Uranium Mineralization in the Ordos Basin: A Comparison with Classical Tabular Sandstone Uranium Deposits

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Summary
A number of uranium deposits occur in Jurassic sandstones along the margin of the Ordos Basin in northern China. These deposits share similarities with classical tabular sandstone uranium deposits in the U.S.A., but formed in different physicochemical and hydrodynamic conditions. This paper describes the geologic characteristics of uranium deposits in the Ordos Basin, summarizes the geochemical data characterizing the mineralization condition, and proposes a hydrodynamic model on the localization of the deposits. Like the classical tabular sandstone uranium deposits, the Ordos uranium deposits are characterized by fine-grained, disseminated mineralization, and formed from interaction between oxidizing and reducing basinal fluids. However, the classical tabular sandstone uranium deposits were formed in early diagenesis, whereas the Ordos deposits were formed at elevated temperatures in deep burial environment. The depth of mineralization is determined by the relative strength of the upward flowing, reducing basinal fluid and the downward moving, oxidizing fluid.

Introduction
Sandstone-hosted uranium deposits are epigenetic deposits occurring in sandstones in sedimentary basins, and constitute about 30% of world uranium resources (Kyser and Cuney, 2009). They are classified into four main types, i.e., the basal type, tabular type, roll-front type, and tectonolithologic type (Kyser and Cuney, 2009). Tabular sandstone uranium deposits, which account for about 65% of the total United States historical production and reserves of uranium, are best developed and well studied in the Colorado Plateau (Sanford, 1994). In recent years, a number of sandstone-hosted uranium deposits have been found in the Ordos Basin in northern China, which is increasingly recognized as an important uranium mineralization province (Xue et al., in press). This paper describes the geologic and geochemical characteristics of the Ordos uranium deposits, and discusses on the similarities and differences with the classical tabular sandstone uranium deposits in the U.S.A. in terms of thermal and hydrodynamic regimes.

Geologic and geochemical characteristics
The Ordos Basin in northern China (Fig. 1) is a Meso-Cenozoic intracontinental basin developed upon Paleozoic sedimentary rocks, which in turn are underlain by Precambrian basement belonging to the North China craton. The Paleozoic rocks consist of Cambrian and Ordovician marine carbonates and mud rocks, followed by a hiatus from Silurian to Devonian, and then by marginal marine, coal-bearing sediments of Carboniferous age and fluvial – lacustrine coal-bearing formations of Permian age. Starting in the Triassic, the Ordos Basin developed as an intracontinental basin, filled with Triassic, Jurassic and Cretaceous fluvial and lacustrine sediments. The strata are generally horizontal or gently dipping (1-3^{o}) in the interior of the basin, but were subjected to significant folding and faulting during the Yashanian (Mesozoic) orogeny in the marginal parts of the basin. Most uranium deposits in Ordos are hosted in

sandstones of the Upper Jurassic (the Zhiluo Formation) and occur near the margin of the basin, whereas major oil and gas reservoirs are located in the Paleozoic strata in the lower part of the basin (Fig. 1).

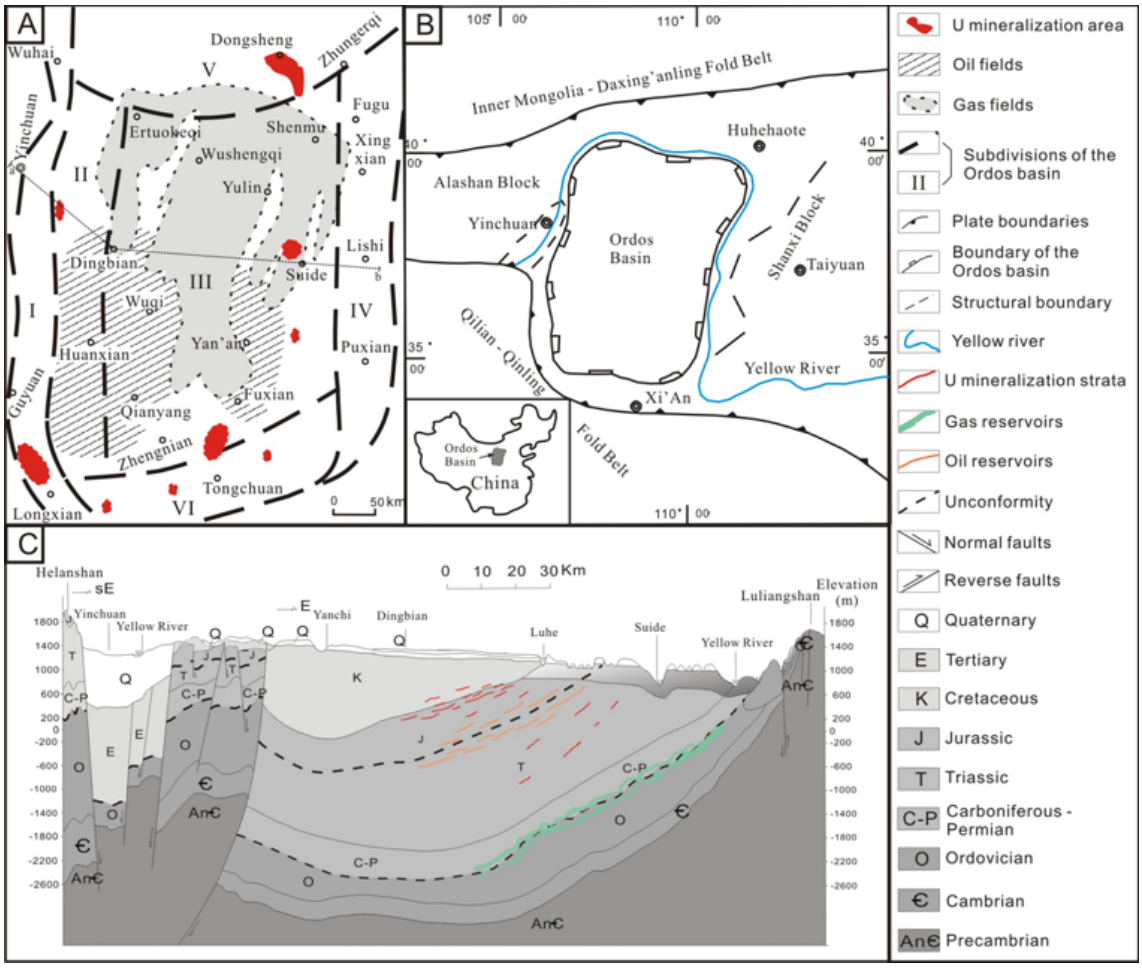

Figure 1. (A) Distribution of oil, gas and uranium mineralization in the Ordos Basin. Subdivisions of the basin include the Western Margin Thrust-Faulting Belt (I), Western Depression Belt (II), Eastern Slope Belt (III), Western Shanxi Fold Belt (IV), Yi-Meng Uplift (V), and Weibei Uplit (VI). Line a-b indicate the approximate location of the cross section shown in Fig. 1C. (B) Regional tectonic setting of the Ordos Basin. The location of the Ordos Basin in China is shown in the insert. (C) A conceptual west-east cross section of the Ordos Basin, showing the major strata of oil and gas accumulations and uranium mineralization (after Wang et al., 2004).

The most important uranium deposits in Ordos include the Shengshangou deposit in the Dongsheng area, the Guojiawan deposit in the Longxian area, and the Diantou deposit in the Huangling area. Except for minor occurrences in carbonaceous shales, most uranium mineralization occurs in sandstones, and the orebodies are typically tabular. Uranium mineralization occurs as uranium minerals and uranium absorbed in organic matter and clay minerals. The main uranium mineral is coffinite, which is fine-grained (a few microns to a few tens of microns) and may show colloform textures, and is typically associated with pyrite, oxidized ilmenite and bitumen. The mineralization is associated with alterations marked by prominent change in color of the host rocks. In the Diantou deposit, the immediate host rocks of the ore bodies are light grey sandstones, whereas the non-mineralized part of the Zhiluo Formation is red-colored. In the Dongsheng deposit, the orebodies are located between grey sandstones in the footwall and greenish grey sandstone in the hanging wall, which changes to purple-red sandstones further upward and away from the orebodies. The red-colored sandstones consist of mainly medium- to fine-grained quartz and feldspars, with minor amounts

of biotite grains and matrix. Both the greenish grey- and grey-colored sandstones are characterized by abundance of alteration minerals including chlorite, epidote, illite, sericite, kaolinite, quartz overgrowth, and calcite, with chlorite being particularly rich in the greenish grey sandstones. Both Fe-poor and Fe-rich calcite are present in the ore (Fig. 2A), occurring as cements or replacing detrital quartz and feldspars. Detrital biotite is commonly replaced by chlorite, and kaolinite occurs as reaction rims around feldspars (Fig. 2B).

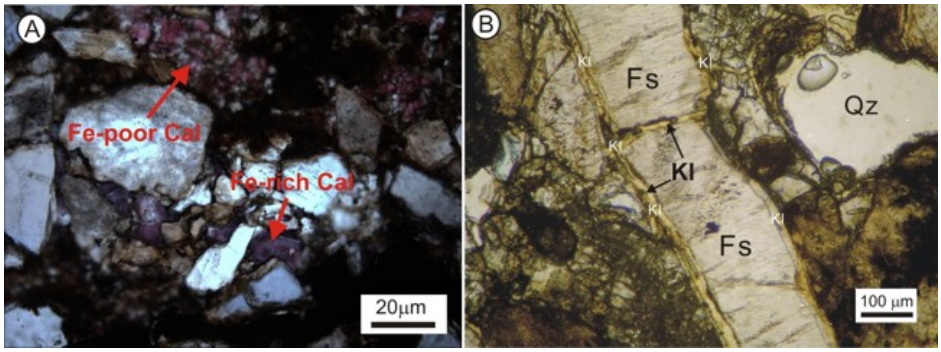

Figure 2. (A) Fe-poor (stained red) and Fe-rich calcite (stained purple) occurring in the ore; (B) kaolinite (Kl) occurring as rims around feldspar (Fs). Both in plane transmitted light, from the Shengshangou deposit in the Donsheng area.

The U-Pb isochron ages obtained in the Dongsheng area fall in a wide range, including 177-149 Ma, 124-107 Ma, 85-74 Ma and 20-8 Ma (Xia et al., 2003; Liu et al., 2007), with the Late Cretaceous being most important, and two U-Pb isochron ages of the Diantou uranium deposit are 42 and 51 Ma (Chen et al., 2006). Fluid inclusions in calcite yielded homogenization temperatures from 58 to 176°C (Xiao et al., 2004). The $\delta^{13}C$ values of calcite range from -14.0 to -2.7‰ V-PDB. The $\delta^{18}O$ values of the mineralizing fluids calculated from those of calcite mainly range from -5.8 to 8.8‰ V-SMOW (Xue et al., in press). The $\delta^{18}O$ values of the fluids calculated from kaolinite range from -9.1 to 4.8‰ V-SMOW, and those of δD range from -130 to -94‰ V-SMOW (Xue et al., in press).

Comparison with tabular sandstone uranium deposits in the U.S.A.

The Ordos uranium deposits are similar to the tabular sandstone uranium deposits in the Colorado Plateau in that the mineralization is fine-grained and disseminated in sandstones. The C-O-H isotopes of calcite and clay mineral associated with mineralization in the Ordos Basin indicate that the mineralizing fluids were depleted in ^{13}C and ^{2}H with respect to marine carbonate and meteoric water, and suggest that mineralization was associated with oxidation of organic matter, like in tabular sandstone uranium deposits. The occurrence of both Fe-rich and Fe-poor calcite is consistent with the environment of redox front.

However, the Ordos and Colorado Plateau deposits are significantly different in terms of mineralization conditions. Most of tabular sandstone uranium deposits in the U.S.A. were formed in early diagenesis (although some are remobilized near faults) (Kyser and Cuney, 2009), whereas the uranium deposits in the Ordos Basin were mainly formed at great burial depths, as indicated by the elevated fluid inclusion homogenization temperatures and ages of mineralization much younger than the host rocks. Both the Ordos and Colorado Plateau deposits are proposed to have formed at the interface of two fluid flow systems, but the depths of the interface and the driving forces of flow systems are different. The Colorado Plateau uranium deposits were formed from mixing of two fluids along a density-stratified interface near the sedimentation surface (Sanford, 1994). The driving forces of the upper flow system are gravity and density, and those of the lower system are gravity and compaction (Sanford, 1994). In the Ordos Basin, two flow systems were established toward the end of Cretaceous: one is downward flowing, oxidizing fluid driven by topographic relief associated with uplifting of the basin margin, and the other is upward flowing, reducing fluid driven by disequilibrium

compaction of sediments in the basin (Xue et al., in press). The interface of the two fluid systems, which is favorable for uranium mineralization, is located in the upper part of the Jurassic strata and is at elevated burial temperature (Fig. 3). This interface may have been maintained at the same stratigraphic interval for a prolonged period of time due to a combination of decreasing compaction-driven and topography-driven flow with time, favoring concentration of uranium in the upper Jurassic strata.

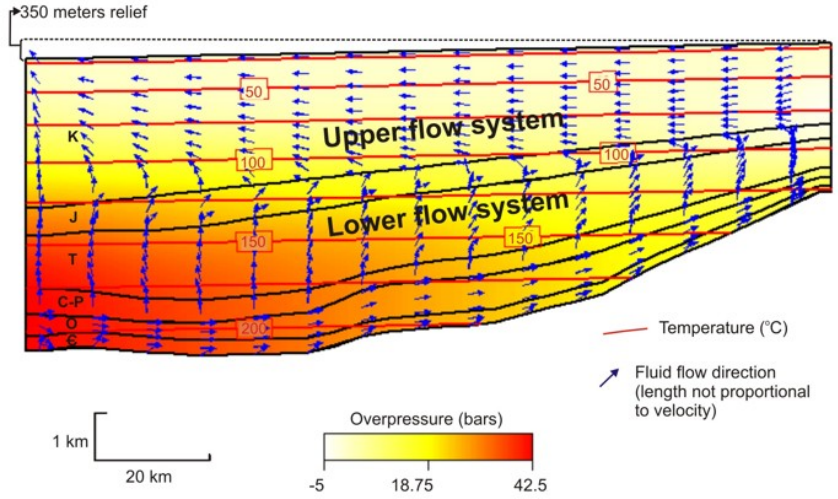

Figure 3. A numerical model of the Ordos Basin showing an upper, gravity-driven flow system and a lower, compaction-driven system with an interface in the upper part of the Jurassic. Note this interface is at elevated temperature (around 100°C) near the basin margin (modified from Xue et al., in press).

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