Understanding the Paleofluid Records of Southern Utah

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Abstract

The ability to understand subsurface fluid-rock systems is critical. Recent debates over geological carbon dioxide sequestration and hydraulic fracturing, and its link to seismicity have resulted in an urgent need to better understand paleofluid flow and interactions. This understanding will allow for inferences onto the modern systems. The Colorado Plateau, USA, has exceptional incised 3D exposure, extensively drilled wells, subsurface samples, and a relatively well-characterised geological history, with some of the best records of flow of diverse fluids in the world. The Jurassic Navajo Sandstones of the Colorado Plateau are a spectacular example of a massive paleofluid flow event, resulting in the bleaching of the upper sandstones and remarkable colour variations seen across the plateau. The fluid flow responsible for this bleaching is highly debated, the main arguments being between a huge exhumed hydrocarbon field bigger than those in Saudi Arabia or from a natural carbon dioxide flow. This article looks to critical review the evidence both for paleo- hydrocarbon and CO2 flows across the basin. Additionally, these previously studies of the flows and other paleofluid flows have mainly focused on one fluid type individual flow (i.e. hydrocarbons, groundwater and ore deposits) due to their economic value. The spatial/temporal interaction of simple, independent factors as seen in the Colorado Plateau leads to complex result not relatable to individual process. Therefore, this article will look at the need for a basin-system-scale perspective to truly understand how both the reservoir and rocks have responded to paleofluid flows.

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Introduction

Recent debates over hydraulic fracturing and its link to seismicity and geological carbon dioxide sequestration have resulted in an urgent need to better understand subsurface fluid and paleofluid flow and interactions. This would allow the development of natural analogues for these modern systems. In addition, there is an increasing awareness about the role of subsurface fluids in connecting the lithosphere with the critical zone (the near-surface environment where the interactions of rocks, fluids, atmosphere and biological organisms control and regulate the availability of resources needed for life to exist). As a result, an understanding of subsurface fluid-rock systems is becoming increasingly important. The subsurface migration for specific types of fluids over short timescales has been extensively studied in order to assess and manage groundwater, hydrocarbon and ore deposit resources. However, fewer studies have been carried out to explore multiple fluids within a flow, and to identify their interactions. An understanding of these interactions during flow, especially in areas of rock deformation, could aid in the human management of subsurface resources. Consequently, a suitable natural laboratory is required to explore and understand the connection between paleofluid flows and the lithosphere and critical zone.

The Colorado Plateau in the United States has some of the most iconic and controversial records of diverse fluid flow in the world, which have been recorded in the rock record as extensive bleaching of the upper sandstones and remarkable colour variations (see Figure 1). This makes the Colorado Plateau an ideal natural laboratory for studying paleofluid flow. The incised 3D exposure in southern Utah, extensively drilled wells, subsurface samples, and a relatively well-characterised geological history make it especially well suited for studying paleofluid flow. The spatial and temporal interaction of simple, independent factors as those seen in the Colorado Plateau leads to complex result not relatable to individual process. Therefore, this article will look at fluid responsible for this bleaching in the basin as well as the need for a basin-system-scale perspective to truly understand how both the reservoir and rocks have responded to paleofluid flows.

Geological Setting

The Colorado Plateau is located in the four corners region (where the states of Arizona, Utah, Colorado and New Mexico meet) in the southwest of the United States (Figure 2). It covers an area of approximately 50,000 km^2. The Plateau's interior is largely unaffected by significant tectonic deformation. Southern Utah is an archetypal location for paleofluid flow: it is made up of a thick Palaeozoic-Mesozoic sedimentary sequence. The Jurassic to Cretaceous system rocks make up the main sedimentary sequence. They consist of thick marine and non-marine sequences from the continents and erosion from the Nevadian and Sevier orogenies to the west of the Colorado Plateau. The Jurassic units are generally flat lying and comprise of four main aeolian units affected by diagenetic iron. In ascending order, these are the Navajo Sandstone, Page Formation, Entrada Formation and the Summerville/Morrisson Formation [1,2,3,4,5]. The Navajo sandstone and its equivalent units are dominated by large scale high angle aeolian cross stratification (Figure 1) [6]. Together, these units form the largest dune field preserved in Earth's history [1]. The Navajo Sandstone is a well sorted, fine-medium grained quartz arenite that was oxidised during diagenesis [6] and it is the main aquifer unit in some areas of the Plateau. The well-preserved porosity and permeability of the Navajo sandstone most likely allowed for large fluid flows and the resultant bleaching through the unit [7]. The Page formation is local to the Moab area and it is only a few metres thick. It is a basal chert–pebble conglomerate and fines upwards to a coarse-grained sandstone [4]; this unit also has a high permeability. The Entrada formation contains three different members (Dewey Bridge, Slick Rock and Moab Tongue) with differing lithologies and characteristics affecting the fluid movement. The Dewey Bridge Member is an interbedded sandstone, siltstone and mudstone with local bed scale breccia. The Slick Rock Member is a largely aeolian sandstone, sea-dune deposit with a moderate permeability [3,8]. The Moab Tongue member is local to southern Utah and pinches out to the south and west of the Moab. It is a relatively thin fine-grained unit which is commonly jointed and contains cross-stratified aeolian dune sets. The permeability is similar to that Navajo Sandstone. The Summerville formation and Tidwell member of the Morrison formation are both very thin-bedded sandstones and mudstones overlying the Moab Tongue. They are non-calcareous red beds from a marine incursion of sandstone in a costal to tidal setting separated by an unconformity; these represent the confining layer in the system and have remained red [4].

Figure 1: Exposure of the bleached Jurassic sandstones in southeastern Utah, near Moab. Cross stratification from dunes (CB) can be seen in both bleached (B) and unbleached units (R).

The Colorado Plateau includes salt tectonics, monoclinal folds and broad flexures, faults, and igneous laccoliths and volcanic features. The Laramide orogeny which occurred during the early Tertiary resulted in uplift of the Colorado Plateau and the monoclinal folding and minor faulting linking to regional faults at depth [9]. The thick salts of the Paradox sub-basin have added additional structure to the Colorado Plateau by deforming and folding the overlying structures and created eight salt anticlines, the crests of which were eroded prior to burial. The salt diapirs have subsequently collapsed, creating valleys at the

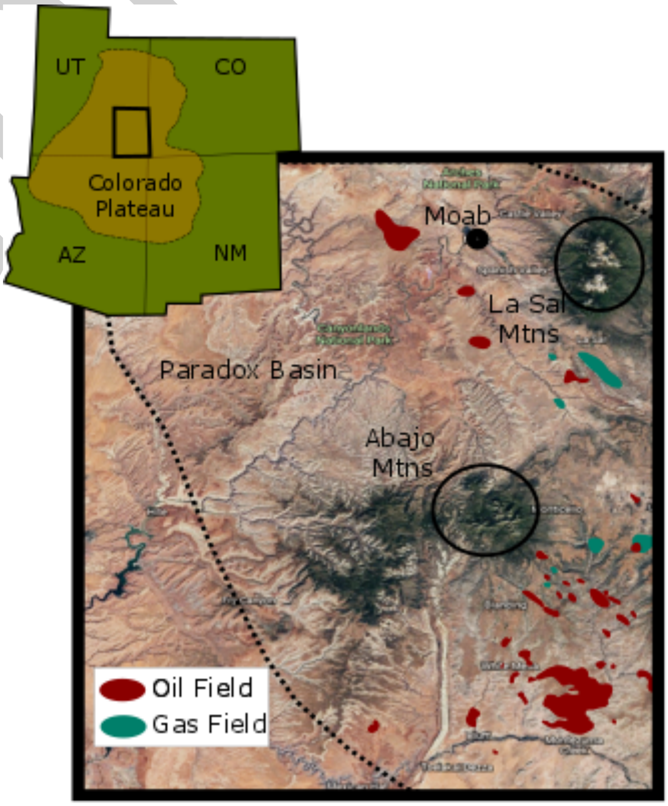

Figure 2: A map of the broader Four Corners Region of the U.S.A and a more detailed map of the study area. Satellite image is taken and modified from Google Earth; Oil and Gas Fields are adapted from assets.geoexpro.com

centre of the anticlines. Between 6 million and 1200 years ago, the edge of the Plateau was subject to volcanic activity which created volcanic extrusive features, laccoliths as well as natural CO_2 fields.

Bleached Sandstone

The Jurassic sandstones of southern Utah were stained red during early diagenesis; this was a result of the release of iron from detrital minerals and subsequently oxidized to form hematite grain coatings or iron cements [10,11]. Today the rocks that remain red represent the least altered parts of the formations. However, large areas of the region have been bleached as a result of a reducing paleofluid flow [6]. The Navajo and Entrada sandstones are both heavily affected by this bleaching [4,10,12]. There is also minor bleaching of the Permian White Rim sandstone [13] and the Triassic Moenkopi Formation [14]. The bleached sandstone tends to be at the top of formations suggesting that the responsible fluid is buoyant. The bleaching also cuts across stratigraphic boundaries and petrographic boundaries. The contacts between the bleached and unbleached zones are sharp which could suggest significant burial of rocks before bleaching [15]. This is consistent with rapid subsidence of up to 10 km during the Cretaceous [16].

Although bleaching occurs across the entire Plateau, the most continuous and extensive bleaching is in southern Utah at the crest of steeply dipping Laramide uplifts and monoclines. There is also a spatial relationship between the iron oxide deposits and faults in the region (especially the Moab fault) [4] indicating that faults in the region were conduits for the reducing fluids that bleached the sandstones.

Iron oxide deposits appear as concretions in the bleached zones and throughout the Jurassic stratum. These concretions vary in shape and size from millimetres to centimetres in scale and they cut across bedding planes. The iron is also deposited as hematite columns and pipes (tens of centimetres in diameter and several meters long) and erosionally resistant towers (up to tens of meters high e.g. at Duma Point). The red staining of the hematite columns decreases toward their cores and they can have both sharp and diffuse edges. The type of edge is dependent on groundwater flow, with the diffuse edges having 'Comet Tails' which indicate paleo flow direction [4].

Detailed geochemical studies of the bleached zones show they are depleted in ^{18}O and ^{13}C suggesting that a reducing fluid ascended through faults and mixed progressively with younger groundwaters. The fluid subsequently became oxidising, causing deposition of calcite, copper and other minerals (see Figure 3) [4,11,17,18]. There is evidence that high salinity brine ascended through the faults from the Upper Palaeozoic aquifer or that it resulted from evaporate dissolution [19]. This brine may have been associated with the reducing agent or may have ascended during a separate event, and at least two different fluids have been found to have ascended up the Moab Fault [4].

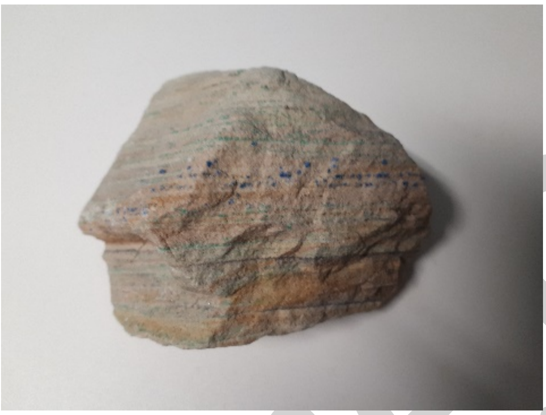

Figure 3: Hand specimen showing copper mineralisation in linear planes as a result of fluid flow along boundaries

The fluid flow responsible for this bleaching is highly debated. The main candidates are a huge exhumed hydrocarbon field or a natural carbon dioxide flow. Both of these options will be discussed below.

Possible bleaching fluids

In order for the sandstone to be bleached, the iron grain coatings must have been reduced and mobilised. To mobilise the iron and to explain the precipitation of uranite, pyrite and pyrite pseudomorphs in the region, the fluid responsible for the bleaching must have been reducing [18]. As the fluid migrated, it must have been both stratigraphically and structurally controlled. Possible iron reducing fluids that could be responsible for the colour change are: hydrogen sulphide (H_2S); hydrocarbon; CO_2; methane; and organic acids [4,20]. This mobilised iron can be seen to have travelled up to several kilometres prior to precipitation.

Similar bleaching is observed in Montana and is a result of the direct contact of hydrocarbons with iron. It has been suggested that this could also be the cause of the bleaching in southern Utah [20,21,22,23,24]. Experiments by Chan et al. confirmed the ability of hydrocarbons to bleach sandstones [4]. They found that hydrocarbons in the presence of an acid reduce and mobilise the iron, producing CO_2 and water as by-products (Eq. 1). Organic acids and methane which may also be present in hydrocarbons can also reduce the iron and release CO_2 and water (Eqs. 2 and 3 respectively). The chemical equations that govern these processes (taken from Chan et al. [4].) are given below.

$$CH_2O + 2Fe_2O_3 + 8H^+ = CO_2 + 5H_2O + 4Fe^{2+} \qquad \text{(Eq. 1)}$$

$$CH_3COOH + 4Fe_2O_3 + 16H^+ = 2CO_2 + 8Fe^{2+} + 10H_2O \qquad \text{(Eq. 2)}$$

$$CH_4 + 4Fe_2O_3 + 16H^+ = 10H_2O + CO_2 + 8Fe^{2+} \qquad \text{(Eq. 3)}$$

Based on bleached rock volumes and on pore volumes, it is estimated that 18.5×10^{12} barrels of oil would have been needed prior to the erosion to cause the observed bleaching. This figure would have made it the world's largest hydrocarbon field (currently, the largest field is the Ghawar field in Saudi Arabia which contains approximately 1×10^{10} barrels) [25]. This is not an unfeasible estimate for southern Utah as several hydrocarbon fields in the Plateau would have reached maturity during the late Cretaceous [14,26,27]. The timing of these fields maturing coincides approximately with the Laramide orogeny and the beginning of the sandstone bleaching. The anticlines associated with the location of bleaching would have also provided major structural traps for this paleo hydrocarbon reservoir. Furthermore, there is evidence that hydrocarbons were once present within the bleached sandstones; this includes bitumen veins and tar sands. Bitumen veins occur across the region with the highest concentration within 250 m of the Moab fault. They have bleached the edges of the sandstone they are in contact with, confirming their ability to cause the bleaching seen [6]. Tar sands occur in are the Slick Rock Member of the Entrada formation, and are up to 9 m thick [4]. The depleted ^{13}C signature seen in the calcite veins and cement of the sandstones can be attributed to carbon exchange with hydrocarbons which can cause decarboxylation [4,6]. This again confirms the viability of hydrocarbons as the reducing fluid and paleo-fluid flow responsible for the bleaching of the sandstones.

However, bitumen is not found in all bleached layers [20] and there is currently no indication as to what happened with the remaining hydrocarbons. Additionally, hydrocarbons would have migrated through the formations as a buoyant fluid (explaining the preferential bleaching at the top of formations) and therefore, they would not have been constrained to down dip directions. However, the comet tails on the hematite pipes suggest a single down dip flow direction [20]. The flow directions suggested by the comet tails are inconsistent with hydrocarbons as a reducing agent. Chan et al. suggested that multiple fluids —one reducing fluid and one that later causes the oxidation— might have migrated up the faults [4]. Nevertheless, the single flow direction seen from comet tails make it unlikely that these fluids would have occurred as distinct episodes with multiple flow directions. This would again suggest that it is unlikely that hydrocarbons alone could be responsible for the extensive bleaching.

Loope et al. (2010) proposed that the reducing nature of the fluid could have been instead a result of dissolved CO_2. Within the pre-Triassic strata in the Colorado Plateau there are eleven CO_2 fields [e.g.28,29,30], and CO_2 springs are associated with local faults [31]. The abundance of CO_2 in the region indicates that CO2 could be responsible for the reducing groundwater. Carbon dioxide could have seeped through the Triassic sealing sediments via faults and it could have interacted with the groundwaters [29]. As well as by the presence of hydrocarbons, the depleted ^{13}C ratio observed by Chan et al. could also be explained by upwelling of dissolved CO_2 [4]. However, laboratory experiments have shown that CO_2 does not cause the bleaching of the iron in sandstones. Though, it was able to aid in the mobilisation of large amounts of iron from the fracture minerals suggesting it is a possible source of iron in modern pore fluids [31]. Therefore, the presence of a reducing agent is required alongside CO_2 to dissolve the hematite [31,32].

Alternatively, hydrogen sulphide on its own (as opposed to mixed with hydrocarbons) could be the cause of the bleaching. It is abundant in southern Utah as evidenced by cold H_2S seeps (especially within Salt Valley), pyrite mineralisation and very H_2S rich brines in the formation underlying the Dolores River. Hydrogen sulphide could then be subsequently brought up to the sandstones via faults. Purser et al. have conducted preliminary experiments to determine the viability of H_2S as the sole cause of iron bleaching, which could be applied to the area (Eq. 4) [31].

$$2H_2S + Fe_2O_3 + 2H^+ = FeS_2 + 3H_2O + Fe^{2+} \qquad \text{(Eq. 4)}$$

Hydrogen sulphide could be sourced from the interaction of groundwater with gypsum, within the paradox salt formation, or from the reaction of thioacetamide and water [41]. Preliminary results show H_2S to have five times the reducing power of dissolved hydrocarbons [31]; however, the volumes are unlikely to be large enough to cause the amount of bleaching seen across southern Utah and the Colorado Plateau, especially as the salt is localised to Paradox Basin and not widespread. Therefore, it is likely that H_2S could have caused some of the sandstone bleaching, especially in southern Utah, but other agents must also have been present to cause the extent of bleaching seen.

Conclusion and additional work required

In conclusion, it seems unlikely that any of the fluids so far proposed (hydrocarbons, CO_2 and H_2S) are responsible on their own for the bleaching of the sandstone in southern Utah. This is mainly due to the volumes of fluid that would be required at a given reducing power. Hydrocarbons seem to be the most plausible cause for the bleaching because it seems feasible that they could reach the required volume. However, whilst hydrocarbons appear to play a key role, they are not the only contributing factor and it is likely that the bleaching was caused by a combination of hydrocarbons, CO_2, H_2S and other agents.

To understand paleofluid flow in Southern Utah and in other regions of the world, the sedimentation, deformation and lithological change through history must be well characterised. This will allow for the development of conceptual models to understand system-scale evolution and the formation and management of resources. An understanding of the modern fluid flow in the basin including sources, residence times, and flow paths, will provide additional insight into the basin characteristic and possible constraints on the paleoflow. This could be determined by the use of several techniques including noble gases, radiocarbon, stable and clumped isotopes and strontium isotopes. This broader outlook will go beyond determining specific fluid types and restricted spatial and temporal perspectives to elucidate long-term relationships and possible evolutionary relationships. Insights from this will improve the understanding of the critical zone interactions, and aid in resource management and the further development of carbon capture and storage.

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Reviews for 'Understanding the Paleofluid Records: a Case Study of Southern Utah' by Rebecca Tyne (STAAR 8 - 2018)

Review 1 - Bridie Davies – Minor corrections

1. Is the subject matter of the article suitable for an interdisciplinary audience?: Yes, the author has clearly identified the relevance of the research to both industry and resource management and the implications for other areas of research such as biological processes and the origin of life.

2. Does the title reflect the subject matter of the article?: The title is not misleading, however it might be more reflective to have something along the lines of Understanding paleofluid flow records: the importance of Southern Utah as a natural laboratory.
The current title is true to the main content – however it doesn't let you know that the article itself presents that these records are particularly useful because Southern Utah is a prime case study and "natural laboratory" to understand "system-scale evolution".

3. Does the article make a contribution to the discussion in its field?: As a non-expert in this field, I found that the article effectively outlined the motivation for research in this area, the key complexities in untangling the problem, the current thinking on this topic as well as presenting ideas for where research may go in the future to solve the problem. In this way, I feel that the article does make a contribution to the field by bringing together these different studies in one place.

4. Is the article clearly written?: On the whole yes, there are some cases where it is difficult to follow the exact line of thought / the importance of various aspects to the readers understanding of the problem. However, some of these may stem from my own lack of understanding of this particular subject and so whether some of these are addressed before final publication will depend on the desired audience, are you appealing to general scientists or people specifically interested in the field.
For example:
"The red staining of the hematite columns decreases toward their cores and they can have both sharp and diffuse edges. The type of edge is dependent on groundwater flow, with the diffuse edges having 'Comet Tails' which indicate paleo flow direction [4]."

Here it is not clear to me as a non-expert how the type of edge depends on the groundwater flow. Do diffuse edges always have comet tails that indicate paleo flow direction? Thus indicating that diffuse edges always indicate that groundwater has a directional flow rather than being a stationary body? Is there a significance between sharp or diffuse edges in this context? If not then this sentence could be re-worded to remove the question from the readers mind about whether they have missed something. The presence of the tails seems to be an important point in terms of the paleo flow, as a reader it felt like the sentence should've ended with "sharp edges would indicate….groundwater flow" for example.

Mostly though, it was easy to follow what the author was trying to say and to identify which parts of the arguments were the most key. My comment would just be to re-read it as if you don’t know the whole history/terminology and check that it is always clear exactly what you want the reader to pick out.

5. Is the article well structured?: Yes, the author has nicely taken the reader through the article with a step by step breakdown of the problem. The introduction sets out the importance really well and the following geological background focusses on aspects that in later sections become important – this was really good, I could see as I read further exactly why each piece of information that was given earlier in the article had been chosen.
The one place where I feel the flow of the article dropped was between the first and second paragraphs of the conclusions. The first paragraph is great and you can clearly see how it links to the remainder of the article – which deals mostly with the problem of which fluid caused the bleaching. The second paragraph jumps to all the different bits of information you need to understand paleo fluid flow. There needs to be a sentence to link how understanding the flow of the paleo fluids is directly linked to the debate about which fluids actually bleached the sandstones here. How do these two things connect – again this may be obvious to the author but for a broader audience it may need to be stated a bit more clearly to really lead them through the story the author is telling.
I think the link is subtly presented through the debate about the flow direction recorded in the tails and the fact that the most likely fluid source wouldn’t have flowed in such a way to produce this record. But it should be stated a bit more clearly in the conclusions to really hammer it home to the reader.
Overall though, nicely structured and written.

6. Are the references relevant and satisfactory?: The references seemed appropriate.

7. Do you feel the article appropriately uses figures, tables and appendices?: I thought the figures used were great, it would be nice to have an image of the comet tails and show how they indicate fluid flow if this is something that is easy to show visually. For a broader audience this would really help to put the discussion around the flow directions into focus, but is not essential to understand the article.

8. What is your recommendation?: Minor revision

Reviewer's comments to the author: This is a nice article and makes for interesting reading for a reader of a different discipline. A really good job was done in outlining the key arguments for the different fluids in an understandable way – just make sure to check you haven’t missed a step in some of your sentences. Intellectual jumps may seem intuitive to you after working on the text but may not be clear to the reader, particularly a non-expert in the field.