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OCCURRENCES OF RADIOACTIVE ELEMENTS IN LINCOLN COUNTY, WYOMING

by

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Abstract

Although Lincoln County has not been a producer of uranium, several different types of occurrences have been reported. The Permian Phosphoria Formation, widespread in Lincoln County, contains anomalous concentrations of uranium (greater than 50 parts per million). Most of the uranium occurs in marine phosphorite; one uranium occurrence may be in marine black shale. An occurrence of uranium in a Quaternary hot spring deposit and an occurrence in a lacustrine phosphatic bed in the Eocene Green River Formation have also been reported in the county.

Because uranium is currently recovered as a by-product from phosphate mining and refining in other states, most notably Florida, the uraniferous phosphorites in Lincoln County are significant. Phosphate rock was mined from the Phosphoria Formation in Lincoln County as late as 1977, and a large resource of phosphate still remains. If phosphate is mined again in Lincoln County, it is possible that some uranium could be produced as a by-product of that mining.

Introduction

This open file report is the second in a county-by-county series of reports on uranium and other radioactive elements in Wyoming. The first report in this series was on Goshen County (Harris and King, 1993). Information for these reports (which are part of a regional study of all Wyoming uranium mines, radioactive elements, and radioactive mineral occurrences) was gathered and compiled over a period of 11 years from publications, mine permits, company data, and field investigations. William L. Chenoweth, Warren I. Finch, and J. David Love have been valuable sources of information throughout this project.

Uranium, thorium, potassium-40 (^{40}K), and their daughter products, such as radium, are the naturally-occurring radioactive elements. The first three elements and their isotopes commonly occur in nature. The element radium and its isotopes, however, are rare in nature. Isotopes are different species of the same chemical element that have different numbers of neutrons in the nucleus of their atoms, and therefore have different atomic masses.

Uranium is the most important radioactive element because of its ability to undergo fission, a spontaneous or induced process in which uranium atoms release large amounts of energy and subatomic particles, and form other atoms. The energy released can be used to produce steam for the generation of electricity.

Thorium is used in refractory materials and aerospace alloys. It also has limited use as a nuclear fuel. Radium, which is only found naturally in any abundance in uranium ores, is used mostly for medicinal purposes. Current demands for radium are met both by recycling and through production as a by-product of reactions in nuclear reactors. Potassium-40 on the other hand occurs in nearly every rock type but has no commercial use.

Background

Radioactive elements in Wyoming

The radioactive element uranium is one of the best known mineral products of Wyoming. Uranium exploration and production has had a colorful history in Wyoming that dates back to about 1918.

Because uranium has been reported in nearly every time-rock unit in the State, Wyoming is often considered a uranium metallogenic province (Stuckless, 1979; Houston, 1979). In the United States, Wyoming ranks first in economic (minable) reserves of uranium (Energy Information Administration, 1990) and ranks second to New Mexico in cumulative uranium production and estimated resources. Twenty-eight uranium minerals and 12 other minerals known to contain accessory uranium have been identified in Wyoming (**Table 1**).

In Wyoming, the largest and most important discovered uranium deposits occur as roll fronts in Paleocene and Eocene sedimentary rocks in Tertiary basins. Over 187 million pounds of uranium oxide concentrate have been produced from roll-front deposits (Chenoweth, 1991) in the Gas Hills, Shirley Basin, Crooks Gap, Southern Powder River Basin, Pumpkin Buttes, and other uranium districts (**Figure 1**).

Other types of uranium deposits in Wyoming have been mined to various extents. Large amounts of ore have been mined from tabular uranium and vanadium deposits in Lower Cretaceous rocks of the Black Hills. Ore has also been mined from Tertiary unconformity-related deposits in the Copper Mountain uranium district, and from paleokarst deposits in Mississippian limestones in the Little Mountain uranium district and in the Shirley Mountains (**Figure 1**).

Although thorium has never been produced in Wyoming or anywhere else in large amounts, the element is abundant at several locations in Wyoming. One of the largest identified thorium resources in the United States occurs in Tertiary peralkaline igneous rocks in the southern Bear Lodge Mountains of northeastern Wyoming (Staatz, 1983). A smaller resource occurs in Cambrian fluvial paleoplacers at Bald Mountain in north-central Wyoming (Borrowman and

Table 1. Uranium- and thorium-bearing minerals identified in Wyoming.

Mineral	Chemical formula	Common occurrence
	URANIUM MINERALS	
Reduced forms (U^{4+})		
brannerite	$(U,Ca,Ce)(Ti,Fe)_2O_6$	placers, pegmatites
coffinite	$U(SiO4)(OH)_4$	widespread
uraninite-thorian uraninite	$(U,Th)O_2$	widespread
Oxidized forms (U^{6+})		
abernathyite	$K_2(UO_2)_2(AsO_4)_2{\bullet}8H_2O$	sedimentary redox
autunite	$Ca(UO_2)_2(PO_4)_2{\bullet}8\text{-}12H_2O$	igneous and metamorphic
bayleyite	$Mg_2(UO_2)(CO_3)_3{\bullet}18H_2O$	sedimentary redox
becquerelite	$CaU_6O_{19}{\bullet}10H_2O$	sedimentary redox
carnotite	$K_2(UO_2)_2V_2O_8{\bullet}3H_2O$	sedimentary redox
liebigite	$Ca_2(UO_2)(CO_3)_3{\bullet}11H_2O$	widespread
meta-autunite	$Ca(UO_2)_2(PO_4)_2{\bullet}4\text{-}6H_2O$	igneous and metamorphic
meta-torbernite	$Cu(UO_2)_2(PO_4)_2{\bullet}8H_2O$	widespread
meta-tyuyamunite	$Ca(UO_2)_2V_2O_8{\bullet}3\text{-}5H_2O$	sedimentary redox
phosphuranylite	$(H_3O)_2Ca(UO_2)_3(PO_4)_2(OH)_4{\bullet}4H_2O$	widespread
rutherfordine	$(UO_2)(CO_3)$	various
sabugalite	$HAl(UO_2)_4(PO_4)_4{\bullet}16H_2O$	widespread
schoepite	$UO_3{\bullet}2H_2O$	sedimentary redox
schroeckingerite	$NaCa_3(UO_2)_2(CO_3)_3SO_4F{\bullet}10H_2O$	widespread
sklodowskite	$(H_3O)_2Mg(UO_2)_2(SiO_4)_2{\bullet}4H_2O$	widespread
torbernite	$Cu(UO_2)_2(PO_4)_2{\bullet}8\text{-}12H_2O$	widespread
tyuyamunite	$Ca(UO_2)_2V_2O_8{\bullet}8H_2O$	sedimentary redox
umohoite	$(UO_2)(MoO_2)(OH)_4{\bullet}2H_2O$	sedimentary redox
uranocircite	$Ba(UO_2)_2(PO_4)_2{\bullet}12H_2O$	various
uranophane	$(H_3O)_2Ca(UO_2)_2(SiO_4)_2{\bullet}3H_2O$	widespread
uranopilite	$(UO_2)_6(SO_4)(OH)_{10}{\bullet}12H_2O$	widespread
weeksite	$K_2(UO_2)_2Si_6O_{15}{\bullet}4H_2O$	various
zellerite	$Ca(UO_2)(CO_3)_2{\bullet}5H_2O$	sedimentary redox
zeuherite	$Cu(UO_2)_2(PO_4)_2{\bullet}40H_2O$	various
zippeite	$K_4(UO_2)_2(SO_4)_3(OH)_{10}{\bullet}16H_2O$	various
	THORIUM MINERALS	
thorianite-uranoan thorianite	$(Th,U)O_2$	pegmatites, placers
thorite-uranothorite	$(Th,U)SiO_4$	igneous rocks
thorutite	$(Th,U,Ca)Ti_2O_6$	igneous rocks
	MINERALS THAT OFTEN CONTAIN ACCESSORY URANIUM AND(OR) THORIUM[1]	
allanite	$(Ce,Ca,Y,U)_2(Al,Fe_2)_3(SiO_4)_3OH$	carbonatites, pegmatites
apatite	$Ca_5(PO_4)_3(F,OH,Cl)_3$	carbonatites, phosphorites
brockite	$(Ca,Th,Ce)PO_4{\bullet}H_2O$	carbonatites
euxenite	$(Y,Ce,U,Th,Ca)(Nb,Ta,Ti)_2(O,OH)_6$	pegmatites, placers
fergusonite	$(Y,Er,Ce,Fe)(Nb,Ta,Ti)O_4$	pegmatites, placers
fluorite	CaF_2	carbonatites, veins
monazite	$(Ce,La,Th,U)PO_4$	placers, carbonatites, and veins
mckelveyite	$Na_2Ba_4(Y,Ca,Sr,U)_3(CO_3)_9{\bullet}5H_2O$	trona, phosphorite

Table 1. *(continued)*

Mineral	Chemical formula	Common occurrence
rhabdophane	$(Ce,Y,La,Di)PO_4 \cdot H_2O$	sedimentary, siliceous
samarskite	$(Y,Fe,Ca,U,Ce,Th)(Nb,Ta,Ti)_2(O,OH)_6$	pegmatites, placers
xenotime	YPO_4	placers, veins(?)
zircon	$ZrSiO_4$	placers

GENERAL OR NONSPECIFIC TERMS

pitchblende: amorphous or cryptocrystalline variety of uraninite that can contain thorium.
gummite: fine-grained, secondary, hydrous, sometimes amorphous, uranium minerals associated with uraninite.
thucolite: uranium and thorium-bearing carbonaceous material.

[1]Apatite, fergusonite, fluorite, rhabdophane, xenotime, and zircon may sometimes contain either uranium or thorium in the interstitial spaces. Because the uranium and thorium **are not** part of the crystal structure of these six minerals, the accessory uranium and thorium are not shown in the chemical formulas. For the other minerals listed, the accessory uranium and thorium **are** part of the crystal structure and the radioactive elements are shown in the chemical formulas.

Rosenbaum, 1962) (**Figure 1**). Thorium is also abundant in other Cambrian paleoplacers and in Cretaceous beach paleoplacer deposits (black sandstones) scattered about central and western Wyoming (Houston and Murphy, 1970). Three thorium minerals and 12 other minerals known to contain accessory thorium have been identified in Wyoming (**Table 1**).

Radium was produced from the Silver Cliff mine near Lusk, in Niobrara County, Wyoming, in the years just after World War I. Radium is a daughter product in the four decay series ^{238}U, ^{235}U, ^{234}U, and ^{232}Th. It is found in small amounts in all uranium and thorium deposits and occurrences. The only recorded radium production from Wyoming was from the Silver Cliff mine. Some of this radium production reportedly was shipped to the Curies in France for their experiments with radiation (Peck, 1969).

Although ^{40}K occurs in all rocks in the State, it has no commercial use. Because it is so abundant in granitic and arkosic rocks that are common in the State, a large portion of the natural gamma radiation in Wyoming is from the decay of ^{40}K.

Classification of deposits and occurrences

Deposits and occurrences of uranium and thorium are of many different types, based upon their method of formation. The classification scheme used in this report (**Table 2**) is modified from

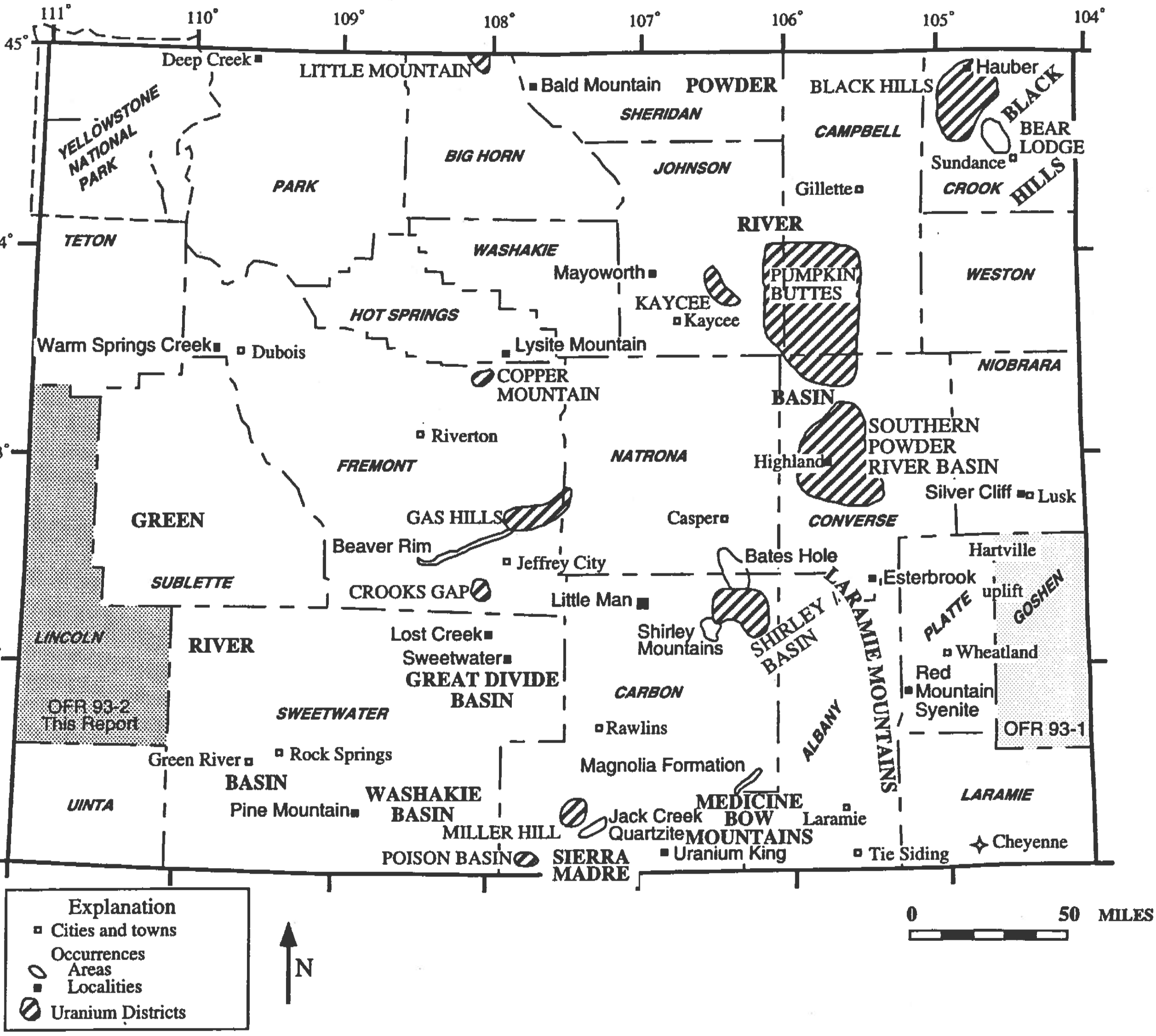


Figure 1. Index map of Wyoming, showing major uranium districts and other occurrences of radioactive elements (both areas and localities); the location of other county reports on radioactive elements (light stipple); and the location of Lincoln County, Wyoming (dark stipple). (OFR refers to a Geological Survey of Wyoming Open File Report number.)

Mickle and Mathews (1978). In part, this classification is based on the type of host rock (sedimentary, igneous, or metamorphic) and the suspected origin. Because the characteristics of classes often overlap and the differences between classes are gradational, some occurrences are unclassified (and are placed in the unknown category). Unconformity-related occurrences are separated because they are found in Wyoming in all types of host rocks. Shear-zone-hosted, vein-hosted, fracture-filling, and replacement occurrences are not dependent on the type of host rock and are also classified separately. Still other occurrences are classified as unknown due to insufficient data.

Table 2. Classification of uranium and thorium mineralization, with Wyoming examples (modified from Mickle and Mathews, 1978).

Symbol	Classification	Wyoming examples
	OCCURRENCES IN SEDIMENTARY ROCKS	
	Redox[1]	
RX	Roll front	Wasatch and Fort Union Formations (and equivalents); Statewide
RT	Tabular	Inyan Kara Group, northeastern Wyoming
	Mechanical accumulations	
BP	Beach placer	Mesaverde Formation, Statewide
FP	Fluvial placer	Flathead Formation, northwestern Wyoming
QC	Quartz-pebble conglomerate	Magnolia Formation, Medicine Bow Mountains (Albany and Carbon Counties)
	Chemical codeposition	
BS	Marine black shale	Minnelusa Formation, eastern Wyoming
MP	Marine phosphorite	Phosphoria Formation, western Wyoming
LP	Lacustrine phosphorite	Wilkins Peak Member, Green River Formation (Sweetwater County)
	Carbonate	
CP	Paleokarst	Madison Limestone, Little Mountain district (Bighorn County)
CS	Surficial coating	Browns Park Formation, Carbon County
CR	Reduction related	Sundance Formation, Mayoworth area (western Johnson County)
DE	Desert evaporite	surface deposits, Lost Creek area (northeastern Sweetwater County)
CL	Coal	Wasatch Formation, Great Divide Basin (eastern Sweetwater County)
	OCCURRENCES IN IGNEOUS ROCKS	
IM	Initial magmatic	Precambrian granites; Statewide
PG	Pegmatitic	Sherman Granite, Tie Siding area (southeastern Albany County)
MH	Magmatic hydrothermal	Eocene intrusives, Bear Lodge Mountains (Crook County)
AT	Autometasomatic	Eocene intrusives, Bear Lodge Mountains (Crook County)
PN	Pneumatolytic	Yellowstone National Park
SP	Postmagmatic silica-poor	uncertain
SR	Postmagmatic silica-rich	possibly Moonstone Formation, central Wyoming
	OCCURRENCES IN METAMORPHIC ROCKS	
CM	Contact metamorphic	uncertain
AN	Anatectic	Ralph Platt pegmatites, Saratoga Valley (southern Carbon County)
MR	Redox[1]	Little Man mine, Pedro Mountains (northern Carbon County)
MV	Vein	Esterbrook area (southern Converse County)
UC	UNCONFORMITY-RELATED	Silver Cliff mine (southern Niobrara County)
UN	UNKNOWN	numerous
	OTHER OCCURRENCES	
SZ	Shear-zone-hosted	Sierra Madre (southern Carbon County)
VN	Vein-hosted	Esterbrook area (southern Converse County)
FR	Fracture-filling	Michigan mine (Goshen County)
RP	Replacement	Bear Lodge Mountains (Crook County)

[1]Formed at a geochemical interface between oxidizing and reducing environments where oxidation-reduction chemical reactions occur.

For the purposes of these county reports, an occurrence of a radioactive element is defined as a concentration in which the amount of the element, as determined by either radiometric or chemical analysis, is greater than 50 parts per million (0.005 percent). Equivalent uranium (eU), thorium (eTh), or other radioactive element is determined by measuring the radioactivity of a sample. Chemical uranium (cU), thorium (cTh), or other radioactive element is determined by quantitative chemical analysis techniques. A concentration of radioactive elements greater than 50 parts per million (ppm), determined by **either** method, is sufficient to define an occurrence. Alternatively, an occurrence (or anomaly) is also defined as a locality with ten times or more radioactivity than the normal background radiation.

Because occurrences of radioactivity in sedimentary rocks have been intensively studied in Wyoming, the classification system for this category has more and better defined subdivisions. Redox occurrences are by far the most common class in Wyoming, and all of the large mines in the State produce or have produced uranium from deposits of this type.

By way of explanation, uranium is soluble in water as various complex ions under oxidizing conditions. Under reducing conditions uranium is not soluble. Redox occurrences are formed by precipitation at geochemical boundaries where the Eh (oxidation-reduction potential) changes from oxidizing to reducing. Most uranium production outside of the United States is from classes of deposits other than redox, particularly from unconformity-related deposits and deposits of Precambrian quartz-pebble conglomerates.

Uses of uranium and thorium

Uranium is primarily used as a fuel in nuclear-powered electrical generating plants. Yellowcake produced from Wyoming's uranium mills is purchased by electric utility companies. Yellowcake (uranium oxide concentrate) contains uranium oxide as ammonium diuranate, sodium diuranate, or uranium peroxide (List and Coleman, 1979). The utilities stockpile yellowcake and ship it to enrichment plants when fuel is needed for their power plants. Enrichment plants concentrate the fissionable uranium isotope ^{235}U from the less than 0.7 percent that is present in natural uranium and yellowcake to the 3 percent needed for nuclear power plants.

Minor amounts of uranium are also used in the manufacture of detonators for nuclear weapons. In the United States, uranium was used as the explosive in the first fission weapons. Nuclear weapons and detonators require concentrations of more than 90 percent ^{235}U (Beckmann, 1976).

The uranium remaining after the fissionable isotope has been removed is called depleted uranium metal. This uranium is used in armor-piercing projectiles, in counterweights (especially for elevators), in chemical catalysts, in reactor shielding (Kirk, 1980), and recently, in armor plating itself (Bob Peck, personal communication, 1988).

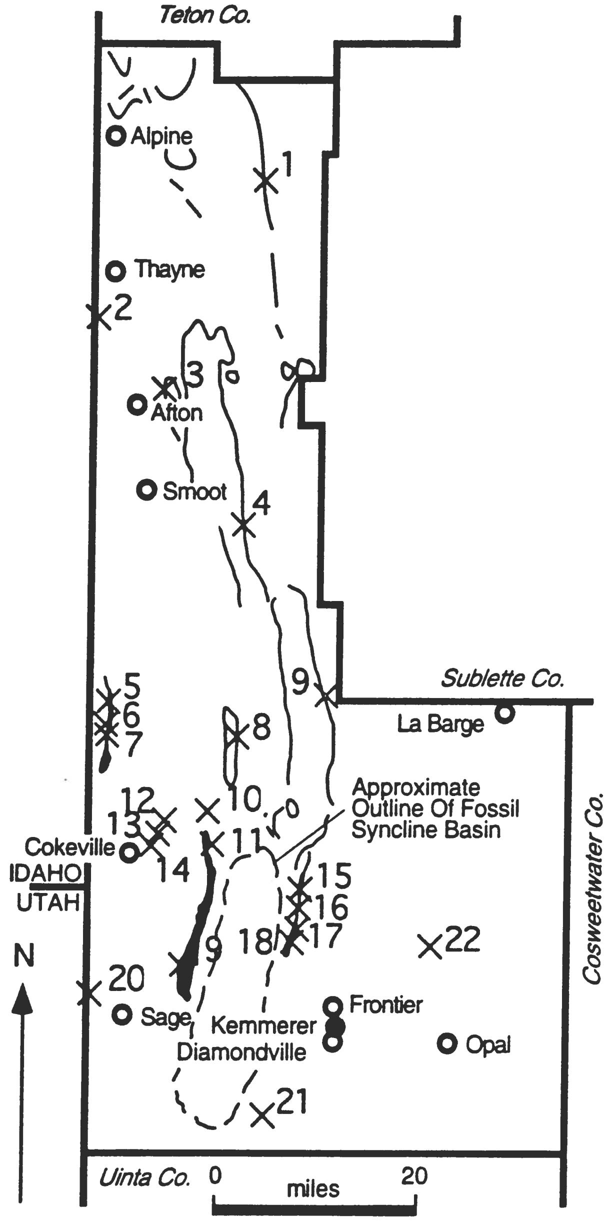
Most thorium is used in aerospace alloys. Other uses include refractory materials, the light-producing material in gas lantern mantles, electronic components, and in chemical catalysts. A few nuclear reactors in foreign countries use ^{232}Th as fuel. The last nuclear reactor in the United States to use thorium as a fuel was the Fort St. Vrain power plant in Colorado. The plant closed over a decade ago. Refractory materials containing thorium oxide (thoria) are used in molds and crucibles that are used for casting and making high temperature alloys. As an alloying material, thorium is primarily added to magnesium to give the magnesium higher strength and resistance to deformation at high temperatures. Thorium as thorium nitrate is used to improve tungsten welding rods and to facilitate welding of stainless steel and nickel alloys. New uses of thorium under development include breeder reactors which use thorium for fuel, and in fuel rods and core retention beds in conventional reactors in order to prevent core meltdown. If these new uses are developed, increased production of thorium would be necessary (Hedrick, 1985; 1992a; 1992b).

Occurrences of radioactive elements in Lincoln County, Wyoming

Summary

Specific radioactive minerals have yet to be identified in Lincoln County. However, the Permian Phosphoria Formation, which occurs throughout the county, contains above average—with respect to average crustal abundances—amounts of uranium, as well as vanadium, copper, gold, and silver. Above average concentrations of uranium are also reported in a lacustrine phosphatic bed in the Eocene Green River Formation at one locality (Love, 1964). While the Tertiary Wasatch Formation in other parts of Wyoming often contains uranium occurrences, the author's work in the Wasatch Formation (Tw) in the Fossil Syncline (**Figure 2**) indicates a lack of uranium enrichment in that area. Also, some coal beds in the upper Cretaceous Sage Junction Formation (Kss) in the Sage area (**Figure 2**) contain higher than normal concentrations of uranium, but because the concentrations are less than 50 ppm (Beroni and McKeown, 1952), they are not considered to be uranium occurrences in this report.

In Lincoln County, uranium is concentrated along with rare earth elements (REE) in phosphorite or phosphate rock of the Phosphoria Formation, which occurs in the subsurface and as narrow, north-south trending outcrops (**Figure 2**). While phosphate rock is any rock that contains



EXPLANATION

5× Uranium occurences (number refers to locality number in the text)

○ Selected towns

● County seat

Generalized outcrop of Permian Phosporia Formation (after Harris and others, 1985; Love and Christiansen, 1985)

Figure 2. Index map showing the occurrences of radioactive elements and associated anomalies in Lincoln County, Wyoming.

one or more phosphatic minerals of sufficient purity and quantity to permit its commercial use as a source of phosphatic compounds or elemental phosphorus (Bates and Jackson, 1987), phosphorite is the term used for a sedimentary rock composed chiefly of phosphate minerals. Uranium substitutes for calcium in calcium phosphate minerals.

The distribution of rocks containing at least 50 ppm uranium in the Phosphoria Formation is probably not restricted to the few sampled sites reported in this compilation (**Figure 2**). In fact, the average uranium content in the Phosphoria Formation in most of Lincoln County is probably greater than 100 ppm (Swanson and others, 1953). This means that nearly every outcrop of phosphorite sampled from the Phosphoria Formation would constitute an occurrence.

Description of occurrences

The alphanumeric notation that precedes each of the following descriptions is keyed to **Figure 2** and **Tables 2** through **5**: the number refers to the map location (**Figure 2**), the letter(s) before the parentheses refers to the elements/anomaly present at the site (**Table 3**). In the parentheses, the group(s) of two letters refers to the deposit type(s) (**Table 2**); in the brackets, the group(s) of letters refers to the formation name(s) or rock type(s) of the host rock(s) (**Table 4**). The lower case letters after the parentheses indicate the status of development and the type of data available for the occurrence (**Table 5**).

1. U (MP) [Pp] ra, ca. **Steer Creek measured section**; located in section 9, T36N, R116W, and first described by Cheney and others (1953). The relative stratigraphic positions and thicknesses of the phosphorite and phosphorite beds containing more than 50 ppm uranium are shown on the columnar section (**Figure 3A**). Pellet phosphorite samples A and B from the Meade Peak Member of the Phosphoria Formation contained 0.012 and 0.015 percent chemical uranium (cU), and 0.010 and 0.012 percent radiometric or equivalent uranium (eU), respectively. The two samples also contained 29.6 and 25.0 percent phosphate content expressed as as oxide (P_2O_5) and 3.03 and 2.33 percent fluorine (F), respectively, and each contained REE enrichment of greater than 100 ppm (Gulbrandsen, 1966).

   Earlier analyses on these two samples (located at A and B, respectively, on **Figure 3A**) yielded 0.011 and 0.012 percent cU (0.012 and 0.014 percent eU) with 29.5 and 25.0 percent P_2O_5, respectively, for the 1.1 and 1.6 feet thick beds (Cheney and others, 1953; Sheldon, 1963).

2. U? (UN) [Qhs] ra. **Auburn Hot Springs**; located in NE SE section 23, T33N, R119W. Hot spring deposits containing sulfur and travertine composed primarily of calcium carbonate at these springs assayed from 0.001 to 0.002 percent cU (0.002 to 0.008 percent eU) (Vine and Moore, 1952). Later sampling and analyses of these deposits yielded from 20 to 590 ppm (0.002 to 0.059 percent) eU, with at most 7 ppm cU (Cadigan and Felmlee, 1982).

Table 3. Chemical symbols for elements and radioactive anomalies.

Symbols	Element or anomaly
Ag	silver
Cu	copper
Fe	iron
Mn	manganese
Ra	radium
Th	thorium
U	uranium
V	vanadium
rad	radioactive material
ra	anomalous radioactivity

Table 4. Key to formation names or rock types used in the descriptions of the occurrences of radioactive elements in Lincoln County, Wyoming.

Formation name	Symbol
CENOZOIC	
QUATERNARY	
Hot spring deposits	Qhs
TERTIARY	
Eocene Green River Formation	Tg
Eocene Wasatch Formation	Tw
MESOZOIC	
Cretaceous Sage Junction Formation	Kss
PALEOZOIC	
Permian Phosphoria Formation	Pp

Table 5. Status and/or type of occurrences of radioactive elements.

Symbol	Status and/or occurrence	Symbol	Status and/or occurrence
ALL RADIOACTIVE ELEMENTS		URANIUM OCURRENCES ONLY	
mn	minerals noted or observed	p	prospect
mi	minerals identified	pr	prospect—reserves delimited
ca	chemical analysis	ma[1]	mine (active)
ra	radiometric analysis	ms[1]	surface mine (inactive)
		mu[1]	underground mine (inactive)
rs	radiometric survey		
rl	radiometric down-hole log		
uo	unverified occurrence		
ia	in-situ operation (active)		
ir	in-situ operation (research)		

[1]An occurrence is considered a mine (instead of a prospect) when the reported cumulative production of uranium ore exceeds 500 short tons.

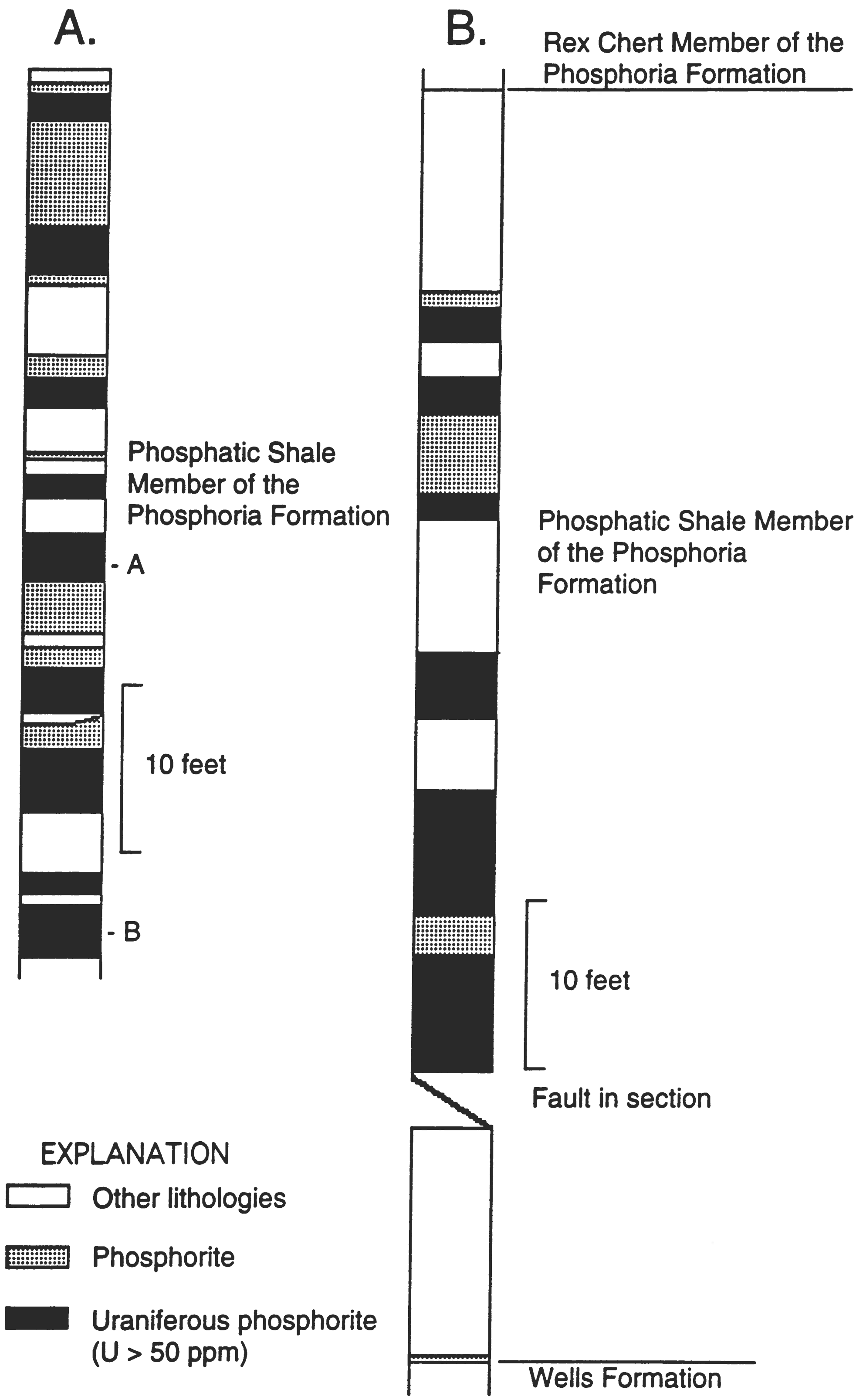


Figure 3. Measured sections of phosphorite and uraniferous phosphorite in the Phosphoria Formation at Steer Creek and Poison Creek, Lincoln County, Wyoming. Letters along right side of columnar section refer to samples described in text. A. Steer Creek section, **Locality 1, Figure 2** (from Cheney and others, 1953). B. Poison Creek section, **Locality 4, Figure 2** (from Sheldon and others, 1953b).

3. U,V (MP) [Pp] ra, ca. **Swift Creek** (sample 70); located in SW section 21, T32N, R118W. A sample of black shale [phosphorite] in a vanadiferous zone from the Phosphoria Formation contained 0.017 percent cU (0.017 percent eU) and 24.0 percent P_2O_5 (Love, 1964).

4. U (MP) [Pp] ra, ca. **Poison Creek measured section**; located in NE NE section 24, T30N, R117W. The relative stratigraphic positions of the phosphorite and uraniferous phosphorite beds are shown on the columnar section (**Figure 3B**). Twelve samples of phosphorite and near-phosphorite from the Phosphoria Formation contained 0.005 to 0.012 percent cU (0.004 to 0.015 percent eU). P_2O_5 contents of these samples ranged from 19.3 to 34.8 percent . The richest phosphorite bed contained the most uranium (Sheldon and others, 1953b).

5. U,V (MP) [Pp] ra, ca. **Raymond Canyon measured section**; located in NW NE section 6, T26N, R119W, and described by Sheldon and others, 1953b). The relative stratigraphic positions of the phosphorite and uraniferous phosphorite beds are shown on the columnar section (**Figure 4A**). Some of these beds are depicted together as one on the columnar section. Six samples from six beds of phosphorite in the Phosphoria Formation (each bed from 0.4 to 3.2 feet thick, with 22.3 to 30.3 percent P_2O_5) contained 0.007 to 0.045 percent cU (0.006 to 0.035 percent eU).

   Sample A (**Figure 4A**) from this section was reportedly the most uraniferous phosphorite in Wyoming, and contained 0.123 percent cU (0.017 percent eU) (Sheldon and others, 1953b). Usually the difference between cU and eU (the disequilibrium ratio) in the Phosphoria Formation is very small; however, the values in this sample show a high disequilibrium ratio. This means that either the uranium has been enriched by recent mobilization or that one of the reported uranium concentration values is in error.

   Phosphorite samples B, C, D, and E (**Figure 4A**) from this stratigraphic section (in beds from 0.4 to 2.2 feet thick, with 15.3 to 18.1 percent P_2O_5) contained 0.006 to 0.037 percent cU (0.004 to 0.032 percent eU). Two other uraniferous units were present in the section: one contained 4.7 percent P_2O_5 with 0.015 percent cU (0.011 percent eU); the other contained 9.6 percent P_2O_5 with only 0.005 percent cU (0.004 percent eU) (Sheldon and others, 1953b).

   At a later date, 31 samples of phosphorite were taken in a 109-foot-thick stratigraphic section of the Meade Peak Member of the Phosphoria Formation at this locality. The samples contained from 0.002 to 0.030 percent eU, minor REE enrichment (less than 100 ppm), and from 10.73 to 36.32 percent P_2O_5 (Vine, 1966).

6. U (MP) [Pp] ca. **Layland Canyon**; located in sections 19 and 30, T26N, R119W, as described by McKelvey and others (1953). At least seven samples of phosphatic material from the Phosphoria Formation contained 50 ppm (0.005 percent cU) or more uranium (DeVoto and Stevens, 1979).

7. U (MP) [Pp] ra, ca. **Coal Canyon**; located in lot #1201, section 7, T26N, R119W. Samples of phosphorite in a 0.7-foot-thick unit of the Phosphatic Shale Member of the Phosphoria Formation, contained from 0.004 to 0.060 percent cU (from four samples) and 0.006 to 0.065

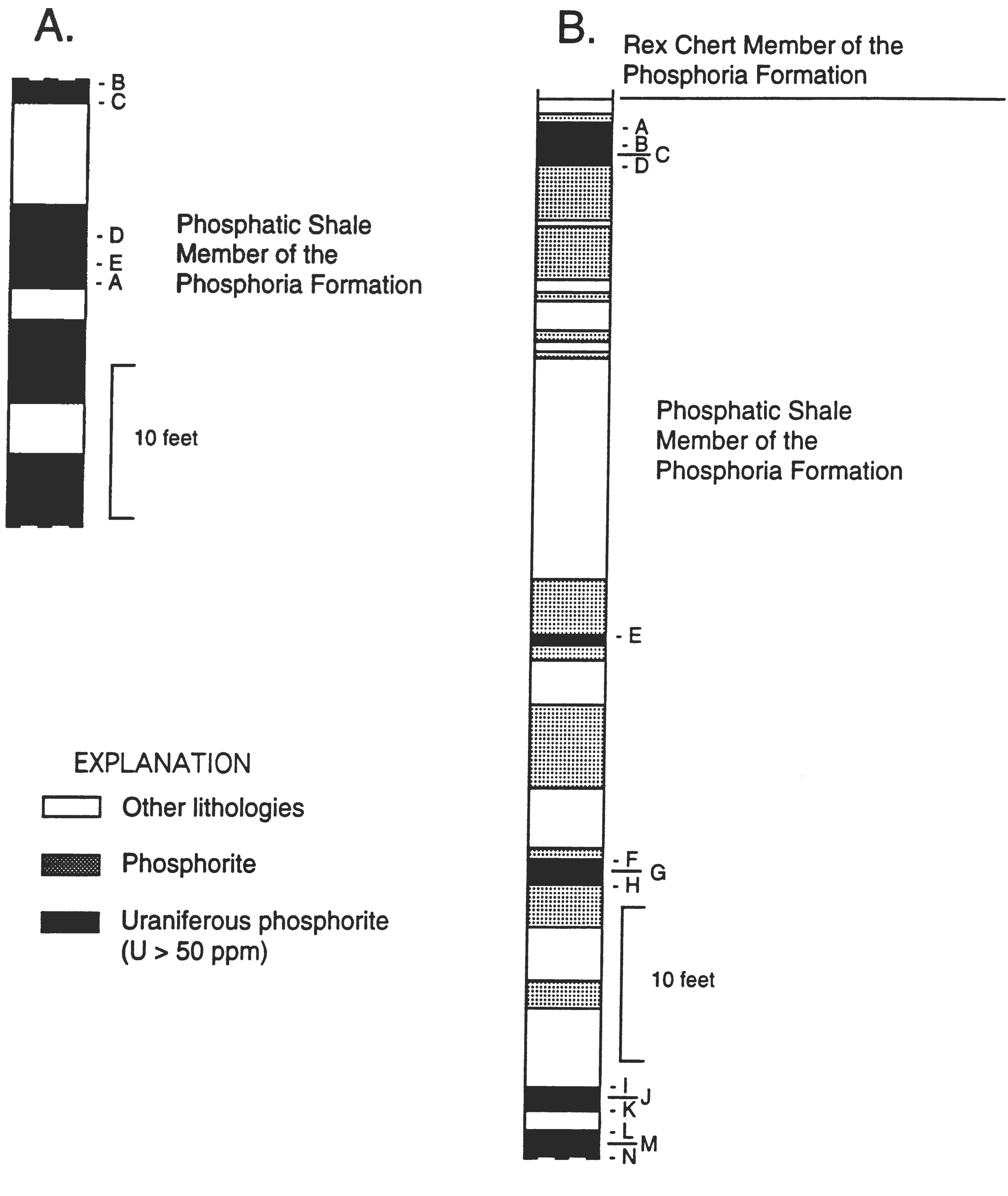


Figure 4. Measured sections of phosphorite and uraniferous phosphorite in the Phosphoria Formation at Raymond Canyon and Basin Creek, Lincoln County, Wyoming. Letters along right side of columnar sections refer to samples described in text. A. Raymond Canyon section, **Locality 5, Figure 2** (from Sheldon and others, 1953b). B. Basin Creek section, **Locality 8, Figure 2** (from Sheldon and others, 1953a).

percent eU (from 12 samples) (McKelvey and others, 1953). The phosphate content (P_2O_5) of all these samples varied from 0.73 to 34.35 percent (Thompson, 1953), and the fluorine content varied from 0.50 to 3.85 percent (Thompson, 1954). Samples with the higher phosphate contents also had the higher fluorine contents.

Individual samples of 39 other beds of phosphorite taken by Gulbrandsen (1960) at Coal Canyon contained from 0.002 to 0.034 percent cU (0.003 to 0.034 percent eU). Phosphate (P_2O_5) contents ranged from 15.5 to 32.9 percent and fluorine contents ranged from1.6 to 3.8 percent. These phosphate-rich beds varied in thickness from 0.3 to 1.9 feet, and were within a stratigraphic interval about 130 feet thick (McKelvey and others, 1953).

In addition to the phosphate-rich beds, five beds also contained at least 0.005 percent uranium (0.007, 0.006, 0.006, 0.007, and 0.005 percent cU), with about the same amount of eU (Gulbrandsen, 1960). These beds consisted of an impure dolomite, two phosphatic mudstones, a dolomitic mudstone, and a mudstone, respectively (McKelvey and others, 1953).

8. U (MP) [Pp] ra, ca. **Basin Creek measured section**; located in sections 12 and 13, T26N, R117 1/2W. The relative stratigraphic positions of the phosphorite and uraniferous phosphorite beds are shown on the columnar section (**Figure 4B**). Fourteen samples of phosphorite (Samples A through N, **Figure 4B**) from 14 beds (ranging from 0.5 to 2.6 feet thick, with 21.3 to 35.6 percent P_2O_5) in the Phosphoria Formation contained from 0.003 to 0.011 percent cU (0.005 to 0.011 percent eU) (Sheldon and others, 1953a).

9. U (MP, BS?) [Pp] ra, ca. **Fontenelle Creek measured section**; located in section 35, T27N, R116W. The relative stratigraphic positions of the phosphorite and uraniferous phosphorite beds are shown on the columnar section (**Figure 5A**). Nine samples of phosphorite (Samples A through E and G through J, **Figure 5A)** from nine beds (ranging from 0.4 to 1.8 feet thick, with 22.7 to 31.8 percent P_2O_5) in the Phosphoria Formation contained from 0.003 to 0.007 percent cU (0.004 to 0.013 percent eU). Four other phosphorite beds (from 0.6 to 3.9 feet thick, with 11.4 to 18.6 percent P_2O_5) contained 0.003 to 0.005 percent cU (0.006 to 0.008 percent eU). Four mudstone samples, all with less than 8 percent P_2O_5, contained at least 0.005 percent uranium, ranging from 0.005 to 0.012 percent cU (0.007 to 0.014 percent eU) (Sheldon and others, 1953a; Sheldon, 1963). The most uranium-rich mudstone (Sample F, **Figure 5A)**, a carbonate-bearing mudstone, might be a black shale uranium-type occurrence; it contained only 0.2 percent P_2O_5 (Sheldon and others, 1953a; Sheldon, 1959).

10. U (MP) [Pp] ca. **North Fork Pine Creek**; located in section 13, T25N, R118W, and first described by McKelvey and others (1953). At least one sample of phosphatic material from the Phosphoria Formation contained at least 50 ppm uranium (DeVoto and Stevens, 1979).

11. U (MP) [Pp] ca. **Middle Fork Pine Creek**; located in section 35, T25N, R118W and first described by McKelvey and others (1953). At least two samples of phosphatic material from the Phosphoria Formation contained 50 ppm or more uranium (DeVoto and Stevens, 1979).

12. U (MP) [Pp] ra, ca. **Cokeville area**; approximately located in SE T25N, R119W, and SW T25N, R118W, approximately 2-1/2 miles north-northeast of Cokeville. Samples of

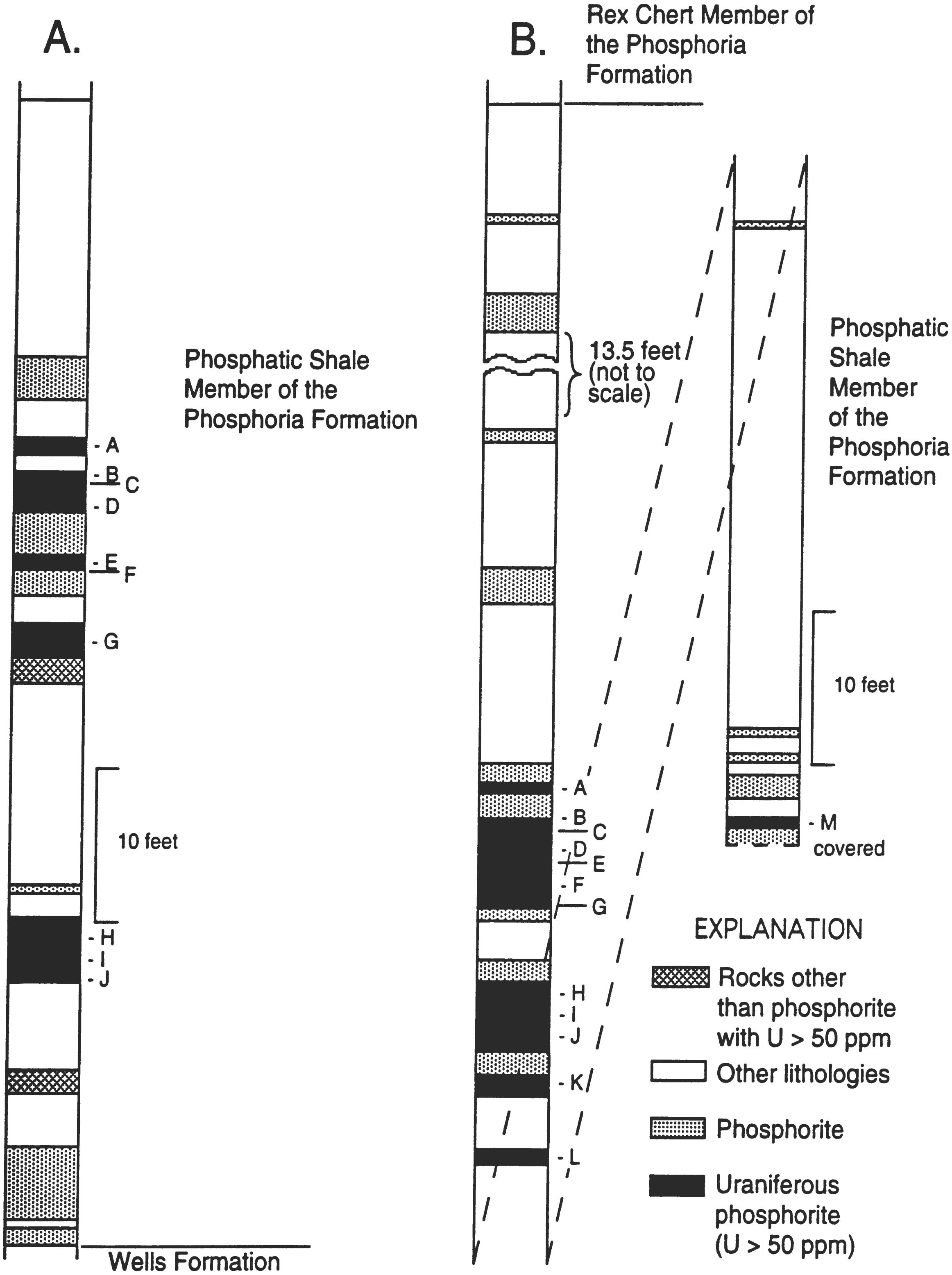


Figure 5. Measured sections of phosphorite and uraniferous phosphorite in the Phosphoria Formation at Fontenelle Creek and Cokeville, Lincoln County, Wyoming. Letters along right side of columnar sections refer to samples described in text. A. Fontenelle Creek section, **Locality 9, Figure 2** (from Sheldon and others, 1953a). B. Cokeville section, **Locality 14, Figure 2** (from Sheldon and others, 1953b).

phosphatic shale and oolitic phosphorite both contained 0.027 percent cU (0.025 and 0.021 percent eU, respectively) (Beroni and McKeown, 1952). The samples were probably from the Phosphoria Formation.

13. U (BS?) [Pp] rs. **Cokeville area**; approximately located in sections 35 and 36, T25N, R119W. A radiometric survey conducted by the author identified radioactive black shales of the Permian Phosphoria Formation on Big Hill and Rocky Point northeast of Cokeville . This locality is adjacent to an extension of the Cokeville phosphorite (**Locality 14**, below).

14. U (MP) [Pp] ra, ca. **Cokeville measured section**; located in NW section 4, T24N, R119W. The relative stratigraphic positions of the phosphorite and uraniferous phosphorite beds are shown on the columnar section (**Figure 4B**). Samples were collected and analyzed from two trenches. In the upper trench at Cokeville, 13 samples (A through M, **Figure 4B**) from 13 phosphorite beds in the Phosphoria Formation (ranging from 0.5 to 2.4 feet thick, with 22.1 to 34.3 percent P_2O_5) contained 0.005 to 0.028 percent cU (0.005 to 0.030 percent eU). Five samples (not shown on **Figure 4B**) from five additional phosphorite beds, each less than a foot thick, contained 0.005 to 0.018 percent cU (0.004 to 0.020 percent eU), with 12.9 to 18.1 percent P_2O_5 (Sheldon and others, 1953b).

    The lower trench at the Cokeville section probably overlaps stratigraphically with part of the upper trench. In this lower trench, seven analyses available for seven phosphorite beds (ranging from 0.5 to 1.9 feet thick, with 25.4 to 31.2 percent P_2O_5) yielded from 0.005 to 0.013 percent cU (0.005 to 0.013 percent eU). Five other phosphorite beds in the trench (ranging from 0.6 to 1.4 feet thick, with 14.7 to 19.8 percent P_2O_5) contained from 0.002 to 0.008 percent cU (0.003 to 0.009 percent eU) (Sheldon and others, 1953b).

    Later analyses of two samples of pellet phosphorite taken from the Meade Peak Member of the Phosphoria Formation at this stratigraphic section contained 0.004 and 0.021 percent cU (0.004 and 0.020 percent eU), 23.0 and 32.4 percent P_2O_5, and 2.03 and 3.55 percent F, respectively. Both samples had slight REE enrichment of greater than 100 ppm (Gulbrandsen, 1966). The exact units sampled at this time are not known.

15. U (MP) [Pp] ra, ca. **Wheat Creek measured section**; located in section 4, T23N, R116W. The relative stratigraphic positions of the phosphorite and uraniferous phosphorite beds are shown on the columnar section (**Figure 6A**). Eleven samples (A through K, **Figure 6A**) of phosphorite from eleven beds (ranging from 0.3 to 1.7 feet thick, with 20.4 to 34.0 percent P_2O_5) in the Phosphoria Formation contained from 0.004 to 0.012 percent cU (0.005 to 0.013 percent eU). Three samples of phosphorite from three other beds (ranging from 0.8 to 2.2 feet thick, with 16.2 to 17.3 percent P_2O_5) contained 0.005 to 0.006 percent cU (all contained 0.006 percent eU) (Sheldon and others, 1953a; Sheldon, 1963).

16. U (MP) [Pp] ra, ca. **South Mountain (Top of the World) Phosphate Mines, Inc.**; located in S2 SE section 9 and northernmost part of section 16, T23N, R116W. Sheldon, Cressman, and others (1953) place this stratigraphic section in sections 8 and 9, but describe the mine workings at the location given above. The relative stratigraphic positions of the phosphorite and uraniferous phosphorite beds are shown on the columnar section (**Figure 6B**). Phosphorite samples A through F (**Figure 6B**) (from beds ranging from 0.5 to 1.9 feet thick,

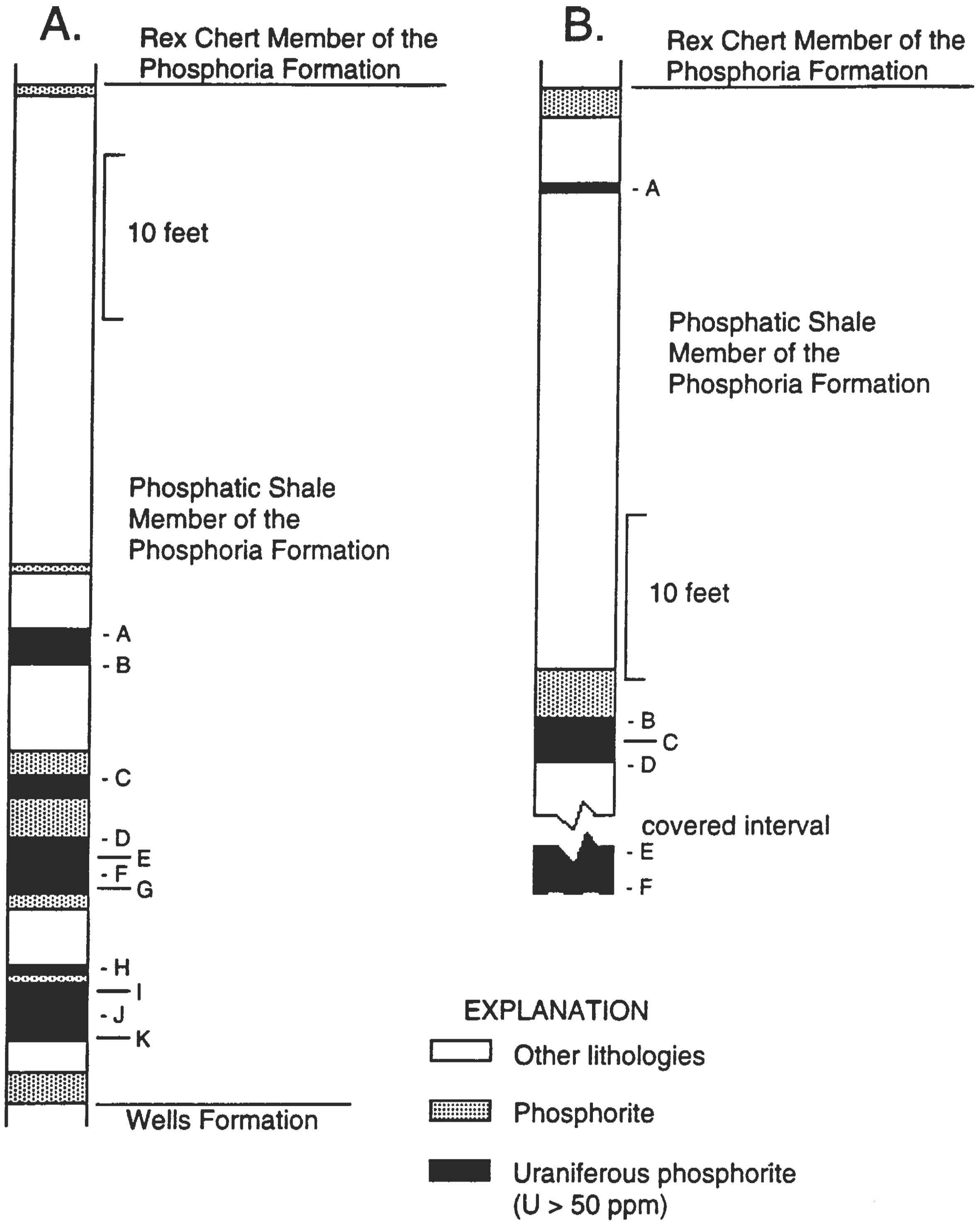


Figure 6. Measured sections of phosphorite and uraniferous phosphorite in the Phosphoria Formation at Wheat Creek and South Mountain (Top of the World), Lincoln County, Wyoming. Letters along right side of columnar sections refer to samples described in text. A. Wheat Creek section, **Locality 15, Figure 2** (from Sheldon and others, 1953a). B. South Mountain (Top of the World) section, **Locality 16, Figure 2** (from Sheldon and others, 1953a).

with 13.9 to 27.3 percent P_2O_5) from a measured section of Phosphoria Formation in these mine workings contained 0.005 to 0.010 percent cU (0.005 to 0.013 percent eU) (Sheldon and others, 1953a; Sheldon, 1963).

A sample of massive phosphorite and a sample of phosphate rock were each taken at a later date from a trench in the Phosphoria Formation on this property. The samples contained 70 and 43 ppm U_3O_8 from chemical analysis (cU_3O_8) (61 and 45 ppm eU), with 23.6 and 14.8 percent P_2O_5, respectively (Madsen and Reinhart, 1982).

The mine workings at this locality are rather extensive and about 60,000 tons of high grade phosphate rock were reportedly removed from the property and stockpiled four miles north of Kemmerer (Thomas, 1949). This stockpile could not be located by the author in June, 1993, and the final disposition of this phosphate rock is unknown.

17. U (MP) [Pp] ra, ca. **Quealy phosphate mine**; located in NE NE section 21, T23N, R116W. A sample of pisolitic phosphorite in the Phosphoria Formation from a mine dump contained 150 ppm cU_3O_8 (150 ppm eU) with 30.4 percent P_2O_5. Another sample, reportedly from the Phosphoria Formation on the property, contained 0.26 percent cU_3O_8, but the sample was not analyzed for phosphate (Madsen and Reinhart, 1982).

18. U (MP) [Pp] ra, ca. **South Commissary Ridge**; located in SW NE section 29, T23N, R116W. A sample of phosphorite from the Phosphoria Formation in this trench contained 150 ppm cU_3O_8 (120 ppm eU) and 27.5 percent P_2O_5 (Madsen and Reinhart, 1982).

19. U (MP) [Pp] ca. **North Watercress Canyon**; located in center N2 N2 section 4, T22N, R118W. A sample of gray phosphatic shale from the Phosphoria Formation contained 53 ppm cU_3O_8 (36 ppm eU) and 12.5 percent P_2O_5 (Madsen and Reinhart, 1982).

20. U (MP) [Pp] ca. **Leefe phosphate mine**; located in sections 10 and 15, T21N, R120W. At least six samples of phosphatic material from the Phosphoria Formation taken from the mine workings contained more than 50 ppm eU. One of these samples contained more than 200 ppm eU (DeVoto and Stevens, 1979).

21. U (MP) [Pp] ra, ca. **Cumberland (Chick Mountain) measured section**; located in center W2 E2 section 19, T19N, R117W. Only one prospect is shown on the Elkol SW 7 1/2-minute Quadrangle, so the same trenched stratigraphic section probably has two different names. Samples of two pisolitic phosphorites from this trench in the Phosphoria Formation contained 99 and 32 ppm cU_3O_8 (77 and 30 ppm eU), and 25.7 and 22.7 percent P_2O_5 (Madsen and Reinhart, 1982). The exact stratigraphic position of these two samples is not known.

    Another sample (0.4 feet thick, with 23.5 percent P_2O_5) of phosphorite from a section measured by Cheney and others (1953) contained only 0.004 percent cU (0.007 percent eU); nine samples of phosphate-rich rock (ranging from 0.5 to 1.9 feet thick, with 9.55 to 19.2 percent P_2O_5) contained 0.003 to 0.038 percent cU (0.005 to 0.034 percent eU). The exact stratigraphic position of the ten samples described above is not known, but the relative stratigraphic positions of the phosphorite and uraniferous phosphorite beds are shown on

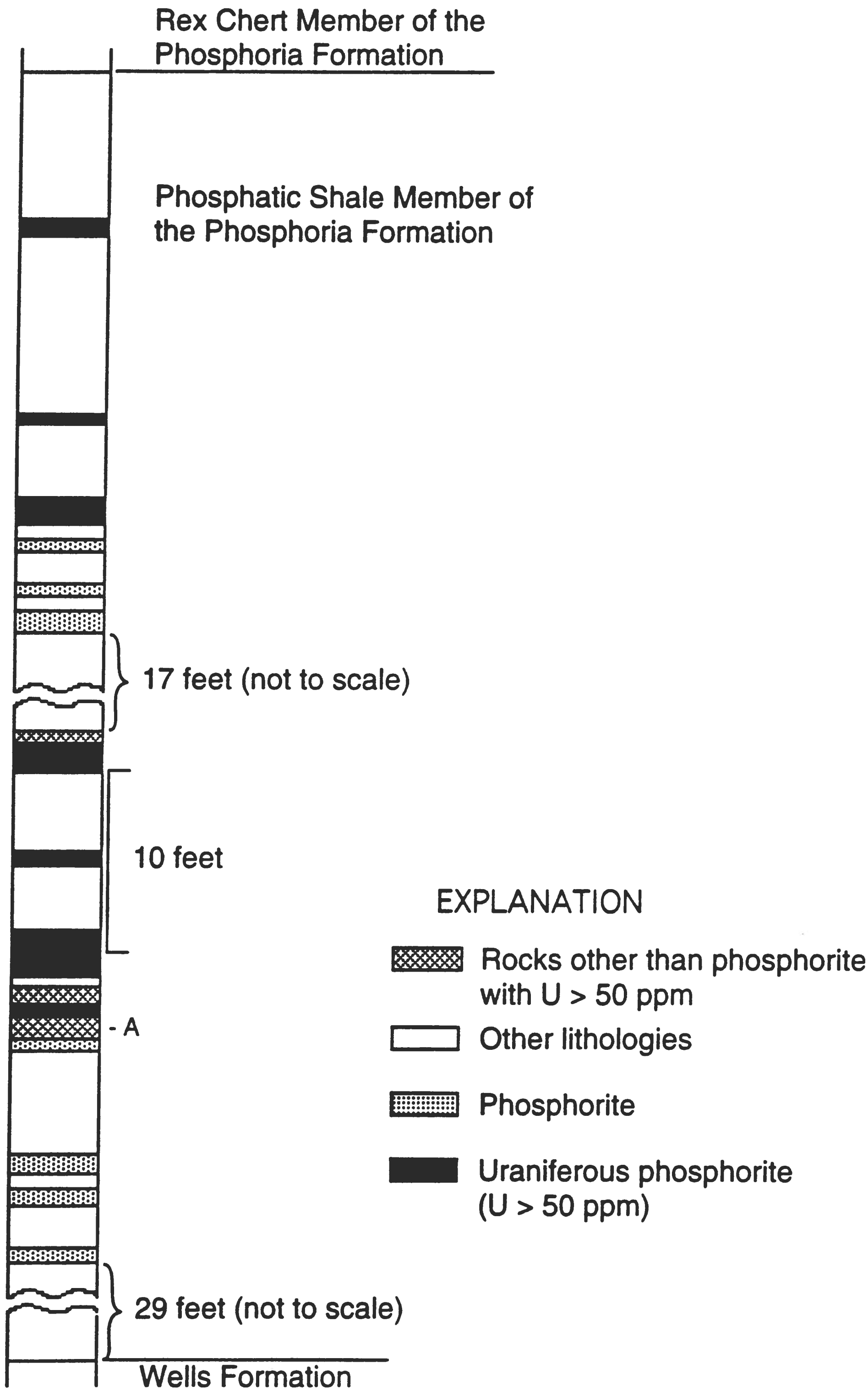


Figure 7. Measured section of phosphorite and uraniferous phosphorite in the Phosphoria Formation at Cumberland (**Locality 21, Figure 2**), Lincoln County, Wyoming (from Cheney and others, 1953). Letter along right side of columnar section refers to sample described in text.

the columnar section (**Figure 7**). A sample of low phosphorus (2.35 percent P_2O_5) carbonate rock contained 0.005 percent cU (0.008 percent eU); Sample A, (**Figure 7**) of the phosphatic (10.7 percent P_2O_5) carbonate rock directly above it contained 0.038 percent cU (0.034 percent eU) (Sheldon, 1963). Some uranium might have been transported from the more phosphatic carbonate into the less phosphatic carbonate.

Finnell and Parrish (1958) plotted an occurrence of uranium in marine rocks on the line between sections 17 and 20, T19N, R117W, and an occurrence approximately located in section 19, T19N, R118W. The present report assumes that both are misplots of the Cumberland site. As located above, the former site is in conglomeratic Tertiary or Cretaceous rocks, and the latter site is in fluvial or lacustrine Tertiary rocks (Love and Christiansen, 1985).

22. U (LP) [Tg] ra, ca. **South Fork Slate Creek**; located on the west side of the Green River Basin in section 5, T22N, R114W. A sample of lacustrine, phosphatic, gastropod-bearing limy sandstone in the Wilkins Peak Member of the Green River Formation at this site contained 0.007 percent cU (0.006 percent eU) with 0.69 percent P_2O_5 (Love, 1964).

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