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Uranium in the U.S.A.: genesis and exploration implications

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Objective review of the genesis of important uranium deposits in the United States suggests that many of the basic assumptions pertaining to source, mobilization and fixation are inadequate or even potentially erroneous. Analysis of empirical evidence, supported by modern uranium geochemistry research, has resulted in a number of genetic concepts that drastically broaden the geological and geographical scope of uranium exploration.

Under especially favourable mobilizing conditions, the primary source of uranium deposits may be deceptively low-grade as well as being obscured, making transport and fixation the basic exploration problems. Mechanisms other than fixation by organic reductants are considered in proposing exploration models. Future reconnaissance should be guided by a multi-conceptual approach assisted by appropriate geological, geophysical and geochemical methods, as opposed to the present heavy dependence on drilling, prospect evaluation and a generally singular depositional model.

Uranium deposits occur in numerous environments throughout the United States. The most significant in terms of known reserves, production and exploration effort are the sandstone type characterized by several districts in the Wyoming Basins, on the Colorado Plateau and on the Gulf Coast of Texas. Although over 80% of exploration expenditure continues to be in the sandstone environment, numerous vein and igneous deposits and geologically favourable features attest to the potential of 'hard-rock' environments.

Encouraged by exciting successes elsewhere in the world, together with higher prices and sustained demand, exploration geologists in the United States are beginning to make use of a more extensive range of exploration models. It is an opportune time to suggest that we objectively re-examine our thoughts about uranium genesis, separate fact from opinion and assumption, and try to collect data to resolve gaps in our knowledge of the geochemical cycle of uranium. Historically, in the United States, the geochemical cycle has not been considered in its entirety. Each aspect must be tied geologically and geochemically to the rest of the cycle if we are to find sizeable new reserves. For example, precipitation of uranium in the orebody cannot be studied properly without considering source, liberation, migration and deposition with an understanding of the bulk mineralogy of the whole.

Much as exploration geologists would like a comprehensive factual review of uranium deposits, only a brief compendium of selected features of a few deposits can be attempted here. I hope that by reviewing some of the facts, questioning several popular assumptions and offering a few hypotheses, I shall evoke dispassionate reappraisal of the evidence as well as stimulating the collection of new data, which when imaginatively interpreted will lead to better exploration models, not only for types of deposit unfamiliar in the United States, but for sandstone types as well.

Epochs

The major uranium deposits in the western United States have resulted from episodes of uranium mineralization in Tertiary and Mesozoic times.

Tertiary uranium mineralization processes were active in many areas of the west and resulted in major sandstone-type deposits in Wyoming, Texas, Colorado, Arizona and California. Several vein deposits, including the Schwartzwalder, Pitch and Thunder Mountain orebodies in Colorado, were formed during Tertiary time. Many centres of volcanism emitted vast amounts of uranium in acid extrusives and ash, as well as in associated intrusives.

On the Colorado Plateau, evidence favours a Jurassic age of mineralization and, in fact, uranium enrichment, albeit mostly uneconomic, is found in Jurassic sediments throughout the Rocky Mountain area. The veins at Bokan Mountain, Alaska, are in a peralkalic stock of Jurassic age.

In the northwestern corner of the country, ore at the Midnight deposit and elsewhere was probably introduced at the same time as Cretaceous intrusives. In the eastern United States, several occurrences suggest Palaeozoic ages.

Although relatively unexplored in the United States, the Precambrian contains evidence of several major eposides of uranium mineralization. Significant occurrences are found in New England, the Great Lakes region, the central Rockies and in the Southwest. In Wyoming, several areas of uranium-rich Archaean granite suggest that the Wyoming uranium province has been evolving at several periods throughout geological time. Overall, the Precambrian often provides key clues to the location of major provinces, even though the main mineralizing epochs may be later.

Many of the uranium epochs are marked by commercial deposits whereas others are primarily indicative of a potential source or migration. In most cases, geological and geochemical data are inadequate to propose workable conceptual models other than those indicated by actual examples in the area. Further mapping, geochemical sampling and dating will undoubtedly add to the extent of known epochs and even identify new provinces.

Source

The uranium-rich Archaean craton in Wyoming can be considered as a source for at least part of the uranium in nearby sandstone districts of Tertiary age. But what of the Proterozoic of the Rockies, elsewhere in the world a favourable time for uranium mineralization? One hypothesis suggests that the source for the rich Schwartzwalder ore was uranium-rich Proterozoic sediments which had in turn evolved from the Wyoming craton to the north. Occurrences of uranium in the Precambrian of southern Wyoming and western South Dakota, as well as the Mt Wheeler deposit and the uranium-rich Front Range in northern Colorado, suggest a uranium province in the Proterozoic sediments around the Wyoming craton. What is needed now to test this suggestion is a comprehensive appraisal of the depositional, evolutionary and geochemical aspects of the region's Precambrian.

All the sandstone districts are characterized by the proximity of uranium-rich tuffaceous sediments. Empirically, the evidence is certainly strong that these sediments were a major source of uranium. Devitrification of the tuffs could also have provided alkaline solutions for

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transport of the uranium, and these solutions could well have played a part in the final precipitation reaction.

As previously noted, granites are the probable source of uranium in some areas. J. S. Stuckless (personal communication) has determined that the Sweetwater granites in Wyoming have released many times the uranium that exists in the Wyoming districts. In another area of the west, springs issuing from a Precambrian granite contain 100–900 parts $U/10^9$. Gabelman (1977) presents evidence for a source of uranium from plumes of rising mantle material. Indeed, several diatremes in Arizona and New Mexico contain uranium ore.

Both the Schwartzwalder, Colorado, and the Midnight, Washington, veins and stockworks, as well as other veins and magmatic disseminations, are usually found in areas where preexisting rocks are slightly enriched in uranium. On the other hand, the source may be deep-seated and only locally evident such as the Rocky Boy pyrochlore deposit in Montana.

It can be argued that given an apparent province where uranium is widely distributed, the source is immaterial in so far as exploration is concerned, and I agree that it is dangerous to restrict exploration areas on the basis of a hypothetical source. However, knowledge of the nature of the source is important if we are to understand the chemistry of the system and the associated clues to ore deposits. Several workers have studied the geochemistry of potential source areas and further examination of these data in the context of genetic models should provide information valuable in exploration.

Liberation and migration

The causes of liberation and migration of uranium from the source are critical to understanding the reaction chemistry of the total system. Unfortunately, little comparative work has been done on altered and unaltered rock to determine the nature of the mineralizing solutions. R. M. Honea (personal communication) points out that bulk mineralogy of the source, 'plumbing', and host rocks, must have an important impact on mobilization regardless of the conceptual model used.

Hydrolysis of tuffaceous sediments or briny connate water from lacustrine sediments could have provided the alkaline groundwater that carried at least some of the uranium and caused diagenetic alteration of the host sandstones. Gabelman's (1977) model brings in uranium in concentrated thermal brines possibly derived from mantle emanations. In the Grants area, it is commonly believed that uranium was introduced as a chelation with soluble humates shortly after deposition of the Morrison host rocks.

Migration and segregation of uranium in metamorphic and igneous environments have proved to be important factors in the formation of many deposits in the world. At the Schwartzwalder deposit, Precambrian metamorphic processes may have reconcentrated uranium from pelitic sediments, and Tertiary magmatism could, in turn, have generated the final ore-forming solutions. Similar geological and geochemical situations exist elsewhere in the Rocky Mountains, in the southern Basin and Range province, the southern Canadian Shield, and in areas of the Appalachian Range. Exploration orientated to understand a uranium province's metamorphic and magmatic features and their genetic implications, as opposed to individual prospect evaluation, holds promise for substantial discoveries in these areas.

In 1960 S. S. Merwin (personal communication) observed a common association of major thrust faults with uranium deposits, which might suggest a mechanism for both rock preparation and slight heating of the solutions. Conceivably, temperatures which could be considered in the hydrothermal range for uranium (100–200 °C) could be produced by the moderate pressures associated with thrusting. Various types of deposits at Copper Mountain, Wyoming, and South Park, Colorado, are in close proximity to thrust blocks of granite. Interestingly, the Schwartzwalder and other nearby veins are in the upper plate of the Front Range thrust, which involved uranium-rich Precambrian rocks. Several occurrences are also found in the sediments in front of this fault. The rôle of thrust faults is primarily suggested because of the empirical association with many uranium deposits. Before serious consideration as a model, the mineralogy and thermogene alteration of the faulted rocks relative to the known deposits should be further investigated.

Regional uplift was necessary to provide the hydraulic gradient for a flow of meteoric water carrying uranium to precipitation sites in the sandstones. Major trunk channels, enhanced by unconformities, collected and transported the uraniferous fluids, as well as contributing to the chemistry of the complex. With few exceptions, the dip of the host sandstones is less than ten degrees, and the deposits are classed as laterogene.

The major discoveries in the past 20 years have been made where alteration and numerous uranium occurrences, though in themselves economically insignificant, are evidence of a strong mineralizing gradient. Tallahasse Creek in Colorado, Date Creek in Arizonia, and Copper Mountain and Powder River Basin in Wyoming, are all examples of substantial discoveries in areas known for years by widespread small uranium occurrences. Likewise, it seems difficult to overestimate the resources of an already prolific district such as Grants, where changing economics and new ideas continue to result in dramatic additions to reserves.

Every uranium province in the country contains veins and disseminations formed by the processes of magmatism, anatexis and metamorphism. This suggests that the sandstone deposits are only one stage in the evolution of the geochemical cycle of uranium. Furthermore, the important vein deposits of Schwartzwalder and Midnight are both low temperature, suggesting the possibility that the type of deposit (i.e. vein or roll front) might be more a factor of *where* the uraniferous solution encounters favourable precipitating conditions than the origin of the solution itself.

Geological environments and metallogenic zoning suggest many other potential uranium source areas. Considering the high mobility of uranium, exploration should not be restricted too much by considerations of source.

Host rocks

Virtually all sandstone-type uranium deposits in the United States occur in arkosic or feldspathic sandstones of fluvial or marginal marine origin. Sand:shale ratios in the range of 1:1 to 1:4 prevail (Grutt 1972). In Wyoming, the major deposits occur in coarse-grained arkosic sandstones of Eocene age. Deposits of lesser importance are found in Cretaceous quartzose and late Tertiary tuffaceous sandstones. In the Grants Mineral Belt and other areas of the Colorado Plateau, the principal host rocks are coarse-grained arkosic units of the Jurassic Morrison Formation. The important deposits in Texas are in feldspathic arkosic and tuffaceous sandstones of Eocene and Miocene ages.

In any given sandstone district, the uranium deposits tend to concentrate in similar situations. At Grants, the thick, coarse sandstones, intercalated with grey mudstones, provide the most favourable host rocks. Most of the Wyoming deposits are found in marginal transition

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zones between the channel thalweg and less permeable overbank or floodplain sediments. The limited range of grain size, sand thicknesses and organic content associated with the ore, indicate that some, if not all, of these characteristics play a critical rôle in precipitation of the uranium. Presumably, then, other rocks with an open-packed structure accompanied by favourable geochemical characteristics could also be suitable hosts. An example is Copper Mountain, Wyoming, where substantial supergene deposits are found in breccia zones within Precambrian granites and metasediments, while exploration in nearby arkosic sandstones has been relatively unsuccessful.

Most of the hydrothermal uranium deposits are in felsic igneous and metamorphic rocks. At the Midnight Mine, fractured Precambrian metapelites are the primary host rock and at the Schwartzwalder major veins occur in faulted Precambrian gneisses and quartzites. Other igneous host rocks include late-stage differentiates, such as Rocky Boy, Montana; Bokan Mountain, Alaska; Wind Mountain, Texas; and Mt Spokane, Washington.

Precipitation

Organic substances are known, or suspected in virtually every sandstone-type, as well as in many supergene, deposits. Vegetal carbonaceous debris is commonly concentrated in or near the Wyoming deposits, and in some cases oil is present in the ore zone. In the Grants Mineral Belt, structureless humic compounds apparently were deposited in substantial amounts. Hydrogen sulphide is known or suspected in Texas, Black Hills, and some Wyoming Tertiary deposits.

Schmidt-Collerus (1969) conducted some fundamental studies on the relation of organic compounds to uranium fixation and reduction, but much remains to be done regarding field relations and reactions. In most occurrences, organic matter does not spatially coincide with the uranium. In fact, organic matter need not be involved in the final reaction. Honea (personal communication), Adler (1974), and others, propose that organic matter might instead provide the initial environment for the formation of pyrite. Uranium tricarbonate, transported by oxygenated groundwater and reacting with the pyrite, would then provide a strong mechanism for the formation of uraninite and hematite. Arkose, with an agitation pH of 8.3, would provide a buffered environment preventing hydrogen-ion accumulation except locally near the ore front. This reaction also makes good sense in the light of the total system and might also generally fit vein deposits such as the Schwartzwalder, Midnight and others. In this context, it is an interesting fact that oil is found in fractured Precambrian rocks overlying the Front Range thrust fault near the Schwartzwalder Mine.

Tectonic activity, already demonstrated as crucial in uranium liberation and transport, may have also been a factor in squeezing or pumping oil and gas into the system. At the Cheyenne Mine in Wyoming, Miocene sediments are saturated with oil of Permian age containing uranium and an unusual suite of metals, which, incidentally, is similar to the suite associated with the Permian phosphate beds further west.

Exploration implications

As can be judged from this brief review of the genetic aspects of uranium in the United States, there are many ideas about each part of the cycle. Diverse opinion exists as to source, liberation, migration and deposition. Diversity in geological and exploration thinking is, of course, normal

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and desirable, for all the factors involved are never known. This point is well illustrated by the popular agreement relating to a favourable host rock for uranium in sandstone formations. By using alteration and mineralization of specific sandstones as our principal exploration guides, a great deal of subjectivity and incompleteness has crept into the model. As we have seen, there are many potential sources of uranium in the United States. The derivation of economic deposits from these sources involves a cycle of liberation, migration and concentration. An understanding of the geology and geochemistry potentially affecting each of these stages, then, should be the backbone of any exploration effort. Indeed, many programmes have matured to the point of recognizing that concepts must be altered to fit the situation and that one general concept should not be applied in all situations. For instance, in the Copper Mountain discovery, the important host rock turned out to be brecciated Precambrian rocks and the process supergene rather than laterogene.

Exploration strategy must also shift from an emphasis on looking for visual or radiometric evidence directly related to mineralization or alteration to a more comprehensive effort of data collection and interpretation with regard to the complete geochemical cycle. In new areas, this implies a substantial delay before discoveries can be expected, while in the old districts it will involve some deviation from the 'normal' procedures and a re-examination of comfortable assumptions.

It is necessary at this time to undertake a comprehensive analysis of potential sources of uranium, through coring and sampling of unmineralized rocks, both altered and unaltered, in the uranium provinces, and to institute an objective search for 'alternative' host rocks that might be geochemically favourable.

Orogenesis, more than anything else, has played a major rôle in the movement of uranium from its source to the site of deposition. Diastrophism exposed the source to weathering, generated heat and pressure, and initiated movement of fluids carrying uranium and organic matter.

Alteration of rocks invaded by mineralizing solutions has been a favoured guide in sandstone exploration; however, emphasis has been on the effects rather than the cause. Understanding the contribution of the bulk mineralogy to the system will encourage exploration in other environments where favourable geochemical alternatives exist.

It is my belief, on the basis of many prolific source areas, active uranium mineralizing processes, and untested potentially favourable host situations, that a multifaceted exploration approach, involving gathering data on the total mineralizing system and utilizing flexible concepts to fit those data, will add very substantially to the uranium reserves of the United States in and near existing districts and in new districts, both in the sandstone and 'hardrock' environments.

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