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Paleofluid Flow in the Paradox Basin: Introduction

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Abstract

This field trip focuses on several of the classic Cu and U(-V) ore systems of the Colorado Plateau in the context of diverse geologic environments, processes, and consequences of fluid flow of the Paradox Basin. The Paradox Basin contains a >300-m.y. history of fluid flow and resource generation. Late Paleozoic development of a K-rich evaporitic foreland basin created a setting upon which later fluid-dominated processes generated economically significant accumulations of hydrocarbons, K-rich brines, CO_2, and—most notably—metals including, significant deposits of Cu and some of the largest U and V resources of the United States. The sourcing and movement of fluids of diverse types and the resulting multiplicity of metasomatic features reflect a complex history starting with salt movement beginning in the Permian, sedimentation continuing intermittently into the Paleogene, distal manifestations of Cretaceous to Paleocene orogenesis, Cenozoic magmatism and, most recently, Neogene exhumation.

In light of this broader context, we will examine Cu(-Ag) systems associated with salt anticlines at Paradox Valley (Cashin mine) and Lisbon Valley (Lisbon Valley mine), superimposed modern and ancient systems at Sinbad Valley, and contrasting U-V systems in the Jurassic Morrison Formation at Monogram Mesa (Uravan district) and Triassic Chinle Formation at Lisbon Valley (Big Indian district). In these areas, we consider the types and sources of various fluids (brines, hydrocarbons, meteoric), their solutes, the sequence of events, and links to overall basin evolution. A key objective of the trip is to use these examples and current interpretations to stimulate discussion and research about fluid flow and mass transfer in basinal settings.

Introduction

The Colorado Plateau and specifically the Paradox Basin of southeastern Utah, southwestern Colorado, and adjacent states provides a marvelous, superbly exposed natural laboratory to consider what drives fluid flow in sedimentary basins and what are its manifold consequences for mineral resources. The rich geologic context, studied over the last 150 years, reveals multiple types and scales of fluid-driven and fluid-mediated phenomena. This field trip's focus is on Cu and U(-V) ore systems in Mesozoic rocks, their settings and deposit-scale geologic characteristics, evidence for their timing, their links to broader flow systems including antecedent or contemporaneous petroleum systems, and what colocated modern fluid systems can illustrate. It is our purpose to stimulate discussion about basinal ore-forming systems while sharing a wide range of observations and interpretations in this well-studied, complex setting.

This field guide touches on the wealth of studies over that past 150 years by the USGS and many others. It also represents a partial progress report from work by the authors who are part of a new multi-disciplinary, multi-organization team working on modern and ancient fluids and their manifestations in the Paradox Basin and surrounding regions. These ongoing projects are supported by the U.S. National Science Foundation (SusChem grant #17-25338) and the W.M. Keck Foundation (grant 929941). We

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The following papers delve into greater detail on aspects of the region. Jon Thorson (2018) provides an overview of Paradox Basin geology with a focus on the copper and uranium deposits. He also discusses a model for metal sources and deposition and considers what may be the key role of preexisting or contemporaneous petroleum systems. The road log further expands on the many features that will be examined during the trip itself. For the areas visited on this trip, Isabel Barton and others (2018) summarize geologic context with a focus on the petrographic features. They integrate previous studies with work in progress. Four reprints provide additional context for aspects of the trip. Petroleum systems represent a major part of Paradox fluid history as reviewed by Whidden et al. (2014). As explained by Thorson and McIntyre (2005) in their description of the Cashin Cu(-Ag) system, Cu-bearing fluids can utilize the same pathways as petroleum systems, with Cu deposition favored by petroleum-related chemical ground preparation. Finally, in two papers Chenoweth (1981, 2006) summarizes the uranium deposits of Uravan mineral belt and the Lisbon Valley (Big Indian) district.

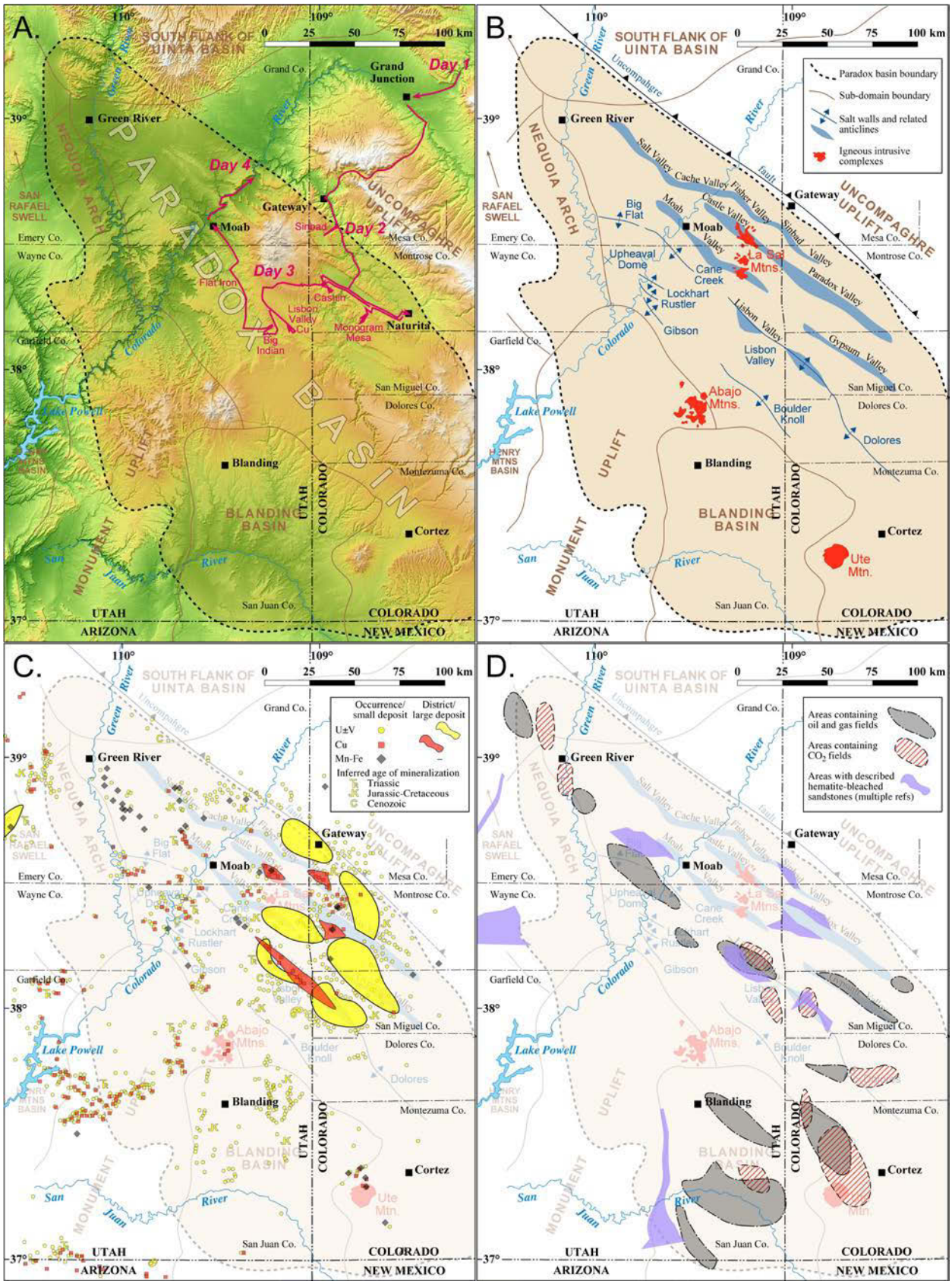
Trip Route

Although the field trip begins and ends in Keystone, Colorado, the geological portion starts early on the second day in Grand Junction, Colorado and finishes late on the third day in Moab, Utah (Fig. 1A). We initially focus on the broader tectonosedimentary setting, then turn to the Cu systems followed by a focus on the U systems.

Upon leaving Grand Junction on day 2, a traverse to Gateway, Colorado, provides a cross section of the Uncompaghre uplift and the eastern edge of the Paradox Basin. Exposed here is the principal source of Late Paleozoic detritus to the basin, the attenuated Mesozoic section across the uplift, and the locus of thickest clastic accumulation adjacent to the Ancestral Rockies (Pennsylvanian) reverse faults that generated the Uncompaghre-Paradox couple. Salt tectonics in the form of salt-cored anticlines and their superimposed valleys are spectacularly illustrated in the next set of stops as the traverse crosses the thickest part of the evaporite-dominated Paradox Formation (Fig. 1B). Along the margins of the Sinbad Valley salt wall, modern H_2S-bearing brines emerge and sulfidize red beds of the Permian Cutler Formation by a process that is inferred to be similar to that which altered rocks in many of the areas seen later in the trip. Nearby at Sinbad, older analogous bleached features host Cu(-Ag-Co) mineralization. Following stops are within and adjacent to the Paradox Valley salt anticline, first to examine cap rock and consider aspects of ancient and modern hydrology, followed by several stops to look at the La Sal Canyon paleo-upflow zone on the SW flank of the anticline. At La Sal Canyon an early hydrocarbon system sulfidized and bleached Jurassic redbeds which were subsequently Cu(-Ag) mineralized in the Cashin mine area, our last field stop of the day. Day 2 ends in Naturita, Colorado, after partially retracing our track SE along Paradox Valley.

Day 3 begins with a series of stops on Monogram Mesa, along the SW extent of the Uravan mineral belt in westernmost Colorado (Fig. 1A, C). Here, tabular U-V orebodies are hosted in Salt Wash Member of the Morrison Formation. Evidence for bleaching, local sulfidation, and Fe mobility are present, suggesting involvement of reduced fluids in mineralization. Following a circuitous route back through Paradox Valley, the next series of stops are along the Lisbon Valley anticline (Fig. 1B). At the Lisbon Valley mine, Cu mineralization is localized in favorable Cretaceous and Jurassic units adjacent to strands

Fig. 1. Location maps showing Paradox Basin geography and various fluid-related features compiled from multiple sources. (A) Topography, basin outline (edge of evaporitic facies), and field trip path. (B) Distribution of principal salt anticlines, igneous rocks, and Uncompaghre uplift. (C) Distribution of metallic mineral occurrences (U-V, Cu(-Ag), Fe(-Mn). (D) Distribution of oil and gas fields, CO_2 fields, and areas with regionally with regionally documented bleaching of red beds.


A.
B.
C.
D.
SOUTH FLANK OF UINTA BASIN
PARADOX BASIN
Day 1
Day 2
Day 3
Day 4
Grand Junction
Green River
Gateway
Moab
Sinbad
Flat Iron
Cashin
Lisbon Valley Cu
Big Indian
Monogram Mesa
Naturita
Blanding
Cortez
Lake Powell
NEQUOIA ARCH
SAN RAFAEL SWELL
UNCOMPAGHRE UPLIFT
UPLIFT
BLANDING BASIN
MONUMENT UPLIFT
HENRY MTNS BASIN
Grand Co.
Emery Co.
Wayne Co.
Garfield Co.
Mesa Co.
Montrose Co.
San Miguel Co.
Dolores Co.
Montezuma Co.
San Juan Co.
UTAH
COLORADO
ARIZONA
NEW MEXICO
Green River
Colorado River
San Juan River
Uncompahgre
Paradox basin boundary
Sub-domain boundary
Salt walls and related anticlines
Igneous intrusive complexes
Salt Valley
Cache Valley
Fisher Valley
Castle Valley
Paradox Valley
Gypsum Valley
Big Flat
Upheaval Dome
Cane Creek
Lockhart
Rustler
Gibson
La Sal Mtns
Abajo Mtns.
Boulder Knoll
Dolores
Ute Mtn.
Occurrence/ small deposit
District/ large deposit
U±V
Cu
Mn-Fe
Inferred age of mineralization
Triassic
Jurassic-Cretaceous
Cenozoic
Areas containing oil and gas fields
Areas containing CO2 fields
Areas with described hematite-bleached sandstones (multiple refs)
0 25 50 75 100 km
110°
109°
39°
38°
37°

of the Lisbon Valley fault, a salt withdrawal structure. Later, on the flank of the anticline at Big Indian, we will examine bleaching, Fe mobility, and bitumen as evidence for the flow of reduced fluids in the Permian and into the basal Mesozoic section. Just to the north at Mi Vida, these features transition into high-grade U mineralization in the Triassic Chinle Formation where it lies immediately above the bleached sands. Finally, time permitting, the Flat Iron Mesa area hosts structurally-controlled Fe-Mn oxides at the top of the Navajo Sandstone in a possible mixing zone between northeast-flowing oxygenated ground waters and a deeper petroleum-bearing fluid system.

Economic Resources—Past and Present

As shown in Figure 1 (C, D), current and past economic resources in the Paradox Basin include metals, salts, brines, oil, natural gas, and CO_2—all related to various stages of basin evolution and superimposed phenomena. Key topics to consider include the contrasting nature (geology, geochemistry) of the various economic resources, the scale(s) of the systems, their timing, and how they interacted.

Salts, brines, hydrocarbons, and CO_2

The Pennsylvanian salts of the Paradox Formation have been of primary economic interest for their K content (e.g., Thorson, 2018-this guide). Potassium is currently produced by solution mining near Potash, west of Moab, and in the past by underground mining. It is widespread and has been explored over much of the central part of the basin. Naturally occurring brines have also been investigated for their K and Li contents. Conversely, saline ground waters derived from dissolution of the salts in meteoric water have a negative economic impact, particularly along the Dolores River where they contribute unwanted salt load to the Colorado River system, necessitating a pump and inject system (Shope and Gerner, 2014).

Oil and gas have been produced for much of the past hundred years from a number of fields spread across the basin (Fig. 1D). Host rocks range from Cretaceous to the sub-salt Mississippian Leadville Limestone (e.g., see Whidden et al., 2014, reprinted in this guide). Production continues, notably from small fields along the Lisbon Valley anticline and in the Greater Aneth area in southeasternmost Utah. The principal source rocks are black shales that are interbedded with the salts of the Paradox formation. Significantly for other aspects of basin chemistry, much of the gas is H_2S-rich. An intriguing possibility is that ancient oil and gas fields may have been far more widespread than what is preserved today—perhaps petroleum giants—as evidenced by extensive bleaching, tar sands, and scattered bitumen across much of the basin (e.g., Huntoon et al., 1999; Beitler et al., 2003). These reservoirs, if originally filled, may have been breached, water-washed, and oxidized during Neogene exhumation of the Colorado Plateau (see below).

The Paradox Basin also is home to some of the world's largest accumulations of non-organic CO_2 (Fig. 1D; e.g., Allis et al., 2001). These reservoirs have been of interest both as sources of CO_2 for use in secondary oil recovery, but also as natural analogs for CO_2 sequestration. Unlike the other modern fluids, which have upper crustal or surficial origins, geochemical evidence suggests that the CO_2 is of deep-seated origin (e.g., Gilfillan et al., 2008).

Metallic deposits

The Paradox Basin is best known for the numerous sandstone-hosted U±V deposits which at various times have been mined for radium, vanadium, and uranium (Fig. 1C). Over the last 70 years, these deposits have contributed a significant fraction of total US uranium production (e.g., see Chenoweth, 1981, 2006 in this guide). Before that, beginning early in the 20th century, they were mined for radium and vanadium (e.g., Coffin, 1921; see Thorson, 2018). Two sandy strata host most of the uranium—the basal member of the Triassic Chinle Formation and the Salt Wash Member of the Jurassic Morrison Formation. The generally tabular orebodies are enriched in a wide variety of elements (U, V, Cu, Zn, Pb, Se, Mo, Cr, Fe, S…) with rather complex mineralogies and parageneses that have been studied by many (see synopsis in Barton et al., 2018, and Chenoweth, 1981, 2006). A striking aspect of many of these deposits is their

association with reduced (bleached or green) portions of their originally red host strata (Thorson, 2018). These reduced zones, which are commonly discordant, may contain recognizable plant material, but in other cases organic materials including bitumens suggest local remobilization or introduction of a reductant from an external source. Ages are problematic. The preponderance of evidence suggests that most mineralization formed within a few tens of millions of years of the host rocks; however, exceptions include smaller, discordant bodies which extend into adjacent strata and may be considerably younger, reflecting later U remobilization from the stratabound deposits (see Barton et al., 2018; Thorson, 2018).

What are the critical components of the U(-V) systems? As reviewed by Thorson (2018) and discussed in the context of the Uravan and Big Indian districts on the field trip, many models call on oxidized ground waters scavenging and then carrying U through hydrologically favorable strata until encountering a reductant either in the rock or in a second fluid. Although these interpretations fit many observations, Thorson suggests that other evidence merits consideration of alternatives for sources (e.g., shales), transporting agents (possibly including reduced fluids), and traps (hydrocarbons rather than terrigeneous materials or sulfide). For any interpretation of primary ores, further complications derive from remobilization by later oxidized ground waters (e.g., Shawe, 2011), a process that may lead to entirely separate ore bodies as in the Big Indian District (Reynolds et al., 1985; Chenoweth, 2006).

A second distinct metal association occurs as stratabound and fault-controlled sulfide Cu(-Ag) mineralization across the eastern portion of the basin with numerous, long-recognized occurrences (Fig. 1C; Fischer, 1936). As described by Thorson (2004, 2018) and Thorson and McIntyre (2005), zoned Cu(-Fe) sulfides replace pyrite and bitumen. In many cases, the precursors reflect hydrocarbon movement through originally red (hematitic) Mesozoic sandstones. Small amounts of Pb and Zn occur distal to the Cu minerals. As will be seen on the field trip, the multiple large deposits at Lisbon Valley and the smaller systems at Cashin and Sinbad are localized along faults, within or adjacent to the salt anticlines, that were critical fluid conduits for Cu mineralization.

Thorson (2018) points out that timing of mineralization is uncertain although the relationships to faults, ages of host rocks, sparse geochronology, and evidence for earlier hydrocarbon ground preparation point to Cretaceous or Cenozoic ages. Morrison and Parry (1986) suggested a mid-Tertiary age related to fluid flow driven by emplacement of the Oligocene (~28 Ma) dioritic laccoliths of the La Sal Mountains. Indeed, the La Sal Mountains (Fig. 1) contain small Cu(-Au-Ag) occurrences (Hunt, 1958) that are associated with sodic-calcic alteration of probable basinal fluid origin (C.M. Getz and M.D. Barton, unpub. data).

What are the critical components of the sediment-hosted Cu(-Ag) systems? As with the U(-V) deposits, it is widely interpreted that the metal sources are nearby strata. In the case of Cu, the source would be the Permian red beds, although a few authors have speculated about a distal La Sal Mountains contribution. As with U, a deeper, Paradox Formation source is also possible (Thorson, 2018). Ultimately, Cu transported in sulfide-poor brines was trapped by some combination of pyritic host, sulfate reduction by bitumen, or mixing with H_2S-bearing fluids. The basin contains all of these ingredients, and of different ages, illustrating the multiplicity of possible mechanisms.

Of little direct economic importance but of considerable interest in understanding element mobility is widespread evidence for redistribution of Fe and Mn (Breit and Goldhaber, 1989; Chan et al., 2000; Loope and Kettler, 2015; Thorson, 2018). Redistribution may be quite local with concentration from the immediate host rock into nodules of pyrite, hematite, or siderite. Histories can be complex with multiple events from early diagenesis to Neogene weathering (Burgess et al., 2016). At a broader scale, redistribution ranges into accumulations of Fe and Mn oxides in the form of small pipes, veins, and stratabound replacements. In many locations, these features accompany areas of bleaching of original red beds and can be quite extensive (e.g., Beitler et al., 2003, 2005). In some cases, as in the Big Indian and Monogram Mesa areas visited on the field trip, Fe oxides are concentrated close to the U(-V) orebodies, whereas in other areas they do not correlate with U(-V) orebody occurrence (Thorson, 2018). A particularly well-developed example occurs at the optional field trip stop on Flat Iron Mesa, where fault-controlled Fe-Mn oxide bodies were prospected during World War II for Mn (Barton et al., 2018; Garcia et al., 2018). In contrast to the Cu and U systems, the evidence suggests that most low-temperature

Fe concentrations reflect oxidizing traps for reduced, Fe^{+2} bearing fluids. The La Sal Mountains laccoliths contain a variation on this theme, wherein sodically altered diorite porphyry is bleached, typically with loss of iron, and minor hematite, magnetite, and ferroan carbonates veins and alteration occur nearby, reflecting cooling of high-T fluids (Hunt, 1958; Getz and Barton, unpub. data). Thus, the Fe occurrences testify to different types of fluids, flows, and mixing events.

Fluid Drives, Sources, and Types

Paradox Basin mineral systems reflect a variety of fluids, drives, and paths and their complex interactions over the last 300 Ma. As schematically illustrated in Figure 2, and explored by Sanford (1990) in a pioneering synthesis, driving forces for fluid movement have ranged from topographic to thermal, from compaction to chemical. Sources have included connate and multiple fresh to saline surface waters with contributions from distal (outside the basin) and deeper (magmatic, mantle, devolatilization) sources, as demonstrated by numerous investigations of modern fluids, fluid inclusions, and indirect geochemical evidence such as stable isotopes (see Thorson, 2018). How and when were these different fluids generated, what drove them, and what was their role in the ore systems? What are their broader manifestations in other parts of the Paradox Basin? These questions form one focus of the field trip and ongoing investigations.

Paradox Basin aqueous fluids are remarkably diverse and include fresh to hypersaline compositions; H_2S and CO_2 are commonly present as are hydrocarbons. As briefly reviewed in Thorson (2018), modern waters range from fresh meteoric waters to salt-saturated brines, the latter having acquired much of their salinity by dissolution of the Paradox Formation salts. Although modern surface waters are dilute, at various times ancient contributions would also have included episodes of evaporitic brines and seawater (Figs. 2, 3). Fluid inclusion observations (e.g., Morrison and Parry, 1986; Breit et al., 1990) indicate that many diagenetic to ore-forming fluids were moderately saline whereas shallower fluids were dilute

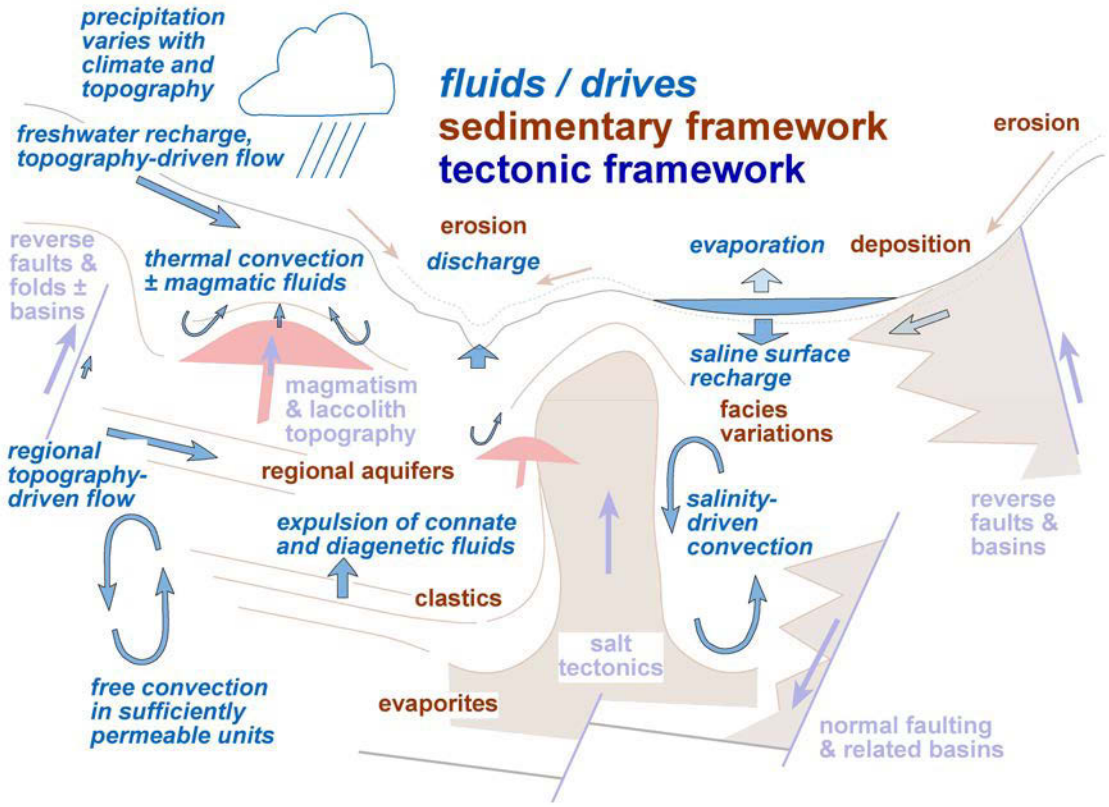


Fig. 2. Synopsis of fluid sources and drives for fluid flow in the Paradox Basin. All existed, often concurrently (cf. Fig. 3).

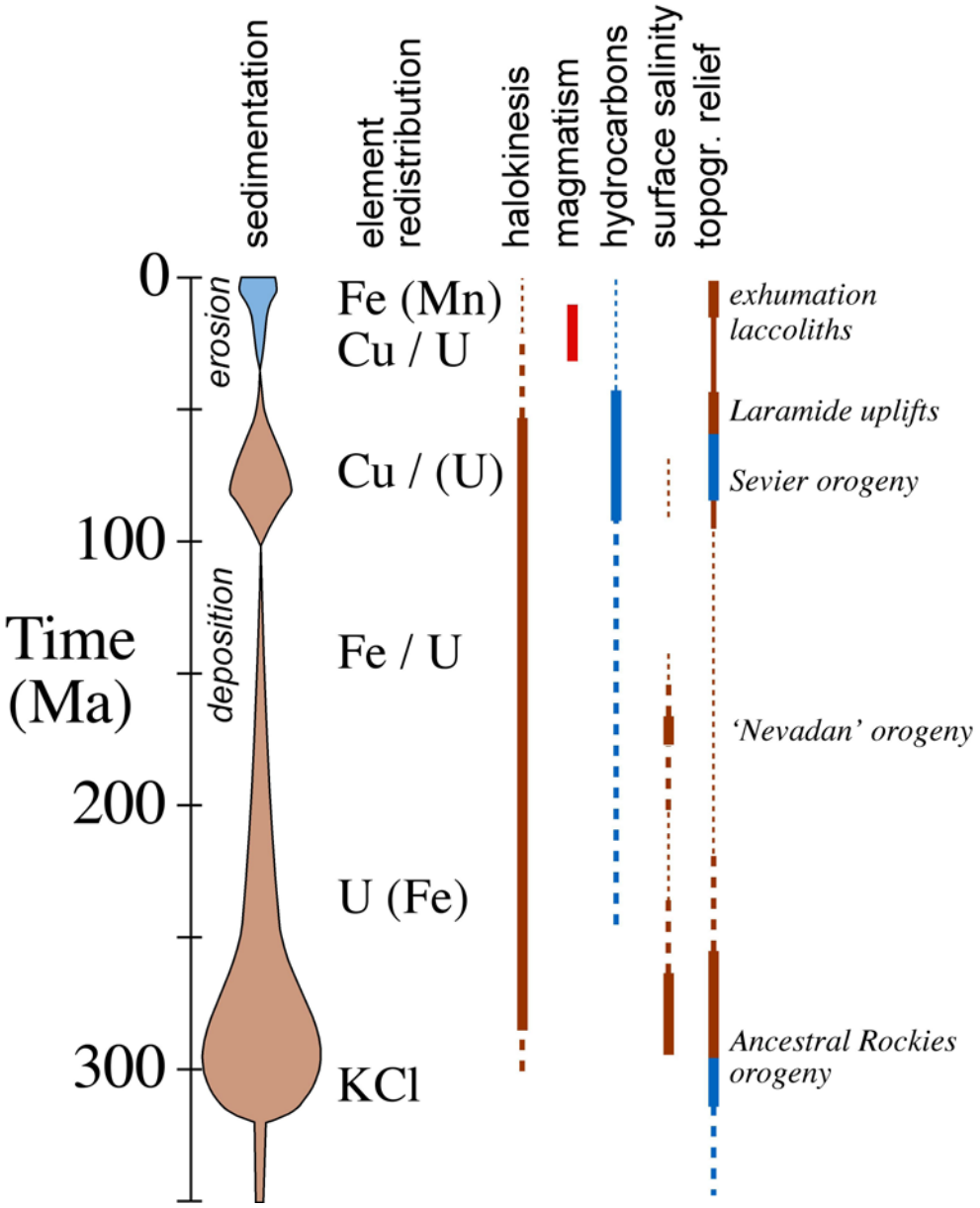


Fig. 3. Temporal summary of key events from Paleozoic through present. Symbol widths indicate general intensity of the phenomena. Blue and brown under topographic relief indicate submarine and subaerial conditions, respectively. Compiled from multiple sources. See text for discussion.

(e.g., Eichhubl et al., 2009). With the exception of what are clearly high-temperature hypersaline inclusions in altered La Sal laccoliths, essentially all inclusions record temperatures <125°C, thus broadly consistent with burial. Beyond chlorides, other solutes are less well known. Paradox oil field brines commonly contain abundant H_2S as well as sulfate. Pyritization associated with bleaching and depleted $\delta^{13}C$ in carbonates points to similar fluids being widespread in the past (Chan et al., 2000). In contrast, other bleached rocks in the region exhibit Fe leaching, which implies mobility under H_2S-poor conditions (e.g., Loope et al., 2010; Wigley et al., 2012).

As noted later, many Paradox ore systems present evidence for involvement of multiple fluids either concurrently or sequentially. For example, tabular U deposits may represent mixing of reduced and oxidized brines (Sanford, 1994), or of oxidized brines with hydrocarbons (Barton et al., 2018); Cu(-Ag)

systems reflect metal-bearing oxidized fluids either mixing with reduced fluids or superimposed on rocks that may have been sulfidized by earlier reduced fluids (Morrison and Parry, 1986; Thorson, 2004; Thorson and MacIntyre, 2005); and Fe(-Mn) oxide occurrences apparently result from mixing of reduced Fe-transporting brines and near-surface oxidized meteoric fluids (Chan et al., 2000; Barton et al., 2018; P. Reiners, pers. commun., 2018).

Although we can postulate many sources and processes (Fig. 2), many aspects of fluid flow and fluid-mediated changes are poorly known. For instance, how did the Na-Ca-K-H-metal budgets of the basin evolve over time with progressive dissolution and loss of salts, formation and destruction of carbonate cements, early diagenetic and later changes in feldspar and clay mineralogy, and metal mobility? Extensive clay and/or carbonate formation within strata and along faults record reactive transport well outside areas of known mineralization (e.g., Jacobs and Kerr, 1965; Merin and Segal, 1989; Eichhubl et al., 2009). Existing geochemical data combining isotopic, fluid inclusion, and chemical changes provides evidence in specific cases for the spectrum of sources indicated in Figure 2 (e.g., Breit et al., 1990; Chan et al., 2000; Eichhubl et al., 2009). Nevertheless, the extent of such changes, their timing, and (in many cases) the origin of the causative fluids, remains uncertain. Other changes can be postulated, such as K-metasomatism due to flow of bittern-derived brines, or K-Na-Ca exchange resulting from thermal convection caused by Cenozoic magmatism or from more subdued ambient gradients. Aspects of this complexity are explored in the papers that follow in this guide, primarily addressing metal mobilization, transport, and deposition.

A Complex History

How have fluid sources and drives varied with time? And what are the implications for known and permissive mineral systems? As summarized in Figure 3 and reviewed by Jon Thorson in his overview paper, the Paradox Basin has a complex history of deposition, deformation, exhumation, and fluid availability. Mobility of salts and related brines date from the earliest history of the basin, however the first evidence for mineralization is in the early Mesozoic.

Tectonic and paleoenvironmental framework

Basin development began in the Late Pennsylvanian with the flexural response to crustal loading by the Uncompaghre uplift, a thick-skinned reverse-fault manifestation of the Ancestral Rockies orogeny (Barbeau, 2003). Accumulation of Late Paleozoic through Jurassic oxidized (red) clastic sediments began in the Pennsylvanian, contemporaneously with Paradox Formation evaporites (up to 2.5 km) and their distal and overlying carbonates. Stratigraphic discontinuities indicate that salt movement began in the Permian with the locus migrating southwestward over time (Trudgill, 2011). Red bed deposition continued voluminously during the Permian as the basin filled (in part between salt walls) with sedimentation ultimately waning into the fluvial systems, sand sheets, and local evaporites of the early to mid-Mesozoic. This early framework partitioned older parts of the basin into hydrologically distinct units, while the mix of available surface fluids fluctuated between hypersaline and relatively fresh with changes in the paleoenvironment (e.g., Sanford, 1990; see Fig. 3).

Apart from intermittent volcanic ash input to the Triassic and Jurassic sediments, orogenic influences did not reemerge until the Cretaceous when the foreland basin generated by the Sevier orogeny renewed abundant sedimentation, leading to a transgressive, relatively reduced, thick (~2 km) sequence of sandstones, coals and shales. Subsequently, monoclines of Paleocene (Laramide) age impinged upon edges of the basin as in the San Rafael Swell and Monument uplift (Fig. 1). Available surface fluids evolved from seawater to fresh waters, while orogenesis around the margins generated significant topographic drives (Sanford, 1990) and the deepening basin in the Cretaceous triggered the principal period of hydrocarbon generation (Fig. 3; Nuccio and Condon, 1996).

Adding another dimension to the thermal history (and as possible fluid sources), sparse late Oligocene and rare Late Cretaceous magmatism is scattered across the region in laccolithic complexes such as the Henry, Abajo, and La Sal Mountains (e.g., papers in Friedman and Huffman, 1997) and in the subsurface as

revealed by deep exploration drilling (e.g., Shawe, 2011). Moreover, recent thermochronology indicates a regionally extensive mid-Tertiary thermal event that is best interpreted as the result of deep-seated advective heat flux (Murray, 2016). Not only did Oligocene magmatism contribute transient heat pulses, the laccolith complexes themselves created topographic highs that would have immediately changed the hydrologic setting, a role they continue to play up to the present. The laccolith-cored mountains (Fig. 1) remain major recharge centers for fresh water, which can now be followed through modern shallow aquifers.

A fundamental transition in fluid regimes began about 6 m.y. ago following integration of the Colorado River system and the subsequent rapid exhumation of the Colorado Plateau, which has removed upwards of 2 km of section and further lowered hydrologic base levels (House et al., 2008; Murray et al., 2016). This led to rapid and ongoing loss of salt from the cores of salt anticlines (Shope and Gerner, 2014). Among other effects, the influx of oxidized ground waters has been interpreted to have been the cause for release and degradation of major hydrocarbon reservoirs (Beitler et al., 2003), the trigger for Fe and Mn oxide deposition by mixing with deeper reduced waters (Barton et al., 2018; Garcia et al., 2018), and could have contributed to the recent redistribution and oxidation of Jurassic and older U(-V) orebodies (Shawe, 2011).

Some complexities in Paradox mineral systems and the role(s) of superposition

As developed in the following papers and in spite of a century of geologic investigation, the timing, sources, and fluid drives for the mineral systems of the Paradox Basin remain poorly understood. What is obvious is that there are a number of distinct mineral systems and that they have protracted complicated histories. Or, to put it another way, over time more than one type of system operated in the same area, leading to multiple outcomes (cf. Figs. 2, 3). To what degree was superposition of nominally unrelated features key to mineralization in the districts examined on this field trip (and perhaps in many others)? Local superposition of distinct fluid systems has long been suggested in the form of mixing models. Sequential superposition is common and can be important in ground preparation for later ore formation or in redistribution of earlier formed ores. Two illustrations suffice here. See Thorson (2018) for additional examples and further discussion.

The Big Indian district is a prime example of multiple processes, a complex history, and many open questions. There, radiometric dating indicates that the age of Chinle-hosted U(-V) mineralization is ~200 Ma (Berglof, 1970), not much younger than the age of the enclosing strata. Conventional interpretation has U and V concentrated on indigenous reduced materials (e.g., coaly plant material; cf. Chenoweth, 2006), however at Big Indian, there is a close correlation of high-grade U mineralization with disconformable reduced (green) zones in the Triassic host rocks, petroleum-bearing fluid inclusions, Fe concentrations, and—notably—an unconformity across an underlying bitumen-bearing sand (Weir and Puffett, 1981; Barton et al., 2018). Indigenous organic material and iron sulfides are widely distributed in Chinle strata irrespective of U(-V) mineralization and thus seem unlikely to be the principal cause for the narrow focus of the high-grade ores.

Could the localized nature of the high-grade mineralization reflect a mixing zone between shallow, oxidized waters carrying U and a deeper, anomalously early petroleum system? Salt movement was vigorous in the Permian and Triassic at Lisbon Valley as elsewhere in the eastern and central parts of the basin. Could this process have generated and mobilized early hydrocarbons which rose in favorable strata near the evolving salt wall and ultimately mixed with U-bearing shallow waters? Alternatively, might there have been an unconventional U source, for instance from the Paradox Formation shales themselves (Thorson, 2018)? A hundred million years or more after their formation, the Big Indian ores were offset and partly oxidatively remobilized from the Chinle into the underlying Permian Cutler Formation. This was probably a response to salt withdrawal from beneath the Lisbon Valley anticline and most likely took place during the Laramide, as suggested by Reynolds et al. (1985) on the basis of paleomagnetic dating (cf. Fig. 3). Continued oxidative redistribution of U and its daughter products continues to the present as evidenced by high Ra–low U carbonates at Mi Vida (Barton et al., 2018).

The Cu(-Ag) ores of Lisbon Valley illustrate different types of superposition and many other open questions. As described in the following papers, Cu(-Fe) sulfide mineralization is present in Mesozoic

strata adjacent to the Lisbon Valley fault system (Hahn and Thorson, 2006; Thorson, 2018). Geologic relationships and preliminary Re-Os geochronology (Jason Kirk, pers. commun.) require that copper introduction must be mid-Cretaceous or younger, presumably by influx of Cu-bearing fluid along the Lisbon Valley fault. Work by Morrison and Parry (1986) and Breit and Meunier (1990) show that the fluids were <115°C, moderately saline (5–20% NaCl equiv), and appear to be evolved meteoric or connate waters that acquired their salinity and Sr during flow through the upper Paleozoic section. However, no single depositional mechanism is required, indeed contributions from multiple traps seem likely given the geologic variability of the ores themselves. Reaction with preexisting pyrite clearly contributed, but that pyrite may have been early diagenetic (in the Cretaceous hosts) or formed by an earlier petroleum system (in the Wingate Sandstone; cf. Cashin mine, see Thorson and MacIntyre, 2005). Other contributions may have included reaction with sour gas (present today in adjacent oil and gas fields), bacterial sulfate reduction by hydrocarbons or coaly material, or mixing with a reduced shallow groundwater (e.g., Morrison and Parry, 1986).

Surely the crux for the Lisbon Valley ores was to focus sufficient saline waters that had passed through plausible source rocks (e.g., predominantly oxidized and Cu-bearing; Rose, 1976; Thorson, 2018). But what can we infer of the overall sources, paths, and drives? To begin, a simple mass balance calculation using the data summarized by Thorson (2018) in the following paper shows that there is ample Cu in the Permian red beds to supply multiple times the total Cu inferred to be present in Lisbon Valley mineralization. No exotic source is required, even from the Permian beyond the domains that are hydrologically separated by the salt anticlines. What about drives and timing? Some authors have proposed that Oligocene magmatism may have driven fluid movement and conceivably contributed components (e.g., Shawe, 2011, and earlier papers), whereas others have suggested that the topography generated by the laccolithic centers would have been sufficient (e.g., Morrison and Parry, 1986). These mechanisms require a mid-Tertiary or younger origin, which is at odds with the preliminary geochronology suggesting an age as old as Cretaceous. If not a laccolithic drive, could there have been sufficient far-field topographic drive in the Laramide? Perhaps, but it seems unlikely that distant fresher waters could displace the relatively deep, saline, and salt wall-isolated fluids in the Paleozoic section. What about internal convection within the older section, as suggested by Hitzman et al. (2005)? Evidence is lacking here as well. The bottom line is that each of these hypotheses deserves a next generation of integrated tests utilizing improved geology, geochemistry, geochronology, and modeling.

Final Thoughts

Understanding the mineral systems of the Paradox Basin in light of the entire development of the basin and its varied fluids and processes continues to be an exciting frontier. The extraordinary exposures and the wealth of work already done offer a chance on this field trip to discuss what we know, but more importantly to consider what are the key questions and how might they take our understanding of this and other basin-related ore-forming systems to the next level.

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