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钨同位素研究进展及其在矿床学中的应用展望

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摘要：钨(W)作为一种关键金属，具有多个稳定同位素。近年来，越来越多的学者关注地球不同圈层W同位素组成，发现岩石圈中不同类型岩石的W同位素组成有较大差别(酸性岩比基性岩更富轻W同位素，海洋沉积岩比岩浆岩更富重W同位素)，因此，可以利用其揭示壳幔相互作用及地球表生过程中钨元素循环及演化规律。研究表明W同位素具有强大的示踪潜力，为开展W同位素的进一步研究奠定了良好基础，然而，目前尚未见钨矿床W同位素的研究，对钨成矿过程中W同位素的分馏机制及控制因素尚不清楚，其示踪复杂成矿过程及判断钨物质来源的潜力亟待研究。本文系统总结了目前W同位素的分析方法、不同类型岩石的W同位素组成及地球表生循环过程中W同位素示踪原理，对W同位素在矿床学中的应用进行了展望，指出目前亟需将W同位素研究引入矿床学中，进而建立W同位素示踪成矿物质来源的方法及钨成矿系统的W同位素演化模型。通过对钨矿床W同位素的研究将有望获取不同地质历史时期、不同区域钨来源的“指纹”信息，揭示钨元素在地球各圈层的地球化学循环过程及其超常聚集行为，为深入认识多类型钨矿化的成因提供新的思路，为研究大规模钨多金属成矿作用提供全新方法，具有重要的理论价值及现实意义。

关键词：W同位素；分馏机制；示踪作用；钨矿床；成矿过程
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Research progress of tungsten isotope and its application prospect in ore geology

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Abstract: Tungsten(W) isotope is a significant non-traditional metallic stable isotope. In recent years, the composition of stable W isotope in different geospheres has become a subject of extensive concern of more scholars. It is found that the W isotope of different rocks in the lithosphere varies greatly(acid rocks are richer in light W isotopes than basic rocks, marine sedimentary rocks are richer in heavy W isotopes than magmatic rocks), which can be used to reveal the cycle and evolution of tungsten during crust-mantle interaction and earth hypergene process. These studies fully demonstrate the powerful tracing potential of W isotope and lay a great foundation for further research on W isotope. However, W isotope study of tungsten deposits is not carried out yet, therefore, the fractionation mechanism and controlling factors of W isotope in its mineralization are not clear, and the potential of tracing complex mineralization process and determining the source of tungsten needs to be explored urgently. In this paper, current methods of W isotope analysis, the composition of W isotope in different types of rocks and the tracing principle of W isotope in the earth's supergenetic cycle were systematically summarized, and the application prospect of W isotope in ore deposits was proposed. It is urgent to introduce W isotope into the study of ore deposits, so as to establish the method of constraining ore-forming material sources as a geological tracer and the evolution model of W isotope in tungsten metallogenic system. The W isotope studies for tungsten deposit is expected to obtain the fingerprint information of tungsten sources in different geological periods and regions, reveal the geochemical cycle and supernormal accumulation of tungsten in various spheres of the earth, offer new ideas for further understanding the genesis of tungsten mineralization, and then provide a new perspective for the study of large-scale tungsten polymetallic mineralization, which has important theoretical value and practical significance.

Key words: tungsten isotope; fractionation mechanism; tracing significance; W deposit; metallogenetic process

对非传统金属稳定同位素地球化学的研究是国际地学领域的新兴热点研究方向，近年来，随着分析测试技术的突飞猛进，稳定同位素技术发展非常迅速[1−5]。成矿金属元素“本身”同位素组成变化显得尤为重要，它可以直接用来示踪成矿金属的来源及成矿过程，具有其他“间接”同位素不可替代的作用，因此，得到越来越多矿床学家的持续关注[6−9]。目前，成矿元素同位素如Fe、Cu、Zn、Mo、Sb、Sn、Ag等元素同位素均被应用于矿床学的研究并取得了丰硕的成果，不断地更新着人们对于金属矿床成矿作用的认知[10−15]。然而，对于分布广泛、具有多成矿时代、多物质来源、多矿化类型的钨矿床而言，钨(W)同位素目前尚未运用于矿床学的研究中，这在某种程度上限制了人们对金属钨“源”“运”“储”的理解。因此，深入探讨热液成矿过程中W同位素的分馏机制并研究其示踪作用，对厘定钨元素来源、揭示成矿流体演化过程及探索钨成矿末端效应意义重大。

自然界中钨有5个稳定同位素即^{180}W、^{182}W、^{183}W、^{184}W和^{186}W，其丰度分别为0.12%、26.50%、14.31%、30.64%和28.43%[16]。目前，W同位素的比值大多用$\delta w(^{186}\mathrm{W})/w(^{184}\mathrm{W})$的形式表示($w$为质量分数)，$\delta w(^{186}\mathrm{W})/w(^{184}\mathrm{W}) = \{[(w(^{186}\mathrm{W})/w(^{184}\mathrm{W})_{样品})]/[(w(^{186}\mathrm{W})/w(^{184}\mathrm{W})_{标样})-1]\}\times 1\,000$。在一些非常古老的样品中(如早期太阳系物质)，有一部分^{183}W由短寿命核素^{183}Hf(半衰期约8.9 Ma)衰变产生[17]。由于W的相对原子质量较大，同位素分馏较小，近年来人们才开始对W稳定同位素变化进行研究[18−21]。目前，人们对W稳定同位素的研究主要集中在两方面：一方面，对非常古老的地质样品和地质过程进行同位素分析，探索与Hf-W同位素年代学相关的偏离质量分馏的W稳定同位素组成变化[22−24]；另一方面，探索各种地质过程中W稳定同位素的分馏过程(如质量分馏)及其控制机制，研究其潜在的示踪应用[5, 17]。自20世纪末以来，大量学者利用W同位素体系研究了太阳系的起源和它的早期增生与分异[25−28]、行星(如地球、火星)和月球的年龄、起源及其早期演化[29−38]、陨石年龄和成因[39−42]等，为探索地球、月球及太阳系内其他星体的起源和演化提供了重要资料[43−44]。近年来，越来越多的学者关注地球不同圈层岩石样品的稳定W同位素组成，试图还原壳幔相互作用及地球表生作用过程中W元素循环及其同位素演化过程[5, 18, 45−46]。本文总结了W的稳定同位素在地质学领域的研究进展，并对其在矿床学中的应用前景提出展望，以便为W

同位素研究及应用提供参考。

1　钨同位素分析测试方法

钨在地质样品中的含量往往不高[47]，而且在化学处理过程中受到的干扰较明显(如在HF介质下Zr、Ti等容易水解)，从而导致W的回收率不高，因而，在高精度W同位素测试中首先要解决的就是W元素的浓缩和纯化问题[17]。张龙等[48]利用离心法分离W同位素，得到了^{186}W丰度大于98%的WF_6，此外，通过单机分离试验还得到了离心机分离W同位素的单位原子质量数的全分离系数。陈娟等[49]通过对样品的消解、W的化学分离与纯化、W同位素的质谱测定等比较研究发现，粒径为37~74 μm的AG1X-8 Cl^-阴离子树脂可高效地对W进行化学分离与纯化，多接收器电感耦合等离子质谱仪(MC-ICPMS)是进行W同位素测定的最佳仪器。梅清风等[50]采用HF−HNO_3混合酸对硅酸盐进行溶解，采用HF−HCl在超声环境下多次溶解提取与氟化物发生共沉淀的W。MEI等[51−52]对W的化学分离纯化流程进行了研究，提出了2种适用于地质样品的W富集纯化流程。

由于W具有很高的第一电离能(约7.98 eV)，用热电离质谱(TIMS)分析W同位素时，电离效率及精度都很低。负热电离质谱(NTIMS)[39, 53−55]和多接收电感耦合等离子体质谱(MC-ICPMS)[20, 56−60]的出现并应用于W同位素测试，推动了W同位素体系的研究进展[43]。许俊杰等[61]研究了NTIMS高精度W同位素测定方法，建立了采用多接收动态方法进行数据处理的在线氧校正W同位素NTIMS测定方法。除了^{183}Hf−^{183}W年代学体系外，研究者还深入研究了W同位素质量分馏方法及利用Hf外标加入法或双稀释剂(^{180}W−^{183}W)法在MC-ICPMS上测定高精度W稳定同位素的方法[16,18−20]，标准溶液的δw(^{186}W)可重复性好，误差可控制在±0.018‰以内。与NTIMS方法相比，MC-ICPMS方法无需从测定的WO_3^-中进行氧化物校正来获得W同位素比值，最大程度地避免了同位素分馏效应，元素的离子化效率显著提高，因此，分析精度及效率得到进一步提高，且样品用量少，分析更加方便、快捷。此外，相对于Hf外标加入法，双稀释剂(^{180}W−^{183}W)法在MC-ICPMS中的引入可以更好地减少同位素分馏效应，获得高正确度的同位素比值，克服了同位素测量时不能进行内部分馏校正的难题。MC-ICPMS方法具有分析灵敏度高、可同时进行多组同位素测量等优点，成为目前用来测量W同位素比值最有效的方法[20, 49]。国际上W同位素测试的标样主要为NIST SRM 3163[20, 45]，目前已积累了丰富的标准数据，可以被广泛地用于对比分析。因此，从当前的进展来看，W同位素的分析测试方法日趋成熟，标样可靠，可以满足各类样品高精度数据获取的需求。

2　不同类型岩石的钨同位素组成

对幔源岩石样品的W同位素进行观测研究发现，部分太古代幔源岩石中正的^{182}W同位素异常可能是在地球形成的早期阶段，在硅酸盐或硅酸盐−铁熔体分异过程中，更亲石的^{182}Hf倾向于留在硅酸盐中，随后衰变形成^{182}W形成的[62]；而那些年轻玄武岩中的负^{182}W异常则被认为是潜在的核−幔相互作用(亏损^{182}W同位素的地核物质与玄武岩的地幔源区混合)的结果[63]。刘耘[14]通过模拟计算发现，正负^{182}W同位素异常可以分别通过硅酸盐熔体的多阶段含W和S的金属相析出以及地幔源区的多阶段熔体抽离过程来解释，在每次熔融或金属相析出过程中，两相间存在着0.01‰~0.02‰的w(^{186}W)/w(^{184}W)同位素分馏。该研究表明熔融和结晶过程中由核体积效应导致的微小同位素分馏可能会在多阶段演化模型中被放大，从而为解释地幔样品中发现的各种微小同位素异常(如^{182}W的异常)提供一种新思路。

近年来，研究者通过对天然地幔岩石样品的W同位素进行分析积累了不少资料，进一步深化了对W同位素示踪意义的认识(图1[18−20, 46])。TAKAMASA等[64]对法属波利尼西亚的洋岛玄武岩进行了W同位素研究，指出岩浆来源于地幔而非地核。LIU等[65]对加拿大拉布拉多北部Saglek地块Uivak片麻岩地体的始太古代超镁铁质岩石(包括岩石圈地幔岩、变质科马提岩、层状超镁铁质体和相关地壳片麻岩和角闪岩)开展了W同位素研究，指出W同位素在地幔中存在不均一性，富含^{182}W

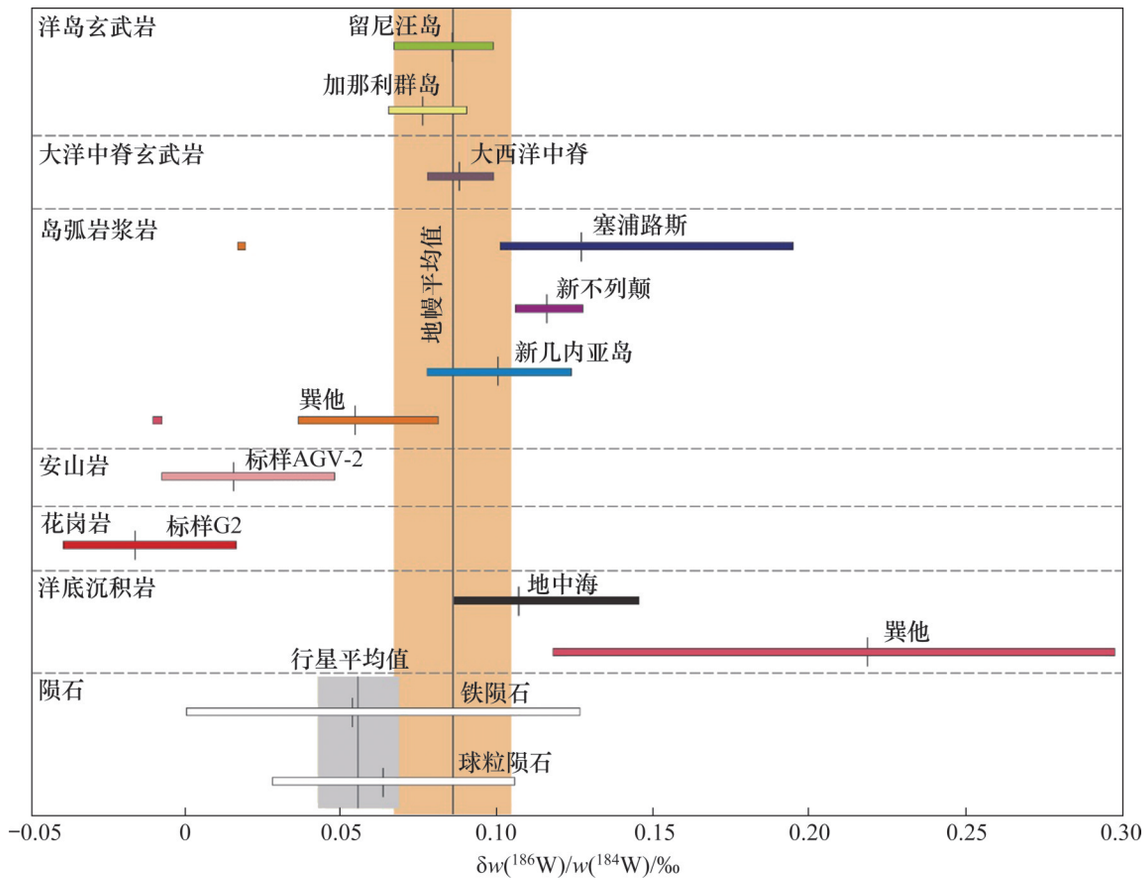


图1 主要地质及陨石样品的W同位素组成(数据来源于文献[18−20, 46])

Fig.1 W isotopic composition of main geological and meteorite samples(data sources are from Refs.[18−20, 46])

的地壳岩石再循环到地幔中可以产生具有异常W同位素组成的新地幔源。最近的分析表明，大型火成岩区(LIPs)和洋岛玄武岩(OIB)的W同位素组成存在差异，而这种差异可以用来反演地幔柱的起源与演化过程[66]。REIMINK等[67]对太古宙Slave克拉通的W同位素进行了研究，发现$\delta w(^{182}W)/w(^{184}W)$异常可以通过上地幔和下地幔之间的同位素物质交换而产生。

除了基性岩外，通过对中酸性岩的W同位素的对比分析增进了人们对岩浆演化过程中W同位素行为的了解(图2[19−21, 46, 68−69])。BRETON等[18]分析了一些天然岩石样品(如花岗岩等)的W同位素组成，发现样品间$\delta w(^{186}W)/w(^{184}W)$差异很大，因此，W同位素具有较强的示踪地质过程的潜力。KRABBE等[19]的研究结果也表明酸性岩比基性岩更富轻W同位素，说明在火成岩的形成过程中发生了W同位素分馏。然而，W同位素分馏不太可能与矿物结晶分异有关，因为作为最不相容的元素之一，大多数造岩矿物中都不含有钨，因此，

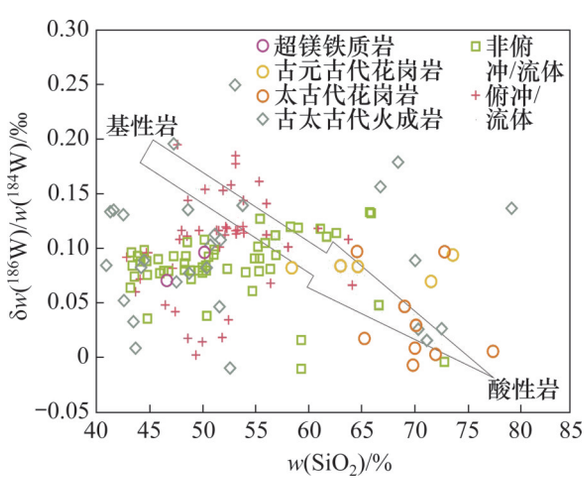


图2 主要岩浆岩样品SiO_2与$\delta w(^{186}W)/w(^{184}W)$散点图(数据来源于文献[19−21, 46, 68−69])

Fig. 2 Plot of SiO_2 and $\delta w(^{186}W)/w(^{184}W)$ of igneous rock samples (data sources are from Refs.[19−21, 46, 68−69])

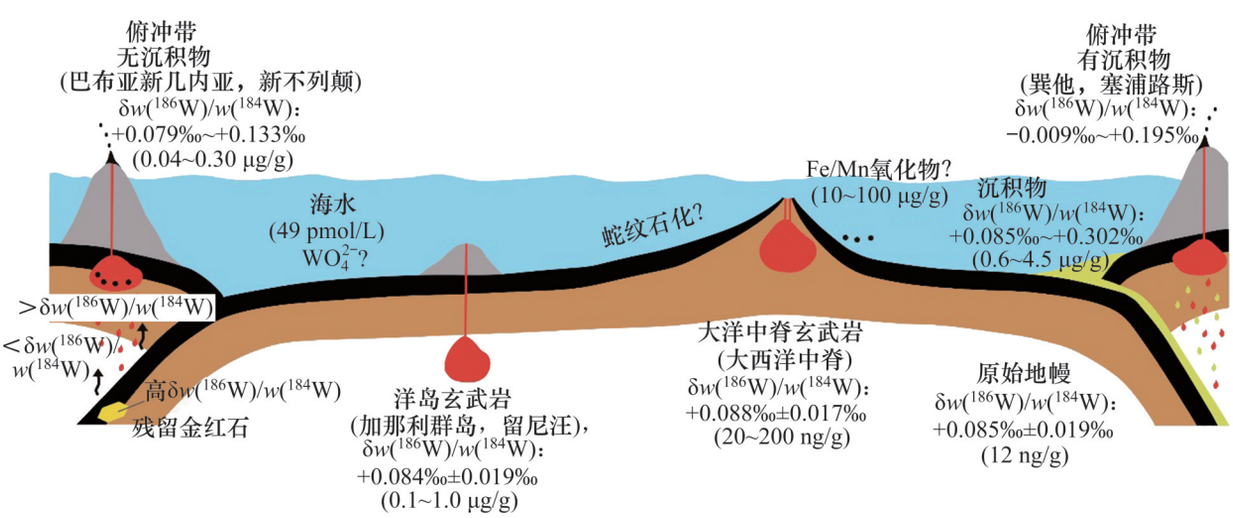
轻W同位素在酸性岩中的富集可能与岩浆源区的同位素继承有关，如在板片俯冲的过程中，俯冲板片可以释放W，轻W同位素优先分配到弧下地幔中，导致弧相关岩浆的$\delta w(^{184}W)/w(^{183}W)$降低。

以上结果均表明不同火成岩中W同位素组成存在差异，说明W稳定同位素可以示踪地球和其他行星岩浆过程，但具体的示踪机制需要进一步研究。

不同构造背景也会引起W同位素的组成存在差异。钨在岩浆过程中强烈不相容，在俯冲带中具有较高流动性，因此，弧熔岩中的W同位素分馏为追踪俯冲带中的板块脱水和熔融提供了强有力的示踪方法。KURZWEIL等[46]对地球上不同构造背景的火山岩(包括大洋中脊玄武岩(MORB)、洋岛玄武岩(OIB)以及各种俯冲相关环境中的玄武岩和英安岩)开展了W同位素分析，发现俯冲构造背景的岩石 $\delta w(^{186}W)/w(^{184}W)$ 变化较大(−0.009‰~+0.195‰)，这些地区的沉积岩的 $\delta w(^{186}W)/w(^{184}W)$ 平均值高达+0.301‰(图3[46])，这可能暗示在浅层流体诱发的熔融事件中，重W同位素被优先释放。这些研究表明火成岩的稳定W同位素组成可被用作追踪硅酸盐地球中W地球化学循环过程的新工具。MAZZA等[21]发现在Sangihe和Izu弧火山前缘的富流体样品中富集重W同位素($\delta w(^{184}W)/w(^{183}W)$=0.06‰)。随着与火山前缘距离增加，富熔体样品的特征是逐渐富集轻W同位素。来自日本西南部的富碱玄武岩(被认为是板块撕裂处地幔熔融的产物)以及相邻的钾玄岩具有最低的W同位素组成($\delta w(^{184}W)/w(^{183}W)$=0)，见图4[21]。W同位素分馏与各种流体释放指数(如 $w(Ce)/w(Pb)$、$w(Ba)/w(Th)$)的相关性表明，重W同位素特征反映了俯冲板块脱水导致的火山前缘附近的流体再循环[21]。在释放重W同位素时，残余板片优先保留轻W同位素，在热俯冲带(如日本西南部)缺水岩性的后续熔融过程中释放。这些数据特征表明，W同位素可用作板片脱水的示踪剂，有助于确定冷俯冲带岩浆作用的开始时间。以上研究均表明，不同地球圈层岩浆岩W同位素组成存在显著差异，说明W稳定同位素在示踪地球岩浆—流体过程中具有非常大的潜力。

3　地球表生循环的钨同位素示踪

除了反演岩浆源区外，W同位素还被广泛应用于跟踪古海洋的演化(与岩浆岩相比，海水及其沉积岩更富重W同位素，图1[18−20, 46])。与常用的Mo同位素示踪剂相比，W具有相似但不完全相同的化学性质，这表明W的稳定同位素可以成为一种新的探索现代和古代海洋环境演变的示踪物。KASHIWABARA等[45]分析了海洋中铁锰氧化物的W同位素组成，指出由于锰铁氧化物吸附原子质量小的W同位素，现代含氧海水可能更加富集原子质量大的W同位素。杨瑞钰等[70]测试了太平洋底铁锰结壳的稳定W同位素组成，发现热液结壳的同位素 $\delta w(^{186}W)/w(^{184}W)$ 几乎无明显变化，证明热液活动可能无法在铁锰结壳上留下W同位素证据，因此，铁、锰结壳可能记录了全球海洋的整体变化。



注：括号内数量为不同环境下W的质量分数。

图3　不同大地构造环境稳定W同位素组成示意图(数据来源于文献[46])

Fig. 3　Sketch illustrating the stable W isotope composition of silicate reservoirs in different tectonic settings (data sources are from Ref.[46])

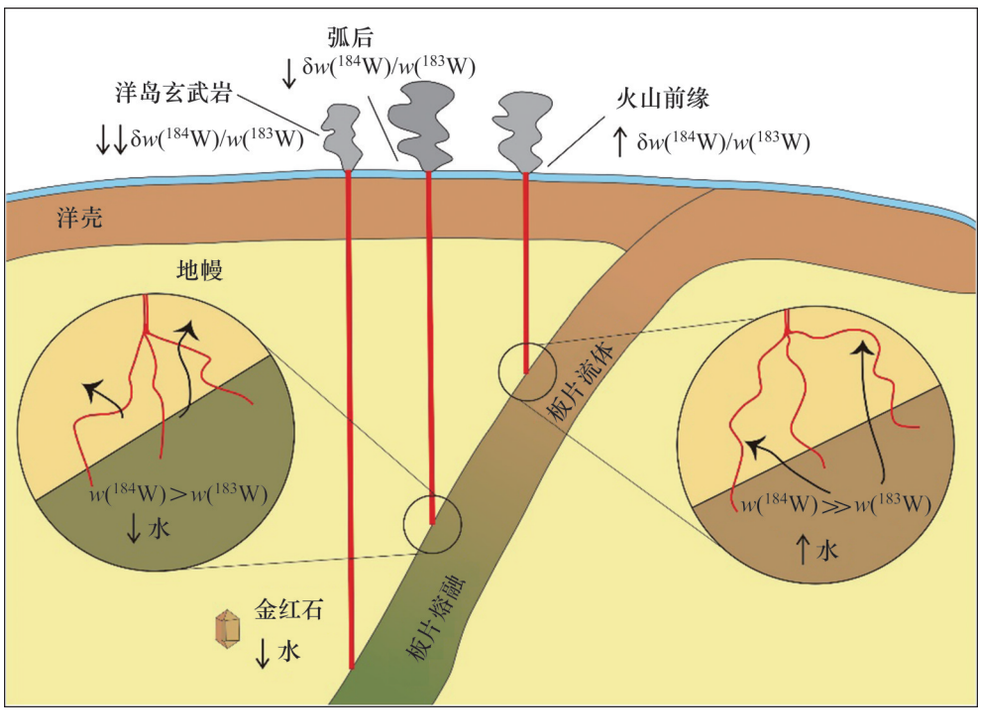


图4 俯冲带中弧岩浆作用脱水过程中 $\delta w(^{184}W)/w(^{183}W)$ 的分馏作用(数据来源于文献[21])

Fig.4 Schematic diagram of a subduction zone displaying $\delta w(^{184}W)/w(^{183}W)$ fractionation corresponding to dehydration in arc magmatism(data sources are from Ref.[21])

钨是氧化还原敏感元素，故其同位素变化可以用于追溯地球演化历史中海洋氧的状态[69]。KURZWEIL 等[71]报道了 $\delta w(^{186}W)/w(^{184}W)$ 变化范围在不同海水深度非常大(+0.347‰~+0.810‰)，指出在地球早期的历史中，从缺氧到富氧的海洋条件的氧化还原环境演变过程中，海水的 $\delta w(^{186}W)/w(^{184}W)$ 持续增加(富氧海水的 $\delta w(^{186}W)/w(^{184}W)$ 平均为+0.54‰)。因此，化学沉积物中可能保存不断变化的海水 W 同位素特征，其稳定同位素组成可能反映了全球海洋氧化还原条件的变化。据此，建立了地球各种储层的稳定 W 同位素组成及其相互关系循环模式(图 5[71])。KURZWEIL 等[5]对波罗的海的腐泥和富锰沉积物开展了 W 同位素分析，发现沉积物的 $\delta w(^{186}W)/w(^{184}W)$ 的变化与锰氧化物的成分及结晶程度有关，而锰氧化物的形成又取决于海洋氧化还原条件的变化，因此，稳定 W 同位素可用于早期地球氧化还原环境的重建。ALAM 等[72]指出，在氧化至亚氧化条件下，海水中 W 同位素不会发生显著分馏，其同位素比值反映了碎屑源区特征。总之，地壳浅部 W 同位素分馏受地球表生环境的控制，水岩作用过程可能对其分馏影响很大，W 同位素对浅层地壳中钨元素的富集循环具有很好的示踪作用，海底沉积岩富重 W 同位素。

4 钨同位素在矿床学中的应用展望

如前所述，钨在地壳和地幔中是一种高度不相容、易迁移、多价态的元素，目前，人们对其在岩浆–热液系统中的地球化学循环演化过程了解并不多。轻钨同位素在更演化的岩浆岩中相对富集，热液和/或岩浆流体对 W 的活化可能伴随同位素分馏[20]。岩石圈地幔具有储存大量 W 的潜力(例如通过富 W 熔体/流体的渗透)，因此，岩石圈地幔可能是地壳中 W 矿化的初始来源[73]。此外，交代流体对 W 的多阶段活化和再富集可能可以完全掩盖原始地球化学信号[68]。尽管目前人们对 W 同位素示踪钨成矿过程的作用了解很少，但通过近年来 W 同位素在岩石地球化学及地球表生作用中的研究成果看，作为直接成矿元素以及氧化还原环境敏感元素，W 同位素将在矿床学的研究中发挥独特而重大的作用，体现在以下 2 个方面。

1) 利用 W 同位素示踪 W 的源区。人们普遍认为钨成矿与地壳重熔型花岗岩有关[74−80]，而由于钨

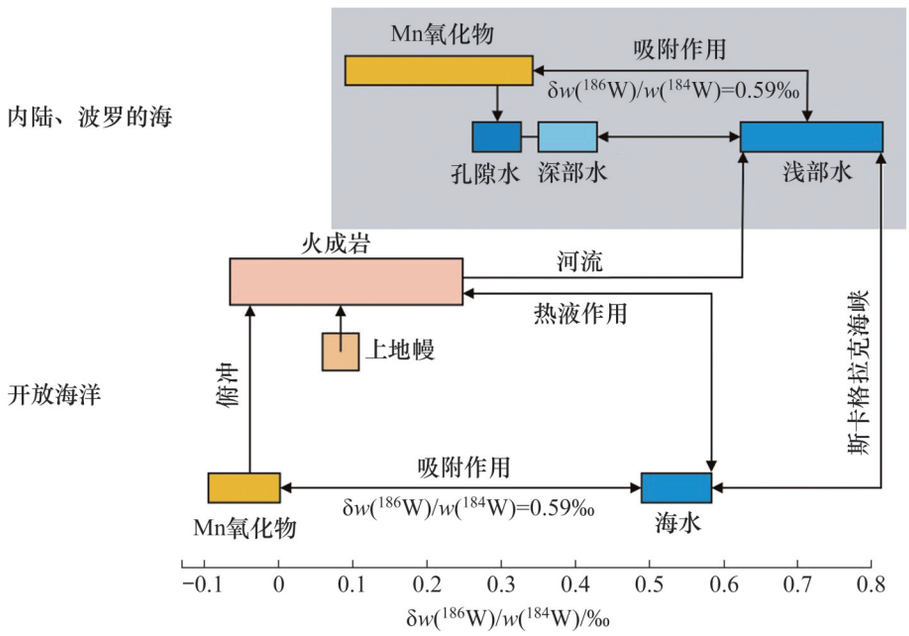


图5　地球各种储层的稳定W同位素组成及其相互关系示意图(据文献[71]修改)

Fig. 5　Stable W isotope compositions of various reservoirs on earth and their interrelations(modified by Ref.[71])

是强不相容元素，所以，在地壳源区局部熔融过程中，钨会倾向富集于熔体中；此外，正因为钨元素与其他元素的强不相容性，钨很难进入岩浆早期结晶矿物中，而是倾向富集于晚期岩浆熔体及出溶流体中，因此，花岗岩全岩或成矿阶段早期含钨矿物(如白钨矿、黑钨矿)可以代表钨源区的同位素组成，可以利用其同位素组成来示踪钨的源区。此外，在一些与花岗岩关系不密切的中低温的钨矿床(如脉状锑金钨矿床)中，研究者[81−85]对钨的来源尚有争议，而W同位素的应用可以从根本上解决钨矿床的成矿物质来源问题。从目前岩石W同位素组成来看，岩石圈不同圈层、源区的W同位素组成有显著差异，因此，在理论上讲，W同位素可用于示踪钨成矿源区，但该方法需通过进一步矿床实例对比进行研究。

2) 利用W同位素反演钨矿床的热液成矿过程。钨矿床中钨的沉淀受诸多因素的控制，包括物化条件的变化(如温度、氧逸度等的变化)[86−92]以及多元流体的混合、沸腾及其与围岩的反应等[93−97]。由于在氧化还原状态(价态+4和+6)和配位(四面体和八面体)变化期间，W同位素可能会发生分馏[46]，因此，在钨矿物结晶生长沉淀过程中，热液流体中的W同位素可能会发生变化，而利用这种变化可以反演不同端元的流体混合以及成矿物化条件变化等精细成矿过程。这种变化已在前人对Sn同位素的研究中得到证实[8, 98]，即在不同阶段，同一矿物间或单颗粒矿物中，不同微区间的Sn同位素组成可能会发生显著的规律性变化。然而，目前这种W同位素分馏机制需要进一步通过钨矿石矿物的精细地球化学研究来证实。

因此，可以预见，未来钨成矿作用过程中的W同位素研究主要集中于示踪及分馏机制的厘定，例如开展不同成矿期、不同成矿带、不同矿床类型花岗岩体及主要含钨矿物(白钨矿、黑钨矿)的W同位素对比研究，探索W同位素在示踪W元素来源方面的作用；进行钨矿物(如白钨矿)的主微量元素、流体包裹体及H-O-Sr-Nd同位素与W同位素的协同耦合研究，厘定热液成矿过程中W同位素分馏的控制因素，进而建立热液矿床W同位素演化模型。中国是产钨大国，拥有全球60%以上的钨资源量，其中，白钨矿资源的储量和开采量均长期居世界首位[78, 99−100]。中国钨矿床主要集中在华南，近年来，在南岭、江南造山带等成矿带钨矿找矿取得重大突破，显示出较大的成矿潜力。华南的钨矿具有成矿时代多期(加里东期、印支期、燕山期)、成矿类型多样(矽卡岩型、石英脉型、斑岩型、云英岩型等)、矿床成因多解(岩浆热液型、非岩浆热液型)等特点[101−105]，且不同钨矿床的壳幔

相互作用程度、成矿物质来源及流体演化过程存在显著差异，是进行W同位素成矿理论研究的理想研究区[74, 106−110]。尽管前人对湖南钨矿床开展了大量卓有成效的研究并提出了多种成矿模式[111−116]，但对于不同时代、不同成矿带钨的物质来源及成矿过程仍有争议，导致钨大规模成矿的根本原因尚待研究。因此，挖掘一种新的能用于准确示踪钨元素超常富集过程的方法迫在眉睫，而W同位素作为直接成矿元素，在揭示地球多圈层相互作用与钨元素富集成矿机制与规律上有着得天独厚的优势。此外，华南钨矿床的矿石矿物白钨矿($CaWO_4$)的矿物晶型、内部结构、主微量元素、流体包裹体等特征变化多样[76−77, 92, 117−119]，含有丰富的关于成矿物质来源、流体成分、成矿物化条件等可能引起W同位素组分变化的关键信息。因此，将白钨矿微区W同位素的分析与其地球化学特征分析结合起来，探讨白钨矿结晶过程中W同位素组成变化与流体成分及物化环境之间的耦合关系，可以厘定热液演化过程中W同位素的分馏控制因素，进而建立W同位素示踪模型。总之，通过对中国华南钨矿床W同位素的研究有望获取不同地质历史时期、不同区域钨来源的“指纹”信息，揭示钨元素在地球各圈层的地球化学循环过程及其超常聚集行为，进而建立一套利用W同位素示踪大规模钨成矿作用的方法。

5 结论

1) 钨(W)同位素是一种新兴的非传统稳定同位素，其在示踪天体演化及地球表生过程中发挥着重要作用，然而，目前，人们对钨成矿过程中W同位素的分馏机制尚不清楚，其示踪复杂成矿过程的潜力亟待挖掘。目前亟需将W同位素的理论与方法引入矿床学的研究中，建立W同位素示踪成矿物质来源的方法及钨成矿系统的W同位素演化模型。

2) 通过对矿床学中W同位素进行研究，揭示壳幔相互作用及多阶段钨成矿过程中成矿物质来源的“指纹”信息，有利于了解地质背景、物质基础和重大地质事件联合控制下钨矿床时空分布规律，促进人们对岩浆/流体性质和物理化学条件控制下钨元素源—运—聚过程的理解，为战略金属超常富集成矿理论的建立及元素驱动机制的研究提供全新思路。

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