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关于辉钼矿中 Re 含量示踪来源的讨论*

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摘要 对近年来国内已发表的 744 个辉钼矿 Re-Os 同位素测年数据进行了汇总, 发现所有样品辉钼矿中的 Re 含量具有混合分布的特征。按照岩性和共生矿物种类对所有数据进行了分类统计分析, 结果显示辉钼矿中 Re 含量(质量分数,下同)与岩性和共生矿物种类存在密切的关系:长英质脉和花岗岩中辉钼矿的 Re 含量最低,几何平均值分别为 7.41×10^{-6} 和 7.99×10^{-6} ,多在 $n \times 10^{-6} \sim n \times 10^{-5}$;砂卡岩中辉钼矿 Re 含量中等,几何平均值为 58.1×10^{-6} ,多在 $n \times 10^{-5} \sim n \times 10^{-4}$;碳酸岩中辉钼矿 Re 含量最高,几何平均值为 231×10^{-6} ,多在 $n \times 10^{-4}$ 左右。辉钼矿的共生矿物种类影响其 Re 含量的变化,仅与白钨矿(或黑钨矿)和(或)方铅矿、闪锌矿、自然金和自然银共生时辉钼矿 Re 含量最低,几何平均值为 $n \times 10^{-7}$,多在 $n \times 10^{-8} \sim n \times 10^{-6}$;仅与黄铜矿和(或)磁铁矿(或磁黄铁矿)共生时辉钼矿 Re 含量最高,几何平均值为 $n \times 10^{-4}$,多在 $n \times 10^{-5} \sim n \times 10^{-3}$;同时与黄铜矿(磁铁矿或磁黄铁矿)和白钨矿(或黑钨矿、方铅矿、闪锌矿、自然金和自然银)共生时辉钼矿 Re 含量处在前两者之间,几何平均值为 $n \times 10^{-6}$,多在 $n \times 10^{-7} \sim n \times 10^{-5}$ 。综合分析说明,辉钼矿与白钨矿(或黑钨矿、方铅矿、闪锌矿、自然金和自然银)共生或产在长英质脉和花岗岩中可能促使其 Re 含量降低,与黄铜矿、黄铁矿和磁铁矿(或磁黄铁矿)共生或产在砂卡岩和碳酸岩中可能促使其 Re 含量升高,辉钼矿 Re 含量的级数变化可能与其产出状态(岩性和共生矿物种类)密切相关,以及结合近年来辉钼矿 Re 含量示踪和其他同位素示踪结果间矛盾的存在,认为辉钼矿 Re 含量的级数变化似乎不能有效地反映出其成矿物质来源。

关键词 地质学 辉钼矿 Re 含量 混合分布 成矿物质来源 共生矿物 岩性

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Discussion on significance of Re content of molybdenite in tracing source of metallogenic materials

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Abstract

744 pieces of molybdenite Re-Os isotopic dating data published in China in recent years were collected and the authors found that the Re content of all the samples is characterized by mixed distribution. Classification and statistical analysis of all the data were based on the lithology and associated mineral types. The results show that the Re content of molybdenite has a close relationship with the lithology and associate minerals, i. e., pure molybdenite in the felsic veins and granite has the lowest Re content with the geometric mean of 7.41×10^{-6}

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and 7.99×10^{-6} respectively, and most of the values range from $n \times 10^{-6}$ to $n \times 10^{-5}$; the Re content of pure molybdenite in the skarn is medium with the geometric mean of 58.1×10^{-6} , and most of the values range from $n \times 10^{-5}$ to $n \times 10^{-4}$; molybdenite in the carbonatite has the highest Re content with the geometric mean of 231×10^{-6} , and most of the values are $n \times 10^{-4}$. The Re content of molybdenite is also affected by its associated mineral type: the Re content of molybdenite has the lowest value when molybdenite is only associated with scheelite (or wolframite) and/or galena, sphalerite, native gold and native silver with the geometric mean of $n \times 10^{-7}$, and most of the values range from $n \times 10^{-8}$ to $n \times 10^{-6}$; when it is only associated with chalcopyrite and/or magnetite (or pyrrhotine), the molybdenite has the highest Re content with the geometric mean of $n \times 10^{-4}$, and most of the values range from $n \times 10^{-5}$ to $n \times 10^{-3}$; the medium Re content occurs when molybdenite is associated with chalcopyrite (magnetite or pyrrhotine) and scheelite (or wolframite, galena, sphalerite, native gold and native silver) with the geometric mean of $n \times 10^{-6}$, and most of the values range from $n \times 10^{-7}$ to $n \times 10^{-5}$. A comprehensive analysis shows that molybdenite associated with scheelite (or wolframite, galena, sphalerite, native gold and native silver) or produced in the felsic veins and granite may reduce the Re content, whereas molybdenite associated with chalcopyrite and/or magnetite (or pyrrhotine) or produced in the skarn and carbonatite may increase the Re content. The magnitude changes of Re content may be related to the modes of occurrence of molybdenite in combination with the contradiction of isotopic tracing between the Re content of molybdenite and other isotopic methods published in recent years. It seems that the magnitude changes of Re content of molybdenite could not effectively represent the source of metallogenic material.

Key words: geology, molybdenite, Re content, mixed distribution, source of metallogenic material, associated mineral, lithology

Re 是极度分散元素,在自然界很少形成独立矿物。Re 在宇宙地球化学分类中属难熔的高度亲铁元素。高度亲铁的地球化学性质,使 Re 在以后的增生和熔融事件中进入金属相。相对地核而言,Re 在地壳和地幔中强烈亏损(涂光炽等,2004)。由于 Re 是中等不相容元素(相容程度相当于稀土元素 Yb),其硅酸盐-硅酸盐熔体分配系数小于 1,因此 Re 将优先进入岩浆熔体,Re 在熔体中的丰度高于残留的地幔岩(Hauri et al., 1997; Shirey et al., 1998)。但是,如果源岩中残留相当数量的石榴子石和硫化物时,将导致熔体亏损 Re(Richter et al., 1998; O'Neill et al., 1995)。Re 也具有中等的亲铜地球化学性质,对于硫化物的相容性类似铜,因此 Re 在硫化物中一般具有较高的丰度,但是变异性也非常大(涂光炽等,2004)。Re 的地球化学性质与钼十分类似,因此 Re 常常在钼的硫化物——辉钼矿中呈类质同象出现并与钼形成固溶体(Terada et al., 1971)。

Badalov 等(1962)研究了中亚钼矿中的 Re 含量(质量分数,下同),认为钼矿的温度降低,Re 含量会升高,与黄铜矿伴生的辉钼矿富 Re。Terada 等(1971)测定了 200 个辉钼矿中 Re 的含量,含量变化

范围在 $10^{-8} \sim 7 \times 10^{-3}$;在火山升华物、斑岩铜矿、接触变质矿床、浸染状矿床和石英脉中辉钼矿的 Re 含量呈逐渐降低的趋势,就侵入岩型中辉钼矿而言,Re 含量随着钼矿的温度降低而升高,但是其中的 Daito 地区的辉钼矿 Re 含量与这两个规律相反。Ivanov 等(1972)通过对前苏联各种类型矿床中辉钼矿的系统研究,发现在单个矿床和在同一类的不同矿床中,Re 的含量总是多变的;在中温成矿阶段形成的辉钼矿或在中温矿床中的辉钼矿,其 Re 的含量一般比高温阶段或高温矿床中的辉钼矿高;辉钼矿中 Re 含量与硒的含量呈正相关。Ishihara(1988)统计了 74 个花岗质岩石中辉钼矿 Re 的含量,认为与磁铁矿系列有关的矿床高于与钛铁矿系列有关的矿床,矽卡岩中辉钼矿通常含有较高的 Re。毛景文等(1999a)汇总了 8 个与磁铁矿系列(I 型)花岗岩有关的钼矿床和铜矿床,1 个与钛铁矿系列(S 型)花岗岩有关的钨锡矿床,1 个碳酸岩脉型钼(铅)矿床(黄典豪等(1985)认为是幔源型矿床)中辉钼矿的 Re 含量,提出从幔源、壳幔混源到壳源,辉钼矿 Re 含量可能递降一个数量级的结论(Mao et al., 1999b)。Stein 等(2001)同样认为地幔底侵或交代作用,或者基性和超基性岩石的熔融,形成的辉钼矿其 Re 含量

要高于壳源矿床中的辉钼矿 Re 含量。Re 在辉钼矿中含量的高低与辉钼矿多型之间的转变没有明显的成因联系 (Selby et al., 2001; Peng et al., 2006)。Berzina 等 (2005) 研究了俄罗斯西伯利亚和蒙古的 5 个铜钼矿床中 24 个辉钼矿样品, 认为斑岩型铜钼矿床中辉钼矿中 Re 的含量与原始岩浆的成分和 (或) 分异、源岩物质和结晶作用的物理化学条件变化有关。由以上可知, 辉钼矿中的 Re 含量变化的控制因素是复杂多样的, 但目前很多学者利用辉钼矿中的 Re 含量示踪成矿物质的来源 (如: 李永峰等, 2003; 2006; 叶会寿等, 2006; 李厚民等, 2007; 蔺志永等, 2008; 刘玉君等, 2008), 主要引用的是毛景文等 (1999a) 总结提出的规律, 这篇文章的国内引用次数截至目前为 30 次 (2010 年 6 月中国引文数据库检索结果), 关于此结论可能存在以下值得探讨的问题: 首先, 文中默认了成岩和成矿物质具有同源性, 且碳酸岩脉、I 型花岗岩和 S 型花岗岩分别代表了幔源、壳幔混源和壳源成因; 其次, 获得此统计规律的样本数不足。

本文汇总了 1994~2010 年间国内发表的 744 个辉钼矿 Re-Os 同位素年龄资料 (黄典豪, 1994; 2009; 刘兰笙等, 1996; 李红艳等, 1996; 赵一鸣等, 1997; 吴良士等, 1997; 王立本, 1997; 陈文明等, 1998; 丁振举等, 1998; 毛景文等, 1999a; 2004; 张作衡等, 2002; 2006; 曹克敏等, 2002; 张达等, 2003; 李泽琴等, 2003; 侯增谦等, 2003; 李永峰等, 2003; 2006; 孟祥金等, 2003; 2007; 蒙义峰等, 2004; 曾普胜等, 2004; 2006; 王登红等, 2004; 2009; 梅燕雄等, 2005; 董方浏, 2005; 李光明, 2005a; 2005b; 2006; 聂凤军等, 2005; 2007a; 2007b; 谢桂青等, 2005; 2009; 郭保健等, 2006; 蔡明海等, 2006; 陈郑辉等, 2006; 叶会寿等, 2006; 李华芹等, 2006a; 2006b; 王长明等, 2006; 王治华等, 2006; 王亮亮等, 2006; 路远发等, 2006; 郑有业等, 2007; 杨泽强, 2007; 马丽艳等, 2007; 代军治等, 2007; 刘晓煌等, 2007; 许建祥等, 2007; 李进文等, 2007; 李建康等, 2007; 李诺等, 2007; 2008; 2009; 丰成友等, 2007a; 2007b; 2009; 付建明等, 2007; 2008; 李厚民等, 2007; 2009; 姚军明等, 2007; 2009; 刘珺等, 2008; 龚福志等, 2008; 杨宗喜等, 2008; 覃锋等, 2008; 宋史刚等, 2008; 蔺志永等, 2008; 杨晓君等, 2008; 王召林等, 2008; 廖香俊等, 2008; 刘国庆等, 2008; 李水如等, 2008; 张刚阳等, 2008; 李世金等, 2008; 张家菁等, 2008; 2009; 李

晓峰等, 2009; 何书跃等, 2009; 焦建刚等, 2009; 李峰等, 2009; 李立兴等, 2009; 刘玉琳等, 2009; 罗锦昌等, 2009; 秦燕等, 2009; 余宏全等, 2009; 苏捷等, 2009; 唐菊兴等, 2009a; 2009b; 陶继雄等, 2009; 王成辉等, 2009a; 2009b; 王光辉等, 2009; 王永磊等, 2009; 魏庆国等, 2009; 伍式崇等, 2009; 邢俊兵等, 2009; 徐辉煌等, 2009; 翟德高等, 2009; 应立娟等, 2009; 张达玉等, 2009; 张彤等, 2009; 张文兰等, 2009; 张作伦等, 2009; 张遵忠等, 2009; 赵斌等, 2009; 赵元芝等, 2009; 周珂, 2009; 祝向平等, 2009; 曾载淋等, 2009; 邵先武等, 2009; 高阳等, 2010; 高亚龙等, 2010; 王义天等, 2010; 瞿泓滢等, 2010; 周振华等, 2010; 闫学义等, 2010)。对辉钼矿中的 Re 含量进行了统计分析, 探讨了 Re 含量变化的几个可能影响因素。

1 数据分类与统计方法

按照辉钼矿的寄主岩性和共生矿物种类, 对汇总的 744 个辉钼矿 Re 含量数据进行了分类。为了保证不同产状辉钼矿的统计样本数尽量多, 分类主要考虑的寄主岩性为: 长英质脉体 (包括石英脉、钾长石脉和长英质脉), 花岗岩 (包括花岗岩中浸染状和细脉浸染状), 砂卡岩和碳酸岩脉, 对其他辉钼矿寄主岩性但样品数太少的数据未进行分类讨论, 如片岩和砂岩中的数据; 主要考虑的共生矿物为黄铁矿、磁铁矿 (或磁黄铁矿)、黄铜矿、白钨矿、黑钨矿、方铅矿、闪锌矿、自然金和自然银。其中岩性和共生矿物种类是根据每篇文章中作者的采样描述确定, 作者详细描述辉钼矿共生矿物种类的以作者描述为准, 未进行详细描述共生矿物种类以矿床类型为准, 如斑岩型铜钼矿床中采样未描述辉钼矿的共生金属矿物, 则看作是辉钼矿伴生铜 (黄铜矿)。文中划分的每种岩性中未明确指出的共生矿物表示可有可无。对于 1 种或 2 种岩性的钼矿床, 采样特征未描述的看作是辉钼矿产出状态未知。744 个数据按以上标准进行分类之后, 已知辉钼矿产出状态的数据 716 个, 未知产出状态的 28 个。由于数据量较大, 所有原始数据在此未列出, 文中的统计结果给出了数据的统计性特征。

考虑到微量元素一般符合对数正态分布, 本文在绘制辉钼矿中 Re 含量的频数分布直方图时, 横坐标 $Lr(Re)$ 表示 $\ln(Re) \times 10^6$ 的自然对数, 方差为对数方差。除了全部样品的直方图以外, 其余每个直

方图的Re含量变化范围为 $0.5[\text{Ln}(\text{Re})]$ 。频数小于5的峰值忽略不计。

2 统计结果

2.1 辉钼矿中Re含量的总体特征

全部样品744个数据, $w(\text{Re})$ 变化在 $0.005 \times 10^{-6} \sim 14\,024 \times 10^{-6}$, $\text{Ln}(\text{Re}) = -5.30 \sim 9.55$ 。Re含量算术平均值为 193.40×10^{-6} ,几何平均值为 17.94×10^{-6} [$\text{Ln}(\text{Re}) = 2.89$]。对数方差为2.71,约61.2%的数据在一个标准偏差范围之内,即: $\text{Ln}(\text{Re}) = 0.18$ [$w(\text{Re}) = 0.18 \times 10^{-6}$] ~ 5.60 [$w(\text{Re}) = 270 \times 10^{-6}$]。约96.5%的数据在两个标准偏差范围之内,即: $\text{Ln}(\text{Re}) = -2.53$ [$w(\text{Re}) = 0.08 \times 10^{-6}$] ~ 8.30 [$w(\text{Re}) = 4\,044 \times 10^{-6}$]。运用SPSS软件对所用数据即 $\text{Ln}(\text{Re})$ 的数值进行了正态性检验,夏皮罗-威尔克(Shapiro-Wilk)和柯尔莫哥洛夫(Kolmogorov-Smirnov)两种算法均否定了数据的正态分布。在频数直方图(图1)中可识别出3个显著的峰和1个不太显著的峰,表明所有数据可能是混合分布。采用Figueiredo等(2002)提出的基于最小信息长度准则(Minimum Message Length Criterion,简称MML)和期望最大化法(Expectation-Maximization Algorithm,简称EM)的方法,简称MML-EM方法与概率图法相比,MML-EM方法在估计混合分布参数时具有更高的精度(刘向冲等,2011),计算得出了3个匹配程度最高的子正态分布。均值最高的子正态分布 $\text{Ln}(\text{Re}) = 5.75$,占23.3%,均值最低的子正态分布 $\text{Ln}(\text{Re}) = 1.82$,占65.8%,均值中等的

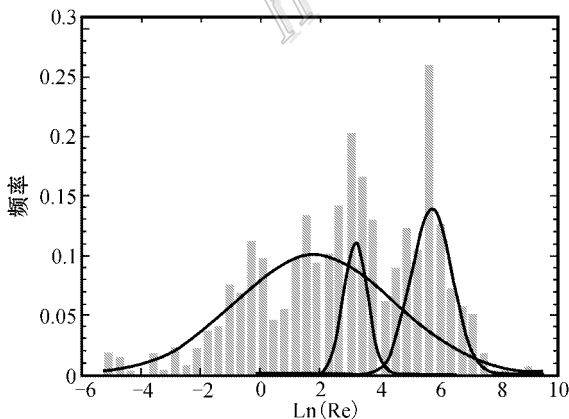


图1 全部样品中辉钼矿Re含量的自然对数频率分布图

Fig. 1 Frequency distribution of natural logarithm of Re content in molybdenite for all the samples

子正态分布 $\text{Ln}(\text{Re}) = 3.18$,占10.9%。所有样品的 $\text{Ln}(\text{Re})$ 值识别出了3个子正态分布,可以初步认为辉钼矿中Re含量具有3个对数正态分布叠加的特征,主导这种总体混合分布的因素可能至少存在3种,下文将按辉钼矿寄主岩性和共生矿物种类详细分类讨论,试图寻找控制总体数据混合分布特征的因素。

2.2 长英质脉体

长英质脉中的辉钼矿共338个数据, $w(\text{Re})$ 变化在 $0.005 \times 10^{-6} \sim 1\,495 \times 10^{-6}$, $\text{Ln}(\text{Re}) = -5.30 \sim 7.31$ 。Re含量算术平均值为 83.95×10^{-6} ,几何平均值为 6.43×10^{-6} [$\text{Ln}(\text{Re}) = 1.86$]。对数方差为2.69,约63%的数据在1个标准偏差范围之内,即: $\text{Ln}(\text{Re}) = -0.83$ [$w(\text{Re}) = 0.43 \times 10^{-6}$] ~ 4.55 [$w(\text{Re}) = 94.97 \times 10^{-6}$]。约97%的数据在两个标准偏差范围之内,即: $\text{Ln}(\text{Re}) = -3.53$ [$w(\text{Re}) = 0.03 \times 10^{-6}$] ~ 7.25 [$w(\text{Re}) = 1\,404 \times 10^{-6}$]。频数直方图(图2A)中出现4个峰值,从小到大依次为: $\text{Ln}(\text{Re}) = -1.3$ [$w(\text{Re}) = 0.273 \times 10^{-6}$] ~ -0.8 [$w(\text{Re}) = 0.449 \times 10^{-6}$]、 $\text{Ln}(\text{Re}) = 1.2$ [$w(\text{Re}) = 3.32 \times 10^{-6}$] ~ 1.7 [$w(\text{Re}) = 5.47 \times 10^{-6}$]、 $\text{Ln}(\text{Re}) = 2.7$ [$w(\text{Re}) = 14.88 \times 10^{-6}$] ~ 3.2 [$w(\text{Re}) = 24.53 \times 10^{-6}$]、 $\text{Ln}(\text{Re}) = 5.2$ [$w(\text{Re}) = 181 \times 10^{-6}$] ~ 5.7 [$w(\text{Re}) = 299 \times 10^{-6}$]。4个峰值占样品总数分别为7.5%、8.6%、8%、5.3%。长英质脉中的4个峰值与全部样品的特征十分接近。

长英质脉中的纯辉钼矿共98个数据, $w(\text{Re})$ 变化在 $0.171 \times 10^{-6} \sim 306 \times 10^{-6}$, $\text{Ln}(\text{Re}) = -1.76 \sim 5.73$ 。Re含量算术平均值为 23.53×10^{-6} ,几何平均值 7.41×10^{-6} [$\text{Ln}(\text{Re}) = 2.00$]。对数方差为1.61,约71.4%的数据在一个标准偏差范围之内,即: $\text{Ln}(\text{Re}) = 0.40$ [$w(\text{Re}) = 1.48 \times 10^{-6}$] ~ 3.61 [$w(\text{Re}) = 36.94 \times 10^{-6}$]。约95.9%的数据在两个标准偏差范围之内,即: $\text{Ln}(\text{Re}) = -1.21$ [$w(\text{Re}) = 0.30 \times 10^{-6}$] ~ 5.22 [$w(\text{Re}) = 184 \times 10^{-6}$]。频数直方图中(图2B)出现2个峰值,从小到大依次为: $\text{Ln}(\text{Re}) = 1.3$ [$w(\text{Re}) = 3.67 \times 10^{-6}$] ~ 1.8 [$w(\text{Re}) = 6.05 \times 10^{-6}$]、 $\text{Ln}(\text{Re}) = 2.8$ [$w(\text{Re}) = 16.44 \times 10^{-6}$] ~ 3.3 [$w(\text{Re}) = 27.11 \times 10^{-6}$]。2个峰值占样品总数分别为16.3%和13.3%。

长英质脉中辉钼矿共生矿物含白钨矿(或黑钨矿)和(或)方铅矿、闪锌矿、自然金和自然银不含黄

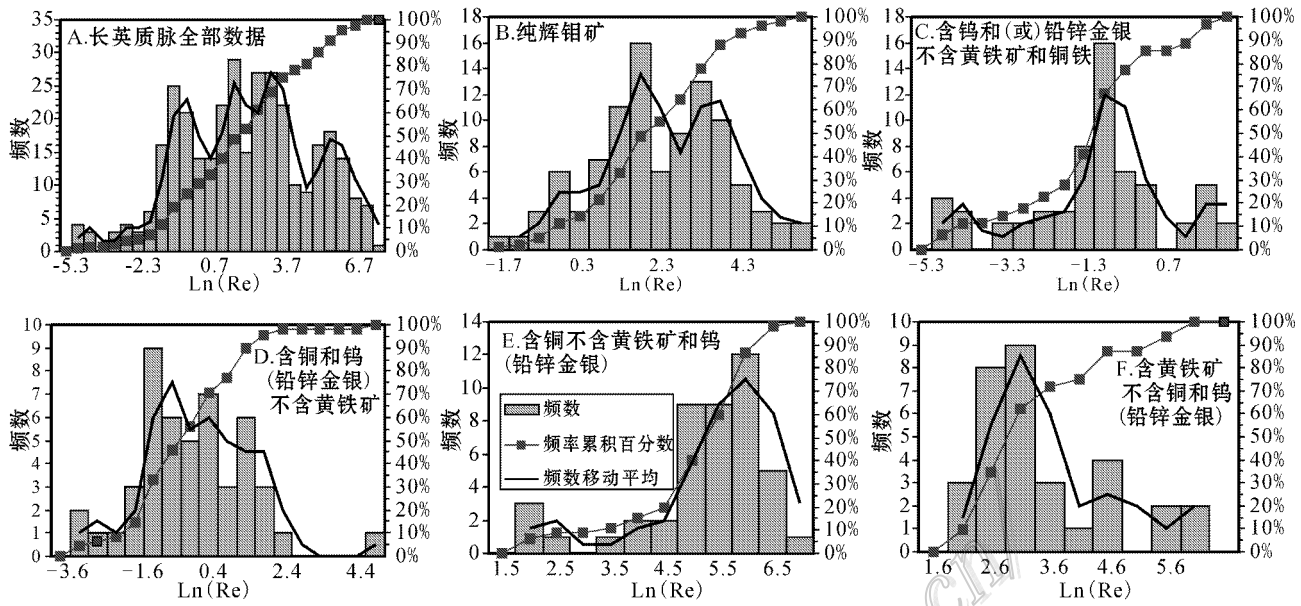


图2 长英质脉中不同产出状态辉钼矿 Re 含量的自然对数频数分布图

图中元素名称含义如下：钨—白钨矿和(或)黑钨矿；铅—方铅矿；锌—闪锌矿；金—自然金；银—自然银；铜—黄铜矿；铁—磁铁矿和(或)磁黄铁矿

Fig. 2 Frequency distribution of natural logarithm of Re content in molybdenite of different modes of occurrence in felsic veins

The meanings of element names are as follows: Tungsten—Scheelite and/or wolframite; Lead—Galena; Zinc—Sphalerite; Gold—Native gold; Silver—Native silver; Copper—Chalcopyrite; Iron—Magnetite and/or pyrrhotite

铁矿、黄铜矿和磁铁矿(或磁黄铁矿),共61个数据, $\omega(\text{Re})$ 变化在 $0.005 \times 10^{-6} \sim 6.17 \times 10^{-6}$, $\text{Ln}(\text{Re}) = -5.3 \sim 1.82$ 。Re含量算术平均值为 0.93×10^{-6} ,几何平均值 0.27×10^{-6} [$\text{Ln}(\text{Re}) = -1.3$],对数方差为1.78,约70.5%的数据在1个标准偏差范围之内,即: $\text{Ln}(\text{Re}) = -3.08$ [$\omega(\text{Re}) = 0.05 \times 10^{-6}$] ~ 0.49 [$\omega(\text{Re}) = 1.62 \times 10^{-6}$],约95.1%的数据在两个标准偏差范围之内,即: $\text{Ln}(\text{Re}) = -4.87$ [$\omega(\text{Re}) = 0.008 \times 10^{-6}$] ~ 2.27 [$\omega(\text{Re}) = 9.67 \times 10^{-6}$]。频数直方图中(图2C)出现1个峰值, $\text{Ln}(\text{Re}) = -1.3$ [$\omega(\text{Re}) = 0.27 \times 10^{-6}$] ~ -0.8 [$\omega(\text{Re}) = 0.45 \times 10^{-6}$],占样品总数26.2%

长英质脉中辉钼矿共生矿物含黄铜矿和白钨矿(或黑钨矿、方铅矿、闪锌矿、自然金和自然银)不含黄铁矿48个数据, $\omega(\text{Re})$ 变化在 $0.03 \times 10^{-6} \sim 104 \times 10^{-6}$, $\text{Ln}(\text{Re}) = -3.54 \sim 4.64$ 。Re含量算术平均值为 3.50×10^{-6} ,几何平均值 0.73×10^{-6} [$\text{Ln}(\text{Re}) = -0.31$],对数方差为1.50,约70.8%的数据在一个标准偏差范围之内,即: $\text{Ln}(\text{Re}) = -1.81$ [$\omega(\text{Re}) = 0.16 \times 10^{-6}$] ~ 1.19 [$\omega(\text{Re}) = 3.29 \times 10^{-6}$],约95.8%的数据在两个标准偏差范围之内,即:

$\text{Ln}(\text{Re}) = -3.32$ [$\omega(\text{Re}) = 0.04 \times 10^{-6}$] ~ 2.69 [$\omega(\text{Re}) = 14.8 \times 10^{-6}$]。频数直方图中(图2D)出现3个峰值,从小到大依次为: $\text{Ln}(\text{Re}) = -1.6$ [$\omega(\text{Re}) = 0.20 \times 10^{-6}$] ~ -1.1 [$\omega(\text{Re}) = 0.33 \times 10^{-6}$], $\text{Ln}(\text{Re}) = -0.1$ [$\omega(\text{Re}) = 0.90 \times 10^{-6}$] ~ 0.4 [$\omega(\text{Re}) = 1.49 \times 10^{-6}$], $\text{Ln}(\text{Re}) = 0.9$ [$\omega(\text{Re}) = 2.46 \times 10^{-6}$] ~ 1.4 [$\omega(\text{Re}) = 4.06 \times 10^{-6}$]。3个峰值占样品总数分别为18.8%、14.6%、12.5%。

长英质脉中辉钼矿共生矿物含黄铜矿,不含黄铁矿、白钨矿、黑钨矿、方铅矿、闪锌矿、自然金和自然银数据共45个, $\omega(\text{Re})$ 变化在 $4.73 \times 10^{-6} \sim 822 \times 10^{-6}$, $\text{Ln}(\text{Re}) = 1.55 \sim 6.71$ 。Re含量算术平均值为 237×10^{-6} ,几何平均值 150×10^{-6} [$\text{Ln}(\text{Re}) = 5.01$],对数方差为1.23,约77.8%的数据在一个标准偏差范围之内,即: $\text{Ln}(\text{Re}) = 3.79$ [$\omega(\text{Re}) = 44.06 \times 10^{-6}$] ~ 6.24 [$\omega(\text{Re}) = 511 \times 10^{-6}$],约91.1%的数据在两个标准偏差范围之内,即: $\text{Ln}(\text{Re}) = 2.56$ [$\omega(\text{Re}) = 12.9 \times 10^{-6}$] ~ 7.46 [$\omega(\text{Re}) = 1741 \times 10^{-6}$]。频数直方图中(图2E)出现1个峰值, $\text{Ln}(\text{Re}) = 5.5$ [$\omega(\text{Re}) = 245 \times 10^{-6}$] ~ 6 [$\omega(\text{Re}) = 403 \times 10^{-6}$],占样品总数26.7%。

长英质脉中辉钼矿共生矿物含黄铁矿,不含黄铜矿、白钨矿、黑钨矿、方铅矿、闪锌矿、自然金和自然银数据共 32 个, $w(\text{Re})$ 变化在 $5.38 \times 10^{-6} \sim 384 \times 10^{-6}$, $\text{Ln}(\text{Re}) = 1.68 \sim 5.95$ 。Re 含量算术平均值为 55.23×10^{-6} , 几何平均值 26.4×10^{-6} ($\text{Ln}(\text{Re}) = 3.27$), 对数方差为 1.11, 约 68.8% 的数据在 1 个标准偏差范围之内, 即: $\text{Ln}(\text{Re}) = 2.16$ [$w(\text{Re}) = 8.68 \times 10^{-6}$] ~ 4.39 [$w(\text{Re}) = 80.3 \times 10^{-6}$], 约 93.8% 的数据在 2 个标准偏差范围之内, 即: $\text{Ln}(\text{Re}) = 1.05$ [$w(\text{Re}) = 2.85 \times 10^{-6}$] ~ 5.50 [$w(\text{Re}) = 244 \times 10^{-6}$]。频数直方图中(图 2F)出现 1 个峰值, $\text{Ln}(\text{Re}) = 2.6$ [$w(\text{Re}) = 13.5 \times 10^{-6}$] ~ 3.1 [$w(\text{Re}) = 22.2 \times 10^{-6}$], 占样品总数 28.1%。

2.3 矽卡岩

矽卡岩中共 165 个数据, $w(\text{Re})$ 变化在 $0.74 \times 10^{-6} \sim 14\,024 \times 10^{-6}$, $\text{Ln}(\text{Re}) = -0.30 \sim 9.55$ 。Re 含量算术平均值为 519×10^{-6} , 几何平均值 $117.4 \times$

10^{-6} ($\text{Ln}(\text{Re}) = 4.77$), 对数方差为 1.95, 约 73.3% 的数据在一个标准偏差范围之内, 即: $\text{Ln}(\text{Re}) = 2.82$ [$w(\text{Re}) = 16.8 \times 10^{-6}$] ~ 6.71 [$w(\text{Re}) = 821 \times 10^{-6}$] 约 92.7% 的数据在两个标准偏差范围之内, 即: $\text{Ln}(\text{Re}) = 0.87$ [$w(\text{Re}) = 2.40 \times 10^{-6}$] ~ 8.66 [$w(\text{Re}) = 5\,745 \times 10^{-6}$]。频数直方图中(图 3A)出现 3 个峰值, 从小到大依次为: $\text{Ln}(\text{Re}) = 3.2$ [$w(\text{Re}) = 24.5 \times 10^{-6}$] ~ 3.7 [$w(\text{Re}) = 40.4 \times 10^{-6}$], $\text{Ln}(\text{Re}) = 5.2$ [$w(\text{Re}) = 181.3 \times 10^{-6}$] ~ 5.7 [$w(\text{Re}) = 298.9 \times 10^{-6}$], $\text{Ln}(\text{Re}) = 6.7$ [$w(\text{Re}) = 812 \times 10^{-6}$] ~ 7.2 [$w(\text{Re}) = 1\,339 \times 10^{-6}$]。3 个峰值占样品总数分别为 9.7%、16.4%、6.5%。

矽卡岩中辉钼矿共生矿物含黄铜矿和(或)磁铁矿(或磁黄铁矿)不含白钨矿、黑钨矿、方铅矿、闪锌矿、自然金和自然银 72 个数据, $w(\text{Re})$ 变化在 $15.4 \times 10^{-6} \sim 14\,024 \times 10^{-6}$, $\text{Ln}(\text{Re}) = 2.73 \sim 9.55$ 。Re 含量算术平均值为 953×10^{-6} , 几何平均值 328×10^{-6}

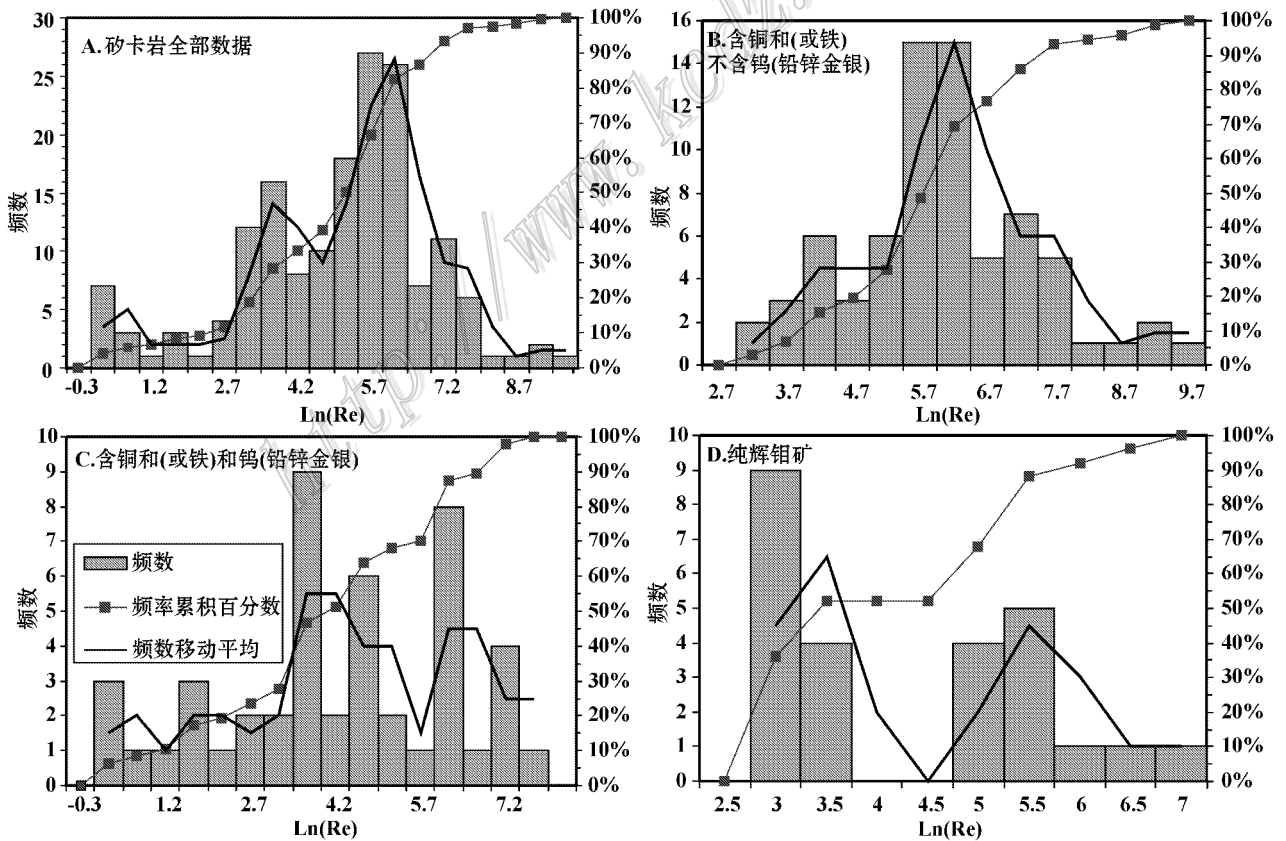


图 3 矽卡岩中不同产出状态辉钼矿 Re 含量的自然对数频数分布图(元素名称含义同图 2)

Fig. 3 Frequency distribution of natural logarithm of Re content in molybdenite of different modes of occurrence in skarn (meanings of element names as for Fig. 2)

[$\text{Ln}(Re) = 5.79$], 对数方差为 1.40, 约 68.1% 的数据在 1 个标准偏差范围之内, 即: $\text{Ln}(Re) = 4.40$ [$w(Re) = 81.3 \times 10^{-6}$] ~ 7.19 [$w(Re) = 1\ 324 \times 10^{-6}$], 约 93.1% 的数据在两个标准偏差范围之内, 即: $\text{Ln}(Re) = 3.00$ [$w(Re) = 20.14 \times 10^{-6}$] ~ 8.58 [$w(Re) = 5\ 341 \times 10^{-6}$]. 频数直方图中(图 3B)出现 1 个峰值, $\text{Ln}(Re) = 5.2$ [$w(Re) = 181 \times 10^{-6}$] ~ 6.2 [$w(Re) = 493 \times 10^{-6}$], 占样品总数 41.7%。

矽卡岩中辉钼矿共生矿物含黄铜矿和(或)磁铁矿(或磁黄铁矿)和白钨矿(或黑钨矿、方铅矿、闪锌矿、自然金和自然银) 47 个数据, $w(Re)$ 变化在 0.74×10^{-6} ~ $1\ 486 \times 10^{-6}$, $\text{Ln}(Re) = -0.30$ ~ 7.30 . Re 含量算术平均值为 234×10^{-6} , 几何平均值 55.5×10^{-6} [$\text{Ln}(Re) = 4.02$], 对数方差为 2.06, 约 66% 的数据在 1 个标准偏差范围之内, 即: $\text{Ln}(Re) = 1.96$ [$w(Re) = 7.07 \times 10^{-6}$] ~ 6.08 [$w(Re) = 435 \times 10^{-6}$], 约 97.9% 的数据在两个标准偏差范围之内, 即: $\text{Ln}(Re) = -0.10$ [$w(Re) = 0.90 \times 10^{-6}$] ~ 8.14 [$w(Re) = 3416 \times 10^{-6}$]. 频数直方图中(图 3C)出现 3 个峰值, 从小到大依次为: $\text{Ln}(Re) = 3.2$ [$w(Re) = 24.5 \times 10^{-6}$] ~ 3.7 [$w(Re) = 40.4 \times 10^{-6}$], $\text{Ln}(Re) = 4.2$ [$w(Re) = 66.7 \times 10^{-6}$] ~ 4.7 [$w(Re) = 109.9 \times 10^{-6}$], $\text{Ln}(Re) = 5.7$ [$w(Re) = 299 \times 10^{-6}$] ~ 6.2 [$w(Re) = 493 \times 10^{-6}$]. 3 个峰值

占样品总数分别为 19.2%、12.8%、17%。

矽卡岩纯辉钼矿 25 个数据, $w(Re)$ 变化在 12.7×10^{-6} ~ 665×10^{-6} , $\text{Ln}(Re) = 2.54$ ~ 6.50 . Re 含量算术平均值为 121.8×10^{-6} , 几何平均值 58.1×10^{-6} [$\text{Ln}(Re) = 4.06$], 对数方差为 1.27, 约 68% 的数据在一个标准偏差范围之内, 即: $\text{Ln}(Re) = 2.79$ [$w(Re) = 16.3 \times 10^{-6}$] ~ 5.33 [$w(Re) = 207 \times 10^{-6}$], 100% 的数据在两个标准偏差范围之内, 即: $\text{Ln}(Re) = 1.52$ [$w(Re) = 4.57 \times 10^{-6}$] ~ 6.60 [$w(Re) = 738 \times 10^{-6}$]. 频数直方图中(图 3D)出现 1 个峰值, $\text{Ln}(Re) = 2.5$ [$w(Re) = 12.2 \times 10^{-6}$] ~ 3.0 [$w(Re) = 20.1 \times 10^{-6}$], 占样品总数 36%。

2.4 花岗岩

花岗岩中 147 个数据, $w(Re)$ 变化在 0.03×10^{-6} ~ $1\ 218 \times 10^{-6}$, $\text{Ln}(Re) = -3.52$ ~ 7.11 . Re 含量算术平均值为 129×10^{-6} , 几何平均值 19.4×10^{-6} [$\text{Ln}(Re) = 2.96$], 对数方差为 2.39, 约 55.1% 的数据在一个标准偏差范围之内, 即: $\text{Ln}(Re) = 0.57$ [$w(Re) = 1.77 \times 10^{-6}$] ~ 5.36 [$w(Re) = 212 \times 10^{-6}$], 约 97.2% 的数据在两个标准偏差范围之内, 即: $\text{Ln}(Re) = -1.82$ [$w(Re) = 0.16 \times 10^{-6}$] ~ 7.75 [$w(Re) = 2\ 325 \times 10^{-6}$]. 频数直方图中(图 4A)出现 3 个峰值, 从小到大依次为: $\text{Ln}(Re) = -0.6$ [$w(Re) = 0.55 \times 10^{-6}$] ~ -0.1 [$w(Re) = 0.90 \times$

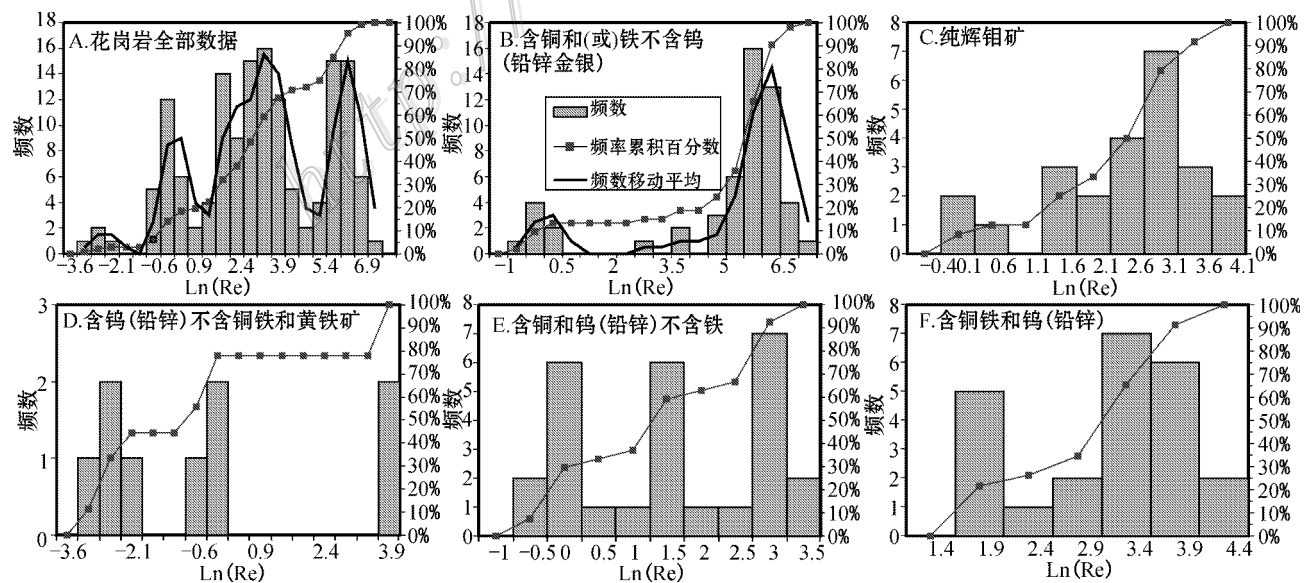


图 4 花岗岩中不同产出状态辉钼矿 Re 含量的自然对数频数分布图(元素名称含义同图 2)

Fig. 4 Frequency distribution of natural logarithm of Re content in molybdenite of different modes of occurrence in granite (meanings of element names as for Fig. 2)

10^{-6}], $Lr(Re) = 2.9$ [$w(Re) = 18.2 \times 10^{-6}$] ~ 3.4 [$w(Re) = 30.0 \times 10^{-6}$], $Ln(Re) = 5.4$ [$w(Re) = 221 \times 10^{-6}$] ~ 6.4 [$w(Re) = 602 \times 10^{-6}$]. 3个峰值占样品总数分别为8.2%、10.9%、20.4%。

花岗岩中辉钼矿共生矿物含黄铜矿和(或)磁铁矿(或磁黄铁矿)不含白钨矿、黑钨矿、方铅矿、闪锌矿、自然金和自然银53个数据, $w(Re)$ 变化在 $0.37 \times 10^{-6} \sim 1.218 \times 10^{-6}$, $Lr(Re) = -0.99 \sim 7.11$ 。Re含量算术平均值为 332×10^{-6} , 几何平均值 140×10^{-6} [$Lr(Re) = 4.94$], 对数方差为2.16, 约84.9%的数据在一个标准偏差范围之内, 即: $Ln(Re) = 2.79$ [$w(Re) = 16.3 \times 10^{-6}$] ~ 7.10 [$w(Re) = 1.212 \times 10^{-6}$], 约86.8%的数据在两个标准偏差范围之内, 即: $Ln(Re) = 0.63$ [$w(Re) = 1.89 \times 10^{-6}$] ~ 9.25 [$w(Re) = 10.455 \times 10^{-6}$]. 频数直方图中(图4B)出现1个峰值, $Lr(Re) = 5.5$ [$w(Re) = 245 \times 10^{-6}$] ~ 6 [$w(Re) = 403 \times 10^{-6}$], 占样品总数11.3%。

花岗岩纯辉钼矿26个数据, $w(Re)$ 变化在 $0.53 \times 10^{-6} \sim 58.2 \times 10^{-6}$, $Lr(Re) = -0.99 \sim 7.11$ 。Re含量算术平均值为 14.6×10^{-6} , 几何平均值 7.99×10^{-6} [$Lr(Re) = 2.08$], 对数方差为1.33, 约69.2%的数据在一个标准偏差范围之内, 即: $Ln(Re) = 0.75$ [$w(Re) = 2.11 \times 10^{-6}$] ~ 3.41 [$w(Re) = 30.2 \times 10^{-6}$], 约96.2%的数据在两个标准偏差范围之内, 即: $Lr(Re) = -0.58$ [$w(Re) = 0.56 \times 10^{-6}$] ~ 4.74 [$w(Re) = 114 \times 10^{-6}$]. 频数直方图中(图4C)出现1个峰值, $Lr(Re) = 2.6$ [$w(Re) = 13.5 \times 10^{-6}$] ~ 3.1 [$w(Re) = 22.2 \times 10^{-6}$], 占样品总数29.2%。

花岗岩中辉钼矿共生矿物含白钨矿和(或)黑钨矿、方铅矿、闪锌矿, 不含黄铜矿、磁铁矿、磁黄铁矿和黄铁矿9个数据(图4D), $w(Re)$ 变化在 $0.03 \times 10^{-6} \sim 32.9 \times 10^{-6}$, $Lr(Re) = -3.52 \sim 3.49$ 。Re含量算术平均值为 7.49×10^{-6} , 几何平均值 0.51×10^{-6} [$Lr(Re) = -0.67$], 对数方差为2.65, 约66.7%的数据在一个标准偏差范围之内, 即: $Lr(Re) = -3.32$ [$w(Re) = 0.04 \times 10^{-6}$] ~ 1.98 [$w(Re) = 7.28 \times 10^{-6}$], 100%的数据在两个标准偏差范围之内, 即: $Lr(Re) = -5.97$ [$w(Re) = 0.003 \times 10^{-6}$] ~ 4.64 [$w(Re) = 103 \times 10^{-6}$].

花岗岩中辉钼矿共生矿物含黄铜矿、白钨矿和

(或)黑钨矿、方铅矿、闪锌矿不含磁铁矿和磁黄铁矿27个样品, $w(Re)$ 变化在 $0.37 \times 10^{-6} \sim 32 \times 10^{-6}$, $Lr(Re) = -0.99 \sim 3.47$ 。Re含量算术平均值为 7.75×10^{-6} , 几何平均值 3.69×10^{-6} [$Lr(Re) = 1.30$], 对数方差为1.38, 约48.1%的数据在一个标准偏差范围之内, 即: $Ln(Re) = -0.07$ [$w(Re) = 0.93 \times 10^{-6}$] ~ 2.68 [$w(Re) = 14.6 \times 10^{-6}$], 100%的数据在两个标准偏差范围之内, 即: $Ln(Re) = -1.45$ [$w(Re) = 0.23 \times 10^{-6}$] ~ 4.06 [$w(Re) = 58 \times 10^{-6}$]. 频数直方图中(图4E)出现3个峰值, 从小到大依次为: $Ln(Re) = -0.5$ [$w(Re) = 0.61 \times 10^{-6}$] ~ 0 [$w(Re) = 1.00 \times 10^{-6}$], $Ln(Re) = 1$ [$w(Re) = 2.72 \times 10^{-6}$] ~ 1.5 [$w(Re) = 4.48 \times 10^{-6}$], $Ln(Re) = 2.5$ [$w(Re) = 12.2 \times 10^{-6}$] ~ 3 [$w(Re) = 20.1 \times 10^{-6}$]. 3个峰值占样品总数分别为22.2%、22.2%、25.9%。

花岗岩中辉钼矿共生矿物含黄铜矿、磁铁矿(或磁黄铁矿)和白钨矿(或黑钨矿、方铅矿、闪锌矿)23个样品, $w(Re)$ 变化在 $4.33 \times 10^{-6} \sim 69.2 \times 10^{-6}$, $Lr(Re) = 1.47 \sim 4.24$ 。Re含量算术平均值为 25.6×10^{-6} , 几何平均值 19.4×10^{-6} [$Lr(Re) = 2.96$], 对数方差为0.84, 约69.6%的数据在一个标准偏差范围之内, 即: $Ln(Re) = 2.13$ [$w(Re) = 8.39 \times 10^{-6}$] ~ 3.80 [$w(Re) = 44.7 \times 10^{-6}$], 100%的数据在两个标准偏差范围之内, 即: $Ln(Re) = 1.29$ [$w(Re) = 3.64 \times 10^{-6}$] ~ 4.64 [$w(Re) = 103 \times 10^{-6}$]. 频数直方图中(图4F)出现1个峰值, $Ln(Re) = 2.9$ [$w(Re) = 18.2 \times 10^{-6}$] ~ 3.4 [$w(Re) = 30.0 \times 10^{-6}$], 占样品总数10.5%。

2.5 碳酸岩

碳酸岩脉中16个数据, 考虑到Stein等(1997)的数据为1个样重复测了7次, 这里只选取其中一个数据, 总的碳酸岩脉中数据变为10个(图5), $w(Re)$ 变化在 $88.1 \sim 633 \times 10^{-6}$, $Lr(Re) = 4.48 \sim 6.45$ 。Re含量算术平均值为 288×10^{-6} , 几何平均值 231×10^{-6} [$Lr(Re) = 5.44$], 对数方差为0.73, 约60%的数据在一个标准偏差范围之内, 即: $Ln(Re) = 4.71$ [$w(Re) = 111 \times 10^{-6}$] ~ 6.17 [$w(Re) = 477 \times 10^{-6}$], 100%的数据在两个标准偏差范围之内, 即: $Lr(Re) = 3.98$ [$w(Re) = 54 \times 10^{-6}$] ~ 6.89 [$w(Re) = 988 \times 10^{-6}$].

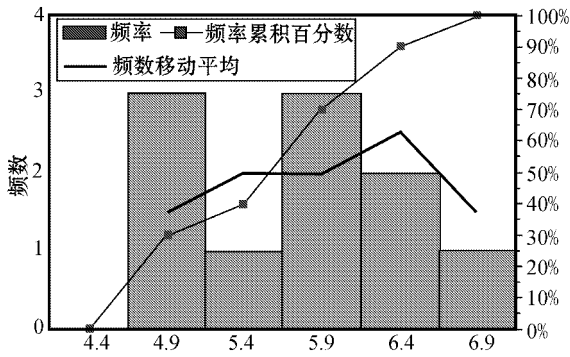


图5 碳酸岩脉中辉钼矿 Re 含量的自然对数频数分布图

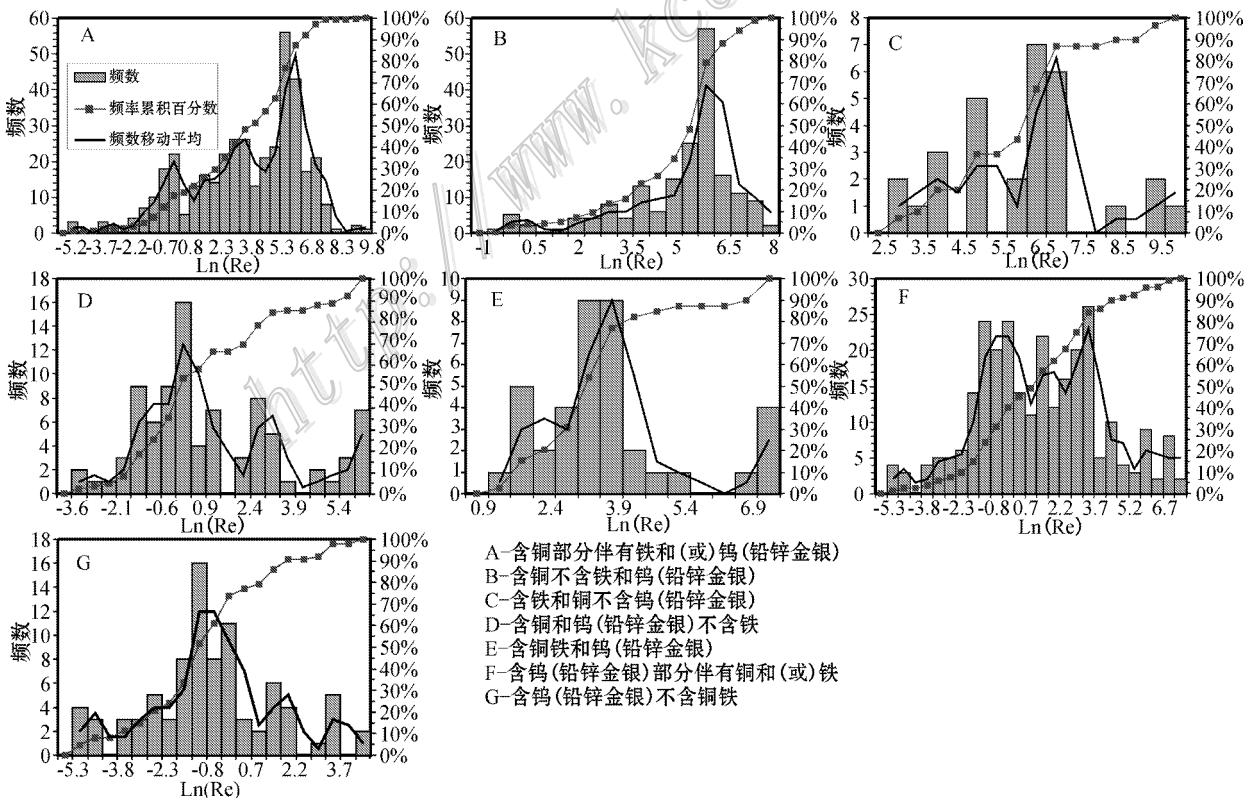
Fig. 5 Frequency distribution of natural logarithm of Re content in molybdenite from carbonatite

3 与不同矿物共生时辉钼矿的 Re 含量

辉钼矿共生矿物含黄铜矿部分伴有磁铁矿

(或磁黄铁矿)和(或)白钨矿(或黑钨矿),方铅矿、闪锌矿、自然金和自然银 398 个数据, $w(Re)$ 变化为 $0.006 \times 10^{-6} \sim 14\ 024 \times 10^{-6}$, $Ln(Re) = -5.13 \sim 9.55$. Re 含量算术平均值为 315×10^{-6} , 几何平均值 36.5×10^{-6} [$Ln(Re) = 3.60$], 对数方差为 2.73, 约 69.3% 的数据在 1 个标准偏差范围之内, 即: $Ln(Re) = 0.87$ [$w(Re) = 2.39 \times 10^{-6}$] \sim 6.32 [$w(Re) = 558 \times 10^{-6}$], 约 96.7% 的数据在两个标准偏差范围之内, 即: $Ln(Re) = -1.86$ [$w(Re) = 0.16 \times 10^{-6}$] \sim 9.05 [$w(Re) = 8\ 534 \times 10^{-6}$]. 频数直方图中(图 6A)出现 3 个峰值, 从小到大依次为: $Ln(Re) = -0.2$ [$w(Re) = 0.82 \times 10^{-6}$] \sim 0.3 [$w(Re) = 1.35 \times 10^{-6}$], $Ln(Re) = 3.3$ [$w(Re) = 27.1 \times 10^{-6}$] \sim 3.8 [$w(Re) = 44.7 \times 10^{-6}$], $Ln(Re) = 5.3$ [$w(Re) = 200 \times 10^{-6}$] \sim 5.8 [$w(Re) = 330 \times 10^{-6}$]. 3 个峰值占样品总数分别为 5.5%、6.5%、14.1%。

辉钼矿共生矿物含黄铜矿不含磁铁矿、磁黄铁矿、白钨矿、黑钨矿、方铅矿、闪锌矿、自然金和自然



- A-含铜部分伴有铁和(或)钨(铅锌金银)
- B-含铜不含铁和钨(铅锌金银)
- C-含铁和铜不含钨(铅锌金银)
- D-含铜和钨(铅锌金银)不含铁
- E-含铜铁和钨(铅锌金银)
- F-含钨(铅锌金银)部分伴有铜和(或)铁
- G-含钨(铅锌金银)不含铜铁

图6 与不同矿物共生时辉钼矿 Re 含量的自然对数频数分布图(元素名称含义同图2)

Fig. 6 Frequency distribution of natural logarithm of Re content in molybdenite with different associated minerals (meanings of element names as for Fig. 2)

银 183 个数据, $w(\text{Re})$ 变化在 $0.37 \sim 2.232 \times 10^{-6}$, $\text{Ln}(\text{Re}) = -0.99 \sim 7.71$ 。Re 含量算术平均值为 327×10^{-6} , 几何平均值为 145.9×10^{-6} [$\text{Ln}(\text{Re}) = 4.98$] 对数方差为 1.70, 约 76% 的数据在一个标准偏差范围之内, 即: $\text{Ln}(\text{Re}) = 3.28$ [$w(\text{Re}) = 26.7 \times 10^{-6}$] ~ 6.68 [$w(\text{Re}) = 797 \times 10^{-6}$] 约 94.5% 的数据在两个标准偏差范围之内, 即: $\text{Ln}(\text{Re}) = 1.59$ [$w(\text{Re}) = 4.88 \times 10^{-6}$] ~ 8.38 [$w(\text{Re}) = 4.358 \times 10^{-6}$]。频数直方图中(图 6B)出现 1 个明显的峰值 $\text{Ln}(\text{Re}) = 5.5$ [$w(\text{Re}) = 245 \times 10^{-6}$] ~ 6 [$w(\text{Re}) = 403 \times 10^{-6}$], 占样品总数 31.1%。

辉钼矿共生矿物含磁铁矿(或磁黄铁矿)和黄铜矿不含白钨矿、黑钨矿、方铅矿、闪锌矿、自然金和自然银 30 个数据, $w(\text{Re})$ 变化在 $15.4 \times 10^{-6} \sim 14.024 \times 10^{-6}$, $\text{Ln}(\text{Re}) = 2.73 \sim 9.55$ 。Re 含量算术平均值为 1.538×10^{-6} , 几何平均值为 358×10^{-6} [$\text{Ln}(\text{Re}) = 5.88$] 对数方差为 1.76, 约 66.7% 的数据在一个标准偏差范围之内, 即: $\text{Ln}(\text{Re}) = 4.12$ [$w(\text{Re}) = 61.3 \times 10^{-6}$] ~ 7.64 [$w(\text{Re}) = 2.086 \times 10^{-6}$] 约 96.7% 的数据在两个标准偏差范围之内, 即: $\text{Ln}(\text{Re}) = 2.35$ [$w(\text{Re}) = 10.52 \times 10^{-6}$] ~ 9.41 [$w(\text{Re}) = 12.164 \times 10^{-6}$]。频数直方图中(图 6C)的峰值, $\text{Ln}(\text{Re}) = 6$ [$w(\text{Re}) = 403 \times 10^{-6}$] ~ 6.5 [$w(\text{Re}) = 665 \times 10^{-6}$], 占样品总数 23.3%。

辉钼矿共生矿物含黄铜矿和白钨矿(或黑钨矿、方铅矿、闪锌矿、自然金和自然银)不含磁铁矿、磁黄铁矿 88 个数据, $w(\text{Re})$ 变化在 $0.029 \times 10^{-6} \sim 560 \times 10^{-6}$, $\text{Ln}(\text{Re}) = -3.54 \sim 6.33$ 。Re 含量算术平均值为 52.8×10^{-6} , 几何平均值为 2.99×10^{-6} [$\text{Ln}(\text{Re}) = 1.09$] 对数方差为 2.47, 约 72.7% 的数据在一个标准偏差范围之内, 即: $\text{Ln}(\text{Re}) = -1.38$ [$w(\text{Re}) = 0.25 \times 10^{-6}$] ~ 3.57 [$w(\text{Re}) = 35.4 \times 10^{-6}$] 约 95.5% 的数据在两个标准偏差范围之内, 即: $\text{Ln}(\text{Re}) = -3.85$ [$w(\text{Re}) = 0.02 \times 10^{-6}$] ~ 6.04 [$w(\text{Re}) = 420 \times 10^{-6}$]。频数直方图中(图 6D)出现 3 个峰值, 从小到大依次为: $\text{Ln}(\text{Re}) = -0.1$ [$w(\text{Re}) = 0.90 \times 10^{-6}$] ~ 0.4 [$w(\text{Re}) = 1.49 \times 10^{-6}$], $\text{Ln}(\text{Re}) = 2.4$ [$w(\text{Re}) = 11.02 \times 10^{-6}$] ~ 2.9 [$w(\text{Re}) = 18.17 \times 10^{-6}$], $\text{Ln}(\text{Re}) = 5.9$ [$w(\text{Re}) = 365 \times 10^{-6}$] ~ 6.4 [$w(\text{Re}) = 602 \times 10^{-6}$]。3 个峰值占样品总数分别为 18.2%、9.1%、8%。右边 $\text{Ln}(\text{Re}) > 5.9$ 的资料与矽卡岩有关。

辉钼矿共生矿物有黄铜矿、磁铁矿(或磁黄铁

矿)和白钨矿(或黑钨矿、方铅矿、闪锌矿、自然金和自然银) 39 个数据, $w(\text{Re})$ 变化在 $4 \times 10^{-6} \sim 1.486 \times 10^{-6}$, $\text{Ln}(\text{Re}) = 1.39 \sim 7.30$ 。Re 含量算术平均值为 172×10^{-6} , 几何平均值为 34.97×10^{-6} [$\text{Ln}(\text{Re}) = 3.55$] 对数方差为 1.59, 约 71.8% 的数据在一个标准偏差范围之内, 即: $\text{Ln}(\text{Re}) = 1.97$ [$w(\text{Re}) = 7.14 \times 10^{-6}$] ~ 5.14 [$w(\text{Re}) = 171 \times 10^{-6}$] 约 87.2% 的数据在两个标准偏差范围之内, 即: $\text{Ln}(\text{Re}) = 0.38$ [$w(\text{Re}) = 1.46 \times 10^{-6}$] ~ 6.73 [$w(\text{Re}) = 838 \times 10^{-6}$]。频数直方图中(图 6E)的峰值, $\text{Ln}(\text{Re}) = 2.9$ [$w(\text{Re}) = 18.2 \times 10^{-6}$] ~ 3.9 [$w(\text{Re}) = 49.4 \times 10^{-6}$], 占样品总数 46.2%。

辉钼矿共生矿物含白钨矿(或黑钨矿)、方铅矿、闪锌矿、自然金和自然银部分伴有黄铜矿和(或)磁铁矿、磁黄铁矿 273 个数据, $w(\text{Re})$ 变化在 $0.005 \times 10^{-6} \sim 1.495 \times 10^{-6}$, $\text{Ln}(\text{Re}) = -5.30 \sim 7.31$ 。Re 含量算术平均值为 75.2×10^{-6} , 几何平均值为 3.64×10^{-6} [$\text{Ln}(\text{Re}) = 1.29$] 对数方差为 2.70, 约 72.2% 的数据在一个标准偏差范围之内, 即: $\text{Ln}(\text{Re}) = -1.41$ [$w(\text{Re}) = 0.25 \times 10^{-6}$] ~ 3.99 [$w(\text{Re}) = 53.9 \times 10^{-6}$] 约 93.8% 的数据在两个标准偏差范围之内, 即: $\text{Ln}(\text{Re}) = -4.1$ [$w(\text{Re}) = 0.17 \times 10^{-6}$] ~ 6.7 [$w(\text{Re}) = 799 \times 10^{-6}$]。频数直方图中(图 6F)出现 3 个峰值, 从小到大依次为: $\text{Ln}(\text{Re}) = -1.3$ [$w(\text{Re}) = 0.27 \times 10^{-6}$] ~ -0.8 [$w(\text{Re}) = 0.45 \times 10^{-6}$], $\text{Ln}(\text{Re}) = 1.2$ [$w(\text{Re}) = 3.32 \times 10^{-6}$] ~ 1.7 [$w(\text{Re}) = 5.47 \times 10^{-6}$], $\text{Ln}(\text{Re}) = 3.2$ [$w(\text{Re}) = 24.5 \times 10^{-6}$] ~ 3.7 [$w(\text{Re}) = 40.4 \times 10^{-6}$]。3 个峰值占样品总数分别为 8.8%、8.1%、9.5%。

含白钨矿和(或)黑钨矿、方铅矿、闪锌矿、自然金和自然银, 不含黄铜矿、磁铁矿和磁黄铁矿。87 个数据的 $w(\text{Re})$ 变化在 $0.005 \times 10^{-6} \sim 88.3 \times 10^{-6}$, $\text{Ln}(\text{Re}) = -5.3 \sim 4.5$ 。Re 含量算术平均值为 4.9×10^{-6} , 几何平均值为 0.52×10^{-6} [$\text{Ln}(\text{Re}) = -0.66$] 对数方差为 2.18, 约 67.8% 的数据在一个标准偏差范围之内, 即: $\text{Ln}(\text{Re}) = -2.84$ [$w(\text{Re}) = 0.06 \times 10^{-6}$] ~ 1.53 [$w(\text{Re}) = 4.6 \times 10^{-6}$] 约 96.6% 的数据在两个标准偏差范围之内, 即: $\text{Ln}(\text{Re}) = -5.02$ [$w(\text{Re}) = 0.007 \times 10^{-6}$] ~ 3.71 [$w(\text{Re}) = 40.8 \times 10^{-6}$]。频数直方图中(图 6G)的峰值, $\text{Ln}(\text{Re}) = -1.3$ [$w(\text{Re}) = 0.27 \times 10^{-6}$] ~ -0.8 [$w(\text{Re}) = 0.45 \times 10^{-6}$], 占样品总数的 18.4%。

4 讨论

对比前文统计的各种产状的辉钼矿频数直方图可以看出,辉钼矿中 Re 含量与辉钼矿的寄主岩性和共生矿物组合存在较为明显的关系,最终概括为以下几种代表性的辉钼矿产出状态:从岩性角度来说,长英质脉和花岗岩中纯辉钼矿 Re 含量最低,几何平均值分别为 7.41×10^{-6} 和 7.99×10^{-6} ,多在 $n \times 10^{-6} \sim n \times 10^{-5}$;矽卡岩中纯辉钼矿 Re 含量中等,几何平均值为 58.1×10^{-6} ,多在 $n \times 10^{-5} \sim n \times 10^{-4}$;而在碳酸岩中最高,几何平均值为 231×10^{-6} ,多在 $n \times 10^{-4}$ 左右。不同岩性中辉钼矿共生不同矿物时 Re 含量均出现明显的变化,一个共同的特征是,仅与白钨矿(或黑钨矿)和(或)方铅矿、闪锌矿、自然金和自然银共生时,辉钼矿 Re 含量最低,几何平均值为 $n \times 10^{-7}$,多在 $n \times 10^{-8} \sim n \times 10^{-6}$;仅与黄铜矿和(或)磁铁矿、磁黄铁矿共生时,辉钼矿 Re 含量最高,几何平均值为 $n \times 10^{-4}$,多在 $n \times 10^{-5} \sim n \times 10^{-3}$;同时与黄铜矿(磁铁矿、磁黄铁矿)和白钨矿(或黑钨矿)方铅矿、闪锌矿、自然金和自然银共生时,辉钼矿 Re 含量处在前两者之间且峰值不是十分明显,几何平均值为 $n \times 10^{-6}$,多在 $n \times 10^{-7} \sim n \times 10^{-5}$ 。辉钼矿共生矿物中存在黄铁矿、磁铁矿和(或)磁黄铁矿时会引起 Re 含量在原有基础上升高,例如:长英质脉中的纯辉钼矿,几何平均值为 7.41×10^{-6} ,而长英质脉中辉钼矿共生矿物含黄铁矿不含黄铜矿、白钨矿(或黑钨矿)方铅矿、闪锌矿、自然金和自然银,几何平均值为 26.4×10^{-6} 。辉钼矿与黄铜矿、白钨矿(或黑钨矿)方铅矿、闪锌矿、自然金和自然银共生时,几何平均值为 2.99×10^{-6} ,而辉钼矿与黄铜矿、磁铁矿和(或)磁黄铁矿、白钨矿、黑钨矿、方铅矿、闪锌矿、金和银共生时,几何平均值为 34.97×10^{-6} 。辉钼矿共生矿物含黄铜矿不含磁铁矿、磁黄铁矿、白钨矿、黑钨矿、方铅矿、闪锌矿、自然金和自然银时,几何平均值为 145.9×10^{-6} ,而辉钼矿共生矿物含磁铁矿和(或)磁黄铁矿和黄铜矿,不含白钨矿、黑钨矿、方铅矿、闪锌矿、自然金和自然银时,几何平均值为 358×10^{-6} 。从共生矿物的角度来看辉钼矿中 Re 含量的变化,白钨矿、黑钨矿、方铅矿、闪锌矿、自然金和自然银可能具有降低辉钼矿中 Re 含量的作用,黄铁矿、磁铁矿、磁黄铁矿和黄铜矿可能具有升高辉钼矿中 Re 含量的作用,后者可能是 Re 的亲铜亲铁特

征的体现。以上辉钼矿中 Re 含量与寄主岩性和共生矿物组合的关系说明,岩性和共生矿物种类的变化都将会引起辉钼矿中 Re 含量的级数变化,在本文所划分的几种代表性的辉钼矿产出状态(寄主岩性和共生矿物组合)之间其 Re 含量差异的总体特征均在一个数量级以上,这从一个侧面说明辉钼矿 Re 含量的级数变化可能与其产出状态密切相关,似乎不能有效地反映出其成矿物质来源。此外,一些研究发现,利用毛景文等(1999a)总结的辉钼矿 Re 含量示踪的成矿物质来源与其他同位素结果出现了矛盾之处,如秋树湾铜钼矿床辉钼矿 $\omega(\text{Re})$ 为 $112.7 \times 10^{-6} \sim 180.0 \times 10^{-6}$,Re 含量示踪显示成矿物质来自地幔,但矿石硫同位素显示为下地壳来源(郭保健等,2006);东秦岭多个矿区辉钼矿中 Re 含量均显示出壳幔混源的特征(黄典豪等,1994;李永峰等,2003,2006;Mao et al.,2008),但卢欣祥等(2002)从氧、铅和硫同位素角度总结分析发现,成矿物质主要显示幔源的特征。

由于本文统计到的辉钼矿中 Re 含量的数据有限,辉钼矿部分产出状态下的样品数偏少,未能形成理想的对数正态分布特征。此外,辉钼矿 Re 含量显示的元素亲和力(亲铜亲铁)可能与元素生成的矿物结构也有关,例如,文中统计结果显示辉钼矿与磁铁矿共生时其 Re 含量显著高于与黄铁矿共生的辉钼矿 Re 含量。共生矿物同样是硫化物时,辉钼矿共生黄铁矿时其 Re 含量又明显高于共生方铅矿和闪锌矿的辉钼矿 Re 含量。因而,辉钼矿 Re 含量的变化依然是多因素的,目前统计得出的岩性和共生矿物的种类仅能反应出定性的影响作用。不同产出状态下辉钼矿 Re 含量出现了一定程度的重合特征,可能与一些样品产出状态的不确定性、个别共生矿物、矿床的形成温度(Badalov et al.,1962;Terada et al.,1971;Ivanov et al.,1972)和结晶物理化学条件有关(Berzina et al.,2005)。因而,寻找辉钼矿中 Re 含量分布更加准确可靠的影响因素,还需要今后结合典型矿床的全面系统研究。

5 结论

(1)辉钼矿中 Re 含量与岩性存在密切的关系,长英质脉和花岗岩中纯辉钼矿 Re 含量最低,几何平均值分别为 7.41×10^{-6} 和 7.99×10^{-6} ,多在 $n \times 10^{-6} \sim n \times 10^{-5}$;矽卡岩中纯辉钼矿 Re 含量中等,几

何平均值为 58.1×10^{-6} , 多在 $n \times 10^{-5} \sim n \times 10^{-4}$; 碳酸岩中最高, 几何平均值为 231×10^{-6} , 多在 $n \times 10^{-4}$ 左右。

(2) 辉钼矿的共生矿物种类影响其 Re 含量的变化, 仅与白钨矿(或黑钨矿)和(或)方铅矿、闪锌矿、自然金和自然银共生, 辉钼矿 Re 含量最低, 几何平均值为 $n \times 10^{-7}$, 多在 $n \times 10^{-8} \sim n \times 10^{-6}$; 仅与黄铜矿和(或)磁铁矿(或磁黄铁矿)共生时, 辉钼矿 Re 含量最高, 几何平均值为 $n \times 10^{-4}$, 多在 $n \times 10^{-5} \sim n \times 10^{-3}$; 同时与黄铜矿(或磁铁矿、磁黄铁矿)和白钨矿(或黑钨矿、方铅矿、闪锌矿、自然金和自然银)共生时, 辉钼矿 Re 含量处在前两者之间, 且峰值不是十分明显, 几何平均值为 $n \times 10^{-6}$, 多在 $n \times 10^{-7} \sim n \times 10^{-5}$ 。

(3) 辉钼矿共生白钨矿(或黑钨矿、方铅矿、闪锌矿、自然金和自然银)或产在长英质脉和花岗岩中, 可能促使其 Re 含量降低, 辉钼矿与黄铁矿、黄铜矿和磁铁矿(或磁黄铁矿)共生或产在矽卡岩和碳酸岩中, 可能促使其 Re 含量升高。辉钼矿 Re 含量的级数变化可能与其产出状态密切相关, 似乎不能有效地反映出其成矿物质来源。

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