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Paradox Basin Uranium-Vanadium Deposits: History and Significance of Geological Research

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Abstract

This article describes and analyzes the history of research into the origins of the uranium-vanadium(-radium) deposits of the Paradox Basin. For several decades after their discovery in 1881, research was desultory and almost entirely descriptive, fluctuating with demand for vanadium and radium. Systematic geologic descriptions, accumulated between 1910 and 1950, supported rapid progress during a government-backed surge of research in the 1950s, when uranium was the chief commodity of interest. Most of the major theoretical innovations date from this decade, including the use of concepts from solution chemistry to identify the conditions and constrain the processes of deposit formation and alteration. Research from this time was highly influential in geology at large, providing the model for sandstone-hosted uranium deposits worldwide and numerous new minerals and mineral structures. After about 1960, mine production remained high but research dwindled, and most new advances were to the details of the hydrothermal model of ore formation rather than its core concepts. By the end of the 1960s, the deposits were understood to have formed at the mixing interface of an oxidized, metal-bearing water with a reducing fluid of debated origin. Research was desultory over the ensuing decades; the source of the metals and the nature of the chemicals constituting the trap were not clearly established. They remain questions today, as do factors like the relationship between ore mineralization and the geologic history of the basin. Analysis of the research history identifies the introduction of solution-chemistry concepts (Pourbaix diagrams) as the most important innovation contributing to progress, with advances in analytical technology playing a lesser role and computers contributing little. A solid foundation of field observations has been necessary to all advances. The patterns of research compared to larger national/global events suggest that geological research makes the most progress when conducted in the framework of a long-term, sustained program independent of commodity prices, and when theories are constructed only after large amounts of observational data are present. The current research focus has shifted from the deposits' characteristics and metallogenesis to what insights they can provide into basinal fluid systems and other basinwide events.

Keywords Paradox Basin · Sandstone-Hosted Uranium Deposits · Radium · Uranium · Vanadium · History of Geology

1 Introduction

1.1 Origins and Objectives of this Article

The history of geological thinking is too often reduced to listing great ideas, books, or papers which seem to have arrived out of nowhere. In contrast, historical evolutions in Paradox Basin uranium (U) and vanadium (V) deposit geology can be clearly related to evolutions in larger-scale scientific methodology and to events in the world at large. This provides a better-than-usual opportunity to examine how geological insights are obtained and geological theories are constructed.

Paradox Basin U-V deposits may be an example of a subject where key areas of research are probably over, though others remain latent. Further serious study of the deposits' field geology, macro-scale characteristics, and petrography is limited by extensive reclamation of mines and dumps and the disappearance of most drill core. The geological community has mostly ignored Paradox Basin U-V for at least three decades now, making the body of research distant enough to be examined with more objectivity than most geological research topics can support. I undertake this examination in

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order to identify how scientific research is partly driven by external political, economic, and social events; how geologists' ideas about a new deposit type evolve over time in the context of prevailing ideas in the larger field of geology; what role new concepts and tools can (and cannot) play in advancing economic geology; and how advances made in the geology of one region ripple outward to affect the geosciences as a whole.

1.2 History and Global Context

In 1881, prospector Tom Talbert sent a sample of strange yellow rock from the Roc Creek area in Montrose County, CO to an assayer in Leadville for analysis (Chenoweth [1]). This was the first record of the Paradox Basin U-V deposits, but probably not the first observation. Settlers had noticed the carnotite by 1880, and it is virtually certain that Navajo, Ute, and other Indian groups in the region had, too (Chenoweth [2]). An early account reports that the Navajo had traditionally prepared black dyes by heating carnotite with pinyon sap long before 1898, but without giving dates or other specifics, and this "uranium black" is not known from preserved archaeological artifacts (O'Connell [3]).

The Leadville assayer's repeated efforts to analyze the samples proved unsuccessful and Talbert's claims passed through several different hands. Around 1887 the matter reached Charles Poulot, a French chemist then living in Denver. Poulot was apparently interested enough to visit a Montrose County carnotite-azurite-malachite deposit estimated to contain about 10 tons of ore. He took samples, determined that they contained valuable V, and passed some of them on to two French mineralogists, Charles Friedel and Edouard Cumenge. After trial, error, and consultation with Pierre and Marie Curie, they succeeded in determining the composition of what proved to be a new mineral: carnotite (Friedel and Cumenge [4]).

Up to this point there had been prospecting, but little mining, interest in the Colorado Plateau ores. (This seems to be the overall consensus but is disputed by one source, which states that Poulot and a colleague produced 15,000 lbs of uranium oxide from the Paradox Valley between 1899 and 1903; Tyler [5].) World demand for U and V was then small and easily supplied by Jachymov pitchblende (recovered while mining for silver) and Mexican vanadinite. But Wilhelm Roentgen had started experimenting with medical X-ray images in 1895, and in 1898 the Curies discovered radium (Ra), whose chloride could emit 900 times the radioactivity of U chloride (Curie et al. [6]). The public imagination was enthralled with the idea of radiation. Almost overnight there emerged a market for radium. In these early years nearly all of it was for X-rays, although luminous paint started to capture a large market share after a while (Robison [7]). A surprisingly large fraction also went to patent medicines that promised to harness the mysterious new form of energy to improve various aspects of human health. This went on for several decades until the early 1930s (Fig. 1). Around that time, a combination of lawsuits from factory workers sickened by radium paint, plus a high-profile fatality from drinking too many radium-based male enhancement potions, started to cause a decline in radium demand (Macklis [8]).

Early in the 1900s both V and Ra also became strategic resources thanks to an all-consuming arms race among the industrialized empires of Europe. The British, French, Germans, Austrians, and probably others as well, were experimenting with new armor and gun steel alloys. By about 1905 their work had established that V made an excellent hardening alloy in steel (U steel was also tested but turned out to be less effective and more expensive; Gillett and Mack [9]). Meanwhile, the potential military advantages of Ra were intriguing enough for the Austro-Hungarian government to assume control of the Jachymov mines, install direct government supervision, and forbid the export of Ra ores (Parsons [10]; Lubenau [11]).

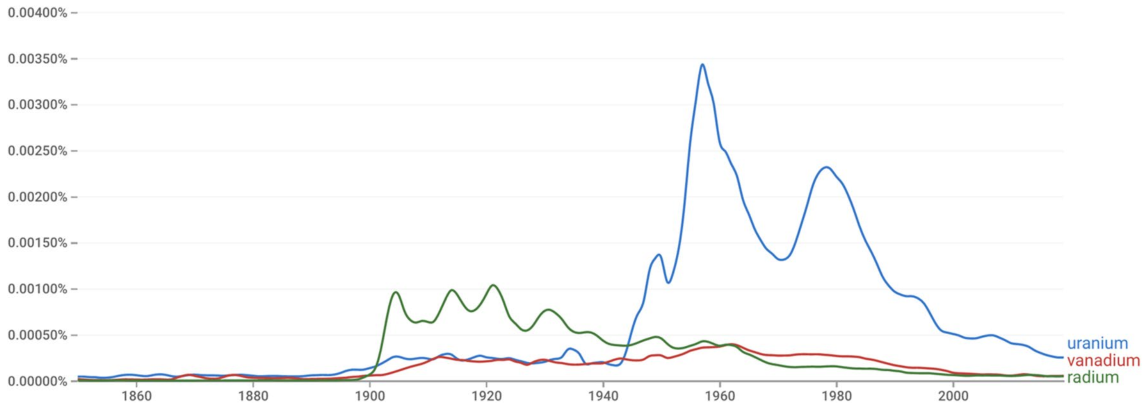

Fig. 1 Google NGram view of mentions of uranium (blue), vanadium (red), and radium (green) in digitized literature from 1860 to 2019 (case-insensitive, smoothing = 1). Google NGrams represent the percent frequencies of each search term's occurrence in Google's database of digitized literature of all types

With Jachymov ores off the market, other European nations established Ra-processing facilities of their own and scrounged around for a viable source. Small quantities of pitchblende and autunite were discovered in Cornwall, Saxony, and Mexico, but the most extensive finds were in western Colorado (Tyler [5]). From 1901–1904, carnotite was mined from the Salt Wash-hosted ores in the Slick Rock district of the Uravan belt and sold inside the USA and abroad for Ra (Boltwood [12]; Chenoweth [1]). Most of it went straight to Europe (Tyler [5]). The U and V were also recovered and sold separately, again mostly to Europe (Robison [7]).

Later in the decade, V steel percolated from European military research into US civilian life. In 1904, a French automobile participating in a car race in Florida crashed. A visiting Michigan observer named Henry Ford noticed that its thin steel components had not broken despite sustaining severe damage (Lubenau [11]). In an instant Ford saw a solution to the automaker's ongoing dilemma: how to build a car that could withstand the era's rough roads without requiring prohibitive masses of steel. Acquiring a sample of the crashed car, he had it analyzed and was informed that it was the new V steel, which no one in the USA then knew how to make. Undeterred, Ford imported a metallurgist who had helped run the British experiments. After a year of trial and error, in March 1907 the first viable American V steel emerged from the converter (Lubenau [11]). It made about 50% of the steel in each Model T automobile.

Most V at this time was coming from Minas Ragra in Peru, but the American company operating the Peruvian mines kept a sharp eye out for both V and Ra opportunities closer to home. Late in the 00's, the company that soon became Standard Chemical amassed a large land position encompassing several hundred carnotite claims around Paradox Valley (Robison, 2015 [7]). Again starting with imported European expertise, Standard began producing V in 1911 from the Monogram Mesa and Bull Canyon areas in the Uravan belt (Robison [7]).

It proved a bad time to get into the business. World War I broke out in August 1914, and neutrality concerns stopped the international sale of carnotite and its products (Coffin et al. [13]). At the same time the US government also tightened restrictions on Ra mining. Until 1914 all Ra mines had been privately owned and operated, but after that date new discoveries on public lands belonged to the government. Prospectors could exploit them but had to sell the produce to the government at prices set by the Department of the Interior (Tyler [5]). Fortunately for most of the miners, there were no such restrictions on V. When the USA entered the war in earnest in 1917, demand for V steel shot up. The market recovered, and in 1919 both demand and production from the Paradox Basin ores reached a new high (Coffin et al. [13]).

The respite was brief. In 1920–1921 a small but sharp postwar depression cut into demand for automobiles and V producers closed (Robison [7]). The Ra industry was yet worse off, though for different reasons. During World War I a joint British-Belgian exploration effort aimed at copper had stumbled across the extremely high-grade pitchblende deposits in the Belgian Congo, which produced their first Ra in 1922. Mining grades above 50% U_3O_8 with what amounted to slave labor, Congolese Ra undersold American Ra by almost half. By 1926 US Ra mining was a thing of the past (Hess [14]; Robison [7]). The few surviving companies in the Paradox Basin shifted to producing V. Even then, demand was small and competition from Broken Hill, Tsumeb, and Minas Ragra was stiff. Despite Congress' imposition of 25 to 40% tariffs on all types of V imports, very little of the mined Paradox Basin ores sold (Hess [14]).

Only in the late 1930s did the demand for V begin to come back. Rumblings of war in Europe, along with the Japanese invasion of China, renewed interest in the Uravan deposits. The beginning of US national strategic materials stockpiles in 1939 created a surge in demand for V, and shortly afterward U finally became a material of interest as well. Uranium from the Colorado Plateau, most of it from tailings discarded after V extraction, was a small but key supply for Manhattan Project research (Chenoweth [15]; Robison [7]).

Unlike the sag that afflicted commodities markets after the previous war, World War II was followed by a sustained increase in demand for U. The government continued and intensified the procurement program that it had begun during the war, which had established that the Paradox Basin deposits were the best resource in the USA. They increased in importance during the early stages of the Cold War, especially after the belated discovery that postwar partitioning had left the Jachymov deposits on the Soviet side of the Iron Curtain (Robison [7]). An independence movement, a civil war, the nationalization of mining, and various other economic and political crises combined to take Congolese U off the international market for some years starting in the 1960s, adding to the appeal of domestic supplies.

The end of the US government U procurement program came in 1970, but without ill effect on mining thanks to the oil price shocks of the 1970s. Investment in alternative energy surged, the US Department of Energy began the National Uranium Resource Exploration (NURE) program, and nuclear reactors started up in record numbers over the next decade (Schneider et al. [16]). The U industry enjoyed unheard-of prices. In 1978 a technical article proclaimed, "The present outlook for the uranium industry of western Colorado has never looked brighter than it does today… This situation is expected to be long term and to last to the 1980s and beyond" (Chenoweth [1]).

Nemesis struck the next year, when the Three Mile Island nuclear accident took public attention away from the benefits of independence from oil and refocused it squarely on the dangers of nuclear power. The U industry staggered. Selling V helped little given the general economic depression then ongoing. Research dwindled to desultory levels, and reactors shut down in record numbers (Schneider et al. [16]). Things began to look up for the industry as another Middle Eastern conflict caused another oil shock in 1983–1984. While waiting in long lines to pay exorbitant prices for scarce gasoline, the American public remembered that Three Mile Island had not actually killed or injured anyone and started reconsidering nuclear energy. Planned reactor startups surpassed their mid-1970s peak, and prices had just begun another steady rise when the Soviet reactor at Chernobyl exploded in 1986 (Schneider et al. [16]). Interest in nuclear energy plunged, and at the same time competition from Canadian and other international U producers rose. By the 1990s U was in oversupply as the nuclear arsenals of the disintegrating Soviet Union and other Cold War powers were sold off (Kahouli [17]). Prices dropped and stayed low. Most remaining mines in the Paradox Basin were permanently closed. Both U and V have seen several transient price spikes since 1990, but none has lasted long enough to support more than a temporary resumption of mining. There has been little sustained interest in the resources and only desultory research.

2 History of Geological Research on Paradox Basin U-V Deposits

2.1 The Early Years through 1918: Reconnaissance on Roscoelite and Carnotite Deposits

The Paradox Basin U-V deposits are absent from the early literature of economic geology. The first textbook since *De Re Metallica in* 1556, Frantisek Posepny's 1893 *The Genesis of Ore Deposits*, made laudable efforts at global coverage. It included numerous American deposits for the first time, but notably not the Paradox Basin ores discovered the decade before, or indeed anything at all about carnotite, U, or V, and Ra had not yet been identified.

Not until 1900 did the Paradox Basin V or V-Ra deposits, as they were then considered, make their debut in the geological literature. Even then it was almost accidental. On his way to study the reported copper deposits around the Utah-Colorado state line, Frederick L. Ransome stopped near Placerville to look at an occurrence of Friedel and Cumenge's newly discovered vanadium mineral. His interest had been piqued by a report that the V^{5+}-bearing carnotite was accompanied by V^{3+}-bearing silicates (Hillebrand and Ransome [18]). Hoping to resolve the relationship between these seemingly disparate species, Ransome made a field reconnaissance of the accessible orebodies and collected samples. He also found time to visit several other carnotite localities along La Sal Creek Canyon and Roc Creek. The resulting paper, published in 1900, documents the occurrence of ores along bedding planes and fractures, discordant to strata, and optically continuous overgrowths around quartz grains in the vicinity of deposits. Hillebrand and Ransome concluded that the deposits were clearly post-depositional and derived from remobilization of some unknown source deposit, but the two types were different in character. The carnotite, they wrote, appeared to be entirely superficial and connected with modern topography and climate, whereas roscoelite accumulations were much more continuous, persistent at depth, and not evidently related to modern conditions (Hillebrand and Ransome [18]).

A lack of intellectual infrastructure hindered most early investigations. Geologists in the area around 1900 barely had a base map to work with, and several apparently simple matters of stratigraphy and mineralogy were anyone's guess. The roscoelite deposits were correctly located in the La Plata (now Entrada) formation, but the carnotite deposits Hillebrand and Ransome examined turned out to be in the McElmo (now Salt Wash). The chemical methods that Friedel and Cumenge had worked out for carnotite failed to yield consistent results on other Colorado samples, which turned out to contain too much Ba and Ca to obtain a reliable analysis (Hillebrand and Ransome [18]). Kithil and Moore [19] and Hillebrand et al. [20] chronicle other mineralogical mishaps.

After the early reconnaissance by Hillebrand and Ransome, geological research in the Paradox Basin paused. It ticked up again around 1910 (Fig. 2) as Europe's arms race caused a surge in demand for V steel. The USGS's Frank Hess was dispatched on several field reconnaissance and sampling expeditions to reported V deposits between Placerville and the San Rafael Swell. He visited, described, and mapped numerous V mines in southwestern Colorado and in Utah's San Rafael Swell and carried out extensive microscopic work on the two known deposit types (carnotite and roscoelite). In the roscoelite deposits he described extensive silicification around mineralized areas and an antithetical, probably replacive relationship between the roscoelite and calcite cements in the rock, with roscoelite replacing even detrital quartz in the highest-grade areas of Entrada-hosted deposits (Hess [21]). He also noted U and V associated with asphalt and mariposite (Cr-mica) in a fracture-hosted deposit in the Chinle-equivalent Dolores Formation near Placerville, commenting that it appeared similar to associations found in the San Rafael Swell (Hess [21]). The carnotite occurrences he described as forming flat lenticular deposits in cross-bedded sandstones (Hess [22]). The deposits showed a strong association with fossilized plant remains, especially tree trunks, but the spatial distribution of mineral types indicated the carnotite was mobilized away from, not toward, the wood; and fossilized plant remains were widespread in areas not known to carry mineralization (Hess [22]).

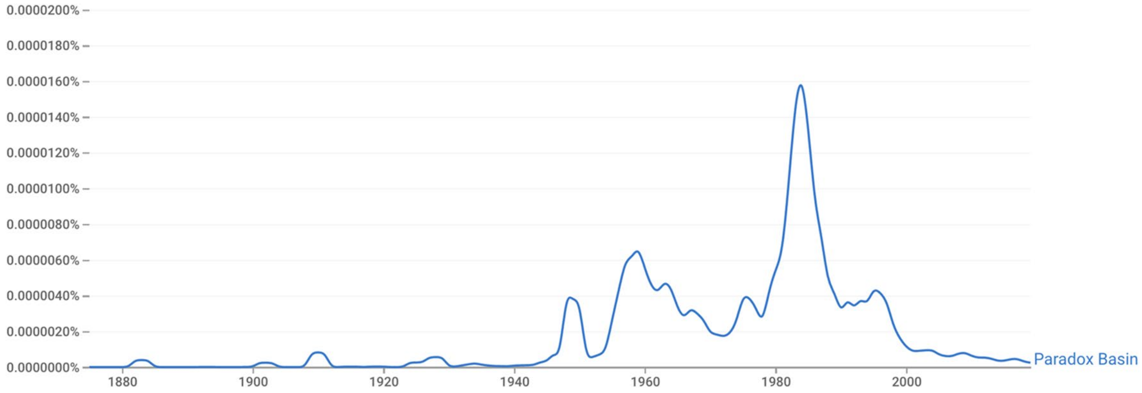

Fig. 2 Google NGram viewer export of mentions of "Paradox Basin" in digitized literature from 1880 to 2019 (case-insensitive, smoothing = 1). Peaks roughly correspond to times of major geological research activity. Excepting the mid-1980s when sequence stratigraphy was all the rage, most of the research was on the U-V deposits

Hess was the first geologist to survey several different deposit types across a wide swath of the Paradox Basin, and became the first to offer an interpreted metallogenetic relationship among them. He suggested that the roscoelite and carnotite deposits shared a common ancestor: U and V had originally been deposited together, along with Cr-mica, in deposits like the asphalt-bearing veins he had also observed in Colorado. Upon regional uplift, the circulation of oxidizing waters through these veins had remobilized the soluble fractions, carried them away, and redeposited them as carnotite, leaving only the insoluble V- and Cr-micas behind (Hess [21, 22]). Hess ended his model with the comment, "[T]his is offered only as a working hypothesis, a tentative tool to be cast aside like any other if unsuited to the job. It, however, seems to me to offer an explanation of phenomena of the deposits so far as observed… Future studies may, of course, cause the rejection of a part or the whole of the hypothesis" (Hess [22]).

For a few years after Hess' work, US neutrality and attendant decline in V exports caused a lack of work and interest in the Paradox Basin deposits. Both mining and research began to recover when America entered World War 1, but publication only started to pick up again near the end of the fighting. By this time economic geology was feeling the impact of Waldemar Lindgren's *Mineral Deposits*. The three then-current metallogenetic hypotheses for Paradox Basin U-V deposits reflected Lindgren's book: hydrothermal mineralization by descending waters that encountered U- and V-bearing minerals in beds overlying deposit locations; syngenetic mineralization by clastic processes; and syngenetic mineralization by chemical processes, in which U and V precipitated from seawater onto reducing, decaying plant matter (Notestein [23]). A magmatic-hydrothermal origin had been considered and already dismissed by then (Hess [22]). Notestein [23] attempted some of the first experimental studies of the ores, examining the dissolution of carnotite. He found it would readily dissolve in sulfuric acid, and that U and V precipitated (along with gypsum) on contact with calcite but not on coal or rotting wood. Fusing these experiments with the geological observations by Hillebrand and Ransome [18] among others, Notestein [23] suggested that groundwaters carrying sulfuric acid from dissolving pyrite could have descended through U- and V-bearing beds, picked up U and V, and precipitated their contained metals on the first calcareous bed they encountered.

Ironically, all the hypotheses from 1900 to 1919 were based on the two least important and least typical types of deposit in the Paradox Basin. Though they supplied some V, Ra, and even U until about 1952, the carnotite and roscoelite deposits then known were significant only because other global sources were either unavailable or even dinkier. They were also all in Colorado. The earliest noted mining on the Utah side of the border was in 1904 or 1912 in minor deposits in the San Rafael Swell, well after the earliest activity in Colorado, and it amounted to little (Hess [24, 25]; Butler et al. [26]). The reasons for this are uncertain but may relate to the longer tradition of mining in Colorado and the discouragement of prospecting by Mormon leaders (Butler et al. [26]). As late as 1930 there was only a single district in Utah listed as a consistent U-V-Ra producer, and all three commodities together barely rated a brief mention in the list of economic metals produced in the *Ore Deposits of Utah* (Butler et al. [26]).

2.2 The 1920s-30s: Hazy but Visible Outlines of the Modern Deposit and Alteration Types

In 1910 manufacturers across the USA had produced roughly 130,000 automobiles; in 1920 the figure approached 1.5 million. Demand for V steel soared accordingly, and with it came a rise in geological interest in the Paradox Basin's resources. Prospectors and miners had been sending ore specimens to the US Geological Survey for some time during and after the war, and apparently succeeded in piquing researchers' interest (Hess [27]). The Paradox Basin deposits began to show up in the geological literature with increasing frequency. A quarter-century after their omission from Posepny's textbook, they merited a brief section in the second edition of Waldemar Lindgren's *Mineral Deposits*, mostly derived from Hess' work. Lindgren, however, demurred from Hess' genetic concept of the roscoelite and carnotite deposits, suggesting instead that meteoric waters had concentrated the U and V from diffuse distribution in an unspecified source and deposited them at a trap of uncertain nature.

Amid these rising commercial and scientific interests, the US Geological Survey dispatched a team led by Reuben Coffin to the Paradox Basin. Their expedition was supposed to map out the boundaries of the McElmo Formation (now Salt Wash), which was by then understood to host more ore than the La Plata (Entrada), and to report on geological features that would aid exploration. Coffin's team soon found that much of the necessary geological foundation was lacking and ended up mapping general stratigraphy around the Paradox anticline as well. Despite some apparent challenges (the team dubbed a local topographic high point "Mount Misery"), the work paid off. The resulting USGS publication (Coffin et al. [13]) was by far the most comprehensive and detailed examination of the ore deposits and region yet published, and for the first time laid out the stratigraphy of the different types of deposits and compared them, finding numerous similarities and differences not previously observed. The new data included several deposits consisting mainly of a blue-black ore, not carnotite, in the fluvial McElmo (Salt Wash) Formation.

At first the Salt Wash deposits had been classified as unusually large examples of the well-known carnotite deposits in the Entrada, with which the Salt Wash was still sometimes confused (Hess [22]). By Coffin's time it was clear that they were something different. They were large and tabular, not the small limestone-capped pods of the Entrada. The ores contained carnotite, but coal-black and bluish-black minerals spotted through the sandstone made up the majority of the resource (Coffin et al. [13]; Hess [27]). Continued mining had by now also confirmed that Hillebrand and Ransome (1900) had been correct that non-carnotite orebodies extended inward and downward a long ways from their outcropping ledges, such that most of the ore was distributed without respect to modern topography and climate. Some of the carnotite was clearly related to recent features, including faults, but Coffin's team settled that most of the ore predated major faulting (Coffin et al. [13]). The new geological research also noted that ore could occur in any, or several, of the four "rims" or sandstone beds in the Salt Wash Formation in a given area. Presciently, the authors also suggested that hints of V mineralization in the Chinle in northern Arizona and U and V at the San Rafael Swell might indicate productive horizons in the Triassic strata in both locations (Coffin et al. [13]).

By this point there were about five different metallogenetic hypotheses, none of them magmatic-hydrothermal (Coffin et al. [13]). These consisted of deposition of U and V scavenged from overlying rocks by descending waters; Lindgren's vague epigenetic concept; Hess' idea of sulfuric acid remobilization from asphaltic U-V veins; Hess' second concept of ore precipitation from seawater on decaying plant matter; and the syngenetic (clastic) concentration of U and V by mechanical deposition of heavy minerals. Coffin et al. favored the last of these, citing the impermeability of the overlying Brushy Basin shales against the first and the correlation of the largest deposits with the thickness of the host sandstones in favor of the last (Coffin et al. [13]). Coffin et al.'s hypothesis did, however, leave room for some ore to form by reductive precipitation from waters onto onto "humus" released by decaying trees.

Around the same time studies of alteration and mineralization made an important conceptual leap. For several decades it had been noticed that the ores occurred only where the host sandstones were white or light tan and not their usual red. This was observed rather than interpreted until 1922, when Frank Hess first explicitly referred to the color change as bleaching, stating that "the red color is entirely removed from both the Moenkopi and the Chinle red beds" (Hess [25]). How he arrived at the conclusion that the white color represented bleaching of original red beds is not known, but was likely connected to his extensive observations of field relations of red and white sandstone.

The same paper is also notable as the first major description of the Chinle-hosted ore deposits in the San Rafael Swell. Hess [25] described the pervasive asphalt in the Shinarump conglomerate as the main host for U and V mineralization, mainly in shoots and asphaltic masses. Noting widespread silicification and the relations among ore minerals and asphalt in the area, Hess suggested that the deposits had formed in two stages: first asphalt had accumulated in the rock, and then a hot-spring or similar system had deposited U, V, and related metals on this reducing trap (Hess [25]).

At this time two other recurring features of Paradox Basin geological research were also becoming clear: the extreme mineralogical diversity of the ores and the difficulty of dating them. Already by 1924, the Salt Wash deposits were being frequented by geologists competing to discover new minerals (Hess [27]). Up to that point most new U and V minerals had been discovered in Germany or the Czech region, but in the early 1900s USGS geologists began producing discoveries from the Paradox Basin ores at an increasing clip (Hess [27]; Butler et al. [26]). Excepting a few bad decades marred by wars and/or depressions, mines in the Paradox Basin would continue as major sources of new mineral discoveries up to the present (Fig. 3).

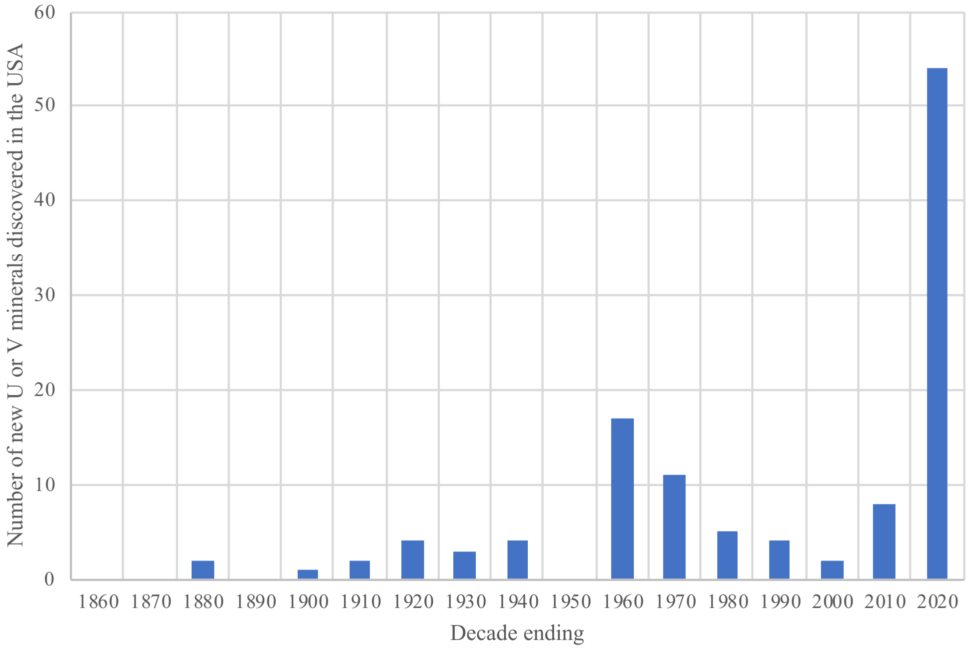

Fig. 3 Number of new U and V minerals discovered in the United States by year, using data from rruff.info. Nearly all are from the Paradox Basin

Early radiometric dating had recently been developed and in some respects was the first actual use of U. Hess ([27]) made an effort to calculate the age of some of the deposits using overall Pb/U ratios in several purified carnotite and tyuyamunite specimens. He obtained an age of around 28.4 Ma, but suspected it was too young due to Pb loss. Recalculating from the highest Pb/U ratio among his analyses, he suggested 42 Ma as a more realistic value for the age of the minerals (Hess [27]; Hess and Foshag [28]). Hess did not, however, attempt the calculation with the black ores now known to constitute most of the resource.

From the later 1920s through the middle 1930s there was little recorded geological research in the Paradox Basin, probably due to the demise of the US Ra industry and later the Great Depression. Most contributions from that time are mineralogical. The discoveries of fervanite, corvusite, rilandite, and steigerite all date from the early to middle 1930s (Hess and Henderson [29]; Henderson and Hess [30]; Henderson [31]) and were from new examinations of samples collected years earlier. Apart from a brief mention of a mine visit in Gypsum Valley in 1932, no fieldwork is attested from the early 1930s (Henderson [31]).

Much of the existing work was synthesized in the *Ore Deposits of Utah*, published in 1930. The authors suggested that the Paradox Basin's Cu(-Ag) and U-V-Ra deposits shared a common type and genetic process (Butler et al. [26]). This consisted of waters circulating through structurally favorable zones, collecting metals from the rocks, and depositing them at a carbonaceous trap, starting in the Tertiary (Butler et al. [26]). As Coffin et al. had done, the authors identified some of the minerals as the result of supergene alteration of the originals, though they were not sure which was which. Pintadoite and other efflorescences were easily identified as supergene, but Butler et al. ([26]) were somewhat less sure about carnotite and hewettite.

In the late 1930s, geological research began to pick up again along with interest in V and other strategic minerals. A notable new figure was Richard Fischer, who had begun examining the Paradox Basin ores as part of his graduate studies in 1934 and would continue for most of his long career. Dispatched by the US Geological Survey to examine the regional resources, he studied both the Cu(-Ag) and the U-V deposits in detail wherever they were known to exist. He agreed with Butler et al. (1930) that both deposit types were probably connected, but disagreed with the assertion of a structural control on the U-V deposits, pointing to the lack of correlation between structural features and deposit locations (Fischer [32]). Rather, Fischer identified local sedimentological variations in permeability as the main control on ore formation. In the Entrada-hosted deposits at Placerville, he mapped clay seams above and below the ore zones, finding that grades were leanest in the absence of the capping shale and best-developed where the ore-hosting sandstones had shale layers above and below. In the Salt Wash deposits, Fischer ([32]) found that ore grades followed the distribution of stream facies, and at last confirmed that carnotite as a secondary mineral created by groundwater redistributing original U and V ores.

Fischer's observations also touched on hypogene metallogenesis. The discovery of more igneous dikes and laccoliths in the Paradox Basin through the 1920s, and the innate tendency of magmatic-hydrothermal theories to outlive their supporting evidence, had led to the resurrection of the hypothesis that the U-V deposits were created by fluids migrating outward from the intruding igneous bodies in the Paradox Basin. Butler et al. [26] had considered this unlikely based on the scarcity of igneous rocks and their generally low-V compositions, but had not been able to rule it out completely. Fischer [32] showed that the local igneous rocks crosscut the Entrada-hosted ores near Placerville, and the magmatic-hydrothermal interpretation died the second of its several deaths. Another theory Fischer doubted would last longer. Despite his opinion "that the genetic role of the plant material in these ores has been over-emphasized" because of the abundance of completely barren plant material all around the ore and within orebodies, the belief that the plant matter was the chief precipitant of U and V would stick around for decades to come.

For himself, Fischer attempted to split the difference between the syngenetic and epigenetic hypotheses and apply the result to both the Cu–Ag and the U-V deposits. He suggested that while the present ore mineralogy was epigenetic, the elements had first been concentrated to ore grades in the host rocks in a syngenetic fashion, probably by biological reduction of metals from solution during host rock deposition (Fischer [32]). Fischer proposed this hypothesis for both the Cu–Ag and U-V deposits, but, like Hess, emphasized that his interpretation was tentative.

2.3 World War II through 1950: Massive Research, but in Secret

A Bureau of Mines circular reports that by 1938, V production in the Paradox Basin was again resurgent (Huleatt et al. [33]). The US entry into World War 2 and concomitant demand for arms administered a fresh stimulus a few years later. Old mines were reopened and new ones discovered, with the United States Vanadium Corporation acting as purchasing and stockpiling agent for the government. The new V boom lasted until late 1943, when the fresh availability of foreign imports terminated the domestic V sourcing program (Huleatt et al. [33]). This time, however, the demise of the major V market did not diminish research interest. USGS geologists still arrived in droves to scour the Paradox Basin for ore, this time solely concerned with U. All parties involved in the massive field exploration project insisted that they were there purely for the V. The U, which before the war was frequently mentioned as an accessory metal, was scrupulously scrubbed from wartime literature; even in classified reports U ore had its own code term, S-37 (Fischer et al. [34]; Chenoweth [15]).

The research, much of it headed by Fischer again, was the single biggest geologic program to that time in the Paradox Basin, and probably in most other parts of the USA. The ore-hosting Entrada and Salt Wash formations were mapped across the Paradox Basin. Temple Mountain, still the only known Chinle-hosted deposit, was scrutinized further. All deposits known and accessible were drilled or mapped, sampled, and tested extensively (Chenoweth [15]).

This huge accumulation of new data had zero discernible effect on research. This was partly because it remained classified well after the war, partly because most of the new work confirmed the earlier deposit geometry, distribution patterns, sedimentology, mineralogy, and geochemistry already worked out through the 1920s–1930s by Coffin, Hess, Fischer, and others (Fischer et al. [34]). What was new mainly concerned details, such as the discovery by XRD that much of the "roscoelite" in the ores was actually a V-hydromica or V-illite (Huleatt et al. [33]). The wartime reports proved to be valuable catalogs of grade, thickness, occurrence, orebody geometry, and mineralogy, but added little or nothing about metallogenesis.

2.4 The 1950s–1970s: Geochemistry, Geochronology, and a Lot More Data

As the Cold War got underway, geological investigations continued under the aegis of the new Atomic Energy Commission (AEC). The AEC had requested and obtained the withdrawal of areas of the Colorado Plateau deemed geologically favorable in order to avoid wildcat exploration and competition with private prospectors (Fischer [35]). Instead they partnered in exploration with the USGS and supported research at Columbia University on what were now termed the Paradox Basin U (rather than V or V-Ra) deposits (Kerr [36]). Published geological studies on the region surged in the next few years (Figs. 1 and 2). Most of them were reports on exploration in specific areas (e.g. Hilpert [37]; Wilmarth and Vickers [38]; Trace [39]), in many cases based on work actually performed in the 1940s. To paraphrase one geologist's view of the situation, the literature began growing at an alarming rate (Gruner, 1956 [40]).

Most of these publications were heavily descriptive. Fischer, working from his extensive background on the region, was one of the few geologists to embark on interpretation. In a new synthesis of the geology and mineralogy described from the deposits, he concluded that their origins were hydrothermal. Sedimentary processes were significant only in controlling permeability pathways for the mineralizing fluids (Fischer [35]). This reversion to the ideas of Hess and Coffin, and departure from his own earlier concept, remains current today, albeit with more detail. However, Fischer still listed the principal ore minerals as carnotite and vanadian micas. Foreshadowing discoveries to come, he reported that a few small, not very productive U deposits had been found in the lower Chinle Formation of southeastern Utah associated with copper (Fischer [35]).

Less than 2 years after Fischer's paper, Mi Vida was discovered in the basal Chinle on the Lisbon Valley anticline.

The conventional story is that prospecting geologist Charlie Steen was driving back into Moab with the core from what he believed had been an unsuccessful drilling expedition, until a gas station attendant and amateur prospector happened to wave a Geiger counter over the core. As an alternative, I was told that in fact Steen encountered John Harshbarger, a USGS geologist exploring for the AEC, in the field, and that it was Harshbarger who told Steen his cores were full of pitchblende (J. David Lowell, oral comm., 2018).

Whatever the true story was, the Mi Vida discovery brought the exploration frenzy to new heights (Fig. 4) and a new deposit type into the ongoing research. Additional data had to be accumulated and the old theories expanded to embrace the Chinle-hosted deposits. This last was easier than it sounds. Fischer's work aside, decades of description had added little to the theoretical picture. The metallogenetic understanding of U-V deposits in 1952 was roughly where it had sat in 1921.

It did not stay there much longer. The Pourbaix (Eh–pH) diagram and other concepts imported from solution chemistry enabled Robert Garrels, a USGS geologist, to make the first quantitative geochemical interpretations of U-V mineral formation. His calculations confirmed what geologists had suspected for decades but had been largely unable to demonstrate: carnotite was a highly oxidized, supergene product of the primary and secondary ores, which were the array of lower-valent oxides and silicates collectively termed the blue-black ores (Garrels, 1953 [41]). With additional thermodynamic data and samples, Garrels and several colleagues spent the next several years working out the Eh and pH relations of the major U and V minerals. Eventually they detailed the geochemical sequences by which original pitchblende and montroseite would alter to successively more oxidized products (Evans and Garrels [42]; Weeks et al. [43]; Garrels and Pommer [44]; Garrels et al. [45]; Weeks [46]). Discovery of hydrocarbons and CO_2-rich gases in the Paradox Basin motivated several variants of the proposed metallogenesis. Garrels and Richter [47] suggested a CO_2-rich groundwater as the transporting agent for the U and V, while Weeks [46] and Hostetler and Garrels [48] offered H_2S as a possible contributor to reduction. This body of work by the USGS remains the foundation for today's understanding of the ore mineralogy.

PROSPECTING DUDS ARE GIRL'S "DIGGERETTE JR." SUIT, MOTHER'S "U-235" SUIT, FATHER'S "SMOCK"

AS THOUSANDS GO PROSPECTING
A NEW INDUSTRY OUTFITS THEM

The great uranium hunt has brought a suddenly burgeoning uranium

Fig. 4 Illustration of uranium prospecting suits for the whole family. From an article in *Time* magazine, May 23, 1955, showing the excitement spawned by the uranium rush on the Colorado Plateau

It also nailed the lid shut on the syngenetic hypothesis of the deposits' origin. The hydrothermal idea was not new, but the addition of geochemical to field evidence now made it difficult to counter. Despite occasional recurrences (e.g. Bain [49]), the idea of syngenetic mineralization never regained traction in Paradox Basin geology, despite being popular for other sediment-hosted metal systems in the 1950s–1960s (e.g. Sales [50]; Garlick [51]).

Originally it had been geochronology, not solution chemistry, that was expected to settle when the ores formed relative to the host rocks. At this time, however, geochronology was mostly creating more confusion. Available data from whole-rock bulk U–Pb ratios suggested the ores were 55 to 80 million years old. More specific isotopic ages, mostly from concentrates, averaged 71 Ma, but Stieff et al. [52] pointed out that this might represent the most recent interaction between the ores and groundwater, not original mineralization. Further, more detailed work produced mostly Cretaceous ages and similar concerns about their meaning, as most studies have since (Miller and Kulp [53, 54]; Bain [55]; Berglof [56]; Ludwig et al. [57]).

The wide acceptance of a hydrothermal origin raised inevitable questions about where the metals came from and how they reached the sites of deposition. Early on the suggested source was igneous rocks, largely because they contained U and contributed metals to other deposit types such as porphyries. (Even after the magmatic-hydrothermal hypothesis proper was eliminated for the second time, igneous rocks still continued to be the favored source.) However, as the known U and V resource in the Paradox Basin increased, and the known extent of igneous rocks did not, mass-balance constraints made them less and less plausible. By the early 1960s, suggested alternative sources included volcanic ash in the upper Chinle and Brushy Basin, which could have released U and V while devitrifying (Kerr [36]; Fischer and Stewart [58]; Miesch [59]); heavy minerals within the host sandstones themselves, plus migrating petroleum enriched in V (Bowers and Shawe [60]; Weeks [46]); Precambrian igneous basement plus petroliferous V-enriched shales (Shoemaker et al. [61]); or formation waters expelled during compaction, after being enriched in metals by an unspecified mechanism (Noble [62]). A retrospective look at the proposed metal sources and means of transport shows a clear divide in opinion. Geologists reasoning on the basis of solution geochemistry tended to favor devitrifying volcanic ash, which could provide both U and perhaps V at different times in the geologic history of the basin. Those reasoning from hydrology, considering the difficulty of getting a fluid through the thick and impermeable Brushy Basin member and the Chinle shales, were more likely to suggest the breakdown of detrital heavy minerals and/or unspecified U- and V-rich formation waters. In the absence of decisive evidence either way, both ideas persisted.

There was a similar lack of agreement over the likely trap for metals. Almost all agreed it was reducing matter, but proposals included H_2 and H_2S (Weeks [46]; Hostetler and Garrels [48]) and petroleum (Kelley and Kerr [63]; Abdel-Gawad and Kerr [64]; Kerr and Jacobs [65]). There was a general consensus that plant coal contributed to reduction, but it was too scarce to account for all the hypogene minerals and had too inconsistent a spatial relationship with grade. (Finch [66]) speculated a possible contribution by U and V adsorbing onto clays, but without elaboration.) Implicitly or explicitly, by the end of the 1960s most discussions of metallogenesis involved a reducing fluid mixing with an oxidized, metal-bearing fluid.

As metallogenetic concepts became more focused, the range of deposits under consideration narrowed. By this time U and V were known throughout the stratigraphic section (Isachsen et al. [67]), but everything outside of the Chinle and Salt Wash began to disappear from the literature. After the early 1950s, the once-important deposits in the Entrada were absent from even the most comprehensive reviews of Colorado Plateau U and V resources (Garrels and Larsen, eds. [68]), though they appeared as geochemical curiosities in the occasional paper (Fischer [69]; Spirakis [70]).

Perhaps because of this narrower focus, there was surprisingly little effort at comparing different deposit types or finding out how they were related. In one of few such efforts, Shoemaker et al. ([61]) proposed that Cretaceous magma under the Paradox Basin heated solutions that rose through the crust, dissolving metals as they went and deposited metals where they mixed with fluids in the various host sandstones. This third edition of a magmatic-hydrothermal hypothesis, however, suffered from a distinct scarcity of Cretaceous magmas compared to the size and extent of U-V deposits.

It nevertheless found a few fans. Paul Kerr was a Columbia University mineralogist who had helped with wartime U procurement, in the process visiting Shinkolobwe (DR Congo) and Eldorado (Canada). Sometime around 1943 he visited the Paradox Basin and developed what would become a multi-decadal interest. After extensive field and lab studies in the San Rafael Swell and northern Arizona, and considerable reading on the other Chinle and the Salt Wash deposits, Kerr ([36]) published an extensive comparison of mineralogy, alteration features, trace element suites, interpreted temperatures of formation, and plausible genetic models for the different deposit types. For their origins he concluded in favor of Shoemaker's magmatic-hydrothermal model, thinking it the best way to explain the elevated temperatures of formation he had determined.

Comparing Chinle to Salt Wash U-V deposits, Finch [66] reached a different conclusion. Among the similarities between the types, he identified the association of ores with bleaching and carbonaceous matter, and common accessory pyrite and white clay. Among the differences, he listed a greater variety of host rock lithologies and a wider range of V, U, and Cu ratios in the Chinle-hosted ores (Finch [66]). He suggested that both types of deposits formed from U and V leached out of the overlying mudstones by passing oxidized groundwaters in the early Tertiary, which moved through permeable horizons and deposited metals on carbonaceous matter or by adsorbing them onto clays. Variations between types he attributed to local variations in chemical conditions, with little discussion.

Besides the work by Shoemaker, Kerr, and Finch, most other reports covering multiple deposit types were almost entirely descriptive. Notable contributions of this type include Shawe [71, 72], Carter and Gualtieri [73], Johnson and Thordarson [74], Davidson [75], and Hawley et al. [76]. The biggest of them all, a massive Incomplete Manuscript on Lisbon Valley by Weir and Puffett [77], was published later, but most of the work it was based on was also done during this time. While many of them described multiple deposit types, there was not much comparison of their characteristics, speculation on their potential relationship, or identification of how the multiple types fit into the genetic model or related to the overall basinal context. Where this analysis was present it was seldom conclusive, mostly confined to listing the available plausible options (Fischer [78]).

2.5 The Later Twentieth Century: Organics, Sedimentology, Computers, and Not Much New

After 1962 U production went into a steep decline, and geological research went with it (Figs. 2 and 5). Production stayed at a plateau from the middle 1960s to the later 1970s, but research did not recover. It took the huge rise in the U price during the 1970s oil crises to resuscitate interest.

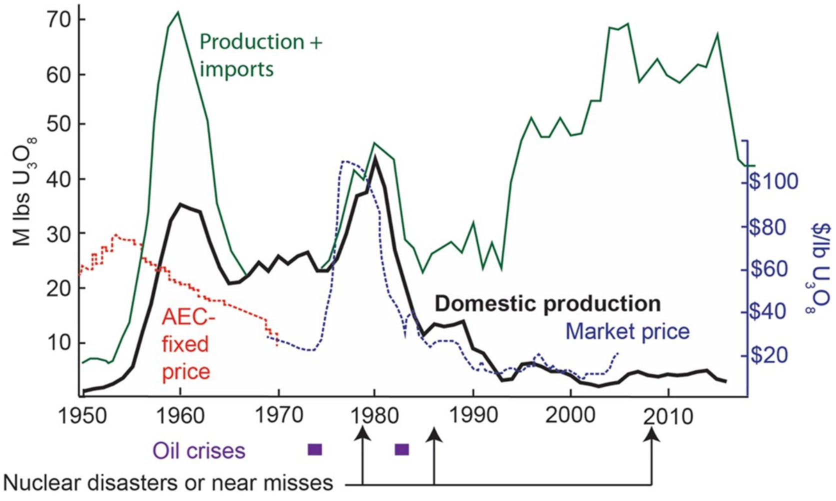

Fig. 5 Production and imports of uranium concentrate in the USA in M lbs U_3O_8 from 1950 to 2016. Modified from https://www.eia.gov/todayinenergy/detail.php?id=31772 and from https://www.eia.gov/todayinenergy/detail.php?id=44416. Also shows price of U_3O_8 in 2004 US$/lb from 1947 to 2004, modified from https://www.neimagazine.com/features/featurehistory-as-prelude-the-outlook-for-uranium/featurehistory-as-prelude-the-outlook-for-uranium-426367.html

Production slowly rose again, and research started to come back up in the middle 1970s. During this time V attracted little attention, and it remained common to refer to the ores as U deposits.

Some of the new work looked a lot like the research done in the previous decade: comprehensive descriptions of U-V resources with little synthesis or comparison across deposit types (e.g. Abdel-Gawad and Kerr [79]; Chenoweth [80]; Shawe [81]). The outlines of the metallogenetic model remained hazy, with a similar variety of proposed metal sources, transporting media, and chemical traps. None had been ruled out, and some new possibilities were added.

Most of the proposed additions were organic. The role of organics and petroleum in trapping U and V had been known since the 1920s, but advances in general geochemistry were expanding their potential role. Jensen [82] had found evidence that the sulfides in Paradox Basin deposits had formed via bacterial reduction of sulfate, a new contribution to the reducing trap. A series of chemical experiments starting in the late 1950s had established that U^{6+} and VO^{2+} formed strong organic complexes in solution (Selbin [83]; Cernia and Mazzei [84]), opening up the possibility that organic compounds had helped carry metals to the site of deposition. The same experiments also suggested that humic, fulvic, and other organic acids could selectively concentrate U and V out of solution at factors exceeding 10,000:1 (Szalay and Szilagyi [85]; Leventhal [86]). This gave rise to a new model in which organic compounds and bacteriogenic H_2S adsorbed U and V out of solution, whence they slowly ripened to discrete U and V minerals (Finch and Davis [87]; Breit and Goldhaber [88]). It was first applied to the Grants Basin and Texas Coastal Plain deposits, whose organic contents were considerably higher (e.g. Brookins et al. [89]; Galloway and Kaiser [90]), but was quickly generalized to any sandstone-hosted U deposit, including those in the Paradox Basin (e.g. Rose and Wright [91]; Reynolds et al. [92]). Comparing the two, Hansley and Spirakis [93] and Spirakis [94] proposed that the Paradox Basin U-V ores formed by reduction mostly by an "amorphous organic matter" inferred to consist partially of humic acid. These still existed in Grants, but they suggested that hotter diagenesis had removed them from the Paradox Basin deposits.

The role of petroleum was also expanding. It had been considered a potential reducing agent since the late 1950s, but in the 1980s hydrocarbons became the prime suspects in the bleaching alteration so commonly associated with the U-V ores (Merin and Segal [95]). Traces of light hydrocarbons were being discovered in bleached rocks near U deposits, and the regional extent of bleaching began to become clear. This coincided with regional evaluation of the oil and gas resources of the Paradox Basin, which (amid Middle Eastern oil crises) had joined U and V as major commodities of economic interest (Clem and Brown [96]; Peterson [97]).

Research on Paradox Basin U-V deposits was also feeling the spillover from another geological field in the late 1970s to early 1980s. Sequence stratigraphy had recently arrived in North America, and its principles were promptly applied to the geology of the U-V deposits (Gabelman [98]). Deposits in the Salt Wash were the most common targets, with numerous fence diagrams, stratigraphic columns, and flow directions constructed in an attempt to link mineralization to a system of Jurassic streams (Young [99]; Thamm et al. [100]). The deposits were still acknowledged to be epigenetic, so most of this work was seeking a permeability control rather than a mechanical process of ore deposition as had earlier been the case. Depositional facies in the Chinle were also scrutinized at length (Huber [101]), but the Chinle deposits were too obviously unconformity-related to attract as much sedimentological attention as the Salt Wash.

Murmurs were also heard of another topic from in the wider world of geology: climate. Hayes [102] combined studies of accessory elements in the Chinle- and Salt

Wash-hosted U, V, and Cu deposits with geochemical modeling of two-fluid mixing to match deposit type with inferred meteoric fluid compositions and link the latter to climate. The general idea was that in deposits with V > U, the descending meteoric water was a dilute, mildly acidic, reduced water that had picked up humic acid percolating through a thick tropical soil. By contrast, the descending water in the more U-rich deposits was a dilute, vadose water rich in bicarbonate, corresponding to a drier climate and more alkaline conditions. Both fluid types, in different times, climates, and geologic settings, had encountered deeper, more concentrated formation waters and precipitated ore at the interface (Hayes [102]). Deposits with Cu as well were attributed to a climatic transition with a corresponding mix of fluid types. This work, however, was not followed up.

The computer revolution began to hit Paradox Basin U-V research in the 1980s. It was first used to make metallogenetic models more precise (not to be confused with more accurate). An early effort by Ethridge et al. [103] combined field measurements and observations with numerical and analytical techniques to model Salt Wash ore formation by mixing between a humic acid solution and a sulfate-bearing fluid within coarse channel sandstones. This paved the way for a series of models beginning with Sanford [104], who related known deposit locations to the thickness and transmissivity of the sandstones. He suggested that both Salt Wash and Chinle deposits formed at an interface where U-bearing meteoric waters mixed with deep reducing brines that upwelled along the edges of buried Precambrian blocks. In a series of later papers he attempted to place this in the context of the geologic and hydrologic history of the Paradox Basin (Sanford [105–107]). Sanford's were some of the few wide-ranging studies across the variety of U and V deposits present in the basin and their relationship to the geologic context.

Computers had another role to play in the 1980s too: they entered the world of resource evaluation. By this time the NURE program had collected a massive series of geological, geochemical, and geophysical datasets. While resource evaluation did not always involve digital computers (e.g. Theis et al. [108]), geologists increasingly experimented with computerized ways to incorporate the giant datasets into their evaluation protocols (Bolivar et al. [109]; Koch et al. [110]). Such early big-data initiatives usually met with mixed success. Mostly they just confirmed and quantified the known associations of accessory metals with various deposits, deposit types, and alteration zones (Spirakis and Pierson [111]). They had no visible impact on the metallogenetic models, but did help quantify resources and establish guidelines for U and V mineral exploration. Usually these guidelines were not very different from the set that USGS field geologists had worked out in the 1950s without benefit of computers.

2.6 To the Present

Despite the still-depressed state of U-V mining, several new articles on the Paradox Basin deposits appeared in the early 1990s. Most of these represented work started and sometimes finished years earlier, before Chernobyl and the collapse of American U mining (Fig. 5). A multipart synthesis edited by Northrop and Goldhaber [112] combined a review of the literature and the existing metallogenetic hypotheses with detailed examination of drill core, thin section petrography, whole-rock and stable-isotope analyses, XRD, and reactive transport modeling to study the deposits in the "Henry Basin," the west flank of the Paradox Basin. They concluded in favor of the existing two-fluid model of mineralization, but added new details. One fluid had been recharged meteoric water, which lay above an Mg-dominated brine derived from evaporites in the Tidwell formation; the interface between the two was density-stabilized and peneconcordant, migrating upward through time (Northrop and Goldhaber [112]). Without additional geochronologic work, they inferred that mineralization occurred early on in compaction, and thus approached the age of the host beds. Their model, using the parameters derived from their chemical and petrographic work, indicated highly localized ore precipitation at multiple interfaces (Northrop and Goldhaber [112]). Meanwhile, fundamental research by Breit and Wanty [113] and others continued to shed new light on the mechanisms of U and V accumulation in rocks, the first major geochemical advances since Garrels' work [44–48]. Experiments by Wanty et al. [114] identified biogenic H_2S as the only abundant geologic chemical with enough reducing power to form the V^{3+} dominating the hypogene ores (with possible assistance from Fe^{2+}), ruling out several previous candidates including the long-theorized plant coal.

These, Sanford's work, and the contributions of Hansley and Spirakis represented most of the major literature of the 1990s. None of the new ideas had conclusive support, and it largely left metallogenetic theory only slightly better defined than it had been 30 years earlier: the deposits formed from the mixing of an oxidized groundwater with a reducing fluid from deeper in the basin. The main difference was that the reducing fluid was now thought to be reduced organic acids, H_2S, or both, rather than plant coal, and modeling now suggested that the multiple ore horizons in the Morrison Formation related to interface migration over time. The only major change was the suggestion by Breit [115] that the vanadian phyllosilicates were a product of post-ore alteration rather than a late stage of the main mineralizing episode. This gained little traction at the time, largely because there was too little active research in the Paradox Basin U-V deposits for it to gain traction in.

Since the middle 1990s, there has not been much additional research. The Paradox Basin U-V deposits continue to be included in reviews (e.g. Dahlkamp [116]; Cuney [117, 118]; Kyser [119]), but these rely entirely on earlier work. Mining in the region is small-scale and intermittent, and many USGS and industry geologists who had been interested in the U-V deposits have retired. Apart from some of their continuing work (e.g. Shawe [120]), the principal new contributions have been a series of new mineral descriptions, which add something to mineralogical science but little to geology or to the overall understanding of the deposits (e.g. Kampf et al. [121]). Due to the extensive reclamation of most Paradox Basin U-V deposits, more recent attempts at examination and synthesis have had to rely on grab or dump samples uncomfortably lacking in geologic context, in many cases heavily oxidized and overprinted by recent alteration (Barton et al. [122]; Hall et al. [123]).

3 Patterns Visible and Lessons Extracted

Taking the long view of research into the Paradox Basin U-V deposits (Table 1), a few patterns are apparent. Figure 6 provides a schematic summary of the interchange between descriptive geology, geologic theory, mineralogy, and other fields of science for Paradox Basin U-V research.

3.1 Flow of Knowledge and Drivers of Research

Until about the late 1960s, research on the Paradox Basin U-V deposits generated an outward flow of geological knowledge. New data and concepts from it influenced the larger field of geology: new minerals, new mineral structures, major aspects of U and V chemistry, early tests of geochronologic and isotopic techniques, and crucial information on supergene processes all came from the studies. In the late 1960s the flow went into reverse, and research in the Paradox Basin felt the influence of ideas from the outside, such as sequence stratigraphy, salt tectonics, biogeochemistry, and computerized fluid flow modeling, while having little impact on the larger world of geology. By the time active research more or less ended in the late 1990s, barely anyone outside the U industry noticed.

What drove research is a complex question. N-grams and numbers of new mineral discoveries are bad proxies for progress, but decent measures of activity. By such measures, the intensity of research peaked slightly before 1960 and around 1980 and 2020 (Figs. 1, 2 and 3). The 1980 peak in Fig. 2 is mainly the surge of stratigraphic research in the Paradox Basin: the N-gram peak in "Paradox Basin" largely postdates the peak in N-grams for "uranium" (Fig. 1). The circa-2020 peak reflects the region's popularity as a mineral collection locality (Fig. 3). But the peak in the late 1950s, which shows up in new mineral discoveries, in Paradox Basin research, and in uranium,

Table 1 Brief summary of some of the seminal research on Paradox Basin U-V deposits

Year	Reference	Description
1900	Hillebrand and Ransome [18]	First geological descriptions of Paradox Basin U-V deposits; carnotite interpreted as recent remobilization of roscoelite ores
1912–1914	Hess [21, 22]	Extensive field and microscopic descriptions of multiple deposit types, first regional interpretation
1921	Coffin [13]	Accurate differentiation of deposits by stratigraphy, firm identification of hypogene ores in Salt Wash Formation
1922	Hess [25]	Recognized light color of ore-hosting rocks as bleaching of formerly red sandstones
1924	Hess [27]	First attempt at U–Pb dating of ores; obtained ages of 28.4 to 42 Ma
1937	Fischer [32]	Confirmed igneous intrusions postdated ore; attempted to relate Cu–Ag to U-V-Ra deposits
1950s	Garrels [41] Evans and Garrels [42] Weeks et al. [43] Weeks [46]	Applied solution chemistry Eh–pH concepts to U-V mineralogy, resolving hypogene vs. supergene and order and redox-based processes of mineral formation; various reductants suggested
1956–1959	Shoemaker et al. [61] Kerr [36] Finch [66]	Major regional syntheses and comparisons across deposit types, with metallogenetic implications
1979	Leventhal [86]	Expanded role for organic acids and other compounds in forming U-V deposits
1989	Merin and Segal [95]	Bleaching of red beds, and preparation of U-V trap, attributed to mobile hydrocarbons
1990–1994	Sanford [105–107]	Quantitative modeling of U and V deposits as a function of fluid flow in the wider basinal context
1990–1991	Northrop and Goldhaber, eds. [112] Wanty et al. [114]	Synthesis of deposit description and metallogenetic interpretation across a wide area, combined with new geochemical experiments on U and V deposition

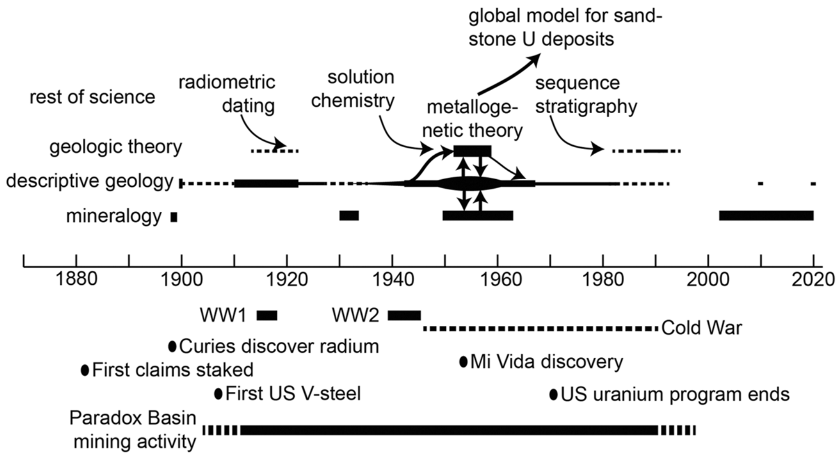

Fig. 6 Schematic illustration of the relative magnitudes, and interchanges between, geological observations, theory, and mineralogical studies over the history of Paradox Basin U-V research

represents a genuine peak in research activity. It coincided with a peak in U output (Fig. 6) and was almost certainly due to the US government's pushing both research and production to support Cold War-era nuclear goals.

The late 1950s saw the biggest conceptual advances, such as Garrels' solution chemistry and detailed understanding of the mineralogy. These grew from the work by the USGS, AEC, and affiliates (like Kerr at Columbia), and represented by far the biggest, most comprehensive geological endeavor in the Paradox Basin's history from its early days to the present. The descriptions and interpretations of the time have remained the foundation of geological understanding of the U-V deposits ever since.

No other research effort came close to equaling the sheer amount of brainpower being aimed at Paradox Basin U-V deposits during the 1950s. As the U price dropped and ceased to have government support, the USGS moved on to other topics, and mining dwindled, research began to depend on the interests, time, and financial resources of individual investigators, mainly at universities. Without the support needed for comprehensive and systematic research on the ground, results dwindled in quantity and turned from field-based to experimental and computer-based studies. From providing conceptual insights that affected the whole of geology and geochemistry, the Paradox Basin U-V deposits became a lab for testing ideas from the outside.

Some of these did help to open up new areas of research in metallogenesis. The relationship of U-V mineralization to the geologic and hydrologic history of the basin, previously almost unstudied, became a hot topic in the 1980s to 1990s. This interest was probably stimulated by advances in sequence stratigraphy and salt tectonics, for both of which the Paradox Basin provided a well-exposed natural laboratory. Papers on these topics likely make up most of the 1980s publication maximum (Fig. 2). Metallogenesis also took on a new dimension as progress in organic geochemistry opened up recognition of a wider range of potential reductants, and brought greater precision to their study.

3.2 Description and Interpretation

Another shift over time was from description to interpretation. The early papers almost uniformly consist of descriptive geology, sometimes to the total exclusion of theorizing. It was only during the 1950s that metallogenetic interpretation began in earnest, and after that date even the mainly descriptive papers included a short section apiece on how the ores formed. Hypothesis never crowded out descriptions, though, perhaps because there was less to argue about. By the time interpretations got underway in the late 1950s, the Paradox Basin had the advantage of a massive descriptive dataset on orebody occurrence, geology, mineralogy, and relationship to the host rocks. This ruled out several of the potential hypotheses almost at first sight, such as the syngenetic model that became so controversial in other deposit settings. Research in the Paradox Basin U-V deposits swiftly converged on a hydrothermal model, which was among the earliest ideas suggested, and what controversy existed concerned its details. A version remains current today (Hofstra and Kreiner, 2020 [124]). By contrast, in other areas and topics the debates over metallogenetic theory raged in inverse proportion to the facts available to either side. Time, effort, ink, and vitriol were wasted in the decades it took to settle on even the first-order processes of formation in other, data-poorer settings (e.g. Sales [50]; Garlick [51]).

Descriptions were not only geological. Probably the most fundamental advance in understanding U-V deposit formation resulted from geochemical descriptions. Robert Garrels' application of solution chemistry and Eh–pH diagrams clarified the long-mysterious relationship between the carnotite and blue-black ores, established the conditions of U and V solubility, and provided the basis for virtually all later metallogenetic theories. Uptake of U and V in oxidizing conditions, and precipitation at a reducing trap, has not been seriously questioned for some decades.

3.3 The Role of Technology

Lastly, it is apparent that progress in Paradox Basin U-V deposit research owed far more to conceptual than to technological advances. The outstanding questions of metallogenesis (hydrothermal mechanism of ore formation, precipitation by reduction, successive alteration to form the more oxidized members of the mineral suite) were solved mainly by Garrels' application of solution chemistry [41, 44–48]. A quarter-century later, computerized crunching of giant NURE datasets failed to extract new geochemical trends, identify new exploration criteria, or shed any fresh light whatsoever on ore genesis. Computerized numerical modeling of fluid flow did somewhat better, with large-scale hydrologic models such as Sanford's providing new insights into the general conditions and drivers of fluid flow around the basin during mineralization [103–107].

Advances in analytical technology, such as XRD and the electron microscope, helped. Weeks et al. [43] and others used the new techniques to work out the mineralogy and crystallography of U and V minerals, but this had more impact on mineralogy than on the understanding of the deposits. The determination of stable isotopes, which brought the role of bacteria into consideration and started the trend toward involving organic species in metallogenesis, could be classified as a technological or a conceptual advance, or both (Jensen [82]).

3.4 Future Prospects

Research in the Paradox Basin may be largely over for the present, but like most mining, it has ended without exhausting the resource. Among the many things yet to be dug up and learned about the U-V deposits are the perennial question of metal source; the nature of the reducing fluid that trapped the ore; the nature of the flow systems, and questions of transport, such as whether some of the vanadium was carried in a mobile hydrocarbon (Barton et al. [122]). The timing of mineralization and its relationship to basinwide geologic history also remain in question.

Unfortunately, prospects for another 1950s-scale epoch of rapid geological progress are dim. There is a rush of claim-staking every time nuclear energy or the V redox battery makes headlines, but what it takes to make progress is a sustained, long-term, large-scale research program insulated from the effects of fluctuating prices and production levels. With most U-V operations in the Paradox Basin producing intermittently if at all, such a program is not likely to come from industry. The best that academia can offer may be something like the research in the 1980s–1990s, driven by interested individuals and small groups. This university-based approach made unquestionable progress, but did not match the advances of the 1950s in either scale or significance—and that was before most of the best exposures were destroyed in the name of safety. Absent the combination of mines reopening, new exposures or drilling being made, and a large push for research into either U, V, or both by the government, further advances in the geology of Paradox Basin U-V deposits are likely to be incremental.

4 Conclusion: Significance of Geological Research on Paradox Basin U-V Deposits

An examination of the research history of Paradox Basin U-V deposits underscores their role as a natural laboratory. The type locality for a new variety of deposit, still (almost) unique around the world, the geological research in the region greatly influenced the geology, mineralogy, and chemistry of U and V, as well as economic geology as a whole. Research for the first ~ 50 years was almost entirely descriptive and often hindered by a lack of geological framework in the region, which was slowly ameliorated in the years leading up to World War 2. The development of nuclear armament and industry led to a sustained and intense government research program in the late 1940s to 1960, the era when most of the core theoretical contributions were made. These included the fundamentals of U-V geochemistry, mineralogy, and metallogenetic theory. After 1960, research began to dwindle, and the net flow of knowledge, which had been outward, reversed. Concepts from sequence stratigraphy, computational geology, paleoclimate, and other fields were brought in and tested on the Paradox Basin deposits, but without repercussions for wider geological thought. The major outlines of metallogenetic theory were refined without changing much and remain largely the same today. Analysis of the major epochs of progress in geological research show that it was mainly driven by US government programs rather than private industry or interest, and that robust fieldwork and fundamental geochemical concepts had a greater impact than new technology on solving the core geological questions.

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