URANIUM GEOLOGY

Virginia T. McLemore

New Mexico Bureau of Geology and Mineral Resources
New Mexico Institute of Mining and Technology, Socorro, NM

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OUTLINE

• Mine-life cycle

• Geology of uranium deposits—mineralogy, types of deposits

• Where are the major deposits found in the U.S.?

• Definition of reserves and resources
Mine-life cycle
Geology of uranium deposits
What are the important parameters that characterize uranium deposits?

- Location
- Shape
- Size and grade
- Depth
- Orientation
- Geotectonics
- Mineralogy
- Hydrology
- Boundary conditions

Uranium deposits, like all mineral deposits, are found in specific locations in the world, dictated by geologic conditions.
Uranium Minerals

- Autunite—$\text{Ca(}\text{UO}_2\text{)(PO}_4\text{)}_2 \text{ 10-12(H}_2\text{O)}$
- Carnotite—$\text{K}_2(\text{UO}_2)_2(\text{VO})_4 \text{ 3(H}_2\text{O)}$
- Tyuyamunite—$\text{Ca(}\text{UO}_2\text{)}_2(\text{VO}_4)_2 \text{ 5-8H}_2\text{O}$
- Uraninite—$\text{UO}_2$
- Uranophane—$\text{Ca(}\text{UO}_2\text{)}_2\text{SiO}_3(\text{OH})_2 \text{ 5(H}_2\text{O)}$
TYPES OF URANIUM DEPOSITS

- Unconformity-related deposits
- Sandstone deposits
- Quartz-pebble conglomerate deposits
- Vein deposits
- Hematite breccia complex deposits (IOCG deposits)
- Intrusive deposits
- Phosphorite deposits

- Collapse breccia pipe deposits
- Volcanic deposits
- Surficial deposits
- Metasomatite deposits
- Metamorphic deposits
- Lignite
- Black shale deposits
- Other types of deposits
- Todilto limestone deposits

Black circles are Iron oxide-Cu-Au (+/- U, REE) deposits (Hematite breccia complex deposits)

Grade verses tonnage for major types of uranium deposits

### TABLE 4. URANIUM RESOURCES BY DEPOSIT TYPE

<table>
<thead>
<tr>
<th>Deposit Type</th>
<th>RAR</th>
<th>Inferred</th>
<th>Total</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unconformity related</td>
<td>491.6</td>
<td>158.1</td>
<td>649.7</td>
<td>11.9</td>
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<tr>
<td>Sandstone</td>
<td>999.5</td>
<td>524.4</td>
<td>1523.9</td>
<td>27.9</td>
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<tr>
<td>Hematite breccia complex</td>
<td>499.4</td>
<td>401.5</td>
<td>900.9</td>
<td>16.5</td>
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<tr>
<td>Quartz-pebble conglomerate</td>
<td>163.6</td>
<td>138.3</td>
<td>301.9</td>
<td>5.5</td>
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<td>Vein</td>
<td>156.8</td>
<td>167.7</td>
<td>324.5</td>
<td>5.9</td>
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<tr>
<td>Intrusive</td>
<td>183.7</td>
<td>104.2</td>
<td>287.9</td>
<td>5.3</td>
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<tr>
<td>Volcanic and caldera related</td>
<td>157.8</td>
<td>53.5</td>
<td>211.3</td>
<td>3.9</td>
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<tr>
<td>Metasomatite</td>
<td>304.9</td>
<td>368.8</td>
<td>673.7</td>
<td>12.3</td>
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<tr>
<td>Others</td>
<td>284.3</td>
<td>154.4</td>
<td>438.7</td>
<td>8.0</td>
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<tr>
<td>Unspecified</td>
<td>96.7</td>
<td>59.7</td>
<td>156.7</td>
<td>2.9</td>
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<tr>
<td><strong>Total</strong></td>
<td>3338.3</td>
<td>2130.6</td>
<td>5468.9</td>
<td>100.00</td>
</tr>
</tbody>
</table>
UNCONFORMITY-RELATED URANIUM DEPOSITS

- Arises from geochemical changes near a major unconformity
- Massive pods, veins and/or disseminated uraninite associated with unconformities between Proterozoic siliciclastic red beds and metamorphic basement that includes graphitic metapelite and radiogenic granite.
- 33% of the world’s uranium resources
- Uraninite and pitchblende
UNCONFORMITY-RELATED URANIUM DEPOSITS

- Pitchblende/uraninite fills extensional features in reactivated fault zones and replaces matrix in sandstone
- Mined by conventional methods

One mining district in Canada
- the Athabasca Basin
- >30 deposits/prospects
- most in eastern ¼ of basin
- produces 1/3 of world’s U
Figure 1. Paleo- to Mesoproterozoic basins within the Canadian Shield that contain unconformity-associated uranium deposits (e.g. Athabasca and Thelon) or are considered to have potential for them.
SANDSTONE URANIUM DEPOSITS

- Medium- to coarse-grained sandstones
- Continental fluvial or marginal marine sedimentary environment
- Shale/mudstone units are interbedded in the sedimentary sequence
- Uranium precipitated under reducing conditions caused by a variety of reducing agents within the sandstone
  - carbonaceous material (detrital plant debris, amorphous humate, marine algae)
  - Sulfides (pyrite, H2S)
  - hydrocarbons (petroleum)
  - interbedded basic volcanics with abundant ferro-magnesian minerals (e.g., chlorite)
Types of sandstone uranium deposits

• **Tabular sandstone uranium deposits**
  – Mined by conventional methods (underground, open pit)
  – 1 ft zones hard to impossible to mine, 4 ft better

• **Redistributed or roll-type uranium deposits**
  – Mined by conventional methods (underground, open pit)
  – Mined by in situ recovery (ISR) methods
    • Below the water table
    • Permeable
    • Surface must be suitable for the infrastructure
    • No acid leaching needed
Types of sandstone uranium deposits
Fluvial facies

Mudflat facies

Playa-lake facies

Detrital magnetite and ilmenite

Ti oxides (Fe leached)

Diagenetic U in organic-rich lenses

Less permeable sandstone

from Turner-Peterson and Fishman (1986)
Redistributed or roll-type uranium deposits

Open pit mine in Wyoming, Power Resources, Inc.

Secondary roll-front ore

Diagenetic U ore lenses (not essential to form roll-front deposit)

Molybenite, pyrite, calcite

Hematite, limonite (magnetite) core

Sidereite, goethite, S

Uraninite, pyrite, Se

Oxidized rocks (diagenetic hematite and limonite)

Reduced sandstone (diagenetic pyrite, marcasite, calcite, organic material)

Ground water movement in permeable sandstone

20 to 100 m

From Nash et al. (1981) and Devoto (1978)
COLLAPSE BRECCIA PIPE DEPOSITS

- Circular, vertical (up to 1000 meters in vertical extent) pipes filled with down-dropped coarse and fine fragments derived from the overlying sediments
- Mineralized pipes range from 30 to 200 meters in diameter
- Small tonnage, but high grade
- Orphan mine, Arizona, USA
Figure 1. The Kanab North Mine is one of several breccia-pipe uranium mines in northern Arizona. USGS scientists conducted field assessments at this mine, where operations are currently on standby (USGS photo by Don Bills).
WHERE ARE THE MAJOR URANIUM DEPOSITS FOUND IN THE US?
Major U.S. Uranium Trend Areas
(Does Not Include Frontier Uranium Areas)

Sources: Based on U.S. Department of Energy, Grand Junction Project Office (GJPO), National Uranium Resources Evaluation, Interim Report (June 1979) Figure 3.2; and GJPO data files.
Uranium in ground water

- Safe drinking water standard of 30 μg/L

- Some drinking water in New Mexico contains more than 1,000 μg/L (NMED data)

- Opportunity to remove the uranium from drinking water and recover the uranium
Another point

- Rare earth elements (REE) needed for green technologies have been recovered in the past from uraninite in unconformity-related deposits

- Deposits in NM should be examined to see if REE are in high enough concentrations that could be recovered
  - Requires conventional mining
DEFINITION OF MINERAL RESERVES AND RESOURCES
DEFINITIONS

• Mineral deposit: An occurrence of any valuable commodity or mineral that is of a sufficient size and grade (concentration) that might under favorable conditions have potential for economic development.

• Mineral resource: a concentration or occurrence any valuable commodity or mineral in or on the Earth’s crust in such form and quantity and of such a grade or quality that it has reasonable prospects for economic extraction.

• Mineral reserve: the economically mineable part of a Measured or Indicated Mineral Resource demonstrated by at least a Preliminary Feasibility Study.)
NOTE ON RESOURCES/RESERVES

- Dependent upon the price at the time of resource/reserve calculation
  - Cut off grades
  - Method of mining
  - Method of recovery (milling, ISR)
- Can change due to changes in
  - Mining technology
  - Recovery technology
  - Cut off grades
  - New information that re-defines the deposit
Mineral reserves must include adequate information on

- Mining methods
- Processing methods
- Metallurgical methods
- Economic evaluation (price, how grade is determined, disequilibrium, supply/demand projections)
  - Chemical $\text{U}_3\text{O}_8$ or radiometric $\text{U}_3\text{O}_8$
- Other relevant factors that demonstrate, at the time of reporting, that economic extraction can be justified
Relationship between reserves and resources

EXPLORATION INFORMATION

MINERAL RESOURCES
“Reported as potentially mineable mineralisation”

MINERAL RESERVES
“Reported as mineable production estimates”

INFERRED

Increasing level of geological knowledge and confidence

INDICATED ↔ PROBABLE

MEASURED

Consideration of mining, metallurgical, economic, marketing, legal, environmental, social and governmental factors (the "modifying factors")

PROVED
IAEA CATEGORIES FOR URANIUM RESOURCES

- Identified Resources (formerly Known Conventional Resources)
  - Reasonable Assured Resources (RAR)
  - Inferred Resources (formerly Estimated Additional Resources I (EAR-I))

- Undiscovered Resources
  - Prognosticated Resources (formerly Estimated Additional Resources II (EAR-II))
  - Speculative Resources (SR)
Probable mineral reserve is the economically mineable part of an indicated and, in some circumstances, a measured mineral resource demonstrated by at least a preliminary feasibility study.

Proven mineral reserve is the economically mineable part of a measured mineral resource demonstrated by at least a preliminary feasibility study.
FUTURE RESEARCH

- Groundwater studies in all areas—aquifer mapping
  - Uranium in ground water, esp drinking water
- More age determinations
- Better understanding of the regional Jurassic tectonics
- Geochemical analyses of the host rocks and ore deposits
- Determining the age of remobilization or redistributed deposits in the Grants district