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铍矿分布特点、主要类型与勘查开发现状

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摘要:【研究目的】铍作为最轻的碱土金属, 由于其特殊的密度、刚度与熔点等物理化学特性, 使其成为具有优异功能和结构的材料, 对其开展成因机制和勘探开发研究, 具有重要的科学价值和经济价值。【研究方法】本文系统梳理和总结国内外典型铍矿床的特征、成因及勘探工艺, 采用相似类比等方法, 从时间和空间尺度总结成矿规律, 提出铍矿的勘查、开发和利用建议。【研究结果】铍矿床可分为内生型和外生型。外生型铍矿床可分为与风化作用或变质作用有关的矿床类型; 内生型矿床根据岩浆系统的碱铝属性, 可分为过铝性、偏铝性、过碱性成矿系统, 根据流体演化阶段, 可分为岩浆型、伟晶岩型、岩浆热液型。【结论】从成矿时代来看, 无论过铝性、偏铝性还是过碱性系统的铍成矿作用均集中于中生代, 燕山期更是铍矿的主要成矿期; 从成矿构造背景角度, 岩浆型铍矿常产于后碰撞环境, 岩浆热液型铍矿则产于大陆边缘, 而伟晶岩型铍矿基本产于造山带。铍是新兴材料之一, 在未来节能减排、碳中和计划中将发挥重要作用, 应加强铍矿综合利用和回收技术的研发。

关键词: 铍矿; 分布特点; 成矿类型; 勘查开发; 远景; 地质调查工程

创新点: 采用相似类比等方法, 结合勘探开发价值, 从时间和空间尺度总结铍矿成矿规律。

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Distribution characteristics, main types and exploration and development status of beryllium deposit

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Abstract: This paper is the result of geological survey engineering.

[Objective] As the lightest alkaline earth metal, beryllium has become an excellent functional and structural material. Due to its special physical and chemical characteristics such as density, stiffness and melting point, it has great scientific and economic value

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for researching the genetic mechanism, exploration and development. **[Methods]** In this paper, the characteristics, genesis and exploration technology of typical beryllium deposits in the domestic and overseas are systematically sorted out and summarized. The metallogenic rules are summarized from time and space scales by means of similarity and analogy, and the exploration, development and utilization suggestions are also put forward. **[Results]** Beryllium deposits can be divided into endogenous and exogenous types. Exogenous beryllium deposits can be subdivided into different deposit types related to weathering or metamorphism. According to the alkali-aluminum properties of magma system, endogenous beryllium deposits can be subdivided into peraluminous, metaluminous and peralkaline metallogenic systems. According to the fluid evolution stage, it can be subdivided into magma type, pegmatite type and magma hydrothermal type. **[Conclusions]** From the perspective of metallogenic age, the beryllium mineralization in either peraluminous, metaluminous or peralkaline systems is concentrated in the Mesozoic. Yanshanian is the main metallogenic period of beryllium deposits. From the perspective of metallogenic structure background, the magma type is often produced in post-collision environments, the magmatic hydrothermal type is produced on the continental margin, and the pegmatite type is basically produced in the orogenic belt. Beryllium is one of the new materials, which will play an important role in energy conservation, emission reduction and carbon neutralization in the future. Research on comprehensive utilization and recovery technology of beryllium deposits should be strengthened.

Key words: beryllium deposit; distribution characteristics; metallogenic types; exploration and development; prospects; geological survey engineering

Highlights: By means of similarity and analogy, combined with the exploration and development value, the metallogenic regularity is summarized from time and space scale.

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1 引言

铍作为一种稀有金属,在元素周期表中排行第四,是最轻的碱土金属,密度与镁相似,刚度与钨相当,熔点高达1285℃,具有非常强的热中子散射能力,以上特殊性能使其成为具有优异功能和结构的材料,被广泛应用于航空航天、计算机、国防、医疗、核能和冶金行业,有“超级金属”、“尖端金属”的美誉(许德美等,2014;李健康等,2017)。自然界中已发现100多种含铍矿物,包括砷酸盐、硼酸盐、氢氧化物、氧化物、磷酸盐和硅酸盐等。目前,可供开采利用的铍矿物主要包括绿柱石、羟硅铍石和矽铍石,绿柱石是与岩浆作用和变质作用有关的主要含铍矿物,而羟硅铍石和矽铍石是火山岩型和碳酸盐岩型矿床中的主要矿物。此外,金绿石和日光榴石也可用于工业选冶。绿柱石是在高温岩石中形成的主要硅酸铍矿物,并且具有较高的丰度,如美国犹他州哇华山脉的红色绿柱石(Lindsey et al., 1973,

1981; Barton, 1986; Keith et al., 1994; Barton and Young, 2002)。羟硅铍石是常温下最稳定的矿物,而矽铍石则在250℃以上才是稳定的,矽铍石在较低的温度下会液化为羟硅铍石(Barton, 1986)。羟硅铍石和矽铍石通常与绿柱石共存于碳酸盐岩、矽卡岩和云英岩中,羟硅铍石是与火山活动有关的矿床中铍的主要矿石矿物,在碳酸盐岩脉中与矽铍石共生。

由于铍矿特殊的赋存状态,其形成机制、矿物组合、成矿背景、矿床成因等方面的研究一直备受关注且较为薄弱。基于此,本文在系统梳理典型铍矿的矿床地质、成矿来源以及成矿时代等方面研究成果的基础上,通过同类型铍矿床的类比研究,总结铍矿的分布、成因类型和勘查开发现状,为中国铍矿的找矿勘查提供借鉴。

2 铍矿分布

铍矿资源丰富且分布集中,美国地质调查局年

报数据显示,按照已探明的资源量计算,美国、巴西、俄罗斯、印度和阿根廷是主要产出国。此外,马达加斯加、莫桑比克、尼日利亚、赞比亚以及卢旺达也是重要的铍生产国(图1)。但目前只有美国和俄罗斯具有工业规模的矿石开采、提取冶金、金属加工的完整工业体系。目前已查证的铍金属资源量338万t,虽然铍资源丰富,但其单一矿床少、品位较低,综合利用难度较大,资源供应高度集中,约60%的资源量集中于美国,且美国铍矿资源主要分布于犹他州斯波山脉、内华达州麦卡洛山脉等地区,其中犹他州的已探明铍金属储量达1.8万t。巴西是绿柱石型铍矿的主要开采国,其中米纳斯吉拉斯州的戈伟尔纳多—瓦拉达雷斯伟晶岩型矿床的矿石储量达38.6万t。Yermakovskiy矿床是俄罗斯最大的铍矿床,储量约1万t,矿床平均品位为1.3%。中国虽然是第二大铍生产国,但铍资源供不应求,对外依存度高达87%。截止2017年,铍矿床主要分布于新疆、内蒙古、云南和四川,这4省(自治区)的合计储量占中国总量的89.5%(林德松,1985;李健康等,2017;张森等,2018;林博磊等,2018;李娜等,2019;乔耿彪等,2020;Zhang et al., 2023),其中新疆的铍资源储量约占全国的三分之一。

3 铍矿床主要类型

传统上,铍矿床可分为内生型和外生型。对于外生型铍矿床来说,成因类型较简单且规模小、数量少,多数与风化作用有关,少量与变质作用关系密切。对于内生型矿床来说,学者们普遍支持根据岩浆系统的铝饱和指数进行分类(Browning et al., 1964; Barton and Young, 2002; Gaillarde et al., 2003; Galeschuk and Vanstone, 2005; 李健康等, 2017),这种分类方案更能有效地反映不同类型铍矿床的地质条件,特别是构造环境、矿物组成、成矿物质来源和赋矿岩石类型等矿床地质特征。因此,根据岩浆系统的碱铝属性,可分为过铝性、偏铝性、过碱性成矿系统;根据流体演化阶段,可分为岩浆型、伟晶岩型、岩浆热液型等3个类型(表1)。过铝性成矿系统的矿石矿物主要为绿柱石,偏铝性成矿系统的矿石矿物主要为羟硅铍石、羟羟硅铍石、日光榴石等,过碱性成矿系统的矿石矿物主要为硅铍钠石、斜方板晶石、硅钡铍矿、羟硅铍石、羟羟硅铍石、硅铍钇矿等。

目前,具有经济价值的铍矿床多与岩浆作用有关,常赋存于富碱性和高铝质岩石中,成矿岩体多为富集稀有金属元素的长英质岩石、火山岩以及伟

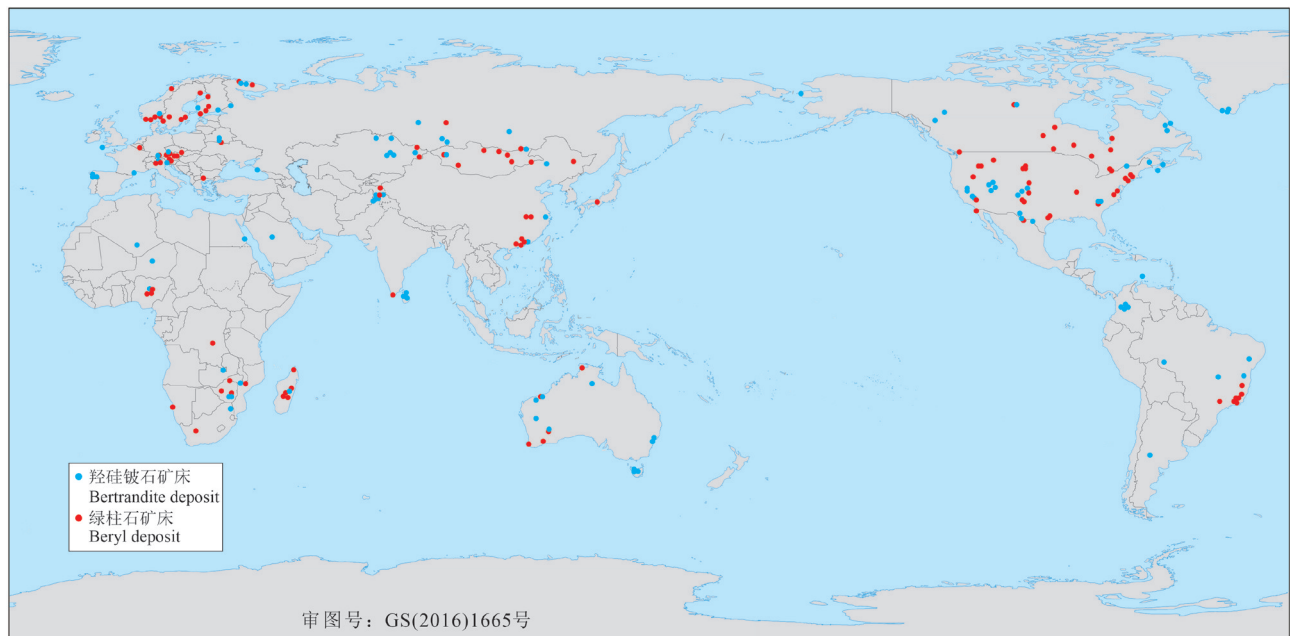


图1 全球主要铍矿床分布图(据Foley et al., 2012; Kesler et al., 2012; Bradley and McCauley, 2013)
Fig.1 Distribution map of the main beryllium deposits in the world (after Foley et al., 2012; Kesler et al., 2012; Bradley and McCauley, 2013)

表1 主要铍矿床特征

Table 1 The characteristic of main beryllium deposits

矿床类型	矿床名称	成矿相关岩体	产地	国家	BeO 品位/%
岩浆型	Apache Warm Springs	火山岩	新墨西哥州	美国	0.26
	Brockman	火山岩	西澳大利亚	澳大利亚	0.08
	Spor Mountain	火山岩	犹他州	美国	0.266~0.720
	Aqshatau	云英岩	Aqshatau	哈萨克斯坦	0.03~0.07
	Boomer, Lake George	云英岩	科罗拉多州	美国	2.0~11.2
	Sheeprock	云英岩	犹他州	美国	0.01~0.1
	Ukrainian Shield	云英岩	乌克兰	乌克兰	0.4
	Ilimaussaq	过碱性岩	Ilimaussaq	格陵兰岛	—
	Kvanefjeld	过碱性岩	Ilimaussaq	格陵兰岛	—
	Seal Lake	过碱性岩	西北地区	加拿大	0.35~0.4
	Strange Lake	过碱性岩	魁北克、纽芬兰 和拉布拉多	加拿大	0.08
	Thor Lake	过碱性岩	西北地区	加拿大	0.76
	Aguachile	碳酸盐岩	科阿韦拉	墨西哥	0.1
	岩浆热液型	Iron Mountain	碳酸盐岩	阿拉斯加州	美国
McCullough Butte		碳酸盐岩	内华达州	美国	0.027
Sierra Blanca		碳酸盐岩	德克萨斯州	美国	0.5~1.9
Victorio Mountains		碳酸盐岩	新墨西哥州	美国	0.023
Lost River		矽卡岩	阿拉斯加州	美国	0.3~1.75
Vozneskoye		矽卡岩	西伯利亚	俄罗斯	0.06
Yermakovskoye		矽卡岩	西伯利亚 布里亚特	俄罗斯	1.3
伟晶岩型		Atlantic shield	伟晶岩/花岗岩	巴西	巴西
	Black Hills	伟晶岩/花岗岩	南达科他州	美国	0.05
	Rodenhouse Wash	伟晶岩/花岗岩	犹他州	美国	0.5
	Tanco	伟晶岩/花岗岩	马尼托巴省	加拿大	0.2
	Tin-spodumene belt	伟晶岩/花岗岩	北卡罗莱纳州 南卡罗莱纳州	美国	0.02~0.1
	Hellroaring Creek	伟晶岩/花岗岩	大不列颠哥伦比亚	加拿大	0.1

资料来源:Griffits, 1954; Browning, 1961; Beus, 1966; Griffits and Pratt, 1973; Barton and Young, 2002; Grew, 2002; Kuperman et al., 2006; Brush Engineered Materials, Inc., 2009; McLemore, 2010a.

晶岩,矿床富含羟硅铍石、绿柱石和矽铍石(Taylor and McLennan, 1985, 1995; Bruce and Odin, 2001; Barton and Young, 2002; Černý, 2002; Bhat et al., 2002; Taylor et al., 2003)。其中,岩浆岩型铍矿床是指铍成矿作用主要发生于岩浆结晶分异阶段的矿床,岩浆岩型→伟晶岩型→热液型铍矿床体现了岩浆-热液的演化过程,三者之间存在连续的演化关系。热液型铍矿床包括矽卡岩型、交代型、云英岩型和热液脉型矿床(表2),主要反映了硅铝质岩、碳酸盐岩和超基性岩等围岩条件的差异(Burt et al., 1982; Walker et al., 1986; Černý et al., 2005),矿物组成和成分随着围岩成分组成的不同而变化。目前规模较大、品位较高的岩浆岩型工业矿床常产于富

含锂、绿柱石的伟晶岩中(Day et al., 2006; Glover et al., 2012; Foley et al., 2012; Bradley and McCauley, 2013)。本文从经济价值和铍矿资源量角度出发,系统总结了主要铍矿床类型(表2)。

3.1 伟晶岩型铍矿床

许多辉长岩、花岗岩和正长岩均含有绿柱石,但只有花岗伟晶岩中的绿柱石可供工业开采,尽管花岗伟晶岩分布广泛且相对普遍,但富含稀有金属元素的伟晶岩仅占0.1%(London, 2005; Laznicka, 2006)。其中,LCT(锂铍钽)型和NYF(铌钇氟)型伟晶岩是绿柱石的主要赋矿岩石,而最重要的工业类型是LCT型花岗伟晶岩(图2),可供利用的绿柱石均产自成分复杂的伟晶岩,如马达加斯加的

表2 与岩浆作用有关的铍矿床特征(据 Barton and Young, 2002)

Table 2 The characteristics of beryllium deposits related to magmatism in the world (after Barton and Young, 2002)

成矿岩体类型	围岩类型			
	火山岩	铝硅酸盐岩	碳酸盐岩	镁铁质—超镁铁质岩石
花岗岩	矿物	锂云母, 绿柱石	绿柱石, 羟硅铍石	羟硅铍石, 金绿宝石, 日光榴石
	产地	Beauvoir(法国)	Sherlova(俄罗斯)	Lost River(美国)
		Sheeprock(美国)	Mt. Antero(美国)	Mt. Bischoff(澳大利亚)
		Aqshatau(哈萨克斯坦)	Mt. Wheeler(美国)	Reft River(俄罗斯) Khaltro(巴基斯坦) Camaiba(巴西)
准铝质到过铝质	矿物	绿柱石		
	花岗岩伟晶岩(LCT型)	产地	Minas Gerais(巴西)	
		Bemic Lake(加拿大)	Transbaikalia(俄罗斯)	
		Bikita(津巴布韦)		
花岗岩伟晶岩(NYF型)	矿物	绿柱石		
	产地	Mt. Antero(美国)		
		Transbaikalia(俄罗斯)		
		Ledu(美国)		
		Amherst Co.(美国)		
流纹岩	矿物	火山玻璃/云母中的铍	绿柱石	羟硅铍石
	产地	Macusani(秘鲁)	Wah Mtns. (美国)	Spor Mtn.(美国)
		Warm Springs(美国)	Black Range(美国)	Aguachile(墨西哥)
		Spor Mtn.(美国)	Sierra Blanca(美国)	
花岗岩	矿物	硅铍钇矿族	羟硅铍石, 日光榴石, 硅铍钇矿	羟硅铍石, 矽铍石, 白铍石
	产地	Khaldzan-Burgtey(蒙古)	VerkneeEspee(哈萨克斯坦)	Yermakovskoye(俄罗斯)
				Iron Mtn.(美国)
花岗岩伟晶岩(NYF型)	矿物	硅铍钇矿, 羟硅铍石		
	产地	Strange Lake(加拿大)		
		Pikes Peak(美国)		
		Sawtooth batholiths(美国)		
碱性到过碱性	矿物	绿柱石		
	花岗岩伟晶岩(LCT型)	产地	Ivisaartoq(格陵兰岛)	
流纹岩	矿物	羟硅铍石, 玻璃中的铍, 透锂长石, 锂铍脆云母, 日光榴石		羟硅铍石
	产地	Brockman(澳大利亚)		Aguachile, Coahuila(墨西哥)
正长岩伟晶岩(LCT型和NYT型)	矿物	斜方板晶石, 双晶石, 硅铍钠石		
	产地	Lovozero(俄罗斯)		
		Ilimaussaq(格陵兰岛)		
		Oslo(挪威)		
正长岩	矿物	硅铍钠石, 斜方板晶石	重晶石, 双晶石	羟硅铍石
	产地	Ilimaussaq(格陵兰岛)	Seal Lake(加拿大)	Hicks Dome(美国)
		Wind Mtn.(美国)	Thor Lake(加拿大)	Thor Lake(加拿大)

Anjanaboina 伟晶岩 (Martin and De Vito, 2005)。LCT型花岗伟晶岩富含铝质成分,符合S型花岗岩特征,通常认为,其形成与板块俯冲作用或陆陆碰撞有关 (London and Evensen, 2002; Lide, 2005; Martin and De Vito, 2005; Černý et al., 2012),也有学者将其与碰撞后期构造演化相联系 (Graedel et al., 2011; London and Kontak, 2012)。此外,LCT型伟晶岩的地球化学特征表明,它们源自地壳未熔融的、富含云母的岩石,而白云母和黑云母类矿物均富含独特的稀有元素 (Černý et al., 2012)。研究表明,过铝质矿物经部分熔融作用,可形成多种流体成分 (富含硼,氟和磷),这在LCT型伟晶岩的形成中起着至关重要的作用,其将包括Be, Cs, Nb, Rb, Sn和Ta在内的稀有金属元素转移到热液中,并富集成矿 (Gaillardet et al., 2003; Linnen et al., 2012)。富含稀有金属矿物的伟晶岩通常产于白垩纪地层,且带状伟晶岩的含矿性更好,矿体中的绿柱石来自于高度分异、结晶完全的伟晶岩,呈块状、脉状产出。绿柱石产量较高的重要伟晶岩地区主要有巴西米纳斯吉拉斯州的Rio Jequitinhonha、葡萄牙Viseu州的Covas do Barroso、莫桑比克赞比亚省的Alto Ligonhain、加拿大曼尼托巴省的伯尼克湖、纳米比亚的卡里比卜、津巴布韦Masvingo省的Bikita以及美国北卡罗莱纳州的金斯山和南达科他州的锡山地区 (Grundmann and Morteani, 1989; Hawkins, 2001; Kesler et al., 2012)。多数伟晶岩矿床储量达几千吨,最大储量高达100万t,较典型的实例是加拿大马尼托巴省的坦科矿床,其绿柱石呈针状、柱状赋存在钠长石花岗岩中,矿石中含有超过350 g/t的铍,这是陆壳背景值的180倍,此外还有13900 g/t的锂,236000 g/t的铯,28900 g/t的铷,和超过1200g/t的钽 (Stilling et al., 2006)。

3.2 矽卡岩和云英岩型铍矿床

含铍矽卡岩和云英岩与许多大型的富含稀土金属元素的花岗岩和正长岩共生,这类矿床是侵入体和围岩之间发生接触交代作用形成的,通常含有羟硅铍石、矽铍石和铍硅酸盐矿物 (图2)。矽卡岩是由碳酸盐岩围岩的高温蚀变形成,而云英岩是由铝硅酸盐成分岩石蚀变形成,分带现象明显,包括铍矿带、萤石带、磁铁矿带和硅酸盐带。铍赋存于萤石和石灰石等矿物中,产于蚀变花岗岩的细脉

中,矿石矿物主要是绿柱石、铍硅酸盐矿物和羟硅铍石,脉石矿物主要是方解石、石榴石、石英、黄玉、电气石、铁锂云母以及其他硫化物。例如,美国的Lost River矽卡岩矿床、俄罗斯的Yermakovskoye矿床以及布里亚共和国的Kizhinginskiy Khrebet矿床 (Reyf, 2008; Aleksandrov, 2010)。

3.3 碳酸盐岩型铍矿床

碳酸盐岩中的铍矿床形成于碳酸盐地层中,富含稀有金属元素的岩浆侵入于碳酸盐岩中,在接触部位发生交代作用,导致铍元素富集、沉淀 (图2)。这类铍矿床的代表是美国德克萨斯州的塞拉布兰卡和墨西哥的Aguachile。其中,在塞拉布兰卡,富铍的萤石矿床与高碱性铝质火山岩有关,白垩纪石灰岩受到后期的流纹岩岩浆作用,导致铍矿的矿化富集,流纹岩偏铝质,铍和氟明显高于背景值 (Shannon, 1976; Hörmann, 1978; Rubin et al., 1987),同时,还富集Li、Nb、Rb、稀土元素(REE)、Th、Y、Zn等。而Aguachile的铍矿化是石灰岩被火山口附近的流纹岩结晶时形成的,角砾岩筒控矿作用明显,羟硅铍石与方解石、石英共生于石灰岩中,矿体中氧化铍的含量约为0.3% (McLemore and Guilinger, 1993; Hu and Gao, 2008; McLemore, 2010b; Kim et al., 2010)。

3.4 火山岩型铍矿床

火山成因类型的铍矿物是通过类质同相碎屑岩中的碳酸盐矿物而形成的,该碎屑岩是由压实的火山灰,火山玻璃和岩石碎屑组成 (图2)。主岩通常是富含稀土金属元素的流纹岩、火山熔岩以及凝灰岩,其组成从偏铝质到高铝质,并富含氟和其他亲石元素(Be、Ce、Li、Rb、REE、Sn、Th、Tl和U)。成矿构造环境是一种伸展的环境,后期火山岩覆盖了较早的白云岩、石灰岩或页岩。矿物是火山作用形成的,产生了富含氟、铍和气体的流纹岩熔体,熔体的脱气会引起强烈的火山活动,当岩浆通过石灰岩层的裂缝而喷发到地表时,石灰岩碎裂、熔融,热的岩浆与地下水相互作用,岩浆和热液的混合物能够从火山玻璃中浸出铍,当热液在凝灰岩中遇到碳酸盐矿物时,铍就可以作为羟硅铍石沉淀。比较典型的实例是美国犹他州的Spor Mountain,其成矿岩体主要是中新世凝灰岩组成,凝灰岩由火山玻璃、火山灰、碳酸盐矿物和其他岩石碎屑组成 (图3)。羟

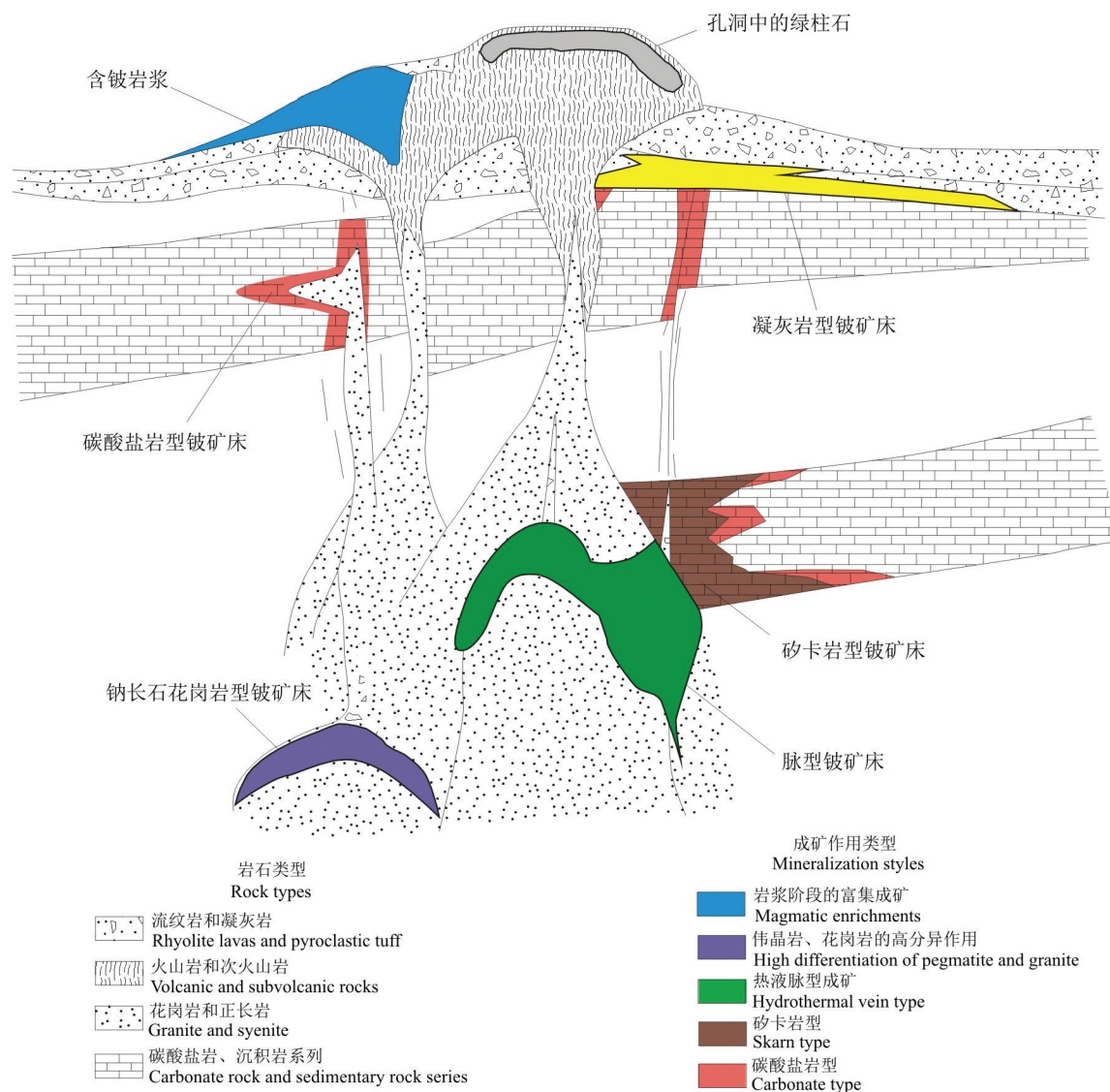


图2 铍矿成矿模式及矿化类型图(据Barton and Young, 2002;李健康等,2017修改)

Fig.2 Metallogenic model and mineralization type of beryllium ore (modified from Barton and Young, 2002; Li Jiankang et al., 2017)

硅铍石以亚微晶的形式存在,并与细粒状萤石、蛋白石和方解石共生,呈层状产出。矿化凝灰岩中玻璃熔体铍含量(59 g/t)约为未矿化凝灰岩的玻璃熔体铍含量(7 g/t)的8倍(Lin et al., 1995; Adams et al., 2009; Emsley, 2001),这表明约90%的铍元素重新富集于矿化的碳酸盐岩中。此类矿床数量较少,仅有澳大利亚的布罗克曼、秘鲁的马库萨尼、蒙古的戈维—阿尔泰矿床,其中布罗克曼矿床与富含挥发性物质的古元古代火山碎屑岩有关,探明储量约为430万t, Nb_2O_5 品位0.44%,铍品位50~1500 g/t

(Kovalenko and Yarmolyuk, 1995)。

3.5 变质和沉积型铍矿床

铍矿物还存在于变质和沉积环境中,通过变质和沉积过程中矿物的原地富集、重结晶和冲积可以促使铍的再次分配和铍矿物的优选重组,进而成矿,该类矿床可进一步细分为盆地卤水型矿床、变质型矿床和砂矿型矿床(李健康等,2017)。通常情况下,变质和沉积型铍矿床不含或少含绿柱石和矽铍石,其以绿宝石形式产出(Kabata-Pendias and Mukherjee, 2007),典型的矿床如哥伦比亚的Muzo

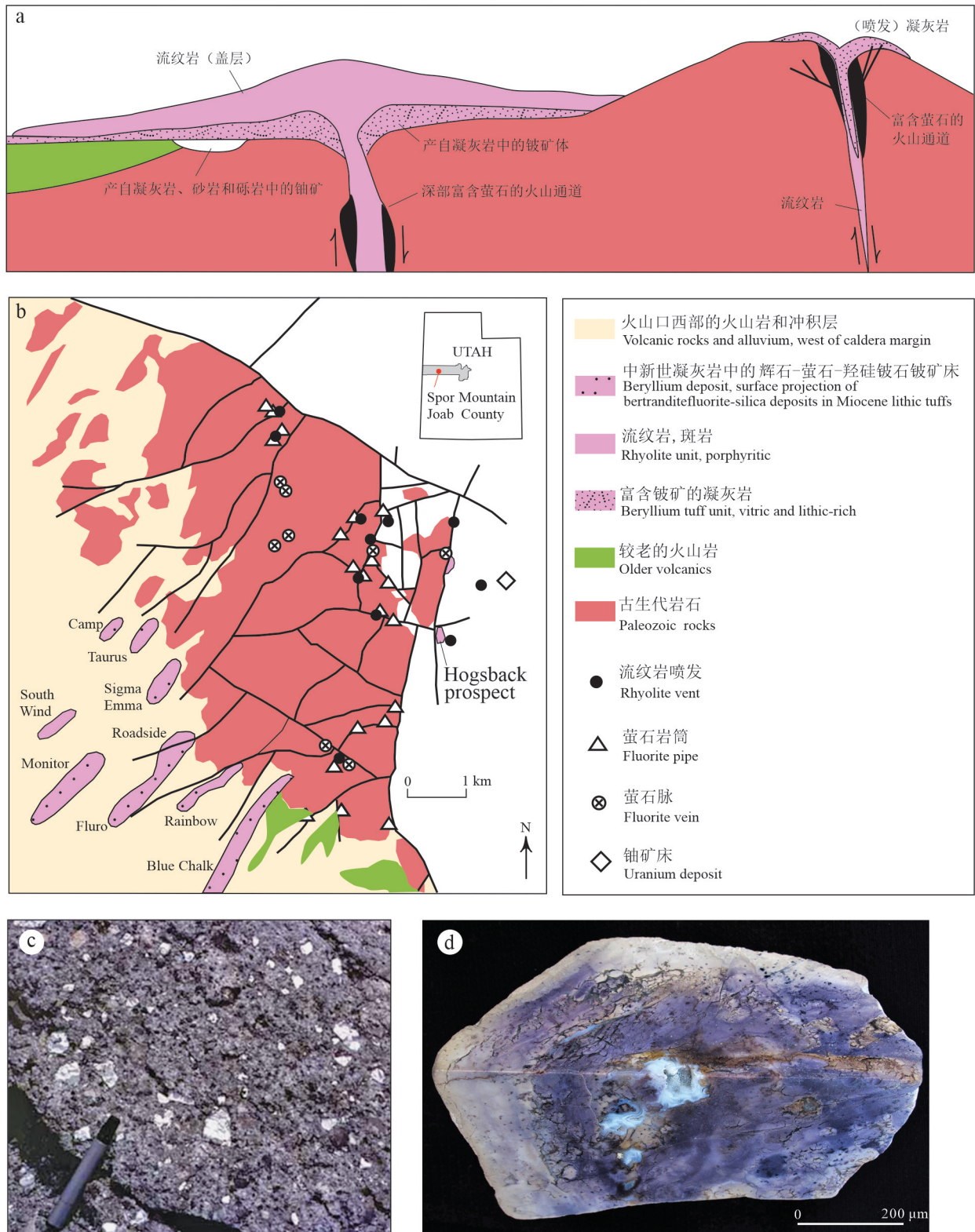


图3 典型火山岩型铍矿床地质及成因类型图(据Lindsey, 1981, 1998; Foley et al., 2012)

a—火山岩型铍矿床成矿模式图;b—犹他州斯波尔山矿区地质图;c—斯波尔山矿区的含铍凝灰岩;d—萤石结核的电子探针显微照片

Fig.3 Geology and genetic type map of typical volcanic beryllium deposits (after Lindsey, 1981, 1998; Foley et al., 2012)

a—Metallogenetic model of volcanic beryllium deposits; b—Geologic map of Spor Mountain area, Utah; c—Photograph of beryllium tuff at Spor Mountain; d—Electron probe micrograph of nodule from the Spor Mountain tuff

和Chivor祖母绿矿床,该矿床的绿柱石和蓝柱石专门作为宝石开采,既提供了铍矿石又提供了宝石(Engell et al., 1971; Epstein, 1991),巴西、马达加斯加和斯里兰卡都有此类矿床。非岩浆系统矿床并不是绿柱石的主要来源,大多数矿山都是绿宝石类矿物的产地,例如海蓝宝石、金绿宝石、祖母绿以及蓝柱石。

4 铍矿成矿特点

典型铍矿床特征显示(表1~2),从成矿时代来看,铍在各类岩浆岩中丰度分布具有一定规律,表现为由基性岩向酸性岩逐渐升高的趋势。同时,从四堡—雪峰期、加里东期、海西期到燕山期,年代越新铍的丰度越高,总体上,无论过铝性、偏铝性还是碱性系统的铍成矿作用均集中在中生代,燕山期更是铍矿的主要成矿期(王登红等, 2017; 梁飞, 2018)。从成矿构造背景角度,不同的构造环境产出不同的矿床类型,如花岗岩型常产于后碰撞环境,沉积岩型则产于大陆边缘,而伟晶岩型铍矿基本产于造山带,学者们普遍认为(Eckel and Jacob, 1988; 李健康等, 2017; Ren et al., 2017),大型的铍矿多赋存在长英质岩石中,这类铍矿床产出环境包括汇聚边缘的挤压环境、碰撞环境、碰撞后转换拉伸环境,裂谷伸展环境和陆内伸展环境,在这些构造背景具有相对增厚的大陆地壳,有利于产生和分异出与铍成矿相关的长英质岩浆。

5 铍矿勘探开发现状

5.1 勘探现状

现有资料表明(Griffitts, 1954; Sainsbury, 1963, 1964a, b; Griffitts and Pratt, 1973; Dobson, 1982; Walker et al., 1986; Rubin et al., 1988; Henry, 1992; Krogstad et al., 1993; Agency for Toxic Substances and Disease Registry, 2002; Sirbescu and Nabelek, 2003; Reyf, 2008; McLemore, 2010b; Kislov et al., 2010; Lykhin et al., 2010; Global Industry Analysts Inc, 2012; Jaskula, 2013b; 任军平等, 2019; 李娜等, 2019; 左立波等, 2020),正在勘探和开发的铍矿床主要分布于美国西部、加拿大东部、巴西东部、非洲的赞比亚、津巴布韦和莫桑比克、澳大利亚的西部、哈萨克斯坦和俄罗斯。另外,印度、马来西亚、哥伦

比亚等国也有少量分布。开采绿柱石的主要伟晶岩区位于巴西 MinasGerais 州、葡萄牙 Covado Barroso 伟晶岩区、莫桑比克赞比西省、加拿大曼尼托巴省、魁北克省、津巴布韦马斯温戈省等地;具有找矿潜力的铍矿远景区主要分布于美国爱达荷州、蒙大拿州—加拿大不列颠哥伦比亚省—美国阿拉斯加州的大型伟晶岩型稀有金属成矿带上(图4)。此外,欧洲和南部非洲也具有较大的找矿潜力,如赞比亚古元古代滑石片岩及古生代伟晶岩中的绿柱石含量较高(Ren et al., 2017)。开采羟硅铍石的地区主要有俄罗斯的 Yermakovskoye 以及美国犹他州的斯波山;具有找矿潜力的远景区位于美国犹他州、新墨西哥州等具有火山成因类型的成矿区带上,以及外贝加尔—蒙古晚中生代稀土金属成矿带上。另外,澳大利亚的北部,秘鲁的东南部也具有一定的潜力。

5.2 开发现状

2011年,铍矿年产量在为260 t(主要来自莫桑比克、葡萄牙和美国),其中235 t产自美国 Spor Mountain 岩浆型铍矿床(Jaskula, 2013a, b),其余25 t为其他地区的伟晶岩型铍矿床。生产绿柱石矿石的国家主要包括巴西、马达加斯加、莫桑比克和葡萄牙,尼日利亚、哈萨克斯坦和乌干达也可生产少量绿柱石。美国是世界上最大的羟硅铍石生产国,而唯一的生产商 Materion Corp. 的生产量占2011年铍矿总产量的91%。

5.3 勘查技术方法

早期的铍矿勘探设备以中子源伽马射线能谱仪为主,它能够对岩石中的铍含量进行快速半定量分析(Meeves, 1966)。随着技术的不断发展,重、磁、电、震等物探手段被利用起来,这些综合物探方法的应用,大大提高了铍矿的勘查精度。目前,主要基于有利的成矿构造背景,利用含铍岩石组合和蚀变模式来进行找矿勘探的技术已成为主流(Foley et al., 2012)。磁场、重力和地震等数据可用于识别有利的成矿构造环境及大型岩体,这些具有成矿潜力的岩体可能含有火山成因的铍矿床。火山岩中富含氟和铍的流纹岩显示出较好的成矿潜力,角砾岩中碳酸盐岩捕虏体、火山口构造及有利的赋矿围岩都是直接的找矿标志,铍矿可能与火山凝灰岩有关,而萤石和铀矿床的存在也是铍矿富集

的有利条件 (Montoya et al., 1962; Pearson, 1963; Lindsey, 1975; Taylor et al., 1995a,b)。研究表明,铍矿体的围岩常发育热液蚀变矿物,特别是大量锂蒙脱石的存在,以及 Be, Ce, F, Ga, Li, Nb 和 Y 等元素的地球化学异常都可指导找矿 (Lindsey et al., 1973; Petkof, 1985; Pichavant et al., 1988a; Wood, 1992; Suter, 1996)。

在伟晶岩发育区,富含绿柱石的 LCT 型伟晶岩是直接的找矿标志,利用物探手段,可以轻易发现伟晶岩体 (Bradley and McCauley, 2013; Olson, 2016)。在浅覆盖区,伟晶岩容易识别,它们具有颜色较浅、晶体颗粒较大且抗风化的特点。伟晶岩型铍矿勘查的首要目标是明确花岗岩岩石组合, Bradley and McCauley (2013) 提出了造山带背景、中压和中高温变质条件、高度演化的花岗岩和花岗伟晶岩的存在是成矿有利条件。由于绿柱石与高度分异的伟晶岩有关,因此花岗岩-伟晶岩的矿物学和地球化学变化特征是间接找矿标志 (Pichavant et al., 1988b; Selway et al., 2005; Deubner et al., 2011)。例如,绿柱石的颜色从绿棕色变为粉白色,

指示着铍元素富集沉淀作用 (Deubner et al., 2001)。同样,特定矿物的化学变化,如钾长石中铷的增加、白云母中锂的增加、石榴石中锰的增加以及铌钽铁矿中铌和锰的增加,可用于在较大的区域中定位 LCT 型伟晶岩体。同时,许多 LCT 型伟晶岩的围岩和土壤中均显示出碱性元素 (铯, 锂和铷) 的地球化学异常 (Rossman, 2004; Galeschuk and Vanstone, 2007), 土壤中 As, Be, Sb 和 Sn 的异常以及锡石等矿物的出现也可指示 LCT 型伟晶岩的存在 (Smith et al., 1987, 2013; Ramsden et al., 1993)。

6 铍矿研究与开发过程中存在的问题

6.1 需要研发储量、品位核算新方法

前期的估算方法仅针对当时有工业意义的铍矿床,较为局限,学者们 (Galeschuk and Vanstone, 2007; Stefaniak et al., 2008; Foley et al., 2012; Duling et al., 2012; Bradley and McCauley, 2013) 对 Spor Mountain 矿床以及其他地区相关类型矿床 (碳酸盐岩和萤石矿床) 进行的地质和地球化学研究表明,估算火山岩系统中的铍矿边界品位和储量是有

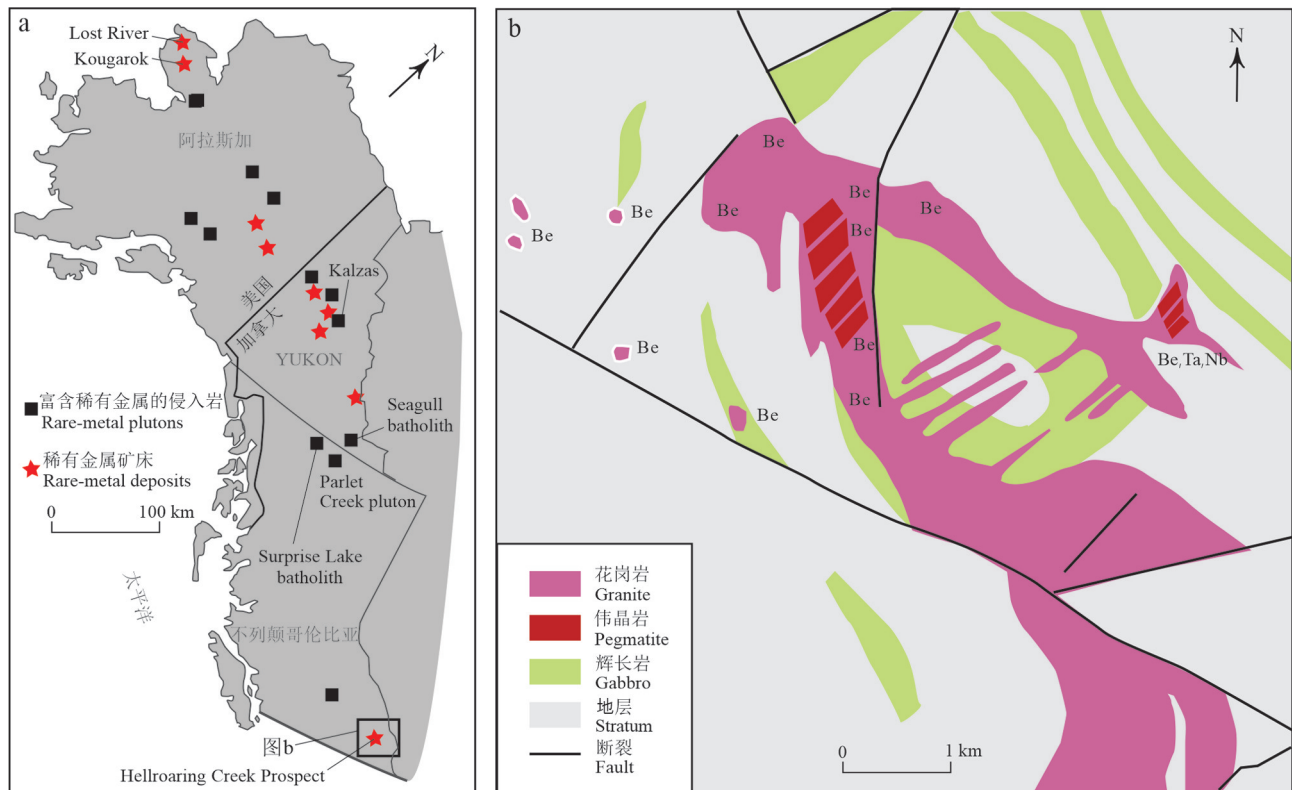


图4 加拿大不列颠哥伦比亚省及美国阿拉斯加稀有金属矿床地质图(据 Soloviev, 2011)

Fig.4 Geological map of rare metal deposits of British Columbia, Canada and Alaska USA (after Soloviev, 2011)

问题的,如蒙古的戈壁中部火山岩带,以及西伯利亚的特贝加尔—蒙古稀有金属成矿省内富含稀土元素的碱性岩—火山岩区内的铍矿床,这些新发现的矿床都需要一种更为适合的储量估算方法。

6.2 实验模拟和地质建模

研究各种流体系统中铍元素的转移、富集、沉淀过程,可以更好地了解富含稀有金属元素的花岗岩和伟晶岩的富氟岩浆系统中铍的形成机制,同时,需要对特殊成矿环境进行地质建模,这些方法对铍矿的找矿勘查及成矿规律研究具有指导意义。

6.3 综合利用与回收

为充分开发伟晶岩型等岩浆热液矿床,铍矿的综合利用技术方法仍需攻关,例如阿拉斯加的花岗岩型、伟晶岩型和矽卡岩型稀有金属矿床,以及阿拉斯加的云英岩型铍矿床,均需要更高效的选冶技术和副矿物(含 Be、Cs、F、Li、Nb、Si、Ta 等副矿物)回收技术,如何回收和处置工业合金、制成品和废料,开发铍与其他元素结合使用的新技术和新产品,有利于改善矿业开发造成的环境影响(例如氧化铍增强型核燃料芯块)。改进铍矿提取技术,处理低于临界工业品位的矿石,还需要研制出高效的精炼方法,从含铍矿物中分离出目标元素(Al、BeO、C、Fe、Mg 和 Si),进而达到用任何铍矿物制备高纯度铍金属材料的目的。随着生产技术和工业需求的增加,迫切需要改进分离技术,如何回收废料中的铍成为一个急需解决的技术难题。

6.4 节能减排与碳中和

铍用于风能、储氢和燃料电池的前景广阔,能够减少工业生产中的碳排放,加拿大 IBC 高级合金公司和华盛顿清洁能源咨询公司正在努力将铍的风能应用商业化,铍的使用有望提高风力涡轮机的耐磨性,从而降低运营成本(IBC Advanced Alloys Corp., 2010, 2013; Jaskula, 2013a; Wang et al., 2021)。此外,氢化铍锂电池在常温下具有较高的活氢容量,可用于笔记本电脑和其他便携式设备的储能,IBC 还与 Hydrogen Link Inc. 合作,推进有关在氢燃料存储中使用铍的研究,有望取得新的突破。

7 结 论

(1)铍矿资源丰富且分布集中,美国、巴西、俄罗斯、印度和阿根廷是主要产出国,另外,马达加斯

加、莫桑比克、尼日利亚、赞比亚以及卢旺达也是重要的铍生产国。已查证的铍金属资源量超过 10 万 t,但铍资源供应高度集中,约有 60%集中于美国,美国的铍矿资源主要分布于犹他州、内华达州等地。

(2)铍矿床可分为内生型和外生型,外生型铍矿床可分为与风化作用和变质作用有关的矿床类型;内生型矿床根据岩浆系统的碱铝属性,可分为过铝性、偏铝性、过碱性成矿系统,根据流体演化阶段,可分为岩浆型、伟晶岩型、岩浆热液型。成矿规律方面,从成矿时代来看,无论过铝性、偏铝性还是过碱性系统的铍成矿作用均集中于中生代,燕山期更是铍矿的主要成矿期;从成矿构造背景角度,花岗岩型常产于后碰撞环境,沉积岩型则产于大陆边缘,而伟晶岩型铍矿基本产于造山带。

(3)现今已探明的铍资源量超过 338 万 t,其中约 65%来自美国的羟硅铍石资源,其余的 35%则来自俄罗斯、加拿大等国家的绿柱石资源。铍矿开发方面,2011 年,铍矿年产量为 260 t,其中 235 t 的铍产自美国 Spor Mountain 岩浆型铍矿床,而其他地区的伟晶岩型铍矿床仅开采 25 t。美国是世界上最大的羟硅铍石生产国,其生产商 Materion Corp. 占铍矿总产量的 91%,绿柱石生产国主要有巴西、马达加斯加、莫桑比克和葡萄牙。

(4)未来应加强铍矿综合利用和回收技术研发,发挥铍矿在能源领域的重要作用,为节能减排、碳中和计划提供支撑。

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