U.S. DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

Mineral Resource Assessment of the Custer National Forest in the Pryor Mountains, Carbon County, South-Central Montana

by

Bradley S. Van Gosen[1], Anna B. Wilson[1], and Jane M. Hammarstrom[2],

with a section on GEOPHYSICS *by* Dolores M. Kulik[1]

Open-File Report 96-256

1996

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards or with the North American Stratigraphic Code. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

[1] U.S. Geological Survey, Denver, Colorado
[2] U.S. Geological Survey, Reston, Virginia

CONTENTS

FIGURES

Page

TABLES

APPENDIXES

ABSTRACT

The U.S. Geological Survey evaluated the mineral resource potential of the Custer National Forest in the Pryor Mountains of south-central Montana. The study area comprises approximately 122 square miles (316 km^2) of National Forest lands, located 40 miles (64 km) south of Billings, Montana. Five uplifted and tilted, fault-bounded blocks form the Pryor Mountains. The National Forest study area includes most of Big Pryor Mountain and East Pryor Mountain, which represent the southwestern and southeastern blocks of the uplift, respectively. These blocks are bordered by high-angle faults on their north and east flanks. Mississippian-aged Madison Limestone is exposed in half of the National Forest.

In the southern Pryor Mountains region, including the study area, a paleokarst horizon in the upper 190-240 ft of the Madison Limestone Group hosts uranium-vanadium deposits. Host structures are shallow chaotic breccia bodies that fill solution caverns in the paleokarst. The breccias formed by the collapse of cavern roof and wall rocks accompanied by inflow of overlying Amsden Formation sediments. Typical "collapsed caverns" hosting uranium-vanadium deposits are about 100 ft or less in diameter, 20-25 ft in height, and often circular in plan view. The primary ore minerals are silt-size, bright yellow tyuyamunite and metatyuyamunite.

Uranium was mined from about 40 small (median size of 154 metric tons), relatively high-grade (median grades of 0.26% U_3O_8, 0.23% V_2O_5) deposits in the region during 1956-70. During 1956 to 1964, 21 properties in the Big Pryor Mountain district of Montana (including at least 3 mines in the study area) produced more than 45,000 pounds of uranium oxide (U_3O_8) and 30,000 pounds of vanadium oxide (V_2O_5). Similar deposits in the Little Mountain district of northern Wyoming, about 10 miles to the southeast, produced about 250,000 pounds of uranium oxide and 205,000 pounds of vanadium oxide from 1956 to 1970. Geologic analysis suggests that any undiscovered uranium-vanadium deposits of the Custer National Forest are likely to be similar in character to those found in the 1950's and 1960's. About 80% of the study area is permissive for undiscovered uranium-vanadium deposits of this type to a maximum depth of 550 ft.

A grade and tonnage model was constructed for the uranium-vanadium deposits using ore data obtained in 1956-70 from the producing mines of the Big Pryor Mountain and Little Mountain districts. Using a computer simulation, estimates of numbers of undiscovered uranium-vanadium deposits in the study area were combined with the grade and tonnage model. The computer simulation generated a probability distribution representing the likelihood of a given amount of ore or metal potentially present in undiscovered deposits of the study area. The results using this method suggest that the Custer National Forest may contain about five times as much ore as was produced from the Big Pryor Mountain district and about as much as the combined total production from the Big Pryor Mountain and Little Mountain districts.

Exploration for uranium in the Custer National Forest is unlikely in the foreseeable future. Active mining, exploration, and infrastructure exist for major uranium reserves elsewhere in the U.S. Land management issues associated with uranium deposits in the Pryor Mountains for the reasonably foreseeable future may be focused on the hazards of localized concentrations of radioactive rocks and high radon levels in the abandoned mines rather than on exploration and mine development on federal lands.

Other mineral resources of the Custer National Forest in the Pryor Mountains include:

1. High purity (high calcium) limestone in the upper parts of the Madison Limestone Group. These rocks are quarried locally, crushed and sold for agricultural and industrial uses. Limestone is exposed in half of the National Forest.
2. Liesegang-banded rocks that may have commercial value as colorful landscaping rock. Rhythmic precipitation of iron-oxides and silica formed attractive banding in wallrocks adjacent to an undetermined number of the uranium-vanadium deposits.
3. Limestones and dolomites of varying purity that may be crushed and used in concrete or as light aggregate. These rocks are exposed in about 7% of the study area and include the lower two-thirds (500 ft) of the Madison Limestone Group, plus the Jefferson Formation and the Bighorn Dolomite.

Sand and gravel resources are very limited in the National Forest and are restricted to public lands along Sage Creek. There is a low probability of oil and gas reserves within the Forest.

INTRODUCTION

The U.S. Geological Survey (USGS) conducted a mineral-resource assessment of the Custer National Forest (Beartooth Division) in the Pryor Mountains of south-central Montana (fig. 1) from 1992 to 1994. This study contributes to a larger USGS evaluation of the undiscovered mineral resources within the entire Custer and Gallatin National Forests, as described by Hammarstrom and others (1993). The USGS studies provide minerals information to the U.S. Forest Service for land-use planning in the management of Federal lands.

The Pryor Mountains study area is a tract of Custer National Forest of approximately 122 square miles (316 km^2), located 40 miles (64 km) south of Billings, Montana, and several miles west of the Bighorn Canyon National Recreation Area (fig. 1). The nearest town is the small town of Frannie, Wyoming, about 9 miles (14 km) to the southwest. The Pryor Mountains study area is bordered on the north by the Crow Indian Reservation and on the southeast by the Pryor Mountain Wild Horse Range. The remainder of the lands along the perimeter are privately owned or managed by the Bureau of Land Management (Billings Resource Area).

The Pryor Mountains study area includes most of Big Pryor (elevation 8,886 ft) and East Pryor Mountains (elevation 8,776 ft), which form the southwestern and southeastern peaks of the Pryor Mountains range, respectively. The bedrock in half of the study area is the Mississippian-aged Madison Limestone Group (figs. 2 and 3), the upper part of which hosts uranium-vanadium deposits in shallow, breccia-filled collapse structures. Uranium was mined from about 40 small (median size of 154 metric tons), relatively high-grade (median grade of 0.26% U_3O_8) deposits in the region during 1956-70. Locatable commodities, as described by the General Mining Law of 1872, include most metals and industrial minerals. Locatable commodities in the study area, hosted by the upper Madison Limestone Group, include: (1) identified and undiscovered uranium-vanadium deposits; and (2) limestones of relatively high purity (high calcium) with potential for agricultural and industrial uses. Salable commodities that have potential in the study area include: (1) liesegang-banded rocks, associated with the uranium-vanadium deposits, that could have commercial value as decorative stone; and (2) limestones and dolomites of varying purity that may be crushed and used as rock aggregate. These resources are described and evaluated in separate sections of this report.

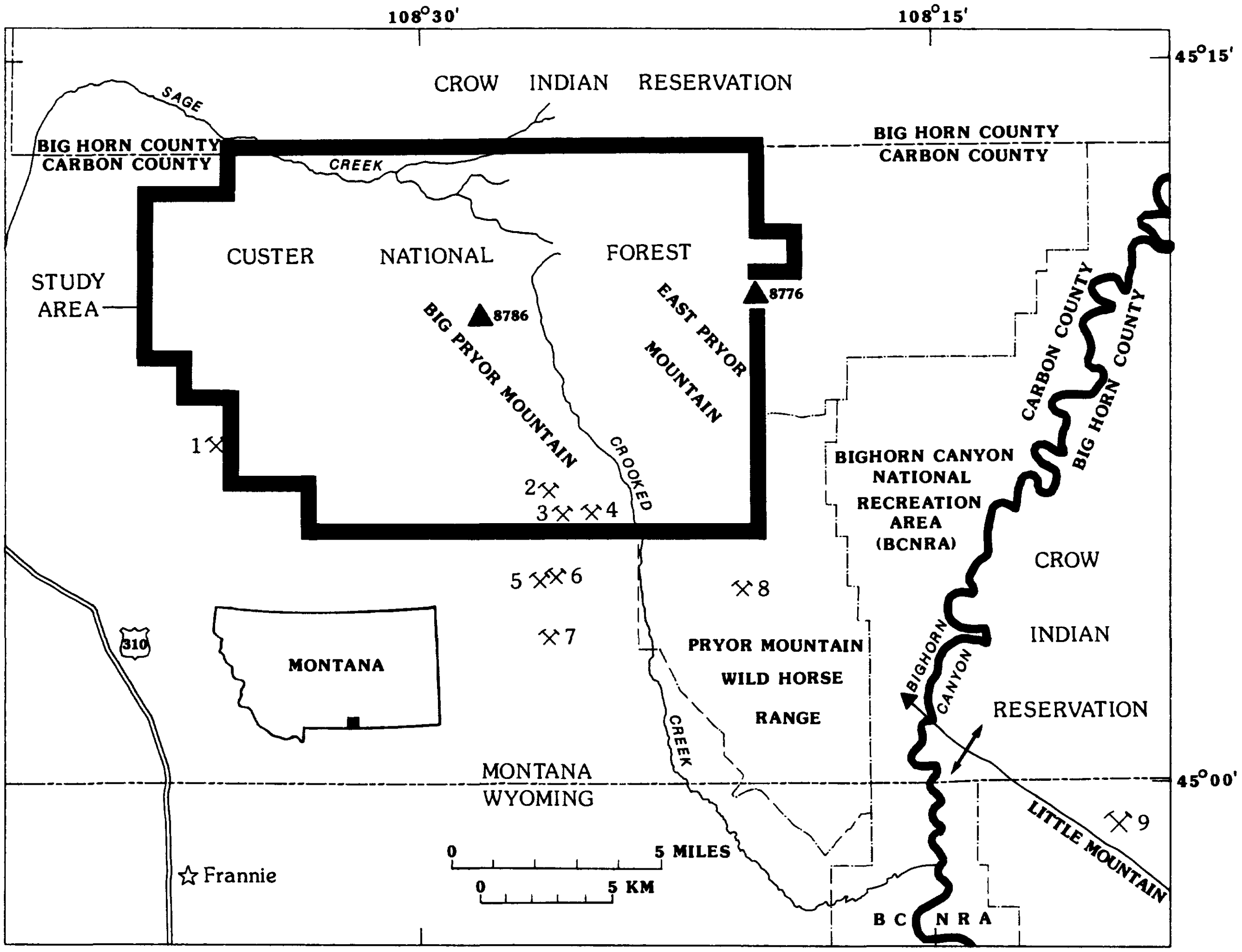


Figure 1. Index map of the southern Pryor Mountains region showing the location of the Custer National Forest study area. Numbered localities refer to active (Warren quarry) and inactive (all others) mine sites, including:

1. Warren quarry
2. Old Glory mine
3. Sandra mine
4. Perc group (location shown is uncertain)
5. Marie mine
6. The Dandy (Pryor Mtn.) mine
7. Swamp Frog mine
8. East Pryor (Fran #3) mine
9. Little Mountain mining district

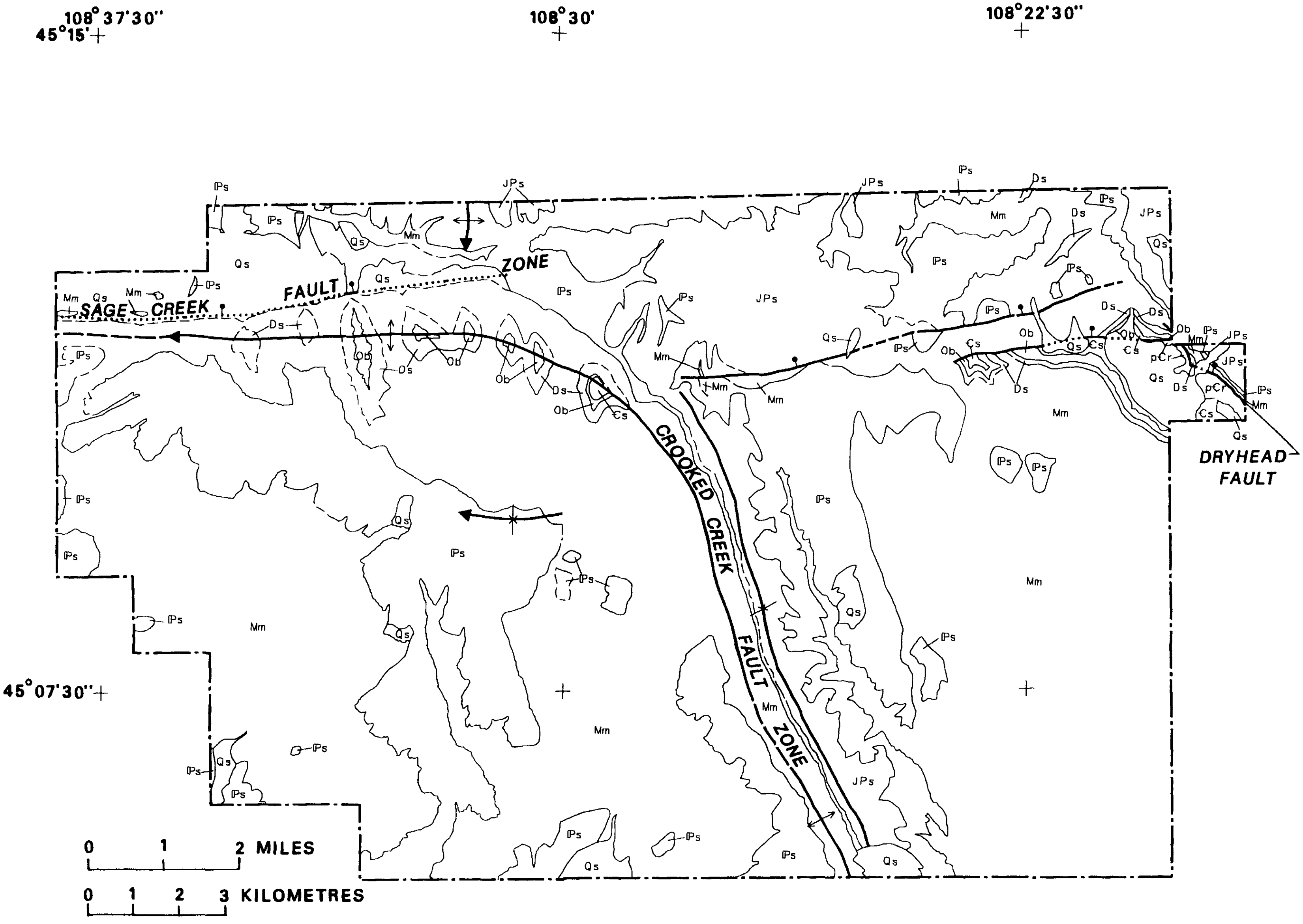


Figure 2. Geologic map of the Custer National Forest in the Pryor Mountains, Montana. Explanation on the following page. Modified by Wilson and Van Gosen from Blackstone (1974a-f; 1975).

EXPLANATION TO FIGURE 2

Quaternary	Qs
Jurassic Triassic Permian	JPs
Pennsylvanian	IPs
Mississippian	Mm
Devonian	Ds
Ordovician	Ob
Cambrian	€s
Precambrian	p€r

Qs Surficial deposits (Quaternary)--Alluvium, colluvium, slope-wash, mudflows, landslides, and pediment gravel

JPs Jurassic, Triassic, and Permian sedimentary rocks--Includes Morrison Formation (Jurassic); Ellis Group (Jurassic) including the Swift, Rierdon, and Piper Formations; Chugwater Formation (Triassic); and Phosphoria Formation equivalents (Permian)

IPs Pennsylvanian sedimentary rocks--Includes Tensleep Sandstone and Amsden Formation

Mm Madison Limestone Group (Mississippian)--(Stratigraphic units A-D proposed by Richards (1955) and summarized by Blackstone (1975)).

Ds Devonian sedimentary rocks--Includes Jefferson Formation (Dolomite) and Beartooth Butte Formation

Ob Bighorn Dolomite (Ordovician)

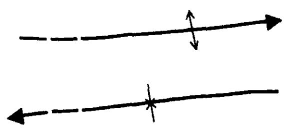
€s Cambrian sedimentary rocks--Includes Gallatin Limestone, Gros Ventre Shale (Formation), and Flathead Quartzite

p€r Precambrian rocks--Includes granitic gneiss; hornblende schist; quartz veins; and aplite dikes

CONTACT--Dashed where inferred

HIGH-ANGLE FAULT--Dashed where inferred, dotted where concealed. Bar and ball on downthrown side

FOLD AXIS--Dashed where inferred; arrows indicate direction of plunge



Anticline

Syncline

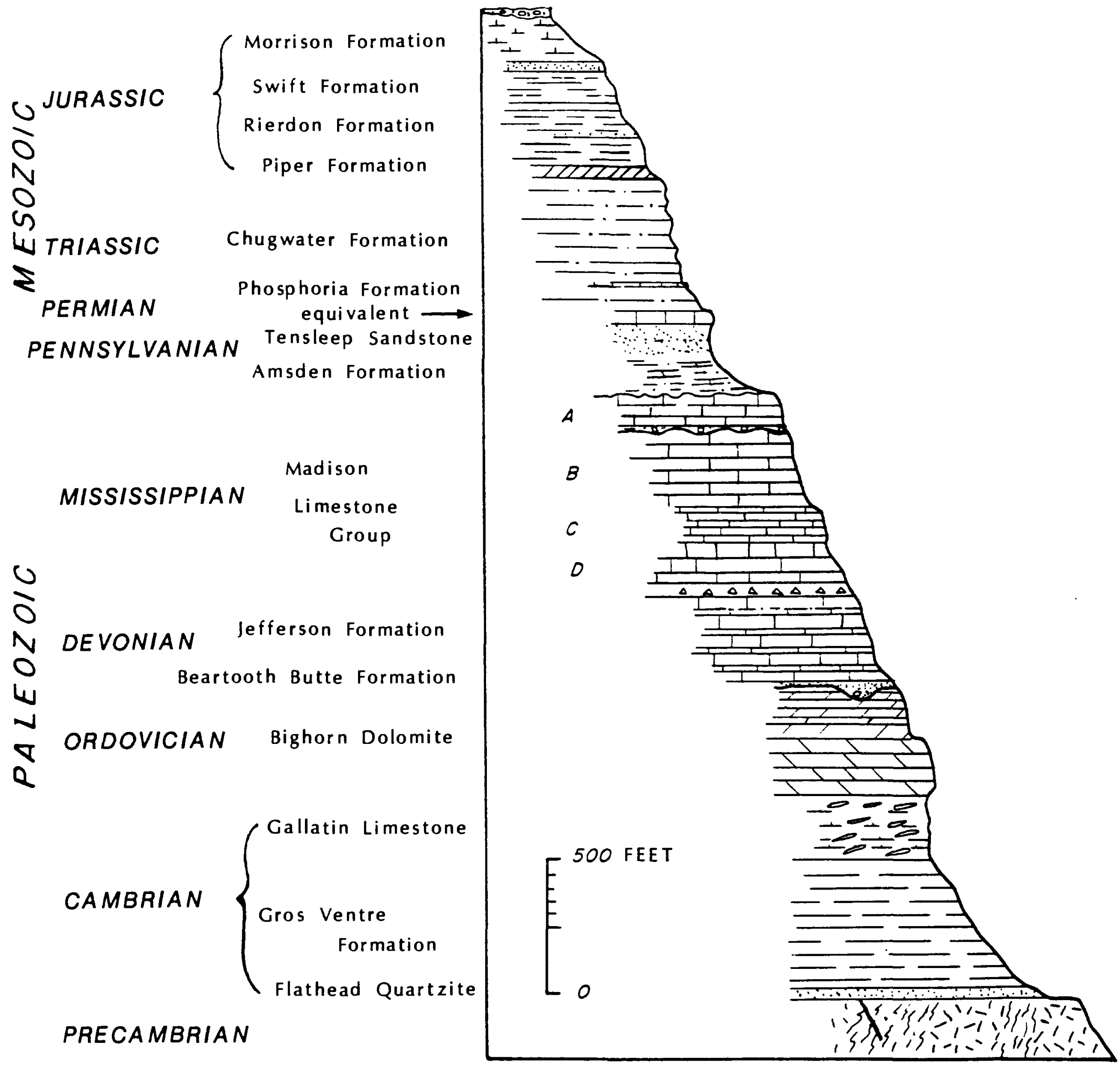


Figure 3. Generalized stratigraphic column showing the rock units exposed in the Custer National Forest of the Pryor Mountains. From Blackstone (1975).

The only detailed geologic mapping in the Pryor Mountains study area was by D.L. Blackstone, Jr., who presented the results of his mapping (1930 to 1934) in a doctoral dissertation for Princeton University (Blackstone, 1936). Later, he published his interpretations in the Journal of Geology (Blackstone, 1940). When modern 7½-minute topographic quadrangles (scale 1:24,000) and aerial photography became available in the 1960s, Blackstone transferred his geologic mapping to the new topographic base maps and released them as eleven Montana Bureau of Mines and Geology publications, seven of which cover the study area (Blackstone, 1974a-f, 1975).

This USGS study relied heavily on the seven geologic quadrangle maps of Blackstone (1974a-f, 1975) that cover the study area. Field inspections by Wilson and Van Gosen during 1993 resulted in modifications to Blackstone's mapping, primarily along the northern and eastern margins of Big Pryor Mountain. The Sage Creek fault zone on the northern flank of Big Pryor Mountain is not as conspicuous as suggested by Blackstone's maps (1974c, 1974d). A small segment of this fault zone is exposed in the canyon south of the Sage Creek Ranger Station, but most of the length of the zone is covered by Quaternary deposits. Observations of this study suggest that the fault zone exists at depth and the minimum visible offset is approximately 140 ft (thickness of the Amsden Formation), much less than the offset suggested by Blackstone (1974c, 1974d). Faults shown by Blackstone (1974b, 1974f) along the eastern crest of Big Pryor Mountain are reinterpreted by this study as asymmetric anticlines (drape folds) that overlie an inclined fault zone (Crooked Creek fault zone, fig. 2) at depth. This drape-fold interpretation for the eastern, as well as northern, margins of the Big Pryor Mountain is described in the subsequent text ("Regional and Local Structural Setting") and shown on figure 2.

Note to reader: All measurement units presented in this paper are given in the unit in which the measurement was made during the study or was provided by the reference. That is, to provide smoother reading, the corresponding metric-U.S. customary unit conversions are not necessarily provided simultaneously herein. References to "tons" throughout the text, figures, tables and appendixes correspond to short tons, which is equal to 2,000 pounds. Metric tons, or tonnes (megagrams), may be calculated by multiplying short tons ("tons") by 0.9072; short tons may calculated by multiplying metric tons by 1.102. Feet may be calculated by multiplying meters by 3.281; meters may be calculated by multiplying feet by 0.3048.

GEOLOGY OF THE PRYOR MOUNTAINS

Regional and Local Structural Setting

The Pryor Mountains cover about 450 square miles in south-central Montana. They are a geographically distinct range located along the northwest continuation of a broad regional arch that formed the Bighorn Mountains. The Bighorn arch plunges northwesterly at a low angle from its crest west of Buffalo, Wyoming. The arch may terminate to the north against the Lake Basin-Huntley fault zone (Blackstone, 1975), or may terminate well south of it, as shown in figure 4 (from Alpha and Fanshawe, 1954). The Lake Basin-Huntley fault zone is described by

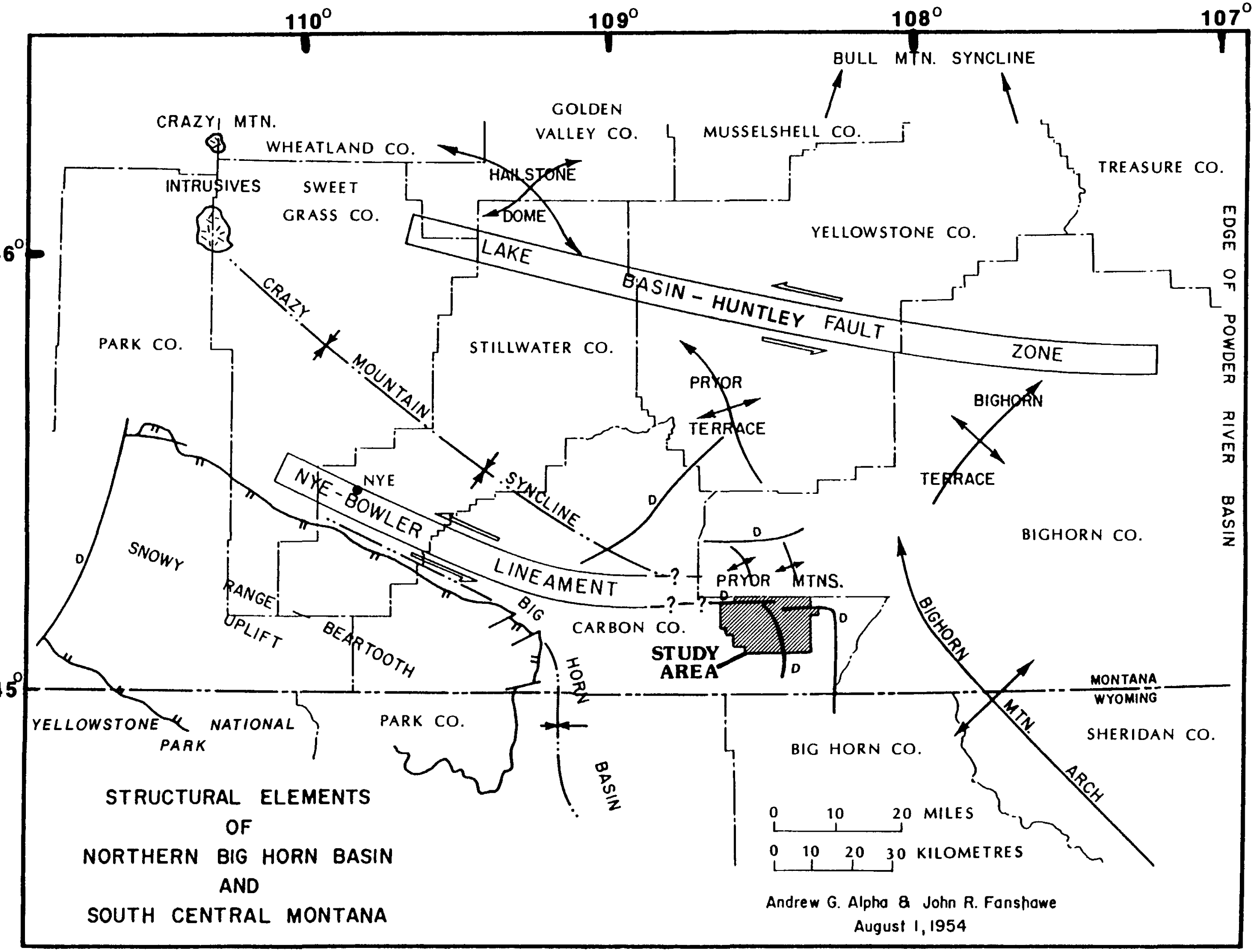


Figure 4. Simplified map of the major structural features of south-central Montana and north-central Wyoming. Modified from Alpha and Fanshawe (1954). Foose and others (1961) suggest that the Nye-Bowler lineament (fault zone) intersects the frontal fault zone of the Beartooth Mountains uplift at an area west of Nye, Montana.

Blackstone (1975) as follows:

> The Lake Basin-Huntley fault zone (Hancock, 1919, 1920; Chamberlin, 1919) trends S. 80° E. [for]........ a distance of 130 miles. The zone consists of normal fault zones that trend N. 60° E., are arranged en echelon, and define half-dome type anticlines.

The Lake Basin-Huntley fault zone forms an eastern part of the Lewis and Clark line, which is also referred to as the Montana lineament (Weidman, 1965).

Another major structural lineament in the Pryor Mountains region is the Nye-Bowler lineament (fig. 4), first recognized by Wilson (1936, 1938). The lineament consists mainly of domal structures and associated en echelon steeply dipping faults that are generally northeast-striking, short in length (2-5 miles), and normal in sense of displacement. This lineament extends about 100 miles with an average trend of approximately N. 70° W., from the abandoned Bowler Post Office (section 25, T. 7 S., R. 25 E.) to an area of the northern Beartooth Mountains uplift. Foose and others (1961) suggest that the Nye-Bowler lineament, or fault zone, enters the Beartooth Mountains frontal fault zone at an area west of Nye, Montana. Alternatively, Alpha and Fanshawe (1954) infer the Nye-Bowler zone to continue along the northern Beartooth Mountains front (fig. 4). The Nye-Bowler fault zone has been interpreted as the tensional expression in upper crustal rocks of lateral (presumably left-lateral) movement along a basement wrench fault (Wilson, 1936; Foose and others, 1961). The location of the Pryor Mountains near the intersection of the Lake Basin-Huntley fault zone, the Nye-Bowler lineament, and the Bighorn Mountains arch is "significant", according to Blackstone (1975), however, he does not elaborate.

Uplift of the Pryor Mountains apparently began in the Late Cretaceous as part of the eastward advance of the Laramide orogeny (Alpha and Fanshawe, 1954). Sedimentary rocks in the Bighorn basin, including conglomeratic alluvial fan deposits, have been correlated to the uplift and simultaneous erosion of the Beartooth, Pryor, and Bighorn Mountains. These facies indicate that the elevation of the Pryors continued from the Late Cretaceous into the Early Eocene (Alpha and Fanshawe, 1954).

Five uplifted and tilted, fault-bounded blocks comprise the Pryor Mountains: Big Pryor (also shown as Red Pryor on some maps) Mountain, East Pryor Mountain, West Pryor Mountain, and Northeast Pryor Mountain crustal blocks, plus a smaller subsidiary block, the Shively Hill dome (Blackstone, 1936, 1940, 1975). Each block is raised highest at its northeast corner. The exposed boundaries of the blocks are faults, symmetric folds displaced by faults, or asymmetric folds that are likely underlain by faults. These structures and subsequent erosion exposed primarily Paleozoic strata along the steep northern and eastern rims of the blocks.

Big Pryor Mountain and East Pryor Mountain represent the southwestern and southeastern blocks of the uplift, respectively (figs. 1 and 2), each bordered by high-angle faults on their north and east flanks. On Big Pryor Mountain, the faults are draped by asymmetric folds. The Sage Creek fault zone forms the northern boundary of the Big Pryor Mountain block. This fault zone, which follows the upper Sage Creek drainage (fig. 2), appears to be a southeastern continuation of the Nye-Bowler lineament (Blackstone, 1975). The steeply-inclined faults that form the northern margin of the East Pryor Mountain block may also represent offset parts of the Sage Creek fault zone and a further eastward continuation of the Nye-Bowler lineament.

The northern flanks of the Big Pryor and East Pryor Mountain blocks exhibit similar structural features and steep scarps that form north-facing cliff faces. The northern rims of these blocks are characterized by asymmetric anticlines and steeply inclined faults with steep northern limbs that expose mostly upper Paleozoic rocks (fig. 2). These anticlines presumably drape inclined fault planes that connect to the basement rocks. The eastern margin of the Big Pryor Mountain block appears similar in character to its northern margin (fig. 2), with an asymmetric anticlinal "faulted fold" (drape fold) marking the eastern edge of the crustal block; the fold is flanked to the east by a south-plunging syncline. The eastern flank of the East Pryor Mountain block is also a steeply inclined fault (the Dryhead fault) that connects to the basement rocks (see Blackstone, 1975); however, this fault is exposed along its length and any overlying drape fold was removed by deep erosion.

The surficial rocks on the southwest flanks of both the Big Pryor and East Pryor Mountain blocks dip gently to the southwest forming an incised dip slope. These slopes consist mainly of Mississippian Madison Limestone (fig. 2) and dip 5-8° southwesterly into the Bighorn basin (fig. 4).

The East Pryor Mountain block is the largest block of the Pryor Mountains uplift and exhibits the greatest structural relief. Its northern margin is bounded by two high-angle faults that form parts of the Sage Creek fault zone (Blackstone, 1975). The eastern boundary of the block is formed mainly by a high-angle fault of undulatory strike and dip named the Dryhead fault by Blackstone (1940, 1975); it extends southward into the Sykes Spring fault zone (see Blackstone, 1975). The Dryhead fault uplifted and exposed Precambrian crystalline rocks along the eastern edge of East Pryor Mountain in the most eastern part of the National Forest (fig. 2), providing the only exposures of Precambrian rocks within the Forest.

The Big Pryor and East Pryor Mountain crustal blocks are separated by the northerly-trending Crooked Creek fault zone (fig. 2). The Paleozoic strata draping over the fault are folded asymmetrically, overturning along some segments of the mountain front, with the eastern limbs of the anticlinal folds displaying the steeper dips. Along the eastern crest of Big Pryor Mountain, rocks of the Madison Limestone dip 2-10° to the west (Blackstone, 1974b). The Madison Limestone and upper Paleozoic strata just to the east of the crest, along the eastern cliff face of the mountain, dip from 45° to the east to overturned more than 60° west (Blackstone, 1974b). The terrain between the easterly and westerly dipping strata consists of steep cliff faces and talus slopes largely devoid of in-place rock. However, bedding attitudes on either side of the escarpments suggest that Paleozoic strata folded abruptly over the cliff areas. The strike of this anticlinal fold axis likely coincides with a steeply inclined fault plane or fault zone at depth that connects to the Precambrian basement. A similar drape fold relation is also apparent along the northern margins of both Big Pryor Mountain and East Pryor Mountain. The rock along each of the hinge zones was highly fractured, which contributed to the mass-wasting, scarp, and talus formation found within these areas.

The character of the Pryor Mountains block faults at depth, especially those bounding East Pryor Mountain, are discussed by Blackstone (1975) and Alpha and Fanshawe (1954). They hypothesize that the uplift and tilt of the Pryor Mountains crustal blocks occurred along listric basement faults. Alpha and Fanshawe (1954) argue that "because of the several thousand feet of sediments involved in each block, it becomes mechanically impossible to tilt blocks such as the Pryor Mountains without a curved thrust plate which begins as a low angle thrust movement within the basement, breaking upward at an ever increasing angle" (concave upward). The sedimentary strata overlying the basement thrust fault zones warped asymmetrically, forming steep northern and eastern limbs that strike with the trend of the thrust front. Ductile flexure of the strata above the bounding faults gave way to brittle failure as displacement proceeded. No evidence exists for any local igneous intrusion activity.

Blackstone (1975) concluded the following in regards to the structural geology of the Pryor Mountains:

1. The faults at East Pryor Mountain are representative of those throughout 1,000 square miles of the Pryor Mountains (region).
2. The movement on all faults in the uplift was virtually contemporaneous.
3. There is no obvious control of fault position by lithologic boundaries within the heterogenous basement.
4. "Drape folds" develop over differential elevations of basement rocks.
5. The Laramide deformation is a response to an earlier basement fracture system.

Stratigraphy

Lithified rocks exposed in the Custer National Forest in the Pryor Mountains range in age from Precambrian to Jurassic (figs. 2 and 3) and are blanketed by Quaternary sediments. Stratigraphy of the region is generally known but detailed stratigraphic work specific to the Pryor Mountains has not been published. Descriptions that follow are taken primarily from Blackstone (1940, 1975) and Richards (1955). Abbreviations in brackets correspond to the map units on figure 2.

The Precambrian rocks [p-Ꞓr] are undifferentiated and undated granitic gneiss and hornblende schist cut by quartz veins and aplite dikes. These basement rocks are only exposed at the base of a cliff along the northeast flank of East Pryor Mountain at the extreme eastern edge of the map area.

Unconformably overlying the Precambrian basement rocks are, in ascending order, the Cambrian Flathead Quartzite, Gros Ventre Formation, and Gallatin Limestone. Flathead Quartzite is a red to brown, coarse-grained, arkosic sandstone approximately 75 ft thick. Gros Ventre Formation is a 450 ft thick green shale with a few thin sandy shale beds. Gallatin Limestone is a mostly green, glauconitic, pebble limestone conglomerate 240 ft thick. Cambrian sedimentary rocks [Ꞓs] are undifferentiated on the geologic map (fig. 2). They are exposed on the steep slopes north of East Pryor Mountain and in a ravine at the northeast corner of Big Pryor Mountain. Estimated thickness of the Cambrian section is 765 ft (Blackstone, 1975).

Ordovician Bighorn Dolomite [Ob] is massive buff dolomite with black chert nodules in the lower part and buff to white, thin bedded, argillaceous dolomite in the upper part. Bighorn Dolomite outcrops on the lower slopes north of East Pryor and Big Pryor Mountains. Its thickness is about 450 ft in the Pryor Mountains (Blackstone, 1975).

An unconformity marks the Ordovician-Devonian boundary. Devonian Beartooth Butte Formation, a red siltstone containing blocks of white Bighorn Dolomite, fills channels cut into the underlying Bighorn Dolomite. Although discontinuous, the Beartooth Butte Formation is as much as 40 ft thick (Blackstone, 1975) where present. It is conformably overlain by the Jefferson Formation, a 250 to 275 ft thick tan to brown dolostone with "free-floating sand grains" in some beds (Blackstone, 1975). The lower part of the formation weathers greenish-yellow. Devonian sedimentary rocks [Ds] are exposed on the north slopes of East Pryor and Big Pryor Mountains. Devonian units were not recognized in the Pryor Mountains during mapping by Blackstone in the 1930s but were added to his later compilations (Blackstone, 1974a-f, 1975). To the east, in Bighorn Canyon, the Three Forks and Jefferson Formations are described (Richards, 1955); however, Three Forks Formation has not been noted in the Pryor

Mountains (Sandberg, 1965).

By far the most extensively exposed rock unit in the study area is the Mississippian Madison Limestone Group [Mm]. Four stratigraphic units forming this Group (Richards, 1955) are described, but not mapped, by Blackstone (1975) within the East Pryor Mountain Quadrangle (fig. 3); these units are combined on figure 2 (subdivisions of the Group, including the Lodgepole and Mission Canyon Formations, have not been extended in the Pryor Mountains). Dark gray basal limestone is overlain by thin-bedded, granular limestone that commonly contains ripple marks and distinctive red to purple fossil hash that is, in turn, overlain by brown, finely crystalline limestone. The upper part of the Madison Limestone hosts red fossil cave breccia with limestone blocks that filled a relic karst topography. Covering the filled, collapsed, paleokarst is gray to silver-weathering, fossiliferous limestone that forms the canyon rims. Reported local thicknesses of the Madison Limestone Group range from 630 to 740 ft (Blackstone, 1975).

The paleokarst horizon of the Madison Limestone Group in the Pryor Mountains occurs in the upper 190-240 ft of the Mississippian section. Numerous breccia-filled caverns formed in the karst terrain, apparently due to the collapse of roof and wallrocks along with an influx of sediments. The considerable in-filling of red Amsden sediments into many of the collapsed caverns, and stratification of these sediments near the floors of many of the collapse structures, indicates that the caverns and solution channels were well-developed and open during the deposition of the Amsden Formation (Elliott, 1963, 1964; Schultz, 1969). Buried paleokarst terrain in the upper Madison Limestone Group is regional in extent; it developed after the lithification of the Late Mississippian host limestone, but prior to the deposition of the Amsden Formation (Early Pennsylvanian) (Denson and Morrisey, 1954; Roberts, 1966; Sando, 1974; Campbell, 1977).

A second period of cavern formation in the Madison Limestone Group, more than 300 million years after the first episode, accompanied the erosional exhumation of the Pryor Mountains region that began in the Pliocene and continues at the present (Elliott, 1963, 1964). Open (unfilled) caverns such as Big Ice and Crater Ice Caves (Elliott, 1963; Campbell, 1978) reflect the recent karst development. Ceilings and floors of the recent caves are relatively planar, formed by dipping strata of the Madison Limestone Group (Elliott, 1963). The principal groundwater movements from Big Pryor and East Pryor Mountains are southwesterly, flowing with the southwest dip of the Paleozoic strata before emptying into the Bighorn basin (fig. 4). Because of the down-dip groundwater flow, the young caverns tend to consist of chambers and passageways that dip with the strata towards the southwest (Campbell, 1977, 1978).

A regional erosional unconformity separates the Mississippian Madison Limestone Group from the 140 ft-thick Pennsylvanian Amsden Formation (Denson and Morrisey, 1954; Blackstone, 1975). The lower part of the Amsden Formation is a red claystone and siltstone with masses of hematite and occasional oolites. The upper part is composed of purple argillaceous, dolomitic limestone and limy claystone. The Amsden Formation is overlain by 158-170 ft of Pennsylvanian Tensleep Sandstone that is white to buff and cross laminated and has chert nodules in the top part. Amsden Formation and Tensleep Sandstone are combined on figure 2 [IPs].

Younger Phanerozoic and Mesozoic sedimentary rocks [JPs] include Permian rocks equivalent to the Phosphoria Formation consisting of hard dense white limestone and red siltstone from 10 to 60 ft thick (Blackstone, 1975). This unit has been referred to locally as the Embar Limestone (Blackstone, 1975) in the Pryor Mountains, although the USGS has abandoned this stratigraphic term (McKelvey and others, 1959, p. 5-11). Triassic Chugwater Formation, 500 to 614 ft thick (Blackstone, 1940, 1975), is a distinctive red siltstone, fine-grained sandstone, and shale on a thin sandy limestone base. Jurassic rocks of the Ellis Group cap Roberts Bench (fig. 2) and also are exposed at the extreme east edge of the Forest. The Ellis Group in the Pryor Mountains includes the Piper, Rierdon, and Swift Formations. The Piper Formation, 60 to 200 ft (Blackstone, 1975) or approximately 170 ft (Imlay, 1954) thick, has a prominent basal gypsum bed overlain by red to pink shales and thin limestone beds. The next 150 to 170 ft forms the Rierdon Formation (Imlay, 1954; Blackstone, 1975) consisting mostly of green shale with thin limestone interbeds and capped by limestone. The upper 100 ft (Blackstone, 1975) or 156 ft (Imlay, 1954) of the Ellis Group is the Swift Formation, a gray green shale and claystone with glauconitic sandstone at the top. Youngest of the Mesozoic units to crop out in the study area is a small amount of basal Jurassic Morrison Formation at the extreme east edge of the map area (see Imlay, 1954 for discussion of the local Jurassic strata). Morrison Formation is gray to greenish gray, thin cross-bedded sandstone and siltstone and massive yellow-brown mudstone with a total thickness of about 240 ft (Blackstone, 1940).

Much of the study area is covered with Quaternary surficial deposits [Qs]. These include alluvium, colluvium, talus, slope-wash, mudflows, landslides, and pediment gravel. In figure 2, surficial deposits are only shown where they are continuously exposed for at least one mile or if the bedrock can not readily be inferred.

URANIUM-VANADIUM DEPOSITS OF THE PRYOR MOUNTAINS

Mining History

Four prospectors—George Guay and Leo Eres of Billings, Mont., and Corwin Rule and Ben Helgeland of Pryor, Mont.—discovered deposits of uranium minerals near the crest of Big Pryor Mountain on Labor Day, 1955 (Hauptman, 1956, p. 14). Their discovery remained secret during the early winter of that year while they staked claims on much of the mountain crest and initiated minor exploration work (Jarrard, 1957, p. 35). These original prospectors incorporated their properties into the Pryor Mining Co., which included the Old Glory claim (fig. 1) (Hauptman, 1956) within the National Forest. In the winter of early 1956, news of the discoveries was announced and a rush of claim staking ensued. Other corporations claimed the remainder of Big Pryor Mountain and parts of East Pryor Mountain (Jarrard, 1957). "By early 1956 some 450 location notices had been filed with the Carbon County recorder at Red Lodge" (Baber and others, 1958). More discoveries were made in the area and in 1958 approximately 500 uranium occurrences were known on Big Pryor Mountain (Hart, 1958).

During the first year of production, 1956, the Old Glory mine (fig. 5) of Pryor Mining Co. was the largest producer in the district (Hauptman, 1956). "Small tonnages of ore" were shipped from the Pryor Mountains deposits by three companies to the AEC (Atomic Energy Commission) ore-buying station in Riverton, Wyoming (Baber and others, 1958). High-grade (hand-picked) uranium ores were hauled by truck to Bridger, Montana, and transferred to railroad cars. Hand-picked ores from the Swamp Frog mine (figs. 1 and 6) were the typical ore extracted in 1956 from these deposits; they were described as follows: "The 5-gallon can of highgrade contains 31.8% uranium, 9.88% vanadium; they have 1500 pounds of this, worth

Figure 5. Main adit of the Old Glory mine. Silicified and brecciated limestones of the uppermost Madison Limestone form the walls of the mine entrance. Red, hematitic silty rocks of the Amsden Formation overlie the adit and infiltrate the cavern breccias of the deposit. Adit entrance is about 6 ft high (Photo by Van Gosen, July, 1993.)

Figure 6. Primary adit for the Swamp Frog mine, which included nearby open-pit excavations. Notice the inward sag of Madison Limestone beds towards the ceiling of the adit, reflecting the dip of strata into the collapsed cavern. Adit entrance is about 7 ft high. (Photo by Van Gosen, August, 1992.)

$5,000 per ton" (Hauptman, 1956, p. 18). Uranium ores at the Old Glory and Swamp Frog mines, as well as later discoveries in the area, were mainly excavated from shallow underground adits and stopes that extended up to a couple hundred feet into the hillsides. Prospect pits and occasional open-pit excavations accounted for the remainder of the ore production. The larger open-pit mines, such as those still visible near the Swamp Frog mine, extended no more than 200 ft in length, 100 ft in width, and 20 ft in depth.

During 1957, "small tonnages of uranium ore were shipped from [seven] mines in the Pryor Mountains to AEC ore-buying stations at Riverton, Wyo., and Grand Junction, Colo." (Baber and others, 1959). In 1958, companies actively mining the Pryor Mountains deposits were: Lisbon Uranium Corp., Midland Mining Co., Planet Exploration Co., Pryor Mining Co., and Balboa Mining and Development Co. (also referred to as Prytana Mining Co.) (Fulkerson and others, 1959; Stout and Ackerman, 1959). In 1958, seven properties produced a total of 690 tons of ore with an average grade of 0.34 percent uranium oxide and a total value of nearly $20,000 (in 1959 dollars) (Fulkerson and others, 1959). In 1959, mining operations were continued at six properties by only three companies—Lisbon Uranium Corp. (leading producer), Midland Mining Co., and Planet Exploration Corp. (Crowley, 1960; Fulkerson and others, 1960). With a total output of 2,890 tons of ore containing 9,912 pounds of uranium oxide this was the record year for uranium ore production from the Pryor Mountains deposits (Fulkerson and others, 1960).

During the early 1960's modest uranium ore production continued in the Pryor Mountains. Six properties were mined in 1960. The Hidden Splendor Mining Co., the largest producer, mined claims in the Dandy, Marie, and Perc groups (fig. 1) and the Bob claim (location unknown) (Fulkerson and others, 1961). Joseph (Joe) A. Highsmith also mined properties in the Dandy and Perc claim groups, while Pryor Mining Co. continued production from the Old Glory mine, and James J. Stoick worked the Swamp Frog mine. Total production from these properties in 1960 was 1,726 tons of ore, which was shipped to the AEC plant at Riverton, Wyo. (Fulkerson and others, 1961). The average grade of the ore (uranium oxide content) increased in 1960 compared to 1959, while total output and value declined (Fulkerson and others, 1961). During 1961 all uranium ore production from the district (at the time known as the Butte district) came from the mines of Joe Highsmith, including the Dandy, Perc (fig. 1) and Leo properties (location unknown) (Fulkerson and others, 1962). Uranium production totals declined $18,984 from 1960 to 1961; only 729 tons of ore containing slightly lower average ore grades were produced in 1961 (Fulkerson and others, 1962). In 1962 only the Swamp Frog property, worked by John Kummerfeld, produced uranium ore resulting in the lowest yearly production from the district (Fulkerson and others, 1963; Geach and Chelini, 1963). Ore output dropped significantly in 1963, with all production coming from the Old Glory mine operated by the Pryor Mining Co. (Knostman and Kauffman, 1964). The last year of reported uranium ore production from the Pryor Mountains was 1964 when production came from underground mines at the Dandy and Marie properties (fig. 1) worked by St. Clair, Inc. Hale and Knostman (1965) indicate that the uranium output of 1964 was above that of 1963, but was still below the nominal output of 1962 (no productivity values were reported for 1964).

From 1957 through 1964, all of the uranium ore production in Montana was derived from the paleokarst deposits of Big Pryor Mountain, East Pryor Mountain, and the Little Mountain district (fig. 1). Small amounts of production continued in the Little Mountain district during 1965-66 (203 total tons of ore) and 1970 (82 tons) (Harris, 1983, p. 176). The Swamp Frog mine, owned and operated by James J. Stoick, was reportedly in development in 1978 (Lawson, 1979); however, no production was reported for this year or any subsequent year.

Table 1 summarizes the history of production from the Pryor Mountains uranium-vanadium deposits based on information provided in the U.S. Bureau of Mines "Minerals Yearbook" series. Table 2 lists the totals of uranium-vanadium ore production (1956-1964) from individual properties of the Big Pryor Mountain area. Because all domestic uranium and vanadium ore production in the 1950's and 1960's was purchased by the U.S. Government at AEC ore-buying stations, the data listed in table 2 represent the entire history of economic production from the uranium-vanadium deposits of Big Pryor Mountain (1956-1964). Table 3 summarizes the uranium-vanadium ore production from properties of the Little Mountain district, which was located outside the Custer National Forest.

Uranium-vanadium deposits of the Little Mountain district (fig. 1) in northern Big Horn County, Wyoming are concentrated along an anticline (Little Mountain) that trends northwest-southeast between East Pryor Mountain and the Big Horn Mountains. The Little Mountain deposits formed in caves and solution cavities in upper parts of Madison Limestone and are identical in mineralogy and geologic setting to the deposits in the Big Pryor Mountain district. Most of the deposits are small (less than 500 tons) with ore grades of less than 0.5 percent U_3O_8 (table 3) and were worked in the late 1950's and early 1960's. Wilson (1966) described production from the Fusner mine of the district that was in addition to the district production data compiled by the AEC (table 3). He reported that the east ore body of Lisbon Uranium Corporation's Fusner mine produced about 5,000 tons of ore averaging 0.80 percent U_3O_8 from a fan-like cave deposit and from separate ore beds up to 8 ft thick composed of interstratified cavern-fill sediments. In 1958, Modern Mines Development Company put in a 740 ft inclined shaft to access an additional ore body (13 ft thick by 100 ft wide by 260 ft long) delineated by drilling (Wilson, 1966).

Geology of the Host Collapse Structures

Uranium-vanadium deposits of the Pryor Mountains are hosted by shallow collapse structures in a paleokarst horizon of the upper 190-240 ft (Blackstone, 1975) of the Madison Limestone Group. Host structures for the uranium-vanadium deposits are chaotic breccia bodies that fill solution caverns of the paleokarst. These breccias apparently formed by the collapse of cavern roof and wall rocks accompanied by inflow of sediments. Cavern fill material in many of the uranium-vanadium-mineralized collapse structures is colored red or maroon due to the infiltration of red (hematitic) claystones and siltstones from the overlying Amsden Formation.

The fill material in the collapsed caverns of the paleokarst is poorly sorted and generally matrix supported. Variously oriented blocks and rock fragments, usually unstratified, are mixed with a fine-grained and silty matrix (Bell, 1963). The matrices of the cave fill are formed by Amsden sediments, mineral deposits (described separately below), and the insoluble residue of dissolved rocks. The blocks and clasts are mainly carbonate rocks and chert of the Madison Limestone that appear to have spalled from the cavern ceilings and walls; they are rotated in random orientations. Breccia fragments are primarily angular to subangular in shape and range from less than a foot to several feet in diameter. Pockets of smaller fragments occur holding clasts one to several centimeters in length. The permeable, friable cavern fill hosting the disseminated uranium-vanadium minerals appears to represent sediments of the overlying Amsden Formation and the insoluble residue of disaggregated silty limestones of the host upper

Table 1. Chronological summary of ore production from the Pryor Mountains uranium-vanadium deposits of south-central Montana. Information provided in the U.S. Bureau of Mines "Minerals Yearbook" series (Baber and others, 1958-59; Fulkerson and others, 1959-63; Knostman and Kauffman, 1964; Hale and Knostman, 1965). n.r., not reported.

Year	Tonnage produced	Average grade	Total value of ore produced
1956	"small tonnages"	n.r.	n.r.
1957	"small tonnages"	n.r.	n.r.
1958	690.	0.34 percent U_3O_8	$20,000.
1959	2890.	0.17 percent U_3O_8	n.r.
1960	1726.	increase over 1959	decrease from 1959
1961	729.	slightly below 1960	$18,984 lower than 1960
1962	lowest since 1955	n.r.	n.r.
1963	significant decrease	n.r.	n.r.
1964	between 1962 and 1963 output	n.r.	n.r.

Madison Limestone Group. An undetermined proportion of the cavern fill material may represent paleosols or residual soil breccias (Maslyn, 1977) that formed on the emergent carbonate surface; these soils were then flushed or collapsed into the caverns.

Host caverns formed by the dissolution of limestones in the upper Mission Canyon Formation (Madison Limestone Group) by a fluctuating meteoric water table. The breccia bodies probably developed later by collapse of cavern ceilings and walls due to mechanical failure (Campbell, 1977, 1978) combined with infiltration of Amsden-age sediments. Recent studies of cave development suggest that: (1) most caves form in the phreatic zone (the saturated interval below the water table); (2) prominent joints control the trends of cavern development; (3) local stream base level controls downward growth of the karst; and (4) mechanical erosion (collapse, spalling) occurs only after cavern openings are well developed (Campbell, 1978). The contorted mixture of Madison Limestone and Amsden Formation rocks in the cavern fill indicates that spalling, collapse, and Amsden deposition acted simultaneously. Thus, most of the cavern collapse and cave-filling episodes occurred during the early Pennsylvanian, the time of Amsden deposition. No evidence of igneous rocks or magmatic processes is found to be associated with the collapsed caverns.

Subtle depressions are found on the surface of the Madison Limestone above the exposed uranium-vanadium-bearing caverns (fig. 6). These depressions, or sinkholes, above the filled caves may be as large as 250 ft in diameter with bedding dipping slightly inward (1-3°) (Patterson and others, 1988). The depressions and mine workings indicate that the typical collapsed cavern is about 100 ft or less in diameter, 20-25 ft in height, and often circular in plan view. Irregular masses of solution breccia exposed along the eastern ridge crest of Big Pryor Mountain are up to 1,000 ft long and 200 ft deep with undetermined widths (Hart, 1958). The floors and ceilings of the filled caverns are formed by relatively undisturbed, slightly slumped limestone beds. Country rocks within 10 ft of the relic cavern walls contain steeply inclined joints with heights of approximately 2-4 ft and spacings of less than 1 ft. These joints are

Table 2. Listing of total ore production from 21 properties (deposits) of the Big Pryor Mountain district for the period 1956-1964, the era of active mining. The localities of these properties, if known, are shown in figure 1. Data shown are from Atomic Energy Commission records transferred to the files of the U.S. Geological Survey. n.r., not reported.

Property name	Tons of ore	Pounds of U_3O_8	Percent U_3O_8 in ore (grade)	Pounds of V_2O_5	Percent V_2O_5 in ore (grade)
Bob 6	229.78	721.55	.16	n.r.	n.r.
Buckhorn 2	14.84	20.65	.07	56.00	.19
Dandy	2,566.28	12,307.15	.24	3,088.00	.06
Dandy & Perc 14	407.50	2,205.93	.27	n.r.	n.r.
Drinkard[1]	138.45	745.57	.27	1,698.17	.61
Fran 2	68.73	219.92	.16	n.r.	n.r.
Fran 3	314.69	921.81	.15	11.00	.002
Key	10.42	10.42	.05	38.00	.18
Leo 6	342.65	1,155.07	.17	n.r.	n.r.
Marie 2	691.70	1,766.33	.13	n.r.	n.r.
Old Glory	696.78	10,650.36	.76	7,968.88	.57
Peach[2]	.49	21.40	2.18	n.r.	n.r.
Perc Group	317.13	2,615.93	.41	6,986.00	1.10
Perc 3	187.17	2,527.05	.68	4,754.12	1.27
Perc 4	57.42	287.12	.25	n.r.	n.r.
Perc 14	1,366.63	4,835.18	.18	n.r.	n.r.
Sandra	51.03	218.45	.21	69.00	.07
Snail 2	262.38	1,069.45	.20	2,897.00	.55
Surprise 6	45.76	27.45	.03	119.00	.13
Swamp Frog	73.71	314.02	.21	19.84	.01
Swamp Frog 34	453.00	2,401.55	.27	2,482.09	.27
Totals	8,296.54	45,042.36		30,187.10	
Weighted average			.27		.29

1 Also referred to as the "Green" lease

2 Not included in assessment model due to high grade and small size

Table 3. Listing of total ore production from properties of the Little Mountain district. Data shown are from Atomic Energy Commission records transferred to the files of the U.S. Geological Survey. n.r., not reported.

Property name	Tons of ore	Pounds of U_3O_8	Percent U_3O_8 in ore (grade)	Pounds of V_2O_5	Percent V_2O_5 in ore (grade)
Broken Heart 8	32.26	709.94	1.10	416.00	.64
High Noon	66.32	119.38	.09	n.r.	n.r.
High Noon 3	54.93	1,678.87	1.53	n.r.	n.r.
Horseshoe 9	8.59	53.25	.31	52.00	.30
Horseshoe John	34.12	61.42	.09	109.00	.16
Jet 5	173.54	520.61	.15	n.r.	n.r.
Jet 8	1,516.79	11,393.64	.38	n.r.	n.r.
John 35	65.14	208.45	.16	n.r.	n.r.
Leo	103.52	607.98	.29	n.r.	n.r.
Leo 16	26.77	208.77	.39	n.r.	n.r.
Midnight	12.47	264.34	1.06	n.r.	n.r.
Mike	968.45	4,991.06	.26	n.r.	n.r.
Mike 8	5,768.63	31,811.12	.28	n.r.	n.r.
Mike 10	12,590.94	115,569.08	.46	202,650.00	.80
Tri Pacer	881.88	7,204.44	.41	1,660.00	.09
Tri Pacer 4	11.85	108.97	.46	237.00	1.00
Tri Pacer 5	165.36	1,566.85	.47	612.00	.185
Totals	22,481.56	177,078.17		205,736.00	
Weighted average			.39		.75

[Wilson (1966) reported production of about 5,000 tons of ore averaging 0.80 percent U_3O_8 from the Fusner mine of the Little Mountain district. The Atomic Energy Commission records did not list this property.]

interpreted as surfaces of separation and vertical slip in wall rocks of the enlarging cavern, essentially extension fractures, that formed during the spalling and collapse of cavern ceilings and walls.

The most productive uranium-vanadium mines of the Pryor Mountains form a cluster of deposits about four miles long (north-south) that roughly coincides with the eastern margin of the Big Pryor Mountain block (fig. 1; table 2; Butler and others, 1962; Finnell and Parrish, 1958; Merewether, 1960; Harris, 1983). Some investigators have suggested a genetic link between the ore deposits and the drape fold-fault structures along the basement block margins. For example, Warchola and Stockton (1982) proposed that "uranium-bearing solutions followed channelways and solution cavities in the limestone and fractures and transverse faults related to the Crooked Creek and Sage Creek fault systems". The period of major displacement along the margins of the Pryor Mountains blocks occurred from the Late Cretaceous to the Early Eocene (Laramide orogeny) (Alpha and Fanshawe, 1954); however, the caverns that host the uranium-vanadium-mineral deposits formed mainly in early Pennsylvanian time (Elliott, 1964; Schultz, 1969). Thus, the host collapse features existed in the Madison Limestone Group long before the main stage of Laramide uplift along the boundaries of the crustal blocks. However, pre-Laramide movement along basement fault systems may have imparted joints and faults into the Madison Limestone Group that influenced the growth of the host paleokarst.

Uranium- and vanadium-bearing fluids that permeated the filled caverns may have accessed either (or both): (1) the fracture pattern that influenced the late Paleozoic karst development; or (2) subsequent fracturing associated with Laramide processes. Hart (1958) suggests that the clusters of known ore deposits in the area—along the ridge crest of Big Pryor Mountain and in the Little Mountain district (fig. 1)—occur along previous routes for major drainages of the basin (such as the Neogene-age channels of the Shoshone and Big Horn Rivers). No systematic study has been conducted to decipher relations between the host caverns, fracture systems, paleohydrology, and mineral deposits. Thus, the significance and trends of controlling fracture systems, and their possible relation to basement structures and paleohydrology, remains largely conjectural.

Mineral Deposits and Associated Alteration

The principal ore minerals of the Pryor Mountains deposits are tyuyamunite [$Ca(UO_2)_2(VO_4)_2 \cdot 5\text{-}8H_2O$] and metatyuyamunite [$Ca(UO_2)_2(VO_4)_2 \cdot 3\text{-}5H_2O$]. These minerals are bright yellow, silt-size and powdery in texture, and easily recognized without magnification due to their bright color. They fill vugs of all sizes in the cavern fill, form thin coatings (up to 1 mm-thick) on fracture surfaces in cavern breccia and wall rocks, and are disseminated throughout the porous, friable cavern fill material. The uranium-vanadium minerals are scattered unevenly throughout the collapse breccia, reflecting the jumbled, heterolithic character of the cavern fill. Uranium-vanadium-mineralized rock ranges from scattered specks of tyuyamunite and metatyuyamunite to cavity fillings that assay more than 50 percent U_3O_8 (Warchola and Stockton, 1982). Disseminated tyuyamunite and metatyuyamunite are concentrated in weakly cemented, often bleached, porous cavern fill that is fine- to very fine-grained in size. Commonly, concentrations of uranium-vanadium minerals follow the bedding of porous sandy and silty layers in the cavern fill, forming laterally continuous deposits of several feet or more in length (for examples, see appendix A, samples 001-V93 and 014A-V92).

"Seams of the mineral[s] varying from two to eight inches thick have been followed for a distance of 50 feet" (Hauptman, 1956). While the ore deposits in Big Pryor Mountain are found mainly in collapsed cavern breccias, "the mineralization on East Pryor Mountain and on Little Mountain is in intensely recrystallized zones in the Madison limestone" (Hauptman, 1956).

The influence of porosity on the distribution of uranium-vanadium-mineralized rock is apparent throughout the deposits. Uranium-vanadium minerals are mostly found within vugs or open fractures and the most permeable cavern fill material (sandy and silty layers or matrix material). Dense interiors of fragments or wall rocks composed of massive limestone, chert, or silicified rock are largely devoid of the uranium-vanadium minerals.

Minor amounts of a few other uranium minerals have been reported in the Pryor Mountains deposits. Traces of autunite $[Ca(UO_2)_2(PO_4)_2 \cdot 10\text{-}12H_2O]$ have been noted at the Swamp Frog mine (Warchola and Stockton, 1982, p. 12). Occurrences of yellow uranophane $[Ca(UO_2)_2Si_2O_7 \cdot 6H_2O]$ and apple green liebigite $[Ca_2U(CO_3)_4 \cdot 10H_2O]$ are reported at the East Pryor mine (Patterson and others, 1988). Davidite $[(Fe^{+2},La,U,Ca)_6(Ti,Fe^{+3})_{15}(O,OH)_{36}]$ was tentatively identified at the Dandy mine by Warchola and Stockton (1982) using optical methods. The davidite "consists of equant grains and aggregates ranging in size from 0.3 mm to more than 50 mm and occurs as disseminations in, and interstitial to, a fluorite matrix" and as "highly discontinuous veinlike linear disseminations" (Warchola and Stockton, 1982, p. 14). The davidite is coated by tyuyamunite or uranophane, which formed by the alteration of the primary davidite. This National Forest study found traces of silt-size uranophane mingled with metatyuyamunite at the Swamp Frog mine (identified by X-ray diffraction techniques).

Reported gangue minerals in the Pryor Mountains deposits include hematite, limonite, iron-hydroxides, calcite, barite (white to golden, vug-filling), clay minerals, gypsum, pyrite or marcasite, and opal, as well as celestite and fluorite at a couple of localities (Hart, 1958; Bell, 1963; Patterson and others, 1988). A black crust-forming manganese mineral, probably pyrolusite, is also common (Patterson and others, 1988). Siliceous alteration in the collapsed caverns is locally intense. Microcrystalline quartz commonly replaces limestone in the breccia and cavern walls, rendering the rocks a mottled appearance with shades of gray and brown. The silicified rock is also denser and much harder than the medium- to light-gray limestones of the unaltered country rock, upper Madison Limestone Group. Tyuyamunite and metatyuyamunite are found coating breccia fragments that are in turn encrusted by dense microcrystalline quartz, suggesting a common depositional fluid for the quartz and the uranium-vanadium minerals (Hart, 1958). Silicified rock is most pervasive along the relict cavern floors and walls (Hart, 1958). Dogtooth calcite grows out of the largest cavities in the limestone walls and radioactive green calcite is found with the ore (Patterson and others, 1988). The dogtooth calcite, and perhaps several other minerals, likely represent recent growth and remobilization of earlier mineral phases in the collapsed caverns due to continuous near-surface contact with meteoric waters.

White to dark-purple fluorite is intimately associated with the uranium-vanadium minerals at the Old Glory and Dandy mines (appendix A, sample 015A-V92). Fluorite at the Old Glory mine is described by Sahinen (1962) and Warchola and Stockton (1982) as colloform in texture, forming fine-grained ovules or spheroids that are interpreted to represent metasomatic replacement of oolites in the limestones. Sahinen (1962) notes that the fluorite is deep purple when found with tyuyamunite and generally colorless when distant from the uranium minerals. Warchola and Stockton (1982) indicate that limestones at the Old Glory mine are replaced by fluorite and quartz: "Fresh colloform fluorite and granoblastic quartz [quartzitic texture] embay corroded remnants of calcite". They interpret the fluorite and replacement textures as the result of hydrothermal processes. In contrast, Jarrard (1957) and Sahinen (1962) suggest that the fluorite was precipitated from meteoric waters that carried fluorine, uranium and vanadium in solution. Theories regarding the origins of the Pryor Mountains uranium-vanadium deposits are discussed further below.

Alteration halos associated with the uranium-vanadium deposits are often limited or minimal in extent. At many of the mined deposits, the host country rock appears fresh and unaltered within several feet below, or lateral to, the cave breccia. The uranium-vanadium mineral deposits are consistently restricted to the cavern fill or the surfaces of fractures within cavern walls (Bell, 1963). At the Swamp Frog mine (figs. 1 and 6), limestone host rocks (upper Madison Limestone Group) only 10 ft outward from the mineralized collapse breccia are recrystallized and encrusted with calcite, but otherwise unaltered. Bleaching of the limestones at the Swamp Frog deposits is generally restricted to 1 ft or less outward from the uranium-vanadium mineralized cavern fill. The Little Mountain deposits tend to exhibit limited alteration adjacent to the orebodies (Hart, 1958; Patterson and others, 1988).

In contrast, wall rock alteration associated with several deposits on Big Pryor Mountain, such as the Old Glory mine site, consists of bleached, silicified and liesegang banded rock (fig. 5; appendix A, samples 002A-V93, 002B-V93, 002C-V93, 002D-V93, 002E-V93, 002F-V93). Liesegang banding is locally abundant. It appears best developed in lower Amsden Formation rocks that immediately flank and cover the collapsed paleokarst features of the upper Madison Limestone Group (fig. 7a). The host rocks for the banding are generally sandy siltstones with less common silty sandstones that are typical of the lower Amsden Formation. Individual bands range from a few millimeters to about 1 cm thick and alternate in color from red or dark brown to white or light brown (fig. 7b). In addition to the detrital grains and matrix material of the host rock, dark bands contain amorphous, microcrystalline hematite, limonite, and various iron-hydroxides; light bands contain mostly clay minerals, microcrystalline quartz, and less common silt-size quartz. The iron-oxides and -hydroxides are amorphous and interstitial to the rock matrix; no evidence was found that suggests the replacement of relict sulfide minerals by the iron-oxides and -hydroxides. Likewise, the quartz is microcrystalline, amorphous, and interstitial to the rock matrix. The silicification strongly cemented the rock, rendering it dense, hard and resistant and significantly lowered its porosity. The silica introduced to the rock was likely deposited during the formation of the Liesegang banding.

Petrographic examinations by this USGS study found that the hematite and hydrous iron oxides forming the Liesegang bands represent mobilized diagenetic minerals inherent to the host "red beds" of the lower Amsden Formation. Textures of the iron-rich bands indicate they are diffusion bands formed by the capillary movement of fluids transporting the diagenetic hematite through the rock. The diffuse appearance of the iron-rich, dark bands is similar to the dispersion ("bleeding") of ink within a sheet of paper after water is added. Intervening light-colored bands are largely devoid of the hematite typical in the matrix of the red beds, which suggests that the diagenetic hematite was leached from these segments of the rock. The leached hematite accumulated only millimeters away as the diffuse, dark bands. The subrounded, but relatively unaltered, appearance of the detrital quartz grains in the host rocks suggests that the fluids responsible for these Liesegang bands had typical groundwater temperatures and chemistries. Thus, the Liesegang bands likely formed by centimeter-scale dispersion and re-deposition of diagenetic hematite due to groundwater saturation of the rock. The lower beds of the Amsden Formation, in contact with the collapsed paleokarst horizon of the upper Madison Limestone Group, became the host rocks for the Liesegang bands. This banding provides

Figure 7a. Outcrop of liesegang-banded, silicified rocks near the Old Glory mine. In this area, the country rocks of the lower Amsden Formation are fractured and intensely silicified sandstones (fine-grained, silty) that contain pervasive laminae of iron-oxide minerals. Exposures of these decorative stones occur near the waste-rock piles of the abandoned Old Glory mine. (Photo by Van Gosen, July, 1993.)

Figure 7b. Cut slabs of liesegang-banded, silicified rock collected from the outcrop shown in figure 7a. Slabs were cut from study sample 002A-V93, which is described in Appendix A. (Photo by Van Gosen, April, 1995.)

further evidence for considerable flow of meteoric fluids through the paleokarst horizon; this occurred at some undetermined time following the cavern formation in the Late Mississippian.

Size, Grade, and Distribution of the Deposits

Most of the known Pryor Mountains deposits are relatively small, containing between 100 to 1,500 tons of uranium ore (Jarrard, 1957). The largest deposits are more than 12,000 tons (appendix B), but most of the deposits are less than 500 tons (Hart, 1958). "Tenor of the ore usually exceeds 0.50% U_3O_8, with V_2O_5 content 20 to 40% higher" (Hart, 1958). Ores purchased by the AEC had average grades of 0.27 percent U_3O_8 and 0.29 percent V_2O_5 (table 2). Individual shipments of hand-picked ore could greatly exceed the average grades. For example, "a recent shipment of approximately 20 tons of ore from one of Big Pryor Mountain deposits assayed approximately six percent U_3O_8" (Jarrard, 1957). Geochemical analyses of rock samples consistently reveal higher uranium contents than suggested by the radiometric assays (Hauptman, 1956; Hart, 1958). Calcium carbonate content of the mined ores was as much as 85-90 percent but was highly variable due to local differences in silicification.

By 1958, approximately 500 uranium occurrences, most containing less than 500 tons of low grade material, were known on Big Pryor Mountain (Hart, 1958). Thus, several hundred uranium-vanadium occurrences, possibly more than one thousand occurrences, may exist near the surfaces of Big Pryor and East Pryor Mountains in the National Forest lands. However, most of these occurrences are relatively small in size with low uranium-vanadium content. The number of undiscovered deposits with the sizes and grades of those mined at the Dandy, Perc, Old Glory, Swamp Frog properties (table 2) is uncertain without considerable exploratory drilling of the area. The geologically favorable terrain for such undiscovered uranium-vanadium deposits within the National Forest is in the upper 240 ft of the Madison Limestone Group on Big Pryor and East Pryor Mountains (fig. 8). An approach to estimating the undiscovered uranium-vanadium deposits in the study area is discussed in a subsequent section entitled "Mineral Resource Assessment".

Numerous prospect pits, perhaps a few hundred in total, occur within the study area. Some of these prospects are shown as small "x's" on 7½-minute topographic maps (scale 1:24,000) published by the USGS, such as the Bear Canyon, Big Ice Cave, Bowler, East Pryor Mountain, Indian Spring, Mystery Cave, and Red Pryor Mountain quadrangles. Most of these prospects represent small bulldozed exploration pits, mainly in the upper beds of the Madison Limestone Group or lowermost Amsden Formation, that were found to lack economically minable deposits of uranium-vanadium minerals. Most of the prospects were unproductive test sites dug during the uranium rush in the late 1950's and early 1960's. Favorable prospects were developed into modest adit and open-pit operations, such as those at the Old Glory and Swamp Frog mines (figs. 5 and 6).

Origin of the Deposits

The age of the uranium-vanadium mineralization in the Pryor Mountains deposits is unknown. The uranium-vanadium-minerals (tyuyamunite and metatyuyamunite) in the collapsed caverns are found filling cavities, impregnating soft porous rocks, forming crusts on the less

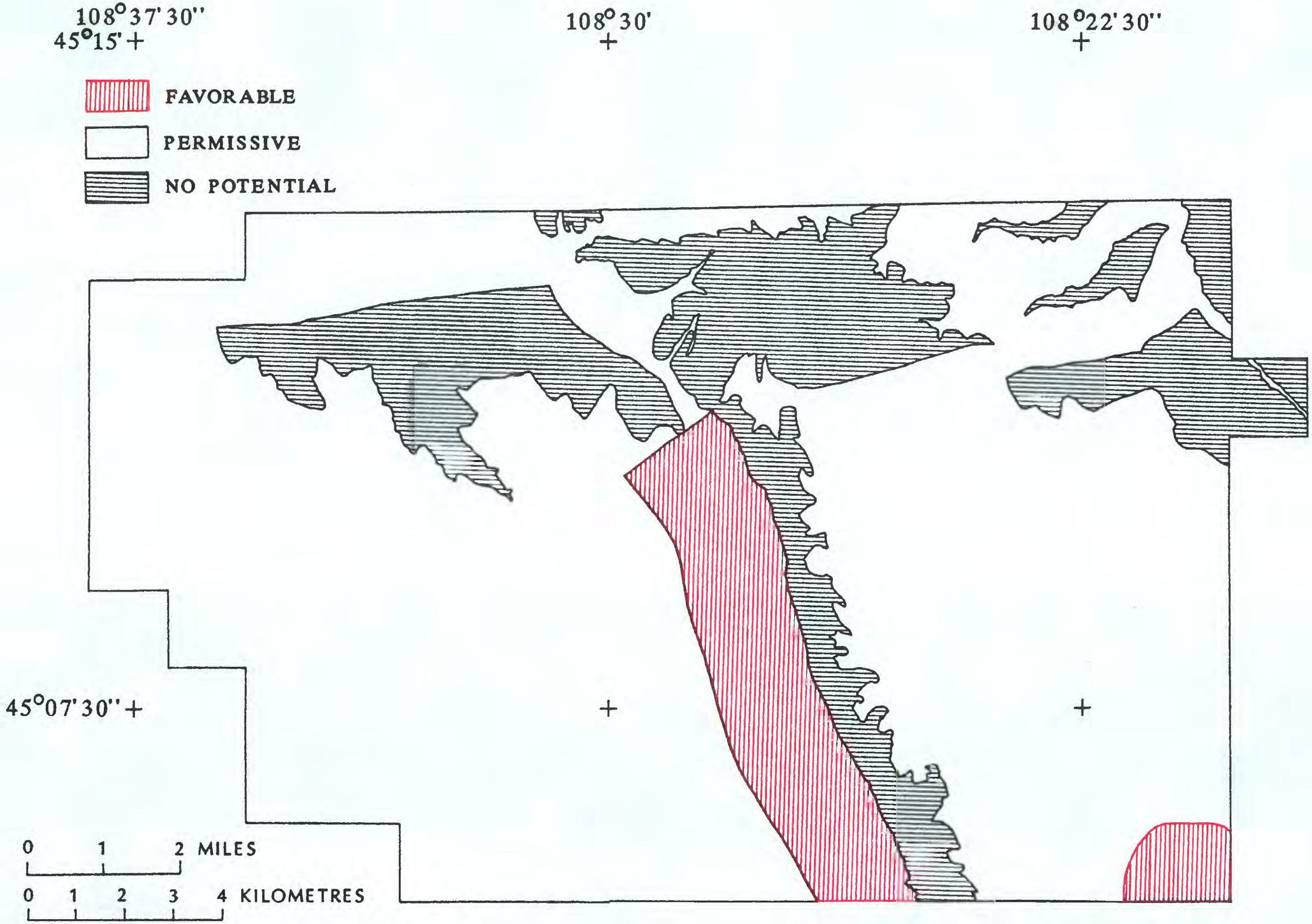


Figure 8. Map showing the potential for uranium-vanadium deposits in the Custer National Forest of the Pryor Mountains. Permissive tracts, shown in white, outline areas in which the host paleokarst horizon of the upper Madison Limestone Group occurs within 500 vertical ft of the ground surface. Areas <u>without</u> potential are shown with horizontal lines. Favorable areas, shown in red, indicate lands considered most likely to host uranium-vanadium deposits like those developed at the Old Glory and other mines.

porous breccia fragments, and as thin coatings on fractures. The cavern fill must have been at least partially lithified (or cemented by earlier uranium-vanadium minerals) prior to the emplacement of the fractures and subsequent uranium-vanadium mineralization. These relations indicate that the tyuyamunite and metatyuyamunite deposition occurred at some time after the cavern fill was in place and fractured. The only reported clue to the age of these ore minerals is provided by Jarrard (1957, p. 37):

> That some of the high-grade material is of recent deposition is shown by the discovery of unchanged bones of small rodent-like mammals occurring embedded as much as a foot or more in the ore material. Other than having at times a coating of soft tyuyamunite, the bones, as yet unidentified, appear to be no more than a very few years of age.

Tyuyamunite and metatyuyamunite are typically secondary mineral phases that replace pre-existing uranium minerals. For example, uranium-bearing solution-collapse breccia pipes are common in the Grand Canyon region of northern Arizona (Wenrich and Sutphin, 1989). These pipe-shaped structures also formed by the collapse of caverns, but propagated upward through thousands of feet of sedimentary rocks by the mechanical stoping of overlying strata. Many of these breccia pipes contain high-grade uranium deposits in which the primary ore mineral is uraninite (UO_2) (Wenrich and others, 1989). Uranium-lead dating of the uranium ores indicated two main episodes of uranium mineralization in the Grand Canyon breccia pipes at 200 ± 20 Ma and about 260 Ma (Ludwig and Simmons, 1992). Many of these uranium orebodies were exposed and oxidized during the last 5.5 Ma by the regional fluvial dissection that formed the Grand Canyon (Wenrich and others, 1990). In the oxidized orebodies the primary uraninite was replaced by several complex oxide minerals, including tyuyamunite and metatyuyamunite (Verbeek and others, 1988; Wenrich and others, 1990). By analogy, the tyuyamunite and metatyuyamunite of the Pryor Mountains deposits may represent new forms of earlier primary uranium mineralization in the collapsed caverns. However, in the Pryor Mountains there is no evidence that tyuyamunite and metatyuyamunite have replaced previously deposited uranium minerals, such as uraninite.

In the Pryor Mountains, tyuyamunite and metatyuyamunite were probably deposited as primary minerals from groundwater. The tyuyamunite and metatyuyamunite, now forming the bulk of the Pryor Mountains orebodies, could be relatively young minerals. These minerals may have begun to form in the late Tertiary, because major incision of stream channels over the Pryor Mountains area was active by post-Miocene time (Elliott, 1964; McKenna and Love, 1972; Reheis, 1985). The initial uranium mineralization in the Pryor Mountains area must have occurred after the cavern fill was in place (Late Mississippian to Early Pennsylvanian), but no other constraints on its timing are presently known.

Two alternate sources of the uranium and vanadium have been postulated for the Pryor Mountains deposits: (1) ascending hydrothermal (magmatic) fluids (Warchola and Stockton, 1982) or (2) meteoric waters (McEldowney and others, 1977). Hauptman (1956) noted that "the hydro-thermal theorists seem to have the edge".

Warchola and Stockton (1982) argued for deposition from ascending hydrothermal solutions, mainly based on their identification of davidite (by optical methods), generally a high-temperature uranium mineral of magmatic origin, in association with fluorite. They interpreted hydrothermal fluids to have ascended along major fault or fracture zones (eastern edge of Big

Pryor Mountain) and anticlinal structures (Little Mountain district). Problems with this theory are: (1) the apparent absence of significant pockets of radioactivity within the larger faults and fractures of the uranium districts; (2) the restriction of uranium-vanadium minerals primarily to the cavern fill and nearby fractures in country rocks; (3) the unaltered character of the limestone outside the host caverns; (4) the inconclusive identification of davidite; and (5) the possibility that the "davidite" is a detrital mineral derived from the erosion of Precambrian rocks.

The alternate hypothesis for the origin of the Pryor Mountains deposits suggests that uranium-bearing meteoric waters, principally groundwaters, flushed through the breccia-filled caverns during the Cenozoic. The well-developed liesegang banding at some deposits, such as the Old Glory mine site, indicates that considerable fluid flow (whether meteoric or hydrothermal in origin) passed through the cavern fill and adjacent wall rocks. Proponents of the meteoric water theory usually cite Tertiary tuffaceous rocks as the possible source for the uranium. Regional groundwater flow during the Pliocene and Pleistocene may have leached uranium from volcanic ash deposits that had accumulated directly on the Madison Limestone surface at an earlier Tertiary time (McEldowney and others, 1977). Bentonite beds of Eocene, Oligocene, and Miocene age are mentioned as possible sources for the uranium (Bell, 1963; Elliott, 1963; Patterson and others, 1988). These tuffaceous rocks are found in the adjacent Big Horn basin and presumably also covered the Pryor Mountains uplift prior to post-Miocene fluvial downcutting of the area (Reheis, 1985).

Another potential source for the uranium of the Pryor Mountains deposits—thermal spring waters—is described by Patterson and others (1988). They note a study by Egemeier (1972) of Madison Limestone caves located about 20 miles south of the National Forest lands. There, black, uranium-rich muds were found accumulating on the cavern floors precipitating from warm (17-34°C) spring waters expelled from fractures. Egemeier (1972) recorded a range of 325-455 ppm (parts per million) total dissolved solids content in the waters, and noted oils floating in some of the pools. In comparison, a study of fluid inclusions in barite crystals from a mined deposit on Big Pryor Mountain revealed salinity values of 36,000-38,000 ppm (Patterson and others, 1988). These salinity values are similar to those measured by Stone (1967) in Madison Limestone Group formation waters—31,800 ppm. Patterson and others (1988) concluded that: "The thermal waters observed by Egemeier, although much more dilute, may represent a mixture of meteoric water with oil-bearing, high-salinity, deep-basin brines, which mingle to produce the observed spring chemistry." Thus, uranium minerals in the Pryor Mountains breccia-filled caverns may have precipitated from similar subterranean warm springs.

Potential sources for the vanadium found in the Pryor Mountains orebodies are equally uncertain. Patterson and others (1988) offer two possible sources for the highly anomalous vanadium: "The vanadium may have originated in the Park City Formation [Phosphoria Formation-Embar Limestone equivalent, fig. 3] (Rubey, 1943), or from vanadium-rich oil (Stone, 1967) that may have seeped up from depth along fractures."

Exploration Criteria and Previous Reconnaissance Studies

Several exploration criteria were suggested by Patterson and others (1988, p. 12) to evaluate the resource potential for uranium and vanadium deposits in the upper Madison Limestone Group of the Pryor Mountains area. Based on the observations and interpretations of this study, a few of these exploration criteria were deemed most meaningful, including:

(1) Suggestion of a depression with slightly inward-dipping strata on the surface of the upper Madison Limestone Group, may indicate the presence of an underlying collapsed cavern or solution channelway.
(2) Occurrence of radioactivity at twice background values or greater measured along fractures and in shallow depressions.
(3) Outcrops of liesegang-banded rock or outcrops that exhibit other anomalous alteration patterns are suspect, such as significant bleaching, silicification, or iron-oxide staining of the rock.
(4) Proximity of favorable host rocks (upper Madison Limestone Group) to the hinge zones of anticlinal structures.
(5) Sets of fractures striking about N. 65° W. are possibly located along the trend in which the paleokarst, and therefore the ore-hosting collapsed caverns, were most likely to form. This trend coincides approximately with a line connecting the deposit clusters at the eastern edge of Big Pryor Mountain, the East Pryor mine and the Little Mountain district (fig. 1).

Due to the small size of these deposits and their narrow alteration halos, reconnaissance surveys using standard geochemical exploration techniques have shown limited success in locating undiscovered deposits. Patterson and others (1988) conducted a stream-sediment sampling study in an area immediately south and east of the Custer National Forest. They found anomalous uranium contents (greater than 4 ppm) and abundant barite and fluorite in only those stream sediments (minus-80-mesh size fraction) that were collected directly beneath sites of previous mining. They also noted that "the presence of barite and fluorite in the heavy-mineral-concentrate samples correlated with the higher uranium values". The sampling survey of Patterson and others (1988) was unable to discover new uranium-vanadium deposits in the area.

Two uranium assessment studies of the Billings 1° x 2° quadrangle, as part of the NURE program (National Uranium Resource Evaluation), included reconnaissance evaluations of the Pryor Mountains area. The first study collected water and sediment samples from the Custer National Forest lands of the Pryor Mountains. Geochemical data for this study were tabulated and plotted by Broxton (1979) and evaluated by Whitlock (1979) and Whitlock and Van Eeckhout (1980). The 41 water samples included 21 from springs, 19 from streams, and 1 from a well; 47 sediment samples included 26 from streams and 21 from springs. No anomalous uranium concentrations were found in any of these samples. All of the water samples showed less than or equal to 5 ppb (parts per billion) uranium content and every sediment sample contained less than 4 ppm uranium. Whitlock and Van Eeckhout (1980) noted clusters of anomalous sediment samples near the northeast flank of the Pryor Mountains uplift, in areas about 20 miles north of the National Forest. Another cluster of anomalous sediments was found downstream from the Big Pryor Mountain uranium district, collected from an area about 8 miles north of Cowley and about 6 miles south of the National Forest. These sediments were the only samples from their reconnaissance survey that appeared to detect the occurrence of the Big Pryor Mountain uranium deposits. Thus, the first NURE water and stream sediment sampling program was unable to delineate the Pryor Mountains district let alone discover new deposits in the area.

The second NURE study of the Pryor Mountains area was conducted by Warchola and Stockton (1982). They collected 41 rock, 12 soil, and 15 spring-water samples and a single well-water sample. The rock samples showed a bimodal distribution of uranium concentrations, generally separating into groups of (1) unmineralized rocks "typical of the area" (1-5 ppm uranium), and (2) rocks from uranium occurrences and mine areas (200-10,000 ppm uranium). They suggested that segregation between background and anomalous uranium concentrations occurs in the 20 to 100 ppm interval. The water samples showed a median U_3O_8 value of 8 ppb (parts per billion) with a maximum value of 31 ppb (greater than 1.5 standard deviations above the median). The majority (83.4 percent) of the soil samples contained less than or equal to 5 ppm uranium; the maximum value was 22 ppm uranium (greater than 1.5 standard deviations above the median). Their study also did not find new discoveries or indicate target areas for the Pryor Mountains area. They recommended deep (1,000-1,500 ft) drilling beneath the previously mined areas to intersect potential uranium deposits in fault zones at depth. However, it is unlikely that mining of deep uranium deposits, if they were found, would be viable in the foreseeable future.

Aerial radiometric surveys, as part of the NURE program, proved equally unsuccessful in finding uranium-vanadium deposits in the Pryor Mountains (Warchola and Stockton, 1982, p. 15). A few radiometric anomalies were detected in the area, but none of these coincided with known uranium concentrations. When field checked, one anomalous area contained radioactive float from mined areas topographically higher, but on-site inspections of the other anomalies did not find abnormal radioactivity (Warchola and Stockton, 1982).

If an adequate uranium or vanadium market returned in the future, then a new technology may assist in discovering new deposits in the Pryor Mountains area. A mobile gamma-ray detector, mounted to a four-wheel drive truck, is (as of 1994) available that records electronic "snapshots" of radionuclides within environmental or manmade materials (Verrengia, 1993). Individual snapshots from the detector can monitor areas 100 ft in diameter, scanning about 80 tons of soil at a time. The detector is attached to a telescoping mast extended from the back of the truck. The germanium crystals in the detector are able to detect one-tenth of a picocurie of radioactive material per gram of soil. An attached computer measures frequencies and intensities of gamma-ray emissions to determine concentrations, while an antenna sends signals to global positioning satellites in orbit about the Earth. This "Mobile Gamma Survey Unit" is being used to detect and map radioactive contamination at specific sites throughout the U.S. (Verrengia, 1993). The mobility and efficiency of this technology should make it a cost-effective uranium exploration tool in the Pryor Mountains.

GEOPHYSICS by Dolores M. Kulik

Introduction

Gravity and aeromagnetic data were evaluated in conjunction with geologic and geochemical data in determining the mineral resource potential of the Custer National Forest in the Pryor Mountains. The eastern part of the present study area was included in an earlier USGS study (Patterson and others, 1988). Gravity anomalies reflect differences in density distribution within the earth's crust—for example, rocks with contrasting densities juxtaposed by faulting and folding, intrusions, facies changes, or lithologic contacts. Magnetic anomalies reflect differences in magnetic susceptibility caused by varying amounts of magnetic minerals. The susceptibility of a rock usually depends only on its magnetite content. Observable magnetic anomalies are commonly produced only by igneous and some metamorphic rocks; sedimentary rocks may usually be considered non-magnetic.

Gravity Data

Gravity data for this study were obtained from files maintained by the Defense Mapping Agency of the U.S. Department of Defense. These data were supplemented by approximately 90 stations measured by the author in 1985 for a previous study (Patterson and others, 1988). Stations measured by the author were established using a Worden gravimeter W-177. The data were tied to the International Gravity Standardization Net 1971 (U.S. Defense Mapping Agency Aerospace Center, 1974) at base station ACIC 1651-1 at Cody, Wyo. Station elevations were obtained from benchmarks, spot elevations and estimates from 1:24,000-scale maps, and are accurate to ± 20 ft. The error in the Bouguer anomaly is less than 1.5 mGal (milligals) for errors in elevation control. Bouguer anomaly values were computed using the 1967 gravity formula (International Association of Geodesy, 1967) and a reduction density of 2.67 gm/cm^3 (grams per cubic centimeter). The mathematical formulas for computing the anomaly are given in Cordell and others (1982). Terrain corrections were made by computer for a distance of 167 km (kilometers) from each station using the method of Plouff (1977). The combined data are shown as a complete Bouguer gravity anomaly map with a contour interval of 2 mGal (fig. 9).

Aeromagnetic Data

The aeromagnetic data for this study are from the National Uranium Resource Evaluation (NURE) program (U.S. Department of Energy, 1982). The survey was flown on east-west lines at a barometric elevation of 12,000 ft and flight-line spacing of two miles. The data were projected to a Transverse Mercator projection, gridded at 1 km and contoured at 10 nT (nanoTeslas). The Definitive International Geomagnetic Reference Field (DGRF) was removed using a program by Sweeney (1990). The residual total-intensity aeromagnetic anomaly map is shown in figure 10. Viki Bankey (USGS) provided assistance in the preliminary processing of the aeromagnetic data.

Geophysical Interpretations

Gravity stations are sparse in the study area (fig. 9), and contours are based on gridded data which were mathematically interpolated between randomly located measurements. The aeromagnetic data were measured on widely-spaced flight lines, interpolated between lines, and gridded and contoured by computer programs based on mathematical algorithms. These data are adequate only to interpret gross structural relationships and should not be used to locate or define individual mineral deposits.

A high gravity ridge (A) at the eastern edge of the Big Pryor Mountain block (fig. 9) occurs over steeply-dipping upper Paleozoic rocks, predominantly high-density Mississippian Madison Limestone. The steeply dipping limb of the "drape fold" creates a thick vertical section of these high-density rocks. The adjacent low anomaly to the east (B) occurs where younger, less-dense sedimentary rocks thicken in the Crooked Creek drainage; the low anomaly broadens to the

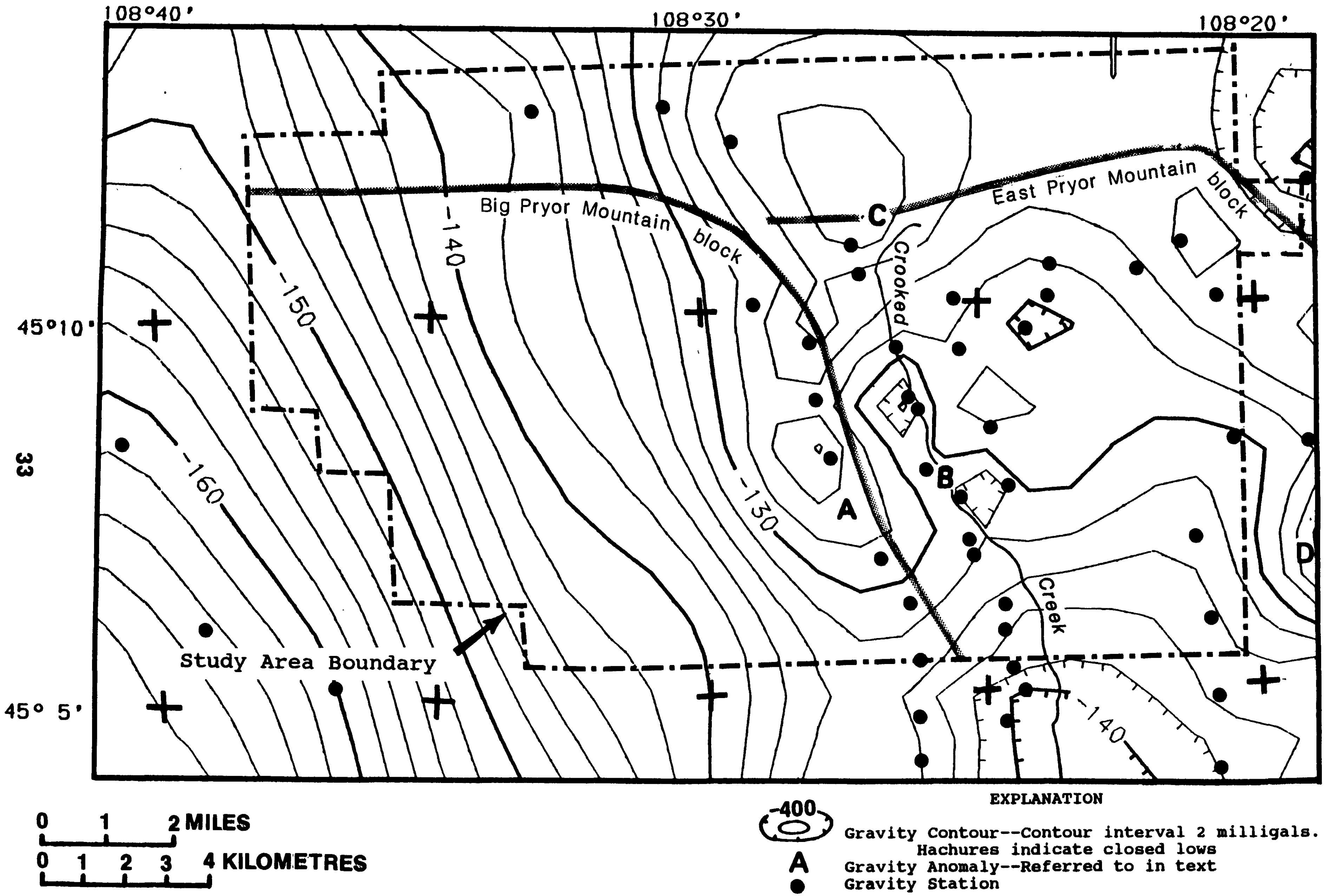
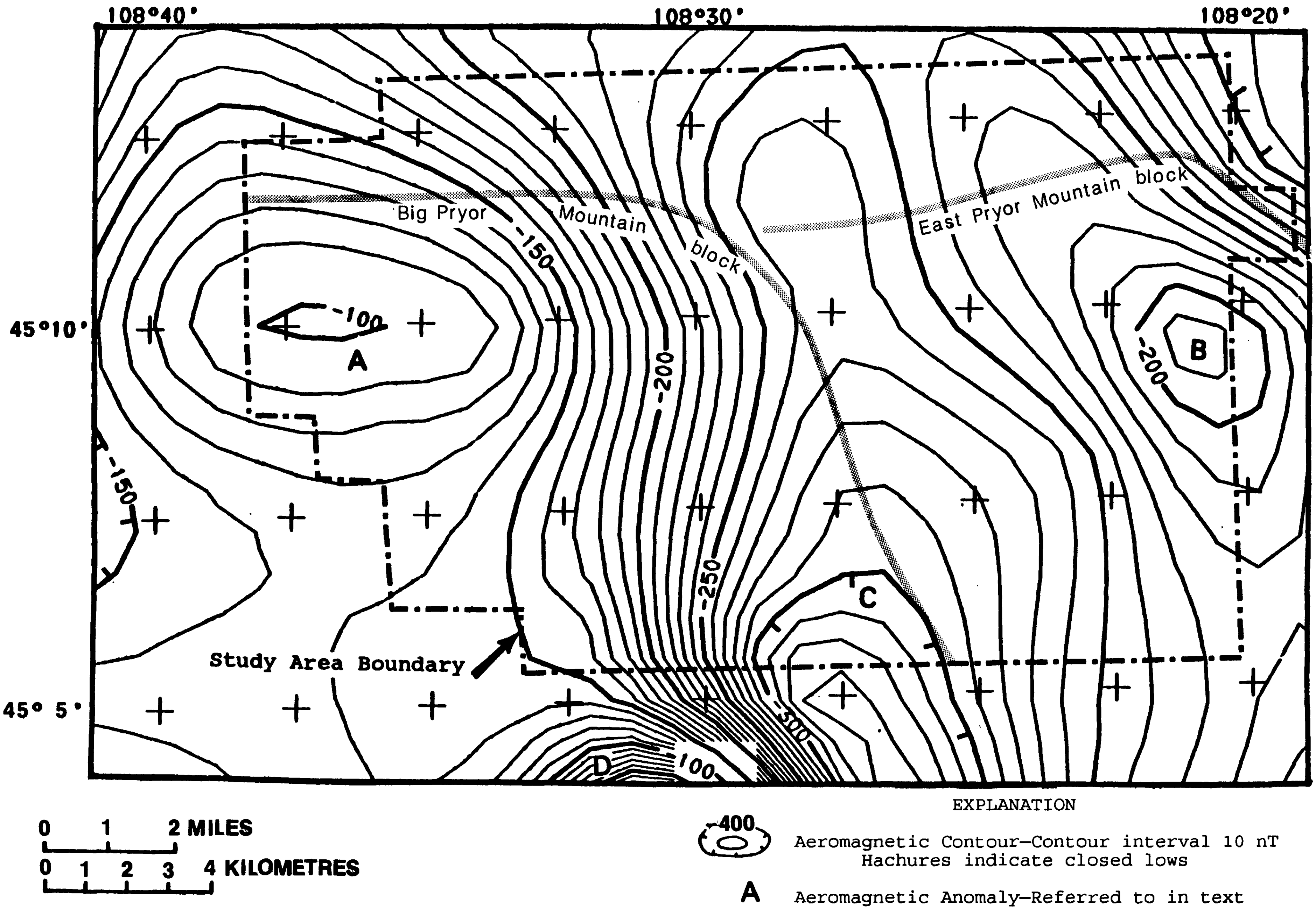


Figure 9. Complete Bouguer gravity anomaly map of the Custer National Forest in the Pryor Mountains, Montana.



EXPLANATION

Aeromagnetic Contour—Contour interval 10 nT
Hachures indicate closed lows

A Aeromagnetic Anomaly—Referred to in text

Figure 10. Total intensity aeromagnetic anomaly map of the Custer National Forest in the Pryor Mountains, Montana.

southeast where those rocks are more widespread in the lower reaches of the drainage. The high anomaly (C) is caused by the outcropping Madison Limestone on the south (upthrown) side of a mapped fault (fig. 2). The anomaly continues northward beyond the fault, but is an artifact of the contouring method, and is unconstrained by data measurements. The high anomaly (D) east of the study area boundary occurs over steeply-dipping Madison Limestone at the eastern edge of the East Pryor Mountain block. Gravity values decrease steadily westward from the faulted eastern edges of both the Big Pryor Mountain and East Pryor Mountain blocks across the west-dipping flanks of the uplifts. The decreasing gravity gradient is caused by the increasing depth to the underlying high density Precambrian basement rocks that core the tilted uplifts.

High magnetic anomalies (A and B), associated with the Big Pryor Mountain and East Pryor Mountain blocks (fig. 10), are caused by the relatively magnetic Precambrian crystalline basement rocks that core the uplifted blocks. The relatively low magnetic anomaly (C) occurs where the non-magnetic sedimentary rocks dip gently on the west flank of the East Pryor Mountain block and the non-magnetic Madison Limestone dips steeply over the east edge of the Big Pryor Mountain block (fig. 2). The northern edge of a high magnetic anomaly (D) is just visible at the southern border of the map (fig. 10). The anomaly extends approximately 20 mi to the south, and reaches a magnitude of more than 1,100 nT.

It is unlikely that magnetic anomaly D (fig. 10) is caused by uplifted crystalline basement rocks. If anomaly D were caused by a basement-cored uplift, it would be expected to have a much lower magnitude than anomalies A and B, because A and B occur at higher elevations (thus closer to the aeromagnetic sensor). Additionally, there is no surface evidence nor associated gravity anomaly to suggest an uplift of high-density crystalline basement into the surrounding sedimentary rocks. The shape and gradient of anomaly D suggest a buried magnetic body that is symmetrical with near vertical boundaries. Estimates, based on half-width formulas, place the top of the body at a depth of 10,000-12,000 ft, which is at or near the top of the basement. The most likely cause of the anomaly is an intrusive body. The inferred intrusion would have been favorably located to access fault systems activated during uplift of the Pryor Mountains. Such an intrusion may have provided ascending hydrothermal fluids or a heat source for subterranean thermal springs, as proposed in some of the hypotheses for the origin of the uranium-vanadium deposits (Warchola and Stockton, 1982; Patterson and others, 1988).

MINERAL RESOURCE ASSESSMENT

The mineral resource assessment of the Pryor Mountains area of the Custer National Forest follows the iterative procedures used throughout the assessment of the Custer and Gallatin National Forests (Singer, 1993a; table 4). Permissive tracts are delineated for four types of mineral deposits in the Pryor Mountains area: (1) uranium-vanadium solution-collapse breccia deposits; (2) high-purity limestone; (3) decorative stone; and (4) limestone and dolomite for crushed stone. Estimates of numbers of undiscovered uranium deposits are combined with grade and tonnage models in a computer simulation (Root and others, 1992) to provide a probabilistic estimate of amounts of uranium, vanadium, and tonnage that may be present in undiscovered deposits. Potential resources of high-purity limestone, decorative stone, limestone and dolomite for crushed stone, and sand and gravel are described under "Other Potential Mineral Resources".

Table 4. Goals and procedures for the mineral resource assessment of the Custer National Forest, Montana.

Purpose	* Provide minerals information for land-use planning * Provide geologic information for ecosystem management
Procedure	* Collect, compile, and evaluate data on geology, geochemistry, mining history, mineral occurrences, and geophysics * Define types of mineral deposits that may be present based on the available geologic data * Delineate permissive areas for the occurrence of undiscovered mineral deposits *If sufficient data for the study area and for the type(s) of expected mineral deposit(s) exist:* * Estimate numbers of undiscovered mineral deposits at various confidence levels * Combine estimates of numbers of deposits with grade and tonnage models in a Monte Carlo type computer simulation * Use simulation results to predict amounts of commodities that could be contained in-place in undiscovered mineral deposits * Provide results to economists for a potential supply analysis to determine economic viability of potential undiscovered deposits

Uranium-Vanadium Deposits

Uranium deposits of the Pryor Mountains of southern Montana and the adjacent Little Mountain area (fig. 1) of northern Wyoming share some characteristics with oxidized parts of solution-collapse breccia pipe uranium deposits of the Colorado Plateau. The Little Mountain area in Big Horn County, Wyoming, represents the southeastern extension of the Big Pryor Mountains uranium district. Compared to the Colorado Plateau deposits, the Montana-Wyoming deposits are orders of magnitude smaller, have lower average uranium grades, and contain a different suite of characteristic ore minerals. The Colorado Plateau deposits were a major source of high-grade uranium in the U.S. in the 1980's and could be important in the future if the demand for raw materials and the price of uranium rise to levels adequate to sustain domestic production. The similarities of the Montana-Wyoming deposits to the important deposits of the Colorado Plateau and the potential environmental hazards associated with uranium deposits warranted an attempt to estimate the amount of uranium that could be present in undiscovered deposits within the Custer National Forest.

Mineral deposit model. A mineral deposit model is the systematically arranged information describing the essential attributes of a class of mineral deposits (Cox and Singer, 1986). Models can be descriptive or genetic and can include information on the characteristic tonnages and ore grades associated with a class of mineral deposits. We examined existing models for uranium deposits, compared them with our observations in the study area, and developed a new model for use in this study.

Finch (1992) developed a mineral deposit model for solution-collapse breccia pipe uranium deposits based on the characteristics of Colorado Plateau deposits in the Grand Canyon region. He described these deposits as "uraninite and associated sulfide, arsenide, sulfate, and arsenic-sulfosalt minerals as disseminated replacements and minor fracture fillings in distinct bodies in near-vertical cylindrical solution-collapse breccia pipes, 30-175 m in diameter and 1,000 m in vertical extent." A cap of massive base-metal and iron sulfide minerals overlies the uranium deposit in many of the pipes and effectively shields the uranium ore from weathering. Tyuyamunite and a variety of other secondary uranium and copper minerals form in pipes that are deeply eroded and weathered; uranium is leached and copper and vanadium may be high-graded through supergene processes in oxidized parts of these deposits.

Finch and others (1992) constructed a uranium grade model and an ore tonnage model using pre-mining reserve data for eight unoxidized breccia deposits in the Grand Canyon region. They noted that minable grades of copper, vanadium, and other metals are present in remnant deposits affected by supergene processes, but such deposits were omitted from their grade and tonnage models. Many of the deposits were first mined for copper and only later proven to be important sources of uranium. Tonnages for the eight breccia pipes range from 100,000 to 500,000 metric tons; average ore grades are 0.4 to 0.7 percent U_3O_8. A cutoff grade of 0.05 percent U_3O_8 was used to construct the model.

The uranium-vanadium deposits of the Pryor Mountains area consist of coatings and fracture fillings of the secondary minerals tyuyamunite and metatyuyamunite in solution-collapse cavern breccias that formed in a paleokarst horizon of the upper part of the Mississippian Madison Limestone. No sulfide minerals or primary uranium minerals (such as uraninite) are present. Individual collapsed caverns are typically on the order of 30 m in diameter and 6 to 8 m in vertical extent. Therefore, the Pryor Mountains deposits are orders of magnitude smaller than the Grand Canyon deposits, especially in vertical extent, and cannot really be considered true "pipes". In addition, the Pryor deposits lack the complex mineral assemblages and diverse geochemical signature associated with the Grand Canyon breccia pipes. Production data for the Big Pryor Mountain district for 1956-1964 (table 2) indicate that most of the mined deposits were small (less than 500 metric tons) and relatively low-grade (average grade 0.27 percent U_3O_8). A descriptive model for the uranium-vanadium deposits considered in this study is given in table 5.

Comparison of the geologic and grade-tonnage characteristics of the Pryor Mountain deposits with the Colorado Plateau deposits shows that although similar processes may have operated, the resulting ore deposits are quite different in scale. Frequency distributions of grade and tonnage data from well-explored deposits can be used as models for predicting grades and tonnages of undiscovered deposits in similar geologic settings of geographically distinct areas. However, the models for Colorado Plateau deposits are unsuitable for assessing the undiscovered uranium potential in solution-collapse breccia deposits in the Custer National Forest for several reasons: (1) the Grand Canyon model is based on primary, unoxidized uranium ores; (2) the Grand Canyon model is based on data for 8 deposits, while 20 deposits is a desirable minimum number of deposits to insure that a model will be robust; and (3) statistical analysis of available production data from the Pryor Mountains area indicates that the data represent a population of

Table 5. Descriptive model of Pryor Mountains area uranium-vanadium solution-collapse breccia deposits

DESCRIPTION: Tyuyamunite and metatyuyamunite as vug fillings, fracture coatings, and disseminations in solution-collapse cavern breccia fill in upper parts of the Mississippian Madison Limestone Group of south-central Montana and north-central Wyoming.

TYPICAL DEPOSITS: Dandy mine, Montana; Fusner mine, Wyoming

RELATIVE IMPORTANCE: During the period 1956 to 1964, 21 properties in the Big Pryor Mountain district of Montana produced more than 45,000 pounds of uranium oxide (U_3O_8) and 30,000 pounds of vanadium oxide (V_2O_5). The Little Mountain district of northern Wyoming produced about 250,000 pounds of uranium oxide and 205,000 pounds of vanadium oxide during the period of 1956 to 1970.

COMMODITIES: Uranium, Vanadium

REGIONAL GEOLOGIC ATTRIBUTES

REGIONAL DEPOSITIONAL ENVIRONMENT: A regional karst surface developed at the upper contact of the Late Mississippian Madison Limestone Group (shelf facies). Overlying claystone and siltstones of the Pennsylvanian Amsden Formation infiltrated the collapsed caverns that host the uranium-vanadium deposits.

AGE OF MINERALIZATION: Post Late-Mississippian

LOCAL GEOLOGIC ATTRIBUTES

HOST ROCKS: Upper parts of the Late Mississippian Madison Limestone Group

ASSOCIATED ROCKS: Early Pennsylvanian Amsden Formation

ORE MINERALOGY: tyuyamunite, metatyuyamunite, $\pm$ uranophane, autunite, davidite, liebigite

GANGUE MINERALS: hematite, limonite, iron-hydroxide minerals, microcrystalline quartz, calcite, barite, clay minerals, gypsum, pyrite or marcasite, opal, celestite, fluorite, pyrolusite

ORE CONTROLS: Collapsed caverns in a paleokarst terrain; faults and hinge zones of anticlinal structures may localize fluid flow.

ALTERATION: Silicification of host limestones and overlying siltstones and sandstones of the Amsden Formation; Liesegang banding; limited local bleaching.

Table 5. Continued.

GEOCHEMICAL SIGNATURE: The orebodies are enriched in U and V. Scattered anomalous enrichments of Ba, F, and Sr in these deposits are associated with local concentrations of barite, fluorite, and celestite. Due to the small size of the deposits and their narrow alteration halos, standard geochemical reconnaissance surveys—such as stream sediment, water, and heavy-mineral-concentrate sampling—have not been successful in locating undiscovered deposits. Typically, anomalous contents of U, Ba, and F only occur in those samples collected directly downstream and less than 1,000 ft from abandoned mines.

GEOPHYSICAL SIGNATURE: Local anomalies in gravity or radiometric data might be expected over these deposits, but they are not detectable on a regional scale.

EXPLORATION GUIDES: Sinkholes or circular surface depressions; anomalous radioactivity or radon

ENVIRONMENTAL HAZARDS: High radon levels in caverns and abandoned mines deposits that is distinct from the population of deposits represented by the Grand Canyon data. Modern uranium exploration techniques could reveal buried deposits that may be larger than the deposits mined in the past; however, the largest deposits in a district tend to be discovered first and the area was heavily prospected in the 1950's. The paleokarst horizon formed in the upper 190 to 240 ft of the Madison Limestone, so deposits of the vertical scale of the Grand Canyon breccia pipes (1,000 m) could not have formed.

We examined the sample population represented by the production data for 21 deposits in the Big Pryor Mountain district (table 2), an additional 17 deposits from the Little Mountain district in Wyoming (table 3), and for Lisbon Uranium Corporation's Fusner mine in the Little Mountain district (Wilson, 1966). These data are sorted and used to construct grade and tonnage models for uranium-vanadium solution-collapse breccia deposits in the upper Madison Limestone. The models are cumulative frequency plots of the proportion of deposits as a function of $\log_{10}$ transformations of tonnage (converted to metric tons) and grade (percent U_3O_8 and V_2O_5). The Peach deposit (table 2) is omitted due to its anomalously low tonnage (less than 0.5 ton) and high grade (2.18 percent U_3O_8) compared with data for the other deposits; such small tonnage and high grade suggest that the data may reflect selectively sorted ore and may not reliably represent the deposit.

Data used to construct the grade and tonnage models for the Pryor Mountains area uranium-vanadium deposits are tabulated along with relevant statistics in Appendix B. Since many geologic variables such as tonnage, ore grades, grain sizes, and geochemical measurements represent highly skewed rather than normal (bell-shaped) distributions when examined as histograms, geologic observations are commonly transformed to logarithms to remove skewness. Many geologic sample distributions that appear highly skewed approach a normal distribution when converted to logarithms and the lognormal sample population can be described by reference to the statistics used for a normal population (Davis, 1986). Examination of the statistics of a data set is a necessary step in creating a grade or tonnage model to determine if the sample set is likely to represent a single type of mineral deposit. Although acquisition of data for additional deposits of a given type may require revision of a model, Singer (1993b) notes that models are most likely to be robust if most of the tonnages and grades approach a lognormal distribution, if 20 or more deposits are used to construct the model, and if grade and tonnage are not significantly correlated. Data sets that contain outliers, subgroups, or deviate from a lognormal distribution may not all represent a single descriptive geologic model and therefore are unsuitable for predicting endowment of undiscovered deposits (Singer, 1993b). In order to use a model for predicting the endowment of undiscovered deposits of a particular type, one estimates numbers of undiscovered deposits with the underlying assumption that the model employed describes the population of undiscovered deposits. Therefore, one would expect the population of undiscovered deposits to have grade and tonnage distributions similar to the model; that is, approximately half of the undiscovered deposits are likely to be bigger than the median value of the tonnage model and half of the undiscovered deposits are likely to be smaller.

Histograms of log-transformed values of tonnage and ore grade production data for 38 solution-collapse breccia uranium-vanadium deposits from the Pryor Mountains area (fig. 11) show that the data approximate a normal distribution. Cumulative frequency diagrams (models) were constructed for tonnage and grade (fig. 12). The tonnages for the Pryor Mountains area deposits range from about 8 metric tons (Horseshoe 9 deposit) to more than 11,000 metric tons (Mike 10 deposit). Median tonnage (50th percentile value) for the 38 deposits is 154 metric

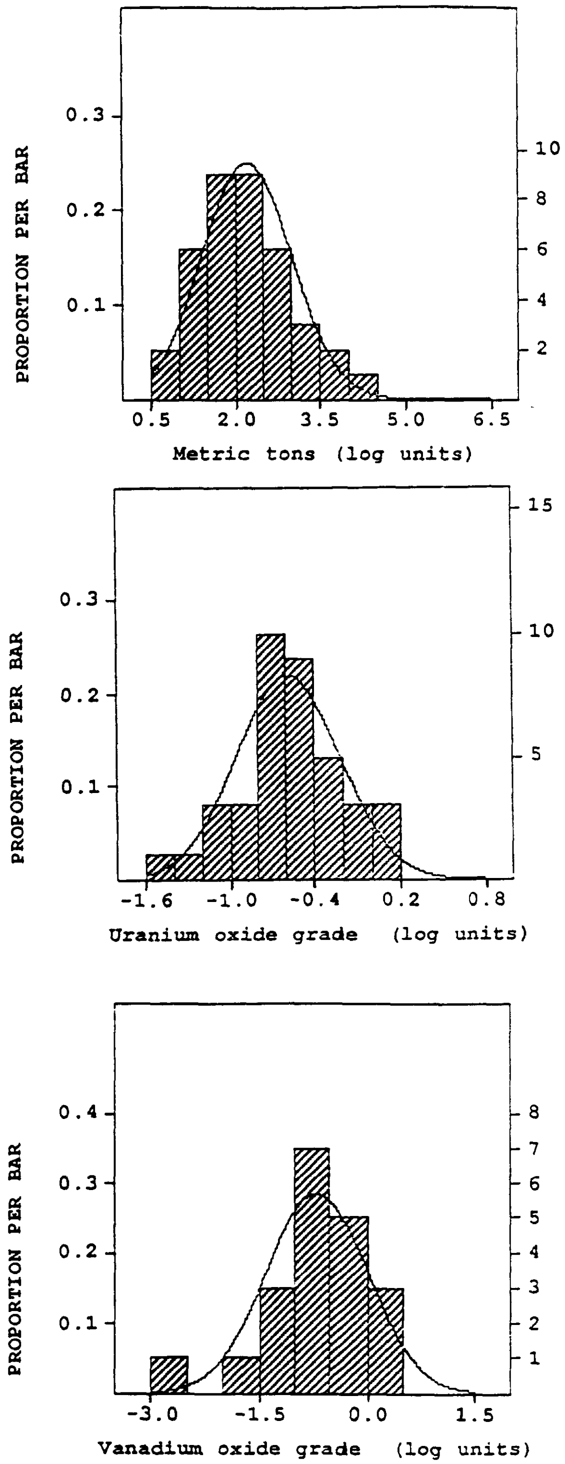


Figure 11. Histograms showing the distribution of tonnages and ore grades for 38 solution-collapse cavern breccia uranium-vanadium deposits from the Pryor Mountains area, Montana, and the Little Mountain district, Wyoming. Superimposed curves show expected curve shape for data sampled from a normal distribution.

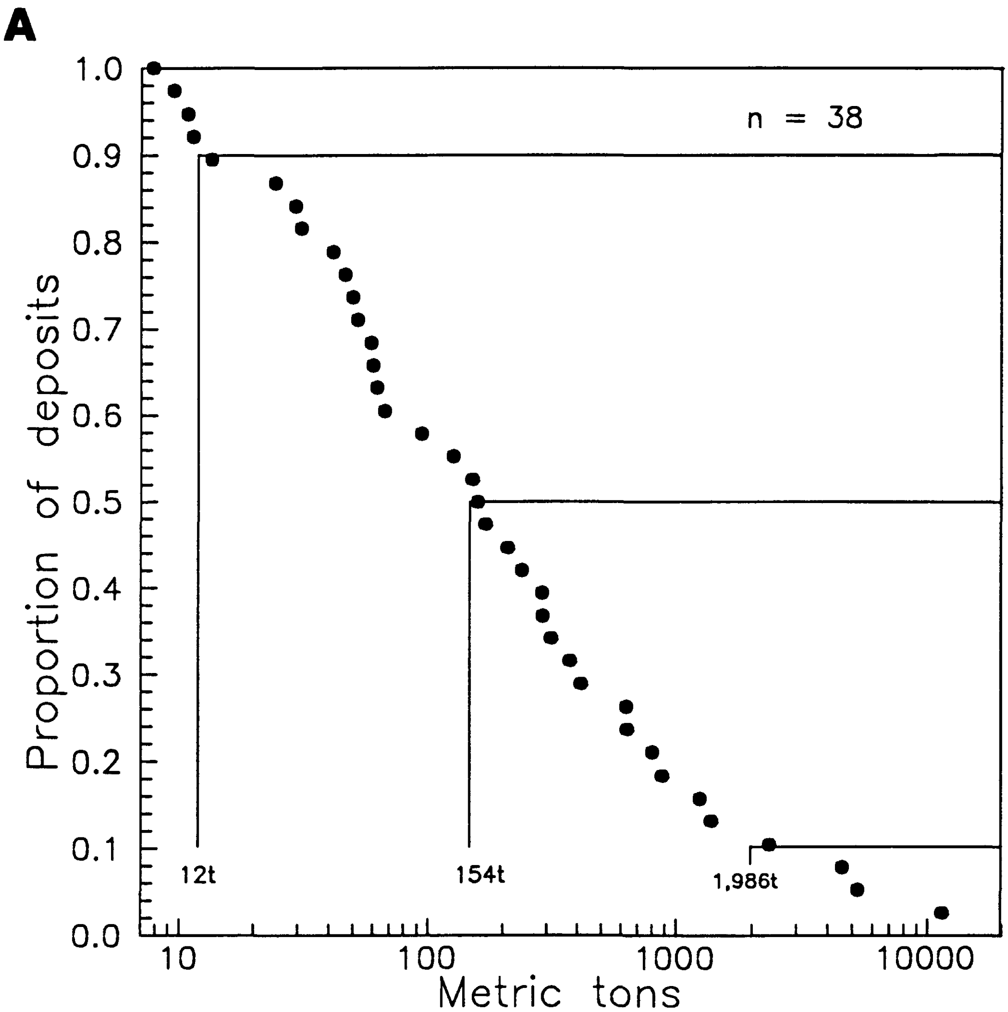
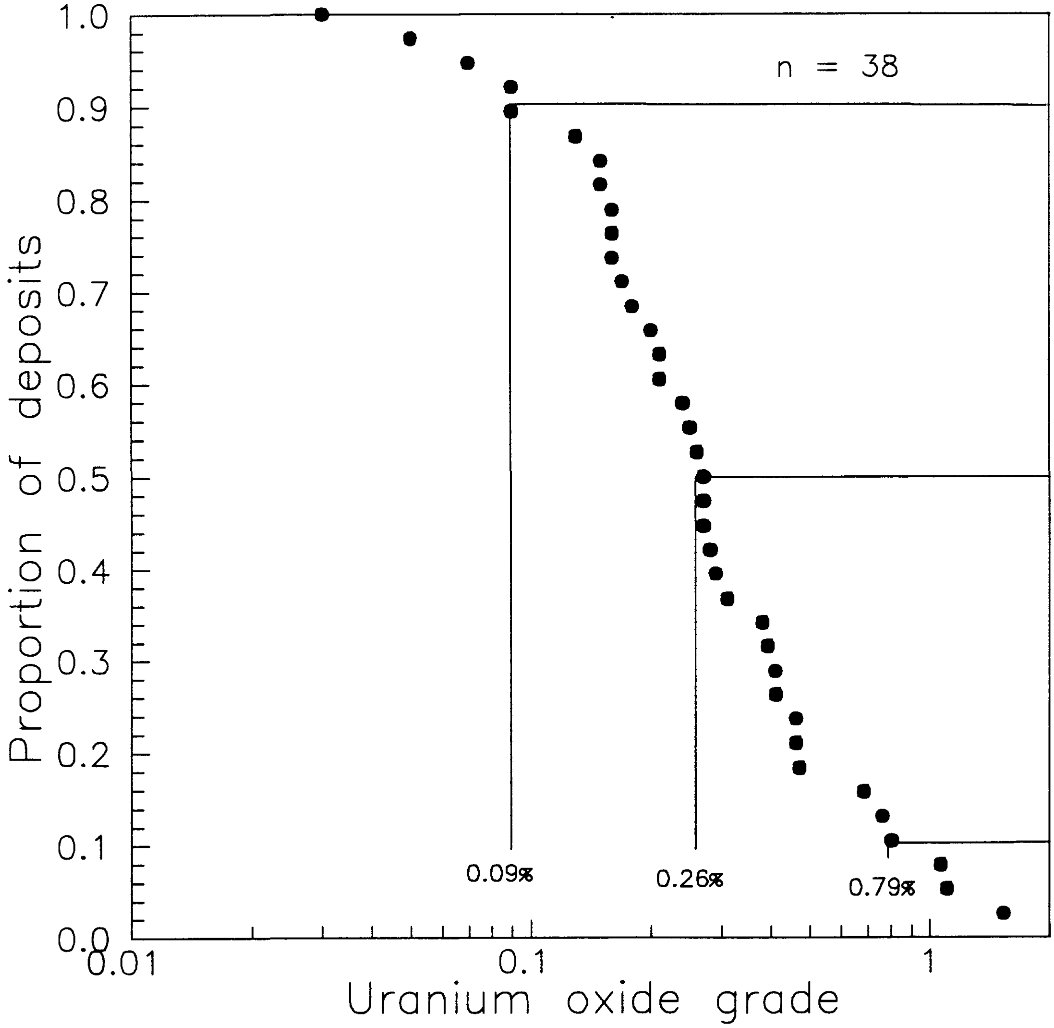
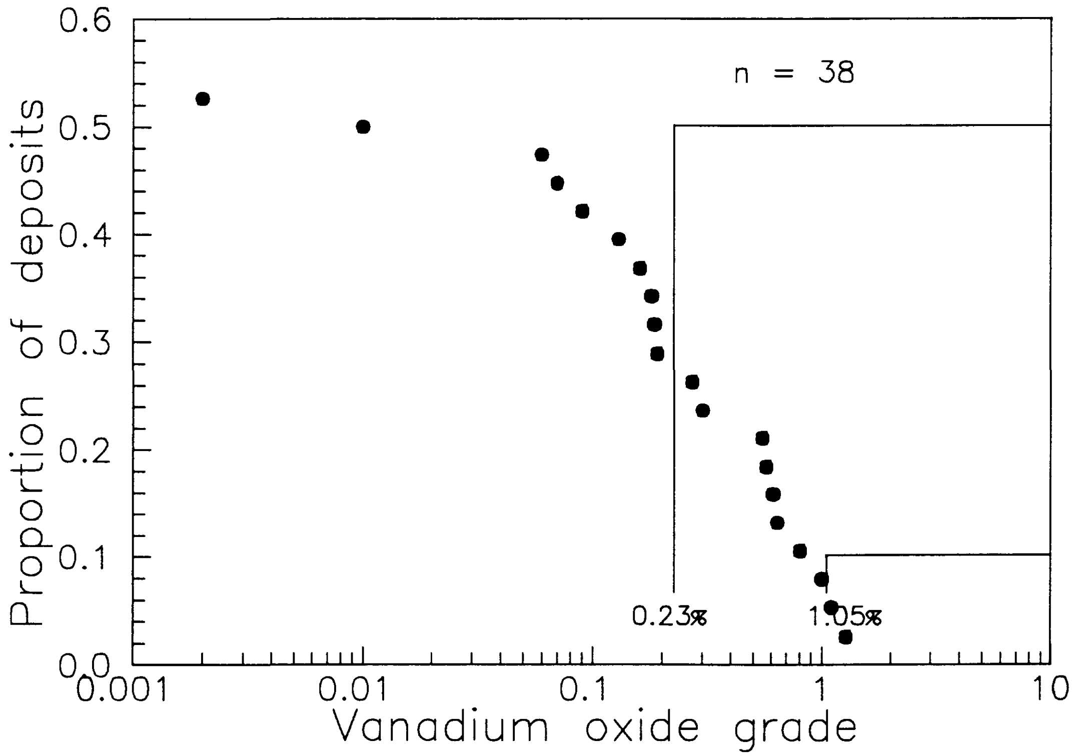


Figure 12. Tonnage (A) and grade (B) models for Pryor Mountains area uranium-vanadium deposits. Each point represents a single deposit. Values for the 90th, 50th, and 10th percentiles are shown for reference; t, metric tons; n, number of deposits. Notice that vanadium oxide grades were reported for only 20 of the 38 deposits used to construct the model (tables 2 and 3).

B



1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Proportion of deposits
n = 38
0.09%
0.26%
0.79%
0.01
0.1
1
Uranium oxide grade



0.6
0.5
0.4
0.3
0.2
0.1
0.0
Proportion of deposits
n = 38
0.23%
1.05%
0.001
0.01
0.1
1
10
Vanadium oxide grade

tons (fig. 12a). Uranium grades range from 0.03 to 1.53 percent U_3O_8 with a median value of 0.26 percent (fig. 12b). Vanadium grades are reported for only 20 of the 38 deposits (fig. 12b). In a number of cases, average vanadium grade exceeds average uranium grade for a given deposit. Plots of uranium grade versus tonnage (fig. 13a) and uranium grade versus vanadium grade (fig. 13b) show no correlations. We believe that any undiscovered uranium-vanadium deposits in the Pryor Mountains study area of the Custer National Forests are likely to be similar in size and grade to the deposits represented by the models in figure 12. Therefore, we used those models to estimate amounts of metal potentially contained (in-place) in undiscovered deposits if the area was thoroughly explored to a depth of 1 km below the surface using modern technology.

Permissive tracts for uranium-vanadium deposits. Most of the study area is permissive for the occurrence of uranium-vanadium solution-collapse breccia deposits (fig. 8). This is because the dominant rock type exposed across the study area is the upper part of the Mississippian Madison Limestone Group that hosts the known deposits. Areas having surface exposures of two other lithologic units (Pennsylvanian Amsden Formation and Tensleep Formation) are included in the permissive tract where the paleokarst horizon of the upper Madison Limestone is likely to be present at shallow depths (within 500 vertical feet) in the subsurface. Criteria used to draw tract boundaries are listed in table 6. Favorable areas (fig. 8) are delineated within the permissive tract to indicate lands considered most likely to host undiscovered uranium-vanadium deposits. Although most of the known deposits are located south of the study area boundary (fig. 1), the rock types and structures (Crooked Creek fault and anticline on East Pryor Mountain) that appear to control the distribution of the known deposits are present in the study area. Therefore, the favorable area is drawn to include known deposits as well as geologically permissive areas proximal to structures that may control deposits.

Estimate of undiscovered uranium-vanadium resources. Probabilistic estimates of numbers of undiscovered uranium-vanadium deposits were elicited from the study team after discussion of all the available geologic data. Pertinent information considered in formulating subjective estimates of numbers of undiscovered deposits included: (1) the stratigraphic units and structures that host the known deposits are present in the study area; (2) the deposits are small (individual caverns) and deposits can be closely spaced; (3) uranium mining and exploration activity in the area has been dormant for 30 years; (4) previous geochemical and aerial radiometric studies (NURE Program) failed to delineate the known deposits; and (5) modern geophysical methods could explore the area more thoroughly and possibly detect deeper deposits (underground caves) than those mined in the past. Exact locations of many of the deposits mined in the 1950's and 1960's are unknown. Production figures are available for 21 deposits in the Big Pryor Mountain district (table 2); 7 deposits or groups of deposits are shown on figure 1 (localities 2 - 8). Similarly, the Little Mountain district (fig. 1, locality 9) represents a group of 18 deposits. The spatial density of known deposits was considered in estimating numbers of undiscovered deposits. The 21 discovered deposits occur within a 4 mi^2 area within and adjacent to the southern boundary of the study area. The favorable subtract (fig. 8) has an area of about 10 mi^2 (26 km^2) and the permissive area for uranium-vanadium deposits is approximately 100 mi^2 (256 km^2).

Each member of the study team contributed estimates of numbers of undiscovered uranium-vanadium deposits at three confidence levels. At the 90 percent confidence level (most

A

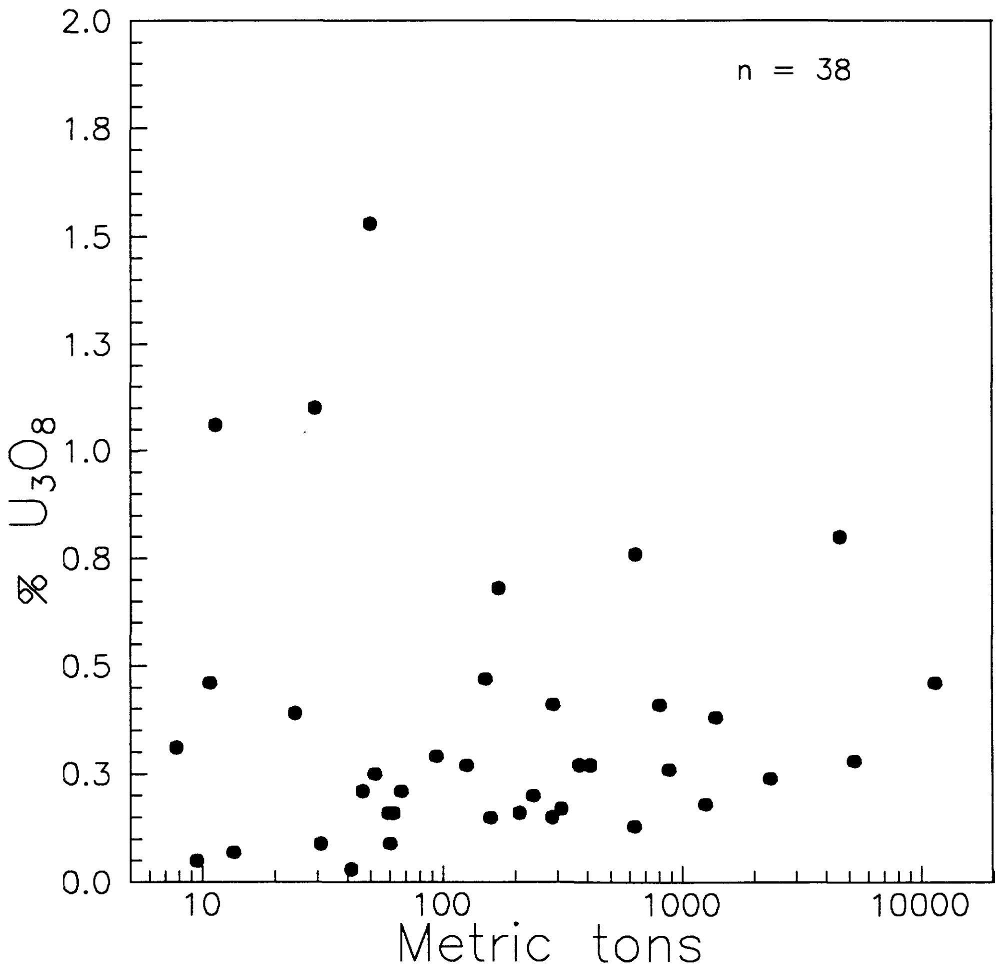


Figure 13. Plots showing the lack of correlation between (A) average uranium grade and tonnage for 38 uranium-vanadium deposits from the Pryor Mountains area and (B) average uranium grade and average vanadium grade for 20 deposits with reported vanadium production data. Grades are reported as percent uranium oxide ($\%U_3O_8$) and percent vanadium oxide ($\%V_2O_5$). Tonnage is shown on a logarithmic scale.

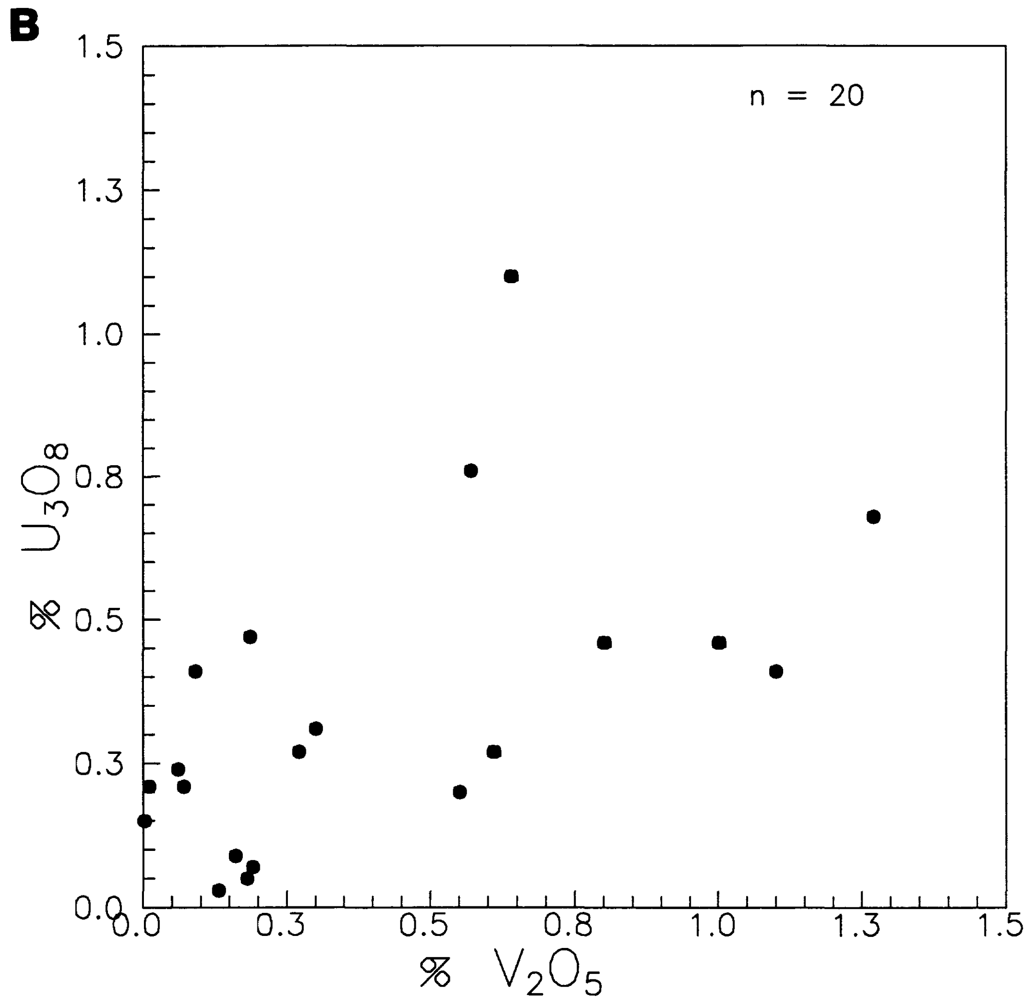


Figure 13. Continued.

Table 6. Criteria for permissive tracts for uranium-vanadium solution-collapse breccia deposits.

Tract name: Pryor Mountains uranium-vanadium

Description: Paleokarst in Mississippian Madison Limestone Group that locally contains uranium and vanadium minerals as cavity fills, crusts, and coatings in cave-fill breccias.

Permitted deposit types	Expected geochemical signature
Solution-collapse breccia-hosted uranium-vanadium deposits	U, V, Ba, F

Area (km^2)	256
Geologic criteria	Tract includes the upper third (240 ft) of Mississippian Madison Limestone Group, as well as areas underlain by Pennsylvanian Amsden and Tensleep Formations. The tract extends to a maximum depth of 550 ft below the surface (in some parts of the tract, 240 ft of upper parts of Madison Limestone Group may be overlain by 140 ft of Amsden Formation and 70 ft of Tensleep Formation). Areas of steeply dipping Amsden Formation, and a strip of Amsden Formation and overlying Triassic rocks east of the Crooked Creek fault, are omitted because any undiscovered U-V deposits would be more than 1 km (3,281 ft) below the surface. The most productive mines are spatially associated with the Crooked Creek and Sage Creek fault systems.
Geophysical signature	No gravity or magnetic signature.
Geochemical signature	Regionally, elevated concentrations of U in stream waters. Locally, elevated concentrations of the minerals barite (Ba) and fluorite (F) correlate with elevated uranium concentrations in heavy mineral concentrates (Patterson and others, 1988).
Mines, prospects, and mineral occurrences	Uranium ore was produced from 1956 through 1970 from deposits on Big Pryor Mountain, East Pryor Mountain, and from the Little Mountain District. Most of these deposits are located south of the Forest boundary. However, permissive rock types and structures that may localize deposits extend into the Forest.

Favorable area within the permissive tract	Area within 1 mile of the Crooked Creek fault where the upper third of the Madison Limestone is exposed at the surface or buried under thin cover of Amsden Formation. Includes cluster of known U-V deposits. Includes postulated northward extension of an anticline mapped on East Pryor Mountain (south of Forest boundary).
Comments	Breccia-filled caves in a paleokarst terrain that formed in the upper Madison Limestone Group prior to deposition of the Amsden Formation are most prospective for additional deposits. Circular sinkholes up to 250 ft in diameter, with bedding dipping subtly inward, may represent the surface expression of some mineral-rich caves. Open caves in Madison Limestone formed during the Quaternary (since Pliocene time) and are not prospective for U-V deposits.

Table 6. Continued.

likely), individual estimates varied from 5 deposits or more to 75 deposits or more. Similarly, our estimates at the 10 percent confidence level (least likely) ranged from 20 deposits to 200 deposits or more. After discussion, we reached a consensus estimate of a 90 percent chance of at least 20 deposits, a 50 percent chance of at least 50 deposits, and a 10 percent chance of at least 75 or more undiscovered deposits in the Pryor Mountains uranium-vanadium tract of the study area.

The consensus estimate (table 7) was combined with the tonnage and grade models for Pryor Mountains area uranium-vanadium deposits (fig. 12) in Mark3 (Root and others, 1992). Mark3 is a computer program that uses a Monte Carlo simulation to generate a probability distribution that represents our estimate of the ore and metal that might be contained in-place in undiscovered deposits in the study area.

Results of the computer simulation calculations are plotted in terms of a probability distribution that shows the likelihood of a given amount of either ore or metal present in undiscovered deposits in the study area (fig. 14). The 90th, 50th (median), and 10th percentile values, as well as the mean value, are listed in table 7, along with the amount of ore and metal produced in the past for comparison. The mean expected number of undiscovered deposits is 48. There is a fifty percent chance that these 48 undiscovered deposits contain at least 160 metric tons of uranium oxide (U_3O_8), at least 110 metric tons of vanadium oxide (V_2O_5), and at least 40,000 metric tons of mineralized rock. Note that the mean values are comparable to the median values. Mean values suggest that undiscovered uranium-vanadium deposits in the Pryor Mountains uranium-vanadium tract (fig. 8) may contain about five times as much ore as was produced from Pryor Mountain district in the past and about as much as the combined total production from the Pryor Mountain and Little Mountain districts.

Outlook for Future Exploration and Development of Uranium-Vanadium Resources

No uranium mines or processing plants have operated in Montana in recent years; however, exploration for uranium has continued in Wyoming. The exploration focus in Wyoming is directed towards roll-front type deposits in sandstones of the Eocene Wasatch Formation in the Powder River Basin. These deposits are amenable to in-situ leaching. Solution-collapse breccia deposits that occur in northern Wyoming adjacent to the study area in the Pryor Mountains have not been the focus of recent exploration. Renewed exploration for uranium and development of a uranium industry in the Custer National Forest is unlikely in the reasonably foreseeable future. This is due to the depressed state of the uranium industry, substantial uranium reserves elsewhere, and the small size and difficulty of discovery of the type of uranium deposit present in the Pryor Mountains area.

Worldwide consumption and production of uranium has steadily declined in recent years and forecasts for the immediate future predict that U.S., as well as world consumption and production, will continue to decline (Pool, 1995). The end of the Cold War in 1993 made available huge amounts of uranium in the C.I.S (former Soviet Union) and the U.S. that can be down-graded for peaceful uses to produce electricity. Estimated U.S. uranium production for 1994 was 3.3 million pounds (1,692 short tons or 1,535 metric tons) of U_3O_8 (Pool, 1995) from seven production centers. None of these centers operated as conventional mines—production represents in-situ leaching, phosphoric acid by-product, and mine water processing

Table 7. Estimate of undiscovered uranium-vanadium solution-collapse breccia deposits compared to past production in the Pryor Mountains area of the Custer National Forest, Montana.

Estimate of the minimum number of uranium-vanadium deposits expected at each of the following probabilities:

90%	50%	10%	Mean expected number of deposits
20	50	75	48

Estimated amounts of commodities contained in undiscovered uranium-vanadium deposits (in metric tons):

Commodity	90th percentile	50th percentile	10th percentile	Mean
Uranium (U_3O_8)	42	160	320	170
Vanadium (V_2O_5)	14	110	290	140
Tonnage	13,000	40,000	70,000	41,000

Past production from the area (in metric tons):[1]

Commodity	Big Pryor Mountain area, Montana	Little Mountain district, Wyoming	Montana and Wyoming districts combined
Uranium (U_3O_8)	20	117	137
Vanadium (V_2O_5)	14	93	107
Tonnage	7,527	24,931	32,458

[1]Data from tables 2 and 3. Data for the Fusner Mine in the Little Mountain district, Wyoming, from Wilson (1966). Includes data for the Peach deposit, table 2.

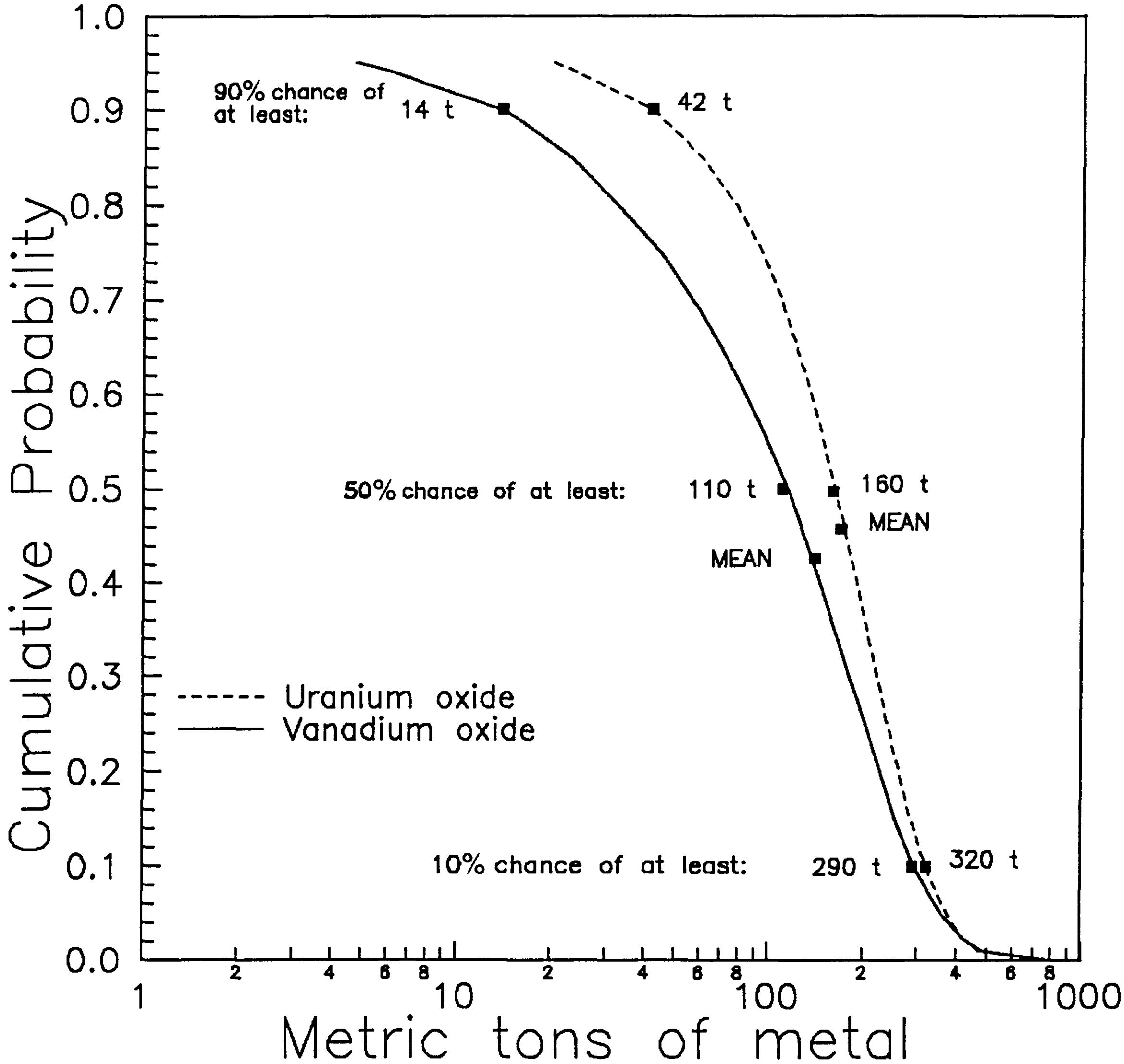


Figure 14. Results of Mark3 computer simulation expressed as probability distributions for uranium oxide and vanadium oxide. These simulations show estimated amounts of commodities that may be present in-place in undiscovered solution-collapse cavern breccia uranium-vanadium deposits in the study area. Most likely amounts (90th percentile), median (50th percentile), mean, and least likely (10th percentile) expected amounts are shown.

operations. The solution-collapse breccia deposits of the Pryor Mountains area were exploited profitably during the uranium boom in the late 1950's and early 1960's. However, these deposits are unsuitable for large-scale in-situ leaching and the mean estimated amount of the total uranium resource in undiscovered deposits on federal lands from this study, 170 metric tons, represents only about a tenth of current annual U.S. production. Potential environmental problems related to localized radioactivity and high radon levels in accessible abandoned mines are more likely to be important issues than uranium mining for land managers in the Custer National Forest for the foreseeable future.

OTHER POTENTIAL MINERAL RESOURCES

High-Purity Limestone

High-purity (high-calcium) limestone has been quarried for more than four decades at the Warren quarry (fig. 1), located about four miles northeast of Warren, Montana. The quarry is developed on private lands that bound the southwestern part of the Custer National Forest on the southwest flank of Big Pryor Mountain. Crushed and sized limestone is hauled by truck from the quarry to a railroad station at Warren. The limestone has been sold for sugar beet refining, agricultural, and construction uses. Sugar beet refineries, which have purchased the Warren quarry products, are located at Billings, Hardin, and Sidney in Montana and at Sheridan, Worland, and Lovell in Wyoming. Grouting material derived from the Warren quarry was used in the construction of the Yellowtail Dam on the Bighorn River (Chelini, 1965, p. 45-46). More recently, limestone from the Warren quarry has been used to mitigate acid mine drainage in Montana.

The Warren quarry has excavated the upper beds of the Madison Limestone Group near the dip-slope surface of Big Pryor Mountain. The limestones at the quarry dips about 3° to the southwest. Two analyses of limestones from the quarry have been described:

(1) The Great Western Sugar Co. of Billings, Mont., reported an analysis of 97.1 percent $CaCO_3$ (54.2 percent CaO), 1.4 percent $MgCO_3$ (0.67 percent MgO), and 1.5 percent insoluble material (silica, iron-oxide and alumina) (Perry, 1949, p. 36).

(2) Chelini (1965, p. 46) reported an analysis from Weaver Construction Co., the quarry operator, "that shows 2.85 percent silica, 0.29 percent ferric iron, 0.19 percent alumina, 53.78 percent calcium oxide, and 0.22 percent magnesia".

Similar limestones in the upper Madison Limestone Group are exposed in large areas of Big Pryor and East Pryor Mountains (see fig. 2). The marketability of the high-purity limestones in the National Forest lands would be primarily dependent upon access to the upper Madison Limestone strata, its proximity to a railroad, and the presence of suitable local markets. An economic analysis of the limestone terrains in the National Forest was beyond the scope of this study. However, a tract was delineated (fig. 15 and table 8) that shows the National Forest lands which contain exposed limestone beds of the upper Madison Limestone Group similar to those excavated at the Warren quarry. This limestone tract outlines only surface exposures of the upper Madison Limestone Group strata, because only exposed limestone beds were considered to be likely target sites for potential quarry ventures.

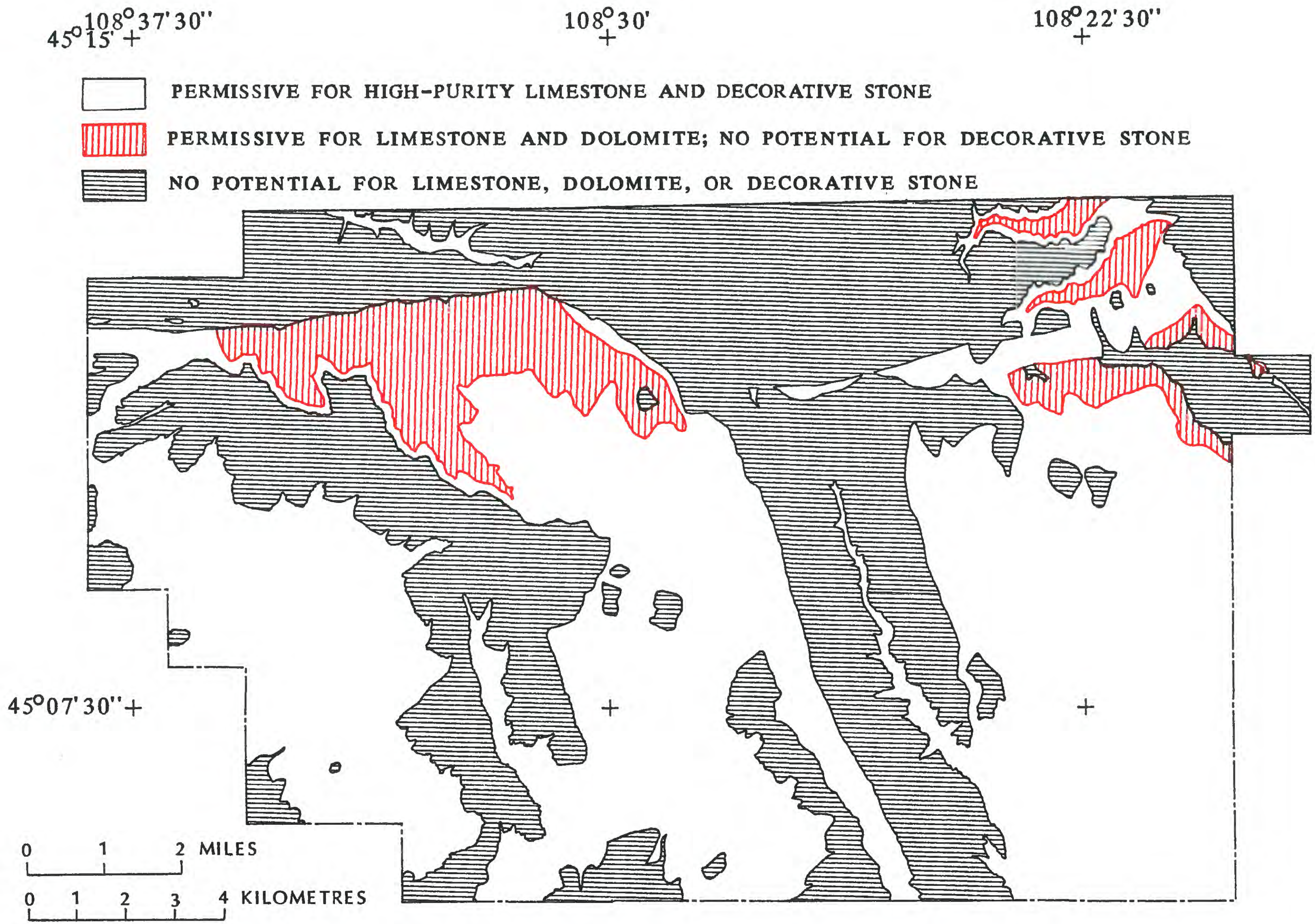


Figure 15. Map showing the availability of limestone, dolomite, and potential decorative stone in the Custer National Forest of the Pryor Mountains. The tracts shown in white indicate areas permissive for exposures of high-purity (high-calcium) limestone and decorative stone. Tracts marked by vertical lines show areas where limestone and dolomite, that may be used as crushed stone, are exposed; however, no potential for decorative stone exists in these areas. Areas shown by horizontal lines have no potential for exposures of limestone, dolomite, or decorative stone.

Table 8. Criteria for permissive tracts for high-purity limestone in the Pryor Mountains study area.

Tract name: Pryor Mountains High-Purity Limestone

Description: Beds of high-purity (high-calcium) limestone in upper parts of the Mississippian Madison Limestone Group.

Permitted deposit types
Limestone for industrial, chemical, and agricultural uses.

Area (km^2)	154
Geologic criteria	Surface exposures of the upper parts (240 ft) of the Mississippian Madison Limestone; excludes all rocks stratigraphically above or below the upper third of the Madison Limestone.
Geophysical signature	None
Geochemical signature	None
Mines, prospects, and mineral occurrences	The Warren Quarry, just west of the National Forest boundary, produces various limestone products from high-purity Madison Limestone. Published reserves for the Warren Quarry are 1 billion tons (for a 6 x 40 mile areal extent).
Comments	The limestone mined at the Warren Quarry extends eastward into the National Forest.

Decorative Stone

Strikingly attractive rock containing liesegang banding is closely associated with many of the uranium-vanadium deposits in the Pryor Mountains. Rhythmic precipitation of iron-oxides and silica produced this spectacularly banded rock in an undetermined number of the deposits. The liesegang banding appears to be concentrated in silicified sandy siltstones and silty sandstones of lower Amsden Formation strata that drape and bound the collapse structures of the upper Madison Limestone Group. The pervasive rhythmic character of the banding indicates that fluid saturation of the rock contributed to their formation (this alteration is discussed in greater detail in the preceding section entitled "Mineral Deposits and Associated Alteration"). One notable occurrence of these banded rocks is at the Old Glory mine site and its immediate vicinity (figs. 1 and 7). Typical outcrops may reach up to 10 ft in height and 50 ft in length.

The banded rocks do not host anomalous concentrations of uranium (appendix A) and therefore, when sorted from the uranium-mineralized material, would not present a potential environmental hazard. Thus, the liesegang banded rocks associated with the mineralized collapse structures have potential commercial use as decorative stone.

Although the banded rocks do not contain elevated concentrations of uranium, it is noteworthy that some of the abandoned mine workings adjacent to the liesegang-banded outcrops contain significant levels of radon gas. Thus, commercial ventures planning to extract these decorative stones should also investigate the potential for radon hazards in these work environments. Radon gas levels measured in inactive mines of the Little Mountain district (Buchanan and others, 1989) are discussed in a subsequent section entitled "Environmental Considerations".

The liesegang-banded rocks are typically highly fractured and broken into centimeter-scale fragments (fig. 7). While this rock is readily broken along the close-spaced fractures, each fragment is usually strongly silicified. Thus, the banded rocks may be used for colorful landscaping stones.

Those parts of the study area geologically permissive for hosting the banded rocks are shown in figure 15 and summarized in table 9. The permissive area (or tract) outlined for decorative stone represents the parts of the permissive tract for uranium-vanadium deposits in which the host rocks of the upper Madison Limestone Group are exposed. That is, the liesegang-banded rocks are in the same paleokarst horizon that hosts the uranium-vanadium deposits, which occurs in the upper 240 ft of the Madison Limestone Group. It was assumed, for the purposes of tract delineation, that only areas where decorative stones are exposed hold potential for quarry operations. Therefore, the criteria used to delineate permissive tracts for decorative stone was identifying the National Forest lands where the upper 240 ft of the Madison Limestone Group are exposed (fig. 15).

Limestone and Dolomite for Crushed Stone

The study area contains thick outcrops of limestones and dolomites that may represent potential sources of natural aggregates for construction-related uses. Ordinary limestones and dolomites are commonly crushed for use as aggregate (rock fragments) in concrete, in bituminous mixes (asphalt), and as roadstone. The national demand for such uses is significant. Langer and Glanzman (1993) note that "construction of 1 mile of four-lane interstate highway

Table 9. Criteria for permissive tracts for decorative stone in the Pryor Mountains study area.

Tract name: Pryor Mountains Decorative Stone

Description: Liesegang banding locally developed in silicified sandstone. These decorative rocks are associated with collapsed structures hosted by a paleokarst horizon in the upper parts of the Mississippian Madison Limestone Group.

<u>Permitted deposit types</u>
Decorative stone

Area (km^2)	154
Geologic criteria	Permissive tract includes upper 240 ft of exposed Mississippian Madison Limestone and is coextensive with permissive tracts for limestone and for uranium-vanadium solution-collapse breccia deposits. Spectacular Liesegang banding formed locally in fine-grained sandstones and brecciated sandstones; the banding is spatially associated with collapsed structures that host uranium-vanadium deposits in solution-collapse breccias.
Geophysical signature	None recognized
Geochemical signature	None recognized
Mines, prospects, and mineral occurrences	No production or exploration for this rock type. Good exposures of banded rocks are present at the Old Glory mine site and in drainages along the western edge of the study area.
Comments	Banded rocks are spatially associated with uranium-bearing rocks, but do not host anomalous concentrations of uranium and therefore constitute no environmental hazard for use as a decorative stone. However, some abandoned mine workings adjacent to the banded outcrops contain significant levels of radon gas and thus may effect the work environment.

requires 85,000 tons of aggregate". Also, "few homeowners realize that construction of an average six-room house requires 90 tons of aggregate or that construction of one average-size hospital or school requires 15,000 tons". They provide a fine summary of the geology, physical and chemical requirements of aggregate, and an overview of the supply, demand, and development considerations in the natural aggregate industry.

Limestone and dolomite comprise about 71% of the crushed stone production, that is, mined or quarried stone that has been crushed, washed, and sized (Langer and Glanzman, 1993). Harben and Bates (1990) note that:

> In the USA, about 2,500 quarries produce 600 million tons/year of limestone for crushed stone, and about 100 quarries mine 25 million tons/year of dolomite. In addition, of the 150 largest crushed-rock quarries in the USA, 99 produce limestone.

The tightly bound calcite grains of the typical limestone and dolomite produce a strong, tough, and hard crushed stone. Limestone or dolomite of the required physical characteristics—hard and dense, not too soft, absorptive, or friable—may be useful for crushed stone.

As described in an earlier section, the upper strata of the Madison Limestone Group in the study area contains high-purity (high-calcium) limestone which has been quarried near the study area for sugar beet refining, agricultural, and construction uses. The lower two-thirds (about 500 ft) of the Madison Limestone Group in the study area contains limestones and dolomitic limestones of lower purity. These rocks may have potential for a variety of uses as crushed rock. Similarly, underlying rock units, specifically the Jefferson Formation and the Bighorn Dolomite (figs. 2 and 3), may represent additional possible sources for crushed stone and light aggregate. It is assumed by this study that only exposed limestones and dolomites would be explored as potential sites for quarry operations, because overburden can restrict the economic viability of a crushed-rock quarry venture. Thus, permissive tracts (areas) for limestones and dolomites in the study area, shown in figure 15 and summarized in table 10, were drawn to include exposed rocks of (1) the lower two-thirds of the Madison Limestone Group, (2) the Jefferson Formation and, (3) the Bighorn Dolomite. It must be noted that some siliceous rocks, such as chert and flint, when used as aggregate in portland-cement concrete, can undergo adverse chemical reactions with the concrete, causing cracking and scaling (Langer, 1988, p. 13-14; Langer and Glanzman, 1993). Scattered nodules of chert occur within the high-purity limestones of the upper 90 to 155 ft of the Madison Limestone Group (Denson and Morrisey, 1954). The underlying 140-160 ft, included in this tract (fig. 15), contains "cherty dolomites and limestones that are locally siliceous" (Denson and Morrisey, 1954). In the lower 350 ft of the Madison Limestone Group, "chert is conspicuous by its absence" (Denson and Morrisey, 1954). Occasional chert nodules are found in the lower part of the Bighorn Dolomite (Blackstone, 1975). The tracts shown in figure 15 include the chert-bearing units, because the chert occurrences are inconsistent and require local detailed study for full evaluation.

As with the high-purity limestones and decorative stone, the economic viability of mining the low-purity limestones and dolomites for crushed stone is primarily dependent on the accessibility of the outcrop, its proximity to a railroad, and the support of a local market. Desired physical and chemical characteristics for these rock types, which are specific to the local market, will control the feasibility of a quarry investment in the area (for a discussion of considerations refer to Langer and Glanzman, 1993). An economic assessment of potential aggregate and specific target areas is beyond the scope of this study.

Table 10. Criteria for permissive tracts for limestone and dolomite in the Pryor Mountains study area.

Tract name: Pryor Mountains Limestone and Dolomite

Description: Beds of limestone and dolomite in (1) the lower two-thirds of the Madison Limestone Group, (2) the Jefferson Formation, and (3) the Bighorn Dolomite.

Permitted deposit types
Limestone and dolomite crushed for use as aggregate in portland-cement concrete, bituminous mixes (asphalt) or roadstone.

Area (km^2)	22
Geologic criteria	Surface exposures of the lower two-thirds (500 ft) of the Mississippian Madison Limestone, plus the Devonian Jefferson Formation and Ordovician Bighorn Dolomite; excludes all rocks stratigraphically above or below the units.
Geophysical signature	None
Geochemical signature	None
Mines, prospects, and mineral occurrences	No production or exploration for this rock type. Good exposures occur on the northern flank of Big Pryor Mountain.
Comments	An economic appraisal of this deposit type, beyond the scope of this study, should consider: (1) outcrop accessibility; (2) proximity to railroad stations or alternate transportation; (3) local markets; and (4) desired physical and chemical rock characteristics, which are specific to the market.

Sand and Gravel

A low potential exists for sand and gravel deposits in the study area. Thin deposits of alluvium occur in the Sage Creek channel (to the high-water mark) in the northwestern part of the National Forest (figs. 1 and 2; Blackstone, 1974c, 1974d). Most of the cobbles and pebbles in the alluvium consist of limestone, derived from the upper Madison Limestone Group, and mudstone and siltstone from the lower Amsden Formation. Silt and clay dominate over sand-size material in these alluvial deposits. These deposits are probably unsuited for use in Portland cement concrete or bituminous mixes due to the relatively low proportion of sand. Therefore, sand and gravel resources are very limited, perhaps nonexistent, in the National Forest.

Oil and Gas

The potential for oil and gas resources in the Custer National Forest of the Pryor Mountains is low. Several producing oilfields occur within 25 miles west and south of the study area; these include: (1) the Elk Basin field, located 15 miles to the southwest, in T. 9 S., R. 23 E., and T. 57-58 N., R. 99-100 W.; and (2) the Frannie field, located 8 miles to the south-southwest, in T. 58 N., R. 98 W. The principal producing formations in the Elk Basin and Frannie oilfields are Paleozoic rocks, such as the Tensleep Sandstone, the Madison Limestone Group, and the Jefferson Formation (Gautier and others, 1995). However, the Paleozoic rocks of the southern Pryor Mountains have been tilted and exposed, thereby breaching structural or stratigraphic traps for oil and gas reservoirs. Also, the Pryor Mountains serve as a major groundwater recharge area for the Bighorn Basin. Continual groundwater flow through the Pryor Mountains would flush hydrocarbon accumulations downdip through the uplifted blocks. In conclusion, there is a low probability of oil and gas reserves within the study area.

ENVIRONMENTAL CONSIDERATIONS

As noted earlier, very high concentrations of radon gas may occur in the abandoned uranium mines, and probably many of the cave systems, in the Pryor Mountains area. Buchanan and others (1989) conducted a study of radon gas levels in cave systems and inactive mines of the Little Mountain area. These caves and mines are developed in the upper 30 m (100 ft) of the Madison Limestone Group, as are similar features in the Pryor Mountains. Buchanan and others (1989) measured 12.6 to 708 picocuries/liter (pCi/l) radon in the atmosphere of five caves, using 24 to 48 hour test periods. Their tests of several inactive uranium mines discovered that "levels of radon within the mines are extraordinarily high, usually exceeding 10,000 pCi/l". They add that "one detector [in a mine] revealed a level of radon so high that it is unprecedented in the literature". They also found a distinct gradient of radon gas concentrations in cave passages that increased with their proximity to inactive mines. Similar radon gas concentrations should be anticipated in the cave passages and abandoned uranium mines of the Custer National Forest study area.

SUMMARY OF RESOURCE POTENTIAL

The Custer National Forest in the Pryor Mountains contains at least four types of mineral commodities with potential for development:

(1) Uranium-vanadium deposits hosted by shallow, breccia-filled collapse structures in the upper 190-240 ft of the Madison Limestone Group.
(2) High purity (high calcium) limestone in the upper Madison Limestone Group, quarried locally for agricultural and industrial uses.
(3) Liesegang-banded rocks, associated with the uranium-vanadium deposits, that may have commercial value as decorative stone. The banded rocks are commonly fractured but tough, and may be used as colorful landscaping gravels.
(4) Limestone and dolomite of varying purity in the Madison Limestone Group, the Jefferson Formation, and the Bighorn Dolomite. These may be crushed and used as light aggregate in concrete, bituminous mixes (asphalt), or road base material.

From 1956-70, uranium-vanadium ore was mined from about 40 small deposits (median size of 154 metric tons; fig. 12a and appendix B) in the southern Pryor Mountains area and nearby in the Little Mountain district. The ores were relatively high-grade, containing median grades of 0.26% U_3O_8 and 0.23% V_2O_5 (as determined by Atomic Energy Commission ore-buying stations; appendix B). Host structures for these deposits are chaotic breccia bodies that fill solution caverns of a paleokarst horizon in the upper Madison Limestone Group. Geologic observations and reasoning suggest that the undiscovered uranium deposits of the study area would be similar in character to the deposits discovered during the local uranium boom that began on Labor Day of 1955. About 80% of the Custer National Forest study area is permissive for undiscovered uranium-vanadium deposits of this type to a maximum depth of 550 ft (fig. 8).

Using a computer simulation, estimates of numbers of undiscovered uranium-vanadium deposits in the study area were combined with a grade and tonnage model for these deposits; the model was constructed from ore data obtained in 1956-70 from the producing mines of the region (fig. 12 and appendix B). The computer simulation generated a probability distribution representing the likelihood of a given amount of metal that may be present in undiscovered deposits of the study area. This method suggested a fifty percent chance of at least 50 undiscovered deposits, with at least 160 metric tons of uranium oxide (U_3O_8), at least 110 metric tons of vanadium oxide (V_2O_5), and at least 40,000 metric tons of mineralized rock (table 7). These values suggest that the study area may contain about five times as much ore as was produced from the Big Pryor Mountain area in the past and about as much as the combined total production from the Big Pryor Mountain area and the Little Mountain district (table 7).

Currently (1996), there is no uranium mining in Montana, whereas neighboring Wyoming is producing uranium. The active mines in Wyoming exploit deposits with geologic characteristics that are significantly different from those in the Pryor Mountains area. Although known uranium deposits of the Pryor Mountains area are smaller, they are higher in grade than most Wyoming deposits. Exploration for uranium in the Custer National Forest is unlikely in the foreseeable future. Active mining, exploration, and infrastructure exists for major uranium reserves elsewhere in the U.S. Land managers in the Custer National Forest may be most interested in the small uranium deposits because of their radioactivity and high radon levels in the abandoned mines.

High purity (high calcium) limestone has been mined for more than four decades at the Warren quarry (locality 1 on fig. 1), located on private lands adjacent to the southwestern part of the Custer National Forest. Crushed limestone from this quarry has been sold for sugar beet refining, agricultural, and construction uses. Similar limestone in layers of the upper Madison Limestone Group is exposed in half of the National Forest (white areas on fig. 15).

Rhythmic precipitation of iron-oxides and silica produced attractive banding (Liesegang-banding) in wallrocks adjacent to an undetermined number of the uranium-vanadium deposits in the Pryor Mountains. The area has no history of production or exploration of this rock type. However, these rocks have aesthetic and physical properties that may make it valuable for commercial uses. These rocks are typically highly fractured, while each fragment is usually strongly silicified. These characteristics make the rock most useful commercially as colorful landscaping gravel. Although closely associated with the uranium-vanadium deposits, the banded rocks do not contain elevated concentrations of uranium, and therefore would not present a potential environmental hazard. A notable outcrop of these banded rocks is at the Old Glory mine site (figs. 1 and 7).

Within the Custer National Forest, limestones and dolomites of lower purity—suitable for crushed stone and light aggregate—are common in the lower two-thirds of the Madison Limestone Group, plus the Jefferson Formation and the Bighorn Dolomite (figs. 2 and 3). These rocks are exposed in about 7% of the National Forest (red areas of fig. 15). They could be crushed and used as aggregate in concrete and bituminous asphalt or as roadstone.

An economic appraisal of the high-purity limestone, banded rocks (decorative stone), and low-purity limestone and dolomite (for concrete or light aggregate) is beyond the scope of this study. An economic evaluation should consider: (1) outcrop accessibility; (2) proximity to railroad stations or alternate transportation; (3) local markets; and (4) desired physical and chemical rock characteristics, all of which are specific to the market.

REFERENCES CITED

Alpha, A.G., and Fanshawe, J.R., 1954, Tectonics of northern Bighorn Basin area and adjacent south-central Montana, *in* Richards, P.W., ed., Pryor Mountains-northern Bighorn Basin, Montana, Billings Geological Society, annual field conference, 5th, September 9-11, 1954, Guidebook: Billings Geological Society, p. 72-79.

Baber, K.D., Fulkerson, F.B., Peterson, N.S., and Kauffman, A.J., Jr., 1958, The mineral industry of Montana, *in* Minerals yearbook, 1956, v. 3, area reports: Bureau of Mines, p. 686 and 695.

______1959, The mineral industry of Montana, *in* Minerals yearbook, 1957, v. 3, area reports: Bureau of Mines, p. 641 and 654.

Baedecker, P.A., and McKown, D.M., 1987, Instrumental neutron activation analyses of geochemical samples, *in* Baedecker, P.A., ed., Methods for geochemical analysis: U.S. Geological Survey Bulletin 1770, p. H1-H14.

Bell, K.G., 1963, Uranium in carbonate rocks: U.S. Geological Survey Professional Paper 474-A, p. A1-A29.

Blackstone, D.L., Jr., 1936, Structure and stratigraphy of the Pryor Mountains, Montana: Princeton, New Jersey, Princeton University, unpublished Ph.D. dissertation, 87 p.

______1940, Structure of the Pryor Mountains, Montana: Journal of Geology, v. 48, no. 6, p. 590-618.

______1974a, Preliminary geologic map of the Bear Canyon 7.5-minute quadrangle, Carbon County, Montana: Montana Bureau of Mines and Geology Open-File Report MBMG 66, 1 sheet, scale 1:24,000.

______1974b, Preliminary geologic map of the Big Ice Cave 7.5-minute quadrangle, Big Horn County, Montana: Montana Bureau of Mines and Geology Open-File Report MBMG 65, 1 sheet, scale 1:24,000.

______1974c, Preliminary geologic map of the Bowler 7.5-minute quadrangle, Carbon and Big Horn Counties, Montana: Montana Bureau of Mines and Geology Open-File Report MBMG 67, 1 sheet, scale 1:24,000.

______1974d, Preliminary geologic map of the Indian Spring 7.5-minute quadrangle, Carbon and Big Horn Counties, Montana: Montana Bureau of Mines and Geology Open-File Report MBMG 71, 1 sheet, scale 1:24,000.

______1974e, Preliminary geologic map of the Mystery Cave 7.5-minute quadrangle, Big Horn and Carbon Counties, Montana: Montana Bureau of Mines and Geology Open-File Report MBMG 70, 1 sheet, scale 1:24,000.

______1974f, Preliminary geologic map of the Red Pryor Mountain 7.5-minute quadrangle, Carbon and Big Horn Counties, Montana: Montana Bureau of Mines and Geology Open-File Report MBMG 68, 1 sheet, scale 1:24,000.

______1975, Geology of the East Pryor Mountain quadrangle, Carbon County, Montana: Montana Bureau of Mines and Geology Special Publication 69, 13 p., 1 plate, scale 1:24,000.

Broxton, D.E., 1979, Uranium hydrogeochemical and stream sediment reconnaissance data release for the Billings NTMS Quadrangle, Montana, including concentrations of forty-three additional elements: U.S. Department of Energy, Grand Junction Office Open-File Report GJBX 150 (79), 200 p., 6 plates.

Buchanan, J.P., Tekverk, R.W., and Fay, J.E., 1989, Radon gas concentration and distribution in cave systems on Little Mountain, Montana and Wyoming: Geological Society of America Abstracts with Programs, v. 21, no. 5, p. 61.

Butler, A.P., Jr., Finch, W.I., and Twenhofel, W.S., 1962, Epigenetic uranium in the United States: U.S. Geological Survey Mineral Investigations Resource Map MR-21, 1 sheet, scale 1:3,168,000, includes pamphlet, 42 p.

Campbell, N.P., 1977, Possible exhumed fossil caverns in the Madison Group (Mississippian) of the northern Rocky Mountains—A discussion: The NSS Bulletin, Quarterly Journal of the National Speleological Society, v. 39, no. 2, p. 43-54.

______1978, Caves of Montana: Montana Bureau of Mines and Geology Bulletin 105, 169 p., 2 plates.

Chamberlin, R.T., 1919, A peculiar belt of oblique faulting: Journal of Geology, v. 27, no. 8, p. 602-613.

Chelini, J.M., 1965, Limestone, dolomite, and travertine in Montana: Montana Bureau of Mines and Geology Bulletin 44, 53 p.

Cordell, Lindreth, Keller, G.R., and Hildenbrand, T.G., 1982, Bouguer gravity map of the Rio Grande Rift, Colorado, New Mexico, and Texas: U.S. Geological Survey Geophysical Investigations Series Map GP-949, scale 1:1,000,000.

Cox, D.P., and Singer, D.A., eds., 1986, Mineral deposit models: U.S. Geological Survey Bulletin 1693, 379 p.

Crowley, F.A., 1960, Directory of known mining enterprises, 1959, *with* List of active coal mines, 1959, by Thomas Morgan, *and [a] section on* The mineral industry of Montana in 1959, by F.B. Fulkerson and G.A. Kingston: Montana Bureau of Mines and Geology Bulletin 14, p. 9-10, 48, and 60.

Davis, J.C., 1986, Statistics and data analysis in geology (2d ed.): New York, John Wiley & Sons, 646 p.

Denson, M.E., Jr., and Morrisey, N.S., 1954, Subsurface correlations within the Madison Group, Bighorn and Wind River Basins, *in* Richards, P.W., ed., Pryor Mountains-northern Bighorn Basin, Montana, Billings Geological Society, annual field conference, 5th, September 9-11, 1954, Guidebook: Billings Geological Society, p. 44-49.

Egemeier, S.J., 1972, Cavern development by thermal waters with a possible bearing on ore deposition: Stanford, Calif., Stanford University, Ph.D. dissertation, 88 p.

Elliott, J.K., 1963, Cave occurrences in the Mississippian Madison Limestone of the Pryor Mountains, Montana: Billings Geological Society Papers, p. 13.

______1964, Cave occurrences in the Pryor Mountains, Montana [abs.]: Bulletin of the National Speleological Society, v. 26, no. 2, p. 65.

Finch, W.I., 1992, Descriptive model of solution-collapse breccia pipe uranium deposits: U.S. Geological Survey Bulletin 2004, p. 33-35.

Finch, W.I., Pierson, C.T., and Sutphin, H.B., 1992, Grade and tonnage model of solution-collapse breccia pipe uranium deposits: U.S. Geological Survey Bulletin 2004, p. 36-38.

Finnell, T.L., and Parrish, I.S., 1958, Uranium deposits and principal ore-bearing formations of the central Cordilleran foreland region: U.S. Geological Survey Mineral Investigations Map MF-120, 2 sheets, scale 1:750,000.

Foose, R.M., Wise, D.U., and Garbarini, G.S., 1961, Structural geology of the Beartooth Mountains, Montana and Wyoming: Geological Society of America Bulletin, v. 72, p. 1143-1172.

Fulkerson, F.B., Kauffman, A.J., Jr., and Knostman, R.W., 1962, The mineral industry of Montana, *in* Minerals yearbook, 1961, v. 3, area reports: Bureau of Mines, p. 624 and 631.

______1963, The mineral industry of Montana, *in* Minerals yearbook, 1962, v. 3, area reports: Bureau of Mines, p. 645.

Fulkerson, F.B., Kingston, G.A., and Kauffman, A.J., Jr., 1959, The mineral industry of Montana, *in* Minerals yearbook, 1958, v. 3, area reports: Bureau of Mines, p. 562 and 569.

______1960, The mineral industry of Montana, *in* Minerals yearbook, 1959, v. 3, area reports: Bureau of Mines, p. 595 and 601.

______1961, The mineral industry of Montana, *in* Minerals yearbook, 1960, v. 3, area reports: Bureau of Mines, p. 605 and 612.

Gautier, D.L., Dolton, G.L., Takahashi, K.I., and Varnes, K.L., eds., 1995, 1995 National Assessment of United States oil and gas resources—Results, methodology, and supporting data: U.S. Geological Survey Digital Data Series DDS-30 [CD-ROM].

Geach, R.D., and Chelini, J.M., 1963, Directory of known mining enterprises, 1962, *with* List of active coal mines, 1962, by Thomas Morgan, *and [a] section on* The mineral industry of Montana in 1962, by F.B. Fulkerson and R.W. Knostman: Montana Bureau of Mines and Geology Bulletin 33, p. 34-35, 43, and 73.

Hale, W.N, and Knostman, R.W., 1965, The mineral industry of Montana, *in* Minerals yearbook, 1964, v. 3, area reports—Domestic: Bureau of Mines, p. 612.

Hammarstrom, J.M., Zientek, M.L., and Elliott, J.E., eds., 1993, Mineral resource assessment of the Absaroka-Beartooth study area, Custer and Gallatin National Forests, Montana: U.S. Geological Survey Open-File Report 93-207, 296 p., 19 plates.

Hancock, E.T., 1919, Geology and oil and gas prospects of the Lake Basin field, Montana: U.S. Geological Survey Bulletin 691-E, p. 101-147.

______1920, Geology and oil and gas prospects of the Huntley field, Montana: U.S. Geological Survey Bulletin 711-G, p. 105-148.

Harben, P.W., and Bates, R.L., 1990, Industrial minerals—Geology and world deposits: London, Industrial Minerals Division Metal Bulletin Plc, p. 41-48.

Harris, R.E., 1983, Uranium and thorium in the Bighorn Basin, *in* Boberg, W.W., ed., Geology of the Bighorn Basin, Wyoming Geological Association, annual field conference, 34th, Billings, Mont., September 17-21, 1983, Guidebook: Wyoming Geological Association, p. 171-177.

Hart, O.M., 1958, Uranium deposits in the Pryor-Big Horn Mountains, Carbon County, Montana, and Big Horn County, Wyoming: United Nations 2nd International Conference on Peaceful Uses of Atomic Energy, Proceedings, v. 2, p. 523-526.

Hauptman, C.M., 1956, Uranium in the Pryor Mountain area of southern Montana and northern Wyoming: Uranium and Modern Mining, v. 3, no. 11, p. 14-21.

Imlay, R.W., 1954, Marine Jurassic Formations in the Pryor Mountains and northern Bighorn Mountains, Montana, *in* Richards, P.W., ed., Pryor Mountains-northern Bighorn Basin, Montana, Billings Geological Society, annual field conference, 5th, September 9-11, 1954, Guidebook: Billings Geological Society, p. 54-64.

International Association of Geodesy, 1967, Geodetic reference system, 1967: International Association of Geodesy Special Publication no. 3, 116 p.

Jarrard, L.D., 1957, Some occurrences of uranium and thorium in Montana: Montana Bureau of Mines and Geology Miscellaneous Contribution no. 15, 90 p.

Knostman, R.W., and Kauffman, A.J., Jr., 1964, The mineral industry of Montana, *in* Minerals yearbook, 1963, v. 3, area reports—Domestic: Bureau of Mines, p. 660.

Langer, W.H., 1988, Natural aggregates of the conterminous United States: U.S. Geological Survey Bulletin 1594, 33 p., 2 plates.

Langer, W.H., and Glanzman, V.M., 1993, Natural aggregate—Building America's future: U.S. Geological Survey Circular 1110, 39 p.

Lawson, D.C., 1979, Directory of mining enterprises for 1978, *with a section on* The mineral industry in Montana in 1978, by George Krempasky: Montana Bureau of Mines and Geology Bulletin 109, p. 22.

Ludwig, K.R., and Simmons, K.R., 1992, U-Pb dating of uranium deposits in collapse breccia pipes of the Grand Canyon region: Economic Geology, v. 87, no. 7, p. 1747-1765.

Maslyn, R.M., 1977, Recognition of fossil karst features in the ancient record—A discussion of several common fossil karst forms, *in* Veal, H.K., ed., Exploration frontiers of the Central and Southern Rockies: Rocky Mountain Association of Geologists, p. 311-319.

McEldowney, R.C., Abshier, J.F., and Lootens, D.J., 1977, Geology of uranium deposits in the Madison Limestone, Little Mountain area, Big Horn County, Wyoming, *in* Veal, H.K., ed., Exploration frontiers of the Central and Southern Rockies: Rocky Mountain Association of Geologists, p. 321-336.

McKelvey, V.E., Cressman, E.R., Sheldon, R.P., and Cheney, T.M., 1959, The Phosphoria, Park City, and Shedhorn Formations in the Western Phosphate Field, *in* McKelvey, V.E., and others, The Phosphoria, Park City and Shedhorn Formations in the Western Phosphate Field: U.S. Geological Survey Professional Paper 313-A, 47 p., 3 plates.

McKenna, M.C., and Love, J.D., 1972, High-level strata containing Early Miocene mammals on the Bighorn Mountains, Wyoming: American Museum Novitates, no. 2490, 31 p.

Merewether, E.A., 1960, Geologic map of the igneous and metamorphic rocks of Montana showing location of uranium deposits: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-311 (east half), 1 sheet, scale 1:500,000.

Patterson, C.G., Toth, M.I., Kulik, D.M., Esparza, L.E., Schmauch, S.W., and Benham, J.R., 1988, Mineral resources of the Pryor Mountain, Burnt Timber Canyon, and Big Horn tack-on wilderness study areas, Carbon County, Montana, and Big Horn County, Wyoming: U.S. Geological Survey Bulletin 1723, 15 p.

Perry, E.S., 1949, Gypsum, lime, and limestone in Montana: Montana Bureau of Mines and Geology Memoir no. 29, 45 p.

Plouff, Donald, 1977, Preliminary documentation for a FORTRAN program to compute gravity terrain corrections based on topography digitized on a geographic grid: U.S. Geological Survey Open-File Report 77-535, 45 p.

Pool, T.C., 1995, Uranium: Engineering and Mining Journal, v. 196, no. 3, p. 78-80.

Reheis, M.C., 1985, Evidence for Quaternary tectonism in the northern Bighorn basin, Wyoming and Montana: Geology, v. 13, no. 5, p. 364-367.

Richards, P.W., 1955, Geology of the Bighorn Canyon-Hardin area, Montana and Wyoming: U.S. Geological Survey Bulletin 1026, 93 p., 7 plates.

Roberts, A.E., 1966, Stratigraphy of Madison Group near Livingston, Montana, and discussion of karst and solution-breccia features: U.S. Geological Survey Professional Paper 526-B, 23 p.

Root, D.H., Menzie, W.D., and Scott, W.A., 1992, Computer Monte Carlo simulation in quantitative resource estimation: Nonrenewable Resources, v. 1, no. 2, p. 125-138.

Rubey, W.W., 1943, Vanadiferous shale in the Phosphoria Formation, Wyoming and Idaho [abs.]: Economic Geology, v. 38, no. 1, p. 87.

Sahinen, U.M., 1962, Fluorspar deposits in Montana: Montana Bureau of Mines and Geology Bulletin 28, p. 34-35.

Sandberg, C.A., 1965, Nomenclature and correlation of lithologic subdivisions of the Jefferson and Three Forks Formations of southern Montana and northern Wyoming: U.S. Geological Survey Bulletin 1194-N, p. N1-N18.

Sando, J.E., 1974, Ancient solution phenomena in the Madison Limestone (Mississippian) of north-central Wyoming: U.S. Geological Survey Journal of Research, v. 2, no. 2, p. 33-41.

Schultz, R.L., 1969, Caves of the Bighorn-Pryor Mountains of Montana and Wyoming: National Speleological Society Guidebook Number 10, 28 p.

Singer, D.A., 1993a, Basic concepts in three-part quantitative assessments of undiscovered mineral resources: Nonrenewable Resources, v. 2, no. 2, p. 69-81.

______1993b, Development of grade and tonnage models for different deposit types, *in* Kirkham, R.V., Sinclair, W.D., Thorpe, R.I., and Duke, J.M., eds., Mineral deposit modeling: Geological Association of Canada Special Paper 40, p. 21-30.

Stone, D.S., 1967, Theory of Paleozoic oil and gas accumulation in Bighorn basin, Wyoming: American Association of Petroleum Geologists Bulletin, v. 51, no. 10, p. 2056-2114.

Stout, Koehler, and Ackerman, Walter, 1959, Directory of known mining enterprises, 1958, *with [a] chapter on* The mineral industry of Montana in 1958 (preliminary annual report) by K.D. Baber, G.A. Kinston, and N.S. Peterson: Montana Bureau of Mines and Geology Bulletin 10, p. 12-13, 72, and 75.

Sweeney, R.E., 1990, IGRFGRID—A program for creation of a total magnetic field (International Geomagnetic Reference Field) grid representing the earth's main magnetic field: U.S. Geological Survey Open-File Report 90-45a-b, 37 p.

U.S. Defense Mapping Agency Aerospace Center, 1974, World Relative Gravity Reference Network, North America, part 2: Defense Mapping Agency Aerospace Center Reference Publication 25, with supplement updating Gravity Standardization Net, 1971, 1635 p.

U.S. Department of Energy, 1982, Billings Quadrangle—Residual intensity magnetic anomaly contour map: U.S. Department of Energy Open-File Report GJM-096, pl. 4.

Verbeek, E.R., Grout, M.A., and Van Gosen, B.S., 1988, Structural evolution of a Grand Canyon breccia pipe—The Ridenour copper-vanadium-uranium mine, Hualapai Indian Reservation, Coconino County, Arizona: U.S. Geological Survey Open-File Report 88-006, 75 p.

Verrengia, J.B., 1993, Zeroing in on radiation sources: Denver, Colo., Rocky Mountain News, Dec. 17, 1993, p. 48A.

Warchola, R.J., and Stockton, T.J., 1982, National Uranium Resource Evaluation, Billings quadrangle, Montana: U.S. Department of Energy publication No. PGJ/F-015(82), prepared for the U.S. Department of Energy, Grand Junction Colo., by Bendix Field Engineering Corp., Grand Junction Operations, 33 p., 25 plates.

Weidman, R.M., 1965, The Montana lineament, *in* Fields, R.W., and Shapard, Warren, eds., Geology of the Flint Creek Range, Montana, Billings Geological Society, annual field conference, 16th, August 12-14, 1965, Guidebook: Billings Geological Society, p. 137-143.

Wenrich, K.J., Chenoweth, W.L., Finch, W.I., and Scarborough, R.B., 1989, Uranium in Arizona, *in* Jenney, J.P., and Reynolds, S.J., eds., Geologic evolution of Arizona: Arizona Geological Society Digest 17, p. 759-794.

Wenrich, K.J., and Sutphin, H.B., 1989, Lithotectonic setting necessary for formation of a uranium rich, solution collapse breccia pipe province, Grand Canyon region, Arizona, *in* Metallogenesis of uranium deposits, Proceedings of a technical committee meeting on metallogenesis of uranium deposits organized by the International Atomic Energy Agency and held in Vienna, 9-12 March, 1987: Vienna, International Atomic Energy Agency publication IAEA-TC-542/20, p. 307-344. (Also released as U.S. Geological Survey Open-File Report 89-173, 1989, 33 p.).

Wenrich, K.J., Verbeek, E.R., Sutphin, H.B., Modreski, P.J., Van Gosen, B.S., and Detra, D.E., 1990, Geology, geochemistry, and mineralogy of the Ridenour mine breccia pipe, Arizona: U.S. Geological Survey Open-File Report 90-0504, 66 p.

Whitlock, J.D., 1979, Utilizing the National Uranium Resource Evaluation (NURE) program's geochemical data—A case study of the Billings quadrangle, Montana/Wyoming: Montana College of Mineral Science and Technology, M.S. thesis, 100 p.

Whitlock, J.D., and Van Eeckhout, E.M., 1980, Utilizing the geochemical data from the National Uranium Resource Evaluation (NURE) program—A case study of the Billings quadrangle, Montana/Wyoming: U.S. Department of Energy, Grand Junction Office Open-File Report GJBX 120 (80), 99 p.

Wilson, C.W., Jr., 1936, Geology of the Nye-Bowler lineament, Stillwater and Carbon Counties, Montana: American Association of Petroleum Geologists Bulletin, v. 20, part 2, no. 9, p. 1161-1188.

______1938, Revision of stratigraphy of Dry Creek and Golden structures, Carbon County, Montana: American Association of Petroleum Geologists Bulletin, v. 22, no. 1, p. 106-108.

Wilson, W.H., 1966, Uranium, thorium, and rare earths, *in* Osterwald, F.W., Osterwald, D.B., Long, J.S., Jr., and Wilson, W.H., eds., Mineral resources of Wyoming: Geological Survey of Wyoming Bulletin 50, p. 201-231.

Appendix A. Geochemical analyses of ten samples representing: (1) uranium-vanadium deposits at the Swamp Frog and Dandy mines (figs. 1 and 6); and (2) liesegang-banded rocks near the Old Glory mine (fig. 7). The data listed were determined by instrumental neutron activation analyses. Analyses were performed by James Budahn of the U.S. Geological Survey laboratories in Denver, Colorado. The analytical technique is described by Baedecker and McKown (1987). Prior to the analyses, each sample was pulverized to a rock flour that passed through a 150 mesh screen opening (less than 0.0059 inch). About one gram of pulverized sample was irradiated in each analysis. [pct, percent of whole rock volume; ppm, parts per million; PPB, parts per billion; cv, the reduced counting statistic error exceeded 30 percent; ic, interference correction exceeded 60 percent]

Element	Sample 001-V93	Sample 002A-V93	Sample 002B-V93	Sample 002C-V93	Sample 002D-V93	Sample 002E-V93	Sample 002F-V93	Sample 014A-V92	Sample 014B-V92	Sample 015A-V92
Al, pct	12.2	2.89	0.77	0.77	2.61	2.14	2.92	2.48	0.82	1.01
As, ppm	3040.	76.5	108.	49.7	78.8	88.2	53.6	1480.	602.	348.
Au, PPB	11.1	298.	23.9	3.12	4.01	2.40	2.47	ic	28.0	18.6
Ba, ppm	265.	525.	25900.	156.	1420.	9540.	514.	12900.	11400.	3940.
Ca, pct	0.87	0.29	0.09	0.20	0.27	2.71	0.11	0.30	0.25	23.4
Ce, ppm	295.	38.5	11.8	27.2	37.4	31.2	24.8	142.	ic	ic
Co, ppm	4.41	1.07	4.64	0.96	1.26	1.22	2.52	1.49	2.52	24.6
Cr, ppm	48.4	80.5	113.	251.	78.3	84.9	55.9	43.8	68.2	35.7
Cs, ppm	4.15	0.43	0.44	0.47	0.76	1.16	2.10	0.58	2.51	1.81
Eu, ppm	2.69	0.73	0.43	0.53	0.85	0.60	0.56	2.89	0.45	1.23
Fe, ppm	3830.	23800.	14600.	3920.	17600.	19200.	13800.	6650.	14400.	11400.
Gd, ppm	7.97	3.22	1.97	2.27	3.08	2.64	2.67	7.89	6.24	8.60
Hf, ppm	0.97	3.22	1.49	0.65	2.74	2.49	2.14	0.29	0.57	0.74
Hg, ppm	2.00	1.30	1.10	1.20	0.40	0.40	0.40	1.20	2.30	6.10
K, ppm	10100.	1230.	cv	2020.	cv	cv	5130.	cv	cv	cv

Appendix A. Continued.

Element	Sample 001-V93	Sample 002A-V93	Sample 002B-V93	Sample 002C-V93	Sample 002D-V93	Sample 002E-V93	Sample 002F-V93	Sample 014A-V92	Sample 014B-V92	Sample 015A-V92
La, ppm	cv	20.3	6.69	8.72	20.7	16.9	12.0	cv	ic	ic
Lu, ppm	ic	0.22	0.10	0.17	0.20	0.19	0.13	0.12	ic	0.48
Mg, pct	cv	0.11	0.12	0.05	0.11	0.02	0.13	0.46	1.82	1.13
Mn, ppm	22.5	17.6	30.9	12.5	13.3	17.2	10.3	9.86	49.6	55.9
Na, ppm	736.	117.	110.	118.	100.	113.	162.	201.	ic	165.
Nd, ppm	cv	20.4	8.11	23.8	20.9	16.5	14.8	cv	ic	ic
Ni, ppm	68.2	8.67	17.2	21.9	9.95	10.9	7.77	49.4	14.0	149.
Rb, ppm	22.2	3.41	3.96	6.45	5.96	8.43	23.0	3.73	8.97	14.7
Sb, ppm	24.0	1.65	10.2	5.18	1.05	3.11	1.40	60.6	164.	18.7
Sc, ppm	13.3	3.82	1.53	1.89	3.69	3.63	6.12	8.89	6.78	5.53
Se, ppm	3.20	7.10	22.7	5.10	8.30	15.4	5.60	2.90	7.70	10.3
Sm, ppm	21.0	4.36	2.09	3.83	4.77	3.57	3.34	21.1	11.7	12.6
Sr, ppm	1640.	342.	794.	172.	443.	415.	539.	801.	501.	338.
Ta, ppm	0.21	0.51	0.19	0.16	0.45	0.42	0.42	0.03	0.11	0.17
Tb, ppm	0.61	0.36	0.27	0.30	0.37	0.29	0.31	0.64	0.45	1.11
Th, ppm	1.84	6.01	1.33	1.30	5.67	4.41	4.07	91.7	0.92	1.89
Ti, pct	0.05	0.22	0.07	0.06	0.18	0.17	0.20	0.02	0.16	0.24
Tm, ppm	0.11	0.22	0.11	0.18	0.20	0.19	0.15	ic	0.18	0.53
U, ppm	2190.	5.58	5.94	52.4	4.53	4.88	12.5	866.	16200.	9860.
V, ppm	770.	810.	322.	199.	378.	393.	575.	626.	7190.	11000.

Appendix A. Continued.

Element	Sample 001-V93	Sample 002A-V93	Sample 002B-V93	Sample 002C-V93	Sample 002D-V93	Sample 002E-V93	Sample 002F-V93	Sample 014A-V92	Sample 014B-V92	Sample 015A-V92
W, ppm	4.20	0.97	1.06	1.01	1.18	1.11	<0.50	2.92	47.7	32.9
Yb, ppm	0.44	1.35	0.65	1.17	1.26	1.20	0.88	0.75	0.85	3.29
Zn, ppm	35.2	7.09	9.54	9.79	11.2	13.2	16.7	9.40	61.2	489.
Zr, ppm	ic	109.	cv	ic	94.8	93.1	cv	ic	ic	ic

Sample number	Sample description
001-V93	Example of a mixed sand-silt layer in the collapse structure at the Swamp Frog mine entrance (fig. 6). This layer is friable, hematitic and contains disseminated concentrations of tyuyamunite.
002A-V93	Liesegang-banded, silicified breccia collected near the Old Glory mine (sample site shown in figure 5). Breccia clasts are mainly sandy mudstone, with less common silty sandstone, derived from the lower Amsden Formation.
002B-V93	Hematitic, silicified breccia with chert nodules collected near the Old Glory mine (fig. 5). Larger vugs in the breccia are often lined by yellow, platy, medium-grained barite crystals. Breccia clasts are mainly sandy siltstones, derived from the lower Amsden Formation.
002C-V93	Silicified, iron oxide-stained breccia with rounded chert nodules; collected near the Old Glory mine (fig. 5). Most clasts are mudstones of the lower Amsden Formation mixed with lesser rocks of the Madison Limestone (chert).
002D-V93	Hematitic and silicified, liesegang-banded breccia collected near the Old Glory mine (fig. 5). Larger vugs are often lined by yellow, platy, medium-grained barite crystals. Clasts are mainly sandy siltstones and claystones, derived from the lower Amsden Formation.

Appendix A. Continued.

Sample number	Sample description
002E-V93	Hematitic, silicified breccia with chert nodules collected near the Old Glory mine (fig. 5). Large vugs are commonly lined by yellow, platy, medium-grained barite crystals.
002F-V93	Hematitic, silicified breccia composed of small clasts (less than 1 cm across); contains chert nodules. Sample was collected near the Old Glory mine (fig. 5). Large vugs are commonly lined by yellow, platy, medium-grained barite crystals.
014A-V92	Example of bedding-parallel uranium-vanadium mineral deposits in the collapsed cavern at the Swamp Frog mine. Collected at the mine entrance (fig. 6). The layer sampled consists mainly of friable siltstone with interstitial hydrous iron oxides (goethite, limonite), bleaching, moderate silicification, and disseminated tyuyamunite.
014B-V92	Sample of the uranium-vanadium ore extracted from the Swamp Frog mine (fig. 6). The sample is a friable, sandy breccia of the cavern-fill material; it contains moderate silicification and about 2-3 percent interstitial, amorphous hematite. The sample hosts concentrations of bright yellow ore minerals identified (by X-ray diffraction techniques) as tyuyamunite and uranophane.
015A-V92	Sample of uranium-vanadium ore from the Dandy mine (fig. 1). The friable, heterolithic, cave-fill breccia hosts abundant yellow uranium-vanadium minerals, including metatyuyamunite. Very fine-grained, purple fluorite commonly lines the walls of small vugs. The uranium-vanadium minerals are mainly hosted by a calcite-rich cave-fill material with fine-grained sand grains; this rock contains about 2 percent amorphous, interstitial hematite.

Appendix B. List of ore production data and their logarithmic transformations for the Pryor Mountains area and Little Mountain mining districts. These data were used to construct grade-tonnage models for the Pryor Mountains area uranium-vanadium deposits. For "Location", PMD indicates the Pryor Mountains district, LMD indicates Little Mountain district. nr, not reported.

Deposit name	Location	Short Tons	Metric Tons	Log (Metric Tons)	%U_3O_8	Log (%U_3O_8)	%V_2O_5	Log (%V_2O_5)
BOB 6	PMD	229.780	208.456	2.319	0.160	-0.796	n.r.	--
BROKEN HEART 8	LMD	32.260	29.266	1.466	1.100	0.041	0.640	-0.194
BUCKHORN 2	PMD	14.840	13.463	1.129	0.070	-1.155	0.190	-0.721
DANDY	PMD	2566.280	2328.129	3.367	0.240	-0.620	0.060	-1.222
DANDY & PERC 14	PMD	407.500	369.684	2.568	0.270	-0.569	n.r.	--
DRINKARD	PMD	138.450	125.602	2.099	0.270	-0.569	0.610	-0.215
FRAN 2	PMD	68.730	62.352	1.795	0.160	-0.796	n.r.	--
FRAN 3	PMD	314.690	285.487	2.456	0.150	-0.824	0.002	-2.699
FUSNER	LMD	5000.000	4536.000	3.657	0.800	-0.097	n.r.	--
HIGH NOON	LMD	66.320	60.166	1.779	0.090	-1.046	n.r.	--
HIGH NOON 3	LMD	54.930	49.832	1.698	1.530	0.185	n.r.	--
HORSESHOE 9	LMD	8.590	7.793	0.892	0.310	-0.509	0.300	-0.523
HORSESHOE JOHN	LMD	34.120	30.954	1.491	0.090	-1.046	0.160	-0.796
JET 5	LMD	173.540	157.435	2.197	0.150	-0.824	n.r.	--
JET 8	LMD	1516.790	1376.032	3.139	0.380	-0.420	n.r.	--
JOHN 35	LMD	65.140	59.095	1.772	0.160	-0.796	n.r.	--
KEY	PMD	10.420	9.453	0.976	0.050	-1.301	0.180	-0.745
LEO	LMD	103.520	93.913	1.973	0.290	-0.538	n.r.	--
LEO 16	LMD	26.770	24.286	1.385	0.390	-0.409	n.r.	--
LEO 6	PMD	342.650	310.852	2.493	0.170	-0.770	n.r.	--
MARIE 2	PMD	691.700	627.510	2.798	0.130	-0.886	n.r.	--
MIDNIGHT	LMD	12.470	11.313	1.054	1.060	0.025	n.r.	--
MIKE	LMD	968.450	878.578	2.944	0.260	-0.585	n.r.	--

Appendix B. Continued.

Deposit name	Location	Short Tons	Metric Tons	Log (Metric Tons)	%U_3O_8	Log (%U_3O_8)	%V_2O_5	Log (%V_2O_5)
MIKE 10	LMD	12590.940	11422.501	4.058	0.460	-0.337	0.800	-0.097
MIKE 8	LMD	5768.630	5233.301	3.719	0.280	-0.553	n.r.	--
OLD GLORY	PMD	696.780	632.119	2.801	0.760	-0.119	0.570	-0.244
PERC 14	PMD	1366.630	1239.807	3.093	0.180	-0.745	n.r.	--
PERC 3	PMD	187.170	169.801	2.230	0.680	-0.167	1.270	0.104
PERC 4	PMD	57.420	52.091	1.717	0.250	-0.602	n.r.	--
PERC GROUP	PMD	317.130	287.700	2.459	0.410	-0.387	1.100	0.041
SANDRA	PMD	51.030	46.294	1.666	0.210	-0.678	0.070	-1.155
SNAIL 2	PMD	262.380	238.031	2.377	0.200	-0.699	0.550	-0.260
SURPRISE 6	PMD	45.760	41.513	1.618	0.030	-1.523	0.130	-0.886
SWAMP FROG	PMD	73.710	66.870	1.825	0.210	-0.678	0.010	-2.000
SWAMP FROG 34	PMD	453.000	410.962	2.614	0.270	-0.569	0.270	-0.569
TRI PACER	LMD	881.880	800.042	2.903	0.410	-0.387	0.090	-1.046
TRI PACER 4	LMD	11.850	10.750	1.031	0.460	-0.337	1.000	0.000
TRI PACER 5	LMD	165.360	150.015	2.176	0.470	-0.328	0.185	-0.733

Summary Statistics

	Metric Tons of Ore (38 deposits)	percent U_3O_8 (38 deposits)	percent V_2O_5 (20 deposits)
10th percentile	1,986	0.79	1.05
50th percentile (median value)	154	0.26	0.23
90th percentile	12	0.09	--

GEOLOGIC TIME CHART

Terms and boundary ages used in this report

EON	ERA	PERIOD		EPOCH	BOUNDARY AGE IN MILLION YEARS
Phanerozoic	Cenozoic	Quaternery		Holocene	0.010
				Pleistocene	1.7
		Tertiary	Neogene Subperiod	Pliocene	5
				Miocene	24
			Paleogene Subperiod	Oligocene	38
				Eocene	55
				Paleocene	66
	Mesozoic	Cretaceous		Late	96
				Early	138
		Jurassic		Late Middle Early	205
		Triassic		Late Middle Early	~ 240
	Paleozoic	Permian		Late Early	290
		Carboniferous Periods	Pennsylvanian	Late Middle Early	~ 330
			Mississippian	Late Early	360
		Devonian		Late Middle Early	410
		Silurian		Late Middle Early	435
		Ordovician		Late Middle Early	500
		Cambrian		Late Middle Early	~ 570[1]
Proterozoic	Late Proterozoic				900
	Middle Proterozoic				1600
	Early Proterozoic				2500
Archean	Late Archean				3000
	Middle Archean				3400
	Early Archean				3800?
pre-Archean[2]					4550

[1] Rocks older than 570 m.y. also called Precambrian, a time term without specific rank.

[2] Informal time term without specific rank.