SANDSTONE AND LIMESTONE URANIUM DEPOSITS

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New Mexico Bureau of Geology and Mineral Resources

New Mexico Institute of Mining and Technology, Socorro, NM

SAFETY

Schedule

- April 4—sandstone/limestone uranium deposits
- April 8—NMGS spring Meeting
  - Students free only if you preregister (report will be required)
- April 9—field trip
- April 11—Mark Pelizza in situ recovery of uranium, final given out
- April 18, 25—class presentations
- April 25—metallurgy (Abe Gundiler)

Field Trip

- Field trip on April 9, 2016 arrangements (Socorro area)
  - I have 3 4WD (John, Bonnie, me driving)—9 additional passengers
  - Vans not the best to take
- Who is going?
  - Darwin Werthessen (dwerthessen@gmail.com)
- AM—Lemitar carbonatites
- PM—Minas del Chupadera mine
- If you can not make this trip you need to talk to me ASAP—the field trip written report is 25% of your grade (see lecture notes for suggested format)

Field Trip References

- Carbonatites in Lemitar Mts http://nmgs.nmt.edu/publications/guidebooks/downloads/34/34_p0235_p0240.pdf
- http://geoinfo.nmt.edu/publications/openfile/details.cfml?Volume=158
- Paper on my web site

- Minas de Chupadero mine
- http://www.ees.nmt.edu/outside/alumni/papers/1973t_jaworski_mj.pdf Copper mineralization of the upper Moya Sandstone, Minas del Chupadero area, Socorro County, New Mexico

May 6—everything is due, earlier if you are graduating

- Summary of 2 presentations at NMGS Spring meeting—powerpoint or word document
  - If you do not attend the NMGS meeting, summarize a publication
- Written field trip report
- Written project report
- Powerpoint presentation of project
- Final

Comments on midterm

- No name— -1 point
- No references— -2 points
  - I would like to see ref cited in answers and a list of ref at the end of the final
- Other comments

Wyoming Trip

- Need students to ask their Student Associations for some funding
- May 23-27
- Day 1 Travel to Cripple Creek, Colo.
- Day 2 Visit Cripple Creek gold mine. Travel to Casper, Wyo.
- Day 3 Visit in-situ leach mine.
- Day 4 Visit in-situ leach mine.
- Day 5 Drive home.

FORMATION OF THE TODILTO URANIUM DEPOSITS, GRANTS DISTRICT, NEW MEXICO

INTRODUCTION

- Uranium deposits in limestone are rare
- Grants district is one of few districts in world with limestone uranium deposits
- 3,335.76 tons of U_3O_8 produced from the Todilto, 1950-1981
- 2% of total Grants production

INTRODUCTION

- Limestone is typically an unfavorable host rock for uranium
  - low permeability and porosity
  - lack of suitable precipitants, such as organic material.

Areas in the world containing uranium deposits in limestones

- Tyuya, Muyun in Ferghana, Turkestan
- Todilto Limestone in Grants, New Mexico
- Georgetown Fm in Sierra de Gomez, Sierra Blanca, Sierra de la Cal; Chihuahua and Durango, Mexico
- Madison in Pryor and Bighorn Mountains, Montana and Wyoming
- St. Geneviere Fm in Missouri

GRANTS DISTRICT

- 100 uranium mines and occurrences
- 42 mines
- Drill holes exceeding depths of 1,000 ft in the Ambrosia Lake area

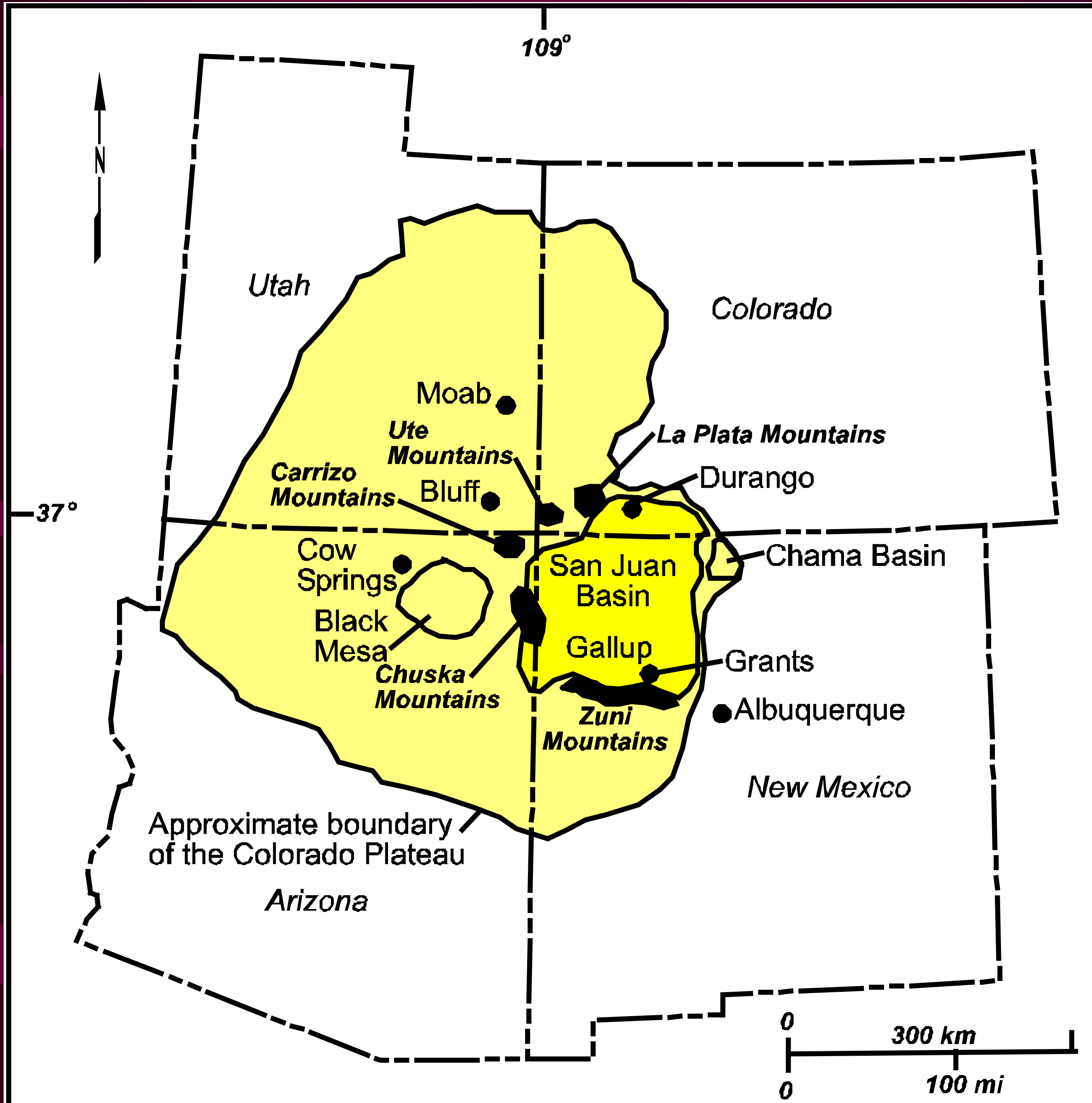
What questions should be asked?

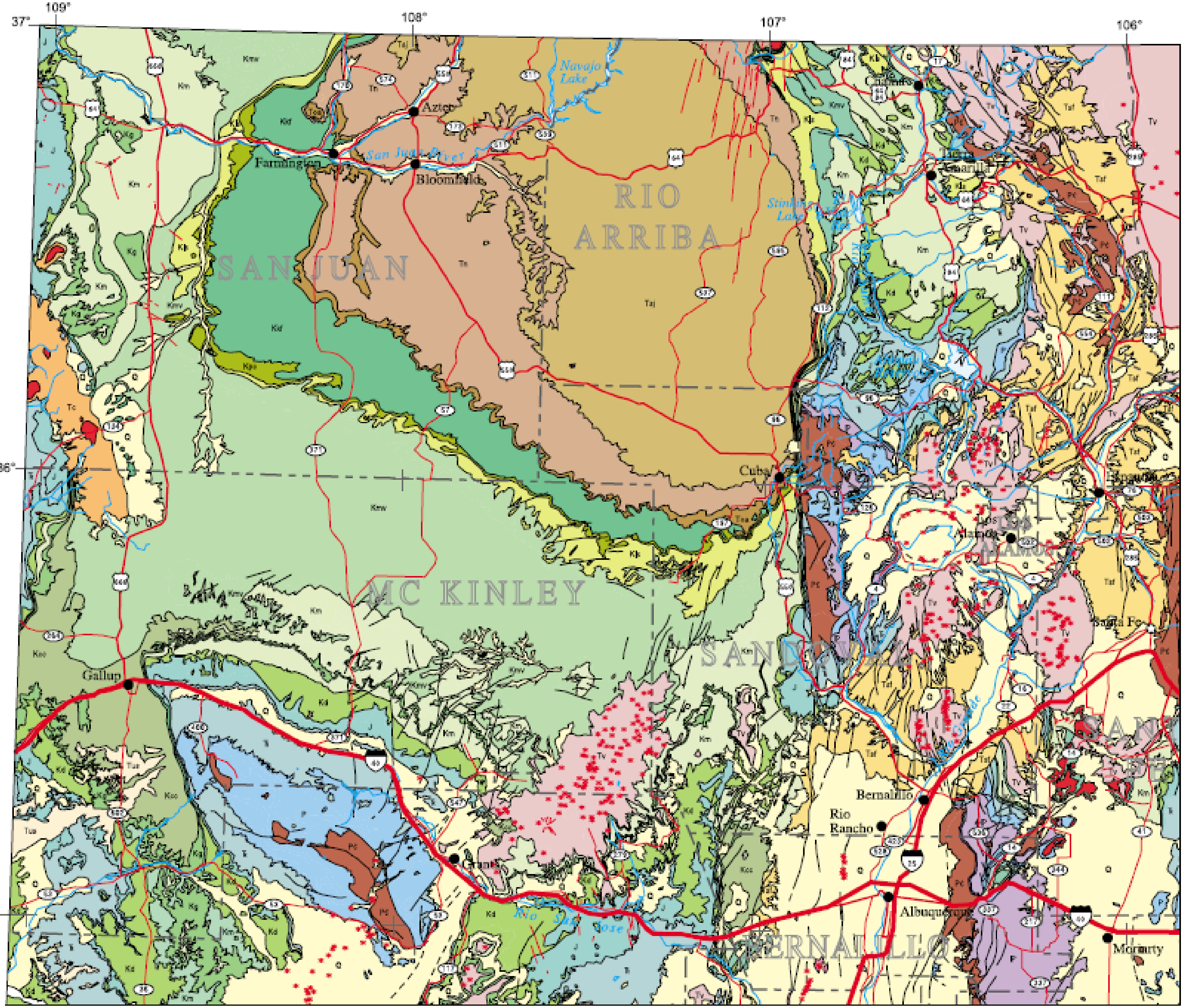
What questions should be asked?

- Geologic history, stratigraphy
- Depositional environment of the Todilto
- Age of the Todilto
- Type of uranium deposits
- Age of the uranium deposits
- Ore controls and how they formed
- Paragenesis
- Origin of the deposits

STRATIGRAPHY

- Correlated with
  - Pony Express Limestone Member of the Wanakah Formation in Colorado
  - Curtis Formation in Utah
- 2 members
  - basal limestone, everywhere present (5-40 ft thick)
  - upper gypsum-anhydrite member, center of basin (0-170 ft thick)


109°
N
Utah
Colorado
Moab
Ute Mountains
La Plata Mountains
Carrizo Mountains
Bluff
Durango
37°
Cow Springs
Chama Basin
San Juan 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



109°
108°
107°
106°
37°
36°
35°
SAN JUAN
RIO ARRIBA
MC KINLEY
SANDOVAL
BERNALILLO
Navajo Lake
San Juan River
Farmington
Aztec
Bloomfield
Stinking Lake
Chama
Tierra Amarilla
Cuba
Espanola
Los Alamos
Santa Fe
Gallup
Grants
Bernalillo
Rio Rancho
Albuquerque
Moriarty
Rio San Jose

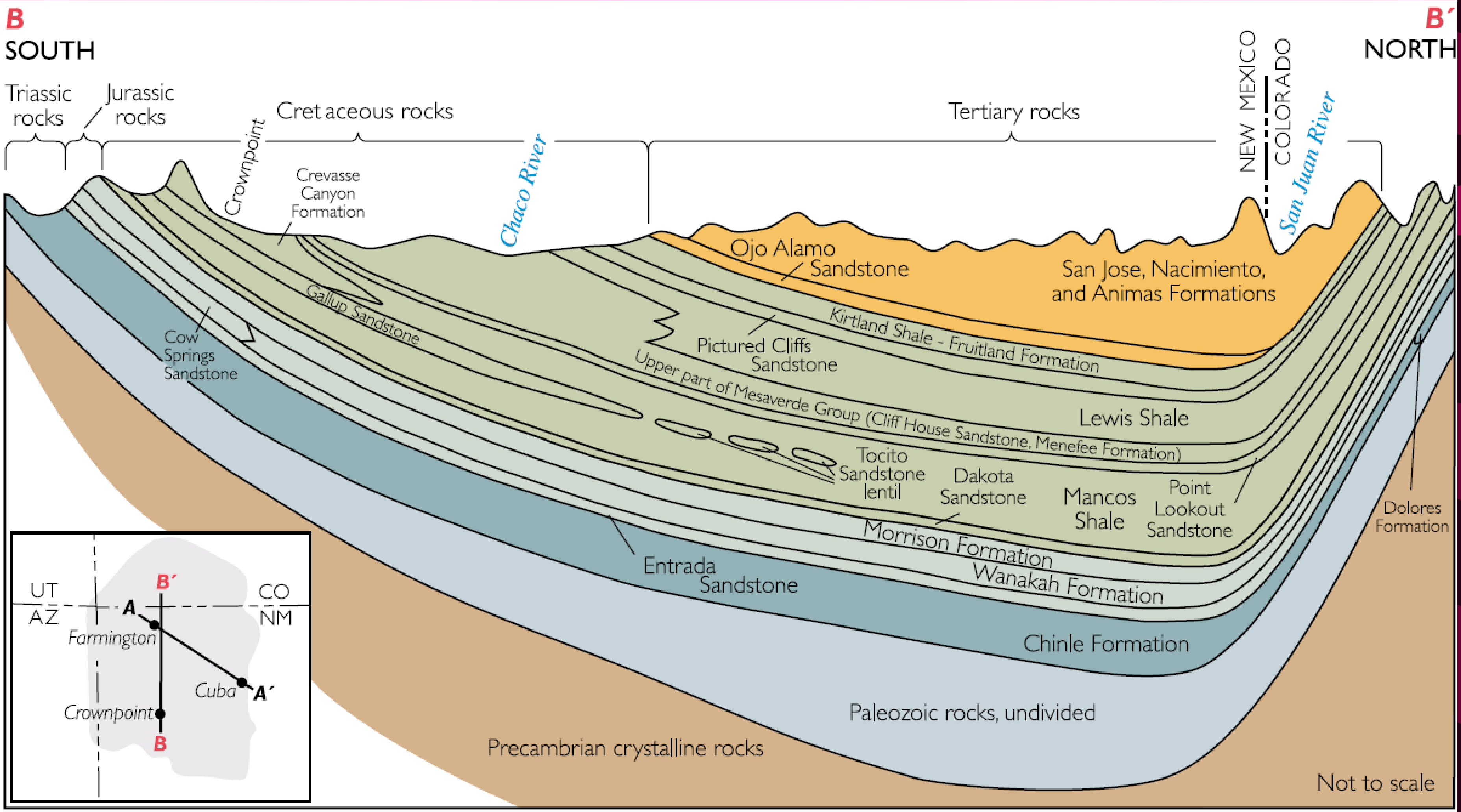
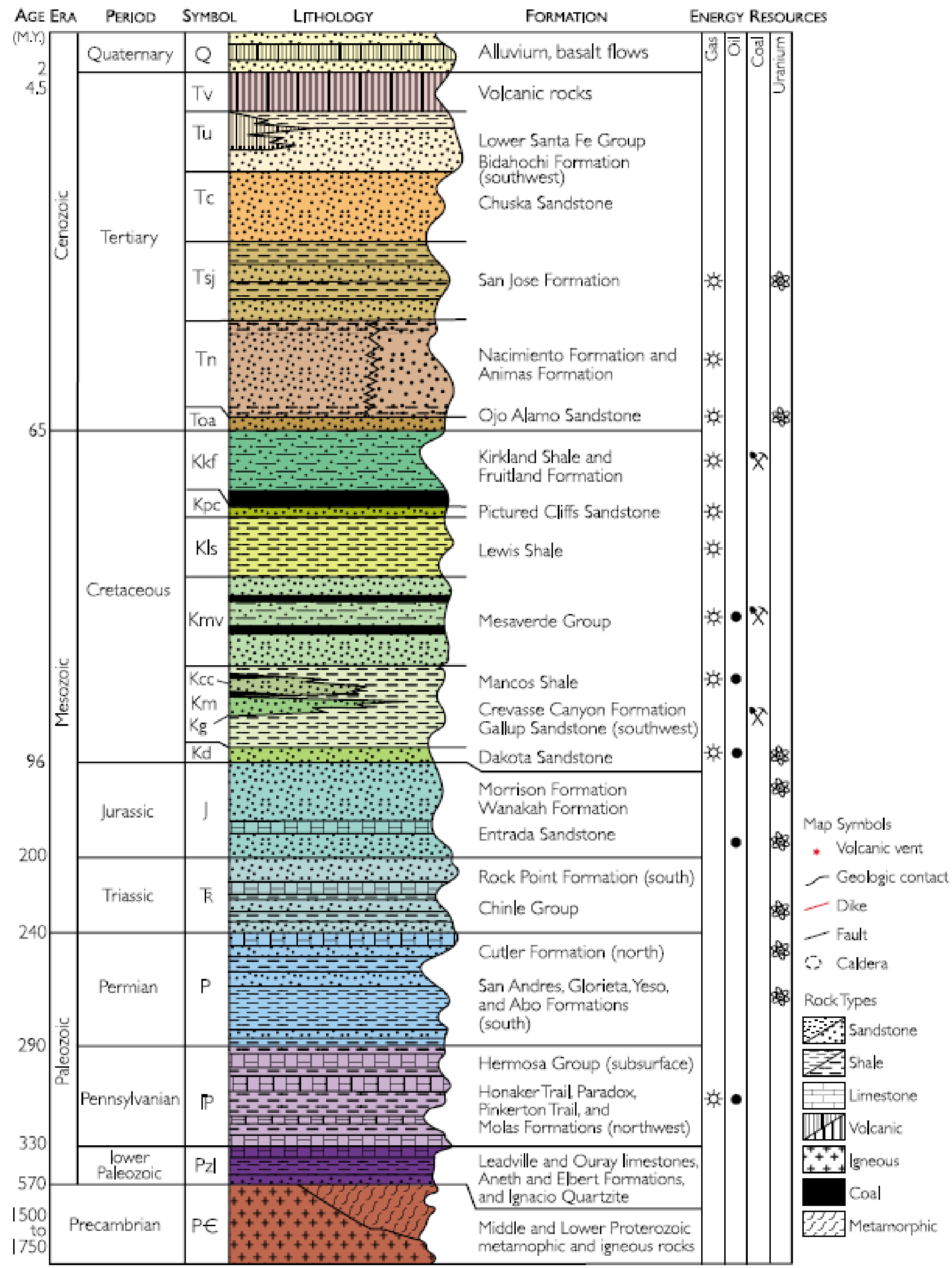
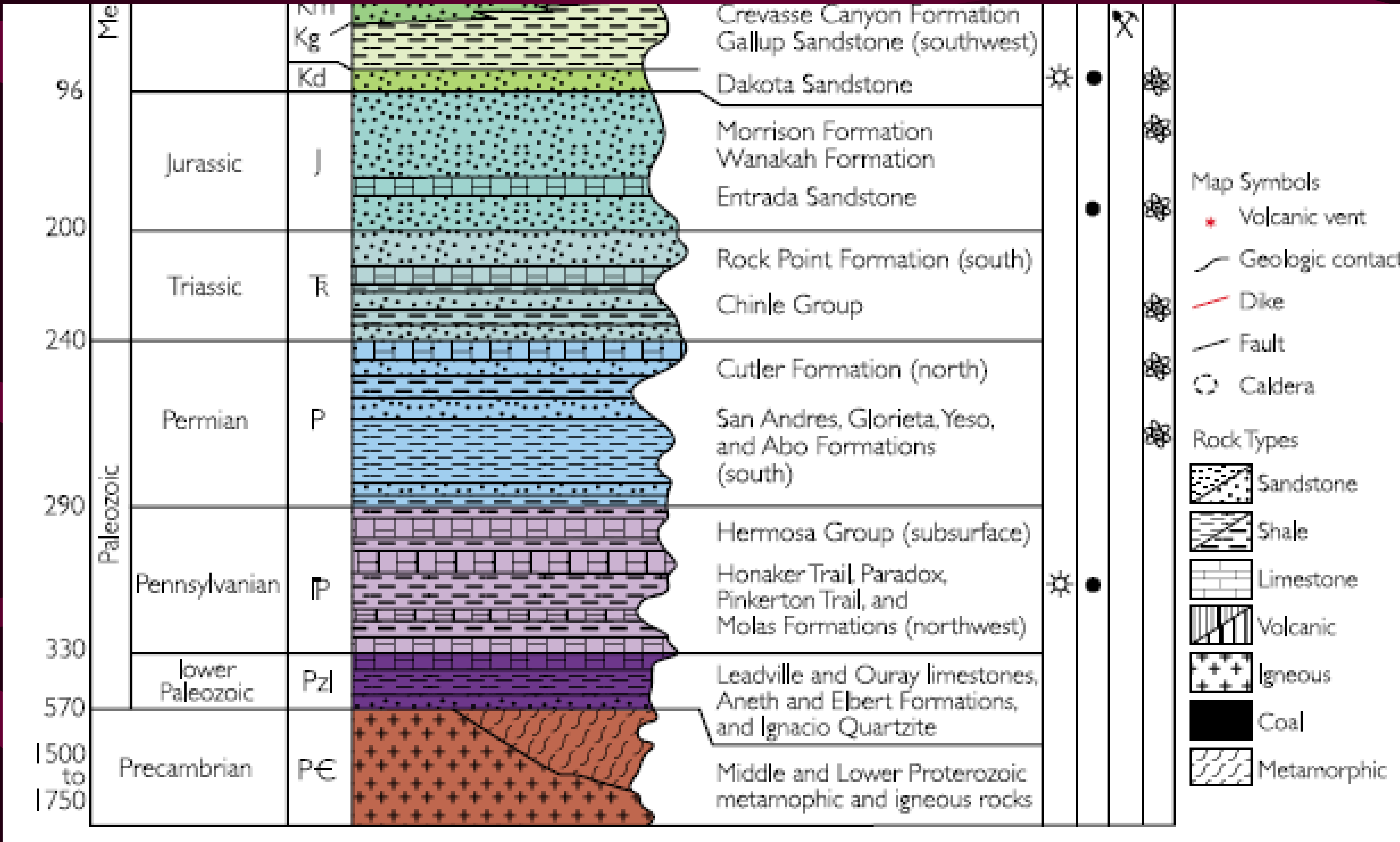


FIGURE 3 Diagrammatic southwest-northeast cross section of San Juan Basin, from Craigg, 2001 (p.12).



Age (M.Y.)
Era
Period
Symbol
Lithology
Formation
Energy Resources
Gas
Oil
Coal
Uranium
Cenozoic
Mesozoic
Paleozoic
2
4.5
65
96
200
240
290
330
570
1500 to 1750
Quaternary
Tertiary
Cretaceous
Jurassic
Triassic
Permian
Pennsylvanian
lower Paleozoic
Precambrian
Q
Tv
Tu
Tc
Tsj
Tn
Toa
Klkf
Kpc
Kls
Kmv
Kcc
Km
Kg
Kd
J
₮R
P
IP
Pzl
P€
Alluvium, basalt flows
Volcanic rocks
Lower Santa Fe Group
Bidahochi Formation (southwest)
Chuska Sandstone
San Jose Formation
Nacimiento Formation and Animas Formation
Ojo Alamo Sandstone
Kirkland Shale and Fruitland Formation
Pictured Cliffs Sandstone
Lewis Shale
Mesaverde Group
Mancos Shale
Crevasse Canyon Formation
Gallup Sandstone (southwest)
Dakota Sandstone
Morrison Formation
Wanakah Formation
Entrada Sandstone
Rock Point Formation (south)
Chinle Group
Cutler Formation (north)
San Andres, Glorieta, Yeso, and Abo Formations (south)
Hermosa Group (subsurface)
Honaker Trail, Paradox, Pinkerton Trail, and Molas Formations (northwest)
Leadville and Ouray limestones, Aneth and Elbert Formations, and Ignacio Quartzite
Middle and Lower Proterozoic metamorphic and igneous rocks
Map Symbols
Volcanic vent
Geologic contact
Dike
Fault
Caldera
Rock Types
Sandstone
Shale
Limestone
Volcanic
Igneous
Coal
Metamorphic



Me
96
200
240
290
330
570
1500
to
1750
Paleozoic
Jurassic
Triassic
Permian
Pennsylvanian
lower Paleozoic
Precambrian
Kg
Kd
J
P
Pzl
P€
Crevasse Canyon Formation
Gallup Sandstone (southwest)
Dakota Sandstone
Morrison Formation
Wanakah Formation
Entrada Sandstone
Rock Point Formation (south)
Chinle Group
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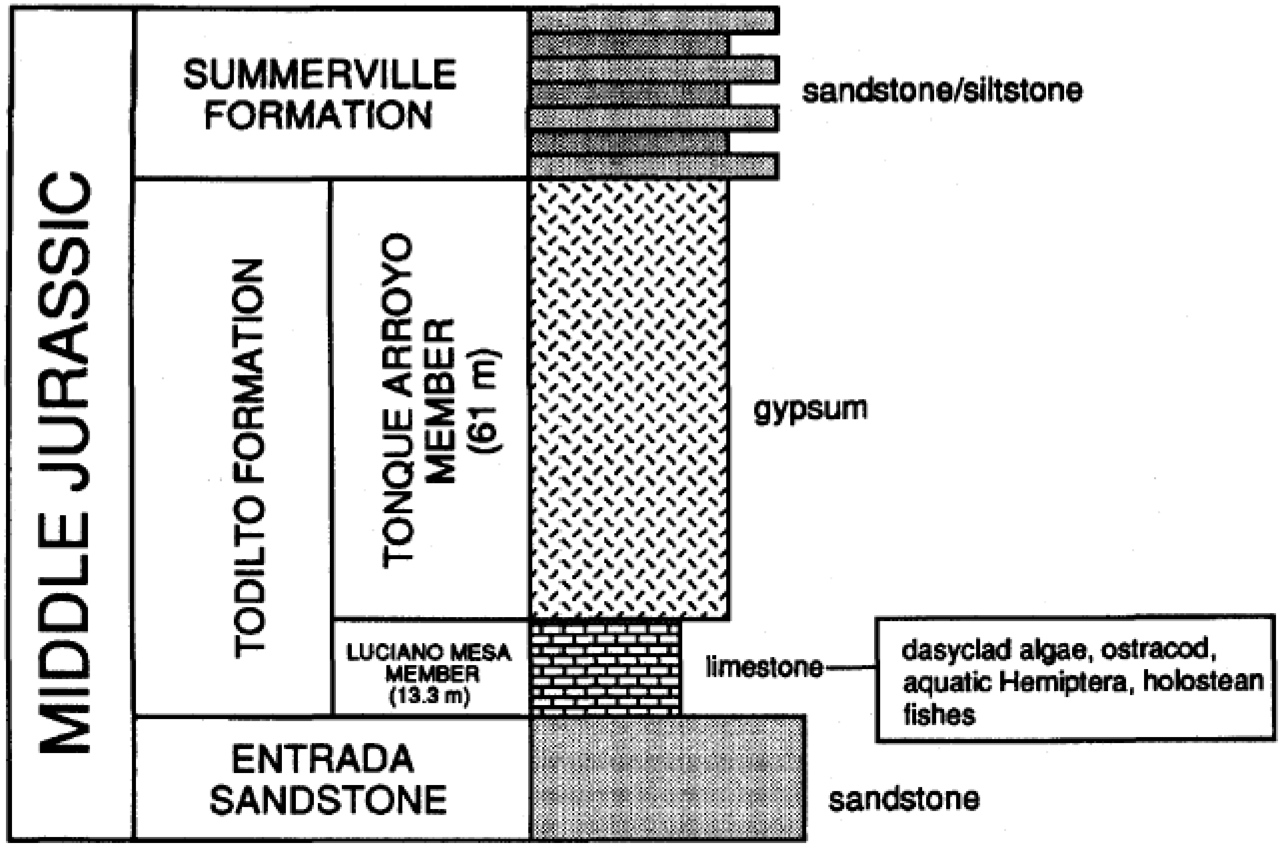
Igneous
Coal
Metamorphic

Figure 2—Summary of the stratigraphy and paleontology of the Todilto Formation.



Lucas and Anderson

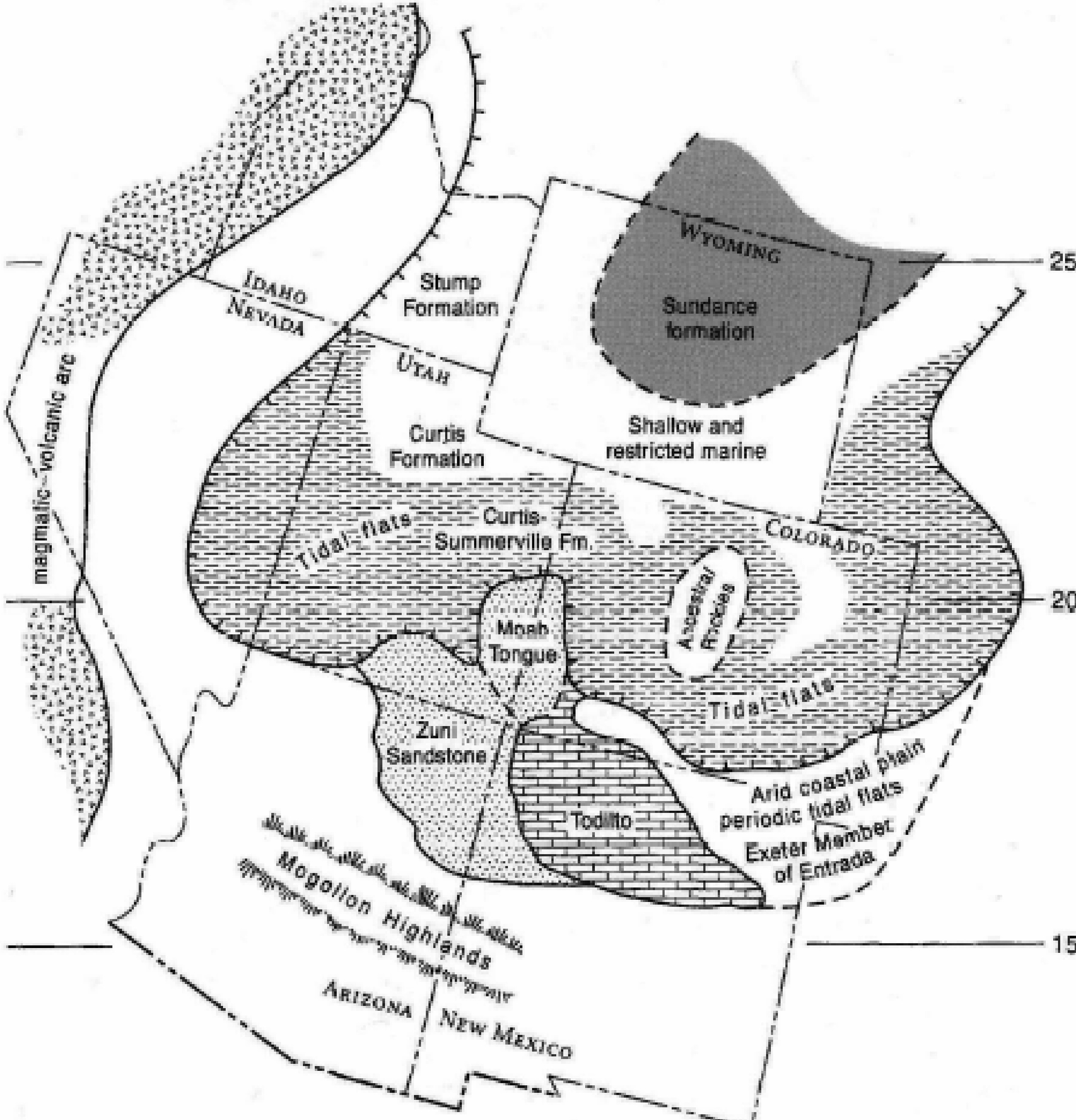
Depositional Environment of the Todilto

- Limestone can be
  - Marine
  - Inland lake
- Todilto fossils indicate a saline lake (Lucas)

Depositional Environment of the Todilto

- Arid to semi-arid climate
- Shallow Sundance Seaway filled in
- The ocean floor became very flat
- Sea level gradually lowered
- The shoreline turned into a sabka/tidal flat environment
- Like the present day Persian Gulf and western Australia

Figure 4—Late Middle Jurassic (Callovian) paleogeography of the American Southwest. After Anderson and Lucas (1994).



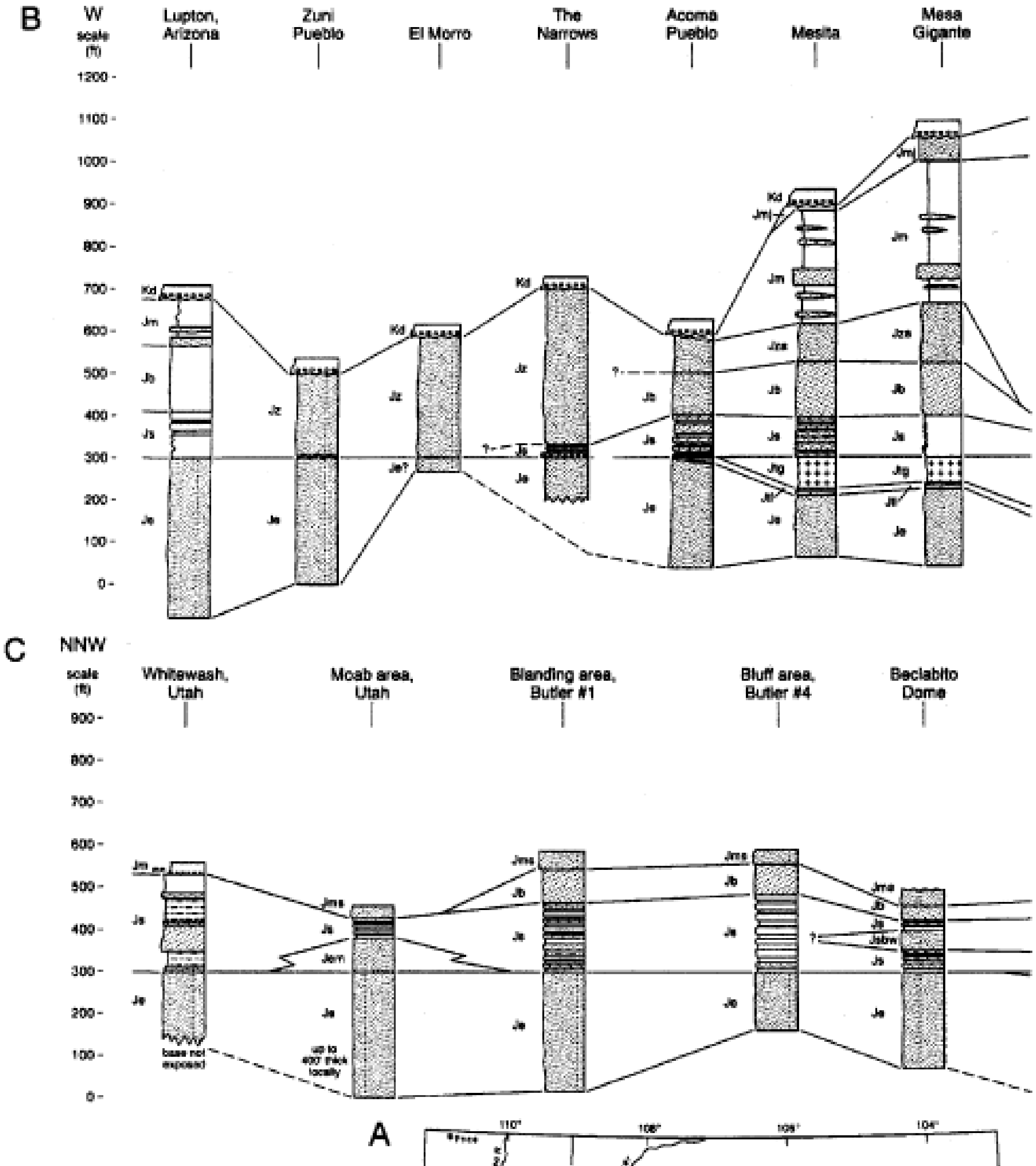


Figure 3— Regional correlation of the Todilto Formation and other San Rafael Group strata. (A) Lines of stratigraphic cross sections shown in B–D. (B) Lupton, Arizona, to northeastern New Mexico. (C) Whitewash, Utah, to Acoma Pueblo, New Mexico. (D) Whitewash, Utah, to Ouray, Colorado.

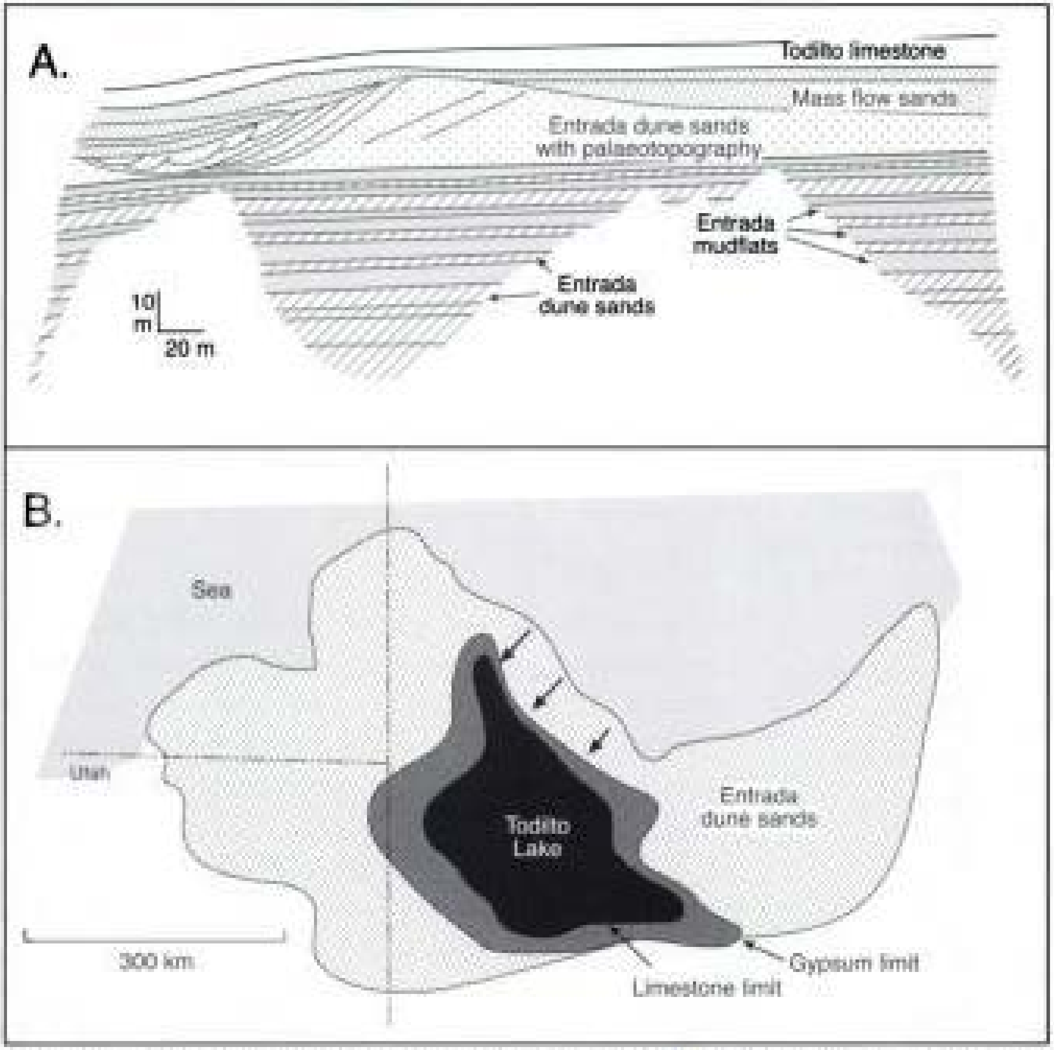


Figure 2.43. A) Outcrop drawing showing preserved dune palaeorelief with onlapping structureless sandstones and overlying limestones of the Formation. The Entrada Sandstone underlying the preserved relief consists of interbedded dune sets and evaporitic mudflat (sabkha) deposits (after Benan and Kocurek, 2000). B) Approximate Late Callovian-Oxfordian(?) palaeogeography of the Four Corners area after partial marine transgression of the Entrada. Extent of the Formation shown with concentric limits of limestone and gypsum within the unit, with surrounding eolian units (after Lucas and Anderson, 1994).

Warren (2006)

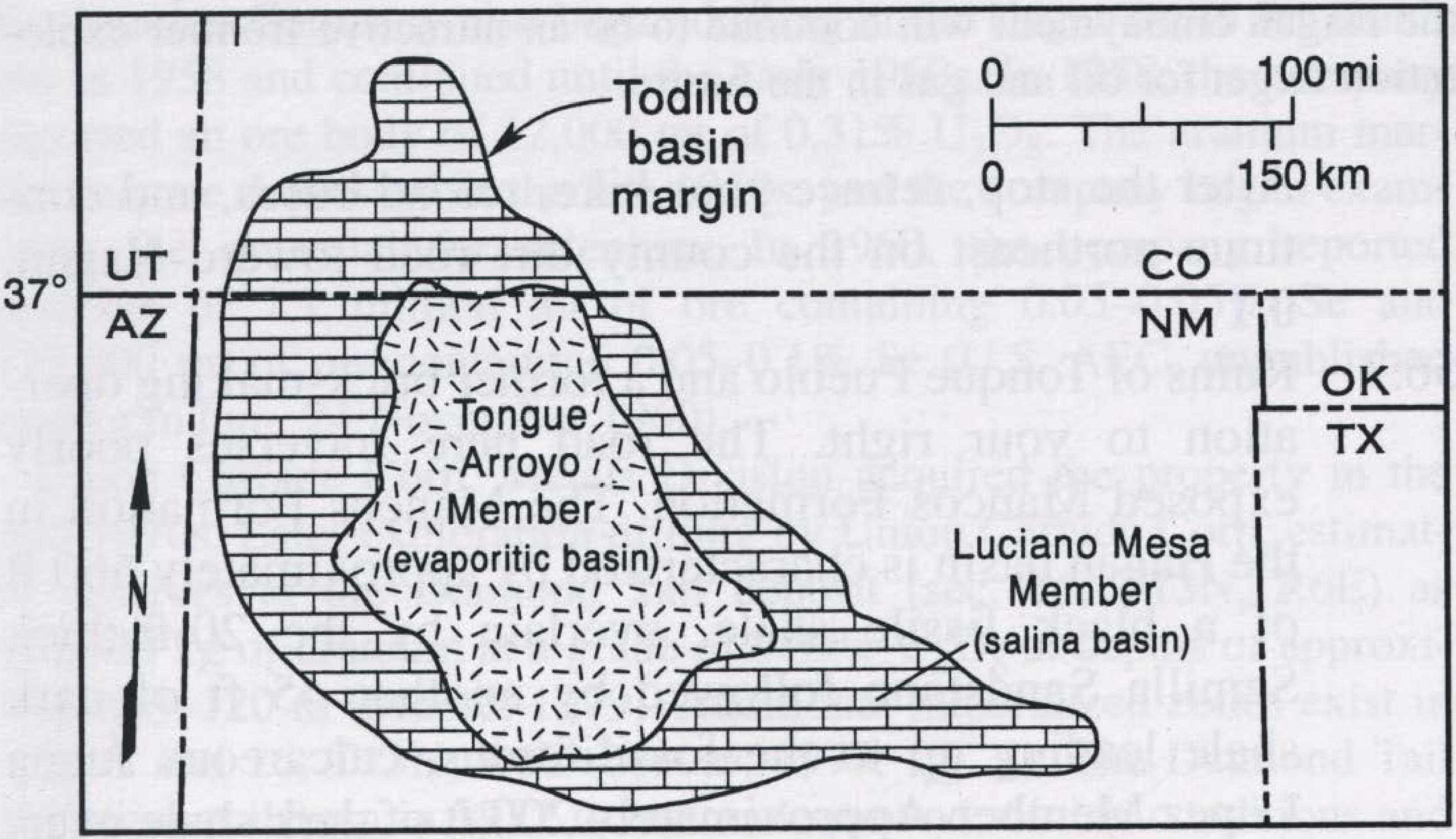


FIGURE 1.17. Extent of the Middle Jurassic Todilto salina basin (after Lucas and Anderson, 1996).

Economic importance of Todilto

- Uranium, vanadium production
- Gypsum production
- Limestone production
- Oil and gas reservoir

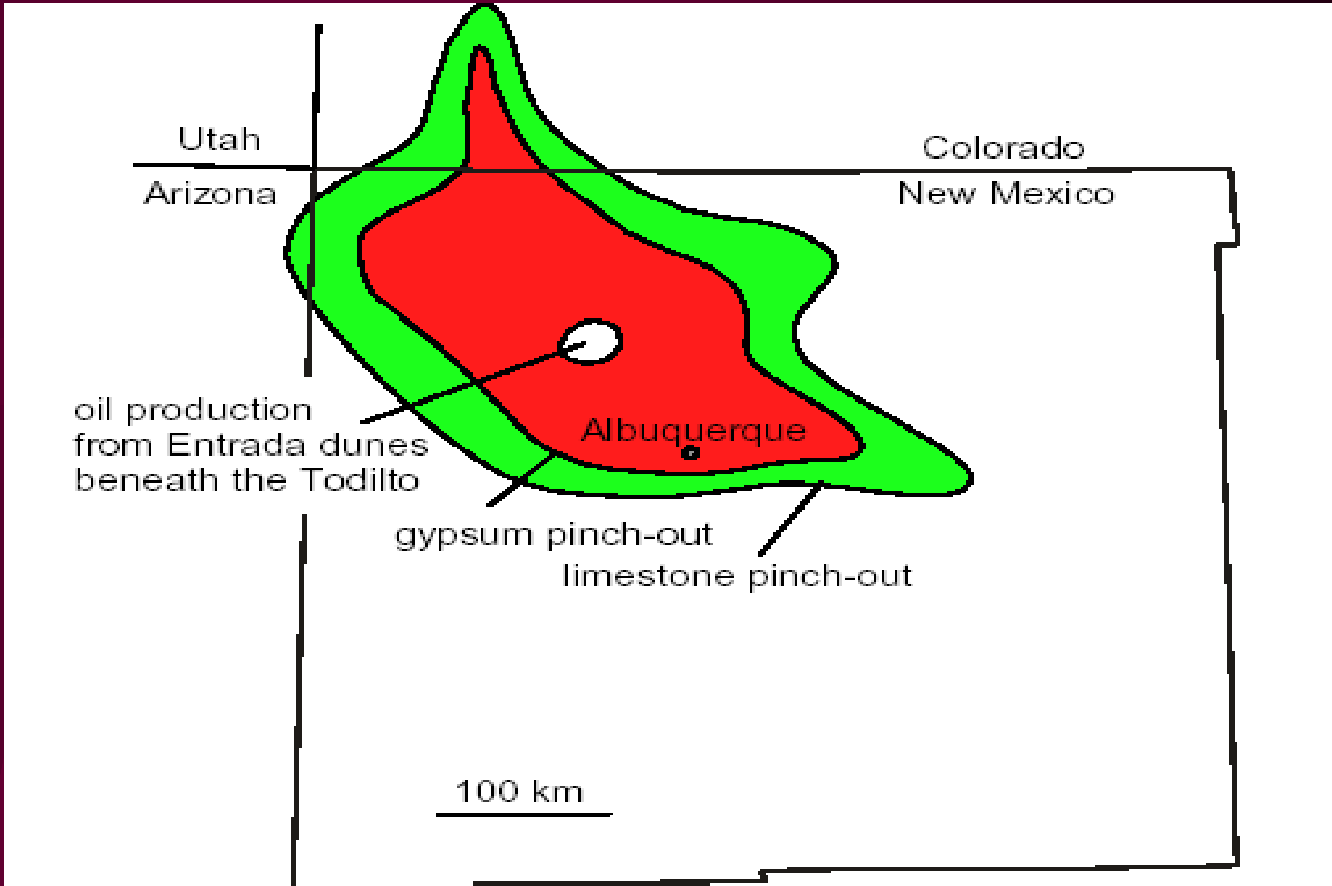


Figure 1: The Todilto Formation

150 Qanati Polygonal Algal Mats (soft & smell of H2S)

http://strata.geol.sc.edu/UAE/AbuDhabi/UAEGallery/pages/150-Qanati-Polygonal-Algal-Mats-(soft-&-smell-of-H2S).html

149 Qanatir Polygonal Alga Mats

http://strata.geol.sc.edu/UAE/AbuDhabi/UAEGallery/pages/150-Qanati-Polygonal-Algal-Mats-(soft-&-smell-of-H2S).html

Ore Controls

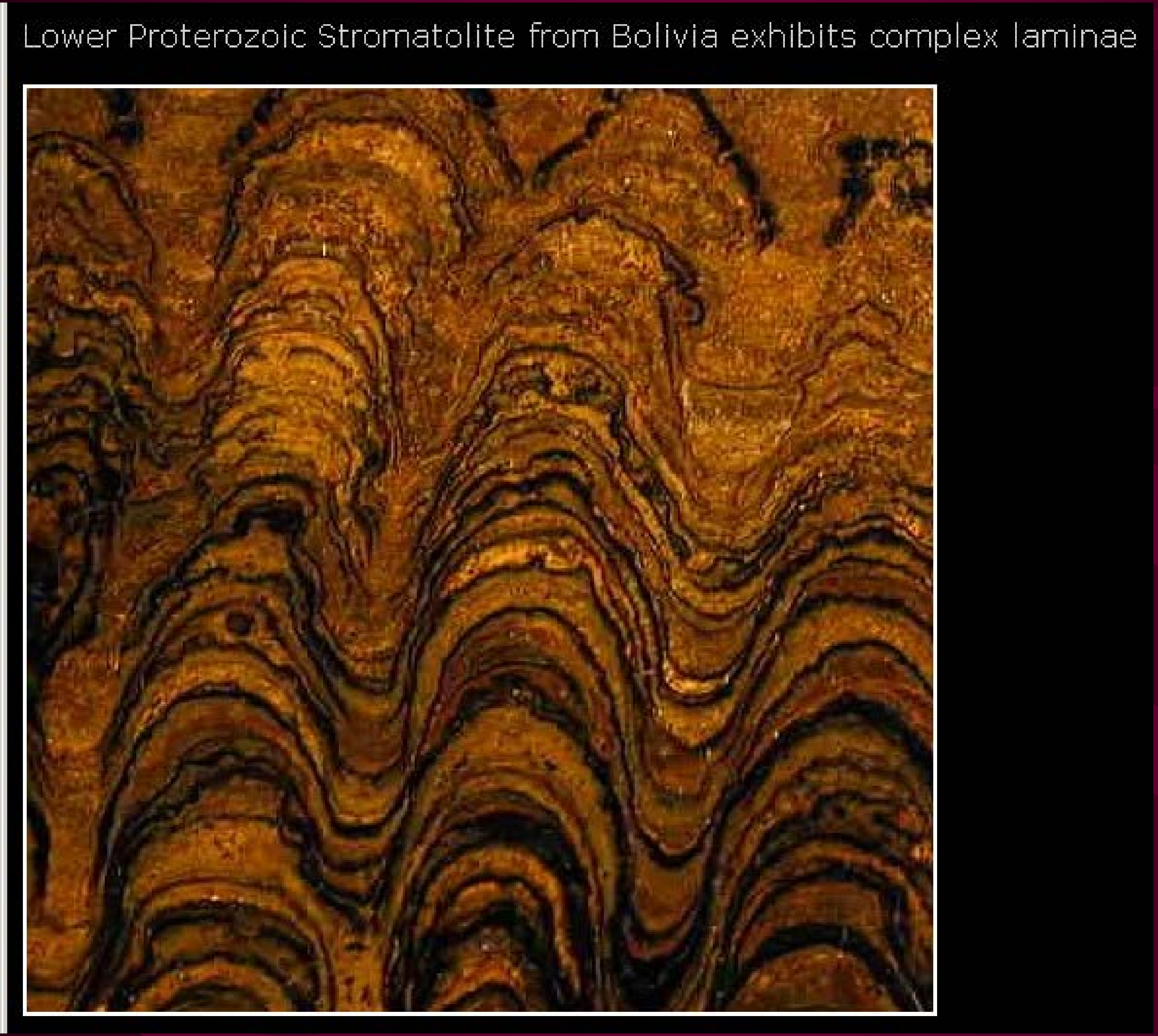
- Recrystallized and organic material
- Stromatalites
- Gypsum-anhydrite member is absent
- Intraformational folds

Stromatalites

- Rock-like buildups of agael or microbial mats that form in limestone- or dolostone-forming environments
- Formed by baffling, trapping, and precipitation of particles by communities of microorganisms such as bacteria and algae
- Oldest fossils

Kalbarri, Australia

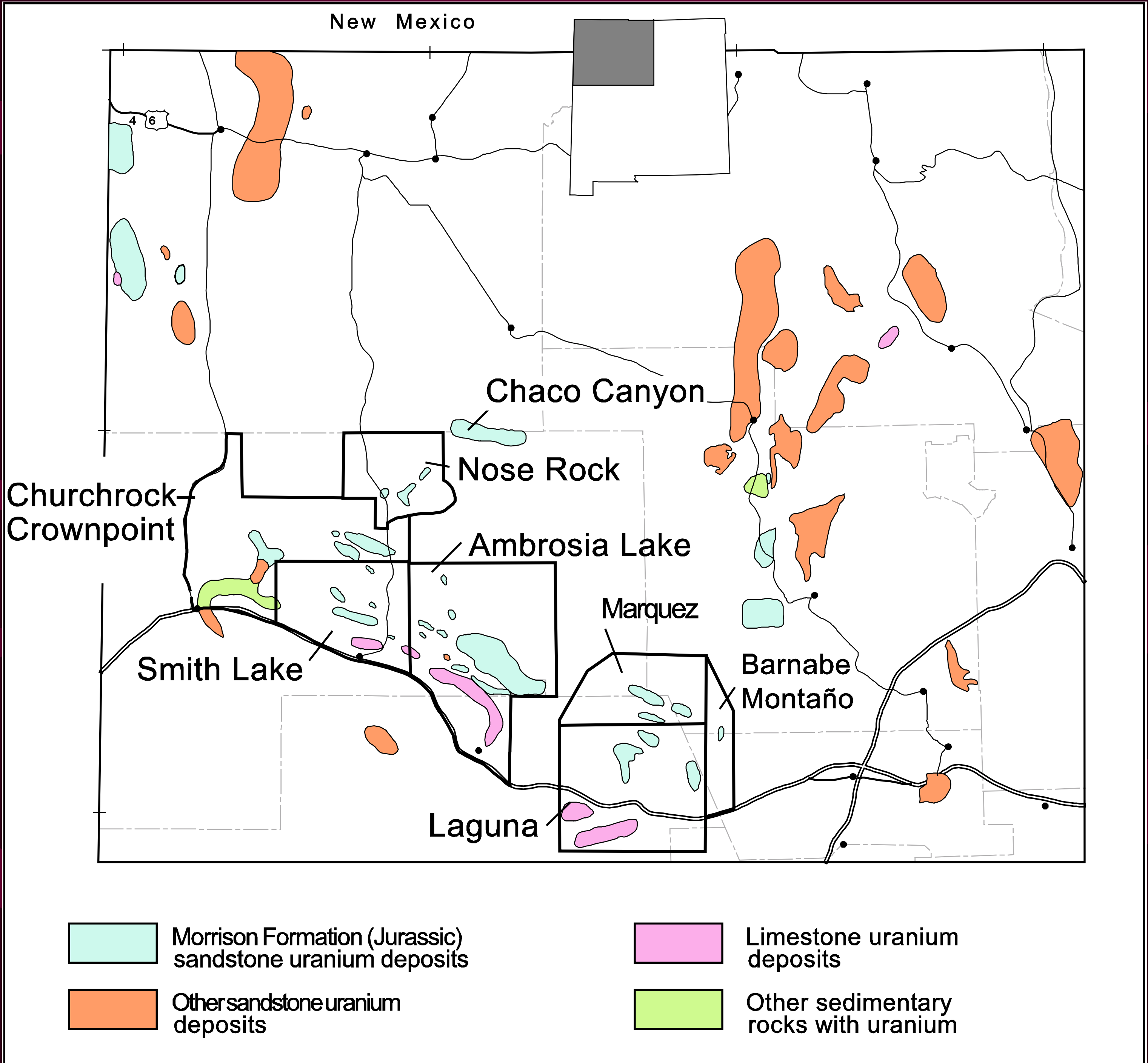
Kalbarri, Australia



http://www.fossilmall.com/Science/Stromatolite/Laminae.htm

156 Qanatir Anhydrite at surface of coastal sabkha

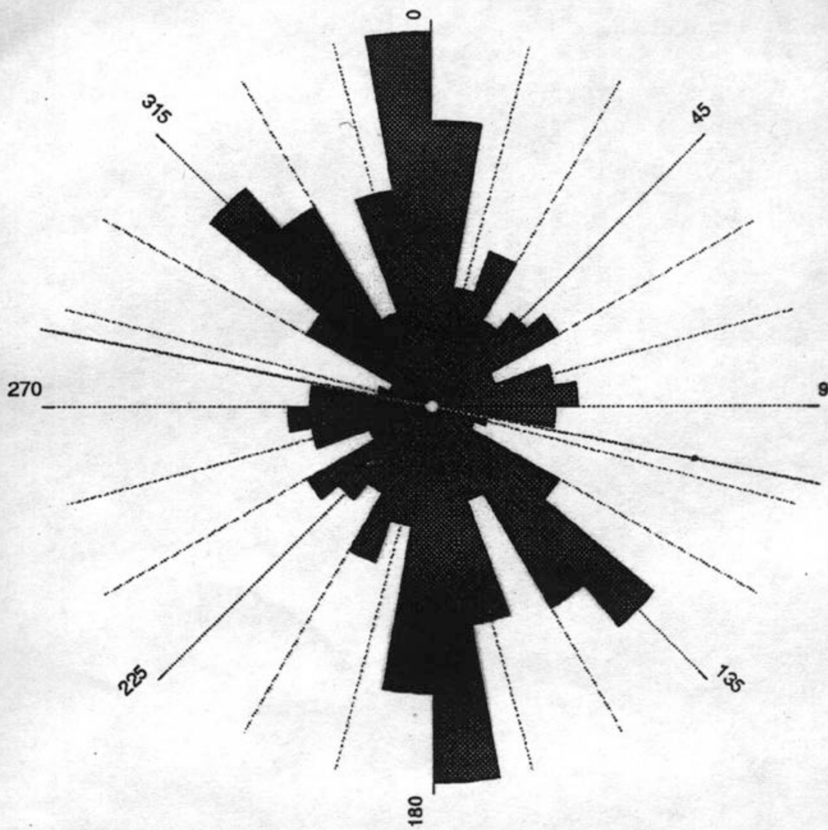
http://strata.geol.sc.edu/UAE/AbuDhabi/UAEGallery/pages/150-Qanati-Polygonal-Algal-Mats-(soft-&-smell-of-H2S).html


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

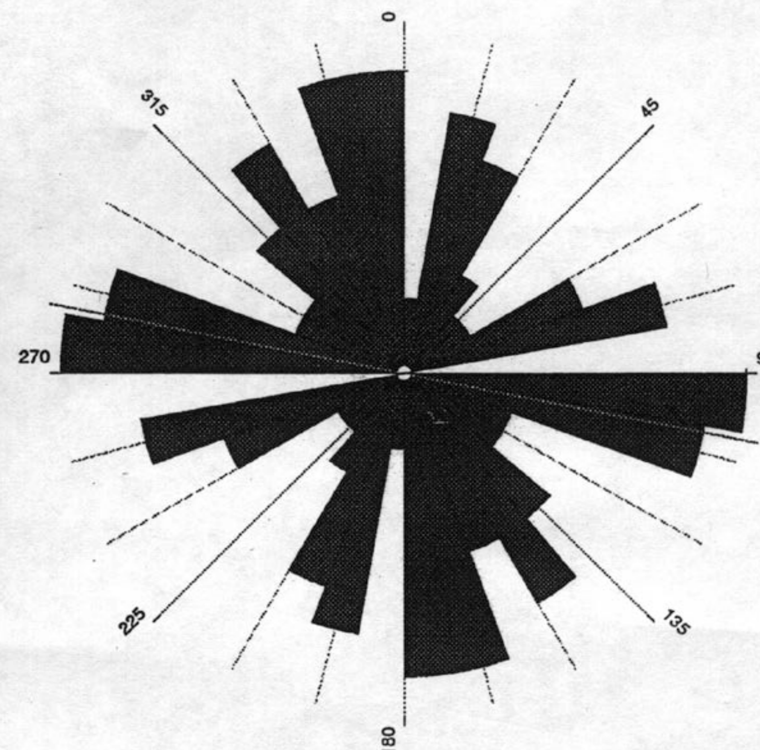
TYPES OF FOLDING IN THE TODILTO LIMESTONE

- Regional large-scale folds of Todilto Limestone and units above and below
- Large-scale intraformational folds with axis
- Mounds or pillows within limestone (reef structures?)
- Small-scale intraformational folds
  - Within-layer folds (varves are folded)
  - Folds of thin layers or thin beds
  - Fine crinkly folding of varves (crinkly zone)

Folds in Todilto at the Flat Top mine



Folds in Todilto at the Section 25 mines



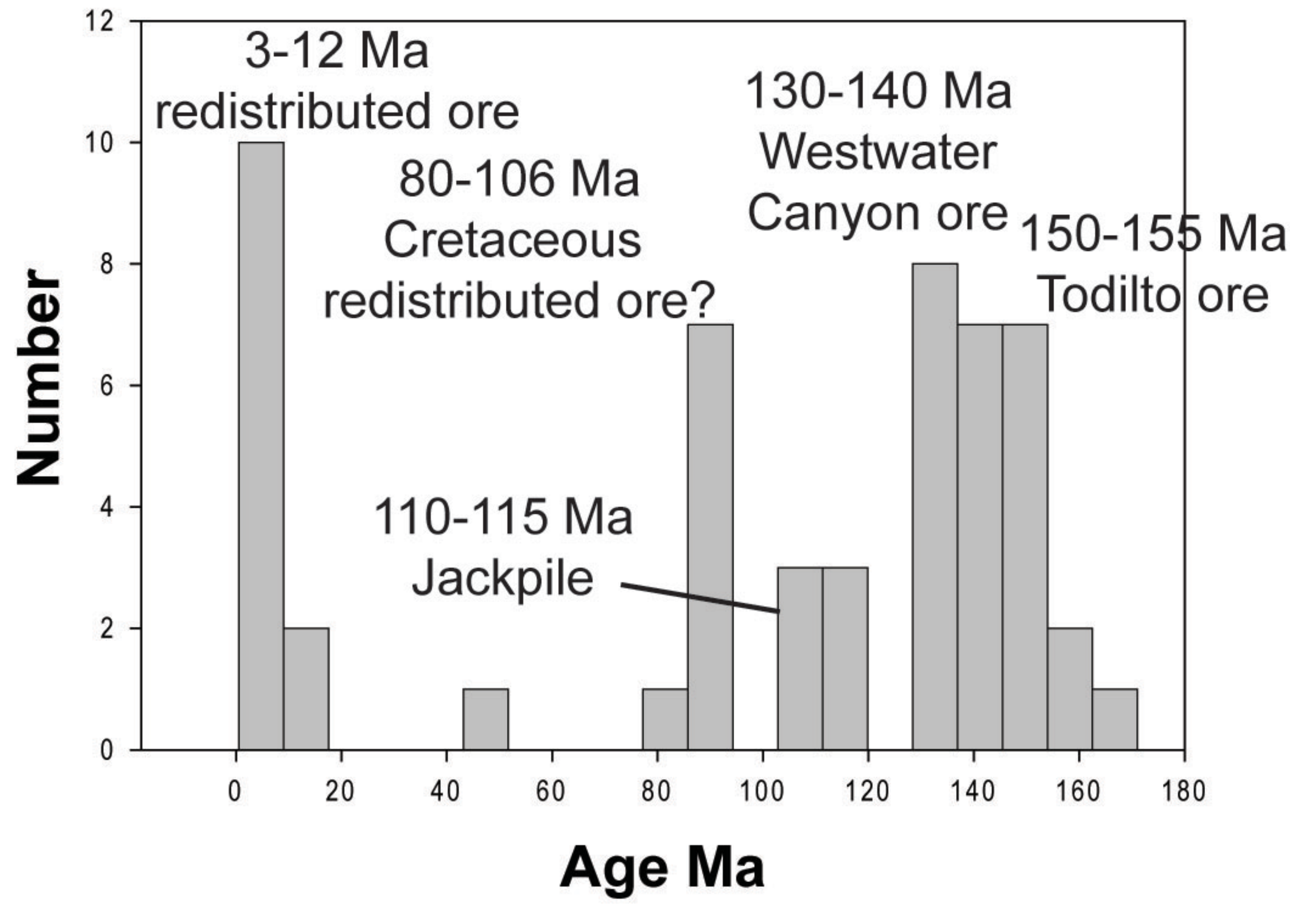
Origin of the folds

- Slumping under the influence of gravity or seismic activity
- Soft-sediment deformation
- Weight of encroaching sediments of the overlying Summerville Formation deformed the soft lime muds of the Todilto
- Some folds resemble tepees; along with small-scale enterolithic folds, these could relate at least in part to forces of crystallization or hydration of calcite and gypsum
- Multiple origins

Age of Todilto uranium deposits

- Todilto limestone is middle Callovian
- 150-155 Ma (U/Pb, Berglof and McLemore)
- 3 to 7 Ma Younger Todilto ores suggesting redistribution of Todilto deposits
- Morrison uranium deposits
  - Primary tabular 130 Ma (U/Pb/ K/Ar, Rb/SR)
  - Redistributed 3 to 12 Ma

Age determinations of Grants district mineralization



Includes Pb/U, K/Ar, Rb/Sr, and fission track dates from Miller and Kulp (1963), Nash and Kerr (1966) , Nash (1968), Berglof (1970, 1992), Brookins et al. (1977), Brookins (1980), Ludwig et al. (1982), Hooper (1983).

MINERAL	CHEMICAL FORMULA
uraninite	UO_2
coffinite	$U(SiO_4)_{1-x}(OH)_{4x}$
häggite	$V_2O_2(OH)_3$
paramontroseite	VO_2
fluorite	CaF_2
barite	$BaSO_4$
pyrite	FeS_2
calcite	$CaCO_3$
hematite	Fe_2O_3
galena	PbS
tyuyamunite	$Ca(UO_2)_2(VO_4)_2 \cdot 5\text{-}8½H_2O$
metatyuyamunite	$Ca(UO_2)_2(VO_4)_2 \cdot 3\text{-}5H_2O$
uranophane	$Ca(UO_2)_2(SiO_3OH)_2 \cdot 5H_2O$
schroeckingerite	$NaCa_3UO_2(CO_3)_3SO_4F \cdot 10H_2O$
curite	$Pb_2U_5O_{17} \cdot 4H_2O$
hewettite	$CaV_6O_{16} \cdot 9H_2O$
metahewettite	$CaV_6O_{16} \cdot 3H_2O$
santafeite	$(Mn,Fe,Al,Mg)_8Mn_8(Ca,Sr,Na)_{12}$ $(VO_4)_{16}(OH,O)_{20} \cdot 8H_2O$
grantsite	$Na_4CaV_{12}O_{32} \cdot 8H_2O$
goldmanite	$Ca_3(V,Fe,Al)_2Si_3O_{12}$

URANIUM MINERALS

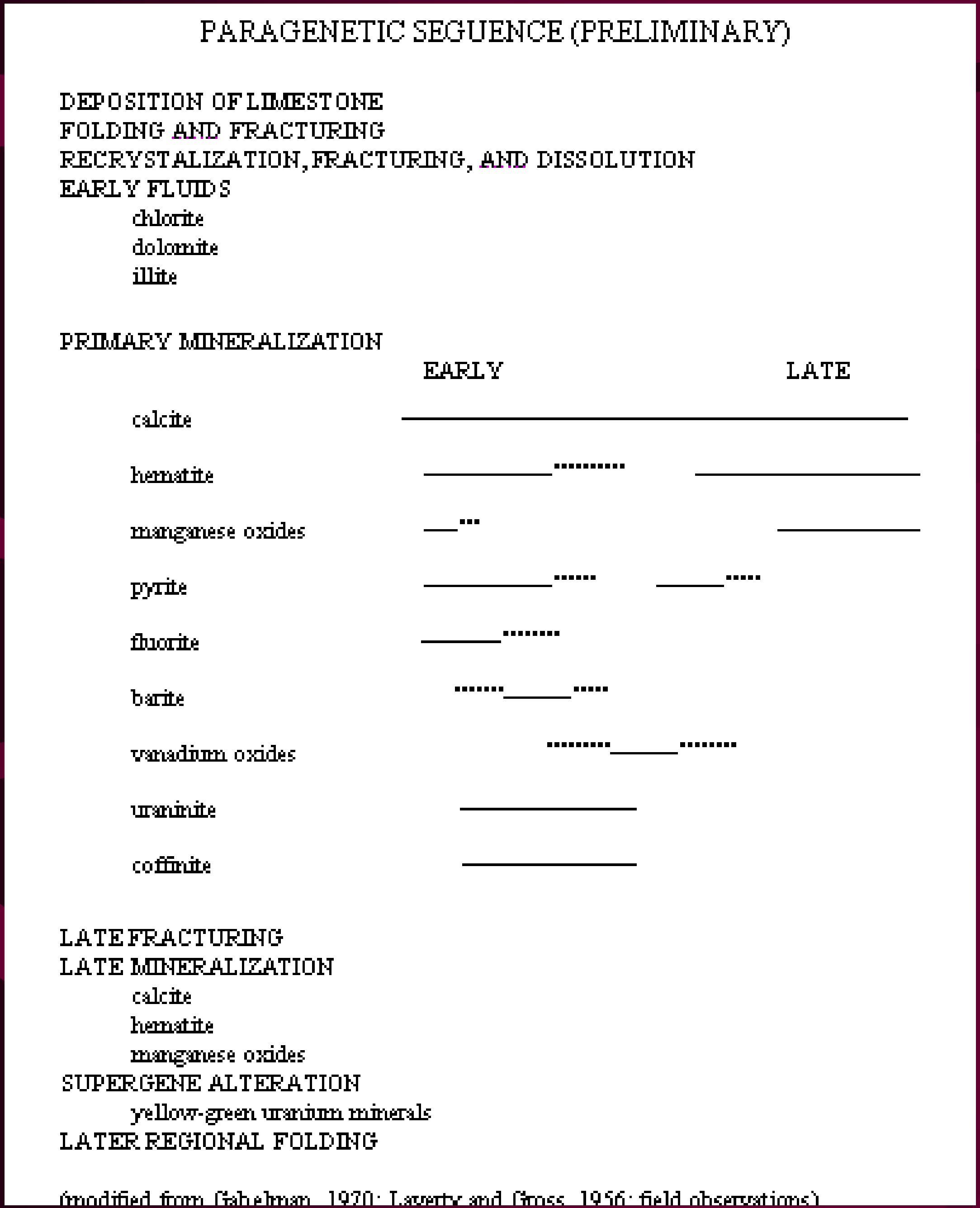
- uraninite, UO_2
- coffinite, $U(SiO_4)_{1-x}(OH)_{4x}$
- tyuyamunite, $Ca(UO_2)_2(VO_4)_{2\cdot5}$-8½$H_2O$
- metatyuyamunite, $Ca(UO_2)_2(VO_4)_{2\cdot3}-5H_2O$
- uranophane, $Ca(UO_2)_2(SiO_3OH)_2 \cdot 5H_2O$
- schroeckingerite, $NaCa_3UO_2(CO_3)_3SO_4F \cdot 10H_2O$
- curite, $Pb_2U_5O_{17} \cdot 4H_2O$

GANGUE MINERALS

- fluorite, CaF_2
- barite, $BaSO_4$
- pyrite, FeS_2
- calcite, $CaCO_3$
- hematite, Fe_2O_3
- galena, PbS

VANADIUM MINERALS

- häggite, $V_2O_2(OH)_3$
- paramontroseite, VO_2
- hewettite, $CaV_6O_{16}\cdot 9H_2O$
- metahewettite, $CaV_6O_{16}\cdot 3H_2O$
- santafeite, $(Mn,Fe,Al,Mg)_8Mn_8(Ca,Sr,Na)_{12}(VO_4)_{16}(OH,O)_{20}\cdot 8H_2O$
- grantsite, $Na_4CaV_{12}O_{32}\cdot 8H_2O$
- goldmanite, $Ca_3(V,Fe,Al)_2Si_3O_{12}$



Bergloff and McLemore (2003)

SUMMARY

- Organic-rich limetones were deposited in a subkha environment on top of the permeable Entrada Sandstone (sand dunes and beach deposits)
- Overlying sand dunes of the Summerville or Wanakah Formation locally deformed the Todilto muds, producing the intraformational folds

SUMMARY-2

- Ground water migrated into the Todilto Limestone by evapotranspiration or evaporative pumping
- Uranium precipitated in the presence of organic material within the intraformational folds and associated fractures in the limestone

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)

SANDSTONE

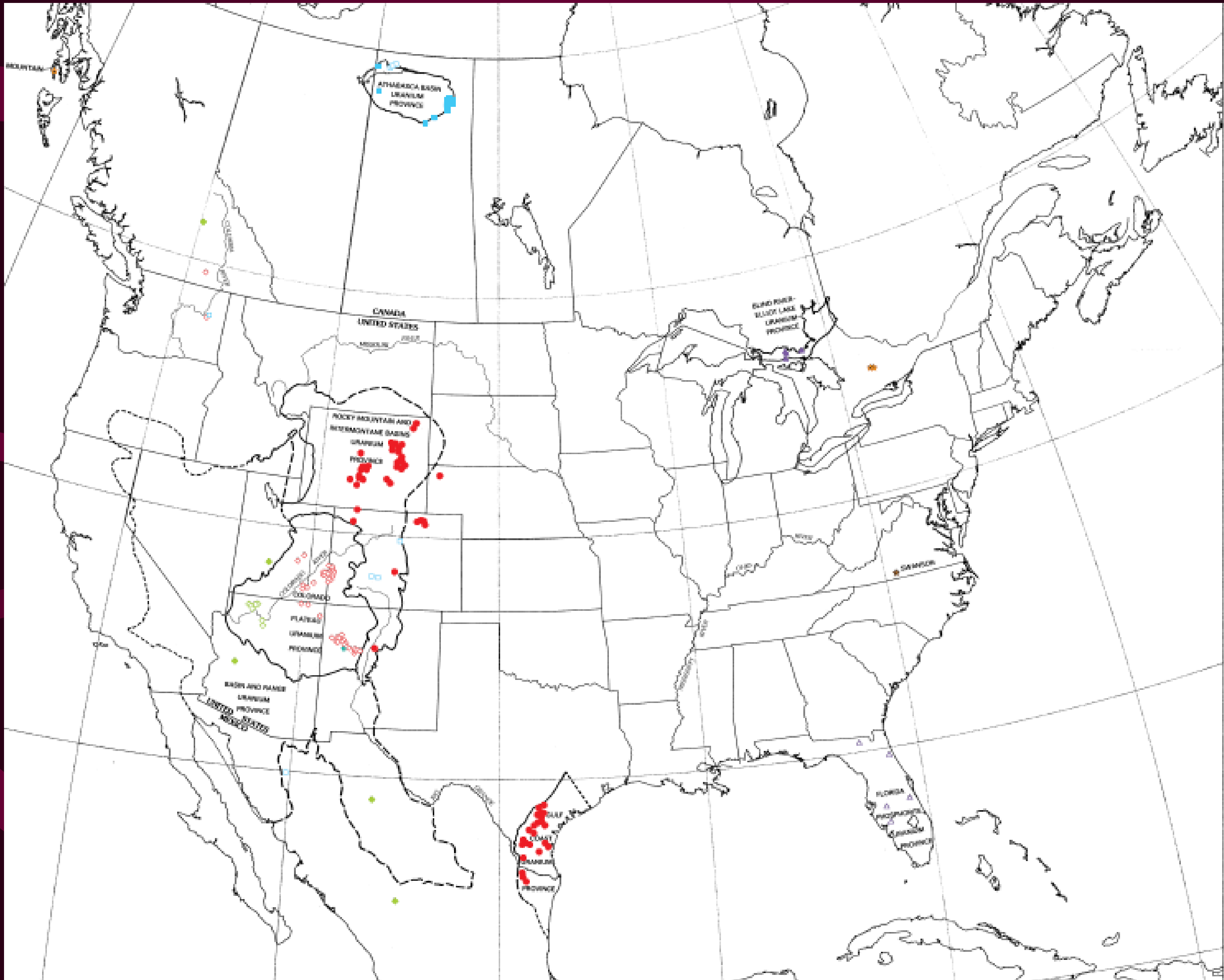
- 18% world's uranium resources
- Grades 0.05-0.4% U3O8
- Uraninite and coffininte

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

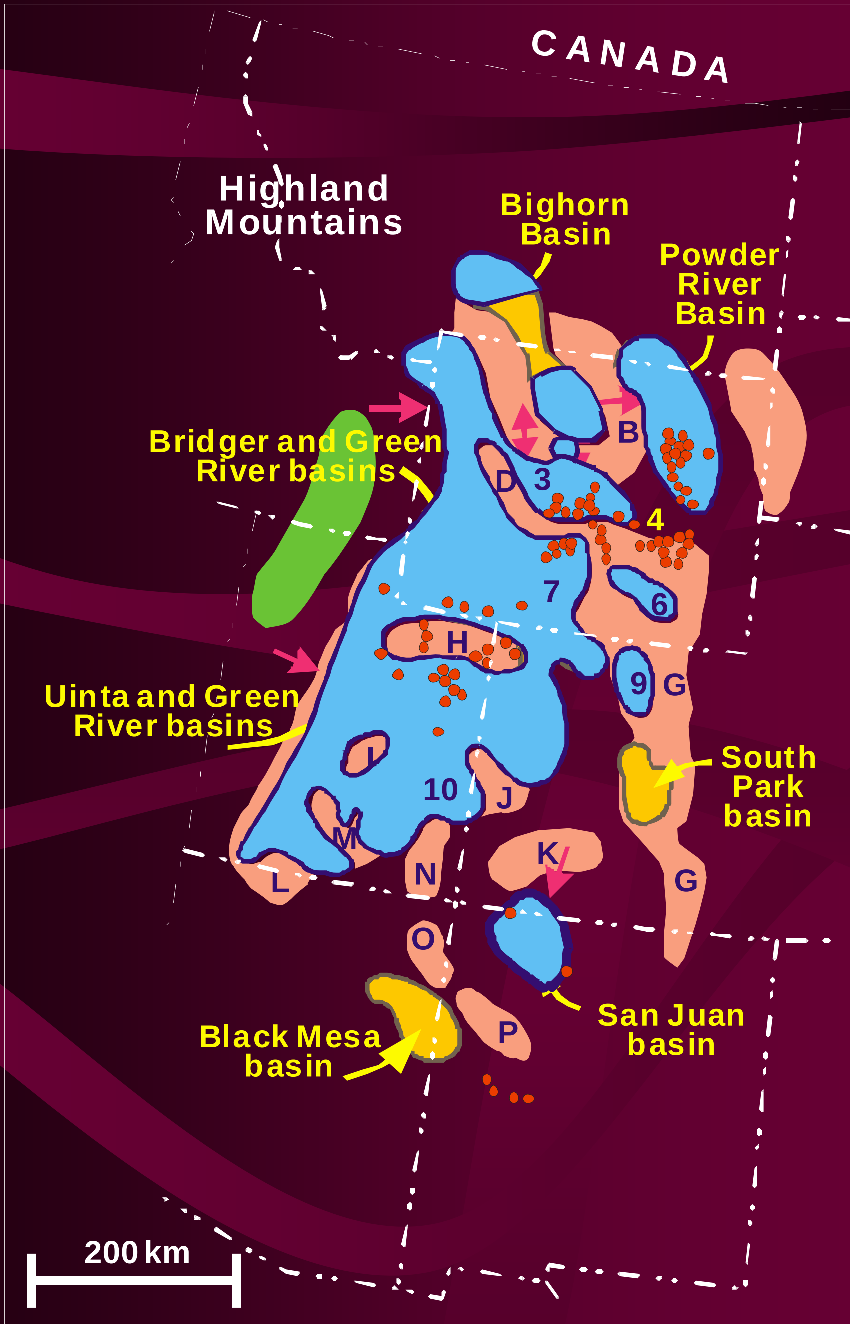
Major sandstone uranium deposits in the world

- Nearly every continent in the world
- United States
  - Powder River Basin, Wyoming
  - Colorado Plateau (including the Grants district)
  - Gulf Coast Plain, south Texas
- Niger
- Kazakhstan
- Uzbekistan
- Gabon (Franceville Basin)
- South Africa (Karoo Basin)


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
MEXICO
GULF COAST URANIUM PROVINCE
FLORIDA PHOSPHORITE URANIUM PROVINCE

Context of Uranium deposits in Eocene sandstone of Western USA

(after Everhart (1985) and Finch (1967).



- Dominantly continental sedimentation
- Positive area
- Area of volcanic activity
- Dominantly lacustrine sedimentation
- Postulated sediment transport
- Uranium deposits

Positive areas:
A = Black Hills; B = Bighorn Mts., C = Owl Creek Mts, D = Wind River Range, E = Rock Springs Uplift, F = Laramie Mts., G = Front Range, H = Uinta Range, I = Sa Rafael Swell, J = Uncompaghre Up-warp, K = San Juan Mts., L = Kaibab Up-warp, M = Circle Cliffs Up-warp, N = Monument Up-warp, O = Defiance Upwarp, P = Zuni Up-warp.

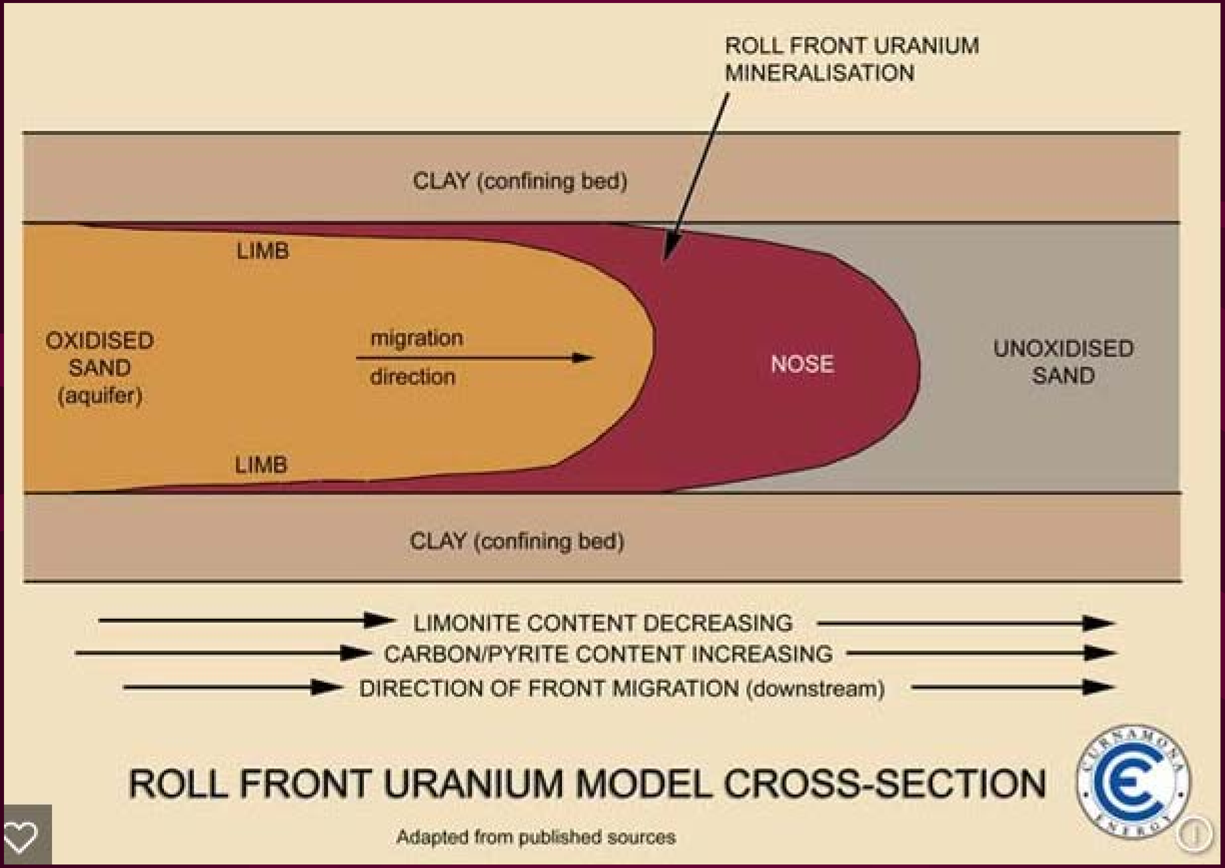
Basins:
3 = Wind River, 4 = Shirley, 6 = Hanna, 7 = Washakie, 9 = North Park, 10 = Green River.

Redistributed or roll-type uranium deposits

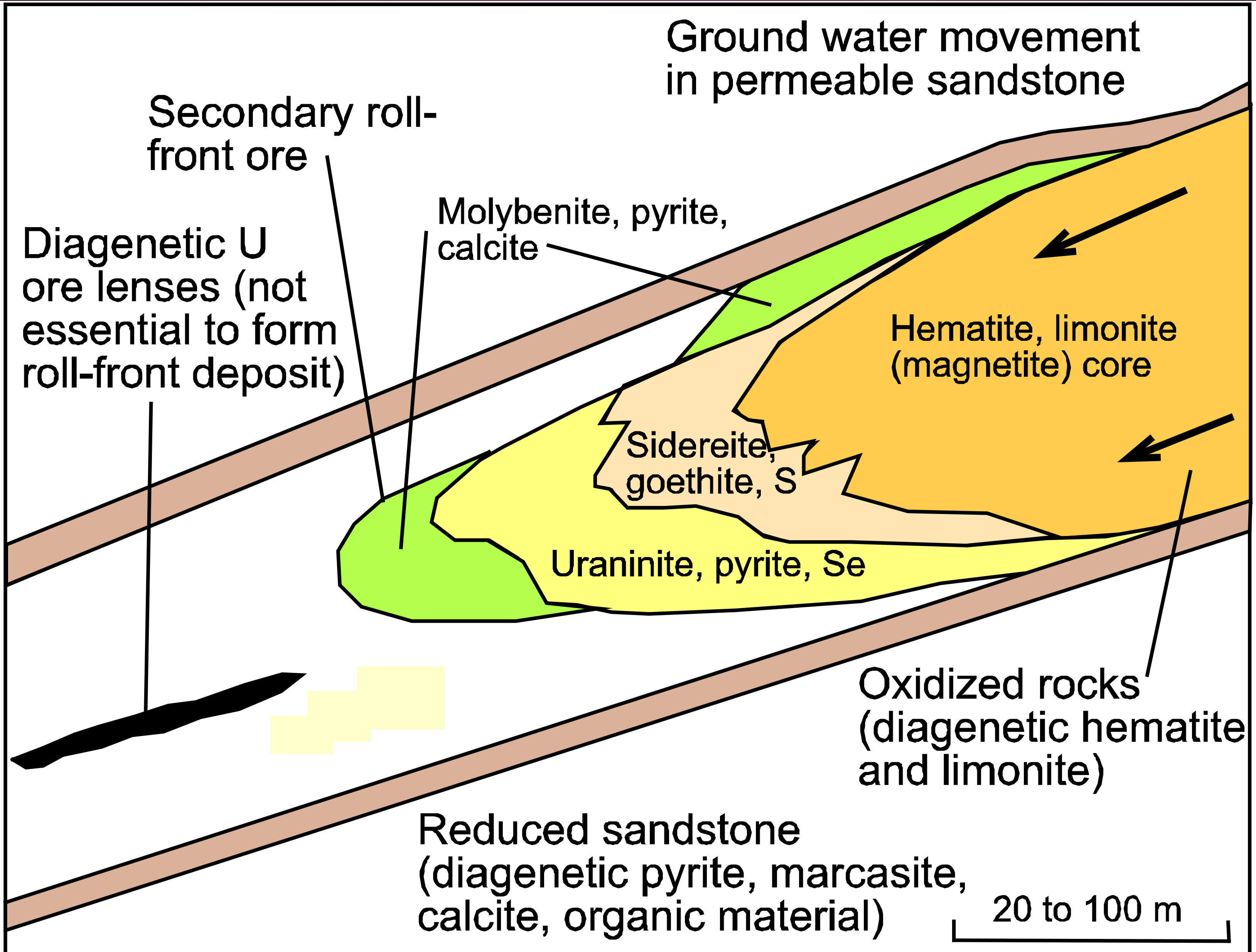
Open pit mine in Wyoming, Power Resources, Inc.

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

Roll front uranium deposits

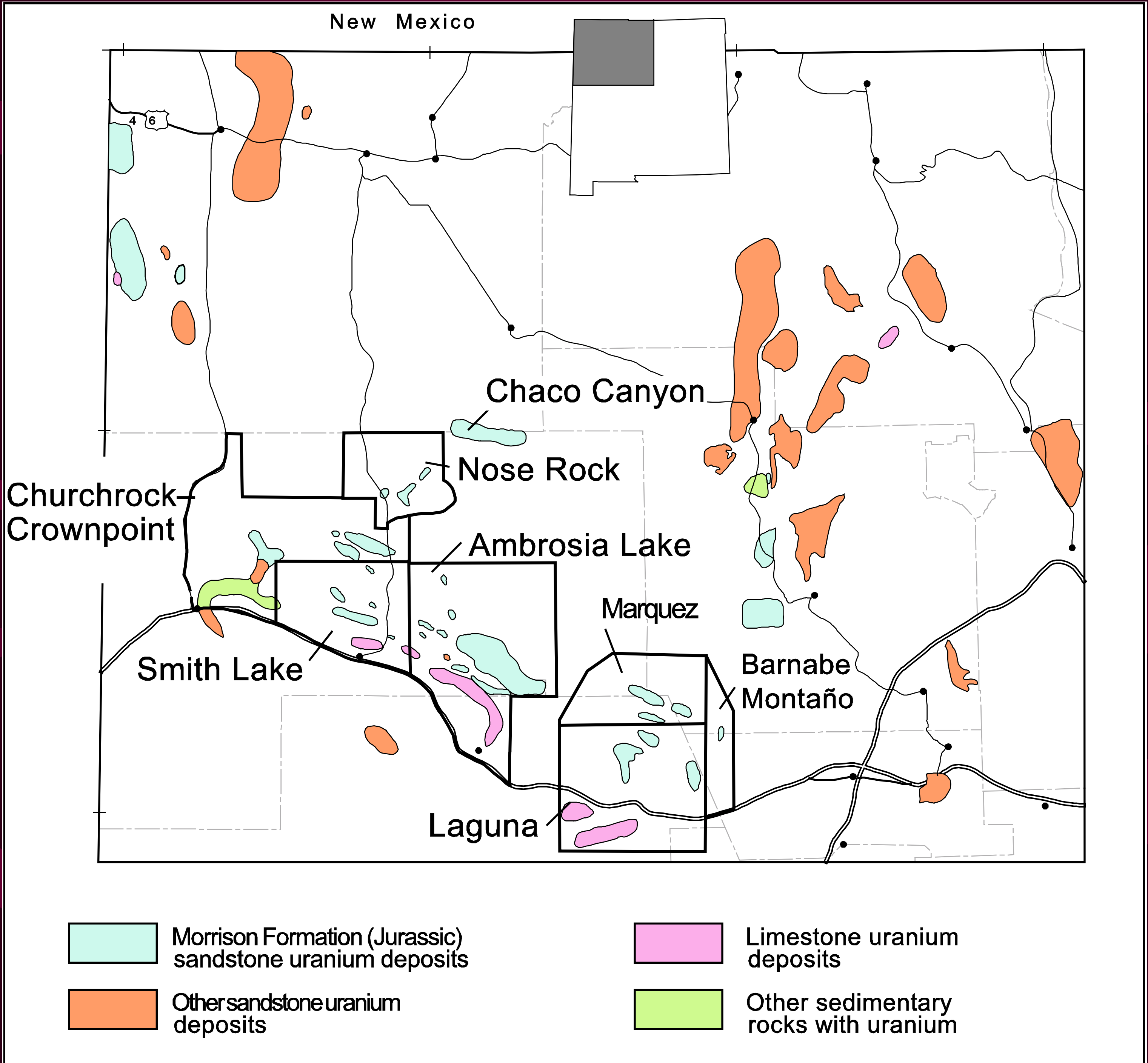


http://www.bing.com/images/search?q=roll+front+uranium+deposits&view=detailv2&&id=4685E173C8813CF33C879C1E0C4A93B6C945D3A5&selectedIndex=0&ccid=buurCwdz&simid=608013601636943525&thid=OIP.M6eebab0b0773d41a7f41234f845f0f4eo0



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

Sandstone uranium deposits in the Westwater Canyon Member


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

Historical Production from the Morrison Formation in Grants District

- 340 million lbs of U_3O_8 from 1948-2002
- Accounting for 97% of the total uranium production in New Mexico
- More than 30% of the total uranium production in the United States
- 4^{th} largest district in total uranium production in the world

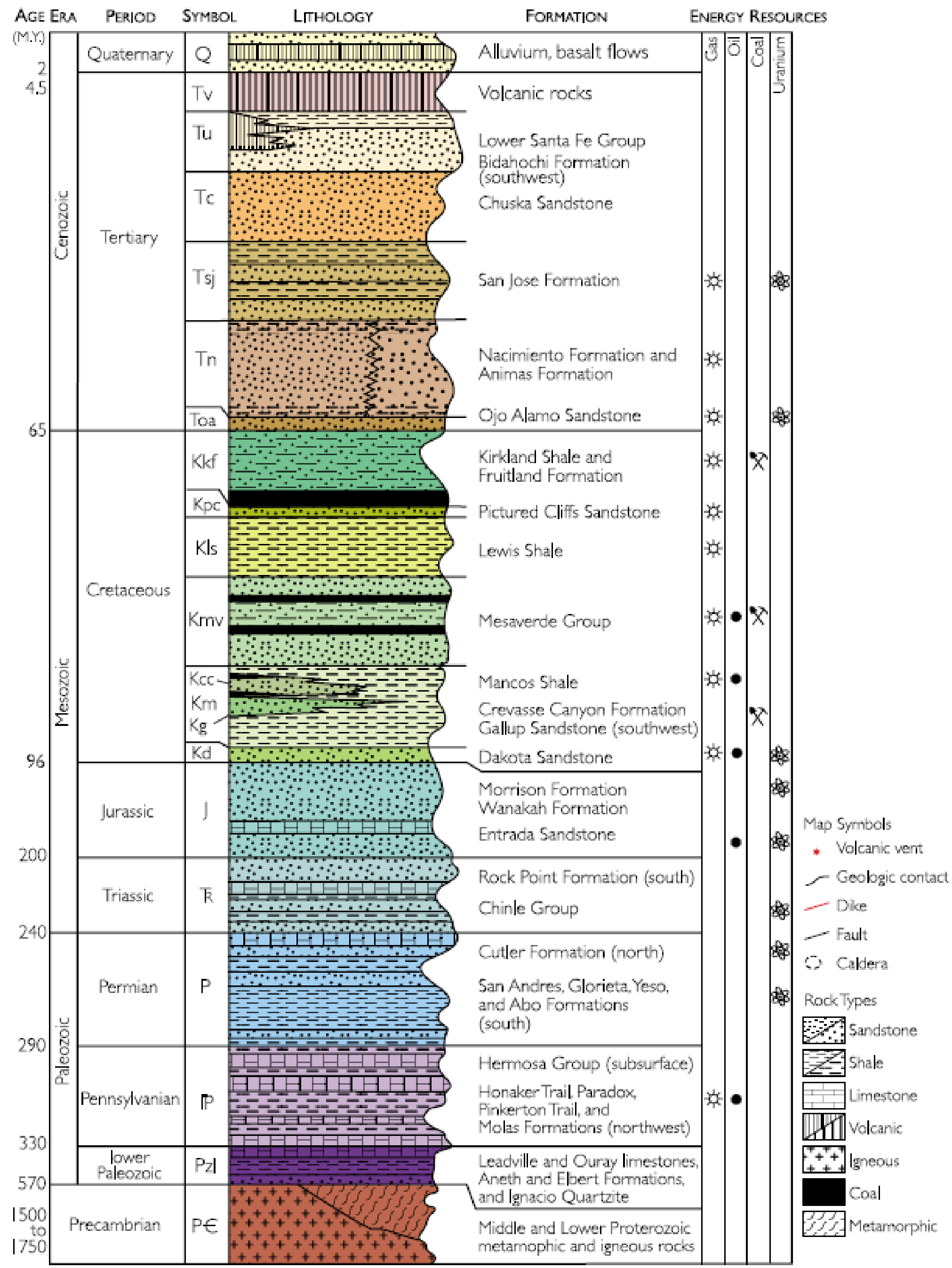
New Mexico is

2nd in uranium reserves 15 million tons ore at 0.277% U_3O_8 (84 million lbs U_3O_8) at $30/lb (2003)

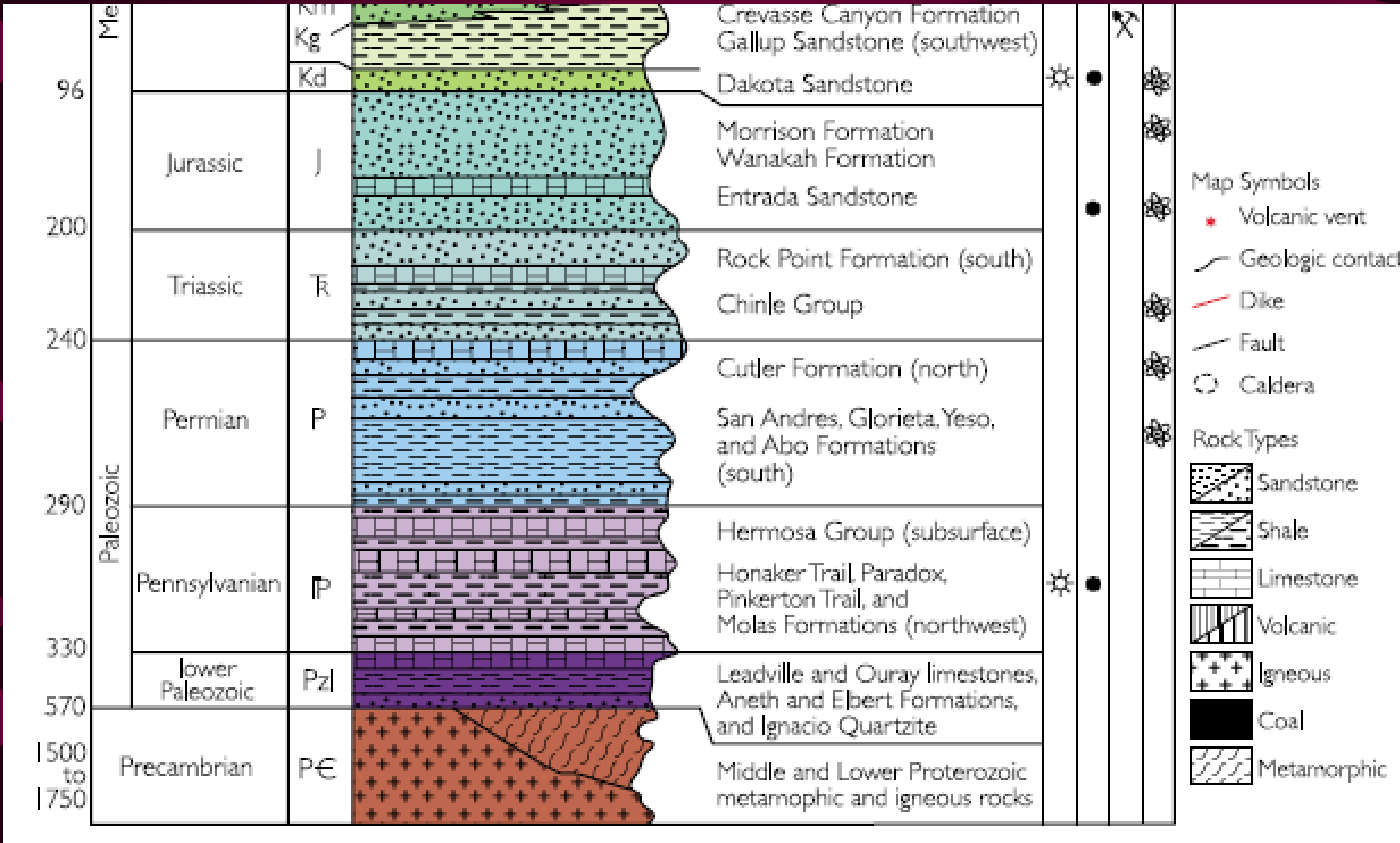
Grants district

- 340 million lbs of U_3O_8 have been produced 1948-2002
- ~400 million lbs of U_3O_8 historic resources have been reported by various companies
- Probably another ~200 million lbs of U_3O_8 remain to be discovered
- The district contained more than 900 million lbs U_3O_8

DESCRIPTION OF THE GRANTS URANIUM DEPOSITS



Age (M.Y.)
Era
Period
Symbol
Lithology
Formation
Energy Resources
Gas
Oil
Coal
Uranium
2
4.5
65
96
200
240
290
330
570
1500 to 1750
Cenozoic
Mesozoic
Paleozoic
Quaternary
Tertiary
Cretaceous
Jurassic
Triassic
Permian
Pennsylvanian
lower Paleozoic
Precambrian
Q
Tv
Tu
Tc
Tsj
Tn
Toa
Klcf
Kpc
Kls
Kmv
Kcc
Km
Kg
Kd
J
Ŧ
P
IP
Pzl
P€
Alluvium, basalt flows
Volcanic rocks
Lower Santa Fe Group
Bidahochi Formation (southwest)
Chuska Sandstone
San Jose Formation
Nacimiento Formation and Animas Formation
Ojo Alamo Sandstone
Kirkland Shale and Fruitland Formation
Pictured Cliffs Sandstone
Lewis Shale
Mesaverde Group
Mancos Shale
Crevasse Canyon Formation
Gallup Sandstone (southwest)
Dakota Sandstone
Morrison Formation
Wanakah Formation
Entrada Sandstone
Rock Point Formation (south)
Chinle Group
Cutler Formation (north)
San Andres, Glorieta, Yeso, and Abo Formations (south)
Hermosa Group (subsurface)
Honaker Trail, Paradox, Pinkerton Trail, and Molas Formations (northwest)
Leadville and Ouray limestones, Aneth and Elbert Formations, and Ignacio Quartzite
Middle and Lower Proterozoic metamorphic and igneous rocks
Map Symbols
Volcanic vent
Geologic contact
Dike
Fault
Caldera
Rock Types
Sandstone
Shale
Limestone
Volcanic
Igneous
Coal
Metamorphic


Me
Kg
Kd
Crevasse Canyon Formation
Gallup Sandstone (southwest)
96
Dakota Sandstone
Jurassic
J
Morrison Formation
Wanakah Formation
Entrada Sandstone
200
Triassic
Ŧ
Rock Point Formation (south)
Chinle Group
240
Permian
P
Cutler Formation (north)
San Andres, Glorieta, Yeso, and Abo Formations (south)
290
Paleozoic
Pennsylvanian
IP
Hermosa Group (subsurface)
Honaker Trail, Paradox, Pinkerton Trail, and Molas Formations (northwest)
330
lower Paleozoic
Pzl
Leadville and Ouray limestones, Aneth and Elbert Formations, and Ignacio Quartzite
570
1500 to 1750
Precambrian
P€
Middle and Lower Proterozoic metamophic and igneous rocks
Map Symbols
Volcanic vent
Geologic contact
Dike
Fault
Caldera
Rock Types
Sandstone
Shale
Limestone
Volcanic
Igneous
Coal
Metamorphic

Primary Tabular Deposits in Westwater Canyon Member

- Less than 2.5 m thick
- Grades exceed 0.2% U_3O_8
- Sharp boundaries
- Locally offset by Laramide (Late Cretaceous)-Tertiary faults
- Black to dark gray because of the associated humate
- Also called primary, trend, prefault, black banded, channel, blanket ore

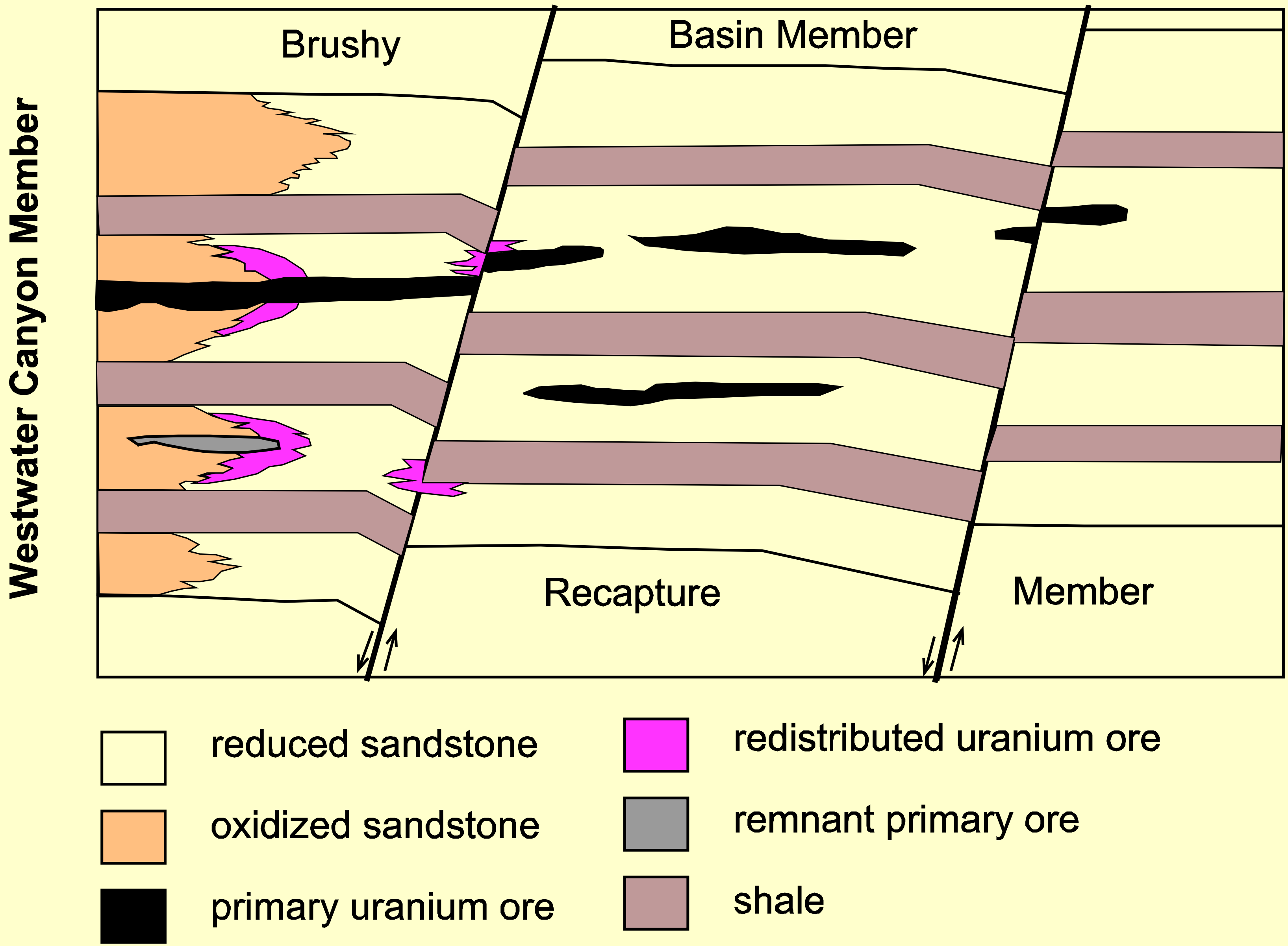

6
3

Redistributed Deposits in Westwater Canyon Member, Dakota Sandstone

- 3-46 m thick
- Grades less than 0.2% U_3O_8
- Commonly localized by faults
- Form roll front geometries locally
- Diffuse ore to waste boundaries
- Dark, brownish gray to light gray
- Also called postfault, stack, secondary, roll front ore

Remnant-primary sandstone uranium deposits

- Surrounded by oxidized sandstone
- Where the sandstone host surrounding the primary deposits was impermeable and the oxidizing waters could not dissolve the deposit, remnant-primary sandstone uranium deposits remain
- Also called ghost ore bodies

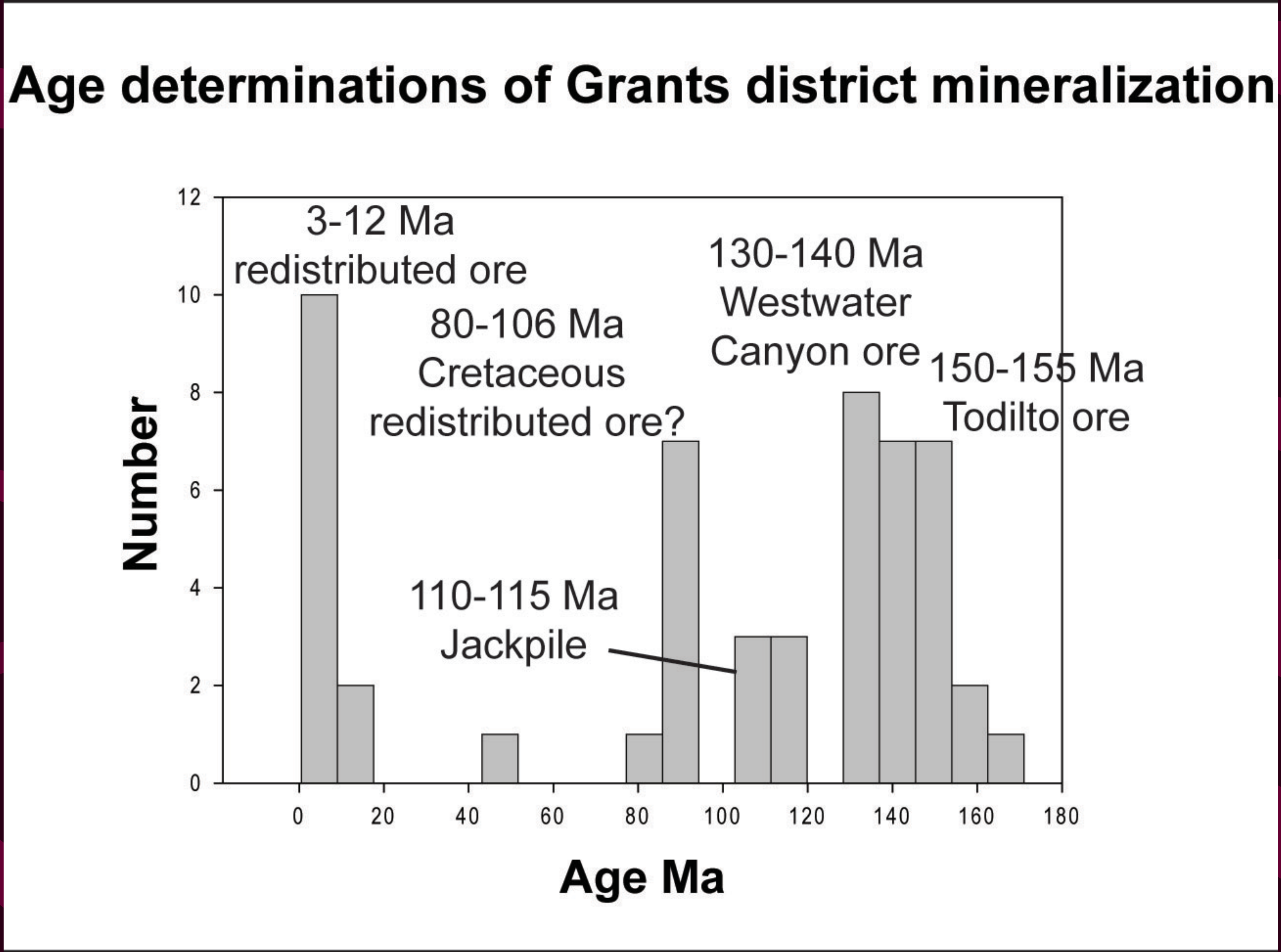


Brushy
Basin Member
Westwater Canyon Member
Recapture
Member
reduced sandstone
oxidized sandstone
primary uranium ore
redistributed uranium ore
remnant primary ore
shale

AGE OF THE DEPOSITS

Possible episodes of primary uranium mineralization

- Early Jurassic (Todilto at 150-155 Ma, U/Pb, Berglof, 1992)
- During and soon after deposition of the Westwater Canyon sandstones
  - 148 Ma (Rb/Sr, Lee and Brookins, 1978) deposition age of Westwater Canyon Member
  - 130-140 Ma based on U/Pb data and Rb/Sr and K/Ar ages of clay minerals penecontemporaneous with uranium minerals
  - Jackpile Sandstone is younger at 110-115 Ma (Lee, 1976)



Includes Pb/U, K/Ar, Rb/Sr, and fission track dates from Miller and Kulp (1963), Nash and Kerr (1966) , Nash (1968), Berglof (1970, 1992), Brookins et al. (1977), Brookins (1980), Ludwig et al. (1982), Hooper (1983).

Possible episodes of redistributed uranium mineralization

- During the Dakota time (Late Cretaceous, 80-106 Ma??????)
- During the present erosional cycle (which started in late Miocene or early Pliocene)
  - Secondary Todilto uranophane yields U/Pb ages of 3 to 7 Ma (Berglof, 1992)
  - Redistributed (stack) ore and an oxidized uranium mineral (uranophane) at Ambrosia Lake have late Tertiary U/Pb ages of 3 to 12 Ma

SOURCE OF URANIUM

The primary uranium deposits are associated with humates. Therefore we need to understand the origin of the humates as well as the uranium.

Origin of humates

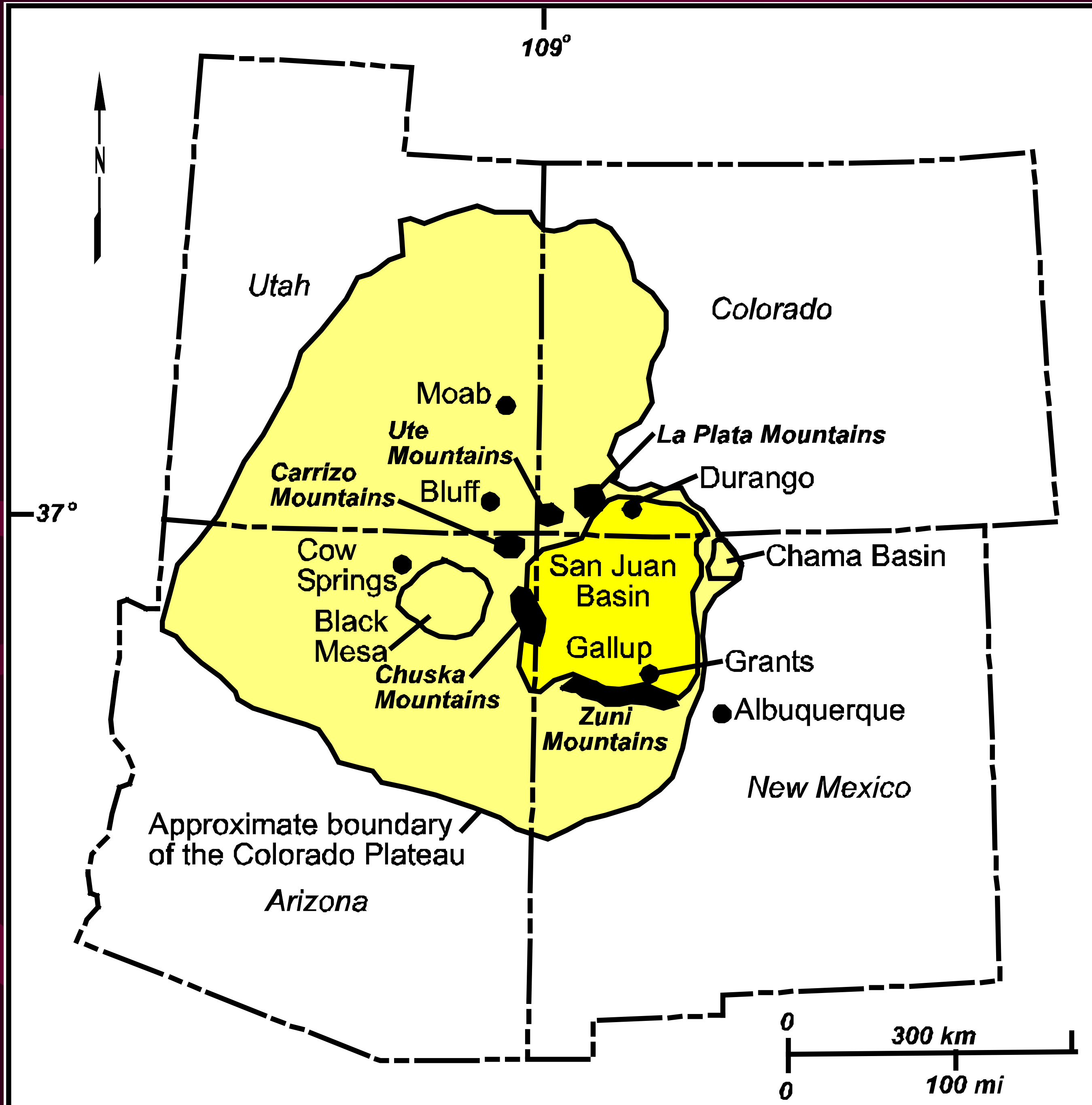
- Organic matter, not petroleum derived
  - Plant debris incorporated into the alluvial fans at the time of deposition
  - Plant material associated with the overlying lacustrine units
  - Dakota and pre-Dakota swamps (????)
- Locally it is detrital (L-Bar deposits)
- At most places, humates were deposited just after the sandstones were emplaced but before the uranium
- Brushy Basin contains little organic material

There is no consensus on details of the origin of the Morrison primary sandstone uranium deposits

- Ground water derived from a granitic highland to the south
- Ground water derived from a volcanic highland to the southwest (Jurassic arc)
- Alteration of volcanic detritus and shales within the Brushy Basin member (Lacustrine-humate model)
- Older uranium deposits
- Combination of the above

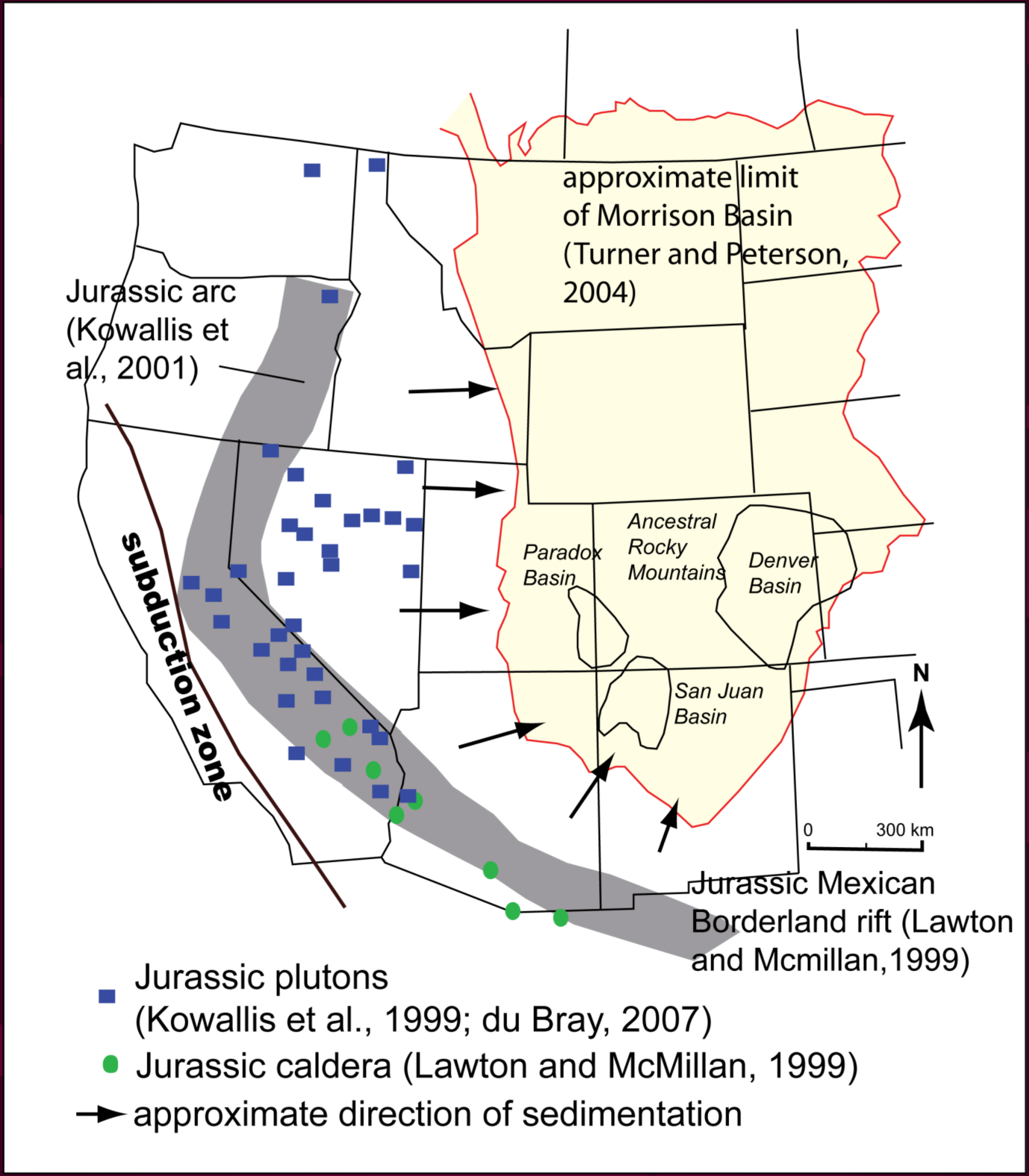
Granitic highland

- Zuni Mountains
- High heat flow (2-2.5 HFU; Reiter et al., 1975)
- Precambrian granites in the Zuni Mountains contain as much as 11 ppm (Brookins, 1978)


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

Volcanic highland

- Jurassic volcanic and plutonic rocks in the southwest
- Meteroic water dissolves uranium from volcanic and plutonic rocks and transport into the San Juan Basin



approximate limit of Morrison Basin (Turner and Peterson, 2004)
Jurassic arc (Kowallis et al., 2001)
subduction zone
Paradox Basin
Ancestral Rocky Mountains
Denver Basin
San Juan Basin
N
0
300 km
Jurassic Mexican Borderland rift (Lawton and Mcmillan,1999)
Jurassic plutons (Kowallis et al., 1999; du Bray, 2007)
Jurassic caldera (Lawton and McMillan, 1999)
approximate direction of sedimentation

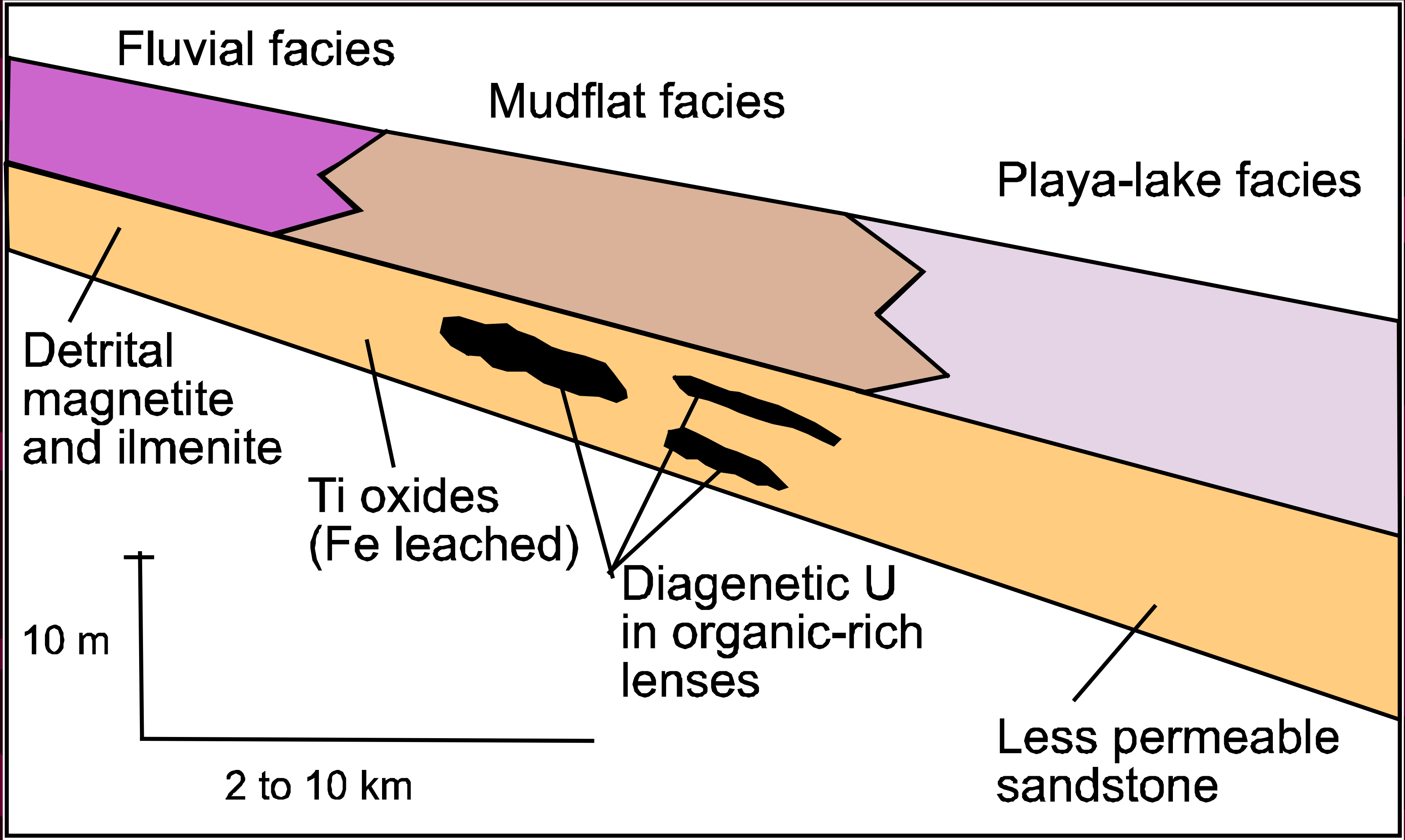
Alteration of volcanic detritus and shales

- Ash fall and other volcanic detritus erupts from the volcanic arc and deposits into the San Juan Basin
- Mechanical weathering of the volcanic arc deposits detritus into the San Juan Basin
- Subsequent weathering of the ash fall deposits immediately after deposition and during diagenesis releases uranium

HOW DID THE DEPOSITS FORM?

Lacustrine-humate model

- Ground water was expelled by compaction from lacustrine muds formed by a large playa lake
- Humate or secondary organic material precipitated as a result of flocculation into tabular bodies
- During or after precipitation of the humate bodies, uranium was precipitated from ground water



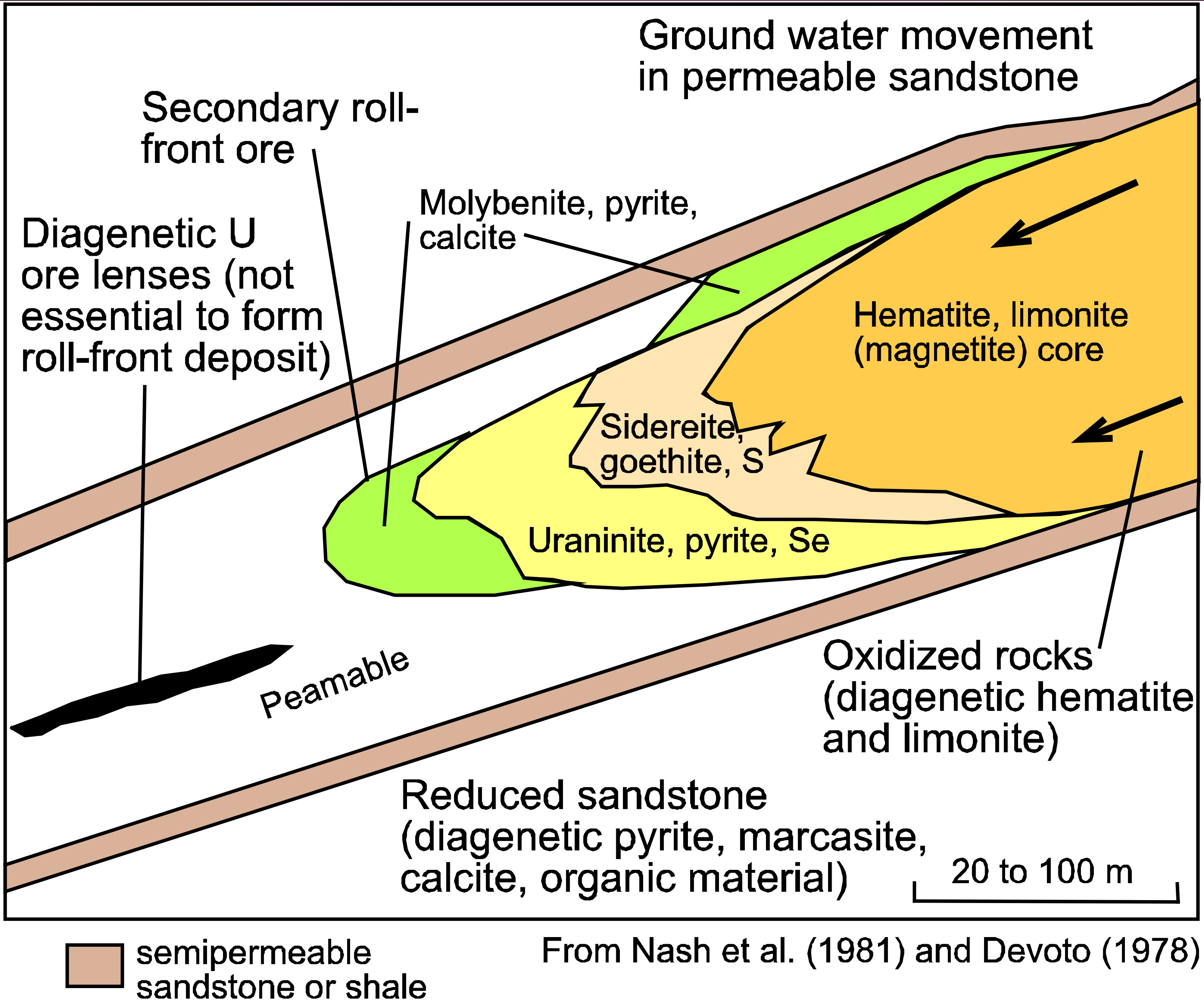
from Turner-Peterson and Fishman (1986)

Brine-interface model

- Uranium and humate were deposited during diagenesis by reduction at the interface of meteoric fresh water and basinal brines or pore water
- Uranium precipitated in the presence of humates at a gravitationally stable interface between relatively dilute, shallow meteoric water and saline brines that migrated up dip from deeper in the basin
- Ground-water flow was impeded by upthrown blocks of Precambrian crust and forced upwards
- These zones of upwelling are closely associated with uranium-vanadium deposits

Redistributed uranium deposits

- After formation of the primary sandstone uranium deposits, oxidizing ground waters migrated through the uranium deposits and remobilized some of the primary sandstone uranium deposits
- Uranium was reprecipitated ahead of the oxidizing waters forming redistributed or roll front sandstone uranium deposits
- Evidence suggests that more than one oxidation front occurred in places (Cretaceous and a Tertiary oxidation front)



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

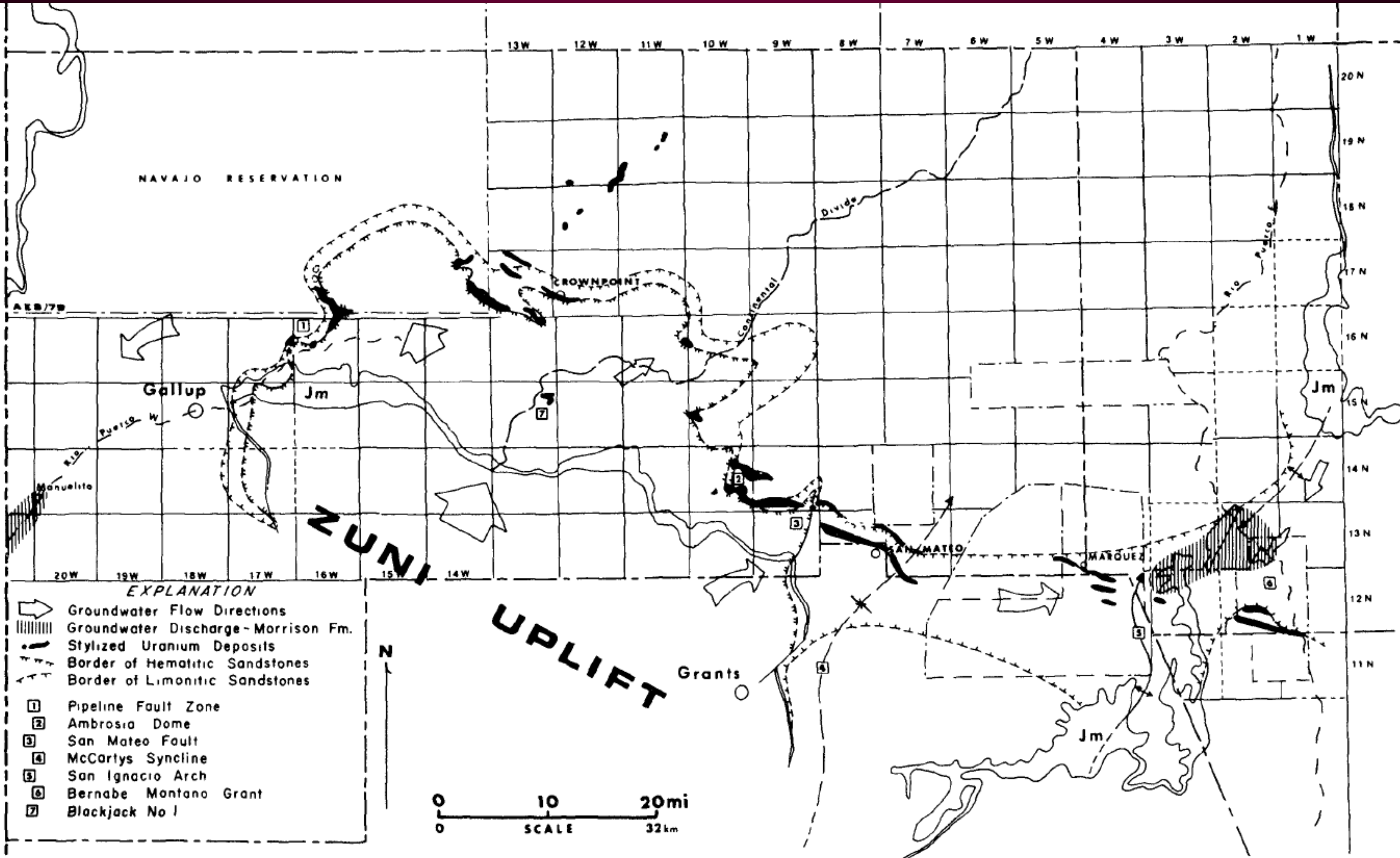


FIGURE 4. Map showing distribution of Tertiary-Quaternary oxidation in sandstone of Westwater Canyon Member, Morrison Formation. See Saucier (11), from which this figure is taken, for full discussion of details shown on map.

COMMENTS

- None of the uranium mills remain in the Grants region.
- Current plans by some companies are to mine uranium by ISR or heap leaching.
- Most conventional mining of uranium will require shipping to an existing mill in Utah or Colorado or licensing and building a new mill in New Mexico.
- The Navajo Nation has declared that no uranium production will occur in Indian Country.

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

FUTURE RESEARCH

- More age determinations
- Better understanding of the regional Jurassic tectonics
- Geochemical analyses of the Jurassic sediments and ore deposits
- Determining the age of remobilization or redistributed deposits
- Leach tests

CONCLUSION

- Grants district primary uranium deposits formed shortly after deposition coincident with Jurassic arc volcanism to the southwest
- Grants district redistributed uranium deposits formed during periods when oxidizing ground waters could enter the mineralized sandstones and remobilize the older primary uranium deposits
  - During the Cretaceous Dakota deposition ?????
  - During the mid-Tertiary to modern erosional cycle

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