186~198.

Liu Dong, Zhao Zhidan, Zhu Dicheng, Niu Yaoling, Elisabeth W, Teng Fangzhen, Donald J D, Ke Shan, Xu Jifeng, Wang Qing, Mo Xuanxue. 2015. Identifying mantle carbonatite metasomatism through Os—Sr—Mg isotopes in Tibetan ultrapotassic rocks. Earth and Planetary Science Letters, 430(1): 458~469.

Liu Fang, Li Xin, Wang Guiqin, Liu Yufei, Zhu Hongli, Kang Jinting, Huang Fang, Sun Weidong, Xia Xiaoping, Zhang Zhaofeng. 2017a. Marine carbonate component in the mantle beneath the southeastern tibetan plateau: evidence from magnesium and calcium isotopes. Journal of Geophysical Research: Solid Earth, 122(12): 9729~9744.

Liu Jin, Zhang Jian, Yin Changqing, Cheng Changquan, Qian Jiahui, Zhao Chen, Chen Ying, Wang Xiao, Hsia Juiyen. 2020. Newly identified Jurassic—Cretaceous migmatites in the Liaodong Peninsula: unravelling a Mesozoic anatectic event related to the lithospheric thinning of the North China Craton. Geological Magazine, 158(3): 1~17.

Liu Pingping, Teng Fangzhen, Dick H J B, Zhou Meifu, Chung Sunlin L. 2016b. Magnesium isotopic composition of abyssal peridotite. Goldschmidt Conference Abstracts,Yokohama, 1853.

Liu Sheng'ao, Li Shuguang. 2019. Tracing the deep carbon cycle using metal stable isotopes: Opportunities and challenges. Engineering, 5 (3): 448~457.

Liu Sheng'ao, Teng Fangzhen, Yang Wei, Wu Fuyuan. 2011. High-temperature inter-mineral magnesium isotope fractionation in mantle xenoliths from the North China craton. Earth and Planetary Science Letters, 308(1~2): 131~140.

Liu Sheng'ao, Wang Zezhou, Li Shuguang, Huang Jian, Yang Wei. 2016a. Zinc isotope evidence for a large-scale carbonated mantle beneath eastern China. Earth and Planetary Science Letters, 444 (2): 169~178.

Liu Xin, Zhao Dapeng, Li Sanzhong, Wei Wei. 2017b. Age of the subducting Pacific slab beneath East Asia and its geodynamic implications. Earth Planet Sci Lett, 464(1): 166~174.

Liu Yongsheng, Chen Chunfei, He Detao, Chen Wei. 2019#. Deep carbon cycle in subduction zone. Chinese Science: Earth Science, 49(12): 1982~2003.

Liu Yongsheng, Gao Shan, Lee C T A, Hu Shenghong, Liu Xiaoming, Yuan Honglin. 2005. Melt—peridotite interactions: Links between garnet pyroxenite and high-$Mg^{\#}$ signature of continental crust. Earth and Planetary Science Letters, 234(1): 39~57.

Manthilake G, Mookherjee M, Miyajima N. 2021. Insights on the deep carbon cycle from the electrical conductivity of carbon-bearing aqueous fluids. Science Reports, 11(1): 1~10.

Mao Jianren, Li Zilong, Ye Haimin. 2014 #. Mesozoic tectono—magmatic activities in South China: Retrospect and prospect. Science China: Earth Sciences, 57(6): 2853~ 2877.

Mattey D P. 1991. Carbon dioxide solubility and carbon isotope fractionation in basaltic melt. Geochimica et Cosmochimica Acta, 55 (11): 3467~3473.

Meng Fanxue, Shan Gao, Niu Yaoling, Liu Yongsheng, Wang Xiaorui. 2015. Mesozoic—Cenozoic mantle evolution beneath the North China Craton: A new perspective from Hf—Nd isotopes of basalts. Gondwana Res, 27(4): 1574~1585.

Menzies M A, Fan Weiming, Zhang Ming. 1993. Palaeozoic and Cenozoic lithoprobe and the loss of>120 km of Archean lithosphere, Sinokorean craton, China. Geological Society, London. Special Publications, 76(1): 71~81.

Morlidge M, Pawley A, Droop G. 2006. Double carbonate breakdown reactions at high pressures: An experimental study in the system CaO—MgO—FeO—MnO—CO_2. Contrib Mineral Petrol, 152(3): 365~373.

Ning Meng, Huang Kangjun, Shen Bing. 2018&. Applications and advances of the magnesium isotope on the "dolomite problem". Acta Petrochemicals, 34(12): 3690~ 3708.

Niu Yaoling. 2005. Generation and evolution of basaltic magmas: Some basic concepts and a new view on the origin of Mesozoic—Cenozoic basaltic volcanism in eastern China. Geological Journal of China Universities, 11(1): 9~46.

Philip A E P, Elliott T, Marschall H R, Coath C, Lai Y, Jeffcoate B A, Ionov A D. 2011. Variations of Li and Mg isotope ratios in bulk chondrites and mantle xenoliths. Geochimica et Cosmochimica Acta, 75(18)：5247～5268.

Plank T, Manning C E. 2019. Subducting carbon. Nature, 574(7778)：343～352.

Pogge S, James P A E, van Calsteren R H, Gislason P, Burton S R, Lithium K W. 2008. magnesium and uranium isotope behaviour in the estuarine environment of basaltic islands. Earth and Planetary Science Letters, 274 (3～4)：462～471.

Pokrovsky B G, Mavromatis V, Pokrovsky O S. 2011. Covariation of Mg and C isotopes in late Precambrian carbonates of the Siberian Platform：A new tool for tracing the change in weathering regime? Chemical Geology, 290(1～2)：67～74.

Poli S, Franzolin E, Fumagalli P, Crottini A. 2009. The transport of carbon and hydrogen in subducted oceanic crust：An experimental study to 5 GPa. Earth and Planetary Science Letters, 278 (3～4)：350～360.

Richter F M, Watson E B, Mendybaev R A, Teng Fanngzhen, Janney P E. 2008. Magnesium isotope fractionation in silicate melts by chemical and thermal diffusion. Geochimica et Cosmochimica Acta, 72(1)：206～220.

Rudnick R L, Gao Shan, Ling Wenli, Liu Yongshen, William F M. 2004. Petrology and geochemistry of spinel peridotite xenoliths from Hannuoba and Qixia, North China craton. Lithos, 77(1～4)：609～637.

Sato K, Katsura T. 2001. Sulfur：a new solvent—catalyst for diamond synthesis under high-pressure and high-temperature conditions. Journal of Crystal Growth, 223(1～2)：189～194.

Sedaghatpoura F, Teng Fangzhen, Liu Yang, Searsc W G D, Taylorb A L. 2013. Magnesium isotopic composition of the Moon. Geochimica et Cosmochimica Acta, 120(2)：1～16.

Shen Ji, Li Wangye, Li Shuguang, Xiao Yilin. 2019&. Crust—Mantle Interactions at Different Depths in the Subduction ChannelMagnesium Isotope Records of Ultramafic Rocks from the Mantle Wedges. Science China, 44(12)：4102～ 4111.

Sun Pu, Guo Pengyuan, Niu Yaoling. 2021. Eastern China continental lithosphere thinning is a consequence of paleo-Pacific plate subduction：A review and new perspectives. Earth-Science Reviews, 218：103680.

Sun S, McDonough W. 1989. Chemical and isotopic systematics of oceanic basalts：implications for mantle composition and processes. Geological Society, London, Special Publications, 42(1)：313～345.

Tang Yanjie, Ying Fenngji, Zhao Yuepeng, Xu Xinran. 2021#. Nature and secular evolution of the lithospheric mantle beneath the North China Craton. Science China：Earth Sciences, 51 (9)：1489～1503.

Tang Yanjie, Zhang Hongfu, Ying Jifeng, Su Benxun. 2013. Widespread refertilization of cratonic and circum-cratonic lithospheric mantle. Earth-Science Reviews, 118(1)：45～68.

Tang Yanjie, Zhang Hongfu, Ying Jifeng. 2006. Asthenospherelitho spheric mantle interaction in an extensional regime：Implication from the geochemistry of Cenozoic basalts from Taihang Mountains. North China Craton. Chemical Geology, 233(3～4)：309～327.

Tang Yanjie, Zhang Hongfu. 2019#. Lithium isotopic characteristics of the lithospheric mantle beneath North China Craton and the melt modification. Bulletin of Mineralogy, Petrology and Geochemistry. Bulletin of Mineral Rock Geochemistry, 38(2)：217 ～ 223+444.

Tao Renbiao, Zhang Lifen, Fei Yingfei, Liu Qiong. 2014. The effect of Fe on the stability of dolomite at high pressure：Experimental study and petrological observation in eclogite from southwestern Tianshan, China. Geochim Cosmochim Acta, 143(2)：253～267.

Tappe S, Romer L R, Stracke A, Steenfelt A, Smart A K, Muehlenbachs K, Torsvik H T. 2017. Sources and mobility of carbonate melts beneath cratons, with implications for deep carbon cycling, metasomatism and rift initiation. Earth and Planetary Science Letters, 466 (2)：152～167.

Teng Fangzhen, Hu Yan, Catherine C. 2016. Magnesium isotope geochemistry in arc volcanism. Proceedings of the National Academy of Sciences of the United States of America, 113(26)：7082～7087.

Teng Fangzhen, Li Wangye, Ke Shan, Bernard M, Dauphas N, Huang Shichun, Wu Fuyauan, Pourmand A. 2010a. Magnesium isotopic composition of the Earth and chondrites. Geochimica et Cosmochimica Acta, 74 (14)：4150～4166.

Teng Fangzhen, Li Wangye, Roberta L R, Robert G. 2010b. Contrasting lithium and magnesium isotope fractionation during continental weathering. Earth and Planetary ScienceLetters, 300(1～2)：63～71.

Teng Fangzhen, Meenakshi Wadhwa, Helz R T. 2007. Investigation of magnesium isotope fractionation during basalt differentiation：Implications for a chondritic composition of the terrestrial mantle. Earh and Planetary Science Letters, 261(1)：84～92.

Teng Fangzhen. 2017. Magnesium isotope geochemistry. Rev. Mineral. Geochem., 82(1)：219～287.

Thomson A R, Walter M J, Kohn S C, Brooker R A. 2016. Slab melting as a barrier to deep carbon subduction. Nature, 529：76～79.

Tian Hengci, Yang Wei, Li Shuguang, Ke Shan, Chu Zhuyin. 2016. Origin of low δ^{26}Mg basalts with EM-I component：Evidence for interaction between enriched lithosphere and carbonated asthenosphere. Geochimica et Cosmochimica Acta, 188：93～105.

Tian Hengci, Yang Wei, Li Shuguang, Ke Shan, Duan Xianzhe. 2018. Low δ^{26}Mg volcanic rocks of Tengchong in Southwestern China：A deep carbon cycle induced by supercritical liquids. Geochimica et Cosmochimica Acta, 240：191～219.

Tian Hengci, Yang Wei, Li Shuguang, Wei Haiquan, Ke Shan. 2017#. Mg isotopic composition reveals the internal evolution process of Changbai Mountain volcanic rocks. Proceedings of the 9th National Member Congress and 16th Annual Academic Conference of Chinese Society of Mineralogy, Petrology and Geochemistry.

Tipper T E, Bickle J M, Galy A, Catherine P, Hazel J C. 2006b. The short term climatic sensitivity of carbonate and silicate weathering fluxes：Insight from seasonal variations in river chemistry. Geochimica et Cosmochimica Acta, 70(11)：2737～2754.

Tipper T E, Galy A, Bickle M J. 2006a. Riverine evidence for a fractionated reservoir of Caand Mg on the continents：Implications for the oceanic Ca cycle. Earth and Planetary Science Letters, 247 (3～4)：267～279.

Wallace M E, Green D H. 1998. An experimental determination of primary carbonatite magma composition. Nature, 335 (6188)：343～346.

Wang Chen, Liu Zhenghong, Li Gang, Dong Xiaojie, Li Shichao, Zhao Qingying. 2021. Geochronology and geochemistry of late triassic intrusions in the liaodong peninsula, eastern north china craton：implications for post-collisional lithospheric thinning. International Geology Review, 64(8)：1033～1050.

Wang Shuijiong, Teng Fangzhen, Li Shuguang, Hong Jian. 2014a. Magnesium isotopic systematics of mafic rocks during continental subduction. Geochimica et Cosmochimica Acta, 143(2)：34～48.

Wang Shuijiong, Teng Fangzhen, Li Shuguang. 2014b. Tracing carbonate—silicate interaction during subduction using magnesium and oxygen isotopes. Nat Commun, 5(1)：1～6.

Wang Shuijiong, Teng Fangzhen, Rudnick L R, Li Shuguang. 2015a. The behavior of magnesium isotopes in low-grade metamorphosed mudrocks. Geochimica et Cosmochimica Acta, 165(2): 435~448.

Wang Shuijiong, Teng Fangzhen, Scott M J. 2016b. Tracing the origin of continental HIMU-like intraplate volcanism using magnesium isotope systematics. Geochimica et Cosmochimica Acta, 185(2): 78~87.

Wang Shuijiong, Teng Fangzhen, Williams M H, Li Shuguang. 2012. Magnesium isotopic variations in cratonic eclogites: Origins and implications. Earth and Planetary Science Letters, 359(1): 219~226.

Wang Xiaojun, Chen Lihui, Albrecht W H, Hanyu T, Hiroshi K, Zhong Yuan, Xie Liewen, Shi Jinhua, Miyazaiki T, Yuka H, Toshiro T, Ryoko S, Qing Chang, Bogdan S V, Jun-lchi K. 2018. Recycled ancient ghost carbonate in the Pitcairn mantle plume. Proc Natl Acad Sci USA, 115(35): 8682~8687.

Wang Xuance, Li Zhengxiang, Li Xianhua, Li Jie, Liu Ying, Long Wenguo, Zhou Jinbo, Wang Fei. 2011. Temperature, pressure, and composition of the mantle source region of Late Cenozoic basalts in Hainan Island, SE Asia: a consequence of a young thermal mantle plume close to subduction zones. Journal of Petrology, 53(1): 177~233.

Wang Xuance, Wilde A S, Li Qiuli, Yang Yanan. 2015b. Continental flood basalts derived from the hydrous mantle transition zone. Nature Communications, 6(1): 1~9.

Wang Yuejun, Fan Weiming, Cawood P A, Li Sanzhong. 2008. Sr—Nd—Pb isotopic constraints on multiple mantle domains for Mesozoic mafic rocks beneath the South China Block hinterland. Lithos, 106(3): 297~308.

Wombacher F, Eisenhauer A, Bohm F, Gussone N, Regenberg M, Dullo W C, Ruggeberg A. 2011. Magnesium stable isotope fractionation in marine biogenic calcite and aragonite. Geochimica et Cosmochimica Acta, 75(19): 5797~5818.

Wu Fuyuan, Walker J R, Ren Xiangwen, Sun Deyou, Zhou Xinhua. 2003. Osmium isotopic constraints on the age of lithospheric mantle beneath northeastern China. Chemical Geology, 196(1~4): 107~129.

Wu Fuyuan, Xu Yigang, Gao Shan, Zheng Jianping. 2008&. Lithospheric thinning and destrution of the North China Craton. Acta Petrochemicals, 24(6): 1145~ 1174.

Wu Hailin, Zhu Wenbin, Ge Rongfeng. 2022. Evidence for carbonatite derived from the earth's crust: The late Paleoproterozoic carbonate-rich magmatic rocks in the southeast Tarim Craton, northwest China. Precambrian Research, 369: 106425.

Wyllie P J, Huang W L. 1975. Peridotite, kimberlite and carbonatite explained in the system $CaO—MgO—SiO_2—CO_2$. Geology, 3(11): 621~624.

Wyllie P J. 1989. Origin of Carbonatites: Evidence from Phase Equilibrium Studies. Geolgy, 52(1): 500 ~ 545.

Xia QunKe, Hao Yantao. 2013. The distribution of water in the continental lithospheric mantle and its implications for the stability of continents. Chinese Science Bulletin, 58(32): 3879~3889.

Xiao Yan, Teng Fangzhen, Zhang Hongfu, Yang Wei. 2013. Large magnesium isotope fractionation in peridotite xenoliths from eastern North China craton: Product of melt—rock interaction. Geochim Cosmochim Acta, 115(3): 241~261.

Xu Yigang, Huang Xiaolong, Ma Jinlong, Wang Yanbin, Iizuka Y, Xu Jifeng, Wang Qiang, Wu Xiangyang. 2004. Crust—mantle interaction during the tectono—thermal reactivation of the North China Craton: Constraints from SHRIMP zircon U-Pb chronology and geochemistry of Mesozoic plutons from western Shandong. Contributions to Mineralogy and Petrology, 147(6): 750~767.

Xu Yigang, Li Hongyan, Hong Lubing, Ma Liang, Sun Mingdao. 2018#. Generation of Cenozoic intraplate basalts in the big mantle wedge under eastern Asia. Science China: Earth Sciences, 48(7): 825~843.

Xu Yigang, Sun Min, Yan Wenjie, Liu Yang, Huang X L, Chen X M. 2002. Xenolith evidence for polybaric melting and stratification of the upper mantle beneath South China. Journal of Asian Earth Sciences, 20(8): 937~954.

Yang Jinbao, Zhao Zhidan, Mo Xuanxue, Sheng Dan, Ding Cong, Wang Lili, Hou Qingye, Li Hongjin. 2015&. Petrogenesis and implications foralkali olivine basalts and its basic xenoliths from Huaiyan in Dao County, Hunan Province. Acta Petrochemicals, 31(5): 1421~ 1432.

Yang Wei, Li Shuguang. 2008. Geochronology and geochemistry of the Mesozoic volcanic rocks in Western Liaoning: Implications for lithospheric thinning of the North China Craton. Lithos, 102(1~2): 88~117.

Yang Wei, Teng Fangzhen, Zhang Hongfu, Li Shuguang. 2012. Magnesium isotopic systematics of continental basalts from the North China craton: Implications for tracing subducted carbonate in the mantle. Chemical Geology, 328(3): 185~194.

Yaxley G M, Brey G P. 2004. Phase relations of carbonate-bearing eclogite assemblages from 2. 5 to 5. 5 GPa: Implications for petrogenesis of carbonatites. Contributions to Mineralogy and Petrology, 146(5): 606~619.

Young E D, Galy A. 2004. The isotope geochemistry and cosmochemistry of magnesium. In: Hohnson C M, Beard B L, Albarede F (Eds.), Geochemistry of Nontraditional Stable Isotopes, Reviews in Mineralogy & Geochemistry. Mineralogical Society of America, Washington: 55 (1): 197~230.

Zhang Hongfu, Goldstein S, Zhou Xinhua, Sun Min, Zheng Jianping, Cai Yue. 2008. Evolution of subcontinental lithospheric mantle beneath eastern China: Re-Os isotopic evidence from mantle xenoliths in Paleozoic kimberlites and Mesozoic basalts. Contributions to Mineralogy and Petrology, 155(3): 271~293.

Zhang Hongfu, Sun Min, Zhou Xinhua, Zhou Meifu, Fan Weiming, Zheng Jianping. 2003. Secular evolution of the lithosphere beneath the eastern North China Craton: Evidence from Mesozoic basalts and high-Mg andesites. Geochimica et Cosmochimica Acta, 67(22): 4373~4387.

Zhang Hongfu, Zheng Jianping. 2003. Geochemical characteristics and petrogenesis of Mesozoic basalts from the North China Craton: A case study in Fuxin, Liaoning Province. Chinese Science Bull., 48(9): 924~930.

Zhang Hongfu. 2005. Transformation of lithospheric mantle through peridotite—melt reaction: A case of Sino—Korean craton. Earth Planet Sci Lett, 237(3~4): 768~780.

Zhang Lifei, Tao Renbiao, Zhu Jianjiang. 2017&. Some Problems of Deep Carbon Cycle in Subduction Zone. Bulletin of Mineral Rock Geochemistry, 36(2): 185~ 196.

Zhang R Y, Liou J G. 1994. Significance of magnesite paragenesis in ultrahigh-pressure metamorphic rocks. American Mineralogist, 79(3~4): 397~ 400.

Zhao Xinmiao, Zhang Zhaofeng, Huang Shichun, Liu Yufei, Li Xin, Zhang Hongfu. 2017. Coupled extremely light Ca and Fe isotopes in peridotites. Geochimica et Cosmochimica Acta, 208(1): 368~380.

Zhao Zhenhua, Bao Zhiwei, Zhang Boyou, Xiong Xiaolin. 2000#. The crust—mantle interaction background of the Shizhuyuan super-large tungsten polymetallic deposit. Science China: Earth Sciences, 3 (S1): 161~168.

Zhao Zhenhua, Bao Zhiwei, Zhang Boyou. 1998 #. Geochemical characteristics of Mesozoic basalts in southern Hunan. Science China: Earth Sciences, 3(S2): 7~14.

Zheng Jianping, Griffin W L, O'Reilly S Y, Yu C M, Zhang Hongfu, Pearson N, Zhang M. 2007. Mechanism and timing of lithospheric modification and replacement beneath the eastern North China Craton: Peridotitic xenoliths from the 100 Ma Fuxin basalts and a regional synthesis. Geochim Cosmochim Acta, 71 (21): 5203 ~ 5225.

Zheng Jianping, Lu Fengxiang. 1999&. Mantle xenoliths from kimberlites,Shandong and Liaoning: Paleozoic mantle character and its heterogeneity. Acta Petrochemicals, 15 (1): 65~ 74.

Zheng Jianping, O'Reilly S Y, Griffin W L, Lu Fengxiang, Zhang Ming, Pearson N J. 2001. Relict refractory mantle beneath the eastern North China block: Significance for lithosphere evolution. Lithos, 57(1): 43~66.

Zheng Jianping, O'Reilly S Y, Griffin W L, Zhang Ming, Lu Fengxiang, Liu Guanliang. 2004. Nature and evolution of Mesozoic—Cenozoic lithospheric mantle beneath the Cathaysia block, SE China. Lithos, 74(1~2): 41~65.

Zheng Tianyu, Chen Ling, Zhao Liang, Xu Weriwei, Zhu Rixiang. 2006. Crust—mantle structure difference across the gravity gradient zone in North China Craton: Seismic image of the thinned continental crust. Physics of the Earth and Planetary Interiors, 159 (1~2): 43~58.

Zheng YongFei. 2012. Metamorphic chemical geodynamics in continental subduction zones. Chemical Geology, 328 (2): 5~48.

Zhong Yuan, Chen Lihui, Wang Xiaojun, Zhang Guoliang, Xie Liewen, Zeng Guang. 2017. Magnesium isotopic variation of oceanic island basalts generated by partial melting and crustal recycling. Earth and Planetary Science Letters, 463(1): 127~135.

Zhou Xinghua, Richard L A. 1982. Cenozoic volcanic rocks of eastern China: Secular and geographic trends in chemistry and strontium isotopic composition. Earth and Planetary Science Letters, 58(3): 301~329.

Zhu Hongli, Liu Fang, Li Xin, Wang Guiqin, Zhang Zhaofeng, Sun Weidong. 2018. Calcium isotopic compositions of normal mid-ocean ridge basalts from the southern Juan de Fuca ridge. Journal of Geophysical Research: Solid Earth, 123(2): 1303~1313.

Zhu Rixiang, Zheng Tianyu. 2009 #. Destruction geodynamics of the North China Craton and its Paleoproterozoic plate tectonics. China Science Bulletin, 54(1): 1950~1961.

Zhu Rixiang, Xu Yigang, Zhu Guang, Zhang Hongfu, Xia Qunke, Zheng Tianyu. 2012 #. Destruction of the North China Craton. Science China, 2(8): 1135~ 1159.

Zhu Xiangkun, Wang Yue, Yan Bin, Li Jin, Dong Aiguo, Li Hongzhi, Sun Jian. 2013#. Developments of Non-Traditional Stable Isotope Geochemistry. Bulletin of Mineralogy, Petrology and Geochemistry, 32(6): 651~ 688.

Zhu Yongfeng, Ogasawara Y. 2002. Carbon recycled into deep earth: Evidence from dolomite dissociation in subduction-zone rocks. Geology, 30 (10): 947~950.

Zong Keqing, Liu Yongsheng. 2018&. Carbonate metasomatism in the lithospheric mantle: Implications for cratonic destruction in North China.. Science China: Earth Sciences, 48(6):732~752.

Mg isotope tracing the Mesozoic deep carbon cycle in eastern China

DUAN Xianzhe[1,2], NIU Sujuan[1], LI Sai[1,2], LI Nan[2], SUN Haoran[1], GUO Cong[1], XIAO Wenzhou[1,2], SUI Qinglin[1,2], FENG Peng[1,2], HE Haiyang[1,2]

1) *School of Resource & Environment and Safety Engineering, University of South China, Hengyang, Hunan*, 421001;

2) *Hunan Key Laboratory of Rare Metal Minerals Exploitation and Geological Disposal of Wastes, Hengyang, Hunan*, 421001

Abstract: The Earth's deep carbon cycle is of great significance for studying the global climate change, life exploration, and lithospheric evolution. The lithosphere beneath the eastern China is an important place for the deep carbon cycle, and its thinning and destruction are closely related to the deep carbon cycle. The subduction of the Pacific plate in the Mesozoic is the key to the thinning and destruction of the lithosphere in Eastern China, and plays a vital role in the large-scale metal mineralization in North China Craton and South China Block. This paper systematically elucidates the principle of Mg isotope tracing the Earth's deep carbon cycle, gives an example of the deep carbon cycle in the eastern China, and discusses the interaction of the mantle with the carbonated melts/fluids released from the subducted paleo-Pacific plate during the Mesozoic, which is an important reason accounting for the commonly existed light Mg isotopic composition in the eastern China. Furthermore, the polysolvability of light magnesium isotopes is pointed out and the future trend of studying the Earth's deep carbon cycle via multi-isotope joint tracing is also proposed.

Keywords: deep carbon cycle; Mesozoic; lithosphere beneath the eastern China; Mg isotope; lithospheric thinning and destruction; paleo-Pacific plate subduction

Acknowledgements: This study is supported by the by the National Natural Science Foundation of China (Nos. 42102060, 42003028), Innovation Project (No. 202110555075), and Talent foundations of University of

South China (No. 2018XQD22)

First author: DUAN Xianzhe, male, born in 1985, Doctor, Associated Professor, mainly engaged in Petro-/Ore deposit geochemistry; Email: duanxianzhe@126.com

Manuscript received on: 2022-01-22; Accepted on: 2022-05-02; Network published on: 2022-06-20

Doi: 10.16509/j.georeview.2022.06.001 **Edited by**: LIU Zhiqiang

中国地质学会印发《创新基地评选和管理办法(试行)》通知

为深入贯彻落实国家创新驱动发展战略,提高地质科技创新能力,促进地质科技成果转化和示范应用,服务国家经济社会发展。中国地质学会依托自身平台优势和行业特色,开展创新基地建设工作。根据中国科协《中国科学技术协会事业发展“十四五”规划(2021-2025年)》、《“科创中国”三年行动计划(2021-2023)》和《“科创中国”创新基地建设实施与管理办法(试行)》的要求,中国地质学会制定了《中国地质学会创新基地评选和管理办法(试行)》,并经中国地质学会第40届理事会第三十七次常务理事会议(通讯)审批通过,现予以印发,请遵照执行。

附件:《中国地质学会创新基地评选和管理办法(试行)》

第一章 总 则

第一条 为深入贯彻落实国家创新驱动发展战略,打造各类科技创新平台,提高地质科技创新能力,促进地质科技成果转化和应用示范,助力国家经济社会发展。根据中国科协《中国科学技术协会事业发展“十四五”规划(2021-2025年)》、《“科创中国”三年行动计划(2021-2023)》和《“科创中国”创新基地建设实施与管理办法(试行)》的要求,中国地质学会将依托自身平台优势和行业特色,建设一批科技创新平台--创新基地,并择优推荐申报中国科协“科创中国”创新基地。为规范中国地质学会创新基地(以下简称创新基地)建设工作,特制定本办法。

第二条 创新基地应坚持“面向世界科技前沿、面向经济主战场、面向国家重大需求、面向人民生命健康”的战略方向,围绕地质科技前沿和“卡脖子”关键核心技术,凝聚创新资源,加强国际合作,开展前瞻性研判、技术研发、成果转化及应用示范,破解地学领域的重大科技难题,助力新时代地质工作创新发展,为国家经济社会高质量发展提供重要地质科技支撑力量。

第三条 创新基地建设坚持“需求导向、协同攻关、开放融合、互信共享、共同发展”的原则。聚焦国家、行业和区域经济社会发展重大需求,汇聚一批有创新能力、创新激情、创新活力的优秀地质科技工作者,沉淀一批先导技术、产业需求、技术标准和数据资源,联合企业、高校、科研院所等单位的创新团队开展协同攻关创新活动,提升自主创新、成果转化与应用示范的能力,引领行业技术进步,助力国家经济社会发展。

第二章 建设任务

第四条 创新基地分为产学研协作、创新创业孵化、国际创新合作三种类型。

第五条 各类型创新基地的主要任务包括以下内容:

(一)产学研协作类。聚焦关键国家和行业内核心技术领域,开展前瞻性研判,组织团队集聚攻关,取得原创性成果,兼顾公益性与市场化属性,探索产学研可持续协作机制,促进科技成果转化,推动行业技术进步,服务国家经济社会发展;

(二)创新创业孵化类。融合产业界、学术界、创投界等创新要素,促进各领域优秀人才密切联系、交流碰撞,科学有序孵化优质科创企业,营造区域良好创新创业创造生态,服务科技创新创业力量有序壮大和良性扩散;

(三)国际创新合作类。引入境外亟需紧缺科技人才团队和成熟度高、具有实用价值和市场潜力的技术成果,通过合作研究、国际技术转移等形式,促进全球科创资源与区域重点产业和企业高效衔接、持续落地。

第六条 创新基地主要采取以下方式开展具体工作:

(一)坚持问题导向,广泛征集或企业发展过程中面临的技术需求、问题,张榜求贤,吸引有能力的科研单位或团队,开展重点创新任务、重大科技难题攻关,推动行业的技术进步;

(二)围绕国家、区域产业共性问题和企业急需解决的关键技术问题,推行从需求端到研发端的自下而上研发模式,联合企业开展项目技术合作;

(三)坚持目标导向,梳理产业发展共性难题,围绕产业发展需要,促使政府科研立项与产业发展实际紧密结合,加快成果转化速度,引导相关产业链上下游企业加强合作、共同发展;

(四)围绕产业发展需要,梳理科创项目清单,促使政府科研立项与产业发展实际紧密结合;

(五)坚持国内国际两个视野,通过甄选国内外具有实用价值和市场潜力的最新研究成果,组织开展技术和性能试验,最终导入到地方,促进产业发展;

(下转第1411页)