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地球科学对人类文明发展的贡献专题 观 点
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地球化学对人类文明的贡献

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地球化学始于社会经济发展对矿产资源开采的新要求. 19世纪是地球化学学科的孕育期, 瑞士化学家舍恩拜因于1838年提出“Geochemistry”一词; 之后分析技术的发展、元素周期律的发现以及原子结构理论的重大突破, 为地球化学学科形成奠定了坚实基础. 20世纪是地球化学学科的形成和发展期, 随着学科体系的建立和完善, 特别是得益于元素和同位素分析仪器的快速发展, 地球化学研究不仅提升了人类对地球系统运行规律的认识, 而且其理论和方法极大推动了地球资源能源的探测与评估以及生态环境安全的建设.



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李献华 中国科学院院士, 现任中国矿物岩石地球化学学会和中国计量测试学会副理事长. 主要从事同位素年代学和地球化学研究以及微区同位素分析技术研发与应用. 曾获国家自然科学二等奖(R2)和何梁何利科技进步奖.

1 提升了人类对地球系统运行规律的准确认识

人们借助地球化学工具, 对地球系统运行规律的认识越来越深入, 主要体现在四个方面, 包括早期地球和月球的形成演化, 地球内部圈层物质组成和相互作用, 地球内部与表层系统间物质循环, 以及地表系统气候变化和生物演化等, 它们的时空框架, 具体过程和动力机制不断完善.

“地球年龄”是自17世纪以来长期悬而未决的难题. 直至20世纪, 地球化学家研发的铅同位素定年技术才将地球年龄精确限定为4.56 Ga[1], 从而解决了持续两百余年的争论, 并为理解地球早期形成过程及其在太阳系中的独特性提供了时间框架[2]. 2024年, Zhang等人[3]基于嫦娥六号月球样品, 通过同位素定年技术揭示着陆区28亿年前还存在火山活动. 其中高铝玄武岩岩屑具嵌晶结构, 同位素年代数据显示喷发时代距今约42亿年, 是迄今月壤返回样品中发现的最古老玄武岩, 指示月球背面火山活动至少持续了14亿年. Cui等人[4] (2024)对3.5 g月壤中玄武岩岩屑内微小含锆矿物(<5 μm)和斜长石以及晚期填隙物开展同位素分析, 确定该低钛玄武岩形成于28.3亿年前的火山喷发, 证实月球背面与正面同样存在年轻的岩浆活动. 这些新的同位素年代学数据填补了月球撞击历史研究中32~20亿年间的样品标定空白, 更新了传统的撞击坑统计定年曲线, 揭示月球经历早期高频小天体撞击后, 于28.3亿年前达到整体稳定状态. 科学家基于陨石和锆石同位素分析, 重建了地球分异与月球形成等关键地质事件的时间节点, 为对比研究地球与其他类地行星的形成演化提供了关键依据[3~6].

地球内部主要边界(如壳-幔和幔-核边界)的物质组成和动力学行为是地球化学研究的核心课题. 元素地球化学和放

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射性同位素示踪技术为这些关键区域的研究提供了直接证据. 例如, 稀有气体同位素(如$^3He/^4He$)组成和高温高压实验揭示了深部地幔与外核之间存在化学交换[7,8]; Hf-W同位素系统研究显示, 外核中铁的部分迁移可能导致地幔出现局部化学异常[9]. 放射性同位素(如Sm-Nd和Lu-Hf)研究限定了地幔分异形成原始大陆地壳的时间约为3.8~4.0 Ga. 玄武岩中主量元素(如Mg、Si、Fe)、微量元素(如稀土元素; REE)和稀有气体(如He、Ar)的含量变化揭示了壳-幔间的化学分异过程[10,11]; Sm-Nd同位素系统进一步刻画了地幔分异的时空结构, 为壳-幔物质循环提供了定量约束[12,13]. 大陆碰撞造山带同碰撞中-酸性岩浆岩与大陆地壳具有相似的主微量元素和Sr-Nd同位素组成, 表明与碰撞相关的岩浆作用可能是陆壳生长的重要机制[14,15]. 全岩主量元素(如K_2O)与锆石O-Hf同位素显示, 弧岩浆系统中富角闪石(超)镁铁质堆晶岩的重熔和后续壳内演化可能是陆壳垂向成分分层的重要机制[16]. 全岩地球化学与Sr-Nd-Pb-Os同位素证据进一步表明, 碰撞造山过程中地壳加厚可引起岩石圈增厚, 促使基性下地壳发生榴辉岩化, 并在碰撞后发生拆沉或去根作用, 从而推动大陆地壳向长英质组分演化[17,18]. 这些认识为构建更完善的地球深部动力学模型奠定了基础.

在揭示地球内部与表层系统间物质循环和动力学过程中, 地球化学亦发挥了关键作用. 例如: Sr同位素广泛应用于示踪河流沉积物来源, 结果表明大量陆源碎屑通过河流输入海洋, 进而影响了全球碳酸盐沉积格局[19]. 全岩Sr-Nd-Re-Os同位素、锆石Hf-O同位素以及其他地球化学指标记录了洋壳与陆壳在深俯冲过程中经历了脱水、变质和部分熔融等过程, 所产生的流体或熔体交代上覆地幔楔, 从而为弧岩浆的形成创造了有利条件[20]. 同碰撞及碰撞后镁铁-超镁铁质岩浆岩的元素和同位素地球化学组成揭示了深俯冲陆壳[21,22]或洋壳物质[23,24]的再循环过程. 不相容元素比值(如Nb/Ta、Nb/Zr、Ti/Eu及$(La/Yb)_N$等)和Li-Sr-Nd-Hf等同位素可进一步判别地幔源区中交代介质的属性(如富水流体、硅酸盐熔体或碳酸盐熔体[25,26]), 识别是否有陆源或远洋沉积物的加入[27]. 俯冲流体中微量元素分配系数研究表明, 俯冲流体可携带大量大离子亲石元素(LILE)、亲铜元素和轻稀土元素(LREE)进入地幔楔, 并提高其氧逸度, 可能为弧岩浆系统提供重要物质基础与成矿条件[28,29]. 近年来, 金属稳定同位素的应用更进一步揭示了地球深部圈层物质循环、及其与浅部生态-环境效应等之间的内部关系.

在此基础上, 地球化学研究进一步推动重建了地表系统气候变化和生物演化、及其对重大地质事件响应[30]. 例如, 通过检测沉积物中硫同位素非质量分馏信号, 识别出约24~23亿年前大气氧含量急剧上升的直接标志, 为大氧化事件成因提供了关键证据[31,32]. 碳同位素记录揭示了二叠-三叠纪之交生物大灭绝期间大气二氧化碳浓度的急剧升高[33]; 通过碳酸盐岩和植物化石碳同位素的分析进一步表明, 该时期大规模火山活动和强烈温室效应导致全球生态系统崩溃[34,35]. 氧同位素分析揭示了地球冰期-间冰期旋回的气候变化规律[36]; 通过对海洋沉积物与冰芯中氧同位素比值的测定, 重建了数十万年以来温度波动和冰川进退历史, 为理解气候系统长期演化提供了关键线索[37]. 近年来, 硼同位素因其对水-岩相互作用的敏感性, 成为重建古海洋pH变化的重要指标, 为揭示海洋碳酸盐系统与大气CO_2浓度关系提供了新视角[38,39]. 此外, 碳、氮等同位素在大气化学研究中的应用, 为理解现代气候变化机制提供了关键约束[40].

2 推动了人类对资源能源的探测与评估

资源能源是人类文明发展的物质基石, 其探测与评估历来是地球科学的终极命题之一. 地球化学凭借其定量表征特征, 能解析地球化学组成、化学作用和化学演化, 可系统揭示资源能源的形成机理和时空分布规律, 并最终指引勘探方向与潜力评价.

2.1 矿产资源探测与评估

成矿模型是对特定矿床类型形成地质背景、控制因素、成因机制和时空分布规律的概括与抽象. 地球化学理论方法揭示的成矿元素源、运、聚过程和条件, 是构建和验证成矿模型的关键. 它以元素地球化学和同位素地球化学为双眼, 洞察成矿物质的来源与旅程; 以成矿年代学为时间标尺, 厘定成矿事件与重大地质事件的关系; 以实验地球化学为手段, 复现与验证成矿过程. 所有这些知识的结晶, 最终凝聚成能够深刻反映地质客观规律的成矿模型, 例如俯冲型斑岩成矿模型[41]、碰撞型斑岩成矿模型[42,43]、陆内成矿模型[44,45]、地幔柱成矿模型[46]、MVT矿床成矿模型[47]、SEDEX矿床成矿模型[48]、VMS矿床成矿模型[49]、造山型金矿成矿模型[50]和卡林型金矿成矿模型[51]等. 从这些模型中提炼出的源区特征、元素分带、蚀变分带、元素组合和矿床组合等标志性地球化学指纹, 如同精准的导航图直接指导着从宏观选区到矿体定位的找矿勘查过程. 例如, 20世纪80年代以来, 在扬子地块西南缘滇黔桂接壤区的右江盆地, 接二连三地找到了一系列卡林型金矿床, 关键是运用了在低温条件下Au可以与Hg、Sb、As等元素密切共生的原理, 而找金是在已知的Hg、Sb、As矿田或矿带中进行的, 这就大大提高了找矿效率[52]. 再如, 同位素数据的持续积累, 已推动部分地质单元实现同位素填图. 相关成果揭示, 深部物质架构对不同类型矿床的形成具有重要控制作用, 对找矿战略选区具有重要意义[53]. 显而易见, 在新区勘查时, 通过对比未知异常与已知模型的地球化学指纹, 可快速进行矿床类型类比与远景判定, 缩小找矿靶区, 实现找矿突破.

成矿模型中关于不同矿床类型具有不同成矿元素组合的认识, 是勘查地球化学的基础[52]. 在区域尺度, 利用水系沉积物、土壤或岩石地球化学测量, 圈定元素异常区, 可以从

广袤地区中快速筛选出最有潜力的勘查靶区[54]; 在靶区内部, 通过加密采样, 分析元素分带序列、蚀变矿物地球化学等的空间变化, 可以推断深部矿体的可能类型, 并初步评估矿化强度与规模[54]; 对于覆盖区或深部找矿, 地球化学方法更具优势. 深穿透地球化学和植物地球化学等方法, 能够探测来自深部矿体的微弱但可识别的化学信号而指导找矿[55]. 同时, 对勘查钻孔岩芯进行系统的元素与同位素剖面分析, 可以建立三维地球化学模型, 精准预测盲矿体的位置与延伸.

成矿模型是找矿勘查的基石, 成矿后矿床保存条件的确定对找矿勘查亦同等重要. 矿床形成后, 能否保存至今并被发现, 取决于其经受的隆升、剥蚀、埋藏等后期地质改造历史. 低温热年代学技术, 如磷灰石/锆石裂变径迹(AFT/ZFT)和(U-Th)/He定年, 通过记录矿物在较低温度区间(约60~300 ℃)的冷却史, 能够定量反演矿床所在地块的隆升剥蚀速率与时间, 从而评价矿床保存的完整性与剥露程度, 判断矿体是已接近剥蚀殆尽还是仍深埋地下, 从而为勘查靶区优选和钻孔深度设计提供关键约束[56]. 例如, 华南中生代成矿大爆发, 形成西部低温金锑和东部高温钨锡两个成矿省, 它们历来被认为是两个独立的成矿系统. 最近研究发现, 它们实为上部低温矿下部高温矿的同一成矿系统, 成矿后自西向东剥蚀程度的增强, 导致了目前西部低温东部高温矿的空间分布格局, 据此预测西部低温成矿省的深部应存在高温钨锡矿, 从而为深部找矿指明了新方向[57].

元素的赋存状态, 也是地球化学的主要研究内容之一. 元素在矿石中以何种物相、价态、化合物形式存在, 以及在矿物中如何分布(如类质同象、吸附态、独立矿物、包裹体等), 是确定矿产资源如何高效利用的关键环节, 直接决定了选矿工艺路线与回收率[58,59]. 它是矿石从“地质资源”转化为“工业原料”的技术瓶颈与价值开关. 例如, 石英具有低Ti、低Al、低Li的特征, 是高品质高纯石英勘查和资源评价的关键工业指标. 在矿床开采前, 必须借助先进观测技术, 系统研究其赋存状态, 以准确预测选冶难度、估算经济成本、设计合理流程, 并判断共伴生元素的综合利用潜力, 最终实现矿产资源的经济、高效、清洁利用.

2.2 油气探测与评估

地球化学在油气勘探与开发过程中也发挥着关键作用, 为油气来源、成因及演化历史研究提供了重要理论支撑. 油气成藏以优质烃源岩为前提条件, 即所谓的“源控论”, 而烃源岩评价和油源对比均依赖于有机地球化学分析技术[60]. 烃源岩评价的核心在于有机质丰度、类型和成熟度的系统表征. 总有机碳含量(TOC)、氯仿沥青“A”及生烃潜量(S_1S_2)被广泛用于定量评价有机质丰度, 目前烃源岩有机质丰度的下限和分级标准已形成成熟体系[61]. 干酪根显微组分分析与岩石热解法可有效判别有机质类型, 为评价生烃潜力提供依据[62]. 镜质组反射率(R_o)和最大热解峰温(T_{max})是表征有机质热成熟度的重要指标, 它们与热演化阶段的对应关系可有效识别烃源岩的生烃演化阶段[63]. 在油源对比中, 分子生物标志化合物具有关键指示意义. 如: 正构烷烃的碳优势指数(CPI)与奇偶优势指数(OEP)可反映烃类的母质来源与成熟度[64]; C_{27}-C_{28}-C_{29}规则甾烷可精确指示生烃母质类型[65]; 在萜烷系列中, 姥鲛烷/植烷(Pr/Ph)比值常反映沉积环境的氧化还原状态, 伽马蜡烷指示水体盐度, Ts/Tm比值则与有机质成熟度相关[66].

地球化学指标是判别油气成因的关键依据, 通过分析油气分子组成、同位素特征, 以及环境响应参数, 可准确揭示其成因类型、形成环境和演化机制. 对于天然气, 碳同位素组成是区分有机与无机成因的核心指标[67]. 结合天然气组分与烷烃气碳氢同位素, 可进一步判别干酪根裂解气、油型气或者混合气, 并明确其成熟度[68]. 针对富氦等特殊天然气, 稀有气体同位素($^3He/^4He$、$^{40}Ar/^{36}Ar$)与烃类气体同位素的联合运用有助于厘清其来源[69]; 在多套烃源岩发育区, 碳同位素序列与非烃气体组成分析可用于细分不同气源的贡献[70]. 对于原油, 生物标志化合物(如萜烷、甾烷、芳烃)可揭示母质输入与沉积环境[66], 结合轻烃(C_5~C_9)组成可进一步指示原油的次生变化与成熟度[71]. 咸化沉积环境可通过盐度敏感参数(硼(B)含量、B/Ga、Sr/Ba)进行分析[72]; 水体氧化还原条件则可借助U、V、Mo、Cr、Co等敏感元素进行判别[73], 其中Mo与U的富集系数(Mo-EF、U-EF)广泛用于区分海洋水体的次氧化、还原与硫化环境, 并在古海洋环境重建中取得显著成效[74]. 此外, 喜湿元素Cu与喜干元素Sr的比值(Sr/Cu)可灵敏反映古气候特征, 低Sr/Cu值通常指示温暖湿润气候条件[75].

在油气成藏研究中, 地球化学方法是确定油气生成、运移和聚集等关键阶段及成因来源的核心手段, 其发展呈现出从定性到微观定量、从间接推断到直接定年的趋势[76]. 对于成藏期次定性分析, 基于“生-储-盖-圈-运-保”要素耦合的研究思路, 形成了烃源岩生排烃法、圈闭形成时间法等传统方法[77]. 此类方法在构造简单、充注单一的浅埋藏单旋回盆地中效果显著, 能够有效实现地球化学特征与成藏要素的耦合验证. 20世纪90年代后, 流体包裹体微观地球化学技术推动成藏研究向精细化发展, 通过烃类包裹体荧光特征、共生盐水包裹体均一温度与盐度等参数, 结合盆地埋藏-热史分析, 可限定油气充注的地球化学环境与关键时期[78]. 然而, 受古地温重建不确定性、埋藏史复杂性, 以及均一温度多解性等因素影响[79], 该方法难以精确确定成藏时代. 放射性同位素地球化学定年技术的发展, 实现了成藏时代的定量表征[76], 其研究主要围绕自生矿物与有机质两类载体的同位素分析展开: 自生伊利石K-Ar定年[80], 石英流体包裹体Ar-Ar定年, 以及钾长石加大边Ar-Ar定年, 在定量确定油气充注时代方面取得良好效果[81]. 随着激光原位测试技术的进步[82], 激光原位方解石U-Pb定年在分析盆地流体活动和成藏过程方面

展现出广阔前景. 对于原生油气藏, 利用Re、Os亲有机质的特性, 原油与沥青的Re-Os同位素定年可直接约束油气藏的形成时代, 在定量揭示油气藏演化历史方面具有重要作用[83].

基于前述分析, 地球化学研究显著深化了对成矿元素在岩石圈中迁移与富集机制以及油气成藏从分子至盆地尺度演化规律的认识. 这些进展持续推动了传统成矿、成藏理论的修正乃至重构, 为矿产与油气资源的勘探提供了新的研究思路与技术支撑. 随着机器学习与大数据建模方法的引入, 构建集地质、地球化学与地球物理信息“三位一体”的成岩-成矿(成藏)模型, 将可有效降低勘探成本与风险, 并显著提升资源能源勘探效率.

3 支撑了生态环境管理和人类可持续发展

地球化学在维护生态环境安全与推动人类文明可持续发展中发挥着关键作用. 一方面, 通过构建关键生命元素的同位素示踪体系与化学计量学理论, 地球化学为理解地球生态环境演变提供了重要科学依据; 另一方面, 系统阐明了有机污染物与重金属等的地球化学行为, 为保障地球环境系统与人类“同一健康”提供了理论与技术支撑.

C-H-O-N-S等同位素示踪体系极大深化了地表物质循环及其与生态环境演变关系的认识. 氢、氧稳定同位素不仅可用于识别水源、解析水循环过程, 还记录了古水文气候信息, 为反演全球降水格局, 以及大气环流对气候变化的响应提供依据[84]. 碳同位素在区分化石燃料排放与生态系统碳收支方面具有重要作用[85]; 叶片碳同位素可有效判别C_3与C_4植物光合途径, 并定量估算水分利用效率[86], 其组合特征进一步揭示了植被群落演化趋势与古生态环境演变[87]. 土壤碳同位素为古植被重建和古人类活动历史研究提供关键线索, 树轮碳同位素则实现了对树木水分利用效率与生长历史的长期反演[88]. 氮同位素在评估区域乃至全球尺度氮循环动态方面具有独特优势, 特别是通过铵-硝氮同位素配对标记与数值模型, 可量化土壤氮转化速率; 结合N_2O氮同位素异构体位差分析, 能够有效区分不同来源的N_2O生成路径, 为温室气体减排提供科学依据[89]. 近年来, 氮氧同位素方法在植物氮利用机制解析、碳氮代谢耦合研究[90], 以及大气活性氮来源识别方面取得重要进展, 为制定氮污染控制策略与评估生态效应提供了新证据[91]. 大气硝酸根氮氧同位素研究进一步揭示了海洋微生物排放对大气氮氧化物的贡献, 填补了海气交换通量估算的空白[92]. 硫同位素非质量分馏效应是识别硫源, 及其转化过程的独特地球化学指纹, 在揭示大气酸度、工业活动以及气候变暖等影响硫酸盐来源与生成机制方面具有重要作用[93]. 此外, $\Delta^{17}O$为示踪大气含氧物种生成与地表过程提供了新手段[94]. 多同位素联用技术进一步推动了地球氧气起源与演化历史的研究. 碳同位素揭示了有机碳埋藏与碳循环, 并阐明了氧气动态积累过程; 硫同位素记录了大氧化事件的时间与强度[95]; 沉积磷酸盐与碳酸盐岩氧同位素则揭示了风化作用与氧气上升的关联[96]; 氮同位素正异常为大氧化期间硝酸盐积累与生物有效氮增加提供了关键证据[97].

生态化学计量学通过研究碳、氮、磷等元素的比率关系, 为理解土壤-植物-水体系统的元素循环与生态过程提供了新框架. 该理论系统阐述了陆地生态系统中氮、磷限制对碳汇能力的调控机制, 并为评估植物氮磷利用效率、凋落物分解, 以及改进碳汇预测模型提供了依据[98]. 研究还发现, 高物种多样性有助于优化生态系统化学计量平衡, 从而提升系统功能[99]. 此外, 化学计量理论揭示了植物入侵的元素策略机制, 即外来种通过差异化养分利用改变土壤循环以获得竞争优势[100]. 在水生系统中, 人为氮磷输入破坏水体化学计量平衡, 引发富营养化[101]. 针对治理策略, 学界存在“控磷为主”与“氮磷协同控制”之争[102]. 近年研究表明, 湖泊对氮、磷的截留效率存在差异, 高营养状态下氮更易释放, 可能加剧下游藻华风险[103]. 因此, 化学计量学为统筹制定水体富营养化治理与陆地生态保护策略提供了科学依据.

高分辨率质谱技术的进步, 提升了溶解有机质的分子结构识别与降解机制解析, 明确了其在全球碳循环中的关键地位[104]. 通过检测解析大气中有机磷酸酯(OPEs)及其转化产物, 发现其来源不仅包括直接排放, 水相二次生成的贡献亦显著[105]. 单体同位素技术在农药、药品, 以及消毒副产物迁移转化研究中也广泛应用[106]. 例如, ^{13}C标记揭示了塑料聚合物在土壤中的生物降解路径[107], 生物标志物$\delta^{13}C$则系统揭示了陆源有机碳由河流至海洋的降解过程与碳汇效应[108]. 气溶胶单体分子^{14}C证实了中国大气二次有机气溶胶中化石源碳的贡献[109], 而受体模型与单体氮同位素结合则实现了大气有机氮来源的精准量化[110]. 重金属同位素体系在识别地方病成因、追踪食物链传递, 及评估健康风险方面具有突出价值. 铅、镉、汞等长期暴露可干扰细胞功能, 甚至诱发疾病. 20世纪20年代含铅汽油的应用导致全球铅污染与健康威胁, 最终通过地球化学研究推动全球禁令. 近年来, 铁、镁、铜、锌等金属同位素分析方法的完善为环境重金属溯源奠定基础[111]. 铅同位素揭示矿区废弃物是人体铅暴露的重要来源[112]; 镉同位素研究表明“土壤-水稻-人体”系统中^{66}Cd优先富集[113]; 汞同位素证实鱼类消费是人体汞暴露主要途径, 并指出摄食低营养级鱼类可降低风险[114].

放射性同位素作为“计时器”与“示踪剂”, 在诊断人类核活动对海洋环境影响方面不可替代. 碘-129(半衰期15.7 Ma)是核泄漏事件的关键示踪核素[115]. 2022年, Zhang等人[116]通过分析中国南海的碘-129与$^{129}I/^{127}I$比值, 揭示其主要源自全球核武器试验沉降及欧洲后处理厂排放, 表明区域海洋已受全球核活动深远影响. 钚同位素(^{239}Pu, ^{240}Pu)是追溯核爆炸历史的经典工具, 2021年Cao等人[117]通过建立中国海域钚数据库, 识别出太平洋试验场沉降为主要来源. 近年来, 铀-236(半衰期23.4 Ma)作为新兴示踪剂, 与钚同位素联用可提升源解析精度[118]. 中国近海铀-236分布研究正逐步完善亚太地区

核活动历史档案[119].

地球化学学科历经百余年的建设和发展, 在多个领域取得重大成果, 保障并推动了人类文明发展. 展望未来, 人们对地球(含天体)的演化历史仍然有很多未解之谜, 对地球的未来命运有很多期待, 探测地外行星、探寻地外生命方兴未艾, 地缘政治冲突、全球灾难频发, 危及人类生存与健康. 地球化学学科应勇担重任, 发展新理论新技术, 定量化研究复杂地质作用, 精细揭示地球和行星的组成和时空演化, 破解资源能源和生态环境等制约人类社会高质量发展的瓶颈问题.

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Summary for “地球化学对人类文明的贡献”

The contribution of geochemistry to human civilization

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Geochemistry, through the quantitative study of the chemical composition, processes, and evolution of the Earth and the other planets, has made indispensable contributions to human civilization across three fundamental dimensions. Firstly, geochemistry has profoundly advanced our understanding of the Earth system processes, establishing a relatively precise temporal framework for understanding our planet’s history and evolution. Isotopic dating techniques have precisely determined the age of the Earth at 4.56 Ga, resolving a centuries-old scientific debate. Furthermore, high-precision analyses of Chang’e-6 lunar samples have revealed volcanic activity on the lunar farside as young as 2.83 billion years and identified the oldest basalts at 4.2 billion years, which significantly updates the chronology of lunar evolution and provides new insights into the thermal history of the planetary bodies. Through systematic elemental and isotopic analyses, geochemistry has not only deciphered the differentiation, interactions, and deep material cycling within the Earth’s interior, including the crust, mantle, and core, but also reconstructed critical environmental and climatic events that have shaped our world, such as the Great Oxidation Event, glacial-interglacial cycles, and mass extinctions, and thereby providing essential evidence for understanding the evolution of Earth’s habitability and the co-evolution of life and the planet. Secondly, geochemistry serves as a cornerstone for resource and energy exploration, directly supporting industrial development and economic growth. In critical mineral exploration, the new mineralization models based on geochemical principles, in combination with elemental assemblages and isotopic fingerprints, directly resulted in breakthroughs in prospecting and reduced exploration risk. Low-temperature thermochronology quantitatively assesses the preservation conditions and exhumation history of ore deposits, while detailed research on the speciation and distribution of elements ensures efficient resource utilization and processing. In petroleum geology, comprehensive organic geochemical indicators are routinely used to determine hydrocarbon genesis and migration pathways. Furthermore, the application of fluid inclusion analysis and advanced isotopic dating techniques, such as Re-Os and U-Pb, has enabled a paradigm shift from qualitative inference to quantitative determination in terms of the time, temperature, and processes of hydrocarbon accumulation, significantly enhancing exploration efficiency and success rates in complex geological settings. Thirdly, geochemistry provides robust support for ecological environmental protection and human health, addressing contemporary challenges related to pollution and sustainability. Stable isotope tracer systems, including those of carbon, hydrogen, oxygen, nitrogen, and sulfur, elucidate surface material cycles, track pollutant sources, and quantify their response to climate change and anthropogenic activities. Ecological stoichiometry offers a conceptual framework for understanding elemental balance and nutrient limitations in terrestrial and aquatic ecosystems, guiding effective management strategies. Heavy metal isotope tracing techniques, such as lead, cadmium, and mercury isotopes, effectively track the transfer pathways and transformations of toxic pollutants through the “soil-biota-human” chain, thereby supporting accurate health risk assessments and regulatory decisions. Additionally, radioactive isotopes (e.g., iodine and plutonium isotopes) serve as crucial tracers, playing an irreplaceable role in diagnosing the transport, distribution, and far-reaching impacts of human nuclear activities on the marine environment, from nuclear weapons testing to accidental releases.

geochemistry, human civilization, Earth system, resources and energy, ecological environment

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