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The Fluid Flows and Uranium Mineralization in the Northern Ordos Basin, North China

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1 INTRODUCTION

A huge quantity of uranium reserves discovered in the northern part of the Ordos basin in north China is interesting more and more uranium geologists in the world. The uranium mineral belt, including a series of deposits, such as Dongsheng Deposit, Nalinggou Deposit, Daying Deposit and West Daying Deposit, extends from east to west >100km long. Moreover, the new deposits are still under discovery. Current exploration situation shows a great potential in the west and south of the belt.

1.1 Change of Exploration Strategy

The exploration work in the Ordos Basin have been undergone an unusual history. During the 1990's, the uranium geologists thought the Ordos Basin is unfavorable to form a large quantity of uranium reserves because the modern ground water goes out of the basin into the Yellow River surrounding the basin. It is then speculated that uranium could not accumulate in the case of going-out water hydrogeological condition. But this hypothesis was soon overturned by the discovery of the Dongsheng Deposit in 2000. Reconsideration of tectonic evolution for the Ordos Basin demonstrates that the water- going-out condition has come into being only because the Yellow River faulted sub-basin separates the northern part of the basin with the uplifted mountainous area since the Cenozoic. Prior to the Cenozoic, the uranium-oxygen-bearing fluids (UOF) sourced from the northern uplifted mountains can flow into the basin and form the uranium ore deposits. The breakthrough of the Dongsheng Deposit encouraged uranium explorers to look for more deposits in the basin.

1.2 Characteristics of Ore Bodies

The burial depth of ore bodies varies from 200˜300m in east to 700˜800 m in west of the north basin. The uranium mineralization is hosted only in the upper part of the Zhiluo FmI in east and in both the upper and lower of the Zhiluo FmII in west. In general, the whole uranium mineral belt is at large controlled by the paleo- oxidized front which is EW-trending snakelike on the plane geologic map. A single ore body is always tabular, lenticular and cystic in all deposits. None of the typical rollfront bodies have been found up to now. Some lenticular ore bodies are controlled by deep-seated fault, such as the Bojianghaizi Fault in the Nalinggou Deposit. Averagely, the mineralization zone is 9000m long, 500˜2000m wide and 3˜4m thick in Nalinggou and 2000˜8000m long, 5.26m thick in Daying.

1.3 Atypical Interlayered Oxidized Zone

It is worthy noticing that the oxidized sandstone in all deposits is not yellow or red and has been turned into green in color. Usually, the ore bodies are lie in the boundary between green and grey sandstones both horizontally and vertically. I.e., the sandstone is green to the north and grey to the south of the mineralized zone belt. Above is green the sandstone and below is grey. Hence, the interlayered oxidized zone seems to be atypical comparing to typical oxidized zone in a sandstone-type uranium deposit.

2 GEOLOGICAL SETTINGS

2.1 Tectonic Evolution

The tectonic evolution of the northern part of the Ordos Basin is accordant to that of the Yin Shan tectonism. The coupling of the mountain and basin determines the relationship between uplift and subsidence. At the end of Permian, the North China Plate collided with the Siberian Plate caused closure of the paleo-Asian ocea 【1】【2】【3】【4】【5】【6】. During the period of Triassic, strong compression resulted in the uplifting of Yin Shan, and formation of large-scaled folds and thrust faults with strong magmatism 【7】【8】【9】. From the Early to Middle Jurassic, a wide spread coal-bearing rock series deposited within the depression area of both uplift and sub-basin. The target layer hosting uranium deposited from the large-scaled fluvial to delta system 【10】. During the Late Jurassic, Yin Shan re-uplifted and re-thrusted again due to the regional shortening 【11】【12】【13】. Accordingly, the Anding Fm and Fenfanghe Fm deposited from the fluvial to lacustrine environments. During Cretaceous, the basin underwent early extension with deposition of the Dongsheng Fm, then late uplifting and being eroded due the compression again 【14】【15】 with eruption of basalt magma at the end of the Mesozoic 【16】. Since the Cenozoic, especially Oligocene, the rapid subsidence surrounding the basin due to the normal faults caused formation of the Hetao, Yinchuan and Fenwei faulted basins, with regional eruption of basalt magma and earthquake 【17】【18】. The northern part of Ordos has been gradually separated from Yin Shan.

2.2 Target Layers and Depositional Facies

Up to present, three rock series have been verified as the target layer for sandstone-type uranium deposits in the Ordos Basin. They are the Yan'an Fm (J2y), the lower Zhiluo FmI(J2z1-1) and the upper Zhiluo FmI(J2z1-2). The Yan'an Fm is composed of thick coal beds intercalated with thin sandstone and mudstone beds, which deposited in swamp and lacustrine at the damp climate. The Zhiluo Fm unconformably overlain the Yan'an Fm with an apparent weathered crust abundant in kaolinite. Different from the Yan'an Fm, the Zhiluo Fm consists of thick layered sandstone and thin to thick layered mudstone, which deposited in braided (J2z1-1) and meandering (J2z1-2) fluvial systems 【10】. The Zhiluo Fm Iabundant in organic matter is partially interbedded with thin coal beds which indicates the damp climate environmental setting.

3 METHOD AND RESULT

In order to study uranium-oxygen-bearing flow and its mineralizing processes, we have sampled both the uplifted area (Yin Shan) and drilling cores in the basin deposits.

3.1 Heavy Minerals

We have taken 32 samples from 18 boreholes in Nalinggou Deposit, Xinsheng Deposit and west Daying Deposit. Firstly, the samples are crashed, then acidified and washed with water and baked. All heavy minerals are separated with heavy solutions. After the 0.063 ˜ 0.5mm mineral grains are separated from heavy solution, all minerals are identified by binocular microscope. Statistics shows that heavy minerals are garnet (41.78%), zircon(6.41%), sphene(1.93%), hornblende(1.54%), tourmaline(1.34%), rutile(1.31%) and so on. It is inferred that the uplift source rock for the target layer (J2z) is mainly metamorphic rocks and neutral to acidic igneous rocks combining with the thin sections.

3.2 SEM & XRD

37 samples for XRD and 18 samples for SEM are selected from the Nalinggou Deposit. Samples for XRD were analyzed with D/max-2500 and TTR at the laboratory of Research Institute of Petroleum Exploration and Development. Samples for SEM were analyzed under NovaSEM450 and X-Max at the Key Laboratory of Nuclear Resources and Environment of Ministry of Education, East China University of Technology. Clay minerals in target sandstone include smectite, kaolinite, chlorite and illite. The average of clay minerals in sandstone is about 15.6%. Among clay minerals, smectite in gray sandstone ranges from 44% to 76% with av.59.4%, in grey green sandstone from 28% to 60% with av.50.1% and in green sandstone from 12% to 62% with av.42.5%. Kaolinite ranges from 15% to 34%, av. 24.9% in gray sandstone, 18% to 44%, av.25.8% in grey green sandstone and 17% to 42% with av.26.5% in green sandstone. Chlorite ranges from 6% to 17% with av.10.8% in grey sandstone, 12% to 41% with av.19.5% in grey green sandstone and 13% to 48% with av.27% in green sandstone. Morphologically, smectite is semi-euhedral to anhedral. It is cotton-like coating the grains of feldspar and quartz, sometimes honeybee-nest like in pores. Kaolinite is usually booklet-like and vermiform in pores of sandstone. Chlorite is light green and foliated, sometimes flower-like and spheroidal, coexisting with pyrite. Overall, illite is less in content and hard to be identified under SEM.

3.3 EMPA (U Minerals and Chl)

In this study the electron probe microanalysis (EPMA) was accomplished in the Key Laboratory of Nuclear Resources and Environment of Ministry of Education, East China University of Technology using: (1) a JXA-8100 electronic microprobe, (2) a IncaEnery energy disperse spectroscopy, (3) an acceleration voltage: 15.0KV and (4) a probe diameter with 1μm beam probes: 2.00×10-8 A. First a rough qualitative analysis was done by the IncaEnery energy disperse spectroscopy and then quantitative analysis on several uranium minerals selected from uranium-bearing ores by means of the observation and analysis of the mineral grains shown in the electron back-scattering Images. Coffinite is the most important uranium mineral in all deposits. It is several μm to several ten μm in size with UO250˜70%wt and SiO2 10˜20%wt and coating grains or filling the pores among grains or in the cleavage plane of biotite. Coffinite sometimes replaces the blocky matrix in sandstone. Coffinite usually co-exists with pyrite and ilmenite. The second important uranium mineral is pitchblende. It is 3 to 15μm in size with UO_2>80%wt, CaO≈4%wt and SiO_2<2%wt. Generally, pitchblende is well crystallized and filling the pores among grains in sandstone. Brannerite and Titanium-bearing uranium minerals are special in sandstone-type uranium deposit because they are formed under higher temperature. They are several μm to about 100μm in size with UO_2 46˜53%wt, SiO_2 6˜16%wt and TiO_2 8˜15%wt and coexisting with calcium cement among sandstone grains. It is worthy to mention that there are some low temperature hydrothermal sulphide minerals such as galena, clausthalite and brookite in mineralized sandstone. Chlorite is particularly analyzed by EMPA in this study. The composition of chlorite is as following (in wt): SiO_2 24.02 ˜ 31.87% (av.28.45%), Al_2O_3 17.16 ˜ 21.31%(av.18.63%), FeOT 21.80˜36.39%(av.27.31%), and MgO 5.80˜16.35%(av.12.42%). The inverse relationship of iron with magnesium means they are replaced each other in chlorite crystal. The gradual decease of silicon from green to grey green to grey sandstones implies that the solution precipitating chlorite turns to less acidic.

4 DISCUSSION AND CONCLUSION

4.1 About Structural Inversion

Structural inversion occurred in early period of Cenozoic is eventful in the evolution of tectonism for the Ordos Basin. During the late Mesozoic, the west and north area to the basin were under compression. The slope between the uplift (Yin Shan) and Yimeng Uplift (in basin) is favorable for UOF to flow into basin. A large quantity of uranium via solution was brought into target layers (Zhiluo Fm). But this metallogenic process was ceased because the Yinchuan faulted subbasin and Hetao faulted subbasin began to form at about 40Ma (the middle Eocene). The strong faulting occurred at about 20Ma (Miocene) with rapid subsidence and thick-layered sediments in subbasins. This extensional tectonism is favorable to upward migration of deep seated hydrothermal solution.

4.2 Target Sandstone Petrology

The clastic grains in target sandstone in the Ordos Basin amount to 76˜92%, which mainly consist of quartz, feldspars and lithic fragments. Quartz, sub-angular to sub-rounded and clean on surface, ranges from 33% (in vol.) to 76%, av.50%. Feldspars, including plagioclase, microcline and perthite, ranges from 10% to 50%, av. 30%. Clayization, epidotization and zoisitization are common within feldspars. Feldspars are sometimes replaced and cut through by carbonate minerals. Lithic fragments range from 5% to 50%, av.30%. The metamorphic rock dominates lithic fragments. The others are quartzite, siliceous rock and granite. Based on the ternary diagram of Folk(1968)【19】, the target sandstones, petrologically, are mainly lithic arkose and partially arkose and feldsparthic lithic sandstones.

4.3 About Uranium Source

Jiao et al. (2012) ‘s【20】study shows there are three kinds of uranium source suppliers, metamorphic rocks, igneous rocks and sandstone itself. As stated above, the sediment source of target sandstone is the rocks of Yin Shan uplift. The metamorphic gneiss contains 2.54×10^{-6} uranium with $-\Delta U$ 43.7% (lost uranium). The igneous rock (acidic intrusions) contains 9.29×10^{-6} uranium with $-\Delta U$ 36.9%. Sandstone itself can contribute uranium to ore deposits. Uranium content in grey sandstone ranges 0.01 to 47.63×10^{-6}, av.5.75×10^{-6}. Grey green sandstone contains uranium at 0.01～9.56×10^{-6}, av.2.16×10^{-6}. Red sandstone contains uranium at 0.01～9.39×10^{-6}, av. 2.63×10^{-6}. Both green and red sandstone (residual) lost more uranium than other colors of sandstone. Hence, uranium in deposits can source from multiply rocks.

4.4 Genetic Model and Hydrothermal Reworking

The enrichment of huge amount of uranium in the Ordos Basin has undergone three stages as following. (1) Pre-enrichment stage. Sediments sourced from the uranium-bearing metamorphic and igneous rocks were transported by surface water via fluvial systems into the basin during the middle Jurassic time. Uranium in sandstone grains and matrix can be dissolved later. So, the depositional process plays pre-enrichment role in mineralization. (2) Interlayered Oxidation Stage. The large quantity of uranium-oxygen-bearing fluids leaching both the uplift provenance rocks and pathway sandstones flow into underground target in the basin during late Jurassic to Cretaceous time. UOF can be reduced at the redox zone created by organic matter to form tabular, and/or rollfront uranium ore bodies. (3) Hydrothermal and Petroleum Reworking Stage. The Yimeng Uplift area in the northern part of the basin was cut off from the Yin Shan (uplift) by the Yinchuan and Hetao faulted sunbbasins under regional extensional stress since the Miocene time. The hydrothermal fluids migrate through normal faults into the uranium ore bodies and redistribute the original mineralization. During this process, a large amount of pitchblende has turned into coffinite because of combination of silicon released from feldspar alteration with uranium in pitchblende, with hydrothermal sulphide minerals forming and co-existing with uranium. At the same time, tabular/rollfront ore bodies changed into tabular, and/or lenticular and cystic. This is the reason why none of rollfront ore body has been found in all deposits. Moreover, a large-scaled petroleum migrated from the hydrocarbon source rock turns the red and/or yellow oxidized sandstones into green in color. The explorers may make good use of this model to predict the uranium ore bodies and drill the exploration boreholes in the future.

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