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花岗伟晶岩型锂矿床研究进展及展望

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摘　要：花岗伟晶岩型锂矿作为锂矿的重要来源，全球分布十分广泛，引起了世界各国的勘查兴趣。本文通过对国内外的重要的花岗伟晶岩型锂矿矿床地质特征和研究进展进行总结归纳，获得以下认识：1) 花岗伟晶岩型锂矿分布广泛且资源量大，是锂资源的主要开发对象；2) 不管是稳定的地台，还是活跃的造山带，都可能是花岗伟晶岩型锂矿的成矿构造环境；3) 矿床从太古宙到新生代都有发育，但中国的花岗伟晶岩型锂矿成矿主要集中在燕山期；4) 锂成矿具有循环性的特征，花岗伟晶岩中的锂也可由沉积岩提供；一般以中高压、中温成矿流体为主，并具有低盐度的特征。此外，锂同位素近年来已成为一个锂成矿过程的良好示踪工具，岩体锂同位素组成可以反映花岗岩和伟晶岩在形成时的源区性质。国内外学者对伟晶岩型锂矿的锂同位素分馏机制开展了一系列研究，普遍认为花岗伟晶岩型锂矿与花岗岩岩浆结晶分异作用、地壳部分熔融密切相关。且锂同位素的特征可指示锂矿母岩成因类型，对于找矿方向的厘定有一定的指示意义，显示出重要的研究与应用前景。不同地区的花岗伟晶岩型锂矿床在矿体形态、遥感、地球化学、地球物理等特征方面表现出较大差异性，找矿过程中应寻找最有效的勘查技术手段，因地制宜，拓展找矿思路。

关键词：花岗伟晶岩；锂辉石；成矿时代；锂同位素；找矿方向

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锂资源在新兴产业中发挥着举足轻重的作用，是低碳化发展的关键元素[1−4]。锂及其化合物因具有高储能、软质地、轻密度、大比热、低能耗和强电化学活性等多种卓越的性能，在新能源、可控核聚变、航空航天工业等领域发挥着显著的作用，有着“21 世的能源金属”之称，被各国列为关键金属，其战略地位不断提升，掀起了世界各国新一轮的矿产资源争夺热潮和新兴材料研究热潮[1, 5−7]。VIKSTRÖM 等[8]认为世界各主要国家对锂的需求将不断增大，预测直到 21 世纪 90 年代才会达到最大产能。

花岗伟晶岩型稀有金属矿床因其所含有的稀有金属元素的多样性和高品位而广为人知[9−10]，是最重要的稀有金属矿床类型之一，也是锂矿的传统来源，其储量和产量占据重要地位[5, 11]。近年来，由于锂电池的消耗量显著增加，全球锂消费呈现出高速增长态势(见图 1)，在大宗矿产萎靡不振的状况下，锂矿价格却持续飙升(见图 2；2020 年碳酸锂交易受新冠疫情影响而价格疲软)，勘查态势愈发活跃，近年来在大型、超大型伟晶岩型锂矿床找矿成果上的突破，成为了市场的最大焦点[12−13]。进入 21 世纪以来，分析测试手段有了飞速进步，国内外对

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于花岗伟晶岩型锂矿床的研究取得了丰硕的成果，在锂矿床成矿物质来源、成矿流体演化及性质、锂矿床勘探方法以及锂同位素等方面取得重大突破，大大加深了人们对于这类型矿床成因的理解，促进了本类型矿床的找矿勘探。

本文就目前国内外在花岗伟晶岩型锂铍矿床方面的研究进展进行系统的阐述，以期提升对花岗岩型锂矿床成矿作用的认识，并对一些关键性的问题进行分析讨论，为今后的花岗岩型锂矿找矿工作和研究提供帮助。

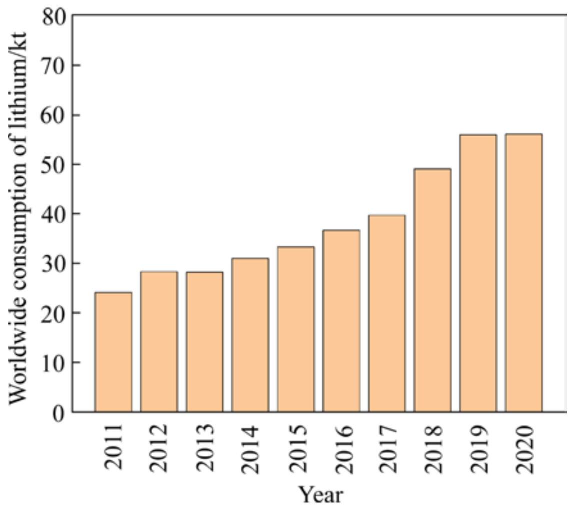

图 1　近年全球的锂消耗费量[14]

Fig. 1　Worldwide consumption of lithium from in recent years[14]

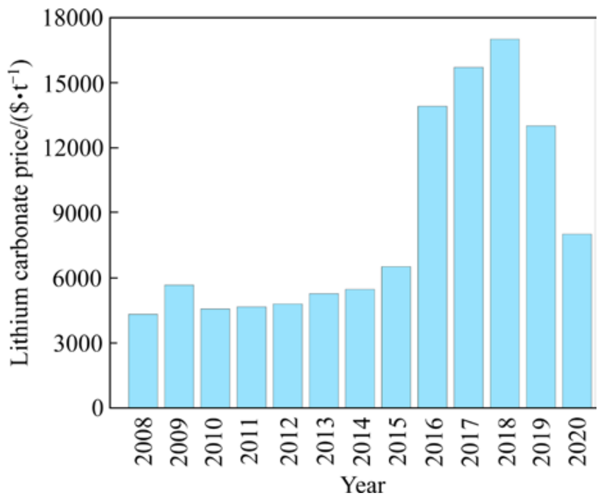

图 2　近年碳酸锂价格走势图[14−15]

Fig. 2　Lithium carbonate price trend chart in recent years[14−15]

1　花岗伟晶岩型锂矿的资源概况

自然界中已发现的锂矿床主要包括两大类：盐湖卤水型和固体型锂矿。后者主要由花岗伟晶岩型和沉积岩型锂矿床两类组成[12, 16−17]，某些地下卤水、油田卤水、地热卤水及湖成蒸发岩型中的锂也具有潜在的开发价值[18]。沉积岩型锂矿属于新动向，最近在中国西南发现的碳酸盐黏土型锂资源储量巨大，已引起学者的重视，有望在未来提供巨量锂资源[19]。但就目前而言，全球锂矿床开发还是以卤水型和花岗伟晶岩型为主，其他类型矿床所占比例较小[20−21]。据美国地质调查局统计，截至 2020 年底，全世界已查明的锂资源量总计达到了 8600 万 t，主要集中在玻利维亚(24%)、阿根廷(22%)、智利(11%)、美国(9%)、澳大利亚(7%)、中国(6%)、刚果(金；3.5%)、加拿大(3.3%)和德国(3%)，这些国家合计占据全球总资源量的 90%左右[14](见图 3)。其中盐湖卤水型的总资源量最大，著名的有由玻利维亚(Salarde Uyuni)、阿根廷(Salarde Hombre Muerto)、智利(Salarde Atacama)组成的“锂三角”区域。但盐湖卤水型矿床的沉积物成分相差大，使得前期资源开发、生产周期长，且卤水中一些成分(如 钾、镁、溴和硼等)限制了锂应对市场的供应能力[16, 20, 22]。伟晶岩型锂矿床的含锂矿物主要为锂辉

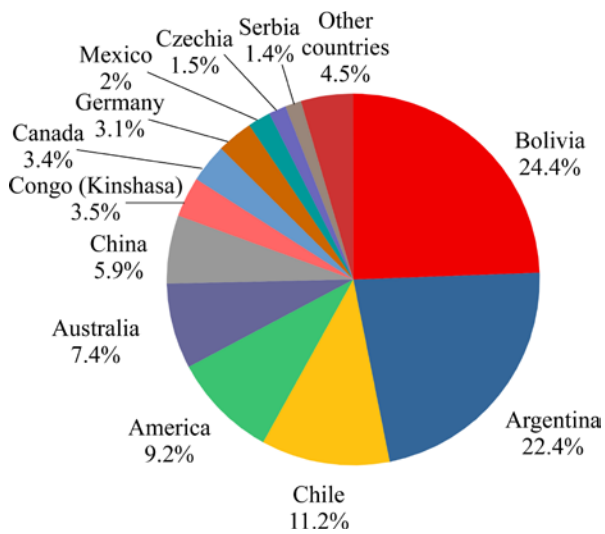

图 3　世界主要产地的锂矿资源量份额[14]

Fig. 3　Lithium resources share in major countries of the world[14]

石。20 世纪 90 年代后期，由于盐湖提锂技术取得突破，其产业化发展迅速，国外的锂辉石矿床提锂生产线大多关闭，我国也由于盐湖提锂的开采成本更低而停止了对伟晶岩型锂矿的勘查。但锂在新能源领域的成功应用，使得市场对锂的需求成倍增长，从花岗伟晶岩锂矿中提锂的优势又逐渐显现出来[23]。相对来说，花岗伟晶岩型锂矿品位高分布广，具有成熟的采选冶技术，供应中断的可能性更小，应对市场的灵活性更强；虽然其总储量和平均规模远小于盐湖卤水型锂矿，但其产量却占全球总产量的一半左右[24−25]。

花岗伟晶岩型锂矿分布广泛(见图 4)，与盐湖卤水型锂矿相比，具有更显著的环境优势，预计在未来市场将占据主导地位[26−28]。世界主要的伟晶岩型锂矿如表 1 所示，其中著名的有：澳大利亚格林布什锂矿(Greenbushes)，是最古老的锂辉石矿之一；加拿大瓦布奇锂矿床(Whabouchi)，Li_2O 平均品位达 1.53%，有着“北美最富的世界级伟晶岩型锂矿”之称；中国川西的甲基卡矿床，被誉为亚洲最大的伟晶岩型锂矿，与之共生的稀有金属也有着较高的品位，例如铍等的储量也达到了大型矿床规模。除此之外，典型伟晶岩型锂矿还有美国金斯山锂矿床(Kings Mountain)、刚果(金)马诺诺锂矿床(Manono)、津巴布韦比基塔锂矿床(Bikita)等[29−30]。

伟晶岩型锂矿因分布范围广泛，被认为是极具潜力的开采对象，近年来有很多勘查新进展和新成果[12]。例如在中国新疆和田地区新发现的白龙山锂铷多金属矿床，矿体品位高，平均锂品位为 0.7%，且矿床规模达到了超大型，估算锂资源量为 236.1 万 t，有望成为我国又一个世界级规模的花岗伟晶岩型巨型锂矿床[25, 31]。在美国缅因州西部巴格山发现的富锂辉石伟晶岩型锂矿，在伟晶岩上部含有高达 50%(质量分数)的锂辉石，一些锂辉石晶体的长度超过 11 m，2019 年的资料显示该矿地区的锂资源量为 21.8 万 t，平均锂品位高达 2.18%，比世界上十大锂矿床的平均品位都要高[32]。

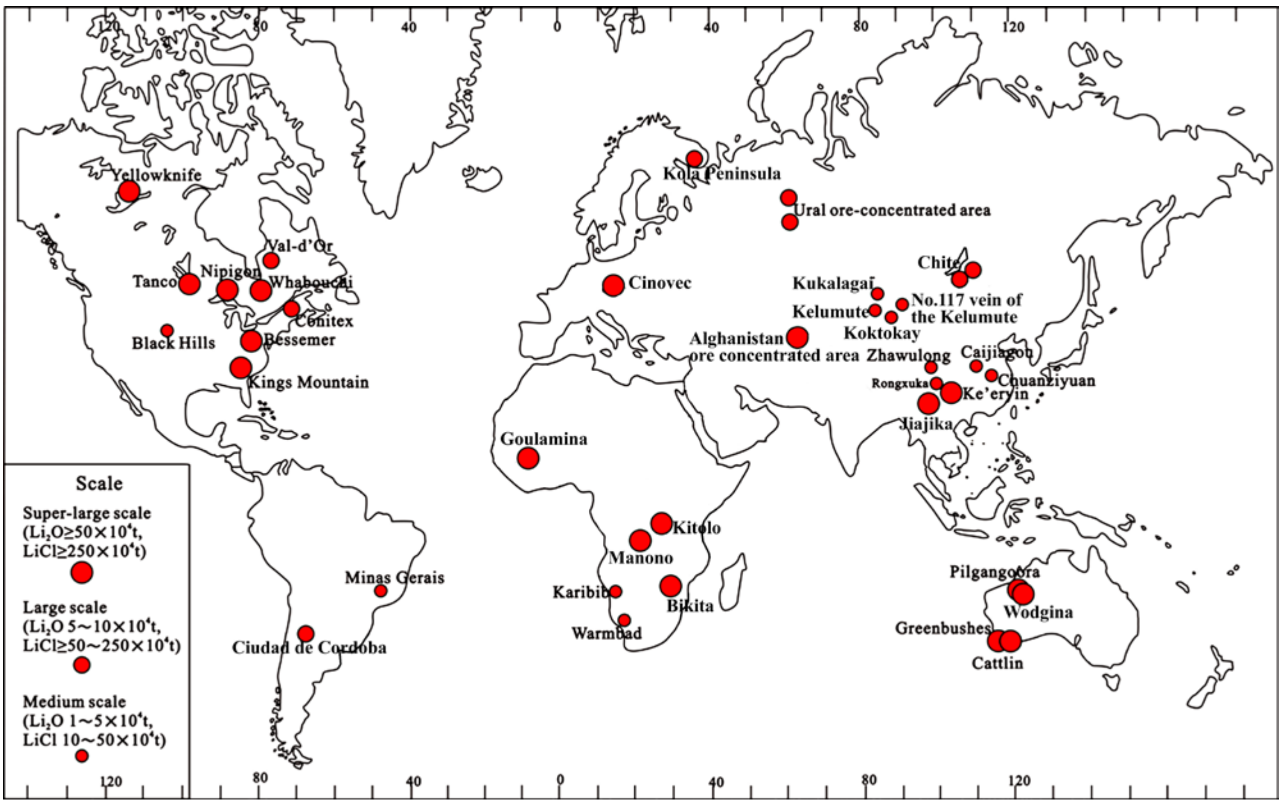

图 4 全球主要花岗伟晶岩型锂矿分布简图(据文献[17, 26]修改)

Fig. 4 Distribution of major granitic pegmatite-type lithium deposits in the world(modified from Refs. [17, 26])

表 1　全球主要花岗伟晶岩型锂矿床(以金属锂当量级)

Table 1　Statistics of major granitic pegmatite-type lithium deposits in the world (equivalent to Li metal)

Continent	Country and region	Deposit	Associated mineral resource	Resources Li/ 10^4 t	Average Li grade/%	Li-bearing mineral	Reference
Oceania	Australia	Greenbushes	Li-Ta	56	0.74	Spodumene	[12]
		Pilgangrooa	Li-Ta	62.7	0.58	Spodumene	[33]
		Wodgina East	Li	82.9	0.54	Spodumene	[34]
		Cattlin	Li-Ta	6.16	0.56	Spodumene	[35]
		LynasFind	Li	–	0.83	Spodumene	[36]
Asia	China	Jiajika	Li-Be	131	0.71	Spodumene	[37]
		Koktokay	Li-Be	–	0.56	Spodumene, Lepidolite	[38]
		Ke’eryin	Li-Nb-Ta-Rb	–	0.58	Spodumene	[39]
		Zhawulong	Li-Nb-Ta	＞0.4	0.56–0.7	Spodumene	[40–41]
		Rongxuka	Li-Be	–	0.19–1.80	Spodumene	[42]
		Kelumute	Li-Nb-Ta	–	0.46	Spodumene	[43]
		Kukalagai	Li	–	0.47-0.96	Spodumene, Lepidolite	[44]
		Caijiagou	Li-Nb-Ta	0.2	0.48	Spodumene	[45]
		Chuanziyuan	Li-Be-Nb-Ta	–	–	Spodumene	[46]
		Dangba	Li-Be-Nb-Ta	0.4	0.63	Spodumene	[47]
	Afghanistan	Pasgushta Pass	Li	49	0.92	Spodumene	[48–49]
		Jamanak	Li	21	0.72	Spodumene	[48–49]
		Taghawlor	Li	68.8	0.03–1.3	Spodumene	[50]
		Drumgal	Li	12	0.65–0.74	Spodumene	[50]
	Russia	Vishnyakovskoe	Li	21	0.49	Spodumene	[16]
Europe	Czech	Cinovec	Li-Sn-W	130	0.2	Lepidolite	[12]
South America	Brazil	Minas Gerais	Li-Sn-Ta	8.5	–	Spodumene	[51]
	Argentina	Ciudad de córdoba	Li-Be	–	–	Spodumene	[52]
North America	Canada	Whabouchi	Li	12	0.71	Spodumene	[53]
		Tanco	Li-Ta-Cs	14	0.64	Spodumene, lepidolite	[16]
		Georgia Lake	Li-Nb-Ta	3.6	0.54	Spodumene	[54]
		Yellowknife	Li-Sn-Be	32	0.65	Spodumene	[55]
	The United States	Bessemer	Li	42	0.67	Petalite	[16]
		KingsMountain	Li-Sn	32	0.7	Spodumene	[16]
		Black hills	Li-Be-Au-Ag	–	–	Spodumene, Lepidolite	[56]
		PlumbagoNorth	Li	21.8	2.18	Spodumene	[32]
Africa	Congo (Kinshasa)	Manono-Kitolo	Li-Ta-Sn	584.3	0.73	Spodumene	[57]
	Zimbabwe	Kamativi	Li-Sn	28	0.28	Spodumene	[16]
		Bikita	Li-Be-Ta-Sn-Cs	15	1.4	Petalite	[16]
	Mali	Goulamina	Li	49	0.58	Spodumene	[58]

Note: “–” indicates that the relevant data and materials are not available or yet to be verified.

2 花岗伟晶岩型锂矿床成因

2.1 矿床地质特征

作为自然界最轻的金属，锂元素十分活泼，导致内生型锂矿的形成过程中总会受到构造环境的约束。全球伟晶岩型锂矿主要产出于相对稳定、封闭的大地构造环境，如古老结晶地盾、地块等[12]；但也有部分产出于活跃的造山构造环境中(如美国阿帕拉契亚褶皱带产出的金斯山锂辉石矿床、中国川西甲基卡锂矿床等)，其中，穹窿构造、复背斜、复向斜等是产出由褶皱控制的花岗伟晶岩型锂矿的主要构造环境[17, 59−60]。

花岗伟晶岩型锂矿床常赋存在大型花岗岩侵入体上部(或边缘)的交代伟晶岩矿脉中，呈似层状、脉状产出。根据前人研究，花岗伟晶岩型锂矿产出部位还受构造形成的裂隙的影响[6, 61−62]。富含挥发分和锂等稀有元素的伟晶岩浆从母花岗岩浆中分离出来，沿着母岩体周围地层的构造裂隙上升、充填，在相对封闭和稳定的环境中缓慢结晶并分馏形成微斜长石型、微斜长石钠长石型、钠长石型、钠长石锂辉石型、锂(白)云母型等伟晶岩岩脉[63−64]。在伟晶岩矿床分带中，具有工业价值的锂矿体多赋存于钠长石−锂辉石伟晶岩带、石英−锂辉石伟晶岩带中[17, 65]。

伟晶岩脉的含矿性与岩体之间空间分布距离有关，且具有一定的规律。从靠近岩体边缘向外，伟晶岩演化程度从简单向复杂变化，稀有金属矿化程度从弱到强变化。完整的脉岩系统的最边缘为石英脉带，远离母岩浆房的花岗伟晶岩含矿性好，接近母岩浆房的花岗伟晶岩含矿性差[60, 66−67](见图5)。一般来说，早期形成的稀有金属矿床靠近母岩体，规模较小。远离母岩体的多为大规模的晚期矿床，岩浆迁移较远，有着较长的成矿时间，所以矿物分带更为复杂，地球化学分异特征的程度更高；除了锂之外，其他稀有金属包括铍、铌、钽、锡等稀有金属矿化也都较好[68−70]。

伟晶岩型锂矿可按照有无带状构造划分为两大类：1) 带状构造伟晶岩型锂矿床，如澳大利亚的格林布什锂矿可作为典型代表。成分复杂，锂辉石含量为20%左右，除含锂矿物外，常伴有其他可综合利用的稀有金属矿物，如绿柱石、铌钽铁矿等。

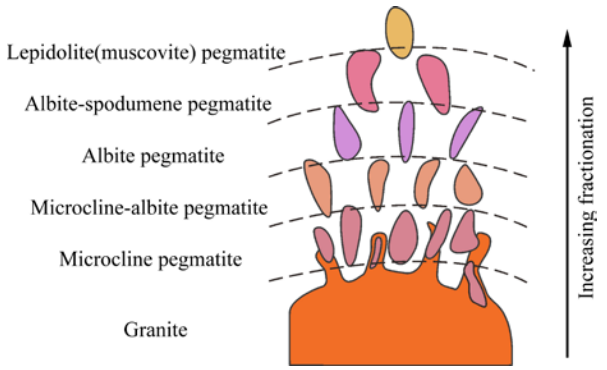

图 5 随着分异程度增加，花岗岩与伟晶岩的分带[64, 66−67]

Fig. 5 Regional zonation within pegmatite and granites with increasing magmatic fractionation[64, 66−67]

2) 无带状构造伟晶岩型锂矿床，如美国的金斯山矿床。锂辉石含量可达总岩体的四分之一左右，多为独立的锂矿床，也可能伴有少量的铍和钽[12]。锂辉石是伟晶岩锂矿资源的主要工业矿物，每年从矿石中提取的锂有30%左右都是来自锂辉石，作为一种储量丰富的矿石锂资源，锂辉石属于非常稳定的链状结构铝硅酸盐矿物，常以板状、柱状产出，亦可见棒状或致密隐晶块状集合体，其 Li_2O 含量可达3%至8%[71−72]。除此之外，锂还赋存于锂云母、透锂长石、锂磷铝石、锂霞石等矿物中[5, 73−74]。

世界花岗伟晶岩型锂矿在稳定地盾、地块以及活动性强的造山带均有产出，而中国的花岗伟晶岩型锂矿主要集中在阿尔泰锂成矿带、川西锂成矿带、东天山锂成矿带等几个褶皱造山带，尤其是大型超大型花岗伟晶岩型锂矿，主要分布在中国新疆和四川等地。花岗伟晶岩型锂矿是花岗质熔体演化程度最高的产物之一，我国花岗伟晶岩型锂矿的一般性地质特征与世界花岗伟晶岩型锂矿一致。例如，可发育粗大的锂辉石晶体，花岗岩与伟晶岩呈现空间分带性，容矿岩石主要为花岗伟晶岩和蚀变花岗岩，多发现于花岗岩侵入体的边缘，常伴生铍、铌、钽等多种稀有金属等。

2.2 成岩成矿时代

关于花岗伟晶岩型锂矿的成岩成矿年代，前人进行了大量的研究[17, 75]。花岗伟晶岩型锂矿床从太古宙到新生代均有产出。其中，澳大利亚的皮尔甘谷拉(Pilgangoora)矿床成矿时代为太古代，是世界级的锂−钽矿，侵位于皮尔巴拉克拉通绿岩带内。

在津巴布韦的比基塔(Bikita)矿床中产出成矿年龄为 2617 Ma 的含矿伟晶岩，该矿床是全球最大的透锂长石矿山，地处南非－津巴布韦太古宙地盾内，区内分布着非洲最古老的岩石。成矿年龄为 2600 Ma 的伯尼克湖坦科(Tanco)锂矿，位于北美加拿大地盾，该矿床成矿与太古宙微斜长石花岗岩相关。澳大利亚格林布什(Greenbushes)伟晶岩型锂矿床的成矿共有三个阶段：2527 Ma 伟晶岩结晶成矿，2430 Ma 伟晶岩在热液作用下蚀变成矿，成矿后期约 1100 Ma 经变形、变质作用再度活化成矿。美国阿帕拉契亚造山带中金斯山(King Mountain)锂矿床内的伟晶岩形成于 373~265 Ma 之间，成矿时代为古生代海西期。目前已发现的时代最年轻的大型花岗伟晶岩型锂矿床产于阿富汗东北部的兴都库什山区，该地区产出的伟晶岩在成因上大多与渐新世二云母花岗岩关系密切[23, 30, 49]。

中国的花岗伟晶岩型锂矿床成矿过程以“多旋回”为特点，但花岗伟晶岩型锂矿成矿时代主要为中生代印支期–燕山期，中国甲基卡、可尔因、可可托海等伟晶岩型锂矿成矿时代均为中生代。其中，燕山期是中国花岗伟晶岩锂矿床成矿的极盛时期[30](见表 2)。中国西部(新疆阿尔泰锂成矿带、东天山锂成矿带、西昆仑–阿尔金锂成矿带和川西松潘–甘孜锂成矿带)伟晶岩型锂矿床成矿时代集中分布在印支晚期–燕山早期[69, 76]。在中国南方地区绝大多数的花岗伟晶岩型锂矿床在燕山期成矿，都与燕山期构造–岩浆活动有关[17, 61]。由图 6 可见，与全球的花岗伟晶岩型锂矿在各个时代均有锂矿形成不同(从晚元古代至渐新世)，中国花岗伟晶岩型锂矿成矿时代(蓝色图案)的峰值出现在燕山期，且暂时还未发现在寒武纪以前和古近纪以来成矿的花岗伟晶岩型锂矿。

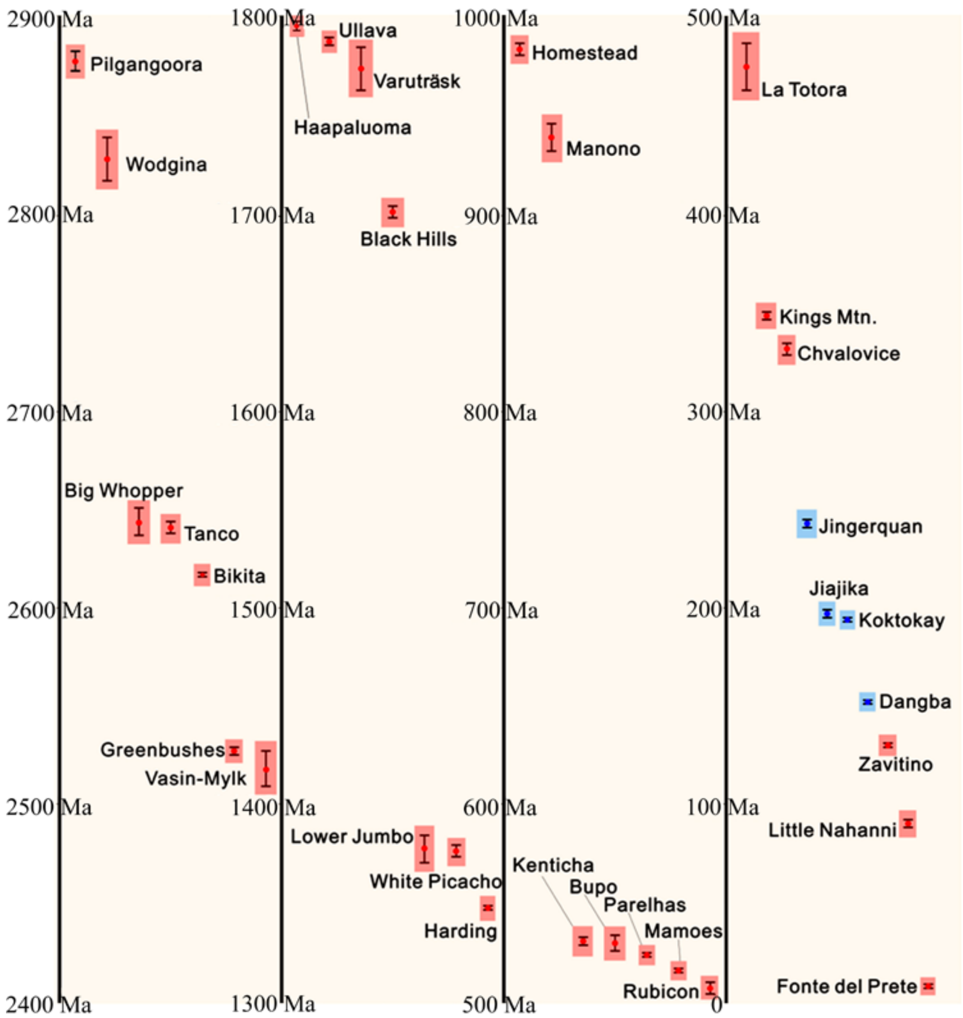

图 6 全球典型花岗伟晶岩型锂矿成矿时代图[17, 77]

Fig. 6 Metallogenic age of typical granitic pegmatite-type lithium deposits in the world[17, 77]

表 2 中国主要花岗伟晶岩型锂矿的成矿年龄

Table 2 Main isotope dating data of granitic pegmatite-type lithium deposits in China

Metallogenic belt	Deposit	Metallogenic age/Ma	Dating method	Reference
Songpan-Ganzi metallogenic belt	Jiajika	(199−195)	Muscovite ^{40}Ar-^{39}Ar	[17, 78]
	Dangba	176.25, 152.43	Muscovite ^{40}Ar-^{39}Ar	[60, 79]
	Ke'eryin	176.25, 152.43	Muscovite ^{40}Ar-^{39}Ar	[79−80]
Karakoram metallogenic belt	Dahongliutan	(185−156)	Muscovite ^{40}Ar-^{39}Ar	[81]
South Altay metallogenic belt	Koktokay	194.51, 160.38	Muscovite K-Ar	[81]
East Tianshan metallogenic belt	Jingerquan	(243)	Muscovite ^{40}Ar-^{39}Ar	[82]
Qinling metallogenic belt	Nanyangshan	396	Muscovite K-Ar	[83]
South China metallogenic belt	Xigang	(160−150)	Muscovite ^{40}Ar-^{39}Ar	[17]
	Nanping	(412−364)	Muscovite K-Ar	[17]

2.3 成矿流体性质与演化

结合前人对花岗伟晶岩型锂矿成矿流体性质的分析[6, 84−85]，认为花岗伟晶岩型锂矿的成矿流体多处于中高压和中温环境，以低盐度流体为主，且认为伟晶岩体系成矿熔体、流体的形成可能主要有两个阶段：1) 温度区间为 600~850 ℃的岩浆阶段[86]，伟晶岩熔体从花岗岩内分异出来；2) 温度区间为 300~700 ℃的岩浆−流体过渡阶段[87]。在 500~700 ℃条件下，流体中主要形成丰富的绿柱石晶体；在 500~600 ℃条件下，流体中主要形成丰富的锂辉石晶体；在 300~450 ℃条件下，流体中的水−氯化钠−二氧化碳体系形成[87−91]。这两个阶段并非两个独立阶段，结晶分异作用是主导作用，贯穿了整个过程。随着结晶分异作用的进行，热液交代作用也不断增强[92−94]。但早期的结晶分异对稀有金属元素的积累作用不大，矿化程度不高。随着岩浆演化，结晶分异作用不断进行，Li 等成矿元素进入残余岩浆出溶的流体中，晚期流体出现富 Li 的特征[92, 94]。主流观点认为，伟晶岩是岩浆高度分异的结果，且稀有金属含量与伟晶岩岩浆的分异演化程度呈正相关，一般表现为随着伟晶岩熔体分异演化程度的逐渐加深，Li 等稀有金属不断富集[46, 61, 63, 95−98]。

成矿流体运移过程中，在还原条件下，CO_2、CH_4 等气体易与流体中的 Li 等元素结合形成较稳定的络合物，增强了 Li 的迁移富集能力[99]。当成矿流体运移至裂隙等开放体系时，压力会急速下降，发生减压沸腾作用，CO_2 气体逸出水−氯化钠−二氧化碳体系，形成流体相分离和流体不混溶；水−氯化钠−二氧化碳体系分离出水−氯化钠、二氧化碳两相体系。同时，CO_2、CH_4、N_2 等挥发性气体从流体中分离，成矿流体性质产生较大变化[100]，导致含锂矿物在适宜的环境下聚集成矿。锂辉石是大多数花岗伟晶岩型锂矿床的赋矿矿物，这是由于岩浆中最早结晶的富锂矿物就是锂辉石，且当温压条件处于 320 ℃、162.12~405.30 MPa 时，透锂长石也能分解为锂辉石和石英[101]。成矿流体沸腾作用或液态不混溶作用导致相分离，是伟晶岩型锂矿的重要成矿机制[87, 91, 102−103]。且挥发组分(F、P、CO_2)对花岗伟晶岩型锂矿床的迁移、富集与沉淀也起着不容忽视的作用[85, 104−107]。不同的岩浆和热液作用可导致花岗伟晶岩型锂矿及其伴生的其他稀有金属的成矿多样性[37, 84, 108]。

2.4 成矿物质来源

内生岩浆锂富集的有利地球动力学背景在造山作用晚期，通常是弧后增生，与陆−陆碰撞同时代，与地壳局部增厚有关，造山后的伸展环境有利于锂富集到外生过程中[6]。由于中等不相容元素的特性，Li 元素在部分熔融和壳幔分异的过程中分别倾向于在硅酸盐熔体和地壳中富集[109]。在岩浆演化序列过程中(超基性岩→酸性岩)，Li 元素含量逐渐增加，在最末端的花岗岩和伟晶岩中含量最高[96]。目前，人们对稀有金属花岗伟晶岩的成因还存在一些争论，有部分学者认为花岗伟晶岩成因是下地壳物质低程度的部分熔融[96, 110]，但大部分花岗伟晶岩与花岗岩在成因和空间上都有一定的联系，锂花岗岩也多伴有锂花岗伟晶岩的产出[111−112]，伟晶岩的岩浆结晶分异成因也因此被广为接受[113−115]。近年

来，在我国四川甲基卡、西昆仑大红柳滩探获的规模巨大的花岗伟晶岩型锂矿都与二云母花岗岩有关[25, 116]。澳洲皮尔布拉地区新太古宙的 Pilgangrooa 和 Greenbushes 等伟晶岩型锂矿与高分异的二云母花岗岩、二长花岗岩有关[117−119]。法国的 Beauvoir 钠长石花岗岩为一个超大型锂铍矿床，其边部发育花岗伟晶岩型锂矿[120]。锂铍伟晶岩为 LCT 型伟晶岩，大多有着 S 型花岗岩的成分特征[121−122]。

花岗伟晶岩型锂矿一般被认为是内生成因，但实际上，花岗伟晶岩型锂矿中锂的来源问题并没有得到解决。近年来更多的研究表明，锂矿的成矿有“循环性”的特征，可以“内生外成”，也可以“外生内成”，即盐湖卤水中的锂可从深部热卤水中得到，也可以是含矿花岗岩风化剥蚀后被沉积盆地中的黏土物质吸附而富集(见图 7)；而富含锂的黏土岩经过深埋、重熔、花岗岩化以及结晶分异可以形成内生成因锂矿床[123]。BENSON 等[24]通过对比不同构造环境中的岩浆锂的浓度，并通过测定石英熔融包裹体内原位微量元素，得出中等至极度富集锂元素的岩浆在成因上与长英质大陆地壳的参与有关。GODFREY 等[124]通过分析盐湖形成过程中锂同位素分馏作用，认为邻近的地热水和火山沉积区的富锂水是安第斯中部 Hombre Muerto 盐湖中的锂元素的主要来源；ORBERGER 等[125]分析了阿根廷 Puna 地区不同含水层的锂同位素组成，结果显示锂主要来自安山岩、伟晶岩及火成碎屑沉积。这些研究表明，花岗伟晶岩中的锂可以是从沉积岩中继承来的，而沉积盆地中富集的锂也可以是火山作用提供的。

3　花岗伟晶岩型锂矿勘探

3.1 地质找矿

1)岩体(脉)标志，伟晶岩型锂矿在空间上的分布与多期次演化晚期的花岗岩体常表现出规律性，从母岩体到边缘的石英脉，矿化由弱到强变化，钠长−锂辉石型伟晶岩脉，可作为直接找矿标志[126]。2)矿物标志，花岗伟晶岩型锂矿化主要以锂辉石、锂云母、透锂长石的形式出现。3)交代蚀变标志，锂矿化与锂云母化、钠长石化有关，一般来说，钠长石化强烈，锂矿化作用越强。4)地貌标志，与围岩相比，伟晶岩锂矿具有较强的抗风化能力，发育的伟晶岩脉以突出的地貌或白色陡坎形式出露。

3.2 遥感标志

自 20 世纪 70 年代以来，遥感技术在世界范围内被广泛地应用于矿产勘查[127]，而直到最近遥感才应用于锂矿勘查。例如，PERROTTA 等[128]采用 ASTER 图像对巴西 Vale do Jequitinhonha 地区的花岗伟晶岩型锂矿开展了试验制图；MENDES 等[129]

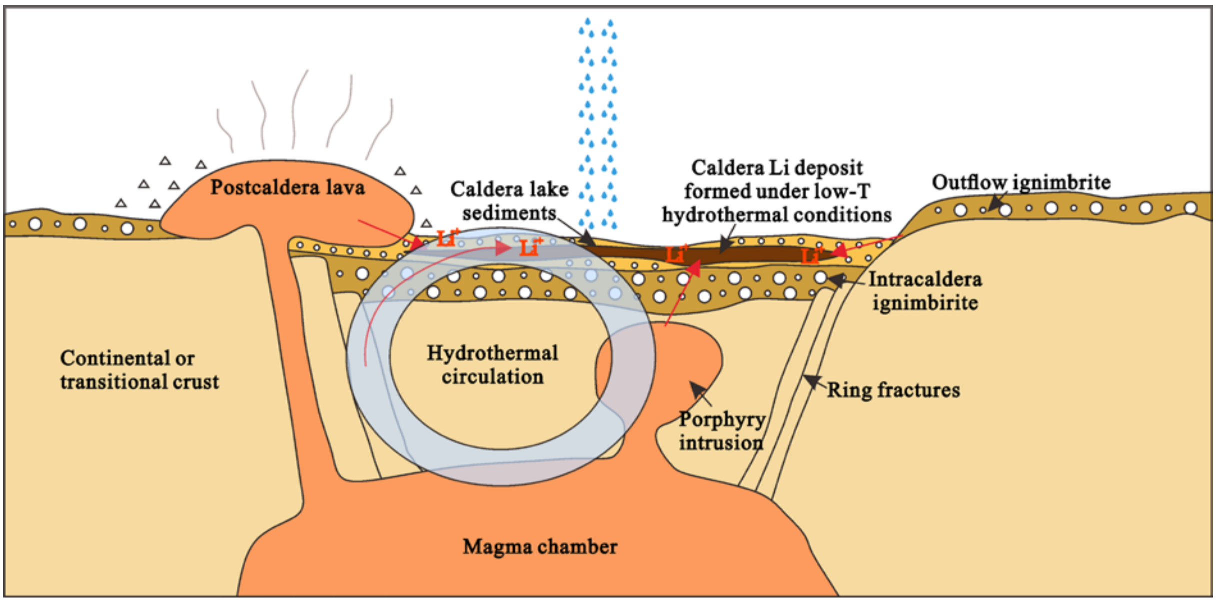

图 7　破火山口黏土型锂矿的形成示意图[24]

Fig. 7　Schematic diagram for formation of caldera-hosted Li clay deposits[24]

在识别未知矿床时，也采用了类似方法来识别锂矿物的光谱特征。CARDOSO-FERNANDES 等[130]提出了新的 RGB 组合、波段比和选择性 PCA 子集，能够有效区分含矿伟晶岩及其母岩的光谱特征。姚佛军等[131]采用了一种岩性微弱信号增强技术对 ASTER 遥感数据进行识别，经过处理后的图像可以清楚地识别出伟晶岩脉体、并于野外查证时发现了一处新的锂铍伟晶岩脉体。利用先进的遥感技术对花岗伟晶岩型锂矿的勘探和采矿都具有十分重要的意义，减少了勘探早期对人力上的要求，提高了勘查的效率和可持续性。

3.3 地球化学标志

在大尺度范围内开展地球化学勘查，可以帮助快速圈定靶区，但是锂元素扩散性强，采用化探异常勘查时需要结合当地的地质情况进行综合分析。肖瑞卿等[132]对甲基卡锂矿床进行土壤地球化学勘查，以原生晕、水化学等方法加以辅助；结果显示，锂、铍和铷三者之间的相关性较强。锂品位在空间分布上与硼、铯品位的特征相似[93]。涂其军等[133]在对甲基卡矿床进行矿区或矿床尺度上的水系沉积物地球化学调查时，发现明显的地球化学异常。

3.4 地球物理标志

伟晶岩型锂矿与围岩的电阻率和密度的差异明显，利用两者之间的差异可缩小找矿范围：围岩的密度相对较高而电阻率低，与含矿体作为“高阻地质体”具有密度低而电阻率高的特点正好相反，伟晶岩体越厚，对应的电阻率越高[61, 93]。杨荣等[134]通过对伟晶岩型锂矿床开展重力、磁法、电法等方法探测，将综合地球物理探测结果与地质、钻探结果结合，筛选出下一步勘查工作的重点区域。

付小方等[95]综合利用多种找矿手段，提出了第四系覆盖区立体地质综合勘查模型，为隐伏的花岗伟晶岩型锂矿以及其他稀有伟晶岩找矿和勘查提供了技术参考。王登红等[61]以甲基卡伟晶岩型锂矿的找矿实践为例，提出灵活运用“五层楼＋地下室”模型能够帮助已经找到矿的区域取得更大的找矿突破。花岗伟晶岩型锂矿的传统勘查、评价方法主要是以地质填图、钻探为主，但实际找矿过程中，仅仅使用传统的地质方法往往是不够的，想要在花岗伟晶岩型锂矿找矿方面有所突破，需要开展多方法的综合探测、分析，结合矿床的实际情况，因地制宜，提高对科学有效的找矿方法的探索，建立合适的勘查模型。

4 前沿及展望

4.1 锂同位素在花岗伟晶岩型锂矿中的应用

锂在自然界主要以+1 价的微量元素的形式存在于各种矿物、熔体以及流体中，而以主量元素在锂辉石、锂云母、透锂长石等矿物中存在。由于只有唯一价态，环境中氧逸度的变化不会影响锂同位素分馏[135]。锂有两种稳定同位素，分别是元素丰度为 7.52%的 ^{6}Li 和元素丰度为 92.48%的 ^{7}Li，二者之间有着较大的相对质量差(16.7%)，使得地质过程中产生强烈的锂同位素平衡分馏，已观察到的自然界不同地质储库间的锂同位素分馏可高达 8‰[136]。近年来，随着新一代多接收电感耦合等离子体质谱仪(MC-ICP-MS)、激光多接收电感耦合等离子体质谱仪(LA-MC-ICP-MS)、以及二次离子质谱仪(SIMS)的发展，使得锂同位素的测试技术有了飞跃性的突破，分馏机制得到更深入的研究，锂同位素逐渐成为一个良好的地球化学示踪工具[137−138]。锂同位素作为一种新兴的“非传统稳定同位素”，已应用在示踪流体来源[139]、陨石研究[140]、洋壳热液活动[141]、壳幔作用等过程的研究[142−147]。

国内外学者针对花岗伟晶岩型锂矿开展了一些锂同位素分馏机理研究，包括平衡分馏、扩散动力分馏、混合或瑞利分馏等研究。锂同位素在花岗伟晶岩体系中的分馏作用取决于矿物、熔体、含水流体等多个富锂同位素相态中的交换机制，而地壳的深熔作用、封闭岩浆热液系统中的水岩反应以及高温条件下的结晶分异都不会产生有意义的锂同位素分馏[92, 148−150]，因此，对锂同位素的研究可用来解决岩浆源区性质方面的问题，但对于形成伟晶岩的流体与花岗原岩是否一致方面还存在较大争论[108, 150−151]。花岗岩是在低温贫水条件下由地壳物质熔融形成，其中分离结晶、气相出溶以及缓慢冷却等过程都可形成显著的锂同位素分馏[152−153]。刘丽君等[154]在对我国新发现的超大型锂辉石矿床甲基卡新三号脉的研究中发现，锂同位素可以用作找矿的“示踪剂”。这是由于 δ^{7}Li 在含矿伟晶岩、不含矿伟晶岩以及围岩之间具有较大差异(见图 8)，且

在误差允许范围内，伟晶岩与二云母花岗岩的锂同位素组成相一致，证明了二者在成因上具有内在联系[155]。侯江龙等[156]进一步对甲基卡锂矿的锂同位素组成开展了研究，结果显示甲基卡二云母花岗岩的 δ^{7}Li 值低于世界花岗岩的 δ^{7}Li 值(见图 9)。研究还显示矿区的 δ^{7}Li 值基本与 Li、Rb、Ga、SiO_2 以及 $\varepsilon_{Nd}(t)$等含量无关，说明 δ^{7}Li 值不受岩浆结晶分异和围岩蚀变作用的影响，且岩体锂同位素能够指示形成时的源区特征。这与 MAGNA 等[147]对不同时代的伟晶岩体的锂同位素研究一致，并为伟晶岩的成矿流体来源于二云母花岗岩提供了证据。FAN 等[157]报道了对西昆仑白龙山锂矿床的研究成果；通过对该矿床的贫锂和富锂伟晶岩开展主微量和锂同位素研究，发现贫锂和富锂伟晶岩是花岗岩岩浆演化晚期熔流体分离所形成，贫锂伟晶岩富集 ^{7}Li，富锂伟晶岩相对富集 ^{6}Li，超临界流体出溶对稀有金属矿化起着重要作用。该研究结论与前人对甲基卡地区伟晶岩型锂矿的锂同位素研究结果相印证，进一步证明了西昆仑与松潘−甘孜锂成矿带之间存在着密切联系。

尽管锂同位素应用于花岗伟晶岩型锂矿床方面

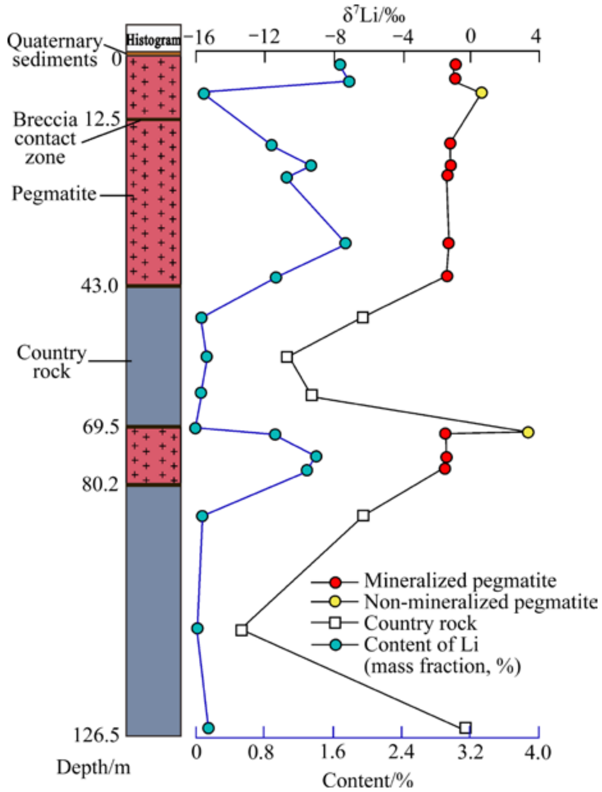

图 8 甲基卡新三号矿脉 δ^{7}Li 值变化折线图[154]

Fig. 8 δ^{7}Li line chart of the X03 ore vein of Jiajika orefield[154]

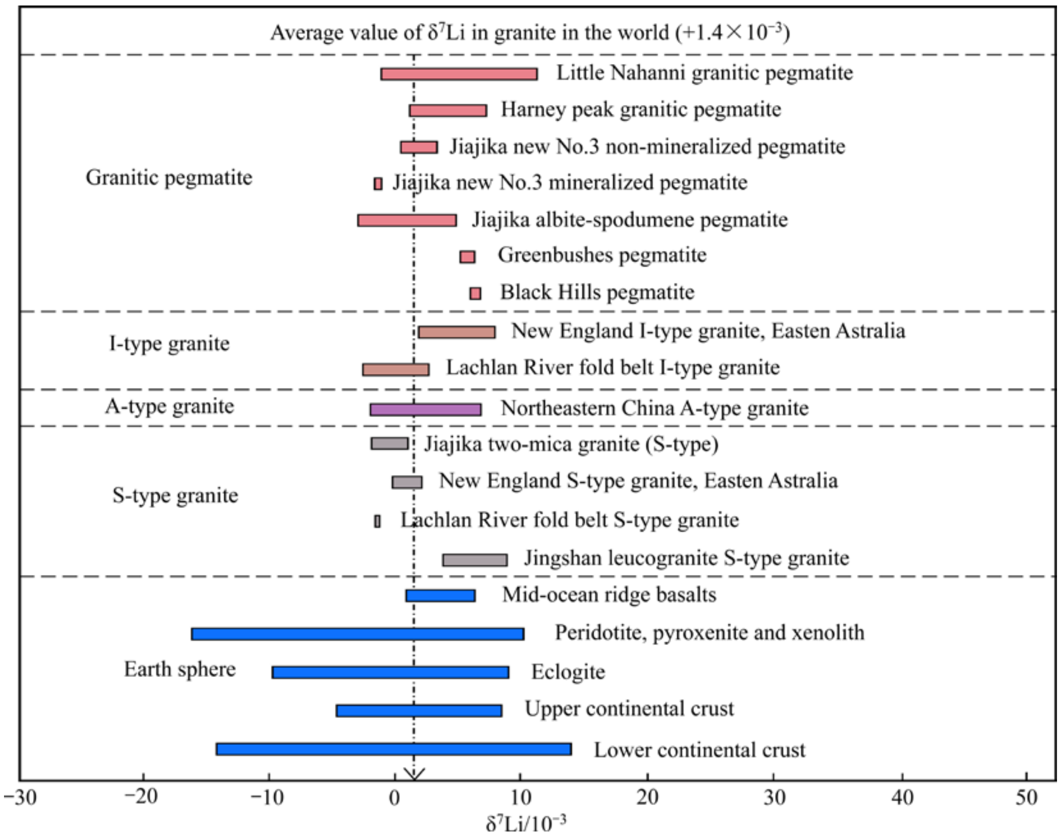

图 9 花岗岩和伟晶岩中锂同位素分布[109, 147, 154, 156, 158−160]

Fig. 9 Li isotopic compositions of different granites and pegmatites[109, 147, 154, 156, 158−160]

的发展和研究还不够成熟，但不同类型多阶段矿体的锂同位素组合可用以区分锂矿母岩成因类型，且可以对锂、铍、铷、铯、铌、钽等稀有金属找矿有一定的指示意义。锂本身作为能源金属又是流体循环过程中的指示剂，对伟晶岩型锂矿床的研究意义重大，特别是在含锂伟晶岩矿床中，锂同位素可作为直接指标进行成因示踪，显示出其未来在伟晶岩矿床研究中更为突出的应用前景[137, 146]。

4.2 对我国勘探开发建议

1) 进一步摸清楚国内和国外的锂资源储量情况，关注世界各国锂矿勘探项目的进展情况，把握前沿动向，在锂资源潜力大的地区有重点地部署找矿工作。锂虽然不是急缺矿种，但随着锂广泛应用于新能源产业，未雨绸缪是必要的，应以国际视野来考虑锂矿的找矿与开发。

2) 花岗伟晶岩型锂矿床具有多构造背景、多成矿时代的特点，所以对具体矿床来说，需要综合勘探，进一步拓展思路。花岗伟晶岩型锂矿在各个大陆上都有发现，无论是在古老的克拉通内，还是在较年轻的造山带，这些都应该作为找矿方向。

3) 比起其他结晶岩，伟晶岩相对有着更小的岩体规模，更为复杂多样的类型与形态，也就是说伟晶岩之间除了矿物成分上的不同，在矿物大小、结构等方面也会出现多样性。因此，对于花岗伟晶岩型锂矿，很难建立一个统一有效的理论模式，需要考虑不同矿集区的实际地质背景，针对实际情况具体分析，对相似的地质情况进行总结分析，才能不断取得突破。

5 结论

锂作为新兴产业最重要的矿产资源之一，各国对锂的需求增长旺盛。花岗伟晶岩型锂矿由于其分布广品位高，带动了全球的勘查热潮，也取得了重大进展。通过本次研究，可以得出以下结论：

1) 花岗伟晶岩型锂矿品位高、资源量大、采选冶技术成熟，尽管锂是稀有金属，但花岗伟晶岩型锂矿床在全球分布广泛，是锂矿储量和产量的主要类型。

2) 在时空分布方面，花岗伟晶岩型锂矿的成矿时代跨度很大，产出的时代可古老至太古宙，又可年轻至新生代；成矿构造环境从稳定的地台区到活跃的造山带均有。

3) 在成矿规律方面，花岗伟晶岩型锂矿床一般以中高压、中温成矿流体成矿为主，并具有低盐度的特征；花岗伟晶岩中的锂元素来源具有多样性，传统观点认为花岗岩浆的结晶分异富集是锂元素的主要来源，而最新的研究表明也可从沉积岩中继承锂元素。

4) 研究锂含量和锂同位素的组成特征不仅可以划分不同类型的锂矿床，还可以反映花岗伟晶岩型锂矿形成时的源区性质，且对花岗伟晶岩型锂矿的找矿工作具有重要意义。

5) 不同地区的花岗伟晶岩型锂矿床均表现出了特殊性，在找矿过程中应综合利用各种技术，寻找最有效的勘查技术手段，因地制宜，拓展找矿思路。

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Research progress and prospect of granitic pegmatite-type lithium deposits

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Abstract: Granitic pegmatite-type lithium deposits are distributed extensively around the world, and as a significant source of lithium resources, they have aroused the exploration interest of all countries all over the world. This paper summarized metallogenic characteristics and the trends of the major granitic pegmatite-type lithium deposits at home and abroad, and the main findings were as follows: 1) Global granitic pegmatite-type lithium resources are abundant and widely distributed, which can be used as a very potential mining target; 2) The metallogenic tectonic environment can be stable platform or active orogenic belt; 3) The metallogenic epoch can be old to the Archean or new to the Cenozoic, but in China the major ore-forming stage is in the Yanshanian period; 4) The mineralization of lithium cyclical, and lithium in granitic pegmatites may inherited from sedimentary rocks. Most of the ore-forming fluids formed under the conditions of medium-high pressure, medium temperature and low salinity. In addition, lithium isotopes have become a good tracer to study various complex metallogenic processes, and can provide evidence for the magmatic source of granites and pegmatites. A series of studies have been carried out on the lithium isotopes fractionation mechanism of granitic pegmatite-type lithium deposits. It's proposed that the main genesis of the granitic pegmatite-type lithium deposits may be the crystallization of granite or the partial melting of the crust. The characteristics of Li isotopes can be used to distinguish the genetic types of the parent rock of the mineralization, which has an indicating significance for the prospecting direction and shows a critical prospect. The granite pegmatite type lithium deposits in different areas show great differences in ore body morphology, remote sensing, geochemistry and geophysics characteristics, so it's urgent for us to seek for the most effective prospecting technology based on the conditions, and expand the prospecting methods.

Key words: lithium resource; metallogenic epoch; spodumene; Li isotopes; prospecting direction

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