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# 造山带岩浆铜镍硫化物矿床深部动力学机制探讨

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**摘 要**：针对造山带岩浆铜镍硫化物矿床成矿岩浆具有富水、源区不均一、弧岩浆元素特征以及矿床中的硫来源多样的特征，前人提出其成矿动力学模式主要包括地幔柱叠加造山带、板块俯冲和地幔柱相互作用、俯冲交代改造的岩石圈地幔部分熔融、后碰撞伸展阶段软流圈地幔和岩石圈地幔共同作用以及板块断裂引起软流圈地幔上涌减压熔融等多种观点。纵观地球演化历史，经历多期次造山作用，但并不是所有造山带均形成了岩浆铜镍硫化物矿床。因此，造山带中能够形成岩浆铜镍硫化物矿床成矿的关键因素有待进一步明晰。基于上述模式均指向造山带岩浆铜镍硫化物矿床均来源于俯冲交代地幔源区，形成时限滞后于俯冲峰期的研究结果和地质事实，笔者提出了造山带岩浆铜镍硫化物矿床两阶段成矿动力学模式。第一阶段：俯冲期内地幔橄榄岩被俯冲板片形成的硅质熔体交代，交代过程中，俯冲熔体导致 Ni 等元素从橄榄石中释放以及自身携带硫的释放，从而形成含有斜方辉石和镍硫化物的辉石岩为主地幔源区。第二阶段：俯冲碰撞期结束后，富集辉石和镍硫化物地幔通过拆沉方式进入软流圈地幔发生再次熔融，熔融条件转变成近似无水条件，镁铁质岩浆会分异形成富集亲铜元素形成的硫化物堆晶或岩浆硫化物矿床。区域上深大断裂、韧性剪切带和缝合带作为岩浆通道，是母岩浆脱离熔融源区后岩浆过程的富集通道，源区和岩浆过程共同作用形成造山带岩浆铜镍硫化物矿床。

**关键词**：岩浆铜镍硫化物矿床；熔体交代；岩石圈拆沉；造山带

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## Study on Dynamic Mechanism of Magmatic Copper-Nickel Sulfide Deposits in Orogenic Belts

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**Abstract**：Previous studies have proposed various ore-forming dynamic models for magmatic Cu-Ni deposits

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in orogenic belts, including mantle plume overlapping orogenic belts, plate subduction and mantle plume interaction, partial melting of the lithospheric mantle, mixing of asthenospheric and lithospheric mantle during post-collision extension, and decompression melting caused by tearing of slab leading to asthenospheric mantle upwelling. However, the multiple episodes of subduction-accretion orogeny throughout the history of Earth evolution, the above dynamic processes have occurred, but Cu-Ni sulfide deposits have not been formed. Therefore, the key factors for the formation of Cu-Ni sulfide deposits in orogenic belts await further clarification. Based on the fact that the above models all point to Cu-Ni sulfide deposits in orogenic belts originating from subducted metasomatic mantle sources and forming after the peak subduction period, we propose a two-stage ore-forming dynamic model for Cu-Ni sulfide deposits in orogenic belts. Stage One: During the subduction period, interactions between mantle peridotites and silicic melts from the subducting slab lead to the release of elements such as nickel from olivine and sulfur carried by the subduction melts, thus forming a mantle source dominated by pyroxenite containing orthopyroxene and nickel sulfides. Stage Two: After the end of the subduction-collision period, the pyroxenite mantle source enriched during subduction enters the asthenospheric mantle through delamination and undergoes remelting, where the melting conditions change to near hydrous-free conditions. In this condition, these mafic magmas differentiate to form sulfur-rich, copper-affinitive sulfides crystallizing into sulfide piles or magma sulfide deposits. The large depth fault, ductile shear zones, and suture zones serve as magma conduits for the enrichment of the parent magma, with the combined action of source region and magmatic process leading to the formation of Cu-Ni sulfide deposits in orogenic belts.

**Keywords**：magmatic copper-nickel sulfide deposits；melt metasomatism；lithosphere delamination；orogenic belt.

近 20 年来, 在北美环太平洋造山带、芬兰斯韦坎尼造山带、西班牙瓦里斯坎造山带、东昆仑造山带以及中亚造山带南缘发现了一系列不同规模的岩浆铜镍硫化物矿床（Peltonen, 1995; Ortega et al., 2004; Piňa et al., 2006; Thakurta et al., 2008; Barnes et al., 2009; Song et al., 2009; Zhang et al., 2009; Qin et al., 2011; Song et al., 2011, 2013; Li et al., 2012; Xie et al., 2012, 2014; Manor et al., 2016; 张照伟等, 2023）。虽然这些造山带中岩浆铜镍硫化物单个矿床品位低、规模小, 但是数量众多, 目前已经成为最重要的经济矿床之一（宋谢炎等, 2019）。造山带中岩浆铜镍硫化物矿床在矿物组成、元素地球化学特征、同位素组成及熔融源区地幔潜能温度等方面明显不同于与板内岩浆作用(和/或地幔柱)有关的绿岩带与科马提岩有关的矿床、大陆边缘裂谷和克拉通内部等岩浆铜镍硫化物矿床, 而是显示出与板块俯冲作用直接或间接相关(Naldrett, 2004)。前人针对造山带中岩浆铜镍硫化物矿床中出现角闪石、金云母等含水矿物、弧岩浆元素特征及壳幔混合同位素组成提出了俯冲带环境、板块俯冲和地幔柱相互作用, 地幔柱远程效应以及造山后伸展环境幔源岩浆受结晶分异、地壳混染等岩浆过程控制等不同动力学机制的认识（Qin et al., 2011; Song et al., 2011, 2021; Li et al., 2012a; Su et al., 2013; Xue et al., 2018; Chen et al., 2021; Wei et al., 2023; 王亚磊等, 2023）。上述观点从不同角度揭示了造山带中岩浆铜镍硫化物矿床形成过程及深部动力学机制, 然而, 自板块构造启动以来（Windley, 2007; O'Neil et al., 2007; Condie et al., 2008; Ge et al., 2018; Deng et al., 2019; 翟明国等, 2020）, 形成了一系列的元古宙和显生宙造山带, 为什么如此众多造山带均没有产出具有经济意义岩浆铜镍硫化物矿床? 因此, 造山带内形成岩浆铜镍硫化物矿床的关键控制因素还需要进一步的研究总结分析。

## 1　典型造山带岩浆铜镍硫化物矿床特征

全球典型的造山带中岩浆铜镍硫化物矿床主要分布在中亚造山带南缘地区、东昆仑、北美环太平洋、芬兰斯韦坎尼（Svecofennian）及西班牙瓦里斯坎（Variscan）等造山带(图 1)（Peltonen, 1995; Ortega et al., 2004; Piňa et al., 2006; Thakurta et al., 2008; Barnes et al.,

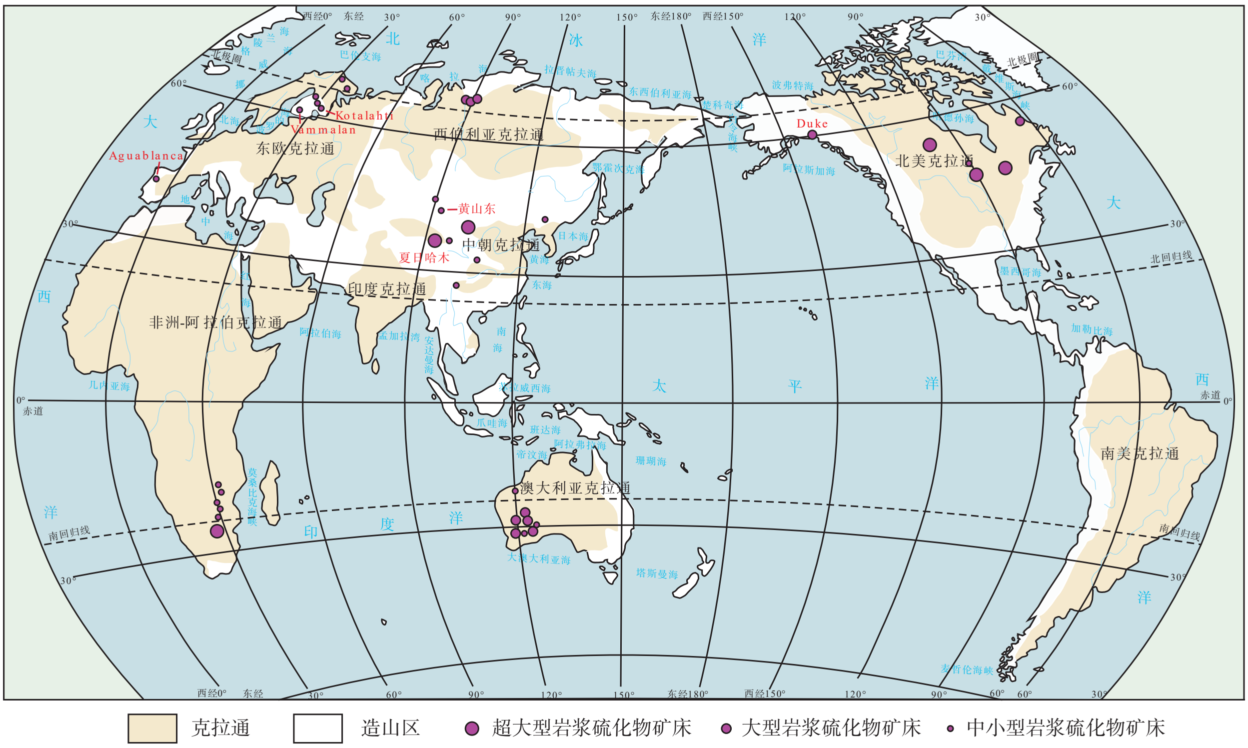



**图1　典型造山带岩浆铜镍硫化物矿床分布图(据李文渊，2007 修改)**

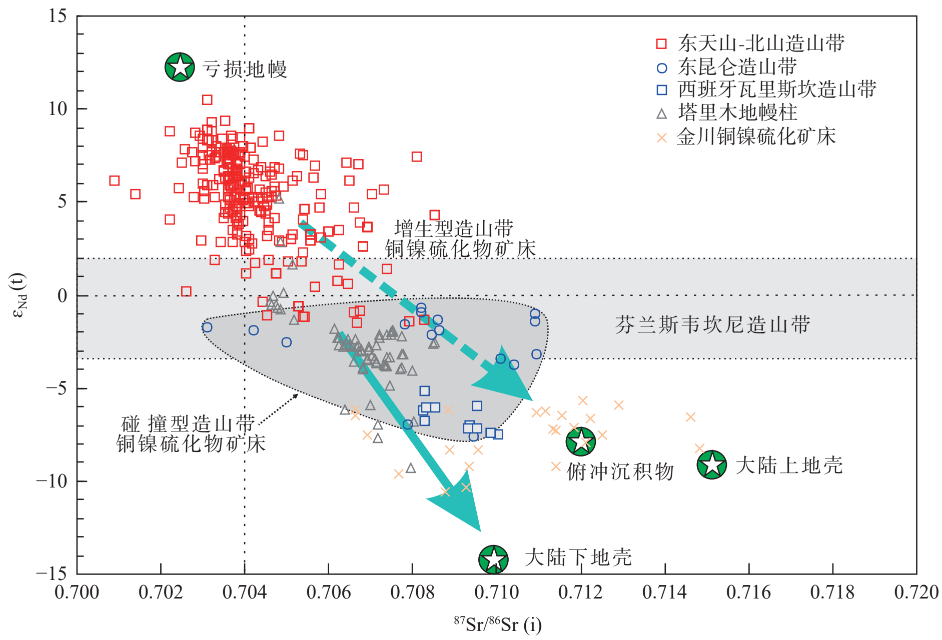
Fig. 1　Distribution of typical orogenic belt magmatic Cu-Ni sulfide deposits

2009; Song et al., 2009; Zhang et al., 2009; Qin et al., 2011; Song et al., 2011, 2013; Li et al., 2012; Xie et al., 2012; 2014; Manor et al., 2016)。根据矿床规模及研究工作程度，以下分别介绍这些造山带铜镍硫化物矿床特征。

### 1.1　中亚造山带南缘铜镍硫化物矿床群

中亚造山带南缘主要发育有 7 条铜镍矿带，分别为阿尔泰南缘喀拉通克铜镍矿带、西南天山菁布拉克铜镍矿带、东天山图拉尔根–黄山–土墩铜镍矿带、中天山天宇–白石泉铜镍矿带、新疆坡北–红石山铜镍矿带、库鲁克塔格兴地铜镍矿带及北山铜镍矿带(韩宝福等, 2004; 姜常义等, 2006; 三金柱等, 2010; 孙涛等, 2010; 夏明哲, 2010; 肖庆华等, 2010; Qin et al., 2011; Sun et al., 2013; 王小红等, 2023)。近年来，研究结果表明，除库鲁克塔格兴地铜镍带、西南天山菁布拉克铜镍矿带和北山铜镍矿带分别形成于前寒武纪、志留纪和泥盆纪外，其余所有铜镍矿带全部形成于早二叠世时期，这些铜镍矿带分布都基本平行于区域性大断裂或板块缝合线(宋谢炎等, 2018)。其中，以东天山图拉尔根–黄山–土墩铜镍矿带最为典型，包含有黄山、黄山东、图拉尔根等 3 个大型矿床，若干含矿岩体分布在 NEE 向、长超过 500 km, 宽度仅约 50 km 的康古尔–黄山韧性剪切带，(杨兴科等, 1998; Wang et al., 2014; 宋谢炎等, 2018)，该韧性剪切带是东天山内部哈尔里克–大南湖岛弧带和雅满苏岛弧带之间的缝合带，早期(300～280 Ma)以推覆剪切为主，与板块俯冲—碰撞过程有关，晚期(262～242 Ma)以右行走滑剪切为主，反映了碰撞后陆内走滑、抬升过程。早二叠世含矿岩体为同构造侵入体，其中黄山岩体独特的“蝌蚪状”形态及黄山东岩体的“菱形”形态，以及向下收敛的楔形纵剖，反映了其分布受韧性剪切构造的控制(陈文等, 2005; Branquet et al., 2012; Wang et al., 2014; 宋谢炎等, 2018)。

东天山镁铁–超镁铁质岩石主要包括二辉橄榄岩、单辉(方辉)橄榄岩、橄榄辉石岩、辉石岩、橄榄苏长岩、辉长苏长岩、辉长岩、辉长闪长岩等，含 Ni-Cu 硫化物主要赋存于超镁铁质岩石中，含矿岩体中含有角闪石和黑云母等富水矿物(Zhou et al., 2004; 尤敏鑫, 2022)。在地球化学方面，东天山地区含矿岩体富集轻稀土(LREE)、大离子亲石元素(LILE)，亏损 Nb、Ta 和 Ti 等类似弧岩浆元素特征，并具有亏损到弱富集 Nd-Hf 同位素组成(图 2)($\varepsilon_{Nd}(t)$ 值为 −1.5～10.5; 锆石 $\varepsilon_{Hf}(t)$ 值为 0～17(尤敏鑫, 2022 及参考文献)及低锆石 $\delta^{18}O$、$^{87}Sr/^{86}Sr(t)$值。总体而言，东天山地区含




数据来源：东天山–北山造山带(尤敏鑫，2022 及参考文献)；东昆仑造山带(姜常义等，2015；Peng et al.，2016)；西班牙瓦里斯坎造山带(Casquet et al.，2001)；芬兰斯韦坎尼造山带(Makkonen et al.，2007)；塔里木地幔柱(余星，2009；Zhou et al.，2009；Zhang et al.，2012；Li et al.，2012；Wei et al.，2014；王振朝，2019)；金川铜镍矿(张宗清等，2004；Duan et al.，2016；Tang et al.，2018)；亏损地幔、大陆地壳和俯冲沉积物(Plank et al.，1998；Vervoort et al.，1999；Chauvel et al.，2009)

**图2　典型造山带岩浆铜镍硫化物矿床 Sr-Nd 同位素组成**

Fig. 2　Sr-Nd isotopic composition of magmatic copper-nickel sulfide deposits in typical orogenic belts

矿岩体反映了其来源于交代地幔熔融源区, 同时具有含水和弧岩浆地球化学特征 (Song et al., 2009; Zhang et al., 2009; Qin et al., 2011; Song et al., 2011, 2013; Li et al., 2012; Xie et al., 2012; 2014; Tang et al., 2012; 尤敏鑫, 2022)。

### 1.2　东昆仑造山带岩浆铜镍硫化物矿床

东昆仑造山带内分布夏日哈木超大型矿床、石头坑德大型矿床和水仙南含铜镍硫化物矿化的镁铁–超镁铁岩体, 形成年龄约为 420～405 Ma, 构成了一个长约 400 km 的晚古生代早期镁铁–超镁铁岩带。东昆仑铜镍矿化的镁铁–超镁铁岩体沿昆中断裂带两侧线性分布, 并与区域内高压–超高压榴辉岩/榴闪岩空间分布上具有重叠性 (祁生胜等, 2014; Song et al., 2018; Zha et al., 2023; 钟世华等, 2025)。同时, 这些镁铁质岩浆和区域内高压变质岩形成年龄在误差范围内是一致的, 均晚于区域上弧岩浆(约 20 Ma), 说明铜镍成矿的镁铁–超镁铁质杂岩体与这些高压变质岩为同一构造背景下的产物 (Dong et al., 2018)。夏日哈木含矿岩体呈近 EW 向展布的椭圆形平缓岩盆, 长约为 2.4 km, 宽约为 1.2 km, 侵位于金水口群斜长片麻岩、黑云母石英片岩或大理岩中, 该岩体由超镁铁岩和镁铁岩构成, 两者间呈侵入接触关系, 超镁铁岩部分主要由橄榄方辉岩、斜方辉石岩和二辉岩构成, 矿化主要产于橄榄方辉岩和斜方辉石岩相中 (Li et al., 2015; Song et al., 2016; 赵达成等, 2023)。夏日哈木矿床的成矿年龄为 411～406 Ma, 镁铁质–超镁铁质岩石具有弱亏损到弱富集的 Sr-Nd 同位素组成(图 2 )($^{87}Sr/^{86}Sr(i)$ 值为 0.703 12～0.710 93; $\varepsilon_{Nd}(t)$值为−7.6～−0.7), 并表现出亏损锆石 Hf 同位素组成 ($\varepsilon_{Hf}(t)$ 值为 4.0～13.7), 斜方辉石岩 O 同位素值高于地幔组成 ($\delta^{18}O$ 值为 5.2 ‰～7.0 ‰), 金属硫化物的原位 S 同位素值为 2.5‰～7.7‰(王冠, 2014; 姜常义等, 2015; Zhang et al., 2017)。石头坑德和水仙南两个含矿镁铁–超镁铁质岩体和夏日哈木矿床具有相似成矿地质特征和化学元素组成 (周伟等, 2016; 马吉雄等, 2022)。东昆仑早古生代末期镍钴矿来源于交代地幔源区、成矿岩浆含水和围岩具有弧岩浆地球化学特征等造山带铜镍硫化物矿床的典型特征。

### 1.3　全球其他地区造山带岩浆铜镍硫化物矿床

全球其他地区造山带岩浆铜镍硫化物矿床中最

为著名的就是阿拉斯加型岩体，岩体以环状岩相结构为特征，从岩体中心的纯橄岩向外依次包括异剥橄榄岩、橄榄单斜辉石岩、单斜辉石岩、角闪单斜辉石岩、角闪石岩，少量岩体边缘还有辉长岩等镁铁质岩石（Taylor, 1967; Himmelberg et al., 1995），各岩相之间一般呈渐变接触关系，赋存于阿拉斯加型岩体中岩浆铜镍硫化物矿床主要包括阿拉斯加东南部 Salt Chuck（Loney et al., 1992）、Duke Island（Ripley et al., 2005; Thakurta et al., 2008）、埃及 Gabbro Akarem（Helmy et al., 2001）、哥伦比亚 Turnagain（Scheel et al., 2009）及加拿大苏必利尔 Quetico（Pettigrew et al., 2006）。一般认为，阿拉斯加型岩体代表岛弧根部，为地幔楔部分熔融产生的玄武质岩浆在地壳深度分离结晶的产物（Taylor, 1967; Himmelberg et al., 1995; Thakurta et al., 2008; Su et al., 2012），其中 Duke Island 成矿岩体含有大量的角闪石，说明矿床来源于富水的地幔源区（Thakurta et al., 2008）。分布于环太平洋造山带加拿大 Giant Mascot 岩体以发育大量斜方辉石和角闪石为特征，主要岩相有纯橄岩、橄榄岩、辉石岩、角闪辉石岩和角闪石，反映了其为汇聚板块边缘产物（Manor et al., 2016）。西班牙瓦里斯坎造山带 Aguablanca 铜镍硫化物矿床形成于 341 Ma 左右，以矿化角砾岩形式产出，分布在切尔内卡塑性剪切带的次级伸展断裂内，含矿岩石显示出富集 LREE 和 LILE，亏损 Nb-Ta 等俯冲带岩浆地球化学特征，为古 Rheic 洋俯冲消减过程的产物（Casquet et al., 2001; Piňa et al., 2006, 2012）。芬兰 Kotalahti-Vammalan 镍矿带分布于斯韦坎尼造山带，形成于 1.88 Ga 左右，成矿镁铁–超镁铁质岩石主要包括辉长岩、橄榄岩或辉长橄榄岩等，呈椭圆形侵位于侵入于云母片麻岩，母岩浆类似于现代岛弧拉斑玄武岩，根据大量与变质、变形、亚固相线平衡反应和年代学有关的证据，这些镁铁–超镁铁质岩石是在渐进的区域变质和变形过程侵位的（Peltonen, 1995; Makkonen et al., 2007; Barnes et al., 2009）。博茨瓦纳 Selebi-Phikwe 铜镍矿带和巴西 Santa Rita 矿床成矿岩石虽然表现出弧特征，鉴于这些早前寒武纪铜镍硫化物矿床的构造环境还存在不确定性（＞2.0 Ga），所以不作为典型矿床来对比分析（Maier et al., 2008; Barnes et al., 2013）。另外值得一提的是，加拿大安大略省赋存于元古界 Coldwell 杂岩体的 Marathon Cu-Pd 超大型矿床（Good et al., 2021）一直被认为是典型大陆裂谷环境形成的岩浆铜镍硫化物矿床，新近的研究表明，其矿化岩体发育原生的含水矿物金云母和角闪石，且 Mg-Fe 同位素研究也证实了 Coldwell 杂岩体母岩浆来源于经历不同程度交代作用的地幔源区（Good et al., 2019; Brzozowski et al., 2021, 2022; Good et al., 2021）。

## 2 造山带岩浆铜镍硫化物矿床动力学机制探讨

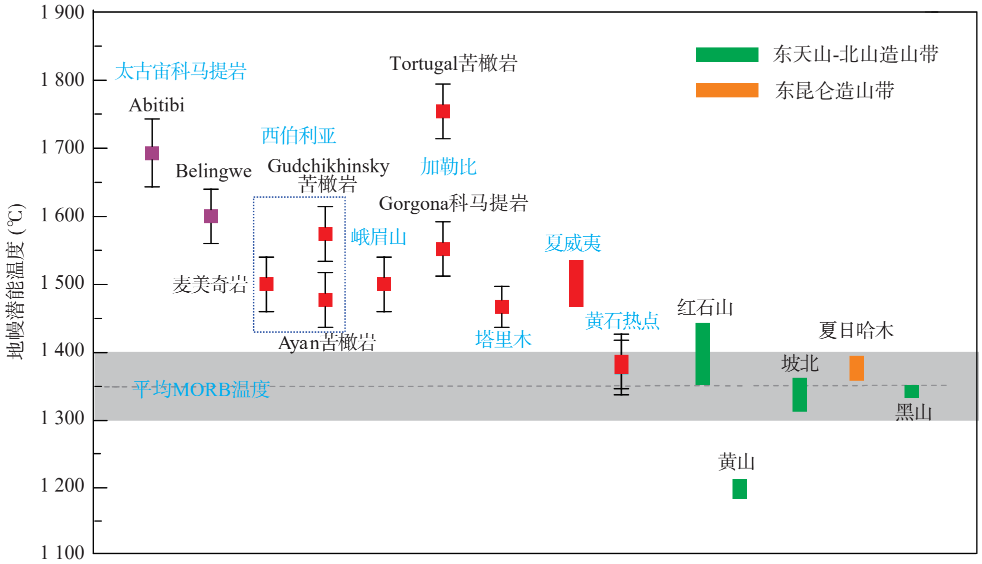
造山带岩浆铜镍硫化物矿床与大陆克拉通和大陆边缘产出的岩浆铜镍硫化物矿床最显著的差异就是其成矿母岩浆来源于交代地幔源区，并且交代作用主要早期或同期俯冲阶段，以往研究重点关注母岩浆脱离地幔源区后岩浆演化过程。例如，结晶分异、地壳混染、岩浆不混溶以及沉淀机制等。笔者尝试在前人已有动力学模式、同位素组成和地幔潜能温度研究基础上，讨论造山带岩浆铜镍硫化物成矿深部动力学机制。

### 2.1 已有的造山带岩浆铜镍硫化物矿床动力学机制

目前关于造山带岩浆铜镍矿床成矿动力学模式主要包括以下几种模式：①地幔柱叠加俯冲带，即深部来源地幔柱叠加到早期俯冲改造的岩石圈地幔（Qin et al., 2011; Su et al., 2011）。②板块俯冲和地幔柱相互作用（李文渊等, 2012, 2018）。③俯冲交代改造的岩石圈地幔部分熔融（邓宇峰等, 2011; Su et al., 2013）。④后碰撞伸展阶段板片断离或加厚岩石圈拆沉，为软流圈地幔和岩石圈地幔共同作用的结果（Li et al., 2012; Xie et al., 2012; Xue et al., 2016; Chen et al., 2021）。⑤俯冲同碰撞阶段俯冲板块断裂引起软流圈地幔上涌减压熔融，同时强调早期阶段水加入强化了这个过程，表现出受区域韧性剪切或走滑断裂控制的空间分布特征（Song et al., 2013, 2021; Lightfoot et al., 2015; Wei et al., 2023）。成矿岩浆来源于俯冲交代改造的不均一地幔源区（Song et al., 2011; Su et al., 2013; Xue et al., 2018; Chen et al., 2021），岩浆性质为富水高镁玄武质（Zhou et al., 2004; Gao et al., 2013）、岩体发育含水矿物（Tang et al., 2011, 2013, 2022; Cui et al., 2022）、成矿与还原性物质混染和外源硫加入密切相关（Su et al., 2013; Tang et al., 2013; Deng et al., 2022; Xue et al., 2023; Wang et al., 2023）。

上述模式为探讨造山带岩浆铜镍硫化物矿床成矿动力学模式奠定了良好的基础，可以归纳为两种观点：第一种观点认为地幔柱加热岩石圈地幔（地幔楔），地幔柱提供热/物质，以中国境内东天山地区最为典型。

然而已有研究表明，早二叠世塔里木地幔柱并未延伸到东天山地区，同时区域上也没有发现高温苦橄岩系列岩石，地幔潜能温度也远低于地幔柱温度（图 3）（Xiao et al., 2004; Yuan et al., 2010; Xie et al., 2016）。此外，鉴于同期区域广泛发育多种类型镁铁质和长英质岩石，天山石炭纪—二叠纪大火成岩省很可能不是地幔柱作用的结果，而是区域上多次俯冲作用形成地壳热区在地幔热扰动的情况下形成的（Annen et al., 2006; Xia et al., 2008, 2012）。因此，地幔柱叠加造山带或者和板块俯冲相互作用可能并不是造山带岩浆铜镍硫化物矿床形成的动力学机制。第二类观点就是软流圈和岩石圈地幔相互作用，不同观点差别在于软流圈地幔仅仅提供热、或者热和物质双重加持，亦或是软流圈本身发生熔融。目前不仅在增生型造山带（如东天山、芬兰斯韦坎尼）发现了造山带岩浆铜镍硫化物矿床（Peltonen, 1995; Barnes et al., 2009; Song et al., 2009; Zhang et al., 2009; Qin et al., 2011; Song et al., 2011, 2013; Li et al., 2012; Xie et al., 2012; 2014; Tang et al., 2012; 尤敏鑫, 2022），在碰撞型造山带也发现该类矿床（如东昆仑、西班牙瓦里斯坎）（Piña et al., 2006, 2012; Li et al., 2015; Song et al., 2016），说明两种类型造山带发生了同样的地质过程，俯冲板片断裂、回转以及软流圈上涌模式在造山带早期形成过程中普遍发生的过程，而大多数造山带并没有形成岩浆铜镍硫化物矿床，这个模式很可能不是造山带岩浆铜镍硫化物矿床动力学机制，但是从与其相关镁铁质-超镁铁质岩石类似弧岩浆元素特征以及弱亏损到弱富集同位素组成来看，软流圈和岩石圈地幔（地幔楔）相互作用是造山带岩浆铜镍硫化物矿床形成的必要条件，但形成机制可能并不是通过板块断裂、回转的方式。




数据来源：东天山-北山造山带（苏本勋, 2011; Mao et al., 2014; 徐刚, 2013; 阮班晓等, 2020）；东昆仑造山带（李文渊等, 2020）；太古宙科马提岩和大火成岩省（Herzberg et al., 2009; Bizimis and Peslier, 2015; Herzberg, 2016; Liu et al., 2017）；平均 MORB（Niu et al., 2011; Ivanov, 2015）

**图3　造山带铜镍硫化物矿床和典型大火成岩省地幔潜能温度（据 Liu et al. 2017 修改）**

Fig. 3　Mantle potential temperature of Cu-Ni sulfide deposits in orogenic belt and typical large igneous provinces

### 2.2　造山带铜镍硫化物两阶段动力学机制

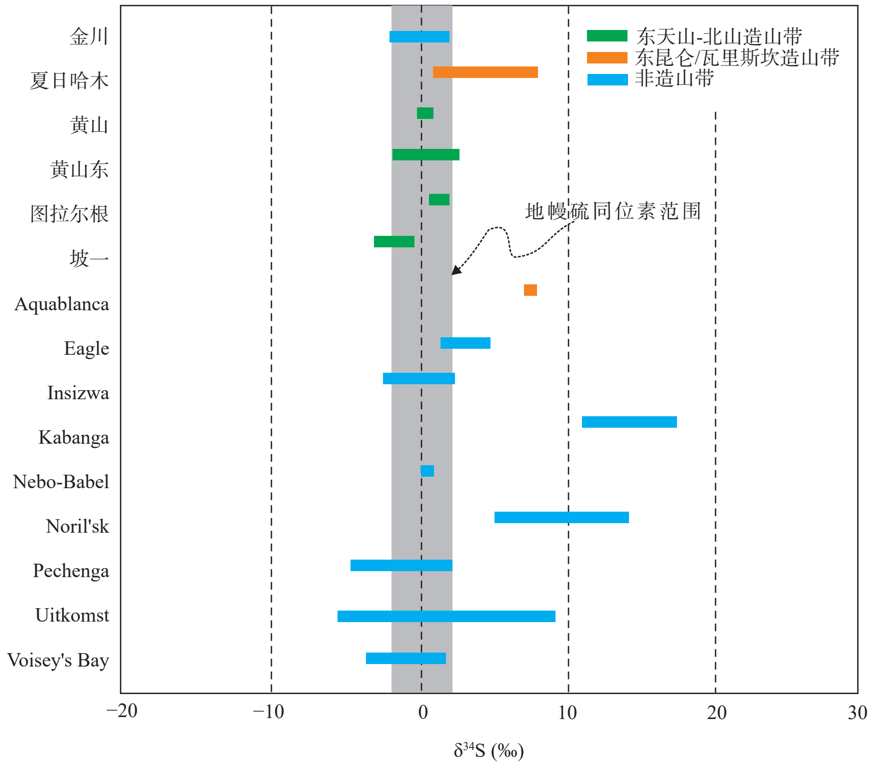
造山带岩浆铜镍硫化物矿床来源于交代地幔源区、母岩浆含水特征以及分布于早期或同期缝合带边缘的特征共同指示了板片俯冲交代过程的存在（Li et al., 2012; Xie et al., 2012; Xue et al., 2016; Chen et al., 2021; 薛胜超等, 2024）。一般来说，地幔橄榄岩和板块俯冲释放熔/流体交代会形成辉石岩，辉石岩较橄榄岩具有更低的熔融温度，同时造山带岩浆铜镍硫化物矿床相对于大陆克拉通内部和边缘的同类矿床具有较低的熔融温度和程度。因此，造山带岩浆铜镍硫化物矿床熔融源区存在辉石岩组分或者就是辉石岩地幔（Song et al., 2016; Zelenski et al., 2024）。最新研究表明，来自俯冲板片熔体能与地幔橄榄岩发生交代作用，富含 $SiO_2$ 的俯冲熔体能导致 Ni 等元素从橄榄石中释放，加之其自身携带 S 元素，从而导致形成以含有斜方辉石和镍硫化物的辉石岩为主的富集地幔源区（Song et al., 2016; Zelenski et al., 2024)。因此，经过俯冲熔体交代的辉石岩地幔是造山带岩浆铜镍硫化物矿床重要源区之一。

目前，已经识别出俯冲过程中交代介质主要包括俯冲流/熔体和超临界流体等 3 种类型（Manning, 2004; Schmidt et al., 2014; 郑永飞等, 2016）。其中，第一种类型的超临界流体性质介于流体和熔体之间，由于不涉及更多细节问题，文中不再讨论超临界流体问题。一般来说，俯冲洋壳和沉积物在俯冲深度较浅的情况下，释放出含水的流体交代上覆地幔橄榄岩形成新生的岩石圈地幔(地幔楔)，是大洋岛弧和大陆岛弧玄武岩的主要熔融源区，这类源区也是橄榄岩为主地幔源区。第二种类型为俯冲洋壳和海洋沉积物在 100～300 km 发生熔融形成硅质熔体，这种熔体交代地幔橄榄岩会形成硅饱和和欠饱和辉石岩，这种辉石岩地幔源区熔融后分别形成拉斑玄武岩和类似 OIB 特征镁铁质岩石，其中拉斑玄武岩因为板片熔体交代作用而具有岛弧特征，同时，海洋沉积物具有较高 Hf 同位素比值，会造成 Hf-Nd 同位素解耦。第三种类型是在俯冲洋壳的拖拽下大陆地壳发生俯冲，由于大陆地壳不同洋壳的高的含水量，在 80 km 以浅这种“干”地壳物质基本不会发生熔融，而在较大的俯冲深度，大陆地壳就会形成长英质的熔体，这种熔体交代的地幔橄榄岩的熔融源区，就会产生类似弧岩浆的元素特征和富集的同位素组成的镁铁质岩石。第二和第三种情况在俯冲–碰撞期很少能够发生熔融，即使发生熔融形成相关岩石占比也非常低，这也就是俯冲期以岛弧火山岩为主和大陆碰撞带少有同期岩浆作用的原因。东天山和东昆仑造山带分别为典型的增生型和碰撞型造山带铜镍矿床产出地，对应了不同俯冲交代作用模式。东天山造山带岩浆铜镍硫化物矿床相关镁铁–超镁铁质岩石表现出弧岩浆元素特征，亏损同位素组成以及未表现出 Hf-Nd 同位素解耦特征，说明俯冲洋壳熔融形成熔体交代起主导作用，俯冲沉积物贡献较小或者可以忽略。东昆仑造山带岩浆铜镍硫化物矿床相对于东天山–北山具有较为富集的同位素组成，且成矿镁铁–超镁铁质岩石与同期高压–超高压榴辉（闪）岩和紧密共生，大陆地壳熔体可能是碰撞型造山带岩浆铜镍硫化物矿床源区主要交代介质（赵子福等, 2015）。

阿拉斯加型岩体代表了汇聚环境下结晶分异程度高的环状杂岩体，成矿主要以钒钛磁铁矿和铂矿床为主，虽然在美国 Duke Island 发现了铜镍硫化物，但矿床规模相对较小，品位相对较低（Thakurta et al., 2008），主要原因在于地幔部分熔融导致硫化物溶解形成含 S 和亲铜元素的镁铁质岩浆，镁铁质岩浆在贫水条件下分异形成富集亲铜元素的硫化物堆晶或岩浆硫化物矿床，但镁铁质岩浆在富水条件下会演化成中酸性岩浆，最后流体出溶毁坏硫化物，形成含矿流体和斑岩型矿床（熊小林等, 2020）。造山带岩浆铜镍硫化物矿床主要形成于俯冲–碰撞后伸展阶段，原因就在于俯冲峰期流体/硫化物比率大，流体出溶导致硫化物不能堆晶和熔离形成硫化物矿床。总的来说，阿拉斯加型岩体代表了一种极为充分结晶分异的成矿类型，成矿元素局部富集成矿。

近 20 年来，无论是在克拉通或造山带发生岩石圈拆沉已经得到证实，尤其是在北美内华达岩基和帕米尔科希斯坦弧均发现了石榴子石辉石岩(又称弧榴辉岩)，并被认为是岩石圈拆沉物质的实例（Lee et al., 2006; Lee 2015; Ducea et al., 2021）。弧榴辉岩富集 Fe、Mn、Co、Ni、Cu、Sc 等元素（Ducea et al., 2021），这些元素和造山带岩浆铜镍硫化物矿床源区要求富集的金属元素具有一致性，暗示了弧原始岩浆演化形成的堆晶体和造山带型岩浆铜镍硫化物矿床之间的可能存在联系。同时，上述能够形成辉石岩地幔源区主要是俯冲交代过程中熔体交代，这就要求俯冲板片具有较大的俯冲深度，俯冲过程中才能形成弧榴辉岩，斜方辉石为主的弧榴辉岩难以通过板片断裂、回转以及软流圈上涌的过程发生熔融，主要原因在于上涌软流圈提供的热较为有限。石榴子石辉石岩在俯冲峰期结束后，由于重力不稳定或去山根作用下，通过岩石圈拆沉的方式进入到软流圈地幔，这种方式不仅能够诱发地幔源区的大规模熔融，同时混合地幔源区也能够形成富含铜镍成矿元素的母岩浆（Lee, et al., 2006; Lee, 2015; Ducea et al., 2021），这种混合地幔源区熔融形成的母岩浆，通过深大断裂、韧性剪切带等构造薄弱区上升，并且通过岩浆过程进一步富集铜镍成矿元素形成岩浆铜镍硫化物矿床。另外一点就是经典的岩石圈拆沉区域通常也是早前俯冲发生的薄弱带（Bird, 1979; Meissner et al., 1998; Ueda et al., 2012），这和造山带岩浆铜镍硫化物矿床产出的区域是一致的。

系统对比造山带和非造山带环境产出的岩浆铜镍硫化物矿床 S 同位素组成(图 4)，增生型造山带岩浆铜镍硫化物矿床 S 同位素基本在地幔 S 同位素组




数据来源：东天山–北山造山带(尤敏鑫，2022 及参考文献)；东昆仑和西班牙瓦里斯坎造山带（Casquet et al.，2001 ；王冠，2014；姜常义等，2015；Zhang et al.，2017)；非造山带(Lightfoot et al.，1984；Grinenko，1985；Abzalov et al.，1997；Ripley et al.，1999；Barnes et al.，2001；Li et al.，2003；Ripley et al.，2003；Li et al.，2003；Ripley et al.，2005a；Ding et al.，2009；Seat et al.，2009；Maier et al.，2010）

**图4　造山带和非造山带铜镍硫化物矿床 S 同位素组成**

Fig. 4　S isotopic composition of Cu-Ni sulfide deposits in orogenic and non-orogenic belts

成范围内,而碰撞型造山带主要反映了大陆地壳 S 同位素组成,两种类型造山带岩浆铜镍硫化物矿床 S 同位素组成与 Sr-Nd 同位素结果是一致的,即增生型和碰撞型造山带岩浆铜镍硫化物矿床熔融源区分别反映了板片熔体和大陆地壳熔体交代作用(图 2、图 4)。坡一和黄山东岩浆铜镍硫化物矿床具有地壳 S 同位素组成,也一定程度反映了在岩浆上升演化过程中,地壳 S 加入导致岩浆铜镍硫化物中 S 进一步饱和,碰撞型造山带 S 同位素是源区或者岩浆过程起主导作用目前还无法识别。相比之下,非造山带环境的岩浆铜镍硫化物矿床 S 同位素横跨了地幔到地壳 S 同位素组成,说明板内岩浆铜镍硫化物矿床形成更为复杂,如果非造山带岩浆铜镍硫化物矿床的地幔源区早期已经经历了俯冲作用交代,可能和造山带岩浆铜镍硫化物矿床源区交代机制是一致的,如果是非交代形成的,可能代表了地幔大比例熔融和/或更为复杂岩浆作用过程的结果。值得补充说明的是,东天山地区俯冲期玄武岩表现出高铝玄武岩特征,与北美内华达岩基镁铁质岩石的高铝特征是一致的,说明两个区域都发生过地壳增厚的过程,弧原始岩浆在演化过程分别形成了高铝镁铁质岩石和弧榴辉岩 (Lee, et al., 2006; Lee, 2015; Xie et al., 2016; Zhang et al., 2018; 未发表资料)。东昆仑碰撞型造山带高压–超高压岩石兼具 B 类和 C 类榴辉岩的特征,说明区域上陆壳和洋壳均在俯冲-碰撞期发生了高压变质作用。同时,榴辉岩不含绿辉石或含量较少,笔者推测它们可能是弧榴辉岩。如果假设是合理的,说明除折返的榴辉岩/榴闪岩外,有相当一部分弧榴辉岩下沉到软流圈,少量折返榴辉岩/榴闪岩与这些成矿镁铁–超镁铁质岩石紧密共生也就不难理解了(祁生胜等, 2014; Li et al., 2015; Song et al., 2018; Zha et al., 2023)。由于造山带中岩浆铜镍硫化物矿床的研究程度问题,其他增生和碰撞型造山带是否也存在相似的岩石和构造演化过程并不是很清楚,笔者就目前研究程度归纳起来造山带岩浆铜镍硫化物关键控制因素主要包括以下几个方面。①无论是增生型或者碰撞型造山带,在俯冲期过程中发生俯

冲熔体的交代作用，富含 $SiO_2$ 的俯冲熔体能导致 Ni 等元素从橄榄石中释放，加之其自身携带 S，从而形成含有斜方辉石和镍硫化物的辉石岩。②辉石岩为主岩石圈地幔在俯冲结束后伸展阶段发生岩石圈拆沉，形成辉石岩地幔和软流圈地幔混合源区，混合源区就是造山带岩浆铜镍硫化物矿床的源区，同时拆沉过程会诱发大规模地幔熔融，熔融形成的岩浆是铜镍硫化物矿床的母岩浆。③区域上深大断裂带是造山带岩浆铜镍硫化物矿床母岩浆上升和岩浆过程中进一步富集的通道，也是关键控制因素之一。总体上，造山带岩浆铜镍硫化物矿床具有含水、滞后俯冲峰期 30～10 Ma，范围宽泛的放射性和 S 同位素组成特征，与俯冲期熔体交代、俯冲期后岩石圈拆沉模式共同作用的结果是一致的。

## 3 结论

（1）大洋板片和大陆地壳在较大俯冲深度形成硅质熔体交代橄榄岩形成辉石岩，辉石岩在俯冲碰撞期后通过拆沉方式进入到软流圈地幔，诱发地幔大规模熔融，并形成含亲铜元素母岩浆，这种母岩浆岩深大断裂、韧性剪切带等构造薄弱区上升，并且通过岩浆过程进一步富集形成岩浆铜镍硫化物矿床。笔者认为上述过程为增生和碰撞型造山带岩浆铜镍硫化物矿床形成的深部动力学机制。

（2）全球尺度上，造山带的形成规模和频次远远高于大火成岩省，因此造山带岩浆铜镍硫化物矿床应该具有更大的资源潜力。同时，岩浆通过深大断裂和韧性剪切带上升形成的铜镍硫化物矿床，受构造作用影响容易造成成矿岩体发生明显变形、错断和隐伏，其找矿勘查需要构造地质学、岩石学、矿床学和地球物理学的紧密协同工作。

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