URANIUM GEOLOGY

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Uranium Fuel Cycle Conference
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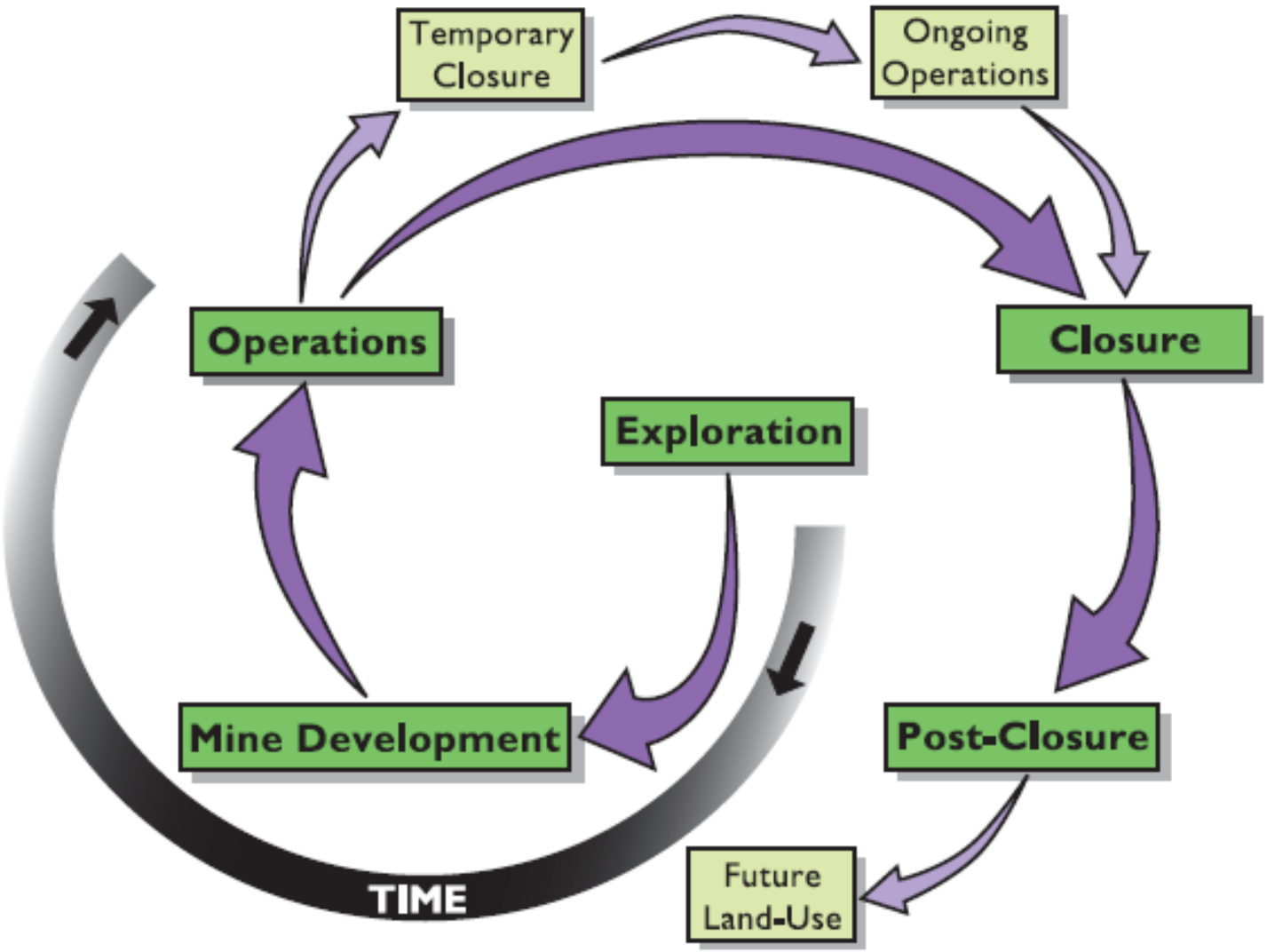
OUTLINE

- 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

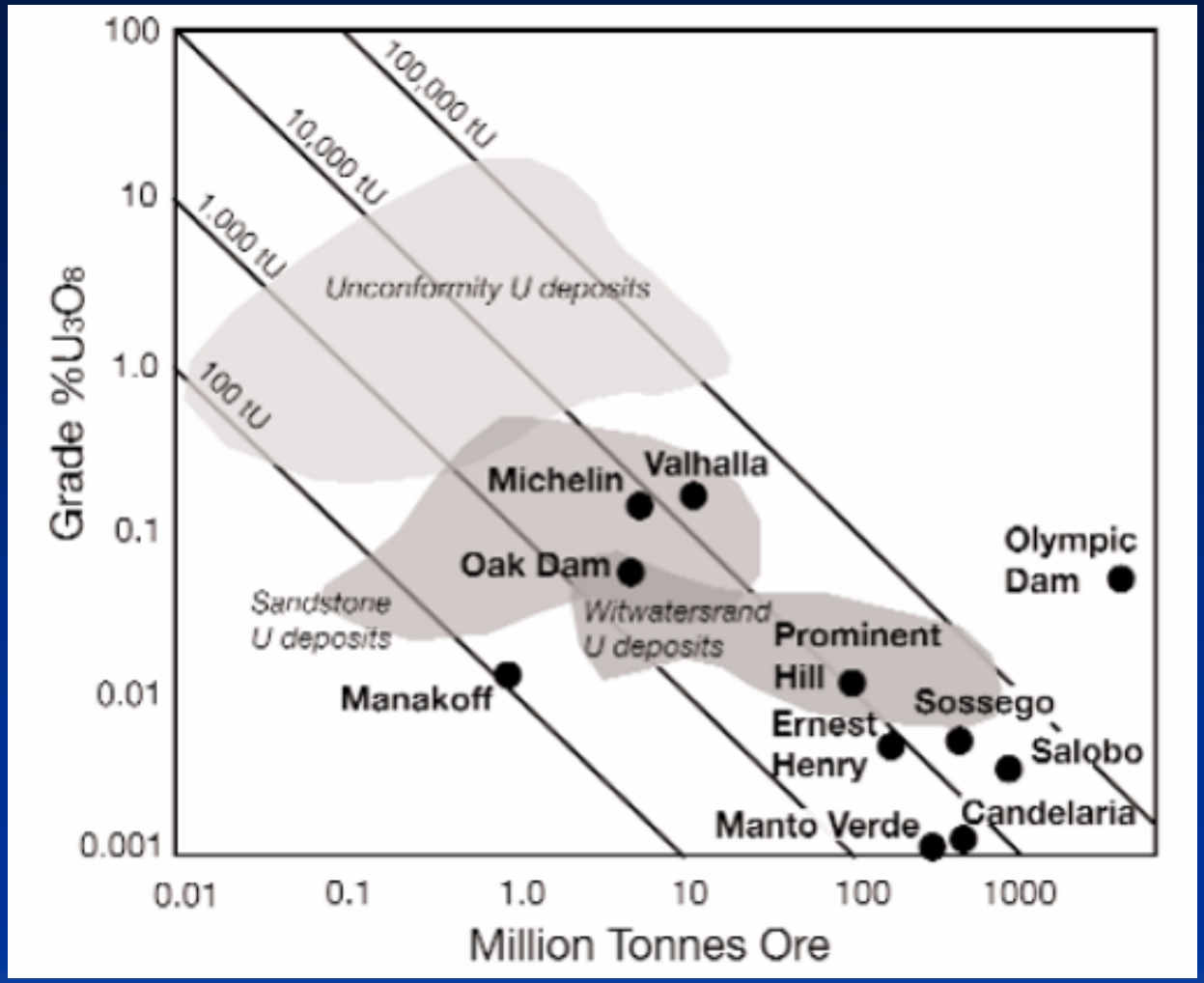
Uranium Minerals

- Autunite—$Ca(UO_2)(PO_4)_2$ 10-12(H_2O)
- Carnotite—$K_2(UO_2)_2(VO)_4$ 3(H_2O)
- Tyuyamunite—$Ca(UO_2)_2(VO_4)_2$ 5-8H_2O
- Uraninite—UO_2
- Uranophane—$Ca(UO_2)_2SiO_3(OH)_2$ 5(H_2O)

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

http://www-pub.iaea.org/MTCD/publications/PDF/TE_1629_web.pdf



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

Grade verses tonnage for major types of uranium deposits

Hitzman and Valenta, 2005, *Economic Geology*, v. 100, pp. 1657–1661

TABLE 4. URANIUM RESOURCES BY DEPOSIT TYPE

	Uranium Resources (t U) (below US$ 130 /kg U)			
Deposit Type	**RAR**	**Inferred**	**Total**	**%**
Unconformity related	491.6	158.1	649.7	11.9
Sandstone	999.5	524.4	1523.9	27.9
Hematite breccia complex	499.4	401.5	900.9	16.5
Quartz-pebble conglomerate	163.6	138.3	301.9	5.5
Vein	156.8	167.7	324.5	5.9
Intrusive	183.7	104.2	287.9	5.3
Volcanic and caldera related	157.8	53.5	211.3	3.9
Metasomatite	304.9	368.8	673.7	12.3
Others	284.3	154.4	438.7	8.0
Unspecified	96.7	59.7	156.7	2.9
Total	**3338.3**	**2130.6**	**5468.9**	**100.00**

http://www-pub.iaea.org/MTCD/publications/PDF/TE_1629_web.pdf

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

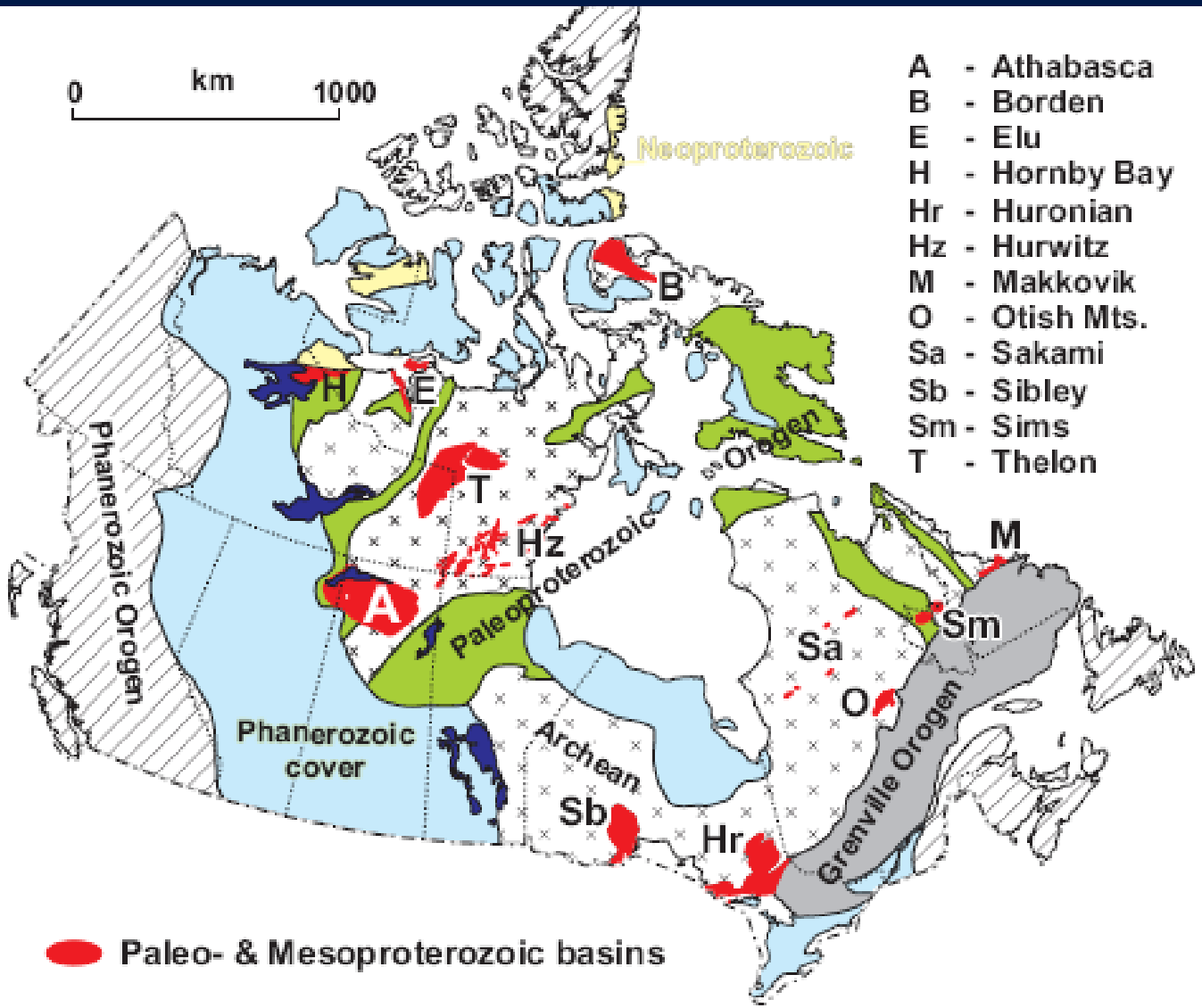
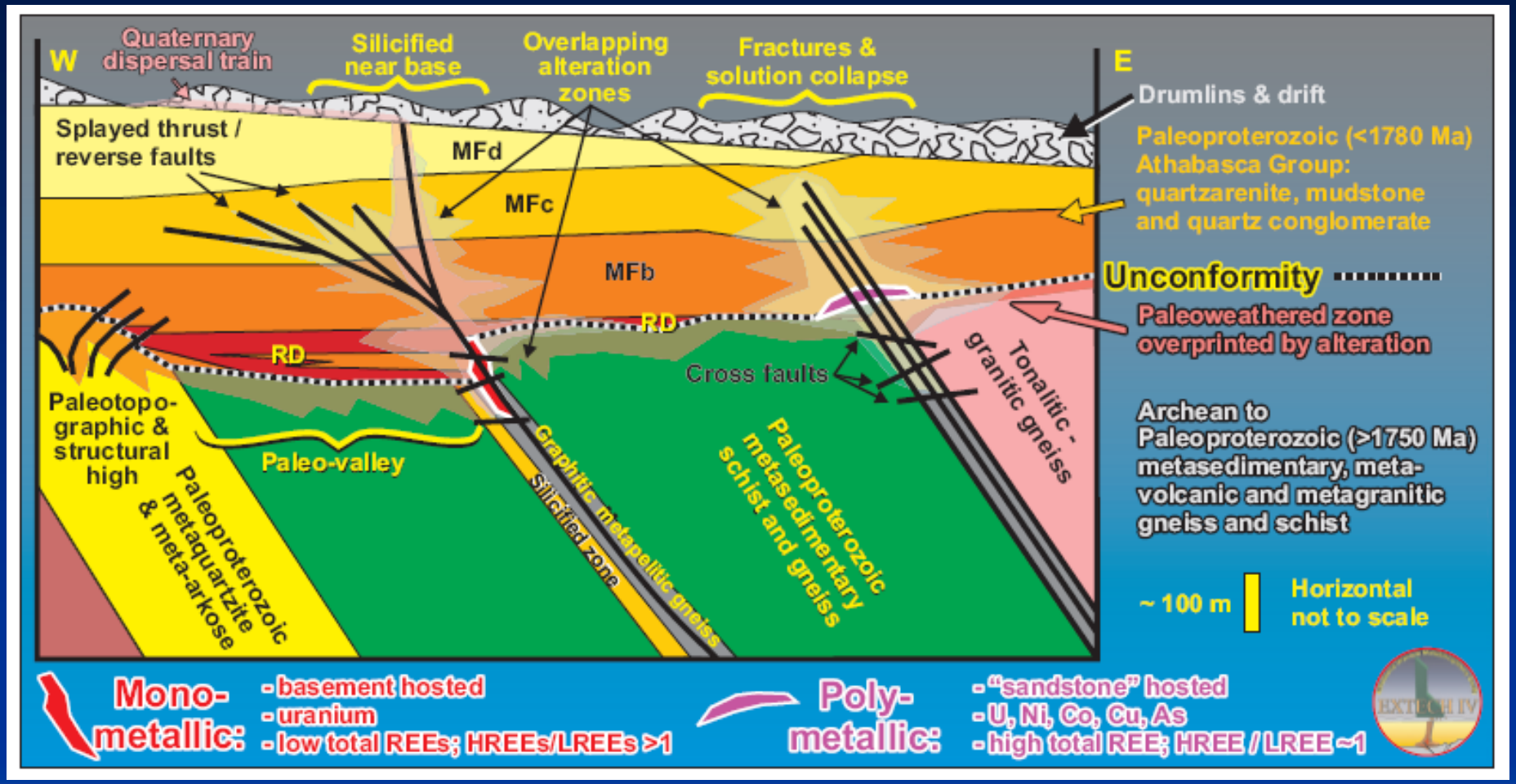


FIGURE 1. Paleo- to Mesoproterozoic basins within the Canadian Shield that contain unconformity-associated uranium deposits (e.g. Athabasca and Thelon) or are considered to have potential for them.

http://gsc.nrcan.gc.ca/mindep/synth_dep/uranium/pdf/deposit_synthesis.uranium.jefferson.pdf



http://gsc.nrcan.gc.ca/mindep/synth_dep/uranium/pdf/deposit_synthesis.uranium.jefferson.pdf

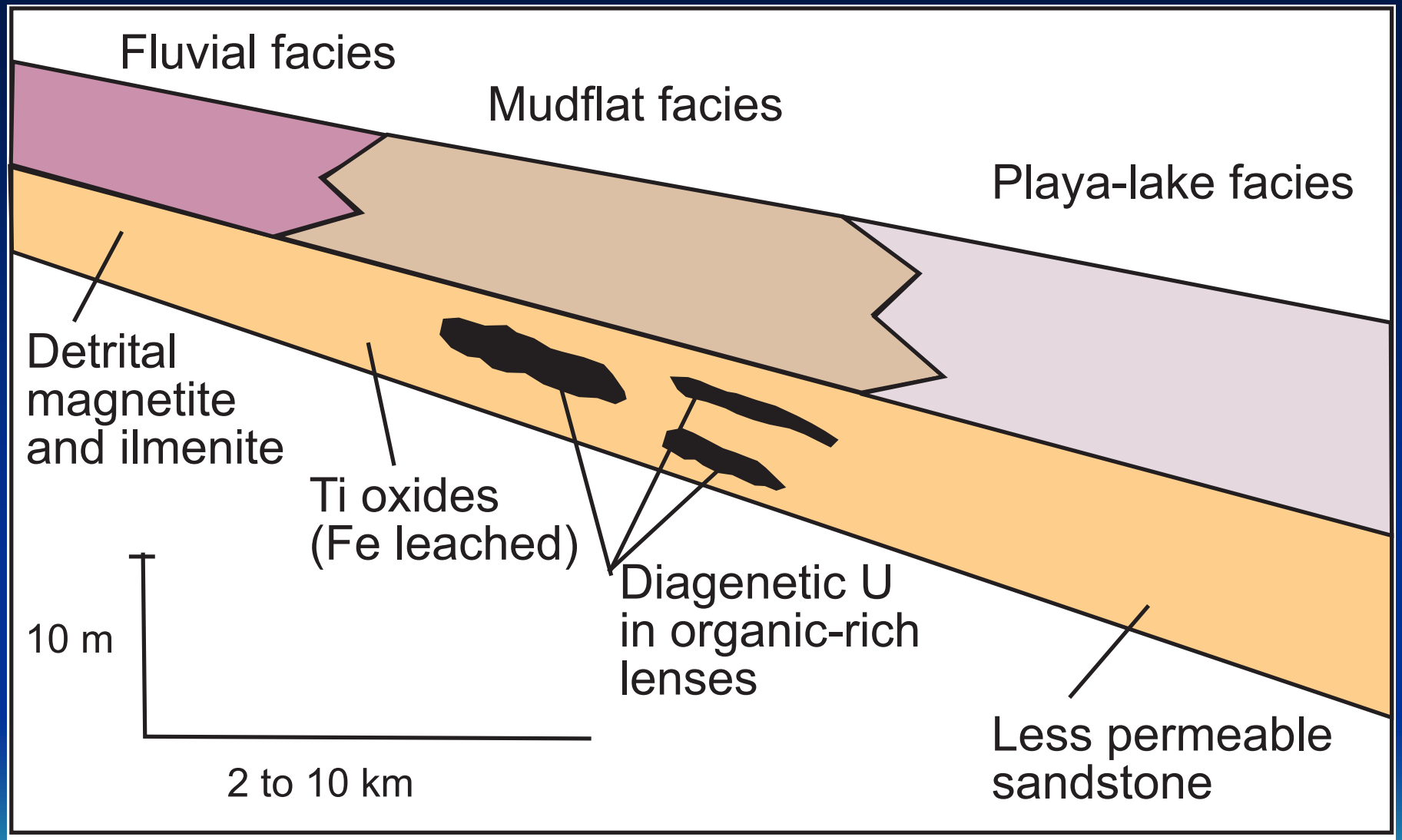
SANDSTONE URANIUM DEPOSITS

- 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, H_2S)
  - hydrocarbons (petroleum)
  - interbedded basic volcanics with abundant ferro-magnesian minerals (eg 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

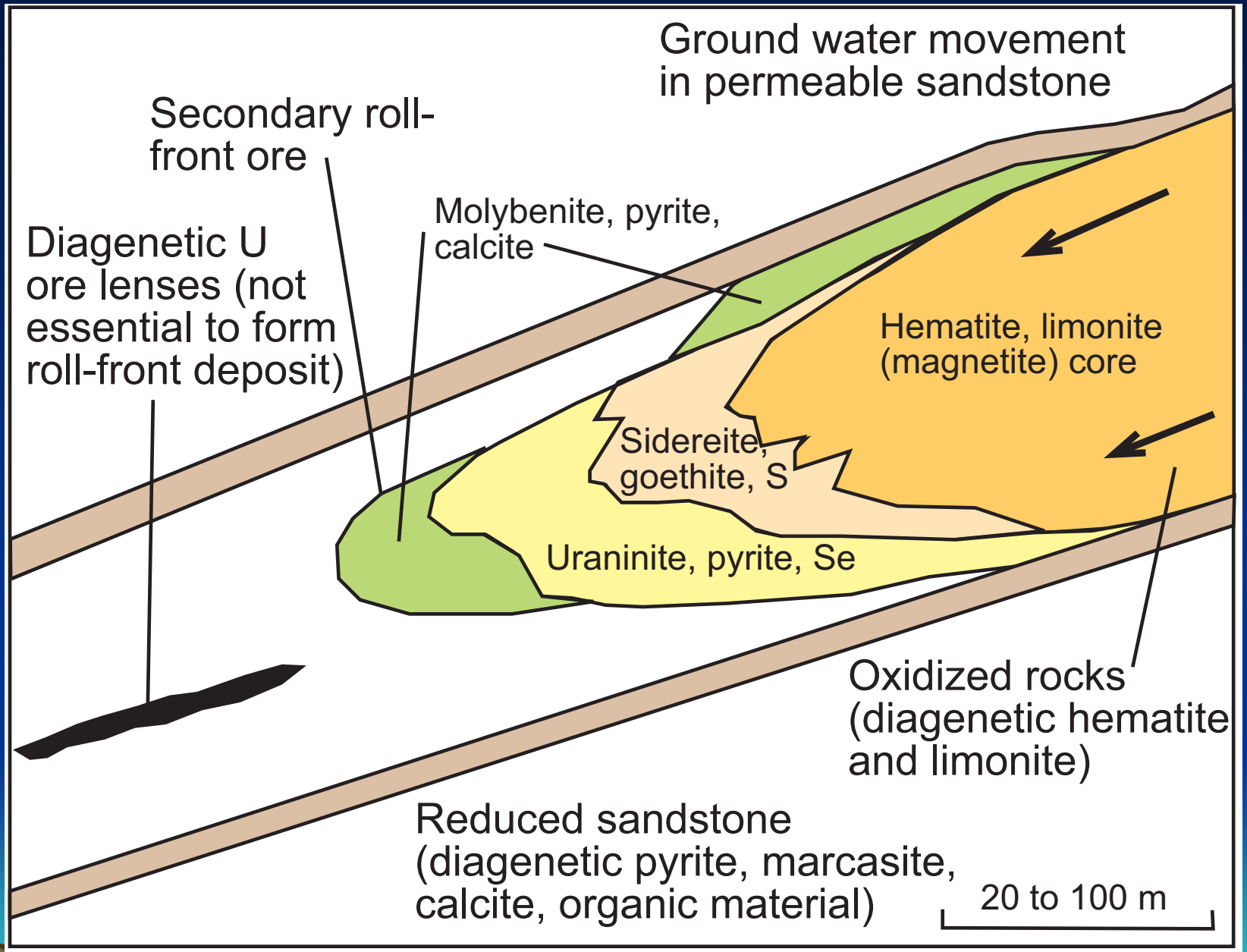


from Turner-Peterson and Fishman (1986)

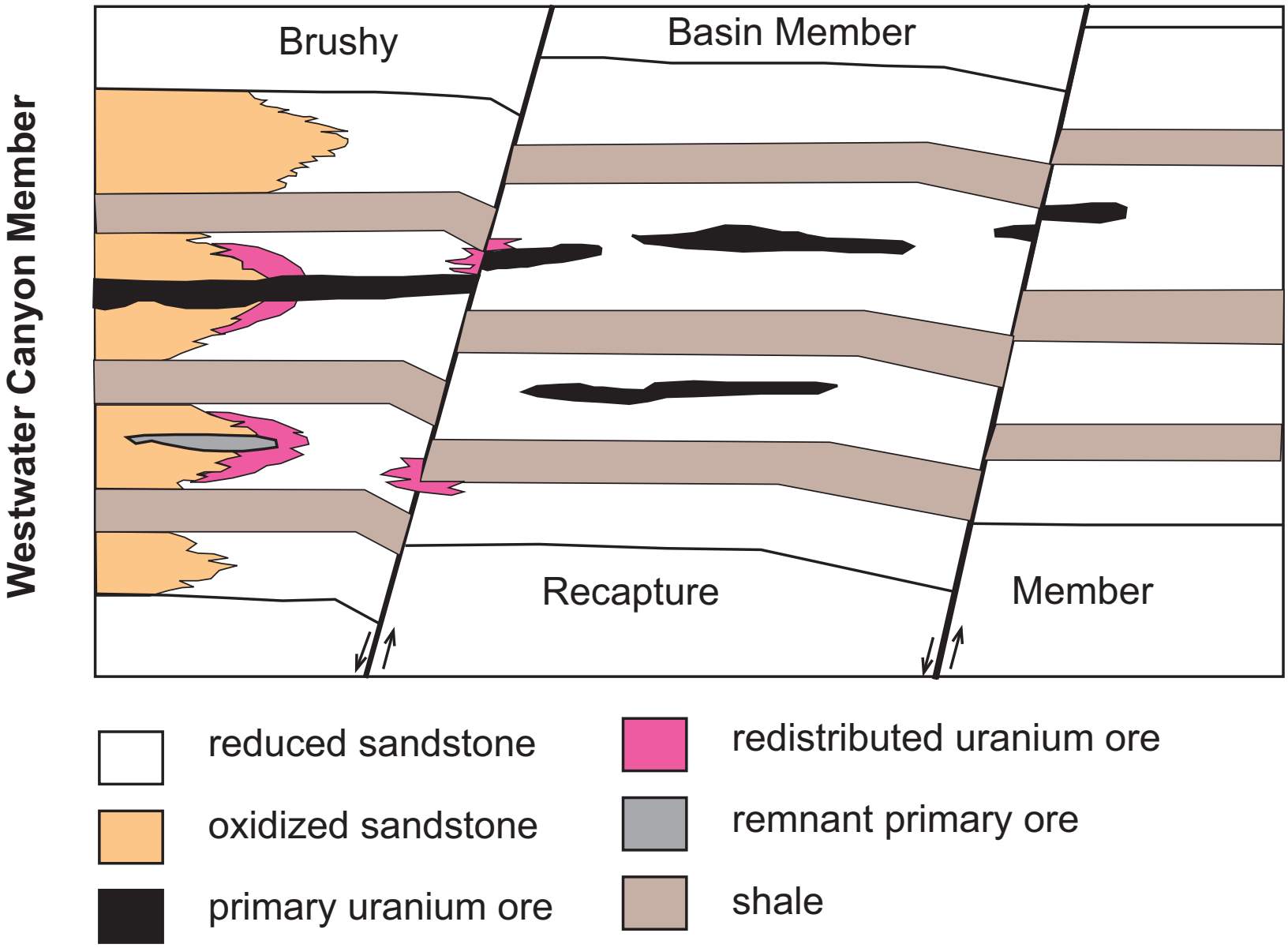
Redistributed or roll-type uranium deposits

Open pit mine in Wyoming, Power Resources, Inc.

http://www.wma-minelife.com/uranium/mining/rllfrnt1.html



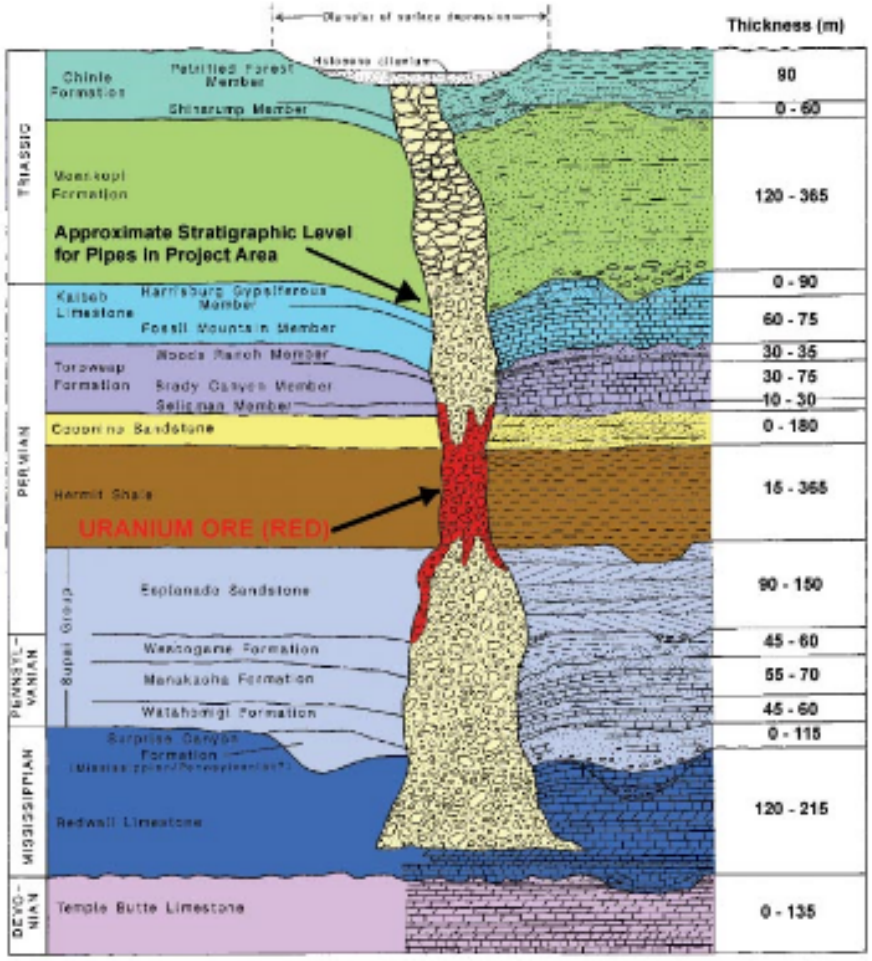
From Nash et al. (1981) and Devoto (1978)


Westwater Canyon Member
Brushy
Basin Member
Recapture
Member
reduced sandstone
oxidized sandstone
primary uranium ore
redistributed uranium ore
remnant primary ore
shale

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

SCHEMATIC CROSS SECTION OF A "TYPICAL" BRECCIA PIPE



Modified after Wenrich, Billlingsley, and Huntoon, 1986

COLLAPSE BRECCIA PIPE DEPOSITS

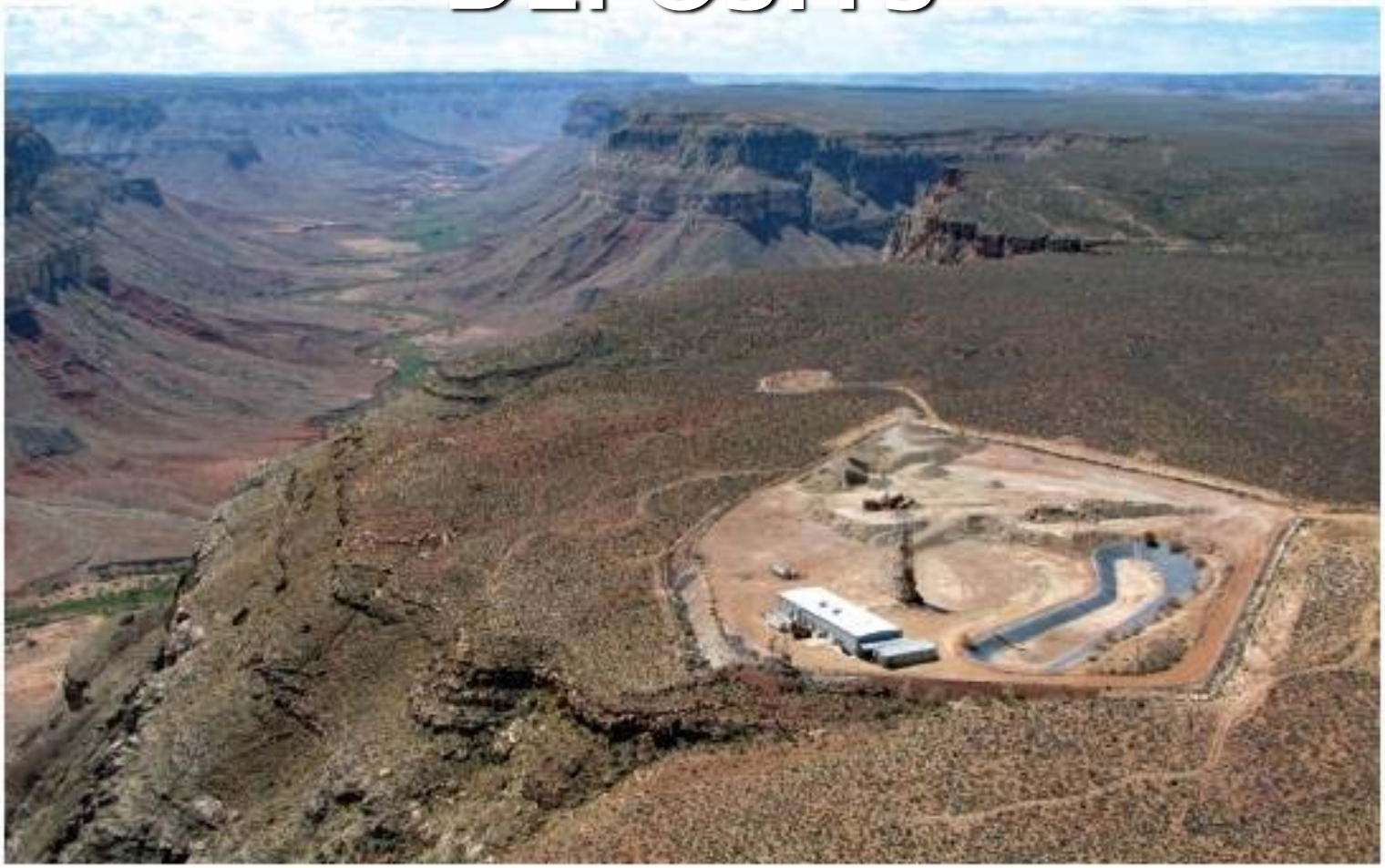
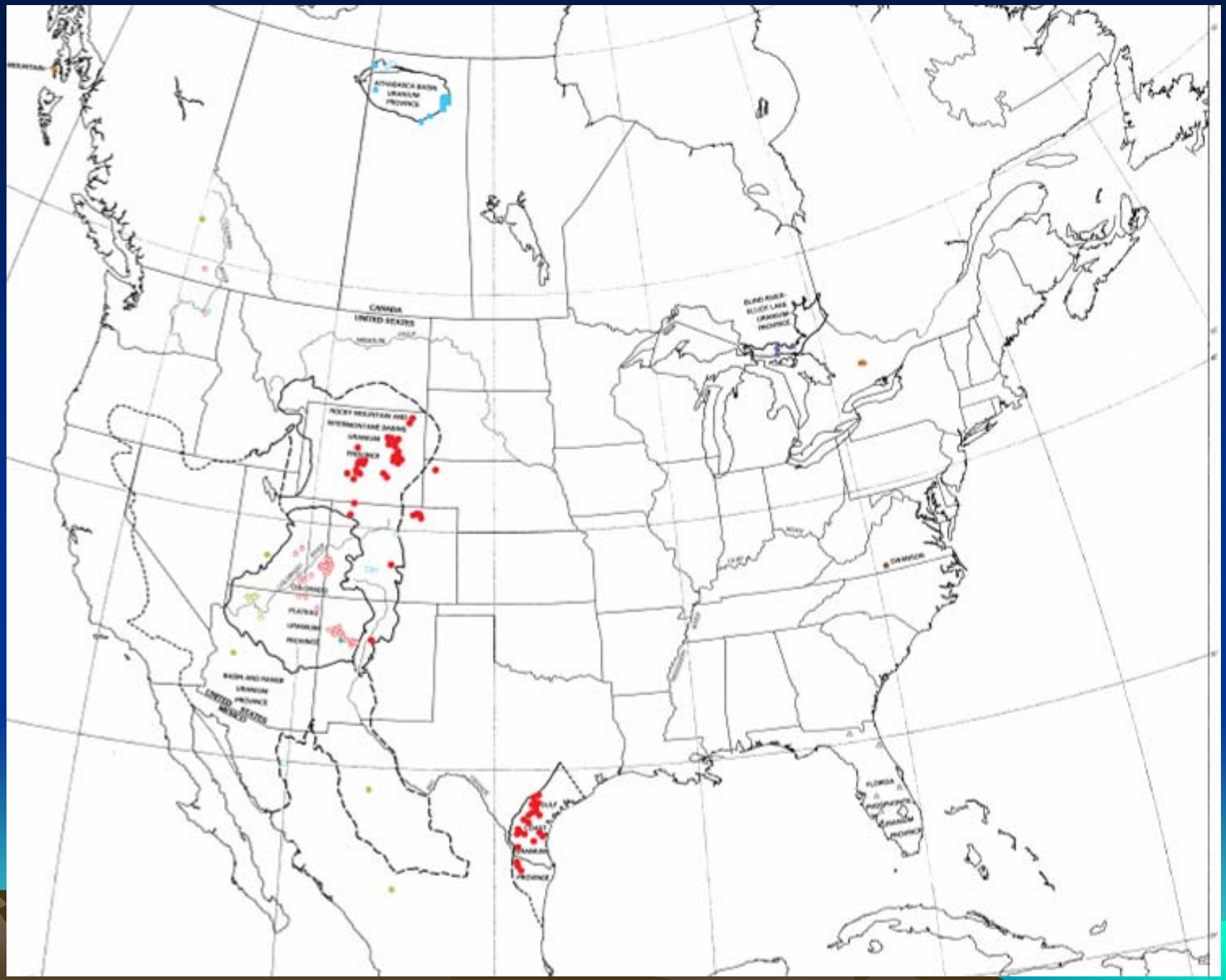
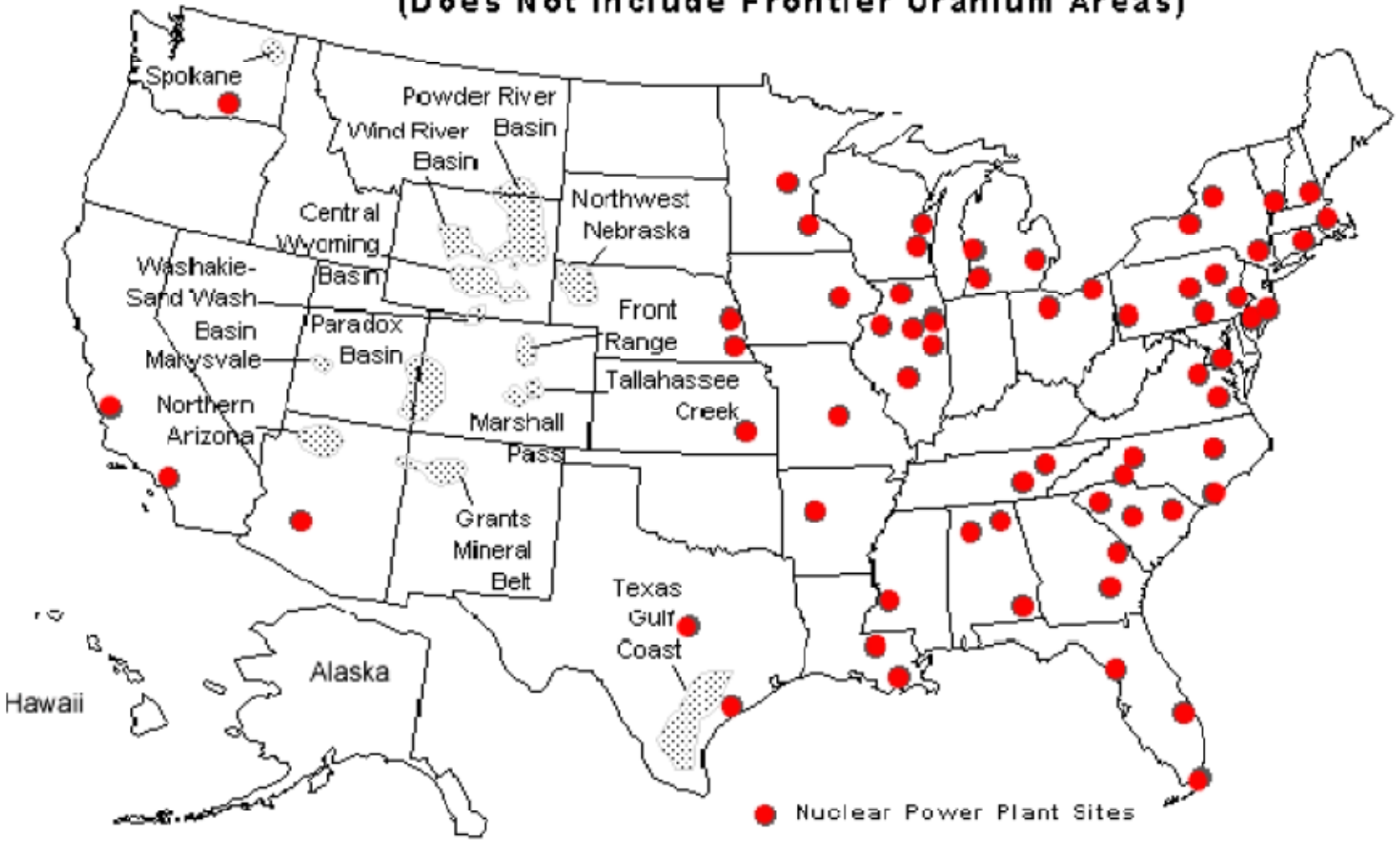


Figure 1. The Kanab North Mine is one of several breccia-pipe uranium mines in northern Arizona. USGS scientists conducted field assessments at this mine, where operations are currently on standby (USGS photo by Don Bills).

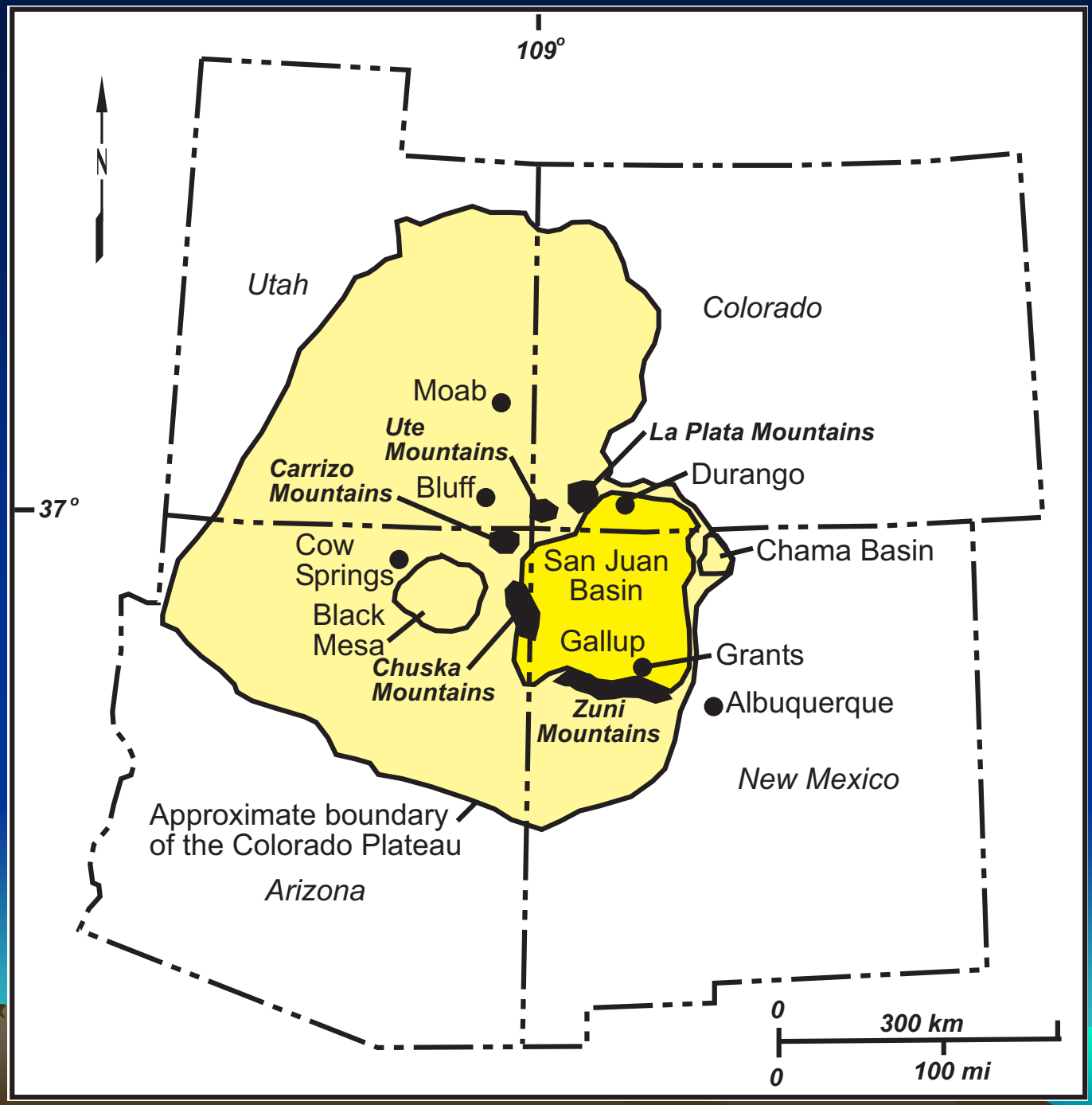
WHERE ARE THE MAJOR URANIUM DEPOSITS FOUND IN THE US?

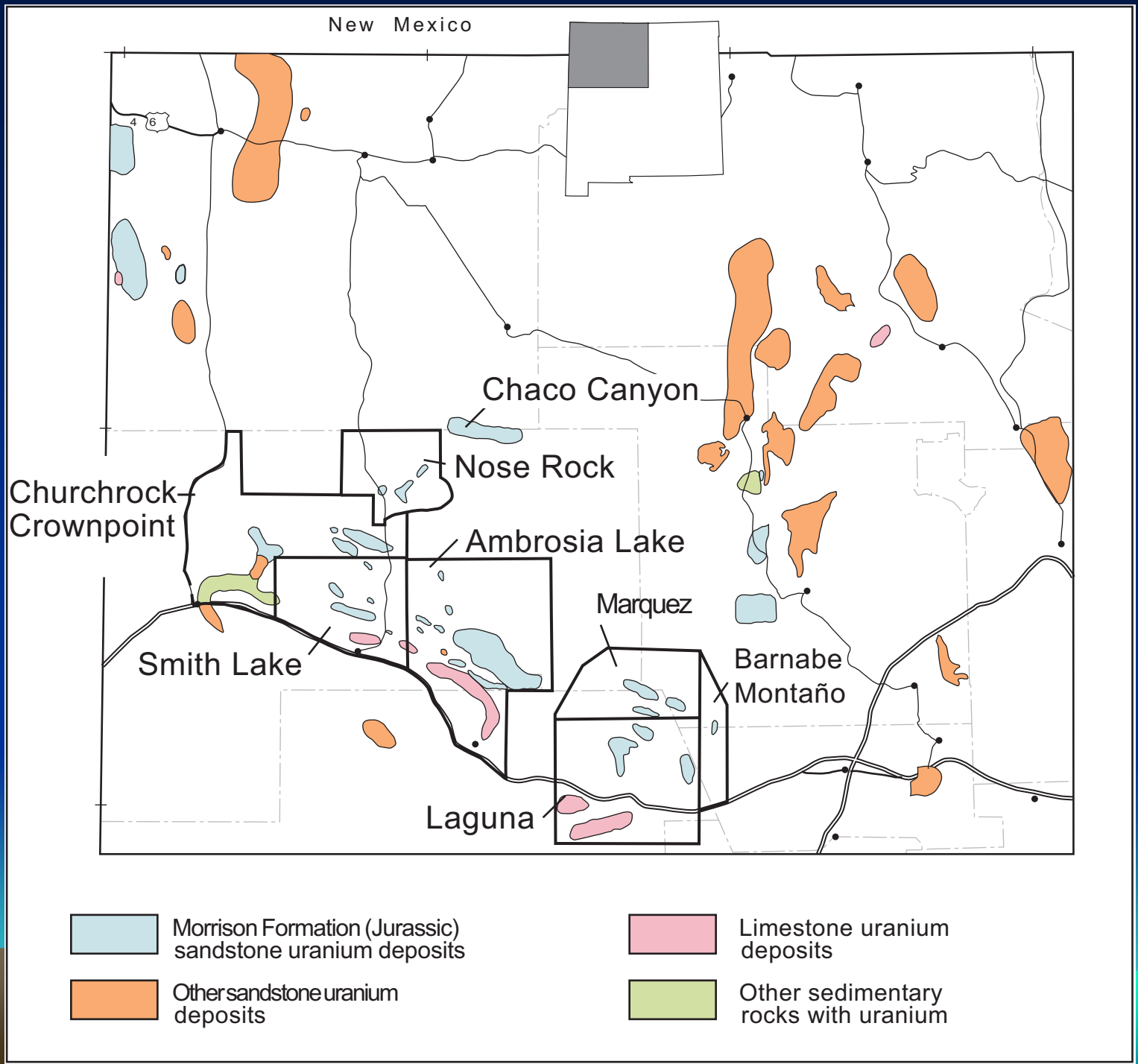

ATHABASCA BASIN
URANIUM
PROVINCE
CANADA
UNITED STATES
ROCKY MOUNTAIN AND
INTERMONTANE BASINS
URANIUM
PROVINCE
COLORADO
PLATEAU
URANIUM
PROVINCE
BASIN AND RANGE
URANIUM
PROVINCE
UNITED STATES
GULF
COAST
URANIUM
PROVINCE
ELLIOT LAKE
URANIUM
PROVINCE
FLORIDA
PHOSPHATE
URANIUM
PROVINCE

Major U.S. Uranium Trend Areas
(Does Not Include Frontier Uranium Areas)



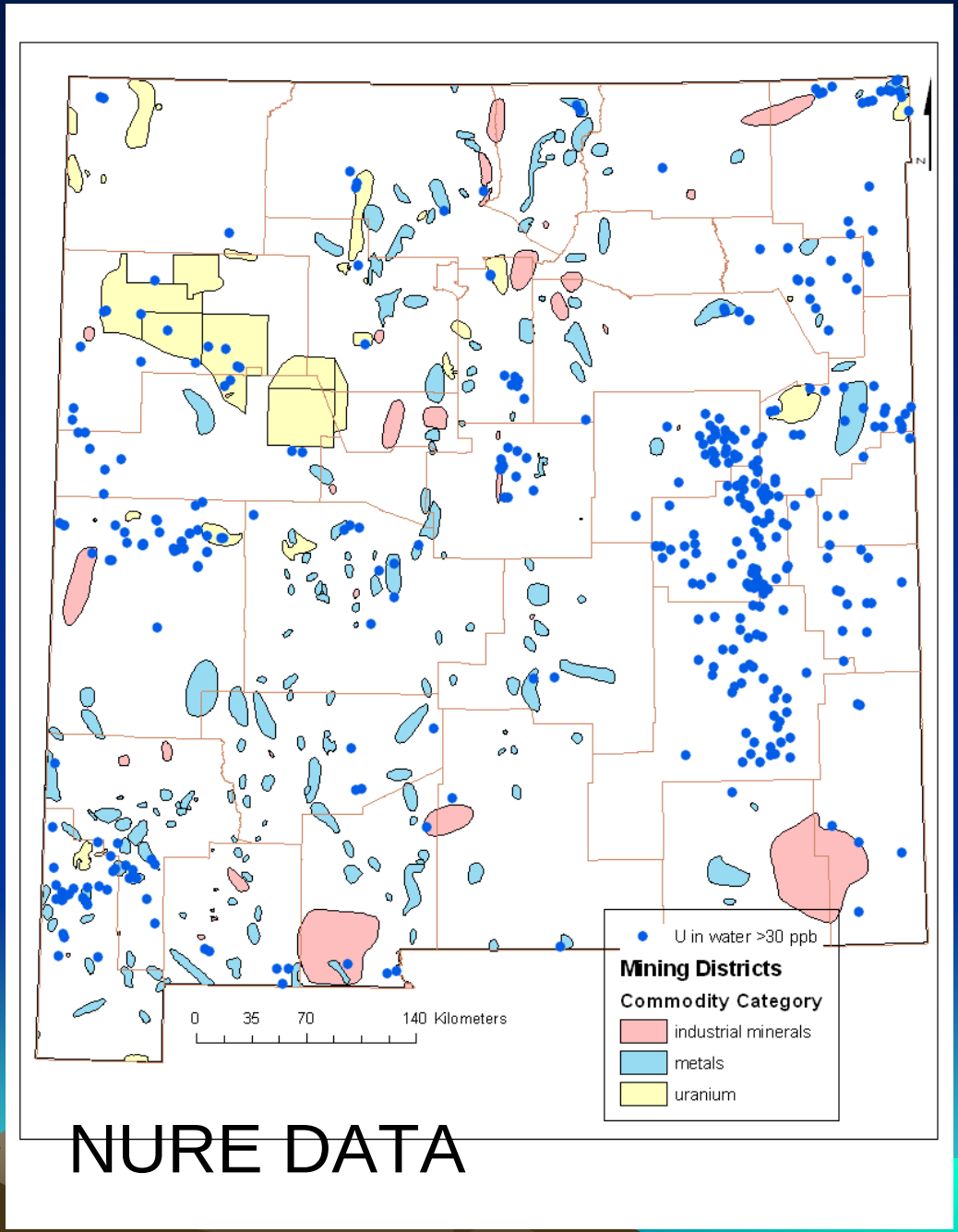
Sources: Based on U.S. Department of Energy, Grand Junction Project Office (GJPO), National Uranium Resources Evaluation, Interim Report (June 1979) Figure 3.2; and GJPO data files.


109°
N
Utah
Colorado
Moab
Ute Mountains
La Plata Mountains
Carrizo Mountains
Bluff
Durango
37°
Cow Springs
San Juan Basin
Chama Basin
Black Mesa
Gallup
Grants
Chuska Mountains
Albuquerque
Zuni Mountains
New Mexico
Approximate boundary of the Colorado Plateau
Arizona
0
300 km
0
100 mi


New Mexico
4
6
Chaco Canyon
Nose Rock
Churchrock
Crownpoint
Ambrosia Lake
Marquez
Barnabe
Montaño
Smith Lake
Laguna
Morrison Formation (Jurassic) sandstone uranium deposits
Other sandstone uranium deposits
Limestone uranium deposits
Other sedimentary rocks with uranium

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



NURE DATA

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)**

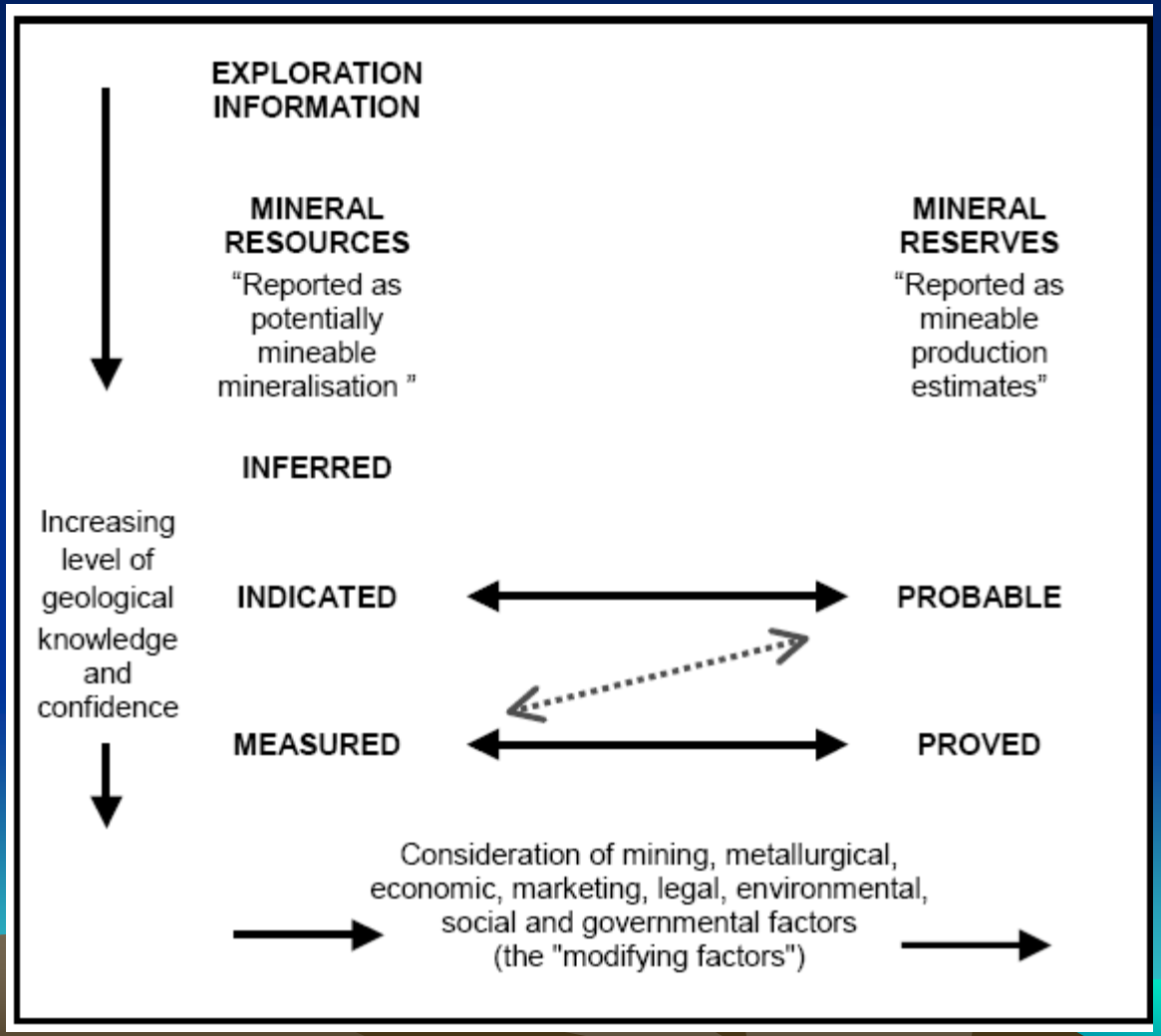
NOTE ON RESOURCES/RESERVES

- 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 U_3O_8 or radiometric U_3O_8
- Other relevant factors that demonstrate, at the time of reporting, that economic extraction can be justified

Relationship between reserves and resources



http://www.smenet.org/resourcesAndReserves/Sme_Guide_for_Reporting_Exploration_Results_2007.pdf

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)

CANADIAN NATIONAL INSTRUMENT 43-101—RESOURCES

- 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