

金矿立体地球化学探测模型与深部钻探验证

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摘要: 深部资源地球化学探测科学问题的焦点是元素大深度垂向迁移机理和立体地球化学探测模型的建立。本文以胶东蚀变岩型金矿和贵州水银洞卡林型金矿钻孔岩芯和地表联合取样获得的数据, 建立千米深度立体地球化学探测模型。蚀变岩型金矿立体地球化学模型显示, Au、S 和 Hg 与金矿密切相关, 分布模式既有相似性又有差异性, Au 的立体几何分布模式兼具矿化剂元素 S 和远程指示元素 Hg 的双重特征, 金异常和矿化剂元素硫与矿体倾斜方向一致, 反映了成矿过程中流体沿控矿构造的轴向运移; 金异常与类气体元素汞在垂向上一致, 而且出现从矿体到地表的连续贯通式异常, 反映了流体沿微裂隙和纳米孔的垂向迁移。卡林型金矿立体地球化学模型显示, Au、As、Sb、Hg、Tl 和 S 在不整合面都显示高含量特征, 与深部层状主矿体分布一致; 在矿体上覆地层中都存在弱异常, 显示了明显的成矿流体沿隐伏微小断裂垂向迁移特点; 所不同的是 Sb 和 Tl 元素在不整合面附近显示了最高的元素含量, 而 Sb 和 Hg 在近地表均显示了明显高的异常特征。立体几何模型清晰地显示了矿体的展布特征和范围, 而且金及其伴生元素垂向迁移在地表形成清晰异常, 为利用金及伴生元素和矿化剂元素进行深部矿体三维预测提供了重要依据, 对指导深部金矿勘查发挥了重要作用。针对胶东蚀变岩型金矿地表完全被土壤覆盖区的穿透性地球化学微细粒级土壤采样, 金属活动态提取分析圈定的异常, 经深部钻探验证, 胶东焦家成矿带五一村 3200 m 钻探, 在 2428.00~3234.16 m 深度发现 6 层矿化体, 其中高品位矿体位于 2854 m 深度; 上宫金矿地表基岩出露, 采集断层泥或裂隙岩石样品, 可以清晰探测深部异常, 经 2000 m 钻探, 在 1312 m 处发现高品位金铅锌银矿体; 贵州水银洞采集地表细粒级土壤, 能够直接有效地揭示深部金矿体, 经 500~1500 m 钻探验证, 在 300~1500 m 深度新增金资源量 203 t。

关键词: 地球化学; 立体探测; 钻探验证; 深部金矿发现

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Three-dimension Geochemical Patterns of Gold Deposits: Implications for the Discovery of Deep-seated Orebodies

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Abstract: The research on geochemical exploration for deep-seated ore deposits in covered terrains is centralized on understanding of long-distance vertical migration of mineralization and associated elements and 3D geochemical patterns. This paper provides an insight into 3D metal dispersion patterns of the buried gold ore deposits by sampling drill core rocks and surface soils. The 3D geometric pattern of the alteration type gold deposit in Jiaodong shows that the highest values of Au, S and Hg are in good correlation with the gold orebody, suggesting that the fluids migrated during the process of gold mineralization formation along the hosting fault channels, whereas Au and Hg exhibit vertical anomalies from the deep-seated orebody to the surface, implying that the elements with vertical dispersion of fluids were permeable upwards through the microfractures or rock pores, as supported by finding nanometer-sized particles of gold in wall rock microfractures. The 3D geometric pattern of the Carlin-type gold deposits in Guizhou shows that high values of Au, As, Sb, Hg, Tl and S are enriched in unconformity, which controls the distribution of deep-seated layer-bedded gold orebody, whereas anomalies of Sb, Hg and Au occur at the surface, implying vertical migration through the microfractures of the wall rocks. The geochemical patterns provide predicting methodology for the deep-seated orebody. A deep-seated orebody was discovered in the depths of 2428~3234 m by followup drilling exploration in the soil covered locations of gold anomalies delineated by fine-fraction soil sampling at Wujiashuang of Jiaodong. An orebody of Au-Ag-Pb-Zn at a depth of 1312 m was discovered by drilling exploration based on fault gouge sampling at Shangong, Henan. A reserve of 203 tones of gold in the depths of 300~1500 m was discovered according to the targets delineated by geochemical sampling of fine-fraction soils at Shuiyindong of Guizhou Province.

Key words: geochemistry; 3D geochemical pattern; drilling verification; deep-drilling exploration

传统地球化学勘查, 由于建立了较为完善的理论方法技术体系以及大规模计划的实施, 在浅表矿找矿中发挥了巨大作用(奚小环, 2003; 谢学锦等, 2009; 王学求, 2013, 2016)。但对深部找矿和覆盖区找矿, 地球化学勘查理论和技术都在不断探索和发展中。自 20 世纪 90 年代开始, 在国内外诞生了深穿透地球化学(Deep-penetrating Geochemistry)(王学求, 1998; Cameron, 1998; Hamilton et al., 2001; 谢学锦和王学求, 2003; Cameron et al., 2004; Anand and Butt, 2010), 并取得了理论技术重大突破和显著找矿应用效果。理论突破主要体现在针对迁移机理的研究发表了大量论文, 根据近 5 年国际主要有关勘查地球化学论文统计, 有关超微细和纳米地球化学技术、选择性化学提取技术和植物地球化学技术发表的文献最多, 分别占比 14%、9%、6%, 其中纳米地球化学和生物地球化学在机理研究上取得的突破最为显著(Wang et al., 1997; Houghet al., 2008, 2011; Cao et al., 2009, 2010a, b; 王学求和叶荣, 2010; Cao, 2011; Deditius et al., 2011; Fairbrother et al., 2012; van Geffen et al., 2012; Wakelin et al., 2012; 叶荣等, 2012; 王学求等, 2012, 2016; Reith et al., 2012, 2013; Lintern et al., 2013; Leslie et al., 2013; Wei et al., 2013; Anand et al., 2014; Dai et al., 2015; Dunn et al., 2015; Luo et al., 2015; Zhang et al., 2015;

Zhang and Wang, 2016; Wang et al., 2016, 2017; 张必敏和王学求, 2018; Hu and Cao, 2019; Jiang et al., 2019; Liu et al., 2019, 2020; Zhang et al., 2019)。中国近几年最大理论进展是发现铜、金等纳米金属晶体(Wang et al., 2016, 2017), 证明来自于深部隐伏矿体, 为深部找矿地球化学理论提供了直接微观证据, 澳大利亚的最大理论进展是利用微区扫描技术对植物吸收元素机理进行了微观研究, 发现植物不同器官对不同元素的吸收是不同的(Anand et al., 2007; Fairbrother et al., 2012)。技术突破主要体现在专利上, 全球诞生专利数 2000 余项, 其中美国占专利总数 28%, 中国仅次于美国占专利总数的 17%, 国际上主要由澳大利亚、中国、美国和加拿大带动该领域的发展, 中国与澳大利亚处于相对领先地位。从找矿案例报道来看, 澳大利亚发明的活动金属离子法和生物地球化学测量技术, 有 100 多个成功找矿案例(Lech et al., 2008), 该技术成为目前最成功的一项穿透性地球化学勘查技术。中国微细粒(纳米)地球化学测量、金属活动态提取技术、地电化学技术等在中国应用较多, 效果明显, 已取得多个覆盖区和深部找矿成功案例(Wang et al., 1995, 2003, 2007, 2011, 2016; 刘大文等, 1999; Williams et al., 2002; 谢学锦和王学求, 2003; Luo et al., 2008; 王学

求和叶荣, 2011; 王学求等, 2012a, b, 2014; 姚文生等, 2012; 张必敏等, 2016; 徐善法等, 2017; 张必敏和王学求, 2018; Zhang et al., 2020)。但如何将地表采样的穿透性地球化学异常与钻孔原生晕相结合, 进行深部立体地球化学探测, 是实现深部找矿突破的关键。本文将以胶东和河南上官蚀变岩型金矿、贵州水银洞卡林型金矿千米深钻和地表联合取样获得的最新数据, 建立千米深度立体地球化学探测模型, 为深部找矿提供理论支持。

1 研究区概况及样品采集

本文将基于胶东焦家和河南熊耳山上官蚀变岩型金矿、贵州水银洞卡林型金矿钻孔岩芯和地表土壤联合观测研究, 建立金矿立体地球化学探测模型, 并开展应用示范。

1.1 胶东金矿

胶东是我国重要的黄金产地。焦家断裂带是胶东地区最重要控矿构造, 前人对焦家断裂带金矿床进行了深入研究, 取得了丰硕的成果(宋明春等, 2011; 杨德平等, 2020a, b)。根据 1950 年以来发现的金矿统计, 历年发现的胶东金矿深度在逐年增加, 特别是 2000 年以后, 有 10 个金矿矿体头部据地表埋深在 500 m 以下, 有 9 个矿体延伸达 1500 m 以下, 有 3 个矿体延伸达 2000 m 以下。胶东蚀变岩型金

矿是研究元素大深度垂向迁移机理与立体地球化学探测的立项选区。焦家金成矿带随着地质勘查程度的不断加大, 该区地表矿、浅部矿越来越少, 金矿找矿难度越来越大, “攻深找盲”成为该区找矿的重点方向(宋明春等, 2008)。穿透性地球化学的金属活动态测量在焦家断裂带和三山岛断裂带之间的吴一村(原吴家庄村)发现高强度地球化学异常(王学求和谢学锦, 2000; Wang, 2003)。

立体模型建立选择焦家蚀变带的曲家金矿开展钻孔原生晕和地表细粒级土壤联合采样(图 1)。钻孔围岩每 10 m 取一块样品, 矿化蚀变带和矿层每 2 m 取一块样品, 每 50 m 组合成 1 个样。按钻孔柱状图上的岩性分层, 要求每个组合样品保证岩性、蚀变类型和矿化类型的一致, 区分地层、岩浆岩、构造破碎带、围岩、围岩蚀变以及矿化体之间的界线, 按自然分层采集, 避免不同岩性、围岩蚀变类型及矿化体样品的混合, 切实保证样品的代表性。共采集-3、-1、1、3、5、6、9 号勘探线, 共 32 个钻孔, 采集 907 件原生晕样品。土壤样品采样选取-5、-3、-1、1、3、5、7 号勘探线(图 1), 采样点距 80 m。同时开展相对应的穿透性地球化学勘查, 穿越三山岛断裂带、焦家断裂带、招平断裂带, 并跨过各成矿带主要的矿床(三山岛金矿、仓上金矿; 焦家金矿; 玲珑金矿、大尹格庄金矿), 采集 3 条长

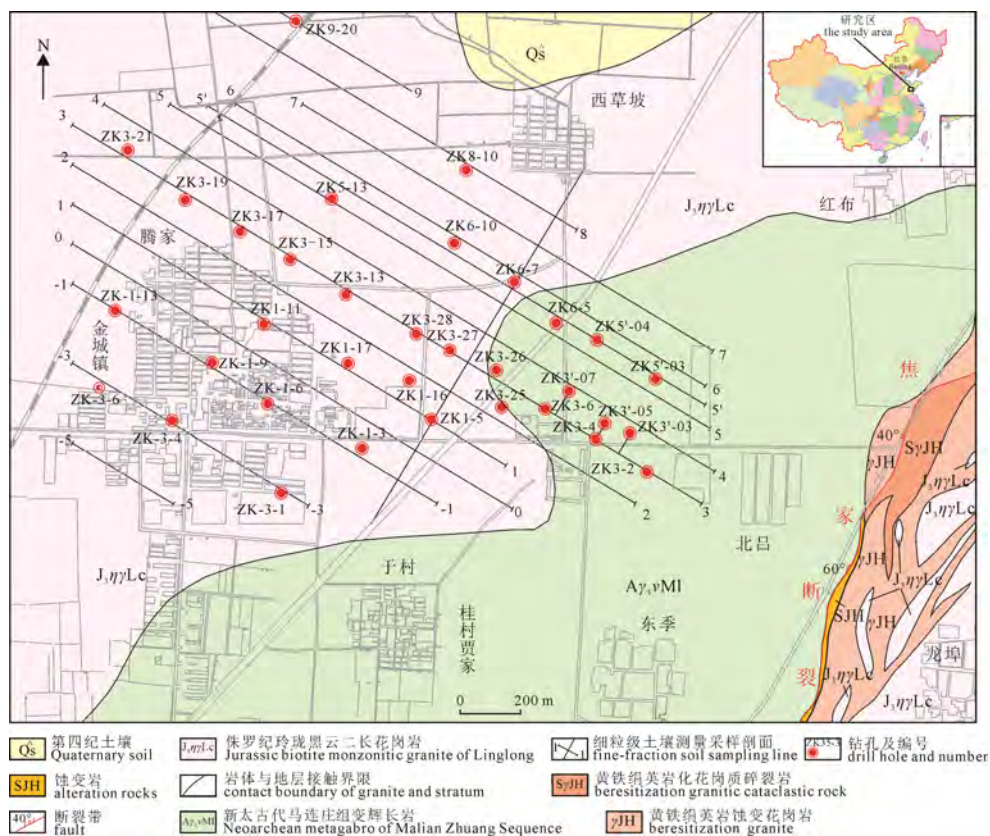


图 1 胶东曲家试验区钻孔原生晕与地表细粒级土壤剖面联合采样图
 Fig. 1 Geochemical sampling profile of fine-fraction soils and drilling holes across the Qujia gold deposit, Jiadong gold ore district

剖面土壤样品(点距 500 m)。为了避免地表污染和采集富含黏土层样品,使用洛阳铲采集地表 100 cm 以下样品,筛选-100 目细粒级。共采集土壤样品 938 件。

1.2 河南熊耳山上宫金矿

上宫金矿位于华北克拉通南缘,熊耳山—小秦岭金成矿带,整个金矿田累计探明金资源量已达 140 余吨,规模达超大型,是继胶东地区后我国又一重要的黄金产地(Mao et al., 2002)。上宫金矿床作为河南省首例发现并探明的大型构造蚀变岩型金矿,众多学者对其开展了大量基础地质和矿床学研究(范宏瑞等, 1998; Chen et al., 2006; 张苏坤等, 2020)。

上宫金矿是根据 1977—1978 年河南区调队在熊耳山北麓 1470 km² 面积开展水系沉积物测量,发现的异常,进而开展一系列详查和勘查工作,于 1982 年发现的大型金矿,也是首例根据地球化学扫面发现的金矿(龚启厚和王秉仁, 1982; 王学求和谢学锦, 2000)。但截至 20 世纪 90 年代,发现的矿体都是在 500 m 以浅。经过 30 余年开采,浅部资源已经接近枯竭,寻找深部矿已经迫在眉睫。2016 年开始,在国家重点研发计划“穿透性地球化学项目”

支持下,并由河南地勘队伍和矿山企业匹配资金,在上宫金矿选择 1000~2000 m 深孔的 3 条剖面开展钻孔原生晕采样(图 2)。以岩性自然分层、不跨层为原则,采样方法为多点连续取样,围岩样长约为 30 m,在矿体和裂隙发育处采样较密,间距 1~2 m,共采集样品 1081 件。采样过程中严格区分地层、岩浆岩、构造破碎带、围岩、围岩蚀变以及矿化体之间的界线,按自然分层采集,避免不同岩性、围岩蚀变类型及矿化体样品的混合,切实保证样品的代表性。同时开展相对应的穿透性地球化学勘查,穿越上宫金矿主要成矿断裂带,采集地表岩石(屑)样品(图 2),样品点距平均为 100 m,围岩部分适当放稀,构造带和裂隙发育部位加密,共采集样品 120 件。

1.3 贵州水银洞卡林型金矿

滇黔桂“金三角”地区大地构造位置处于扬子陆块与华夏陆块两大构造单元结合部位,出露地层为泥盆系至三叠系,以三叠系广泛分布为特征,二叠系次之,泥盆系和石炭系则仅见于少数背斜核部(Tan et al., 2019),岩浆活动不强烈,出露的岩浆岩主要是晚二叠世峨眉山溢流斑玄武岩和少量零星分布的偏碱性辉绿岩和钙碱性煌斑岩。水银洞金矿

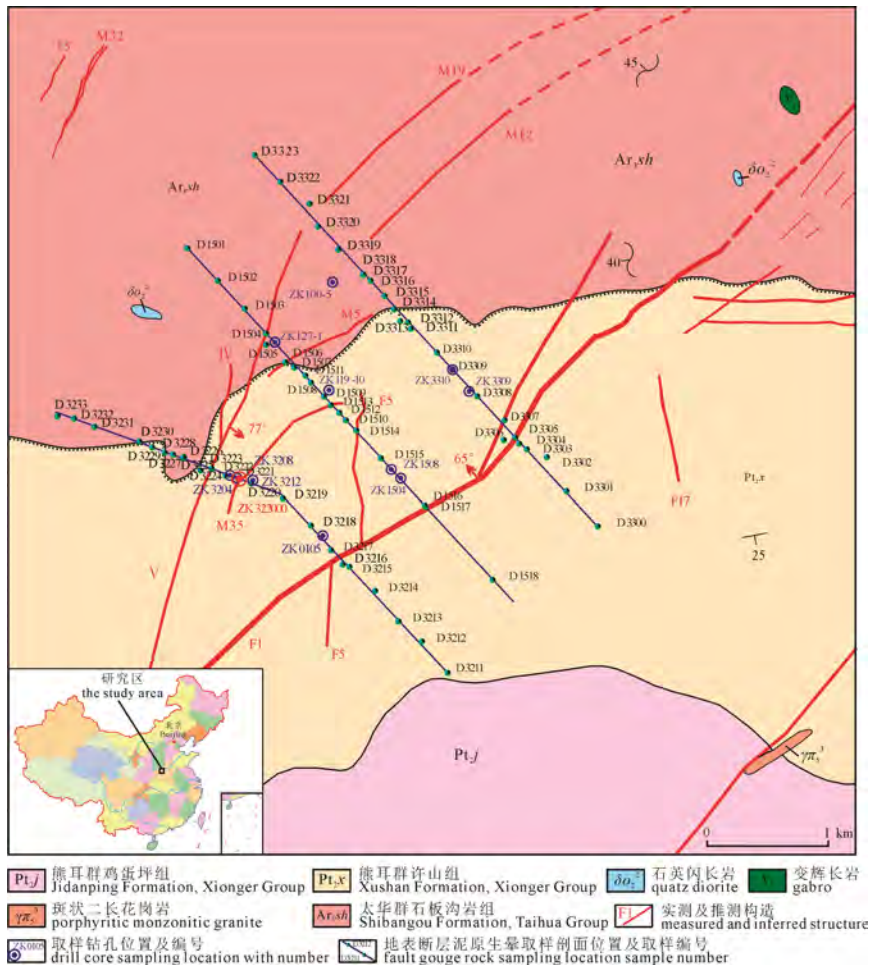


图 2 河南上宫金矿区地表与钻孔采样点位图
 Fig. 2 Geochemical soil and drilling sampling locations across the Shangong gold deposit, Xiongershan–Xiaoqinling gold ore district, Henan

位于灰家堡金矿田的东部, 是黔西南卡林型金矿的典型代表, 为全隐伏, 埋深 150 ~ 1400 m 的超大型矿床, 探明资源量达 260 多吨(刘建中等, 2017)。水银洞金矿体受中—上二叠统之间的不整合面构造(构造蚀变体)、灰家堡背斜和相关逆断层的联合控制, 主要包括“断控型”和“层控型”矿体(郭振春, 2002; 刘建中等, 2009; 夏勇等, 2009)。灰家堡背斜是水银洞矿区内的主干构造。谭亲平等(2017, 2020)总结了灰家堡背斜的构造模式, 认为龙潭组及其之上的地层沿着龙潭组和茅口组之间的不整合面顺层滑动, 产生横向缩短和纵向加厚, 形成灰家堡背斜构造。

本次研究选择水银洞金矿床东部 407、423 和 439 三条勘探线剖面进行地表土壤和钻孔岩石样品的采集(图 3)。地表土壤沿着 407、423 和 439 勘探线及其两边各两条勘探线布置样品, 勘探线间距和样品点距均为 200 m。野外土壤采集根据地形、地貌、村庄、公路等因素, 点距浮动约 20 m, 采样的深度约为 5 ~ 25 cm(去掉腐质层后采集新鲜土壤), 共采集样品 190 件。钻孔岩石样品的采集以 407 勘探线剖面为例, 展示样品的采样空间位置, 采样间距 5 ~ 50 m, 在矿体、背斜核部和裂隙发育处采样较密, 间距大约 5 ~ 20 m, 在裂隙构造不发育, 成矿作用弱的部位采样稀疏, 间距大约 20 ~ 50 m, 取样同时考虑岩性的变化, 样品不跨岩性采集, 共采集样品 890 件。

2 立体地球化学模型建立

穿透性地球化学勘查技术是基于成矿过程中流体携带成矿元素沿构造裂隙和岩石孔喉迁移以及成矿后元素的再次分散到达地表, 提取深部含矿信

息用于寻找隐伏矿。目前深部地球化学探测科学问题的焦点是元素大深度垂向迁移机理及立体地球化学模型的建立。本文将基于胶东曲家蚀变岩型金矿和贵州水银洞卡林型金矿钻孔与地表地球化学联合测量, 建立从原生晕到地表的三维地球化学模型, 展示矿体空间几何分布, 用于指导深部资源预测。

2.1 蚀变岩型金矿立体地球化学模型

传统隐伏矿地球化学勘查主要基于元素的轴向分带, 对金矿而言, 依据前缘指示元素 As、Hg、Sb 预测深部矿体。但这一方法存在两个缺陷, 一是轴向分带是基于成矿流体沿控矿构造的迁移, 但对于覆盖区勘查不可能预知构造部位, 正好把点部署在构造部位, 二是前缘元素有其多解性, 而且不是每个金矿都发育这套前缘指示元素。因此, 对金矿而言, 金能否垂向大深度迁移, 是在整个矿体上方随机布点采样发现异常的关键。成矿金属要围岩中扩散迁移必须具备两个基本条件: 一是围岩具有微裂隙或纳米孔, 二是成矿金属在流体中以化合物形式或微细颗粒(纳米颗粒或胶体粒子)形式存在。通过对胶东焦家蚀变岩型金矿的研究发现, 围岩中大量存在小于 1 μm 的微裂隙或纳米孔, 并用离子束扫面电镜在微裂隙中发现纳米金和黄铁矿等矿化(图 4)。微裂隙纳米金的形成是成矿过程中携带金的流体, 穿过微裂隙、纳米孔发生垂向扩散, 随着流体降温、压力降低、氧化还原条件和流体成分改变, 金溶解度饱和而析出或随黄铁矿沉淀后导致金出溶, 形成纳米金(图 4), 岩石再经过风化解离出纳米金进入到地表土壤中(图 4), 由于细粒级土壤地球化学障(黏土、胶体、氧化物、有机物等)的存在, 捕获纳米金, 因此在地表细粒级土壤形成金异常(图 4)。

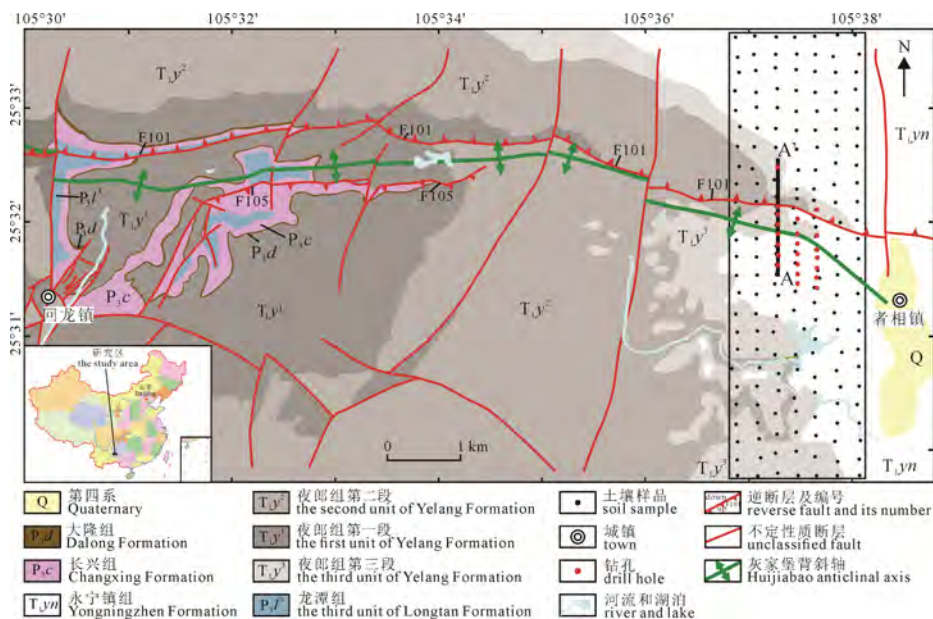


图 3 贵州水银洞金矿地表土壤采样剖面及钻孔点位

Fig. 3 Soil geochemical survey with drill hole locations, Shuiyindong gold deposit, Guizhou

根据胶东曲家金矿钻孔岩心取样和地表取样,分析成矿元素、矿化剂元素和伴生元素,建立了胶东金矿立体地球化学模型(图 5)。从图中可以看出:(1)成矿元素金异常与深部具有连续继承关系,金异常与矿体同倾斜方向反映了成矿过程中流体沿控矿断裂的轴向运移,这与地质观测和传统地球化学轴向迁移理论是一致的,金从深部矿体到地表存在连续的投影异常,反映了流体沿微裂隙或纳米孔的垂向扩散迁移;(2)矿化剂元素硫,与金的分布高度一致,说明硫作为矿化剂对金的搬运起着重要作用,黄铁绢英岩化越好,金的品位越高相一致;(3)远程指示元素汞,具有气体性质,从矿体到地表连续垂直贯通,表明其强烈的垂向迁移特征。综合来看,金的立体几何模型兼具矿化剂元素硫沿构造的轴向迁

移特征,又具有类气体元素沿纳米孔或微裂隙的垂向迁移的双重特征,这一模型对我们利用成矿元素、矿化剂元素和远程指示元素预测深部矿床提供了重要理论依据,特别是金具有类气体元素的垂向迁移特征,为深部矿体定位预测提供了理论基础。

2.2 卡林型金矿立体地球化学模型

卡林型金矿立体地球化学模型基于贵州西南部贞丰县水银洞金矿东段建立。根据 21 个钻孔,1095 件钻孔样品测试数据,绘制了 Au、As、Sb、Hg、S 和 Tl 三维地球化学图(图 6)。Au 从深部到地表的迁移途径,异常程度从下至上具有强→弱→较强的变化特征。As、S、Hg、Tl、Sb、S 的三维地球化学图显示它们的由深至浅的迁移途径和变化趋势和 Au 大致相似。

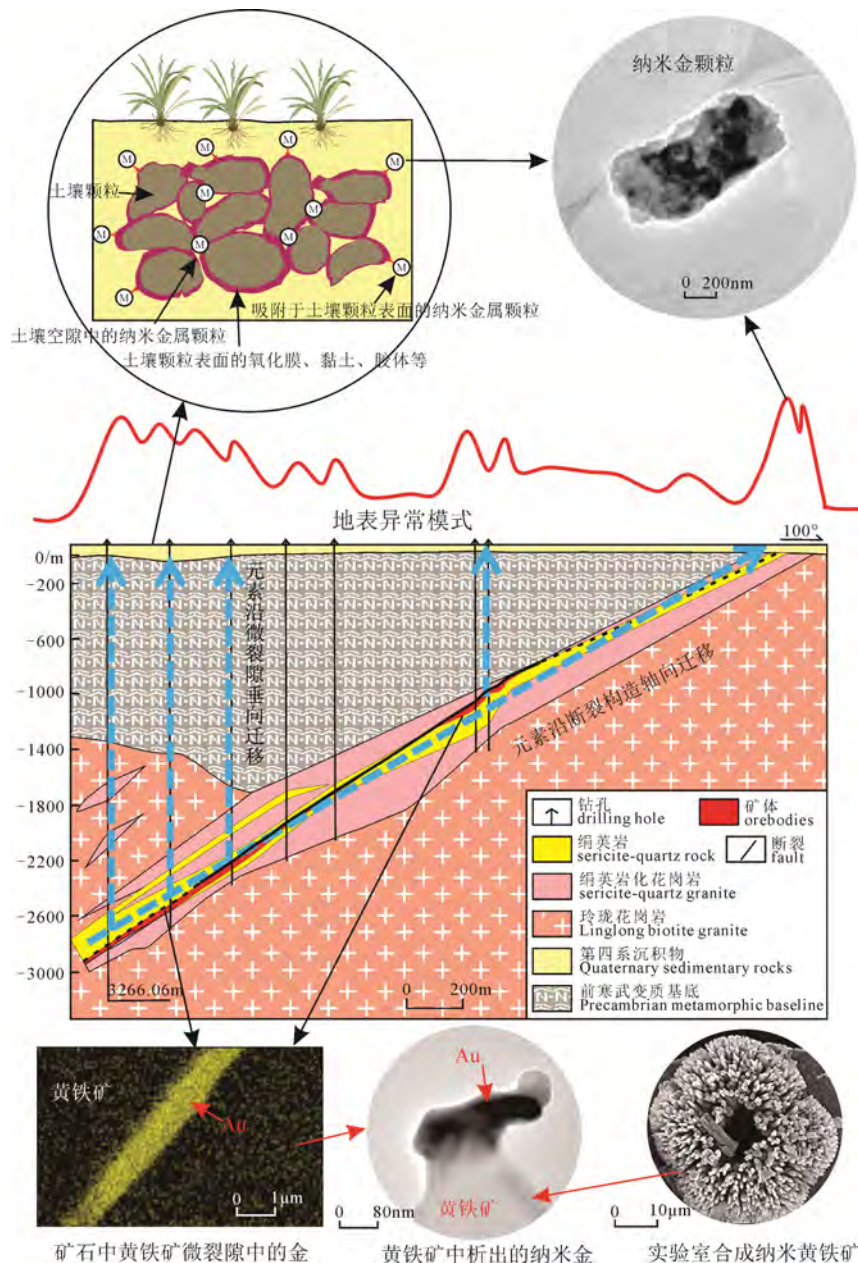


图 4 胶东金矿大深度地球化学迁移模型

Fig. 4 Geochemical modelling of gold vertical migration from depth to surface in the Jiaodong gold deposit

通过三维的地质图与地球化学图对比观察, Au 元素显示了四点的特征。一是在茅口组和龙潭组之间的不整合面附近整体显示了弱的 Au 异常(图 7), 不整合面是水银洞金矿乃至整个黔西南卡林型金矿的导矿构造(Tan et al., 2015)。二是在龙潭组第二段显示了高的 Au 异常, 与矿体主要位于该位置一致(图 7)。三是在龙潭组第三段、长兴组和大隆组整体显示了极低的 Au 含量, 但在上覆夜郎组第一段中整体显示略高的 Au 含量并且在局部形成一定的弱 Au 异常, 显示了成矿流体在龙潭组第二段发生水岩反映沉淀大部分 Au 后, 仍然会沿着有利空间(断层、裂隙、微孔隙等)向上部地层运移; 四是在最上部的永宁镇组中, 局部(如钻孔 ZK42316 处)仍然有弱的 Au 异常显示, 显示成矿流体在经历成矿作用之后, 能够继续运移, 可以穿过逾 800 m 的盖层到达近地表并被岩石所记录。

As、Sb、Hg、Tl 和 S 的三维地球化学特征与 Au 既有相似性又有差异性。相似性主要体现在: 在不整合面和矿体附近, As、Sb、Hg、Tl 和 S 均显示了高的含量特征; 在矿体上覆的夜郎组第一段中 Au 弱异常处, As、Sb、Hg、Tl 和 S 统一显示了地球化学异常, 这些元素的印迹可能揭示该处存在隐伏微小断裂。差异性体现在: Sb 和 Tl 元素在不整合面附近显示了最高含量, 与前人的研究一致(Tan et

al., 2015); Sb 和 Hg 在近地表均显示了明显高的异常特征(如钻孔 ZK40780 附近), 并且二者之间异常较为相似, 另外 As 也有类似的特征, 但异常较弱; As、Sb、Hg、Tl 和 S 在近地表均有或强或弱的异常显示, 但异常位置与 Au 元素并不完全重合。

3 深部钻探验证

3.1 胶东吴家庄 3000 m 钻探验证

山东焦家成矿带和三山岛成矿带之间是大片完全覆盖区, 穿透性地球化学的细粒级土壤采样, 实验室金属活动态分析, 在焦家断裂带和三山岛断裂带之间的吴一村(原吴家庄村)发现高强度地球化学异常(图 8)(王学求和谢学锦, 2000)。2016 年实施了穿越焦家和三山岛成矿带的两条地球化学剖面测量, 利用穿透性地球化学的细粒级土壤采样, 全量分析获得的金高含量峰值点出现在焦家和三山岛断裂带正上方, 在两条断裂带之间出现多个次一级峰值点(图 9)。根据金垂直迁移模型, 推测深部存在多段隐伏矿体, 并结合地质推断和物探测量解译(熊玉新等, 2018), 在山东省地勘经费的支持下, 由国家重点研发项目的课题承担单位山东地质科学研究院负责在莱州市吴一村地区实施了一深孔钻探项目, 最终于 2017 年 8 月钻进至 3266.06 m, 在 2428.00~3234.16 m 成功控制焦家金矿带, 新发现

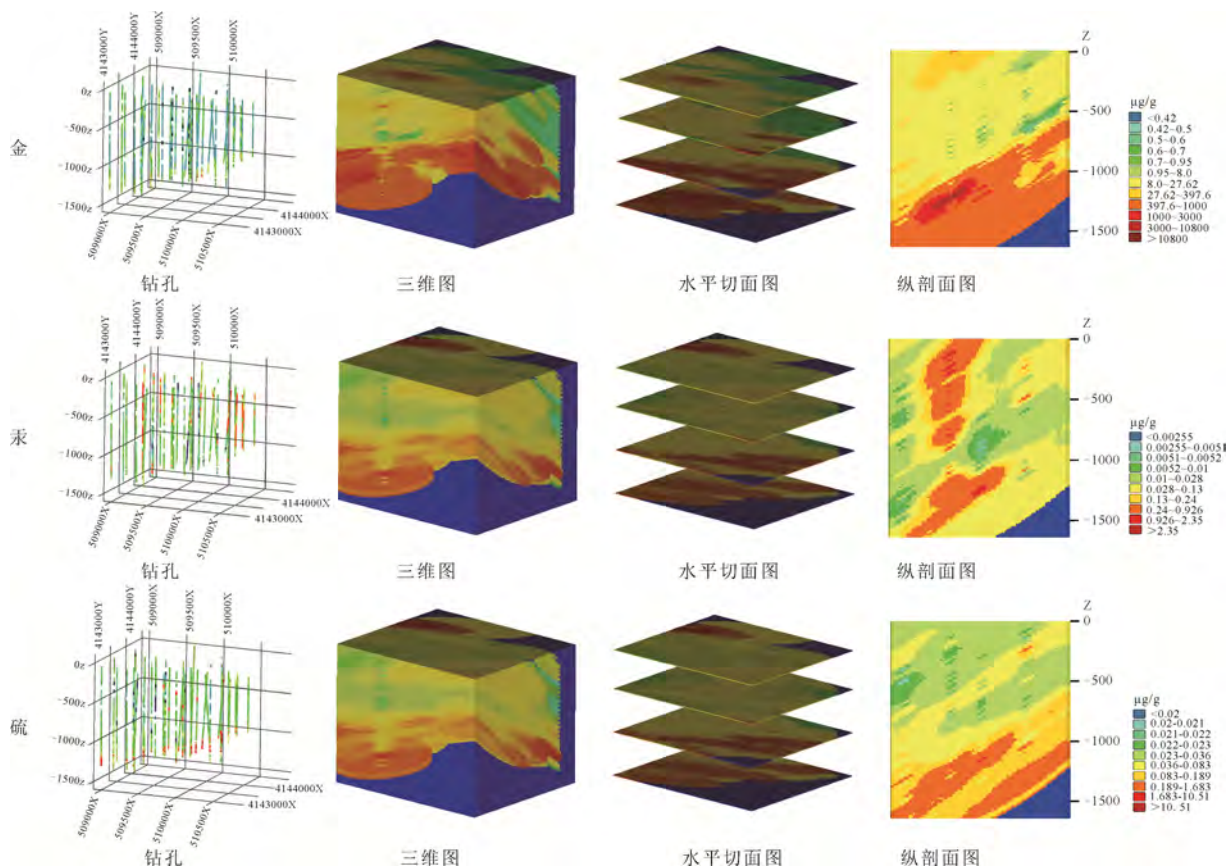


图 5 胶东蚀变岩型金矿立体地球化学模型

Fig. 5 3D geochemical pattern of the Jiaojia gold deposit, Jiaodong gold ore district

金矿体 6 层, 累计见矿厚度 20.87 m, 平均品位 1.85 g/t, 主矿体位于 2850 m 深度, 成为名副其实的“中国岩金“第一见矿深钻”(于学峰等, 2019)。

3.2 上宫金矿 2000 m 钻探验证

河南熊耳山上宫金矿是 20 世纪 80 年代找到的

河南省第一例大型构造蚀变岩型金矿床, 经过 30 多年的开采, 浅部 500 m 以上矿体接近枯竭, 亟需在深部取得找矿突破。为进一步发挥科研在该地区地质找矿过程中的指导作用, “穿透性地球化学勘查技术”项目专门设立了“熊耳山上宫金矿立体

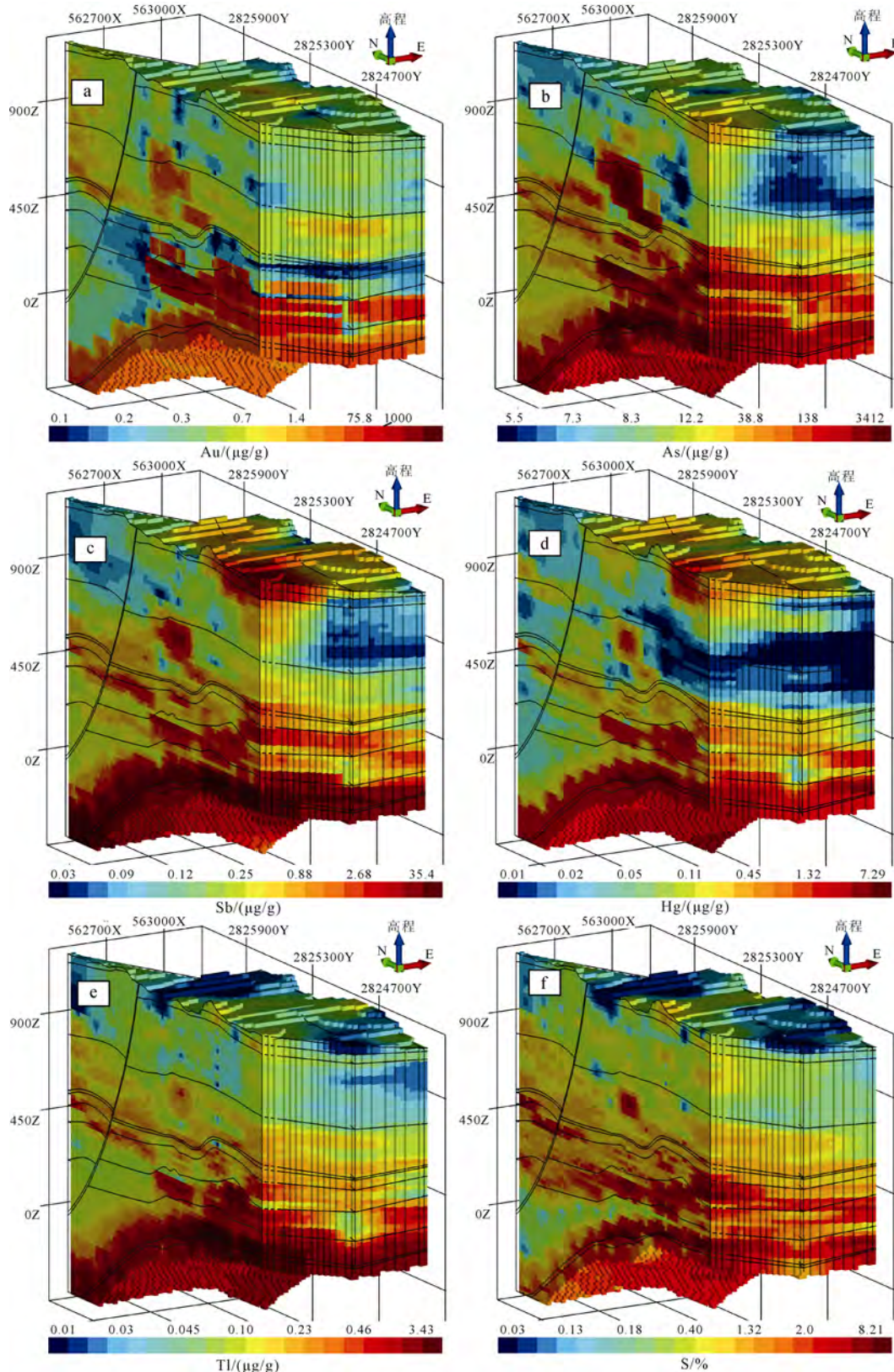


图 6 贵州水银洞卡林型金矿 Au 及伴生元素三维地球化学图

Fig. 6 3D geochemical patterns of Au and associated elements in the Shuiyindong gold deposit, Guizhou Province

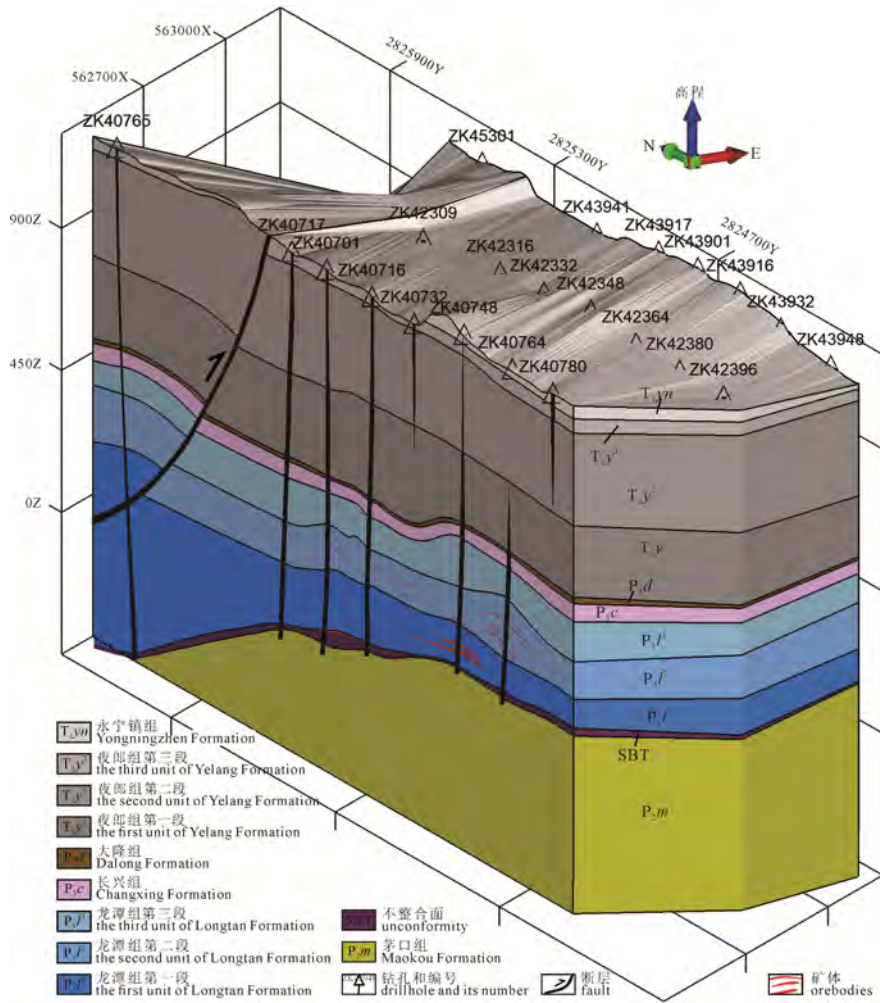


图7 贵州水银洞金矿床东部三维立体地质图

Fig. 7 3D geological characteristics of the Shuiyindong gold deposit, Guizhou Province

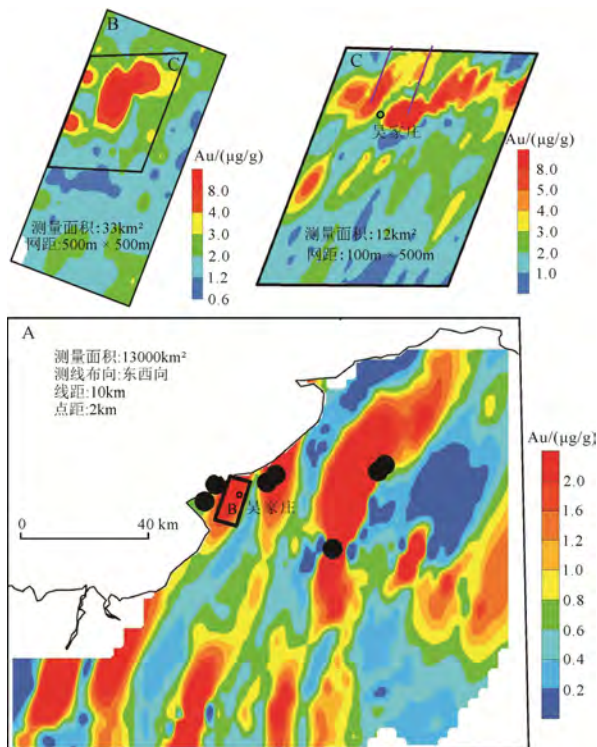


图8 胶东逐步缩小隐伏金矿勘查靶区的深穿透地球化学探测(引自王学求和谢学锦, 2000)

Fig. 8 Deep-penetrating geochemical survey for step-by-step reduction of target size of concealed gold deposits in Jiaodong (after WANG and XIE, 2000)

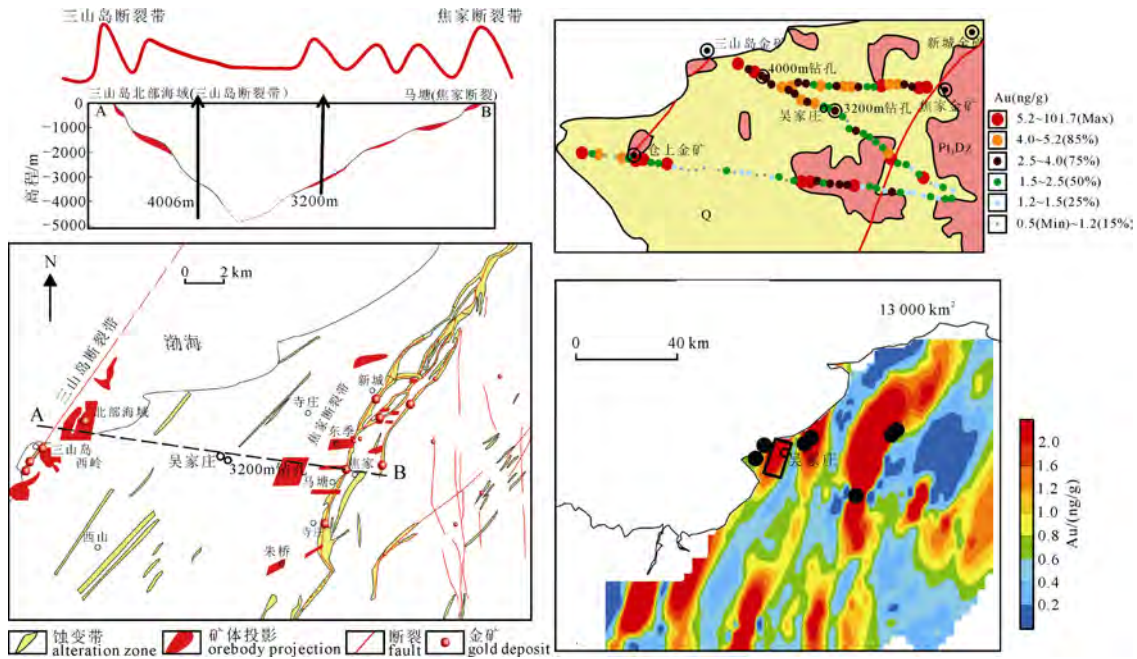


图9 胶东焦家—三山岛穿透性地球化学测量与吴家庄异常靶区钻探验证

Fig. 9 Drilling target delineated by deep-penetrating geochemical survey at Wujiashuang, the Jiaodong gold orefield

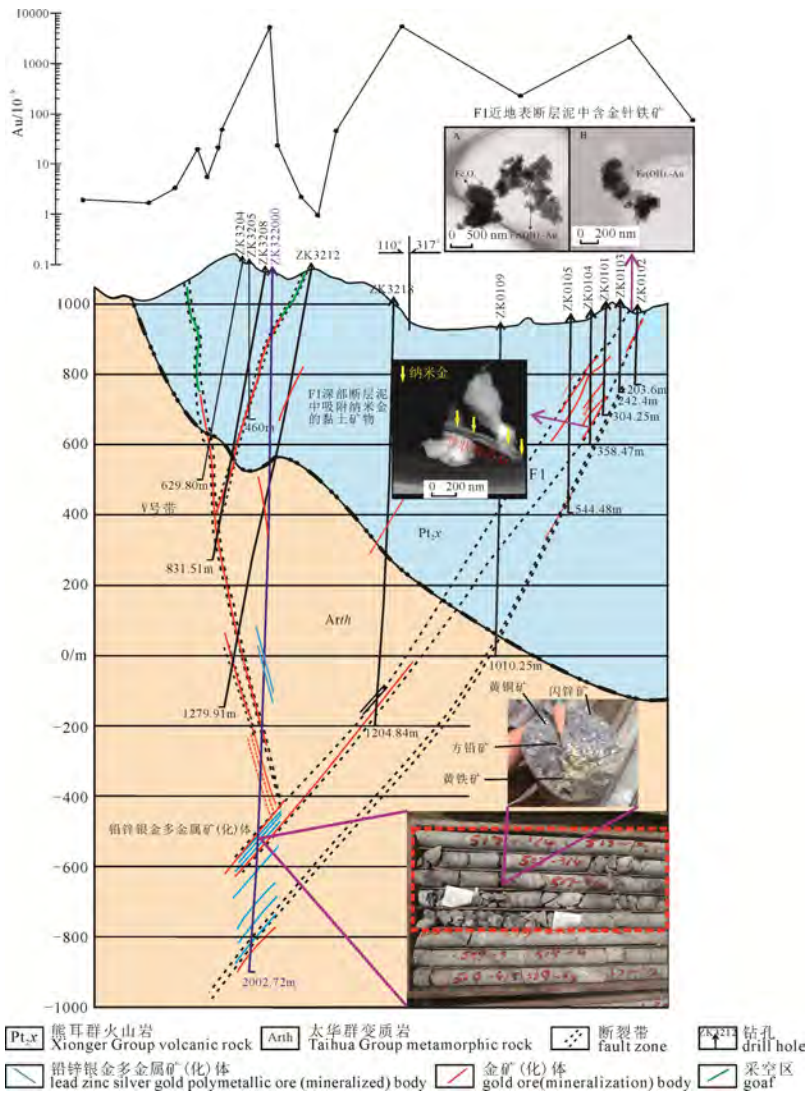


图10 河南上宫金矿32勘探线地表裂隙岩石测量与深部2000m深钻验证

Fig. 10 Gold anomalies discovered by using fracture rock sampling and the deep-seated orebody discovered by drilling exploration across line 32 of the Shangong gold deposit in Henan Province

地球化学探测试验示范”子课题。研究发现断层泥黏土矿物埃洛石和针铁矿表面吸附纳米金(图 10), 断层是流体运移的通道, 因此采集断层泥或裂隙岩石样品, 可以探测深部矿体。图 10 是 32 线裂隙岩石地球化学测量异常图, 结合地质构造, 定出了 ZK322000 的孔位。经 2000 m 钻孔验证, 在孔深 1312 m 处探获一层真厚度 4.56 m 的高品位铅锌银金多金属矿体(图 10)。这在上宫金矿区深部尚属首次发现, 且表现出热液成因的特征, 说明在上宫金矿区可能存在着与蚀变岩型金矿化不同期次的, 具

有一定规模的铅锌银的多金属成矿事件。

3.3 贵州卡林型金矿立体地球化学探测试验示范

前述水银洞金矿立体地球化学模型显示成矿流体在深部有利岩性组合部位发生水岩反映沉淀大部分 Au 后, 仍然会沿着隐伏断层/裂隙和微孔隙等向上运移, 并形成或强或弱的地球化学印迹。在水银洞金矿床簸箕田矿段沿主要断裂带采集地表土壤并分析 Au 及成矿相关元素含量, 显示地表裂隙附近土壤成矿元素地球化学异常与深部隐伏矿体具有高度一致的对应关系, 地表裂隙附近的土壤能够

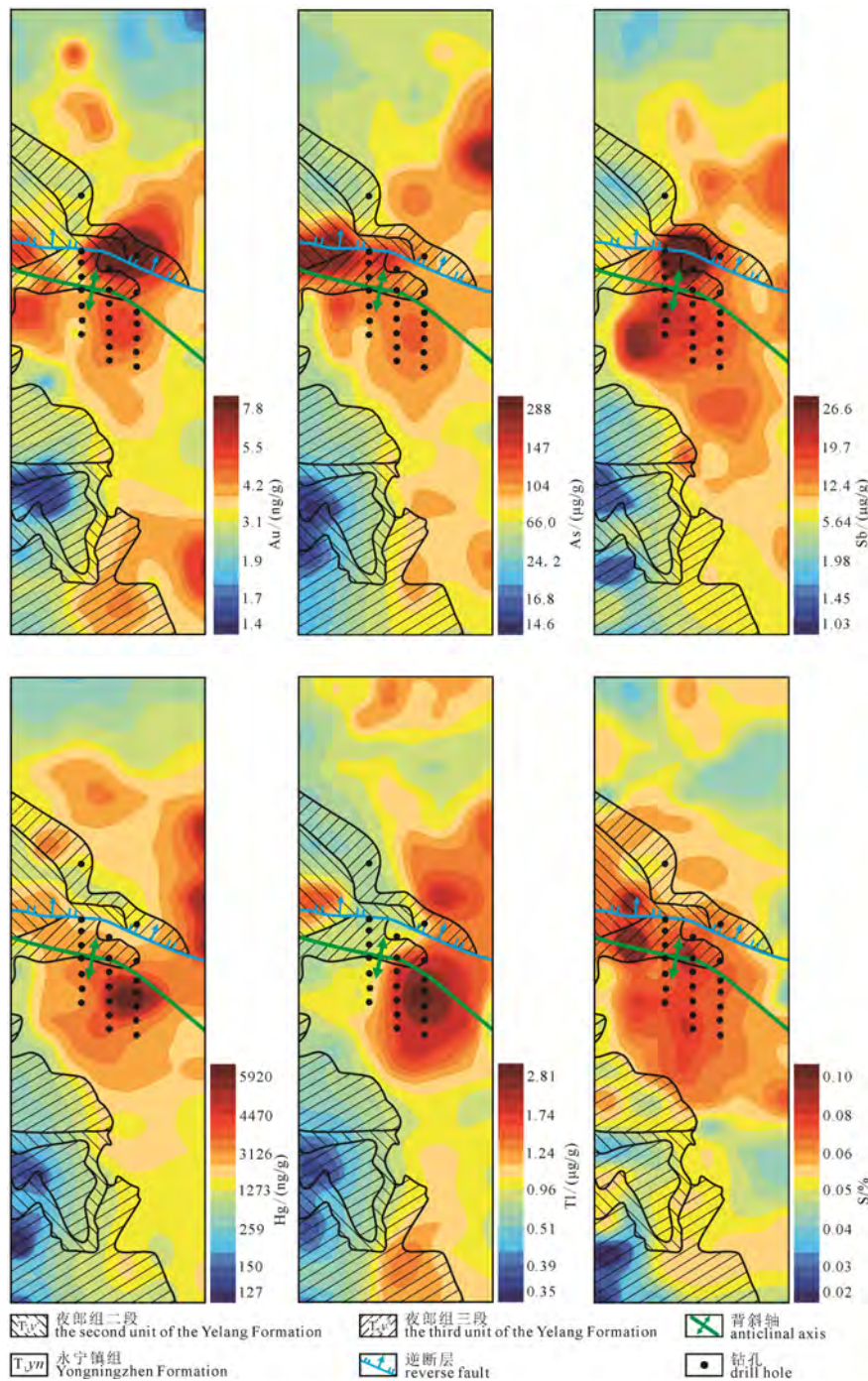


图 11 水银洞金矿地表细粒级土壤 Au、As、Sb、Hg、Tl、S 地球化学图
 Fig. 11 Geochemical maps of Au, As, Sb, Hg, Tl and S discovered by using fine-fraction soil sampling at the Shuiyindong gold deposit

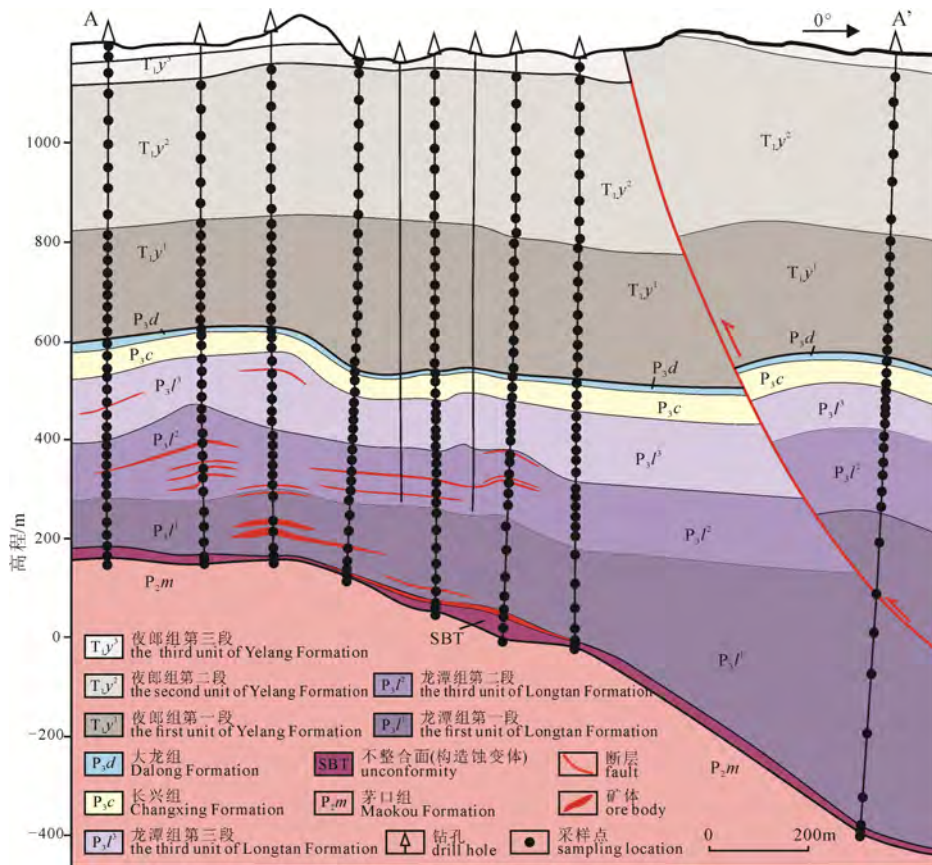


图 12 水银洞金矿 A-A'剖面地质图及钻探发现的深部矿体

Fig. 12 Geological map with deep-seated orebodies discovered by drilling exploration along A-A' cross section at the Shuiyindong gold deposit

有效记录深部成矿作用信息, 达到直接探寻深部盲矿体的目的(谭亲平等, 2020, 本专辑)。徐良易(2016)开展水银洞金矿东部(者相)构造地球化学测量, 采集断裂构造岩、断层泥、角砾岩、胶结物、节理裂隙充填物、细小脉体(石英细脉、方解石细脉、黄铁矿细脉等)以及裂隙周缘蚀变岩石等等, 分析 Au 等成矿相关元素含量, 发现了大量构造地球化学异常, 并对测量区的隐伏、半隐伏矿体进行成矿预测。本次“穿透性地球化学勘查技术”示范, 在水银洞金矿床纳纳矿段采集了地表细粒级土壤, 并分析 Au、As、Sb、Hg、Tl、S 含量。Au 及其成矿相关元素在见矿钻孔处具有明显的异常(图 11), 虽然这些元素的异常中心的位置不完全吻合, 显示了地表细粒级土壤地球化学测量能够直接有效地揭示深部 Au 的成矿作用, 避免了构造地球化学采样工作的随机性和偶然性。根据穿透性地球化学异常, 对黔西南水银洞金矿的成矿条件、控矿因素、成矿规律和矿床成因等方面进行深入研究并建立成矿和找矿模型的基础之上, 贵州省地矿局 105 地质大队、中国科学院地球化学研究所和贵州紫金矿业股份有限公司密切合作, 对水银洞金矿床深部和外围进行了成矿预测, 利用穿透性地球化学细粒级土壤测量圈定了多个找矿靶区, 经过钻探验证, 取得找矿重大突破,

发现了 300~1400 m 以深的隐伏矿体(图 12), 累计获得金资源量 367 t, 新增金资源量 203 t。

4 结论

建立元素大深度垂向迁移机理和立体地球化学探测模型是解决地球化学勘查从传统的浅表矿到覆盖区和深部资源勘查必须解决的理论基础问题。本文从已知矿的钻孔岩芯和地表土壤联合采样实际观测, 建立立体地球化学探测模型, 再到未知区钻探验证, 将地球化学探测能力由百米深度提高到千米深度, 从二维扩展到三维, 对深部找矿具有重要理论意义和实践意义。

金矿体及上方围岩微裂隙、断层泥和土壤中都发现纳米金, 表明成矿过程中流体从深部向浅部运移降温过程中析出纳米金, 岩石中纳米金又经风化作用进入到地表土壤中, 构成了从矿体到地表覆盖物的完整的垂向运移过程。这一新发现, 对传统地球化学迁移机理做出了重要修正: 一是传统认为金是惰性的, 不能长距离大深度迁移, 新的发现证明成矿过程中流体从深部向浅部运移降温过程中析出纳米金, 纳米金可以在次生作用下发生二次运移, 形成长距离大深度迁移; 二是传统原生晕测量的理论基础是成矿元素及伴生元素沿控矿构造的轴向迁

移, 并产生元素分带, 新的发现表明成矿元素和伴生元素不仅可以轴向迁移, 而且可以沿围岩微裂隙、微断层或纳米孔隙发生垂向迁移。这大深度地球化学迁移模型的建立为深部地球化学探测提供了重要理论基础。

以胶东蚀变岩型金矿和贵州水银洞卡林型金矿钻孔岩芯和地表土壤联合取样获得的数据, 建立的金矿 1000~3000 m 立体地球化学模型显示: 蚀变岩型金矿, 金的立体几何模型兼具矿化剂元素硫和远程指示元素汞的双重特征, 金异常和矿化剂元素硫与控矿构造矿体倾斜方向一致, 反映了成矿过程中流体沿断裂的轴向运移, 金异常与类气体元素汞在垂向上的一致, 反映了流体沿微裂隙和纳米孔的垂向迁移。卡林型金矿立体地球化学模型显示, Au、As、Sb、Hg、Tl 和 S 在茅口组和龙潭组之间的不整合面显示高含量特征, 与深部层状主矿体分布一致; 在矿体上覆地层中都存在弱异常, 显示了明显的成矿流体沿隐伏微小断裂垂向迁移特点; 所不同的是 Sb 和 Tl 元素在不整合面附近显示了最高的元素含量, 而 Sb 和 Hg 在近地表均显示了明显高的异常特征。

立体几何模型不仅清晰地显示了矿体的展布特征和范围, 而且为利用金及伴生元素和矿化剂元素进行深部矿体三维预测提供了重要依据。胶东焦家-三山岛断裂带之间为大片第四系覆盖区, 地表使用土壤采样, 进行微细粒和动态提取, 金-汞异常峰值位于断裂带头部和矿体正上方, 金-硫异常峰值位于断裂带头部, 异常浓集中心位于吴家庄村附近, 经 3200 m 深钻验证, 并发现 2800 埋深矿体。河南熊耳山一小秦岭地区的上宫金矿基岩出露, 主要使用岩石裂隙或断层泥采样, 预测深部矿体, 实施的 2000 m 钻探验证, 在 1200 m 发现矿体。贵州水银洞地区地表细粒级土壤采样, 呈现金-砷-汞-锑-铊-硫组合异常, 经 1500 m 钻探验证, 在 300~1500 m 探获深部矿体。从验证结果可以看出, 根据地表覆盖物特点和不同矿床的指示元素组合, 开展针对性的深穿透地球化学探测取得深部找矿突破。

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