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片麻岩穹窿与伟晶岩型锂矿的成矿规律探讨

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摘要:"片麻岩穹窿"是指中下地壳热动力过程产生的与岩浆作用(或混合岩化作用)密切相关的穹状构造,是折返造山的产物.片麻岩穹窿的形成经历了从垂直上升的地壳流导致的岩浆上涌的挤压收缩到岩体侵位的顶部伸展机制的转化过程,这一过程有利于富含锂-铯-钽型(LCT)型伟晶岩的生成和锂族元素的富集.研究表明,位于青藏高原北部的中国松潘-甘孜-甜水海印支造山带是中国大型"伟晶岩型"锂矿资源赋存的基地,松潘-甘孜东南部的超大型甲基卡型伟晶岩型锂矿带,产于具有巴罗式"低/中压-高温"变质组合的三叠纪复理石围岩中,早中生代花岗岩以及衍生的大量含锂稀土矿物的伟晶岩脉侵位有成因关系.研究认为,探究片麻岩穹窿的形成过程和构造成因机制;识别花岗岩-含矿伟晶岩的地球化学属性,揭示花岗岩浆分异作用与含矿伟晶岩相演变的成因联系,以及锂元素迁移、富集熔浆的过程;圈定三叠纪地层中巴罗式变质相带的展布,探明富锂伟晶岩矿带赋存的有利变质相带及形成的 P-T 条件;揭示"变形-变质-岩浆深熔-成矿"的时空耦合、制约与相互作用,再造造山过程中锂资源富集和保存的规律,以及建立成矿动力学模式;是揭示片麻岩穹窿与伟晶岩型锂矿的成矿规律的重要科学途径.

关键词:片麻岩穹窿;花岗岩;含锂伟晶岩;"变质-变形-岩浆-成矿"四位一体;锂矿;矿床学.

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Discussion on Relationships of Gneiss Dome and Metallogenic Regularity of Pegmatite-Type Lithium Deposits

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Abstract: Gneiss domes develop in exhuming orogens, where they constitute an efficient mechanism for material and heat advection of continental crust during orogenesis, which is always related to magmatism (or migmatization). Dome formation may be accompanied by heterogeneous thinning of the upper crust that may occur as the ductile lower crust flows into a gneiss dome by convergent flow and lead to contraction strain in the core. During gneiss dome formation process, lithium-rich (with other rare earth elements) pegmatite is beneficial to form and hence, lead to lithium enrichment. Previous researches indicate that the Songpan-Ganzi-Tianshuihai Indosinian orogenic belt, located in the northern part of the Qinghai-Tibetan Plateau, is the "pegmatite-type" lithium mine resources base in China. The ultra-large pegmatite-type lithium belt in the southwestern of the Songpan-Ganzi occurs in the Triassic flysch which is the country rock of Barrow-type metamorphism with low/medium pressure-high temperature metamorphic traits. It has a genetic relationship with the Late Triassic granite and the lithium-bearing pegma-

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tite intrusion. The authors suggest that future studies should focus on (1) exploring the formation process and tectonic mechanism of gneiss domes; (2) identifying the geochemical properties of granite-bearing pegmatites; (3) revealing the genetic relationship between the differentiation of granite and the evolution of ore-bearing pegmatite; (4) clarifying lithium migrating and enriching process in the melt; (5) delineating the distribution of the Barrow-type metamorphic facies belt in the Triassic strata; (6) proving the favorable metamorphic facies belts and *P*-*T* conditions where the lithium-rich pegmatite formed can reveal the space-time coupling of "deformation-metamorphism-magmatic deep-melting-metallogenesis". Moreover, the law of enrichment and preservation of lithium ore, used to establish the metallogenic kinetics model, is an important scientific aspect to reveal the relationships of gneiss dome and metallogenic regularity of pegmatite-type lithium deposits.

Key words: gneiss dome; granite; lithium-bearing pegmatite; four integrated factors of "metamorphism-deformation-magmatism-mineralization"; lithium deposit; mineral deposit.

0　引言

片麻岩穹窿(Eskola,1948)是造山折返的产物(Vanderhaeghe, 2004; Whitney *et al.*, 2004).绝大部分片麻岩穹窿的构造组合从里到外可以分为核、边和幔3部分,核部为花岗岩和深熔混合岩,边部为花岗片麻岩,幔部典型特征是以高级变质沉积岩和变质火山岩为标志的高角闪岩到麻粒岩相片麻岩(或者高温片岩)(Whitney *et al.*, 2004),也被简化为核部(例如混合岩和花岗质岩体)和上覆的变质层(例如边部的片岩和片麻岩)的双层构造(Stübner *et al.*, 2013).在幔部变质岩中,发育从片麻岩穹窿顶部向两侧下滑的典型层叠式褶皱(Cascading folds)(图1)(Burg *et al.*, 2004),反映片麻岩穹窿以全熔岩或花岗质岩石为主的核部,由于岩石的部分熔融作用产生的流动及褶皱效应.在一些片麻岩穹窿的深部,流动面理通道以漏斗状为主,在地表则以穹窿状为主,并且多数情况下在大的片麻岩穹窿内部或边缘会有次级的片麻岩穹窿体出露,或多个片麻岩穹窿呈线状或面状成群出露(Lagarde *et al.*, 1994; Arnold *et al.*, 1995; Vanderhaeghe *et al.*, 1999; Fisher and Olsen, 2004; Gervais *et al.*, 2004; Ayarza and Martínez Catalán, 2007),如北—中帕米尔片麻岩穹窿群由空喀山、慕孜塔格、Yazgulom和Muskol片麻岩穹窿组成(图2)(Schmidt *et al.*, 2011),松潘—甘孜造山带中雅江片麻岩穹窿群包含长征、容须卡、甲基卡和瓦多4个片麻岩穹窿(许志琴等,1992),以及马尔康片麻岩穹窿群包含可尔因和太阳河片麻岩穹窿(de Sigoyer *et al.*, 2014; Zhao *et al.*, 2019);北喜马拉雅的拉

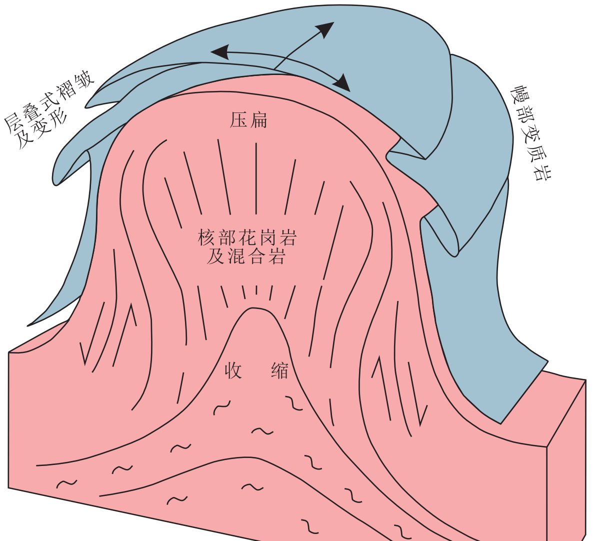

图1　片麻岩穹窿的结构示意

Fig.1　Schematic diagram of the structure of gneiss dome

据 Whitney *et al*.(2004);核部为混合岩化的花岗岩,边部为花岗片麻岩,幔部为变质岩和层叠褶皱;箭头代表剪切指向

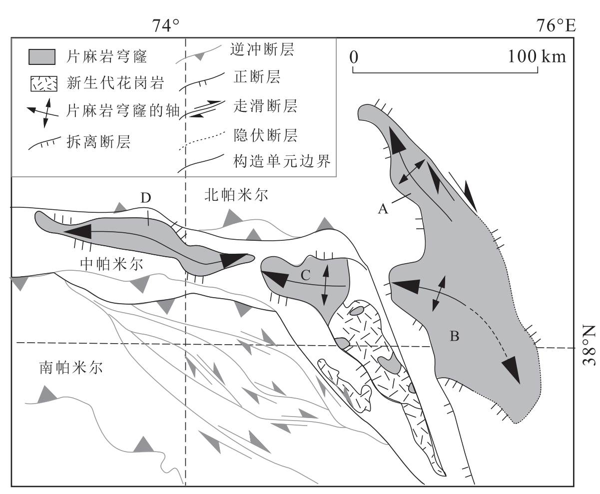

图2　北—中帕米尔片麻岩穹窿群示意

Fig.2　Schematic diagram of the North-Central Pamir gneiss dome group

据 Schmidt *et al*.(2011);A.空喀山穹窿;B.慕孜塔格穹窿;C.Yazgulom 穹窿;D.Muskol 穹窿

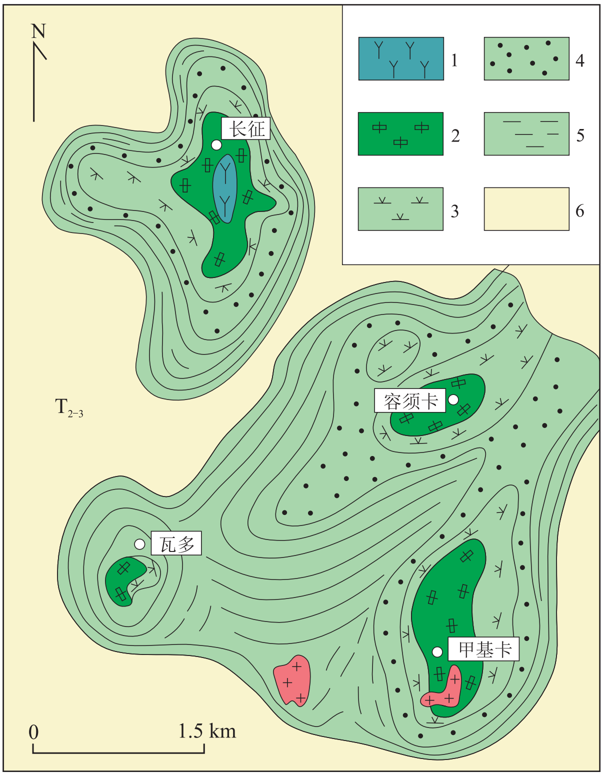

图 3 松潘—甘孜造山带雅江片麻岩穹窿群分布

Fig.3 Distribution of the Yajiang gneiss dome group in the Songpan-Ganzi orogenic belt

据许志琴等(1992);1.矽线石带;2.十字石带;3.红柱石带;4.石榴石带;5.黑云母带;6.花岗岩

轨岗日片麻岩穹窿群包含雅拉香波—马波加—康马—普弄抗日—萨加—马拉山—错那洞等多个片麻岩穹窿(张金阳等,2003;Guo *et al*., 2008; 高利娥等,2011;辜平阳等,2013;董汉文等,2018).

片麻岩穹窿幔部的变质岩有很好的分带性和规律性.如中国松潘—甘孜造山带位于三叠系西康群中的“雅江”和“马尔康”地区片麻岩穹窿(图3),以及喜马拉雅片麻岩穹窿群.片麻岩穹窿的幔部变质岩由内而外分别为矽线石带、十字石带、红柱石带、石榴石带、黑云母带和绢云母—绿泥石带的巴罗式变质分带(许志琴等,1992; Guo *et al*., 2008;辜平阳等,2013;付小方等,2017;董汉文等,2018; Zhao *et al*., 2019).这说明中压Barrovian式变质分带是片麻岩穹窿幔部变质的主要特点.

片麻岩穹窿的形成经历了从垂直上升的地壳流导致的岩浆上涌的挤压收缩到岩浆体侵位的顶部伸展机制的转化过程(Whitney *et al*., 2004),这一过程将有利于大量富含稀土的伟晶岩脉的侵位和锂元素的富集.瑞典化学家阿·阿尔夫维特桑在1817年发现的锂(Li)金属是地球上最轻的银白色金属,为什么当今富含稀土金属元素的锂(铍铌钽铯铷)资源会引起人们极大的兴趣和重视?因为它已经从普通的矿产资源变成“能源金属”和“高能金属”(许志琴和马绪宣,2015).锂资源的开发利用贯穿节能环保、新一代信息技术、高端装备制造、新材料和新能源汽车等产业,也被广泛应用于原子能工业、电子、化学、冶金、宇航等领域,具有非常重要的经济和战略意义.

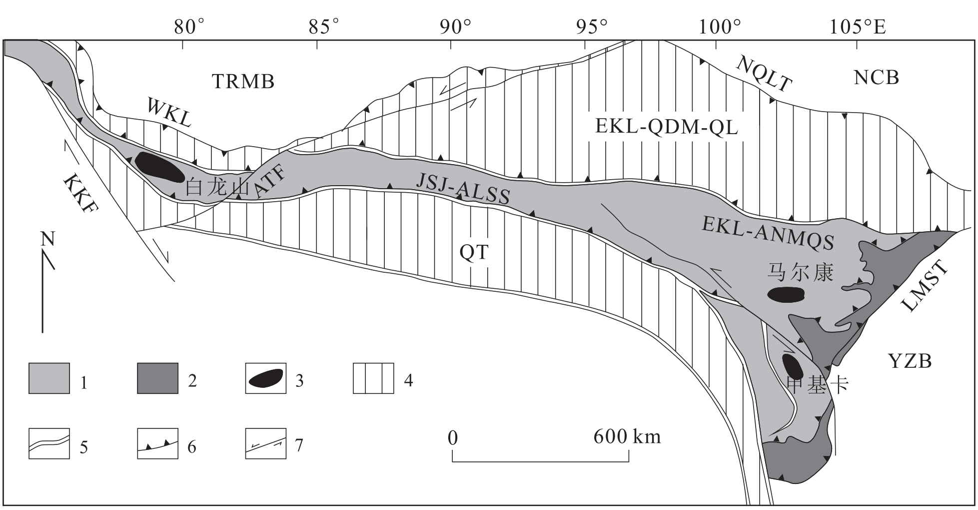

图 4 位于青藏高原北部的松潘—甘孜—甜水海地体位置

Fig.4 Location of the Songpan-Ganzi-Tianshuihai terrane in the northern part of the Qinghai-Tibet Plateau

1.松潘—甘孜—甜水海造山带的三叠系;2.松潘—甘孜造山带中新元古代—古生代地层;3.锂矿带位置;4.周围地体;5.缝合带;6.逆冲断裂;7.走滑断裂;TRMB.塔里木盆地;WKL.西昆仑;KKF.喀喇昆仑断裂;NCB.北中国陆块;NQLT.北祁连逆冲断裂;EKL-QDM-QL.东昆仑—柴达木—祁连地体;EKL-ANMQS.东昆仑—阿尼玛卿缝合带;JSJ-ALSS.金沙江—哀牢山缝合带;QT.羌塘地体;LMST.龙门山逆冲断裂;YZB.扬子陆块

最近的探测和研究表明,川西雅江的甲基卡、马尔康的李家沟和新疆喀喇昆仑的白龙山超大型锂矿带,展布在青藏高原北部横跨 2 800 km 的巨型(松潘－甘孜－甜水海)造山带中,将成为我国未来新能源发展的重要后备基地(图 4).该巨型锂矿带就是赋存于巴罗式变质的三叠纪复理石地层、印支期花岗岩与含锂的伟晶岩脉相伴的片麻岩穹窿构造样式中(图 2;许志琴等,1992;许志琴和马绪宣, 2015).甲基卡矿床是目前亚洲规模最大的固体锂矿床,规模大、品位高、矿种多、埋藏浅、选矿性能好.预测远景资源量达 500×10^4 t,铍、铌、钽、铯可综合利用,具有广阔的开发前景(黄韬等,2018).

伟晶岩型锂矿的形成具有独特的物理、化学形成条件.尽管在伟晶岩的成分分带、新矿物的发现、地球化学的演化与稀有金属的富集机制、熔体－流体的来源与结晶分异、成岩成矿的物理化学条件等研究方面已经取得了重要进展,但是,在造山过程中“岩浆－变形－变质－成矿”四位一体的片麻岩穹窿的形成机制,与伟晶岩型锂矿成矿规律的关系,以及对于伟晶岩及其相关成矿作用发生的地球动力学背景研究,依然没有根本解决,成为大陆动力学研究的重要前沿和探索课题.这一研究不仅可以提供学科发展和交叉的最佳窗口,而且为找矿突破提供科学依据,具有重要的科学意义和实用价值.

1　川西片麻岩穹窿与伟晶－花岗岩型锂矿床

松潘－甘孜造山带是三叠纪末－早侏罗世时期大规模的印支造山运动的产物.研究表明其与早中三叠世古特提斯洋盆(昆仑－阿尼玛卿和金沙－理塘洋盆)的双向俯冲有关(许志琴等, 1992; Roger *et al*., 2010; de Sigoyer *et al*., 2014).印支造山作用表现为巨量的三叠纪复理石沉积构造楔的形成(Mattauer *et al*.,1992)、大量 228～195 Ma 同造山花岗岩体 (Zhang *et al*., 2006,2007; Xiao *et al*., 2007; Yuan *et al*.,2010) 以及后造山花岗岩的侵位.目前发现的雅江甲基卡和马尔康李家沟的大型－特大型“伟晶岩型”锂矿床均产在片麻岩穹窿的构造样式中,与侵位在三叠纪巴罗式变质相带的印支期伟晶花岗岩有成因关系.因此,在特定的三叠纪变质相带和特殊的片麻岩穹窿中,寻找新的大型－超大型锂矿集区,成为重要的科学瓶颈问题.我们通过甲基卡含锂伟晶岩型片麻岩穹窿和马尔康可尔因含锂伟晶岩型片麻岩穹窿的解析,为建立川西锂矿基地和提供新的找矿靶区提供科学依据.

1.1　甲基卡含锂伟晶岩型片麻岩穹窿

研究表明,位于松潘－甘孜造山带西南部的雅江片麻岩穹窿群由长征、容须卡、甲基卡和瓦多 4 个片麻岩穹窿组成,具有典型以 N-S 向为主、以 E-W 向为辅的穹状组构的穹窿构造,产在具有巴罗式低/中压－高温变质组合[(矽线石(Sil)－十字石(St)－红柱石(And)－石榴子石(Grt)－黑云母(Bi))]的三叠纪西康群变质复理石岩系之中,陆壳重熔的二云母花岗岩－黑云母花岗闪长岩基局部出露和大范围隐伏在三叠纪变质地层之下.这些穹窿构造曾被称作为“热隆”(许志琴等,1992)、“片麻岩穹窿”(许志琴和马绪宣,2015)和“花岗岩浆底辟穹窿”(付小方等,2017).

在甲基卡,片麻岩穹窿的围岩三叠纪巴罗式变质岩系中,自中心到边部显示了“红柱石－十字石－石榴石－黑云母－绢云母－绿泥石带”.目前,矿区南部出露的马颈子二长花岗岩体(图 5),为高钾钙碱性强过铝质 S 型花岗岩,显示轻稀土富集、重稀土亏损的特征,含锂矿的花岗伟晶岩脉产于花岗岩穹窿

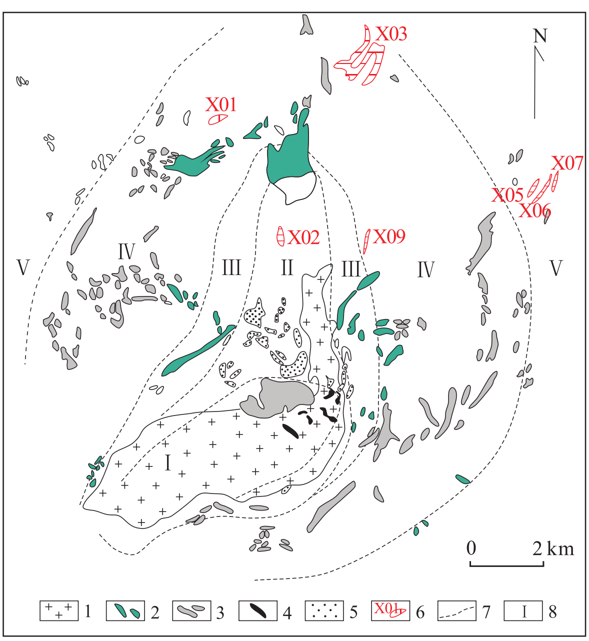

图 5　甲基卡锂矿床的矿田地质简图

Fig.5　Schematic diagram of the ore field of the Jiajika lithium deposit

据梁斌等(2016);1.马颈子二云母花岗岩;2.微斜长石型伟晶岩;3.微斜长石钠长石型伟晶岩;4.钠长石型伟晶岩;5.钠长石锂辉石型伟晶岩;6.钠长锂云母型伟晶岩脉及编号;7.伟晶岩脉类型分带线;8.核部花岗岩基;9.伟晶岩脉类型分带线;X03.巨型伟晶岩脉

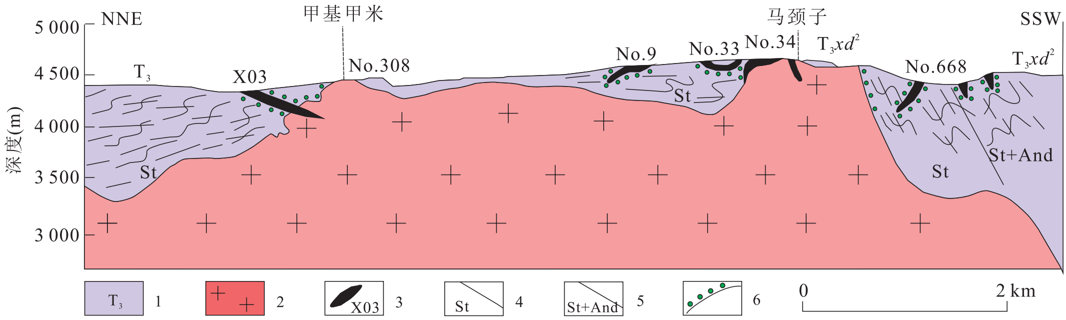

图 6 雅江甲基卡片麻岩穹窿的 E-W 向构造示意剖面

Fig.6 E-W cross-section of the Jiajika gneiss dome

据付小方等(2017);1.上三叠统变质含碳泥质粉砂岩与粉砂岩互层;2.印支期二云母花岗岩;3.花岗伟晶岩脉及编号;4.十字石变质带;5.十字石、红柱石变质带;6.电气石、堇青石接触变质带

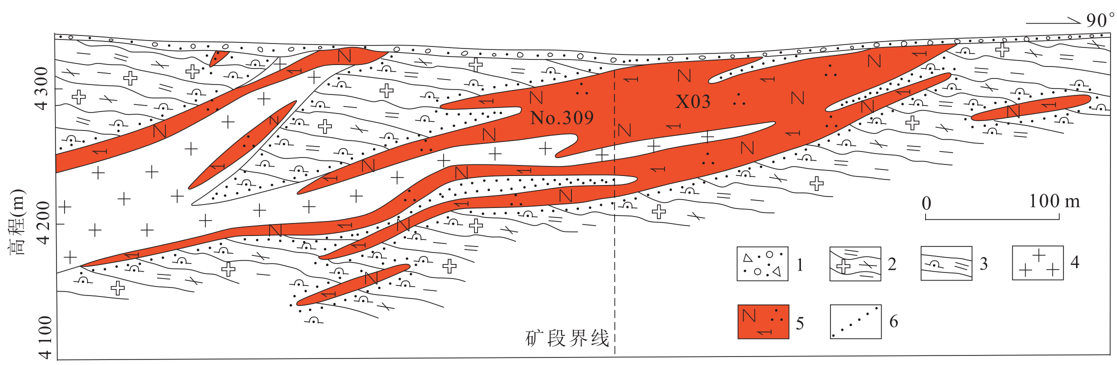

图 7 甲基卡 X03 伟晶岩脉 15 号勘探线和邻区 No.309 孔连接剖面

Fig.7 Cross-section view of the Jiajika X03 pegmatite vein and adjacent No. 309 drilling hole

据付小方等(2017);1.第四系;2.十字石—红柱石二云母片岩;3.堇青石化十字石—红柱石二云母片岩;4.花岗岩细晶岩;5.钠长锂辉石伟晶岩;6.电气石化角岩带

顶部及周缘封闭条件良好的石榴石—红柱石云母片岩中.共发现花岗伟晶岩脉约 478 条,围岩中的含矿的花岗伟晶脉有 114 条(付小方等,2014).花岗伟晶岩的类型由中心花岗岩向外发生微斜长石带—微斜长石钠长石带—钠长石带—钠长锂辉石—锂(白)云母带—石英脉带的变化.已经验证的巨大 X03 号伟晶脉产在十字石二云母片岩中,属于钠长石—锂辉石型花岗伟晶岩脉(图 6,图 7).与锂共生的有铌、钽、铍、铷、铯等稀有金属及锡等.Li 资源的工业矿物以锂辉石为主,少量为锂云母、磷铝锂石、锂绿泥石等(付小方等,2014).甲基卡花岗岩的锆石 U-Pb 同位素年龄约为 223 Ma,为岩体的结晶年龄,含矿伟晶岩脉形成于 216 Ma,两者在时间和空间上的一致性,表明具有成因的联系(付小方等,2017).

研究表明,甲基卡岩体的岩浆结晶分异程度最高,重稀土(HREE)相对更加亏损;伟晶岩是花岗岩结晶分异的产物,从甲基卡花岗岩露头向外,伟晶岩带可以分为微斜长石型伟晶岩、微斜长石钠长石型伟晶岩、钠长石型伟晶岩、钠长石锂辉石型伟晶岩和钠长石锂云母型伟晶岩(图 5).伟晶岩的稀土元素中轻稀土由富集趋向亏损,重稀土由亏损趋向富集;二云母花岗岩体与伟晶岩具类似稀土、微量及相似的锂同位素特征,具有渊源关系.

1.2 马尔康可尔因含锂伟晶岩型片麻岩穹窿

马尔康片麻岩穹窿群位于川西金川县以北,包括以可尔因二云母花岗岩(219 Ma)为核部的片麻岩穹窿和以太阳河黑云母二长花岗岩(216～217 Ma)为核部的片麻岩穹窿(图 8)(de Sigoyer *et al.*, 2014).马尔康可尔因片麻岩穹窿以二云母花岗岩为核部,侵位于幔部的三叠纪复理石变质地层中,自里往外的变质分带为:矽线石—蓝晶石带、石榴石—十字石带、黑云母—红柱石带和白云母—绿泥石带,为典型的中—低压、高—中温的巴罗式变质组合(图 9),变质峰期的温度为 618～632 ℃,压力为 0.6～0.8 GPa(Zhao *et al.*, 2019).

围绕马尔康片麻岩穹窿有许多伟晶岩矿床,包

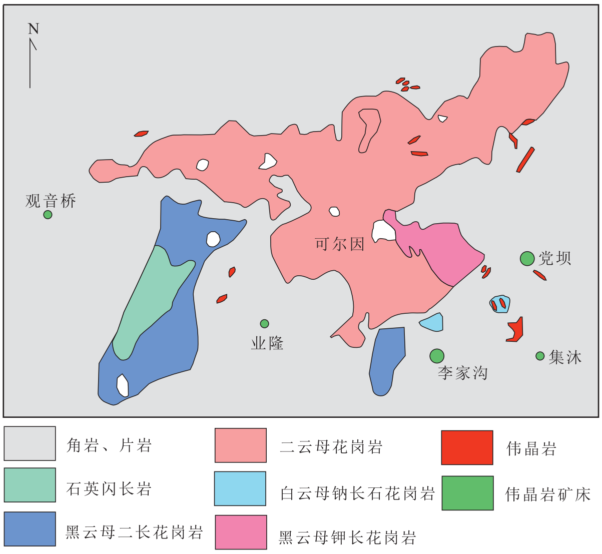

图 8　马尔康片麻岩穹窿地质图

Fig.8　Geological map of the Markam gneiss dome

据 de Sigoyer *et al*.(2014)；该穹窿包括可尔因二云母花岗岩(粉红色)片麻岩穹窿和太阳河黑云母二长花岗岩(蓝色和绿色)片麻岩穹窿

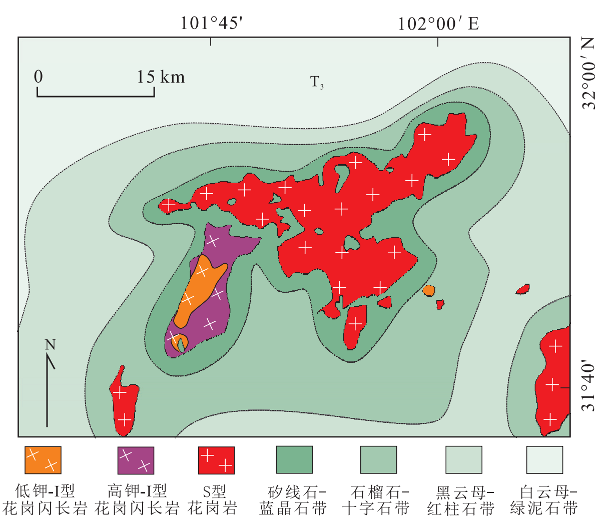

图 9　马尔康穹窿群的变质相带图

Fig.9　Metamorphic phase diagram of the Markam gneiss dome

据 Zhao *et al*.(2019)；自花岗岩体的幔部变质岩自内向外分别为矽线石－蓝晶石带、石榴石－十字石带、黑云母－红柱石带和白云母－绿泥石带

括李家沟、党坝大中型稀有金属矿床(李建康，2006；Li *et al*.，2015).随着进一步探查，新的含锂伟晶岩的不断发现，在李家沟确定了 0.51×10^4 t 的锂矿资源，在党坝乡确定了 0.48×10^4 t 的锂资源，业隆沟的锂资源可达 0.38×10^4 t 等(Fei *et al*.，2017).因此，马尔康地区成为了一个大矿田.所有的找矿突破都是在可尔因岩基的围岩西康群中，包括中三叠世的轧辊脑组(T_2z)、晚三叠世的侏倭组(T_3zh)和新都桥组(T_3x)等一系列灰色至黑色长英质砂岩、粉砂岩、绢云母板岩、粉质板岩地层中.马尔康片麻岩穹窿呈北西向分布，受到了北东向的挤压应力，在穹窿的东北部发育北西走向的逆冲断裂带，在穹窿的西部则以地层的褶皱为主，这些都是印支造山带晚期的产物 (Zhao *et al*.，2019).所有的矿化和穹窿的形态密切相关(图 8).

2　片麻岩穹窿与伟晶岩型锂矿成矿规律的探讨

2.1　造山过程“变形－变质－岩浆(熔融)－成矿”四位一体的高度融合

活动的大陆造山带是一个非平衡的开放系统.造山过程是一个能量消耗过程，表现为大量深部流体或熔融体的聚集、上升、存储到排放－丢失的转换.造山带通过变形－变质－深熔作用的自组织系统来建立耗散结构(Brown，2007).在造山事件中，变形－变质－岩浆(熔融)－成矿作用(四位一体)时空上的高度协调，是造山过程自组织行为建立耗散结构表现 (Brown，2007).变形与变质作用通过流体迁移和应变能以及矿物属性与承载机制转换，变质作用和地壳熔融通过矿物组合转变和熔体－矿物反应相互转换，变形与地壳熔融又通过熔体弱化和剪切生热相互转换.核心是“温度场”－岩浆(热的扩散)(图 10).“甲基卡型”伟晶岩锂矿的形成，体现了花岗岩侵位、巴罗式变质事件发生、片麻岩穹窿形成以及含锂矿伟晶岩的侵位的高度协调和近乎一致性.在此基础上，进行锂矿构造成因和成矿规律的深入研究，是服务于新能源战略的一种新的思考和科学探究.

2.2　片麻岩穹窿的构造成因

研究表明，甲基卡片麻岩穹窿的构造产出直接与马颈子花岗岩的深部产状有关，表现穹窿幔部变质岩顶部平缓、翼部陡直的构造面理.侵位在片麻岩穹窿幔部巴罗式变质地层中的甲基卡含锂伟晶岩脉，作为马颈子花岗岩的析出物，它们大多数呈水平板状、透镜状或岩席状侵位在穹窿(或花岗岩体)顶部的近水平面理中，少量呈岩株或岩墙状侵位在穹窿(或花岗岩体)侧部，与面理相交.含锂伟晶岩脉还可以通常片麻岩穹窿形成过程中产生的断裂产出(图 5，图 6).

片麻岩穹窿构造成因的多样性引起学者们的关注.一种观点认为片麻岩穹窿是由底辟作用形成的

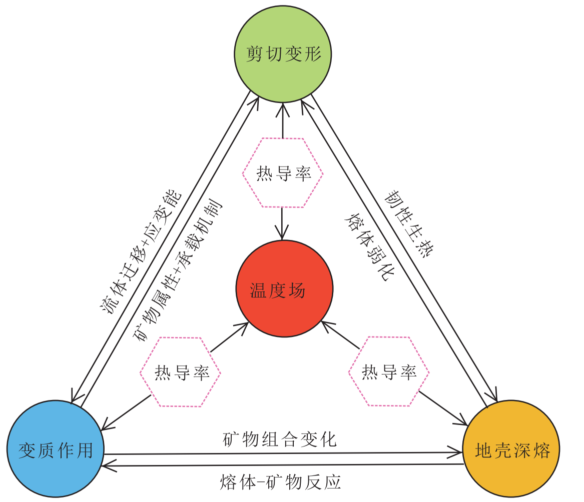

图 10 造山过程中变形—变质—岩浆深熔之间关系示意

Fig.10 Schematic diagram of the relationship among deformation-metamorphism-anatexis during orogenic process

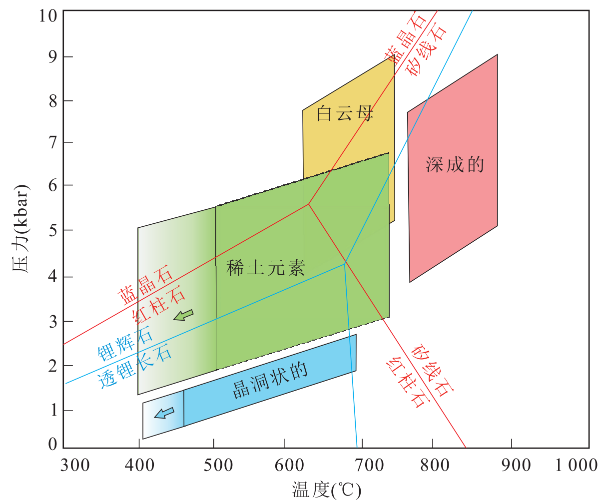

图 11 伟晶岩分类的铝硅酸盐相图

Fig.11 Aluminum silicate phase diagram showing pegmatite classes

据 London(2008);根据结晶温度估算显示,在含锂辉石—透锂辉石的伟晶岩和晶洞型伟晶岩均可在低温低压区形成

(Reesor and Moore, 1971; Fletcher, 1972; Soula, 1982; Chardon *et al*., 1998; Calvert *et al*., 1999; Edwards *et al*., 2002; Teyssier and Whitney, 2002; Siddoway *et al*., 2004).此外,还有"地壳缩短产生的褶皱和挤出"(Duncan, 1984; Burg *et al*., 1997;Štípská *et al*., 1999)、"与低角度拆离有关的地壳减薄"(Wernicke, 1981; Jolivet *et al*., 2004; Tirel *et al*., 2006)、"造山裂陷造成的拉伸"(Vanderhaeghe *et al*., 1999; Vanderhaeghe, 2004)、"地壳细颈化"(Fletcher and Hallet, 2004)、"地壳隧道流"(Beaumont *et al*., 2001; Burchfiel *et al*., 2008)和"下部地壳的收缩伴随上部地壳的伸展"(Lee *et al*., 2000; Crowley *et al*., 2001)等多种成因机制的提出.

在造山折返过程中片麻岩穹窿的普遍存在,说明片麻岩穹窿的形态和成因受造山过程地壳流动力学(包括垂直于侧向流动的相对速率比)的控制(Whitney *et al*., 2004),垂直地壳流动产生垂直底辟、侧向地壳流动产生隧道流以及具有垂直与侧向分量的地壳流动造成岩浆的挤出(Ramsay and Huber, 1983; Beaumont *et al*.,2001; Rey, 2001).实际上,形成片麻岩穹窿的地壳垂直流动是造山带演化中物质和热重新分配的驱动力.查明川西地区含锂花岗伟晶岩型片麻岩穹窿的构造成因和机制,可以作为造山带中的地壳流对物质流变学、热能耗散以及含矿元素的时空演化的制约.

2.3 地壳重熔及花岗伟晶岩的含矿性

大规模的变形产生的增温效应引起造山带上部的泥质岩的局部熔融,熔体的出现改变了地壳的流变学性质,导致了应变的局部化,其结果是熔体优先沿着高应变区从源区移出,协助整个系统的调整.造山型的伟晶岩主要为锂—铯—钽(LCT)伟晶岩(London and Manning, 1995),LCT 伟晶岩一般产在高绿片岩和角闪岩相,是造山晚期产物;LCT 出露在高分异、过铝质花岗岩地区,伟晶岩形成温度低(350~550 ℃),结晶时间短(Bradley *et al*., 2017).根据结晶温度估算,伟晶岩分类的铝硅酸盐相图也显示,含锂辉石—透锂辉石的伟晶岩和含稀土矿物的晶洞型伟晶岩均可在低温低压区形成(图 11)(London, 2008).

LCT 花岗伟晶岩的主要造岩矿物为钾长石—石英—钠长石—白云母,副矿物是黑云母、石榴石、电气石和锂云母;工业矿物为锂辉石、透锂长石、锂云母、铯榴石、柯铁矿、钽铁矿、锡石和绿柱石.LCT 花岗伟晶岩是过铝质 S 型花岗质熔体分异的端员成员,它们高度富集锂、铯和钽等不相容元素,在空间和成因上与 S 型母岩—花岗岩联系(Bradley *et al*., 2017).锂作为最轻的元素,也是最不相容元素,在岩浆演化过程中,最倾向于富集在熔浆中,因此常见于岩浆演化的最末端——花岗岩或者伟晶岩.因此,伟晶岩显示与花岗岩相关的分带模式,最远端的伟晶岩中不相容元素最富集(图 12).

在花岗岩体上部的锂—铯—钽(LCT)伟晶岩分带图(London, 2018)显示了花岗岩相,形成在 700 ℃等温线、400 MPa 和 12 km 深度以下;在花岗

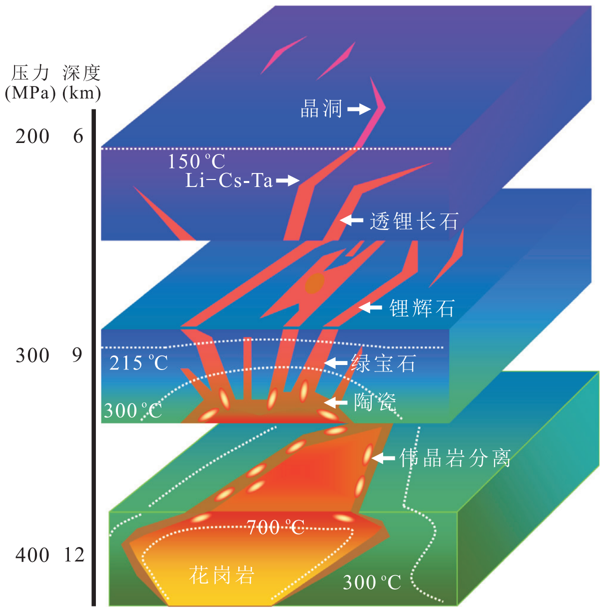

图 12　形成在花岗岩体上部的锂－铯－钽(LCT)伟晶岩分带

Fig.12　Regional zonation within a pegmatite group of the LCT family

据 London(2018)；显示花岗岩相边部及其上部依次出现含铯榴石伟晶岩(Ceramic pegmatite)、含绿柱石伟晶岩(Beryl pegmatite)、含锂辉石伟晶岩(Spondumene pegmatite)、含透锂辉石伟晶岩(petalite pegmatite)和含锂－铯－钽的晶洞型伟晶岩(Li-Cs-Tamiarolitic pegmatite)形成的等温线、压力和深度区间

岩边部的铯榴石伟晶岩(Ceramic pegmatite)形成在700～300 ℃等温线、400～300 MPa 和 10～7 km 深度，铍伟晶岩(Beryl pegmatite)形成在 300～215 ℃等温线、300 MPa 和 9 km 深度；锂辉石伟晶岩(Spondumene pegmatite)形成在 300～215 ℃等温线、300 MPa 和 9 km 深度；透锂辉石伟晶岩(Petalite pegmatite)形成在 215～150 ℃等温线、300～200 MPa 和 7 km 深度，以及含锂－铯－钽的晶洞型伟晶岩(Miarolitic pegmatite)形成在 215～150 ℃等温线、200 MPa 和 6 km 深度.

大部分学者认为川西晚三叠世－早侏罗世的花岗岩是地壳重熔的结果(Roger *et al*., 2004；Zhang *et al*., 2010；de Sigoyer *et al*., 2014)，因为含锂辉石伟晶岩矿脉是 S 型花岗岩高度分异的产物，岩体的结晶分异伴随着锂元素的富集(付小方等，2015；梁斌等，2016；王登红等，2017).马尔康可尔因片麻岩穹窿的研究表明，随着结晶分异程度增高，P-T 降低＋挥发分富集，可尔因花岗岩体中不同岩性岩石的侵入顺序自里往外为：石英闪长岩→黑云母二长花岗岩→黑云母钾长花岗岩→二云母花岗岩→白云母钠长花岗岩，并衍生白云母－钠长石型、白云

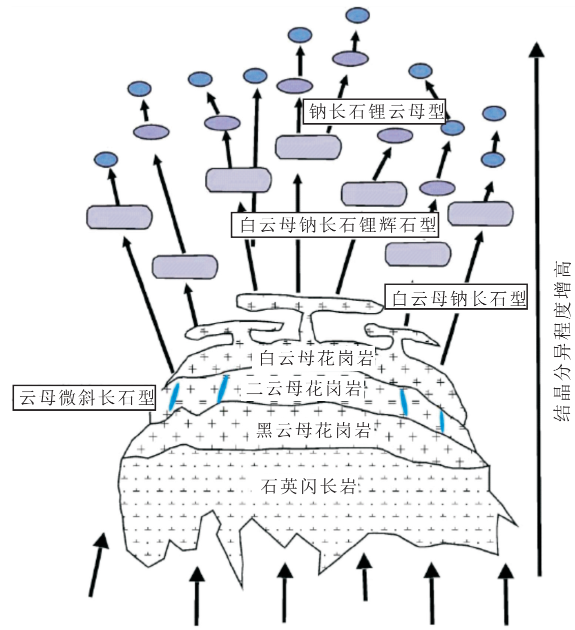

图 13　可尔因花岗－伟晶岩的岩浆分异记录

Fig. 13　Magmatic differentiation of the Keeryin granite-pegmatite

据李建康(2006)

母－钠长石锂辉石和钠长石－锂辉石型伟晶岩的分带以及伴随的含矿元素从 Barren→Be→Be/Nb/Ta→Li/Be/Ta/Nb→Li/Cs/Be/Ta/Nb 的分异过程，可以作为岩浆分异记录(图 13；李建康，2006).

3　讨论和探求

川西伟晶岩型锂矿以特殊的片麻岩穹窿的构造样式赋存，产在松潘－甘孜印支造山带大规模出露的三叠纪巴罗式变质地层中，与早中生代花岗岩有成因联系.因此，如何在浩大的松潘－甘孜三叠纪复理石覆盖的“海洋”中，在无数的中生代花岗岩以及衍生的伟晶岩脉中，在特定的三叠纪变质相带中，寻找与片麻岩穹窿相关的新的大型－超大型锂矿集区？成为解决锂矿资源增储的关键科学问题.笔者认为片麻岩穹窿与含锂伟晶岩型矿床的成矿规律的研究，拟围绕以下几个方面进行：

(1)确定川西雅江甲基卡和马尔康可尔因的含锂伟晶岩脉型片麻岩穹窿的产出规模和状况，探究片麻岩穹窿的形成过程和构造成因机制.

(2)识别花岗岩－含矿伟晶岩的地球化学属性，揭示花岗岩浆分异作用与含矿伟晶岩相演变的成因联系以及锂元素迁移、富集熔浆的过程.

(3)圈定三叠纪地层中巴罗式变质相带的展布，

探明富锂伟晶岩矿带赋存的有利变质相带及形成的 P-T-t 条件.

(4)通过地球物理探测和矿集区的科学钻探(约 3 000～5 000 m),建立精细的岩性－构造－成矿地壳柱,揭示"变形－变质－岩浆深熔－成矿"的时空耦合、制约与相互作用,再造印支造山过程中锂资源富集和保存的规律以及建立成矿动力学模式.

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