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贵州三穗铀矿床矿石矿物学特征及其对找矿的指示

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摘要:三穗铀矿床位于黔中—湘西北铀成矿带内,产于震旦—寒武系老堡组炭质泥岩中,是贵州省近年勘查发现的第一个大型铀矿床。[研究目的]鉴于黔东地区铀矿成矿规律、富集机理及矿石矿物学等研究程度低,查明典型铀矿床矿石矿物组合及化学组分,探讨成矿环境,揭示成矿过程,深化成矿理论认识,将为促进区域成矿预测、扩大找矿勘查成果及丰富该类型铀矿成矿理论提供科学依据。[研究方法]基于三穗铀矿床地质、地球化学特征,通过电子探针、扫描电镜等测试,分析了铀成矿机理及成岩成矿的环境演化。[研究结果]本区含铀岩系老堡组形成于震旦纪/寒武纪转折期的陆缘裂谷和陆缘裂陷缺氧还原环境,铀成矿初始物源与海底火山活动有关;铀矿石主要由铀矿物、铁矿物、黏土矿物、有机质及白云石、石英(或玉髓)、重晶石、方解石等组成,呈微晶—隐晶结构、微晶—粉晶晶粒状结构,层状、纹层状构造;铀矿物丰富,主要有沥青铀矿、硅钙铀矿、硒铅铀矿、钍铀矿、磷铀矿及水碳铀等,以纳米—微米级粒状、柱状(粒径多<10 μm)、细脉状、或隐晶质形式赋存于有机质、铁质、黏土矿物等聚铀矿物中。[结论]三穗铀矿床形成物源具有多源性,与雪峰期海底火山作用带来部分成矿物质、燕山—喜马拉雅期成矿流体在运移的途中不断浸取地层内的成矿物质密切相关,经历了铀初始富集、氧化淋滤及热液叠加再富集过程,成因属典型的碳硅泥岩型。三穗铀矿床中发现大量铀矿物显示,铀富集程度高、成矿作用强,找矿远景好、潜力大。

关键词:铀矿床;碳硅泥岩型;矿石矿物学;成矿环境;矿产勘查工程;三穗;贵州省

创新点:基于三穗铀矿床地质地球化学特征,通过电子探针、扫描电镜等矿物学研究,揭示本区铀成岩成矿的环境演化及成矿机理,探讨了找矿远景。

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Ore mineralogical characteristics of Sansui uranium deposit in Guizhou Province, China and indication for prospecting

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Abstract: This paper is the result of mineral exploration engineering.

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The Sansui deposit is located in the uranium metallogenic belt between central Guizhou and northwest Hunan Province. It is the first large uranium deposit discovered in Guizhou Province in recent years. The uranium deposit situates in the carbonaceous mudstone of Laobao Formation of Sinian – Cambrian and is stratified and like stratified. **[Objective]** The purpose of this paper is to find out the ore and mineral composition of Sansui uranium deposit, explore the uranium mineralization environment, reveal the mineralization process of uranium initial enrichment, leaching, superposition and re-enrichment, and provide new information for regional metallogenic prediction, ore exploration and enrichment of this type of uranium ore-forming theory. **[Methods]** The study on mineral mineralogy and geological characteristics of ore deposits shows that **[Results]** (1) The Laobao Formation of uranium-bearing rocks was formed in the anoxic reduction environment of the continental margin rift and continental margin rifting during the Sinian/Cambrian transitional period. (2) The uranium ore is mainly composed of uranium mineral, iron ore, clay mineral, organic matter, dolomite, quartz (or chalcedite), barite, calcite, etc., with microcrystal-cryptocrystal structure, microcrystal-powder grain structure, layered and lamellar structure. (3) The uranium ore is rich in uranium minerals, mainly pitchblende, silica-calcined uranium ore, selenium-lead uranium ore, titanium-uranium ore, phosphorus uranium ore and water-carbon uranium, etc. They occur in the form of nano-micron granule, column (particle size <10 microns), veinlet, or in the form of cryptocrystalline occurrence in the organic matter, iron, clay minerals and other uranium minerals. (4) The constant element in the ore were enriched in SiO₂, CaO and LOI (burning loss), which was consistent with the rich silica, calcium and organic minerals. **[Conclusions]** The uranium source of the Sansui deposit was related to the submarine volcanic eruption, spillage during the Xuefeng period and the weathering and leaching of uranium-bearing geological bodies. Mineralization and its associated trace elements such as U, V, Mo, Cd, Se, Ni, Zn, etc. are significantly enriched, which is related to the fact that some ore-forming materials and ore-forming fluids are continuously leaching ore-forming materials in the strata during the process of submarine volcanic eruption and spill.

Key words: uranium deposit; carbonosilicon mudstone type; mineral mineralogy; metallogenic environment; mineral exploration engineering; Sansui; Guizhou Province

Highlights: Ore-forming materials and ore-forming fluids of the Sansui deposit are continuously leaching ore-forming materials in the strata during the process of submarine volcanic eruption and spill.

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1 引言

黔中—湘西北铀成矿带是中国碳硅泥岩型铀矿的主要成矿区之一,属华南大面积低温成矿域的组成部分,含铀地层形成于晚震旦世—二叠纪,成矿时代集中在燕山—喜马拉雅期(140~30 Ma)(杜乐天等,1984;张祖还,1986;Hu et al.,2008,2017;赵凤民等,2009;漆富成等,2012;蔡煜琦等,2015)。碳硅泥岩型铀矿大规模铀成矿作用受控于陆缘裂谷、陆缘裂陷环境,并常伴随海底喷流和海底火山喷发作用(漆富成等,2011)。据Rawat et al.(2010)研究印度喜马拉雅西摩地区克罗尔—塔尔新元古代—寒武纪含铀黑色页岩的矿化特征表明,黑色页岩型铀矿床虽然品位较低(U₃O₈<0.001%~0.05%),但由于体积巨大,蕴藏着丰富的铀资源;瑞典产于黑

色岩系中的铀矿床丰富,Ranstad铀矿床(产于前寒武系—寒武系)是最著名的铀矿床之一,可采U₃O₈储量30万t,平均品位U₃O₈0.035%(Young,1984),此外,Haggan、Viken铀矿床铀资源量分别为44.73万t(U品位0.016%)和40.27万t(U品位0.02%),为全球第一、第二大未开采的低品位矿床(黄文斌等,2017),这些矿床均共生Mo、V、Zn等元素,与黔中—湘西北铀成矿带的碳硅泥岩型铀矿床特征相似,表明找矿潜力及资源利用前景巨大。扬子陆块东南缘是中国重要的碳硅泥岩型铀矿集区,在桂北、湘西北地区现已探明的大中型铀矿床10余个(漆富成等,2011),表明该区域成矿条件优越。近年实施整装勘查,在黔东三穗发现了贵州省第一个大型铀矿床,由于综合研究程度低,勘查中未发现独立的铀矿物。本次研究通过岩矿鉴定、电子探

针、扫描电镜等手段,详细查明了铀矿床的矿石矿物组成及主要的常量、微量元素含量特征,初步了解了铀矿赋存状态,探讨了形成环境及成矿机理,为黔东及相邻区铀矿成矿预测、扩大找矿勘查成果,丰富该类型铀矿理论提供了科学依据。

2 区域地质背景及矿床地质

2.1 区域地质背景

研究区位于扬子陆块南缘与江南造山带的结合部位,基底为新元古代变质岩建造,盖层为显生宙碳酸盐岩-细碎屑岩建造(Hu et al.,2012;胡瑞忠等,2016),出露地层有青白口系浅变质岩,南华系浅变质岩、碎屑岩,震旦系-志留系及二叠系-三叠系碳酸盐岩、碎屑岩,中生代地层局部区域沉积,

缺失泥盆系、石炭系、下二叠统。震旦系-寒武系老堡组(Zel)为区内铀的含矿层位。NE、NNE及EW向断裂发育,代表性断层有NNE向石阡-松桃断层(F₁),NE向施洞断层(F₂),EW向施秉-镇远断层(F₃)。褶皱主要以紧密(武陵期)和宽缓(雪峰-加东期)的阿尔卑斯式形态展布,典型褶皱有雷公山复式背斜、梵净山复式背斜、三穗向斜等。岩浆活动弱,在梵净山见与武陵运动有关的基性、超基性侵入岩体和花岗岩体产出,在凯里-镇远、雷山分别见与加里东运动、燕山-喜马拉雅运动有关的钾镁煌斑岩出露。区内有铀、钒、金、铅锌、锑、锰、汞、重晶石等矿产产出(图1)。

2.2 矿床地质特征

研究区出露青白口系下江群清水江组,南华系

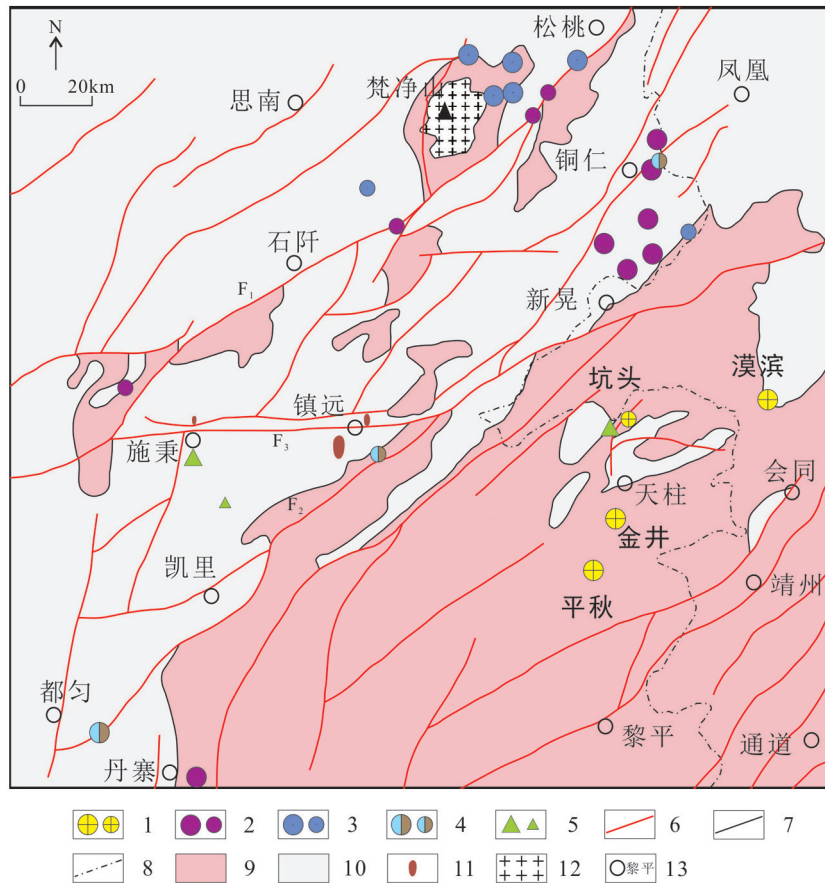


图1 贵州东部地质矿产略图(据陶平等,2009修编)

1—金矿床(点);2—汞矿床(点);3—锰矿床(点);4—铅锌矿床(点);5—重晶石床(点);6—断层;7—地层界线;8—省界;9—新元古界;10—古生界;11—煌斑岩体;12—花岗岩体;13—地名

Fig.1 Geological sketch map of eastern Guizhou(after Tao Ping et al., 2009)

1—Gold deposit (point); 2—Mercury deposit (point); 3—Manganese deposit (point); 4—Lead-zinc deposit (point); 5—Barite bed (point); 6—Fault; 7—Stratigraphic boundary; 8—Boundary; 9—Neoproterozoic strata; 10—Paleozoic strata; 11—Lamprophyre; 12—Granite mass; 13—Place names

南沱组、大塘坡组,震旦系陡山沱组、震旦系—寒武系老堡组和寒武系九门冲组等地层(图2),其中老堡组(Z_{El})为区内铀多金属的主要含矿层位,岩性为黑色、灰黑色薄至中厚层硅质岩、条纹状硅质岩、含炭质硅化角砾岩、硅化白云岩、泥质夹薄层炭质泥岩,细粒黄铁矿发育,为海相缺氧或无氧的水体环境形成的沉积岩石组合(吴朝东等,1999),厚度约44 m。硅化角砾岩、硅化白云岩、炭质泥岩为容矿岩石,条纹状硅质岩为赋矿围岩。含矿层位与断层叠加部位或向斜级褶皱发育区,铀矿化强烈。矿区铀矿(化)体呈层状、似层状产出(图3),控制走向约5 km,倾向延伸>3 km,厚度0.20~4.4 m,品位0.10%~22.00%,探获的铀资源量为大型矿床规模。综合评价铀矿层中共伴生V、Se为大型矿床规模,Mo、Cd为中型矿床^①。

3 样品采集及分析方法

样品均采自三穗矿床的槽探、钻探工程,其中矿石样(炭质泥岩)21件、围岩(硅质岩)9件。常量元素分析为电感耦合等离子体发射光谱法(其中容量法测定SiO₂、CaO;重量法测定LOI)、微量元素分析为电感耦合等离子体质谱法测定(U为激光荧光法,Se为原子荧光法),测试单位为四川省核工业辐射测试防护院。岩矿鉴定由中国核工业集团二三〇研究所完成,电子探针和扫描电镜由中国科学院地球化学研究所矿床地球化学国家实验室完成,电子探针及扫描电镜使用JSM-7800F型显微镜(FE-SEM)和EDAX TEAM Apollo XL能谱仪。扫描电镜能谱测试条件为加速电压20 kV,电流10 nA,电子束斑直径为1 μm。

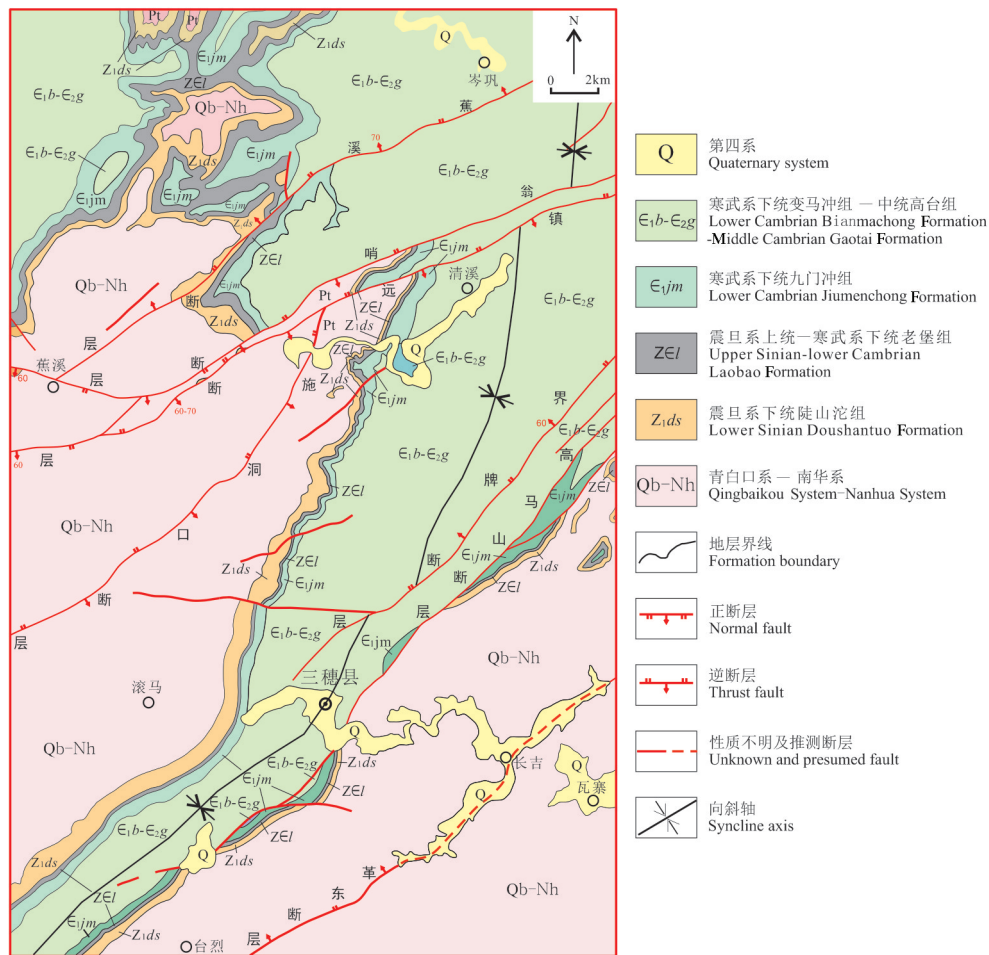


图2 三穗矿区地质图

Fig.2 Geological map of Sansui mining area

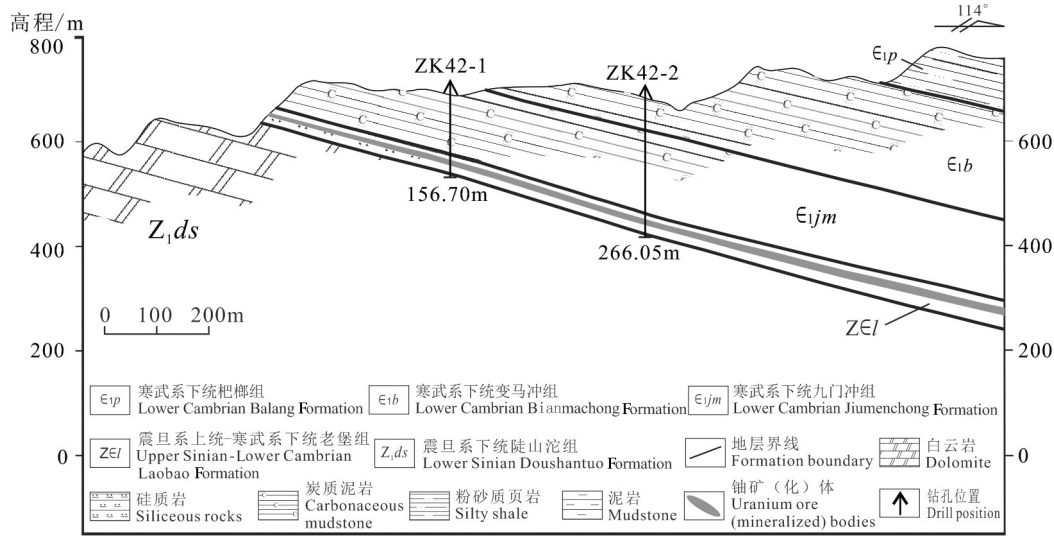


图3 铀矿床42—42'勘探线剖面图
Fig.3 Profile of 42-42' exploration line of uranium deposit

4 矿石矿物组成

4.1 矿石矿物化学组分

4.1.1 常量元素特征

围岩中以SiO₂含量高为显著特征(为46.35%~80.96%,平均64.21%),其次LOI、CaO含量相对高,分别为3.08%~19.29%(平均10.74%)和6.00%~14.88%(平均8.63%),Al₂O₃、Fe₂O₃、MgO和P₂O₅的平均含量均小于3%,与赋矿层位为硅质岩,富含钙质、有机质吻合。矿石中以LOI含量(11.43%~63.63%,平均40.70%)高为特点,其次为SiO₂和CaO,平均值分别为29.49%、11.71%,与容矿岩石为炭质泥岩,富含炭质、有机质、黏土矿物一致。矿石与围岩相比,LOI、CaO、MgO、Al₂O₃含量相对高,而SiO₂、Fe₂O₃、P₂O₅含量相对低(表1)。

4.1.2 主要微量元素特征

围岩和矿石中U、Mo、Cd、Se、Ni、Zn均为富集元素,以U、Mo、Cd、Se最突出(表2);而Th为贫化元素,Cu为弱富集元素。Th的贫化,与在表生氧化

作用下,U⁴⁺易被氧化成活泼的U⁶⁺迁移至适宜环境叠加富集,而较惰性的Th仍然保存在原地稳定的含Th矿物晶格中,导致U、Th分离有关(刘英俊等,1986)。U、Mo在矿石中超常富集(富集系数分别为229.21和310.90),与含铀炭质泥岩中富含对Mo、U有强烈吸附作用的有机质和黏土矿物密切相关(刘英俊等,1986);Se的超常富集,推测为深部存在碱性—超基性岩浆演化引起(罗泰义等,2005),同时不排除生物对海水中Se元素的吸收作用和生物有机成矿作用(Wen et al., 2011;施春华等,2011)。

赋矿层位中常量组份SiO₂、CaO、MgO、LOI和微量元素U、Mo、Cd、Se、Ni、Zn均较富集,而贫Al₂O₃、K₂O,且U与CaO、LOI正相关关系显著,稀土元素均为Ce亏损(金中国等,2019),U/Th远大于1,表明它们在沉积—成岩过程中具有共同初始聚集的特点,并与热水沉积作用有关(彭军等,2000),与湘西北、赣西北地区碳硅泥岩型铀矿床中岩矿石的元素组成特征相似(郭葆墀等,1995;吴朝东等,1999;张万良等,2019)。

表1 三穗铀矿床主要常量元素分析结果(%)

Table 1 Analysis results of constant element in Sansui uranium deposit (%)

元素	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	K ₂ O	P ₂ O ₅	CaO	LOI
硅质岩9件	46.35~80.96	0.87~2.88	3.64~5.14	0.65~3.96	0.28~1.32	0.36~6.70	6.00~14.88	3.08~19.29
	64.21	1.53	4.49	2.50	0.66	2.55	8.63	10.74
矿石21件	12.46~79.40	0.70~6.81	1.54~5.14	0.40~11.81	0.25~2.74	0.16~8.75	1.83~18.16	11.43~63.63
	29.49	2.67	2.69	5.68	1.09	1.57	11.71	40.70

表2 三穗铀矿床微量元素分析结果(10⁻⁶)
Table 2 Analysis results of trace element in Sansui uranium deposit (10⁻⁶)

元素	U	Th	Mo	Cd	Ni	Cu	Zn	Se
硅质岩	26.60~192.89	1.46~5.60	16.90~163.24	0.53~20.72	23.74~101.80	35.68~218.16	19.55~461.73	0.06~3.79
9件	115.85	2.64	80.53	6.03	58.19	96.75	174.04	0.93
矿石	122.66~1100.00	1.79~6.41	103.30~1050.00	0.57~120.00	36.87~318.00	41.40~738.00	28.14~1160.00	0.01~55.16
15件	573.03	3.10	466.35	14.33	163.09	184.07	353.56	5.48
$K_{矿}/K_{围}$	229.21/46.34	0.32/0.28	310.90/53.69	71.65/30.15	8.15/2.91	3.35/1.76	5.05/2.49	109.60/18.60
	4.95	1.14	5.79	2.38	2.80	1.90	2.03	5.89
地壳丰度	2.50	9.6	1.50	0.20	20.0	55.0	70.0	0.05*

注:地壳丰度据Rudnick et al.,2003;*为刘英俊等,1986; $K_{围}$ 为围岩富集系数, $K_{矿}$ 为矿石富集系数。

4.2 岩矿鉴定

岩矿鉴定,矿石中富含白云石、石英(或玉髓)、铁矿物、黏土矿物及有机质,见少量方解石、长石、绢云母等,呈微晶—隐晶结构、微晶—粉晶晶粒状结构,层状、纹层状构造。矿物粒径差异大(图4)。

矿石中白云石、方解石含量为7%~64%,呈自形、半自形菱面体状结构,他形粒状产出(粒径7~270 μm),双晶、解理发育,方解石一般<15%(图4a、c);石英、玉髓含量5%~63%,呈微晶粒状、梳状、齿

状,微晶—隐晶质结构、重结晶结构等,沿炭质泥岩层理分布明显,粒径1~25 μm(图4a、b、c)。

矿石中黏土矿物主要由绿泥石、高岭石、绢云母、水云母等组成,含量10%~30%,呈隐晶质状、胶状、团粒状产出,多与炭质等互混,水云母大部分过渡为绢云母,顺层理分布明显(图4b);铁矿物主要见黄铁矿、褐铁矿,零星见磁铁矿、菱铁矿,含量1%~5%,与徐达忠(1990)研究黄铁矿、赤铁矿共生所需的pH、Eh范围宽,而磁铁矿、菱铁矿存在对pH、

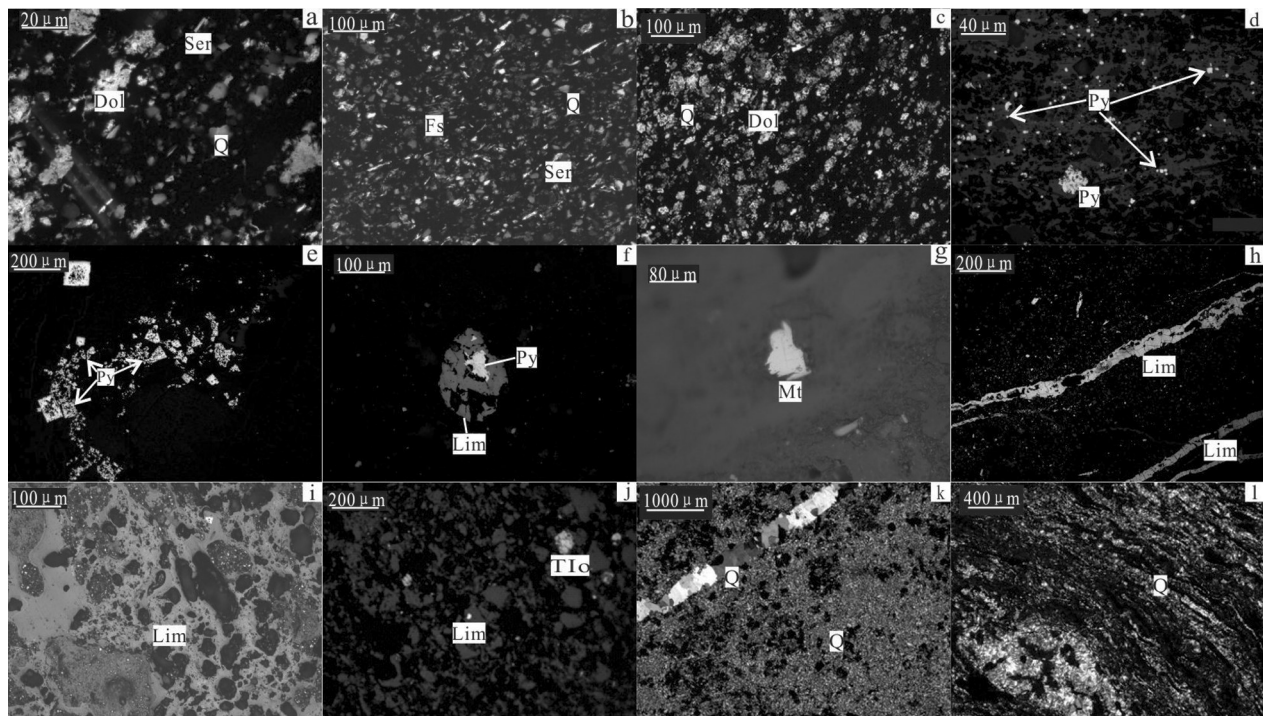


图4 岩矿鉴定矿石中主要矿物组成

Dol—白云石;Q—石英;Fs—长石;Ser—绢云母;Py—黄铁矿;Lim—褐铁矿;Mt—磁铁矿;TIO—钛铁氧化物

Fig.4 Main mineral composition in rock ore appraisal

Dol—Dolomite;Q—Quartz;Fs—Feldspar; Ser—Sericite; Py—Pyrite; Lim—Limonite; Mt—Magnetite; TIO—Ferric titanium oxide

Eh所需条件较严格有关(磁铁矿为 $\text{pH}<3$ 和 $\text{Eh}>0.8$;菱铁矿为 $\text{pH}>8$ 和 $\text{Eh}<0$)。黄铁矿呈自形、半自形、他形粒状结构,浸染状分散分布,粒径 $1\sim 85\ \mu\text{m}$ 。褐铁矿呈非均质,胶状、脉状分布于黏土矿物及炭质、有机质中,为黄铁矿次生氧化的产物(图4d~j)。

围岩(硅质岩)由薄层、沉积流动特征明显的石英、玉髓(含量 $92\%\sim 98\%$)及少量黏土矿物(含量 $2\%\sim 5\%$)、铁质矿物(含量 $1\%\sim 3\%$)组成(图4a、b、c)。石英、玉髓呈隐晶—微晶粒状、纤维状、放射状、重结晶结构,纹层状、气孔状构造,粒径 $1\sim 25\ \mu\text{m}$,与泥质、炭质层呈层状分布明显(图4k~l)。

矿石中见钛铁氧化物(图4j)、气孔构造(图4l),白云石、石英、绢云母、浸染状黄铁矿发育(图4a、b、c、d),褐铁矿多呈岛状、脉状、蜂窝状产出(图4k、h、i),后期石英脉穿插明显(图4k),进一步揭示该区域铀成矿可能受多期热液叠加作用和火山喷气作用的影响,具后生富集成矿特点(Zhang,1983;江永宏等,2005)。

4.3 电子探针背散射分析

矿石中含铁矿物发育,主要为黄铁矿,其次见赤铁矿、褐铁矿、菱铁矿、磁铁矿等;黄铁矿主要呈细粒状(图5a)、莓球状(图5b)、半自形—他形颗粒状(图5a、c)产出。细粒状黄铁矿呈浸染状产于含铀炭质泥岩中,粒度多小于 $1\ \mu\text{m}$;颗粒状黄铁矿自形程度高,结晶好,多呈正方体、五角十二面体分布在白云石、炭质泥岩中,粒度一般 $1\sim 5\ \mu\text{m}$;另有少量莓球状黄铁矿,反映沉积成岩的产物。赤铁矿、褐铁矿主要为黄铁矿氧化形成的次生产物。含矿层中细粒黄铁矿发育,可能为沉积成岩时期海平面迅速上升,造成海底极度缺氧,丰富的有机质还原出大量的 HS^- 与游离的 Fe^{2+} 结合形成,导致铀、有机质、黄铁矿共生(Wilkin et al., 1996;吴朝东, 2000; Algeo et al., 2004;蔡郁文等, 2017)。

石英与有机质、黏土矿物、白云石、重晶石等混杂分布,多呈不规则形状集合体、隐晶质结构产出,少量为表面较光滑、自形粒状晶体,粒径 $1\sim 5\ \mu\text{m}$

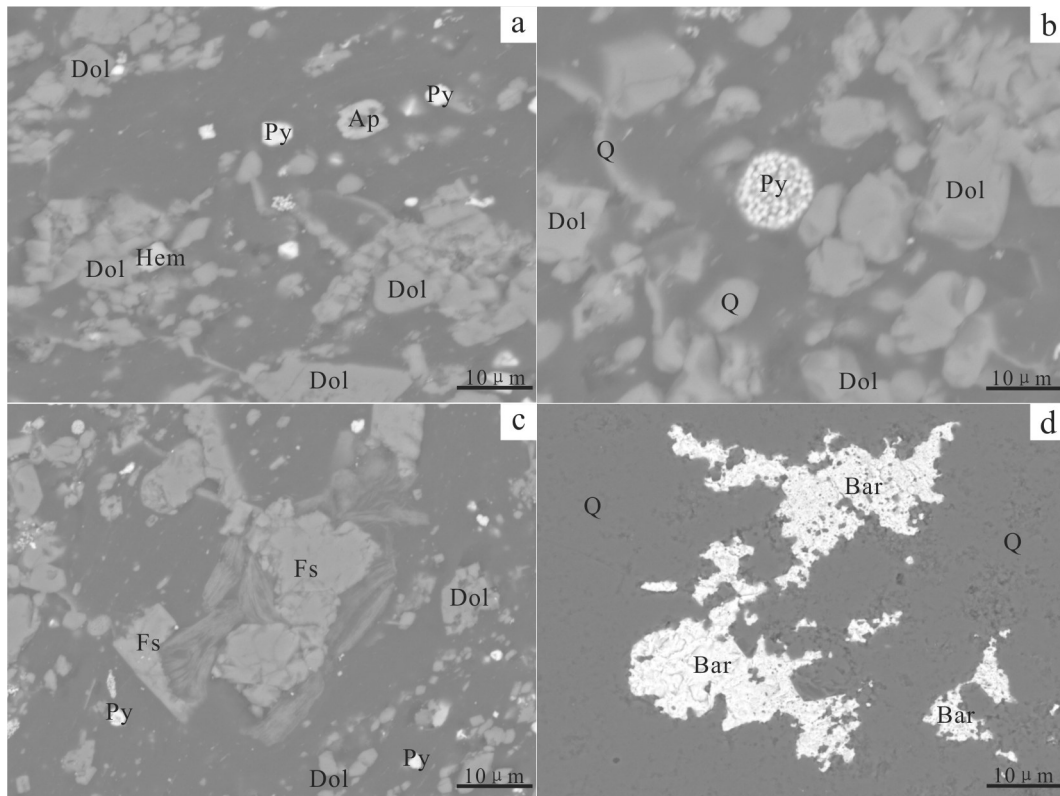


图5 三穗铀矿床矿石电子探针背散射图像

Ap—磷灰石;Bar—重晶石;Dol—白云石;Hem—菱铁矿;Fs—长石;Py—黄铁矿;Q—石英

Fig .5 Electron probe backscattering image of ore in Sansui uranium deposit

Ap—Apatite; Bar—Barite; Dol—Dolomite; Hem—Siderite; Fs—Feldspar; Py—Pyrite; Q—Quartz

(图5b,d)。白云石十分发育,以自形、半自形菱面体为主,少量为他形粒状产出,粒径5~10 μm,与含铀炭质泥岩混杂产出(图5a,b,c)。矿石中零星见磷灰石(图5a)、长石(图5c)和结晶较好的重晶石(图5d),推测均为海底火山或热液喷流沉积的产物(吴朝东等,2000)。

4.4 扫描电镜分析

扫描电镜分析测试发现铀矿物丰富,主要有沥青铀矿、硅钙铀矿、硒铅铀矿、钛铀矿、磷铀矿及水碳铀等,它们以纳米—微米级粒状、柱状(粒径多<10 μm)、细脉状或隐晶质形式赋存于有机质、黏土矿物等聚铀矿物中(图6)。

沥青铀矿相对较发育,主要呈胶态肾状、钟乳状、不规则团块状、细脉状产于有机质及黏土矿物中,粒径1~6 μm(图6a);晶质铀矿呈长方形柱状(长5 μm×宽1 μm)、不规则粒状、絮状、胶结状(粒径<1 μm)产于有机质中(图6b);硅钙铀矿沿黑色炭质泥岩裂隙呈细脉状、钟乳状产于有机质中,粒径1~7 μm(图6h,i);硒铅铀矿、钛铀矿呈不规则粒状产出(图6a,c,e,i),与硅钙铀矿、水碳铀矿、沥

青铀矿及磷灰石、黄铁矿、有机质共生,粒径较小,多小于1 μm(图6a,c,e,g,h);磷铀矿呈细脉状、胶态肾状、钟乳状、粒状分布在有机质及黏土矿物中,粒径0.5~4 μm(图6d,f)。铀矿物中除沥青铀矿外,其余铀矿物均为产于氧化带的次生产物,与见铜蓝(图6g)及样品采于地表吻合。矿石中硅钙铀矿与钛铀矿、晶质铀矿,沥青铀矿与磷铀矿、硒铅铀矿等矿物之间呈环带状分布,暗示该区铀成矿具多期热流体叠加改造成矿特点。晶质铀矿主要呈不规则粒状、絮状、胶结状形态产于炭质泥岩中,并与沥青铀矿、硅钙铀矿、莓球状黄铁矿、高岭石、褐铁矿共生,推测矿床为中低温热液成因(张静宜等,1995;张成江等,2007),与漆富成等(2014,2015)在湘西北海相磷块岩中见形成于高温高压环境,以包体形式呈立方体、八面体产于辉镍矿物的晶质铀矿有较大差异。矿石中偶见锌铁尖晶石矿物(图6c、f),可能为深层高温热液作用的反映(Hitzman,2003;杨永强等,2010)。

通过微观研究,三穗铀矿床矿石矿物组成如表3所示。

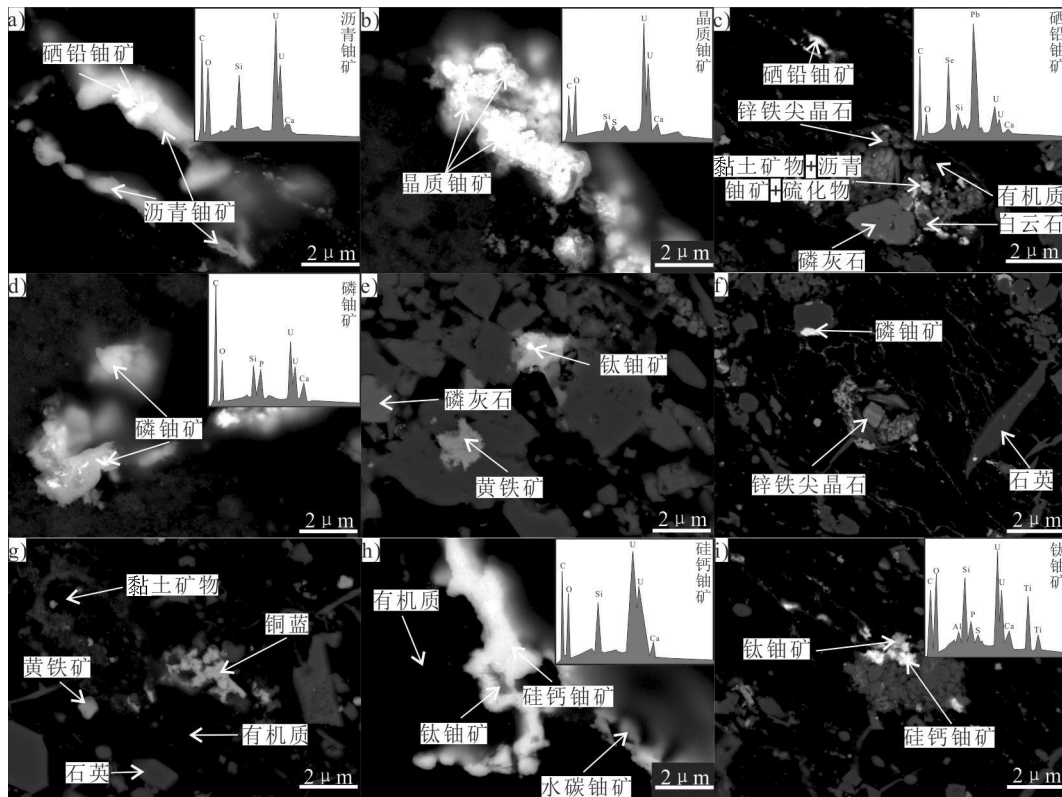


图6 三穗铀矿床铀赋存形式BSE图像

Fig.6 BSE image of uranium occurrence form of Sansui uranium deposit

表3 三穗铀矿床矿石矿物组成

Table 3 Mineral composition of ore in Sansui uranium deposit

铀矿物	共伴生金属矿物	非金属矿物	黏土矿物
沥青铀矿、晶质铀矿、硅钙铀矿、钍铀矿、磷铀矿、硒铅铀矿、钙铀云母、水碳铀矿、铜铀云母等	黄铁矿、辉铜矿、铜蓝、锌铁尖晶石、铁矿、赤铁矿、磁铁矿、菱铁矿、重晶石、钛铁氧化物等	石英、白云石、方解石、磷灰石、长石等	绿泥石、高岭石、绢云母、水云母等

5 讨 论

5.1 铀成矿机理

矿床中富含有机质的黏土矿物和黄铁矿发育,这些矿物具有极强的吸附能力和聚铀作用,能吸附大量纳米级铀以吸附态赋存,仅少量铀以超微或超显微的沥青铀矿、钍铀矿、晶质铀矿微粒、球粒或微脉产出。基于成矿地质背景及前述相关分析,认为该区域铀矿形成经历了含矿岩系中的初始富集、后生氧化淋滤及热液叠加富集等过程。

5.1.1 含铀岩系的形成及铀的初始富集

晚震旦世—早寒武世,受全球“雪球事件”、Rodinia超大陆裂解及新元古代雪峰运动的影响,华南陆块发生裂解作用,海平面迅速上升,研究区形成深海—半深海的滞流还原环境和裂谷盆地沉积中心(杨恩林等,2014),基底地层及侵入其中的富铀花岗岩的风化剥蚀,为区域铀成矿提供丰富的铀源(钟福军等,2017),沉积形成铀地球化学背景值高的含铀岩系($14 \times 10^{-6} \sim 270 \times 10^{-6}$,杜乐天,1984; 40.70×10^{-6} ,蔡郁文等,2017),同时由于裂谷拉张、区域性大断裂深切地幔,海底喷发的热流体沿断层构造带来大量U、V、Mo、Cd、Co、Ni、Cu、Pb、Zn、Fe、Se等成矿物质及对铀成矿具有重要控制作用的CO₂等深源矿化剂(胡瑞忠,1991;漆富成等,2012;Pi et al.,2013;杜乐天,2014),导致裂谷盆地“铀库”增加(Sleep,1990),促进铀初始富集。

在沉积成岩及铀矿化过程中,铀主要以分散吸附形式赋存于炭质泥岩中,可能有少量的铀在碱性的成矿流体运移过程中,以碳酸铀酰络合物(UO₂(CO₃)₂²⁻、UO₂(CO₃)₃⁴⁻)、硅酸盐络合物(nNa₂O·mSiO₂)迁移,当物理化学条件发生变化,络合物分解,形成少量的沥青铀矿、晶质铀矿,当含铀流体中Ti浓度较高时,则可形成钍铀矿(刘英俊等,1986),这些铀矿物主要以纳米—微米级粒度赋存。

据研究(郭葆墀等,1995;牟保磊,1999;漆富成

等,2015;王文广,2015),次生铀矿物主要分布于聚铀矿物的晶格缺陷、微裂隙及微孔隙中,特别是微细粒钛铁氧化矿物对U有极强的吸附能力,部分U被其结构破坏的矿物晶格吸附,部分U被还原沉淀在含钛矿物边缘富集(陈路路等,2018)。共伴生脉石矿物主要为黄铁矿、石英及少量与海底火山喷发、气相交代、氧化和凝聚作用有关的磷灰石、绢云母、重晶石等(郑大中,2001;王文广,2015)。该阶段形成的矿物组合为沥青铀矿(少量晶质铀矿、钍铀矿)+黄铁矿+微晶石英或玉髓+重晶石+磷灰石(少量)+绢云母(少量)。

5.1.2 表生氧化淋滤及后生富集

研究区铀初始富集的老堡组沉积形成后,经历了加里东—印支碰撞造山运动,长期隆起遭受风化剥蚀,为后期铀聚集成矿提供了丰富的物源(郭葆墀等,1995)。燕山—喜马拉雅板内伸展运动形成系列断陷盆地(Hu et al.,2008,2009),盆地边缘发育的断裂构造为大气降水下渗及铀的活化迁移提供了较好的水文地质循环系统,并在运移的途中不断吸收、浸取地层内的U、V、Se、Cd、Mo、Ni等成矿物质,形成富U⁶⁺的碳酸铀酰络合物(UO₂(CO₃)₂²⁻、UO₂(CO₃)₃⁴⁻等)成矿流体(胡瑞忠,1991;胡瑞忠等,2004),迁移进入低洼区域的老堡组碳硅泥岩中。在白垩纪—古近—新近纪干燥炎热的气候条件下(贵州省地质调查院,2017),蒸发作用、氧化作用、生物作用强烈,利于形成分布范围广、厚度大的氧化带。加之斜切三穗向斜的界牌、施洞口断层产状陡、延伸大(图2),促进氧化带向深部发展。在此背景下,部分停留在氧化带的碳酸铀酰络合物、磷酸铀酰络合物与Ca、Se、Pb等成矿元素形成次生铀矿物,如硅钙铀矿、硒铅铀矿、磷铀矿、芙蓉铀矿、水碳矿等;继续沿断层、裂隙及层间裂隙向深部运移的流体,在有机质的热演化和新生代古近纪煌斑岩的侵入作用下(贵州省地质调查院,2017),产生大量H₂、CH₄、H₂S、CO、CO₂等还原剂,快速消耗水体特别

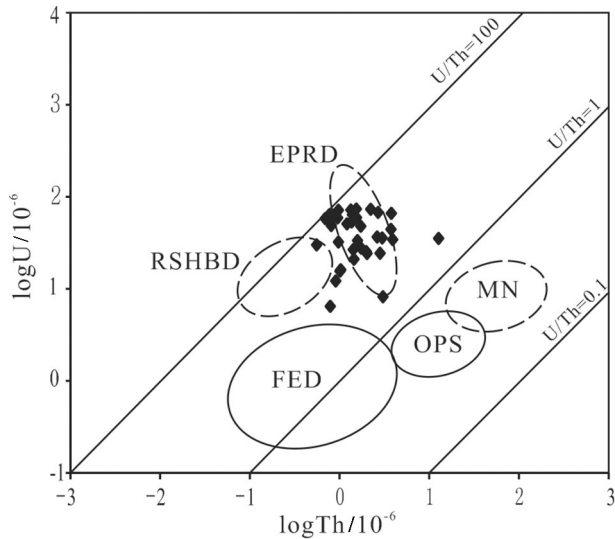


图7 三穗铀矿床围岩U-Th图解(据Bostrom, 1983)
RSHBD—红海热卤水矿床;EPRD—东太平洋隆起沉积物;MN—
锰结核;FED—古热水喷流沉积;OPS—正常远洋沉积
Fig.7 U-Th diagram of surrounding rock of Sansui uranium
deposit (after Bostrom, 1983)
RSHBD—Red sea hot brine deposit; EPRD—Eastern Pacific uplift
sediments; MN—Manganese nodules; FED—Paleohot water jet
deposit; OPS—Normal pelagic deposit

是成矿流体中氧形成还原地球化学障(黎富成等, 2015;李延河等, 2016;蔡郁文等, 2017),同时,含铁矿物在氧化还原过渡带对 U^{6+} 的吸附、吸收及还原等作用(Scott et al., 2005; Massey et al., 2014),导致成矿流体中 U^{6+} 被还原为 U^{4+} 沉淀,并与初始富集的铀叠加形成工业铀矿体。该过程形成的矿物组合为铀次生矿物(硅钙铀矿+硒铅铀矿+磷铀矿+钛铀矿等)+沥青铀矿(残留)+褐铁矿+黄铁矿(残留)+石英(少量)+方解石(少量)+铜蓝(少量)。

5.2 铀成岩成矿的环境演化

据闵茂中等(1992)、郑大中(2001)、王文广(2015)研究,在地壳深部的还原环境中,氢易于与铀化合成为气相 UH_3 、 UTi_2H_7 (铀钛合金氢化物),与磷化合成为 PH_3 、 $Ca_3P_3H_{16}$ (磷钙合金氢化物),并与其他壳层元素氢化物(如 SiH_4 、 BaH_2 、 AlH_3 、 CaH_2 、 MgH_2 、 KH)以及 CO 、 CH_4 、 C_2H_6 等碳的化合物,在伴随断裂构造活动或海底火山活动时,以气态或部分溶于水呈气液混合流体喷出,部分金属以纳米微粒由深部向地表迁移(王学求等, 2011)。U、P、Si、Ba、K、Al、Fe的氢化物喷出若遇充足的氧气,或随热液、热汽迁移至地壳浅部,可形成钛铀矿、晶质铀矿、硅

钙铀矿等铀矿矿物及石英、玉髓、褐铁矿、白云石、方解石、重晶石、磷灰石、高岭石、水云母等共生矿物,与湘西地区下寒武统黑色岩系中铀矿物的成因相一致(王文广, 2015)。

黔东地区老堡组Zr/Si硅质岩的 $\delta^{30}Si$ 、 $\delta^{18}O$ 值变化范围均较大,分别为 $-0.1\text{‰} \sim 0.9\text{‰}$ (0.314‰)和 $12.8\text{‰} \sim 21.2\text{‰}$ (17.3‰)(张位华等, 2003), $\delta^{30}Si$ 和 $\delta^{18}O$ 值显示,该区硅质岩具热水沉积成因,沉积环境为深海—半深海水体(Douthitt, 1982;高常林等, 1999)。三穗矿床36件硅质岩(含收集27件 \bullet)的 δU 为 $1.78 \sim 1.99$ ($\delta U = 2U/[U+Th/3]$),平均1.96,均远大于1(Wignall, 1994); $Al/(Al+Fe+Mn)$ 均值为0.19, $Fe/Ti > 20$ (Bostrom et al., 1969, 1973),U-Th图解样品主要落于东太平洋隆起沉积物区,且发育大量重晶石(图7),表明该区硅质岩的深源特征显著,含铀岩系主要为海底火山喷发、喷溢沉积成岩的产物,其中富含莓球黄铁矿、有机质及碱金属和碱土金属,显示为还原、碱性的环境,与区域上,在震旦纪/寒武纪的转折期存在一次较大规模的缺氧事件吻合(吴朝东等, 1999, 2000),也与有关学者研究认为,研究区震旦—寒武系黑色岩系成岩成矿具热水喷流成因结果一致(李胜荣等, 1995;江永宏等, 2005)。

含铀岩系形成后,经历了多次区域性陆内挤压造山隆起和伸展拉张构造活动(宋传中等, 2019),干燥炎热气候的风化剥蚀,碱金属和碱土金属的流失,有机质及黄铁矿被氧化等作用。据研究(窦小平等, 2015),矿石中 Fe_2O_3 含量与铀的沉淀呈正相关关系,这是由于 $Fe^{2+} \rightarrow Fe^{3+}$ 转化的氧化电位比 $U^{6+} \rightarrow U^{4+}$ 要高, Fe^{2+} 被氧化为 Fe^{3+} 的同时,可将水体可溶态中的 U^{6+} 还原为 U^{4+} (蔡郁文等, 2017)。

综上所述,该区铀矿形成经历了还原、碱性环境(铀预富集) \rightarrow 氧化、酸性环境(剥蚀区铀的淋滤,次生铀矿物形成) \rightarrow 还原、碱性环境(吸附、热液叠加富集)的成矿环境演变过程。

6 结 论

(1)黔东地区含铀岩系形成于震旦纪/寒武纪转折期的陆缘裂谷和陆缘裂陷缺氧还原环境,铀源与雪峰期海底火山喷发、喷溢作用及含铀地质体的风化淋滤有关。

(2)铀矿床形成经历了含铀岩系的沉积成岩及

铀的初始富集,燕山期—喜马拉雅期板内伸展构造背景下的淋滤、热液叠加改造再富集的成矿过程,后生成矿特征明显,成因属碳硅泥岩型。

(3)三穗铀矿床铀矿物丰富,主要有沥青铀矿、硅钙铀矿、硒铅铀矿、钛铀矿、磷铀矿及芙蓉铀矿、水碳铀矿等,它们以纳米—微米级粒状、柱状(粒径多 $<10\ \mu\text{m}$)、细脉状或隐晶质形式赋存于富含有机质、黄铁矿、黏土矿物、含磷矿物等聚铀矿物中,主要为热液叠加及次生改造形成。同时形成白云石、方解石、石英、玉髓、重晶石、赤铁矿、褐铁矿、绢云母等共伴生矿物。

(4)黔东三穗大型铀矿床的发现,表明黔东地区陆缘裂谷、裂隙缺氧还原环境沉积形成的老堡组含铀岩系是大规模铀矿成矿作用的产物,其找矿潜力大,远景好,加强成矿规律、矿床地质地球化学、矿石矿物学及成因研究,将为促进区域成矿预测、扩大找矿勘查成果及丰富该类型铀矿成矿理论提供科学依据。

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注释:

①贵州省有色和核工业地质局核资源地质调查院.2015.贵州省岑巩注溪—剑河南明铀矿整装勘查报告[R].

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