Stable Isotope Geochemistry and Paleohydrology of the Poison Strip Sandstone, Early Cretaceous, Eastern Utah

By

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Abstract

The Poison Strip Sandstone Member is a unique unit in the early Cretaceous Cedar Mountain Formation of eastern Utah. A previous chemostratigraphic study of the Poison Strip Sandstone at the Ruby Ranch Road (RRR) section east of Green River, Utah produced a noteworthy dataset with interesting $\delta^{18}O$ results (Ludvigson et al., 2015). The Poison Strip at the type section of the Ruby Ranch Member contains poikilotopic calcite cements that yield $\delta^{18}O$ values that range between -16 and -13.5‰ VPDB (Ludvigson et al, 2015). These isotopic values represent a major departure from the typical $\delta^{18}O$ values of about -8‰ VPDB documented during earlier studies of the Cedar Mountain formation and have either major paleoclimatic or later diagenetic implications for the unit. Through detailed petrographic, diagenetic, and stable isotopic analysis, we were able to determine that that the atypical $\delta^{18}O$ values produced from the poikilotopic calcite cements of the Poison Strip Sandstone are the result of deep burial diagenesis. The precipitation of poikilotopic calcite cements were likely influenced by petroleum migration through the basin and may have also been impacted by hydrothermal fluids. Preliminary temperature and depth estimates of 2 – 3km and 73 to 90° C were calculated from the intergranular volumes and isotopic data.

Acknowledgements

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Lastly, I want to thank my family. I cannot begin to repay the debt I owe them for all the love and support they have given me over the years. My wife Megan deserves as much credit as me for the completion of this graduate degree. It makes school and life much easier to navigate when you have someone who loves you waiting for you to come home every day.

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Chapter 1: Preface

Origins of Project

This project represents the newest addition to a study seventeen years in the making. Dr. Ludvigson and others have produced the stable isotopic chemostratigraphic framework upon which this project relies. An earlier study collected stratigraphic hand samples collected from the type section of the Ruby Ranch Member from the Ruby Ranch Road section in 2007 and published in 2010. This study focused on two hand samples from the Poison Strip Member at Ruby Ranch Road, designated RRR-12 and RRR-15, as well as samples collected from drill core UGS GRN 184 archived at the Utah Geological Survey, pulled by the US Department of Energy near Green River, Utah in 2002, that were collected and prepared for an earlier unpublished study by G.A. Ludvigson, R.M. Joeckel, and J. Davis in 2004. These previous chemostratigraphic studies revealed uncharacteristically low calcite $\delta^{18}O$ values collected from the whole rock samples—likely from poikilotopic calcite cements commonly present in the Poison Strip Sandstone. The goals of this project were to address uncertainties about the diagenetic context of the low calcite $\delta^{18}O$ values, and to develop a more complete understanding of the diagenetic history of the Poison Strip Sandstone.

The format of the main thesis chapter is based on the format required for publication in the journal *Rocky Mountain Geology*—the intended publication target. This publication venue seems like a natural fit given the location and focus of the subject matter. Chapter 2 of this thesis includes the manuscript to be submitted for publication. A brief discussion of the project and its results will be covered in Chapter 3.

Chapter 2: Stable Isotope Geochemistry and Paleohydrology of the Poison Strip Sandstone, Early Cretaceous, Eastern Utah

Introduction

The Cedar Mountain Formation, and by extension the constituent Poison Strip Sandstone Member, play an important role in understanding the paleoclimatology of the continental western interior of North America during the Cretaceous Period. Chemostratigraphic studies have already shown a tight temporal coupling of Aptian-Albian marine, atmospheric, and terrestrial carbon pools (Grocke et al., 1999, 2002; Hasegawa 1997; Jahren et al., 2005; Ludvigson el al., 1998, 2010, 2015; Unfar et al., 2002, 2004) that permit increasingly refined correlations of Cretaceous continental strata.

The published work on the Cedar Mountain Formation uncovered some unusually low δ^{18}O values, likely from poikilotopic calcite cements that are common in the Poison Strip Sandstone. These values, ranging from -16.0 to -13.5‰ VPDB, significantly differ from the more typical δ^{18}O values of -8‰ VPDB recorded during early meteoric diagenesis in the Cedar Mountain Formation (Ludvigson et al., 2010, 2015). Vein calcite δ^{18}O values ranging between -9 to -11% VPDB have been reported from burial diagenetic cements sampled from the Cedar Mountain Formation but are still different from those reported from the Poison Strip Sandstone.

Although there are several possible hypotheses that could explain the unusual δ^{18}O values in the calcite cements of the Poison Strip Sandstone, two preliminary ideas are considered here. (1) This unit might record an early diagenetic record of paleoclimatic event in the basin, possibly a deglaciation event in the nearby Sevier orogenic highlands (Fig. 1). The low δ^{18}O values do resemble those reported from well-preserved Early and Late Cretaceous unionid bivalves that are interpreted to have inhabited ancient rivers fed by snowmelt runoff (Glancy et al., 1993; Dettman and Lohmann, 2000); and (2) The anomalous oxygen isotopic values might have resulted from later secondary processes related to higher burial temperatures. This would be related to late-stage fluid movement through the sedimentary basin, either through hydrothermal processes or petroleum migration. The goals of this project were to address uncertainties about the diagenetic context of the low calcite $\delta^{18}O$ values, and to develop a more complete understanding of the diagenetic history of the Poison Strip Sandstone.

BACKGROUND

The Poison Strip Sandstone is one of five recently subdivided members of the early Cretaceous Cedar Mountain Formation of eastern Utah (Kirkland et al., 2016). A U-Pb date of 119.4 ± 2.6 Ma was reported from a shallow-lacustrine limestone near the base of the Poison Strip Sandstone at the Ruby Ranch Road section (Fig. 1), placing the unit in the lower Aptian (Ludvigson et al., 2010). The Poison Strip Sandstone is comprised of very fine to very coarse-grained sandstones and conglomerates and contains a framework grain population of primarily quartz with minor feldspar and lithic fragments (Stikes 2007). The Poison Strip was deposited in the foreland basin that developed as a result of the subduction of the Farallon plate along the western margin of North America. This subduction formed the Sevier orogeny and fold and thrust belt across the Western Interior (DeCelles and Coogan, 2006; Lawton, 1994; Jordan 1981). Loading from this thrust-belt flexurally deformed the crust creating the foreland basin subsequently filled by Cretaceous sediments (Currie, 2002; Stikes 2007).

The Poison Strip Sandstone is 2-15 m thick and is interpreted to represent deposition by a braided fluvial system. Flow directions, determined by paleocurrent measurements and detrital zircon analyses, was likely north-eastward to eastward (Currie, 2002; Dickinson and Gehrels, 2008; Lawton et al., 2010) and northward to north eastward (Dickinson and Gehrels, 2008; Ludvigson et al., 2010, 2015), making the likely source areas the Sevier Thrust Front and Mogollon Highlands respectively (Fig. 1).

METHODS

This study focused on two hand samples from the Poison Strip Member at Ruby Ranch Road, designated RRR-12 and RRR-15, and samples from drill core UGS GRN 184 archived at the Utah Geological Survey, pulled by the US Department of Energy near Green River, Utah in 2002. The samples were collected and prepared for an earlier unpublished study by G.A. Ludvigson, R.M. Joeckel, and J. Davis in 2004. The Ruby Ranch Road samples, RRR-12 and RRR-15, are medium grained sandstone units within the upper portion of the member, while the core sample, labeled UGS 184 A, was taken from a pebble conglomerate closer to the base of the Poison Strip (Fig. 1). The low $\delta^{18}O$ values present in the Poison Strip Sandstone Member at Ruby Ranch Road were discovered during whole rock carbonate mineral analyses of the samples (Ludvigson et al., 2010, 2015). To determine the isotopic variability of cements and isolate results from the individual components, detailed petrographic, diagenetic, and stable isotopic analyses of calcite cement was performed. Calcite cement zones are expressed at sub-millimeter spatial scales, so precise targeting and sampling was required to elucidate the cementation sequence, while avoiding inadvertent contamination from adjacent calcite cements.

Petrography

Petrographic identification of the mineral constituents and rock fabrics was carried out using an Olympus BX51 polarized light compound microscope with a digital 10.5 Mpx Olympus SC100 color camera.

Cathodoluminescence Imaging

A cathodoluminescence (CL) imaging system allowed for identification of cement types and zones, as well as clarifying the mineral paragenesis of the samples. A stainless steel Relion Industries Reliotron III cold cathode chamber was used for imaging. Macroscale imaging through the 5 cm top window of the chamber was carried out using a 16 Mpx Canon EOS SL1 DSLR camera mounted on a Diagnostic Instruments boom stand, suspended over the CL chamber mounted on a table top stand. Microscale imaging was carried out with the CL chamber mounted on a modified Olympus BX41 research microscope using a Peltier-cooled 17 Mpx Olympus DP73 color camera.

Microsampling

Carbonate microsampling for stable isotopes was guided by digital maps of micropolished thick sections (counterparts to thin sections) captured by flatbed scanner (Epson V600 Photoscanner at 600 dpi) and using perfectly-registered microscopic reflected light and CL images captured by the Olympus DP73 camera (Fig. 3). A high-precision dental drill with a 0.3 mm-diameter carbide drill bit was used to extract sample powders (0.05 – 0.1 mg/sample) from the polished thick sections (Fig. 3). Sample sites were chosen and mapped on matching CL/reflected light images of polished thick sections in advance to isolate the calcite components in sub-millimeter space, and to characterize the carbon and oxygen isotopic heterogeneity specific to each cement zone. The samples, in powder form, were roasted in vacuum for 1 h at 200° C to remove volatile contaminants prior to analysis.

Mass Spectrometer Analysis

Roasted sample powders were loaded into single reaction vessels in an automated Kiel III acid-dosing device and reacted with anhydrous phosphoric acid to produce a cryogenically-purified CO_2 gas that was carried to a dual-inlet ThermoFinnigan MAT 253 stable isotope mass spectrometer. Results were calibrated using the Vienna Pee Dee Belemnite (VPDB) carbonate isotope standard. (Ludvigson et al., 2015). All samples were micro-sampled and analyzed at The University of Kansas Keck-NSF Paleoenvironmental and Environmental Stable Isotope Laboratory.

RESULTS

Petrographic Observations

Samples RRR-12 and RRR-15

Rocks taken from the Ruby Ranch Road section consist of medium-grained sandstones with framework grain populations mainly composed of quartz and chert. In cross-polarized light, the continuity of optical domains in the calcite cements (3 to 5 mm) engulf the framework grains (1 to 2 mm), denoting a poikilotopic fabric. An average intergranular volume of 26% was calculated for the sandstone samples of RRR-12 and RRR-15 using Image J, a Java-based image processing program (Fig. 6). In addition to the poikilotopic calcite cement, another earlier zone of grain-fringing cement crystals less than 10 microns in width are also present in samples RRR-12 and RRR-15 (Fig. 2). Samples from the Ruby Ranch Road section also contain late-phase pore-filling bitumen that has undergone shrinkage (Fig. 2A). The common paragenetic sequence includes, calcite cements first infilled intergranular pore spaces, with cementation then terminated by incoming petroleum fluid migration that filled the remaining pore space with bitumen.

In addition to polarized light microscopy, cathodoluminescence imaging was used to document the characteristics of the calcite cements within and between samples. The poikilotopic cements in RRR-12 and RRR-15 are uniformly luminescent throughout both sandstone samples and lack any variability in CL brightness or color (Fig. 3). High temperature, blue-luminescing quartz framework grains (Boggs and Krinsley 2006), as well as a purple-luminescing diagenetic silica cement are present in both Ruby Ranch Road samples.

Sample UGS 184a: Sample GRN-184 A was taken from a conglomerate near the base of the Poison Strip Sandstone. The conglomerate includes large sheltered intergranular voids between framework grains (0.1 to 1 cm size) that were infilled by calcite cements with scalar dimensions, permitting the mapping of a paragenetic sequence of cementation.

Cement development observed in sample UGS 184A follows a paragenetic sequence of (1) Calcite Cement Zone 1: non-luminescent dogtooth isopachous spar 0.5 mm to 1mm in width that coated framework grains; (2) Calcite Cement Zone 2: infilling of remaining pore space by brightly luminescent calcite with equant crystal sizes ranging from 0.1 to 2 mm in size; and (3) chalcedony cement overprinting of Zone 1 (Fig. 3). The chalcedony cement preserved ghost structures related to Zone 1 calcite cement. A critical aspect to this research is understanding the relationship between Zone 1 and Zone 2 calcite cements of sample UGS 184A and the poikilotopic calcite cements present in samples RRR-12 and RRR-15.

Mass Spectrometer Analysis

A total of 18 carbon and oxygen isotope microsamples were taken from the poikilotopic calcite cements of RRR-12 and RRR-15, 10 samples came from UGS 184a "Zone 1", while 17 were extracted from "Zone 2".

Rock Samples RRR-12 and RRR-15

The two samples taken from the Ruby Ranch Road type section yielded similar isotopic results. RRR-12 yielded $\delta^{18}O$ values ranging from -18 to -15‰ VPDB, while RRR-15 yielded a slightly narrower range of -17.0 to -16.0‰ VPDB. $\delta^{13}C$ values ranged from -8.0 to -7.0‰ VPDB in RRR-12 and -7.0 to -6.0 in RRR-15 (Fig. 4). Calcite cements in both samples yielded relatively invariant carbon and oxygen isotopic compositions. Although similar, these values are slightly lower than the range of -16.0 to -13.5‰ VPDB recorded by earlier studies of these same samples using whole rock analysis (Ludvigson et al., 2010, 2015).

Core Sample UGS 184a

Zone 1 and Zone 2 calcite cements of UGS 184a yielded overlapping isotopic results. The initial non-luminescent dogtooth sparry calcite cement of Zone 1 yielded $\delta^{18}O$ values ranging from -10.0 to -8.5‰ VPDB and $\delta^{13}C$ values ranging from -5.2 to -4.7‰ VPDB (Fig. 4). The pore filling brightly luminescent sparry calcite of Zone 2 exhibited a far wider range of isotopic compositions. $\delta^{18}O$ values in Zone 2 ranged from -17.0 to -8.5‰ VPDB and $\delta^{13}C$ values ranged from -6.5 to -5.0‰ VPDB (Fig. 4).

DISCUSSION

Paragenesis of Mineral Cementation in the Poison Strip Sandstone

Calcite Spar Zone 1: The non-luminescent dogtooth calcite of Zone 1 coated the largest framework grains in the conglomerate sample. As the first phase of pore-filling cementation, Zone 1 provides the earliest record of diagenetic processes (Fig. 7).

Chalcedony: Developing after Zone 1 was the non-luminescent chalcedony cement (Fig. 3). This chalcedony cement overprints the calcite spar of Zone 1, preserving ghost structures of earlier cement development.

Calcite Spar Zone 2: The brightly luminescent pore filling calcite cements of Zone 2 in the UGS 184a sample clearly penetrate the chalcedony cement and Zone 1 calcite as a later pore-filling phase, providing evidence for its placement in the paragenetic sequence (Fig. 3).

Poikilotopic Calcite Cement: The poikilotopic calcite cement the Poison Strip Sandstone at Ruby Ranch Road section fills intergranular volumes that range between 23.5% and 26.5%. Intergranular volumes in this range are characteristic of a mineral cementation under deep burial conditions at depths between 2 to 3 km where pore space has collapsed under lithostatic loading (Paxton et al., 2002; Fig. 6).

Bitumin: The presence of bitumen as a late-stage pore-filling is a clear indicator that petroleum migrated through the Poison Strip Sandstone. Poikilotopic calcite cementation was terminated by incoming petroleum fluid migration that filled the remaining pore spaces. The current space gap between the remaining bitumen and the surrounding calcite cement is likely due to volume reduction from loss of organic volatiles when the formation was exposed at the surface (Fig. 2).

Silica Cements: What is still not clear is the origin or timing of the bright violet-colored silica cements captured by cathodoluminescence imaging of samples RRR-12 and RRR-15. The CL properties of the silica cement is not like that of the non-luminescent chalcedony cements observed in UGS 184a that replaced Zone 1, likely indicating no genetic relationship. The silica cement overprints the poikilotopic calcite cement placing it after the cements in the paragenetic sequence (Fig. 7).

Diagenetic Interpretations of Stable Isotope Data

Interpretations of the carbon and oxygen isotope data from calcite cements in the Poison Strip Sandstone are based on recognition of distinctive patterns in C & O isotope space that are characteristic of individual carbonate components, and on the well-documented scientific literature on interpretations of carbonate diagenesis. Burial cements typically have highly variable $\delta^{18}O$ values and comparatively invariant $\delta^{13}C$ values. This covariant isotope pattern is primarily the result of increasing temperatures of precipitating waters (Choquette and James, 1987; Hasiuk et al 2016). A differing covariant spatial pattern is characteristic of early meteoric diagenesis, where a vertical trend in carbon-oxygen isotope space develops, known as the "Meteoritic Calcite Line" or MCL (Lohmann, 1983; Choquette and James, 1987; Hasiuk et al 2016; Lohmann, 1988). Early meteoric diagenetic cements possess highly variable $\delta^{13}C$ values with relatively invariant $\delta^{18}O$ values. The carbon and oxygen isotope pattern observed in burial diagenetic environments was recently verified by Hasiuk et al. (2016) in a study that examined 28 subsurface petroleum reservoirs. The carbonate isotopic data taken from the Poison Strip Sandstone clearly displays highly variable $\delta^{18}O$ values with a covariant carbon and oxygen isotope linear trend with positive slope, matching the signature typically associated with carbonates that formed in burial diagenetic environments (Fig. 4 & 5).

Calcite Spar Zone 1: Zone 1, which is present in all samples but is only large enough in the core sample UGS 184a to be micro-sampled, contains the highest $\delta^{18}O$ values recorded in this study of the Poison Strip Sandstone member, with values ranging from -10.0 to -8.5‰ VPDB. Zone 1 is the first phase of pore-filling cement and provides the earliest record of diagenesis in the member. These values fall between the reported baseline $\delta^{18}O$ values of -11.3 to -9.6‰ VPDB reported from burial diagenetic cements, and the values of -8.0 to -7.5‰ VPDB reported from the early diagenetic cements sampled from the Cedar Mountain Formation (Ludvigson et al., 2010, 2015). These ambiguous results could be the result of inadvertent mixing between Zone 1 and Zone 2 during sample extraction. The brightly luminescent calcite cements of Zone 2 very clearly penetrated the non-luminescent cements of Zone 1. This provided the evidence for the paragenetic sequence, but it also makes it very difficult to completely isolate Zone 1 during the microsampling process. It is also possible that the microdrill over penetrated Zone 1 during sampling and extracted cements from Zone 2. Although it is possible that Calcite Spar Zone 1 represents cementation in an early meteoric diagenetic setting, the overall pattern of the isotopic data in C and O space could also suggest that Zone 1 is the earliest stage of cement development in a burial diagenetic environment.

Calcite Spar Zone 2: Zone 2 $\delta^{18}O$ values ranged from -17.0 to -8.5‰ VPDB, bridging the gap between the higher Zone 1 $\delta^{18}O$ values and the much lower $\delta^{18}O$ values observed in the poikilotopic calcite cements samples from the Ruby Ranch Road section (RRR-12, RRR-15).

The variability of Zone 2 may suggest that this cement precipitated over time spans longer than the other calcite cements present in the Poison Strip Sandstone.

Poikilotopic Calcite Cements: The poikilotopic calcite cements present in samples RRR-12 and RRR-15 possess the lowest $\delta^{18}O$ values recorded in the study and were undoubtably responsible for the anomalously low $\delta^{18}O$ values originally discovered by whole rock isotopic analysis of the Poison Strip Sandstone (Ludvigson et al., 2010, 2015). The stable isotopic data obtained from the UGS 184 core clarified questions concerning the timing and diagenetic environments of the poikilotopic cements observed in the Ruby Ranch Road samples. As they represent the lowest values recorded in this study, they likely represent a later stage of pore-filling in the paragenetic sequence of the Poison Strip Sandstone. The bitumen filling remaining pore spaces indicate that it migrated the Poison Strip Sandstone after development of the poikilotopic cement, placing bitumen at the end of the paragenetic sequence (Fig. 7).

Estimates of Depth and Temperature

Depth Estimates using IGV: As part of the petrographic analysis, image analysis software (Image J) was utilized to calculate the intergranular volumes of the Ruby Ranch Road samples. An average IGV of 26.5% was recorded in the poikilotopic cements of RRR-12 and RRR-15 (Fig. 6). IGVs in this range are indicative of burial depths ranging from two to three (3) km (Paxton et al. 2002). Using an average geothermal gradient of 25 - 30° C/km of depth, the estimated burial temperatures for precipitation of the poikilotopic calcites cements in the Poison Strip Sandstone ranged between 75° - 90° C.

Burial Temperature Estimates using Stable Isotope Data: Using a method described by Suarez et al. (2009), it is possible to estimate the temperatures of early meteoric diagenesis during deposition of the Poison Strip Sandstone. Suarez et al. (2009) utilized the second-order polynomial regression generated by Ufnar et al. (2002) from the latitudinal temperature gradient presented by Spicer and Corfield (1992) and based on fossil leaf physiognomy data of Wolfe and Upchurch (1987) to develop the following equation:

$$t = 30.25 - 0.2025l - 0.0006l^2$$

where t is temperature in degrees Celsius, and l is paleolatitude. Using the paleolatitude of 34° N specified for the Cedar Mountain Formation by (Suarez et al. 2009) results in a calculated mean annual surface temperature of 23.43° C. This mean annual temperature represents an estimate of the temperatures of the meteoric waters associated with the calcite crystallization taking place during early meteoric diagenesis.

As previously discussed, meteoric diagenetic environments can be identified by a vertical trend in carbon-oxygen isotope space known as *meteoric calcite lines* or MCLs (Fig. 5). Ludvigson et al. (2010) reported MCL values of -8 to -7.5‰ VPDB from calcrete deposits in the Cedar Mountain Formation (Fig. 8). The poikilotopic calcite cements of the Poison Strip Sandstone produced the lowest oxygen isotopic values in the unit, with $\delta^{18}O$ values of -18.5 to -17 ‰ VPDB. This difference in the oxygen isotope values between early and late diagenetic calcites can be used with reference to a general rule of thumb that a one per mil decrease in $\delta^{18}O$ values corresponds to an increase in temperature of 5 °C (pers. comm.; Luis Gonzalez) to estimate the higher temperatures of the basinal fluids responsible for the burial diagenetic cements found in the Poison Strip Sandstone. This approach assumes no changes in fluid compositions.

Assuming that the estimated mean annual temperature of 23.4° C corresponds with calcite $\delta^{18}O$ values of -8.0 ‰ VPDB, and utilizing an oxygen isotope change of 1 mil decrease per 5° C warming leads to an estimated a temperature of 73.4° C for the burial fluids responsible for precipitating the poikilotopic cements of the Poison Strip Sandstone. The two methods for estimating burial depth and temperatures described above yielded similar results.

Influence of Petroleum Migration

The presence of bitumen in the samples taken from the Ruby Ranch Roach section is a clear indicator that petroleum migrated through the Poison Strip Sandstone within the basin. These are not surprising results as the Cedar Mountain Formation is an important natural gas reservoir in several basins including the Uinita Basin where the Cedar Mountain Formation, along with the Dakota Formation, are estimated to hold as much as 70 TCF of natural gas (Rose et al., 2004). Petroleum and its associated fluids have clearly played an important role in the diagenetic history of the Poison Strip Sandstone, but direct physical evidence of its influence has not been previously been described.

Bitumen has been determined to be the last stage in the paragenesis of the Poison Strip Sandstone, as it filled the last remaining pore spaces not filled by the poikilotopic calcite cement. However, it is might be possible that petroleum migration and precipitation of the poikilotopic calcite cement occurred contemporaneously. The burial temperature estimates provided by the intergranular volume (26.5%) and oxygen isotope data, in the range of 75 - 90° C, would place the Poison Strip Sandstone within the oil generation window during the growth of the poikilotopic calcite cement (Eremenko and Tverdova, 1980), making it plausible that the brines associated with petroleum migration influenced the precipitation of the poikilotopic calcite cements, and were likely responsible for the low $\delta^{18}O$ values present in the unit. Independent fluid inclusion analysis to determine the filling temperature, and salinity of the basinal fluids associated with the Poison Strip Sandstone is currently underway by Dr. Sahar Mohammadi at the Kansas Geological Survey, and could in the near future provide additional insight into the nature of the relationship between the migrating petroleum fluids and the poikilotopic calcite cement present in samples RRR-12 and RRR-15.

Potential Impact of Hydrothermal Fluids

The timing and origin of the brightly colored violet silica cements observed in the Ruby Ranch Road samples is still uncertain (Fig. 3). Cathodoluminescent characteristics (color) can be used as a tool to estimate origin of the authigenic silica cements. The violet color observed in these samples is indicative of quartz polymorphs that crystallized from hydrothermal solutions (Gotze 2000; Gotze et al. 2001a, b; Witke et al. 2004; Boggs and Krinsley 2006). Although this is a subjective method, it is plausible that the violet-colored CL silica cements present in the Poison Strip Sandstone crystallized as overprinting an phase from hydrothermal fluids associated with proximal igneous activity. Located roughly 40 km to the east of the Ruby Ranch Road type section, are the La Sal Mountains. The La Sal Mountains represent the erosional remnants of Eocene laccoliths (Ross 1998). These laccoliths are in close enough proximity that they could have provided the sedimentary pile with an infusion of hydrothermal fluids.

CONCLUSIONS

The Poison Strip Sandstone has proved an invaluable resource for paleontologists, stable isotope geochemists, petroleum and uranium exploration geologists and others trying to understand the geological evolution of the continental western interior of North America during the Cretaceous Period. Through detailed petrographic, staple isotopic, and diagenetic analyses, this study was able to determine that the atypical $\delta^{18}O$ values produced from the poikilotopic calcite cements of the Poison Strip Sandstone do not represent an authigenic record of a major paleoclimatic event in the basin, but rather are the result of deep burial diagenesis. The precipitation of poikilotopic calcite cements in the Poison Strip Sandstone was likely influenced by petroleum migration through the basin. Nearby Eocene volcanism may have also played a role by providing hydrothermal fluids from laccolith emplacement in the La Sal Mountains. Additional geochemical studies are needed to determine if hydrothermal fluids played a role in the paragenesis of the Poison Strip Sandstone.

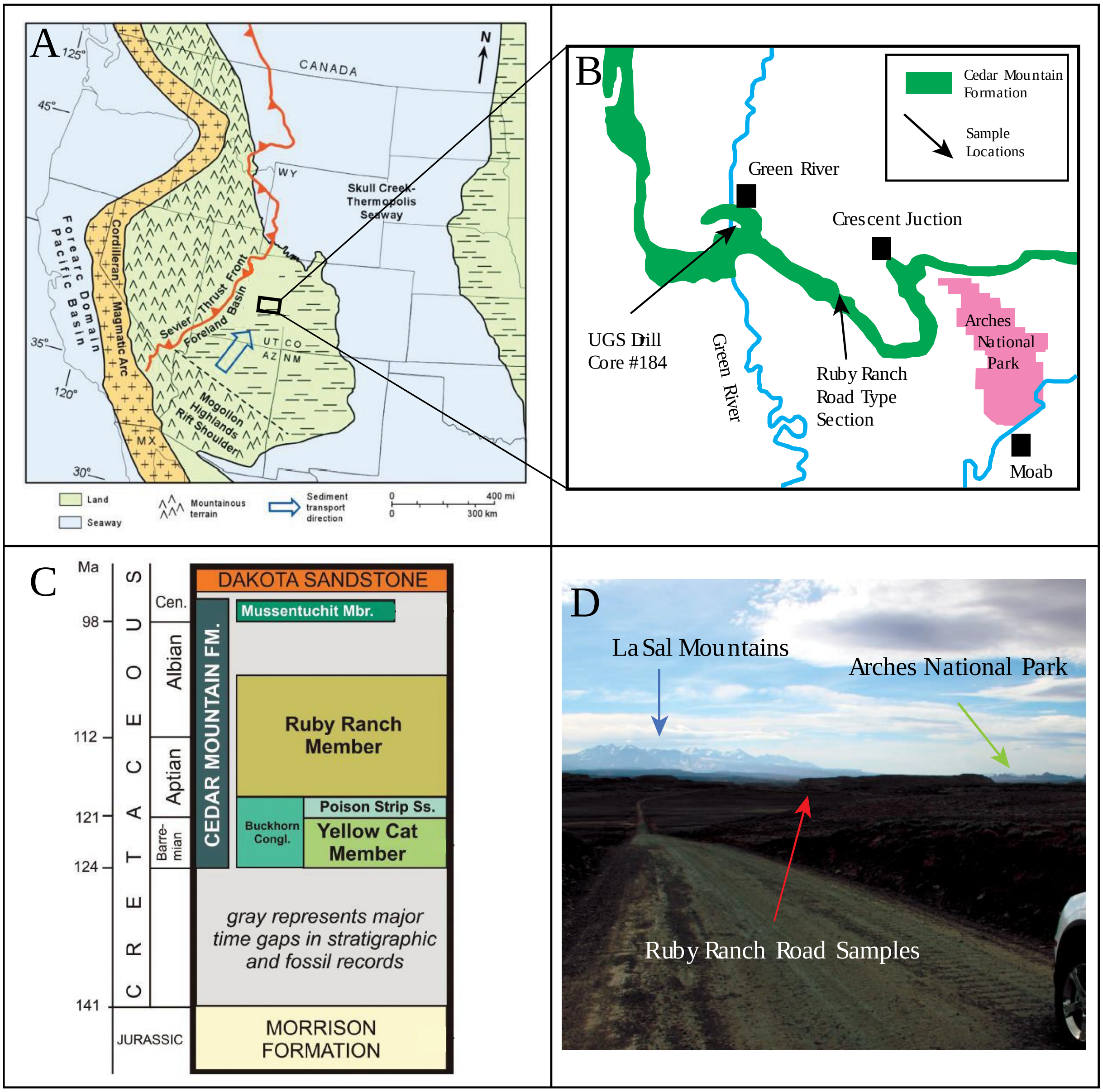

Fig. 1. (A) Location map and Cretaceous paleogeography from Ludvigson et al. (2015). The tectonic setting is from Dickinson (2006), and the Albian paleoshoreline is from Cobban et al. (1994). **(B)** Locations of sample locations discussed in this paper. **(C)** Stratigraphy of the Early Cretaceous Cedar Mountain formation (after Kirkland et al. 1997). **(D)** Photograph taken looking southeast along Ruby Ranch Road. The La Sal Mountains, a potential source of hydrothermal fluids, can be seen in the far background.

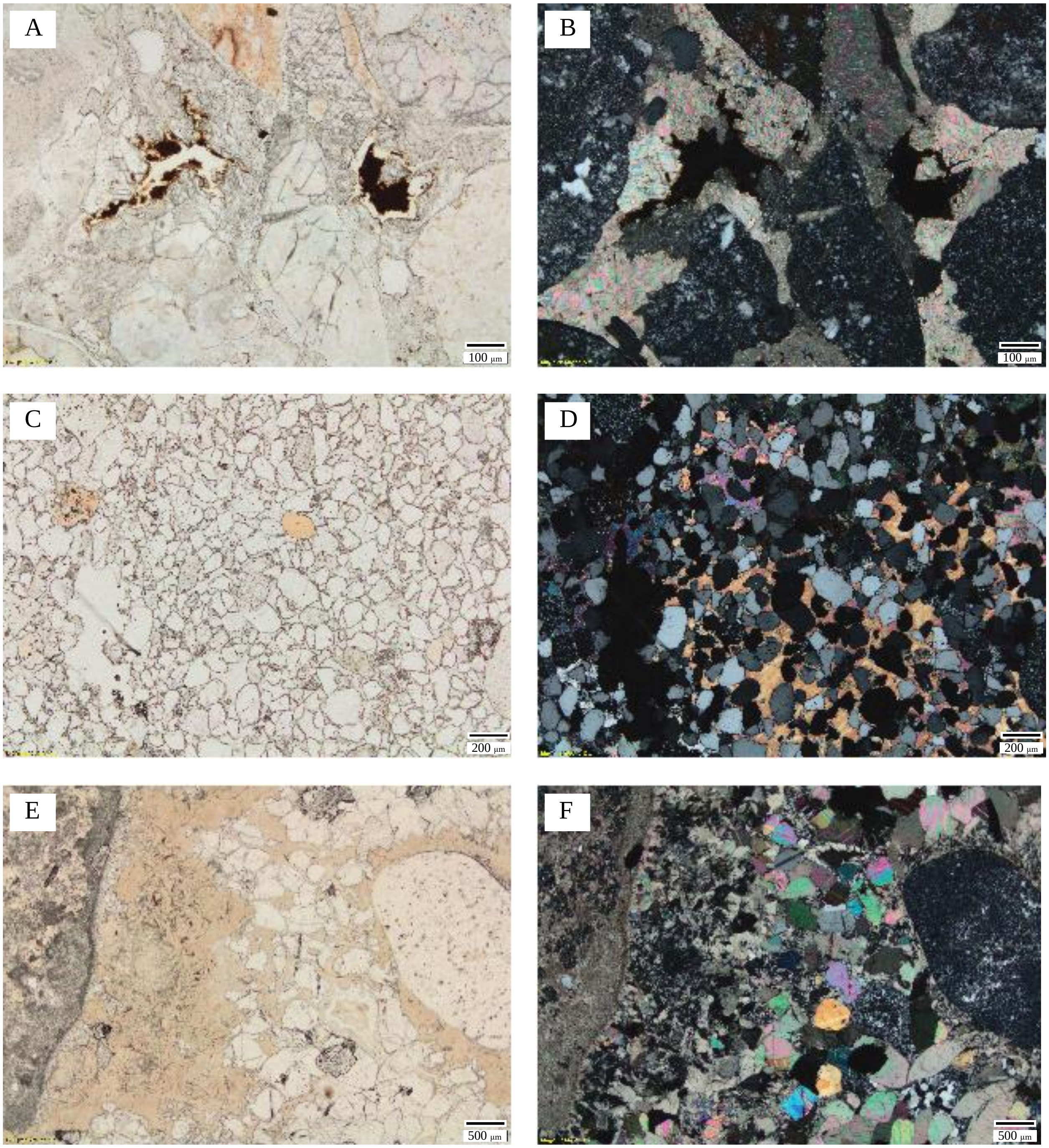

Fig. 2. Photomicrographs of rock samples from the Poison Strip Sandstone. Plane-polarized light (PPL) and cross-polarized light (XPL) thin section micrographs taken from the Poison Strip Sandstone Member. **A,B** –RRR-12 – Bitumen surrounded by calcite spar cement. **C,D** –RRR-15 – The continuity of optical domains in calcite cements (3 to 5 mm) engulf the framework grains (1 to 2 mm), denoting a poikilotopic fabric. **E,F** – UGS 184a – Taken from a conglomerate at the base of the Poison Strip. Includes large sheltered intergranular voids between framework grains.

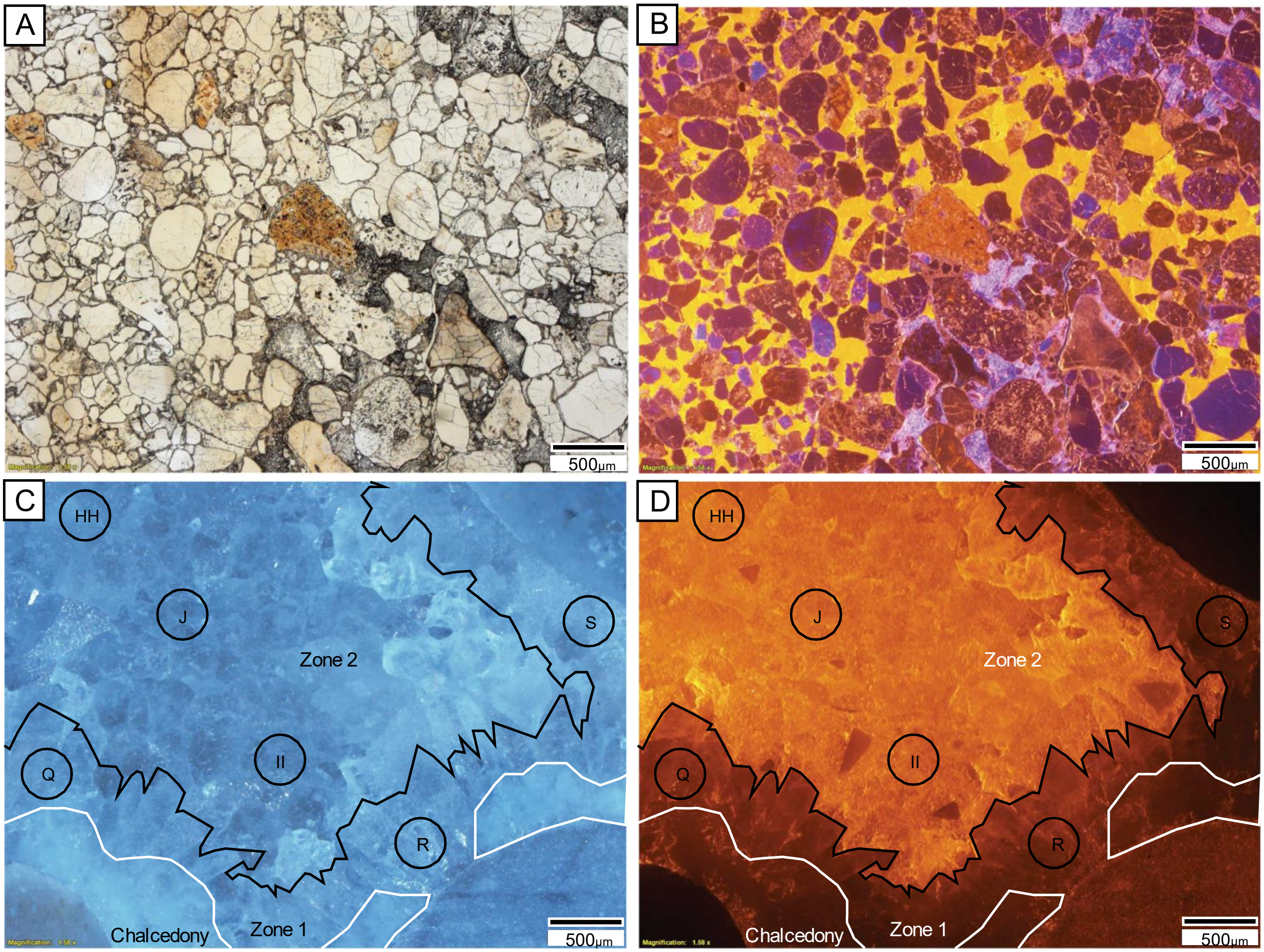

Fig. 3. Cathodoluminescence (CL) -mages of samples from the Poison Strip Sandstone. **(A,B)** Sample RRR-12. Seen here is the poikilotopic calcite cement (light orange) and the overprinting cryptic silica cement (violet-colored). **(C,D)** Sample UGS 184a. Sample extraction locations for stable isotope analyses are shown with black circles. The various cement zones are also labeled and outlined. Nonluminescent chalcedony is shown with the white outline.

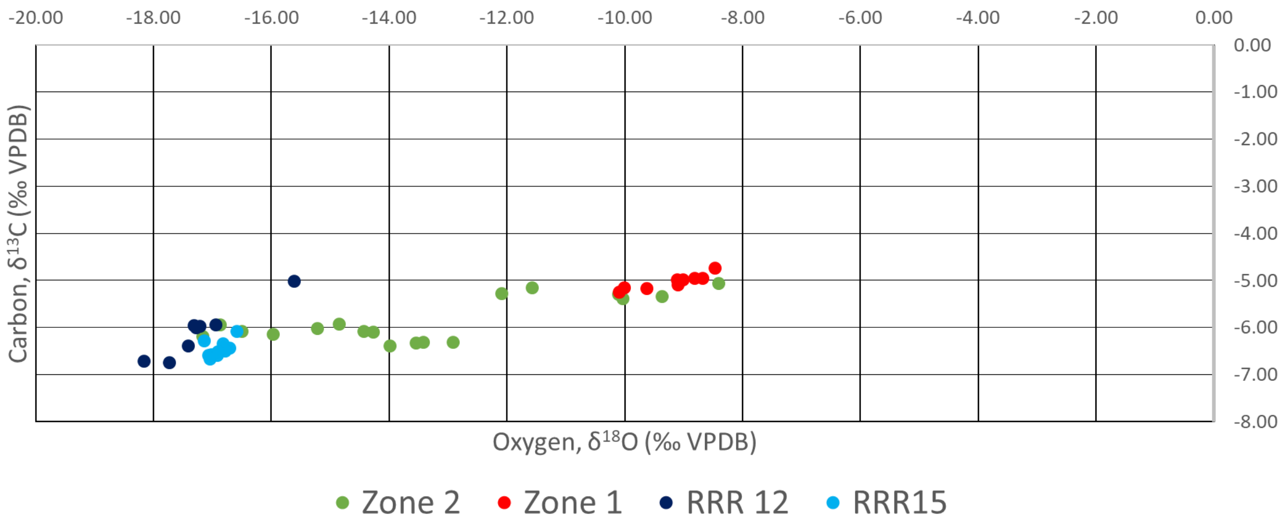

Fig. 4. Carbon and oxygen isotope plot of the calcite cements from the Poison Strip Sandstone. The isotopic data taken from the Poison Strip clearly displays a wide range of $\delta^{18}O$ values matching the signature typically observed from carbonates that crystallized in a burial diagenetic environment arrayed along a linear trend with slightly positive slope.

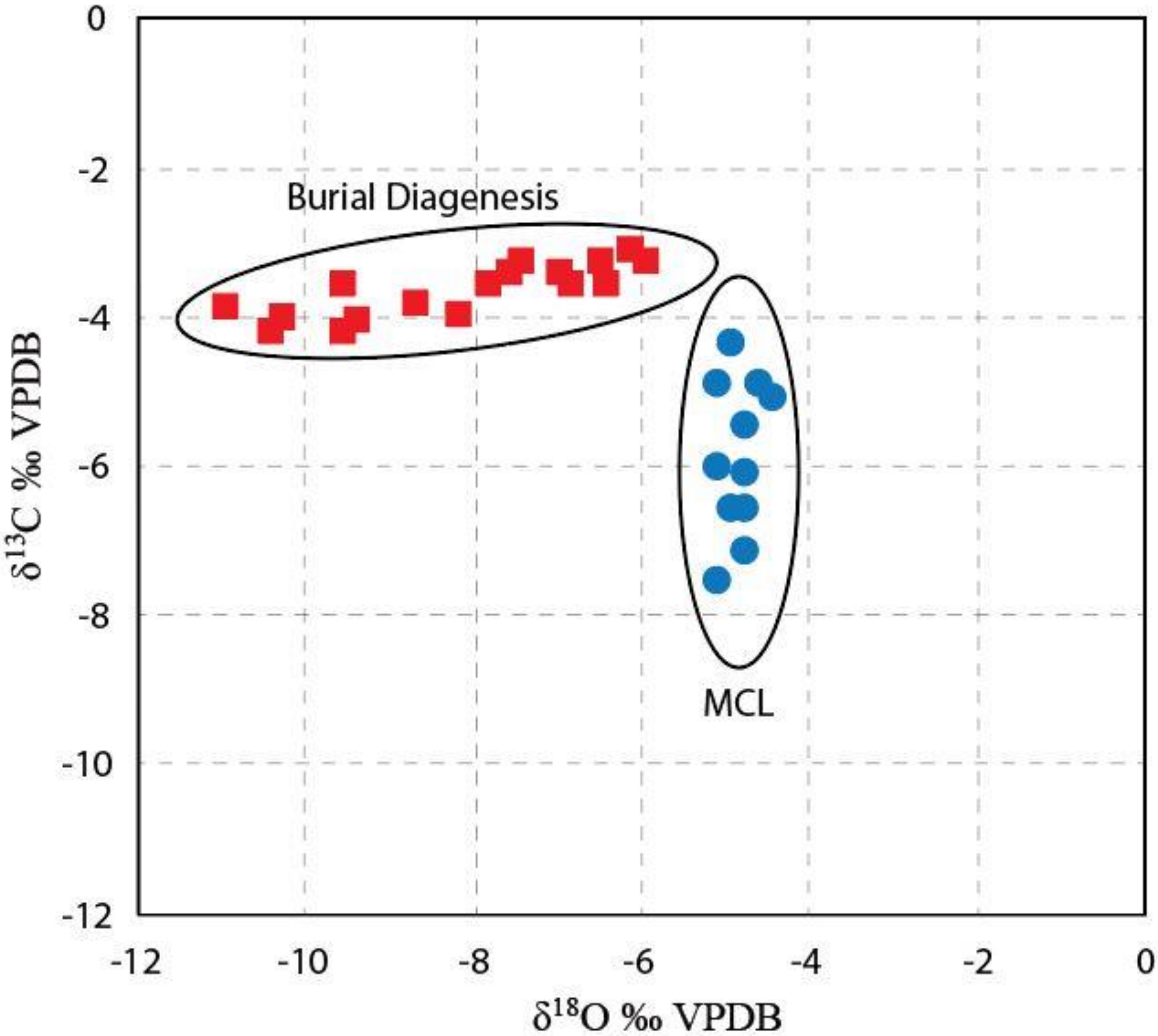

Fig. 5. Idealized carbon and oxygen isotope plot illustrating the trends typically observed in early meteoric (MCL) and burial diagenetic environments. Modified from Choquette and James, 1987.

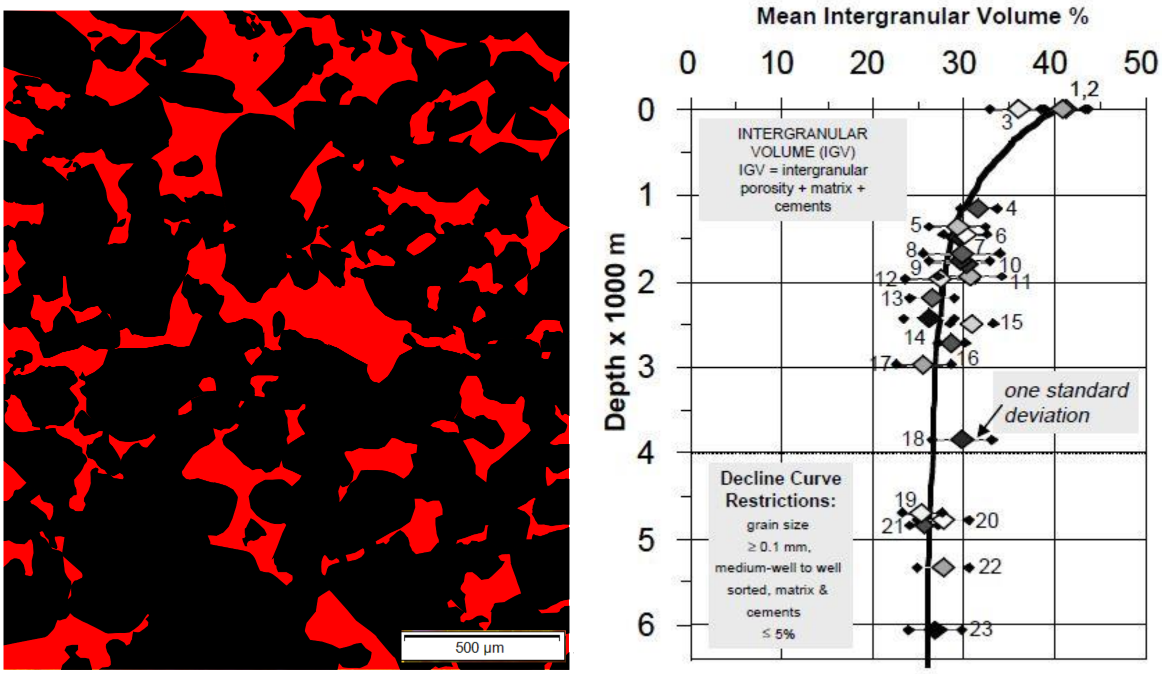

Fig. 6. (Left) Image illustrating the intergranular volume calculated for sample RRR-12 using Image J, A Java-based image processing program. **(Right)** Utilizing the curve published by Paxton et al. (2002), it is possible to estimate the depths at which sandstone were cemented (2 – 3 km for the Poison Strip Sandstone).

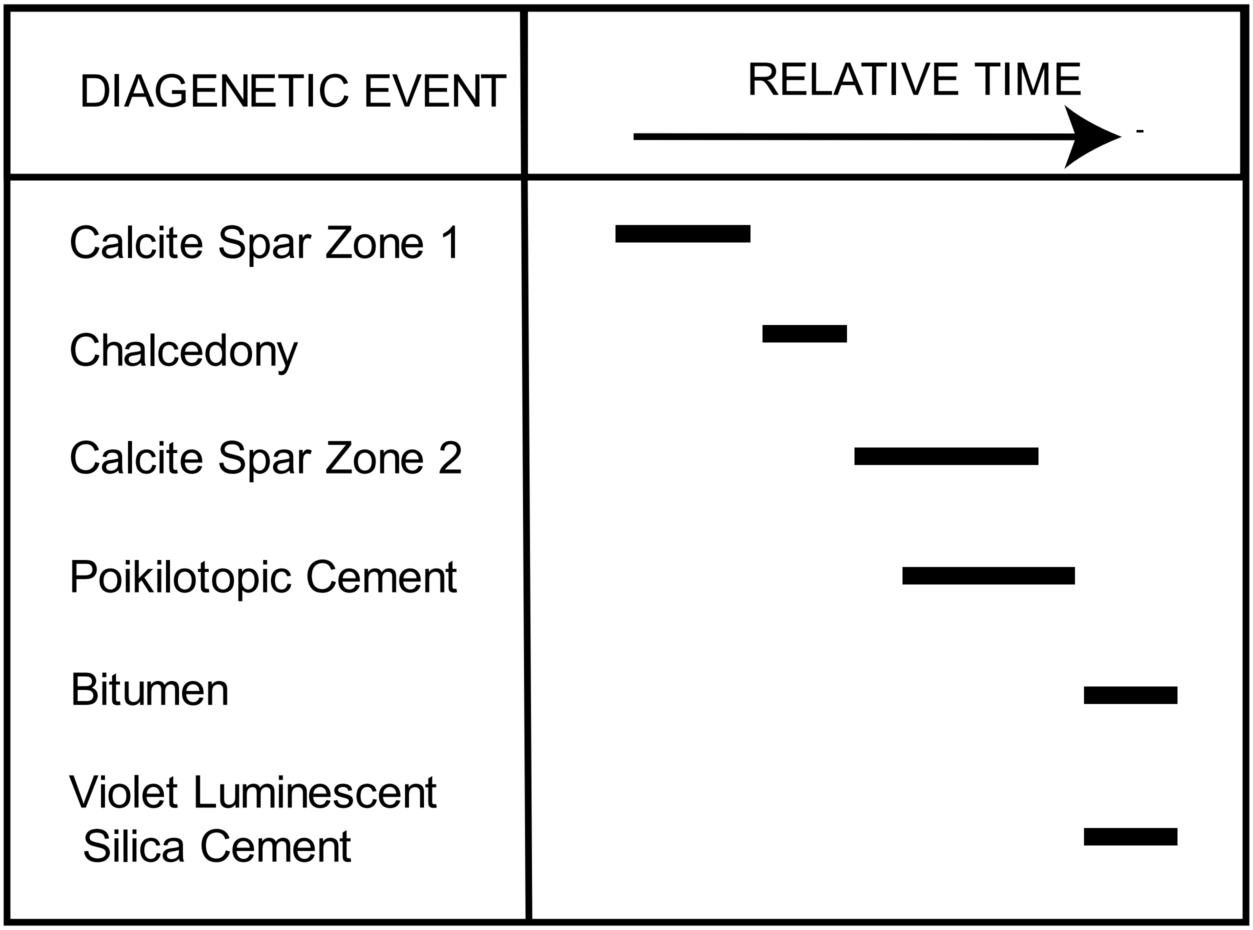

Fig. 7. Summary of the paragenetic sequence inferred from this study of the Poison Strip Sandstone.

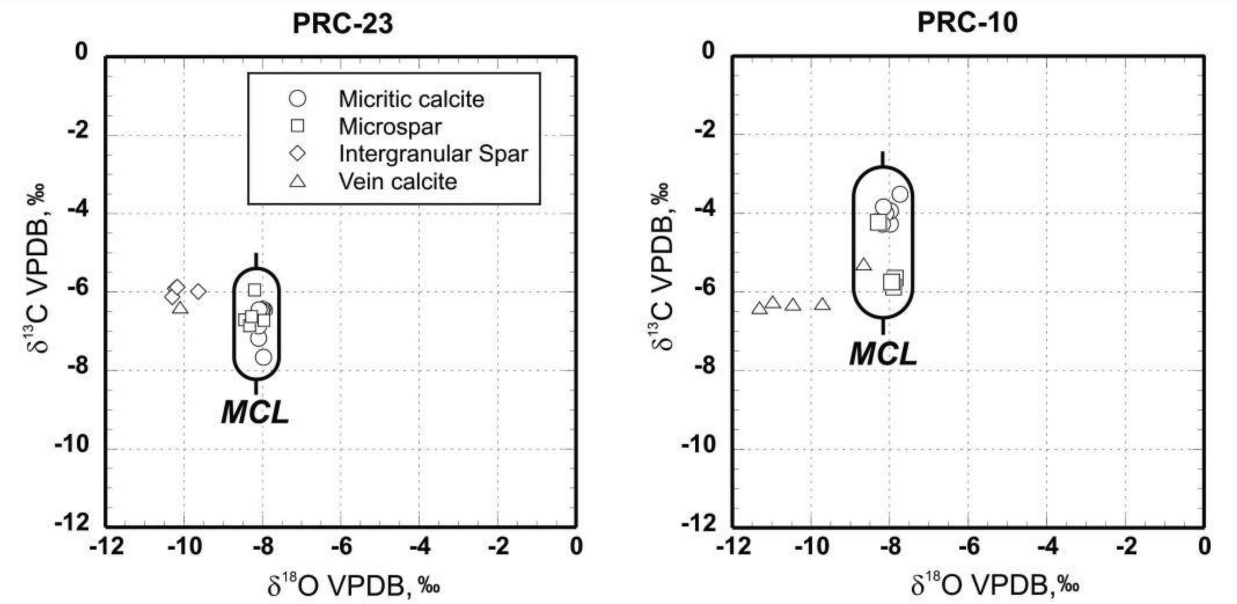

Fig. 8. Carbon and oxygen isotope plots showing δ^{1C}C and δ^{18}O values measured from carbonate components in rock samples PRC-23 and PRC-10. The symbols MCL denote the vertical linear trends of meteoric calcite lines that are characteristic of the authigenic micritic and microspar calcites in these samples. From Ludvigson et al. 2010

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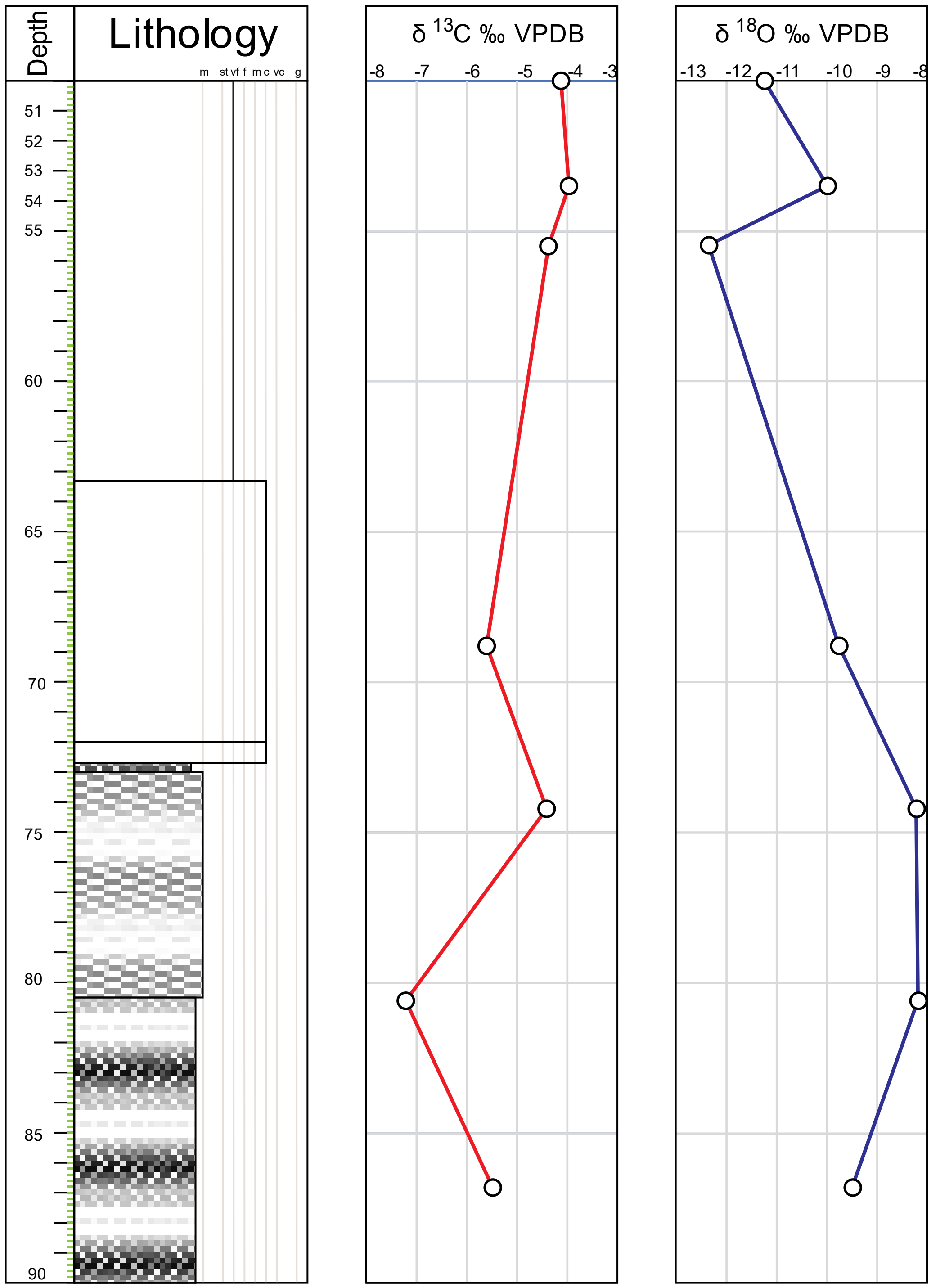
APPENDIX

Sample ID	Cement Zone	Mineral	$\delta\ ^{13}C$ VPDB	$\delta\ ^{18}O$ VPDB
184 A	2	Calcite	-6.10	-16.50
184 B	2	Calcite	-6.20	-17.15
184 C	2	Calcite	-5.95	-16.86
184 D	2	Calcite	-5.93	-14.84
184 E	2	Calcite	-6.09	-14.42
184 F	2	Calcite	-6.11	-14.27
184 G	2	Calcite	-6.40	-13.98
184 H	2	Calcite	-6.33	-13.41
184 I	2	Calcite	-5.17	-11.57
184 J	2	Calcite	-5.29	-12.08
184 K	1	Calcite	-4.97	-8.67
184 L	1	Calcite	-5.16	-10.00
184 M	1	Calcite	-4.99	-9.10
184 N	1	Calcite	-5.25	-10.08
184 O	1	Calcite	-4.99	-9.01
184 P	1	Calcite	-4.96	-8.81
184 Q	1	Calcite	-4.75	-8.46
184 R	1	Calcite	-5.18	-9.62
184 S	1	Calcite	-5.10	-9.09
184 AA	2	Calcite	-6.15	-15.97
184 BB	2	Calcite	-6.33	-13.53
184 CC	2	Calcite	-6.03	-15.21
184 DD	2	Calcite	-5.40	-10.03
184 GG	2	Calcite	-6.32	-12.90
184 HH	2	Calcite	-5.06	-8.40
184 II	2	Calcite	-5.36	-9.36
184 JJ	2	Calcite	-5.30	-10.11

Sample ID	Cement Zone	Mineral	δ ^{13}C VPDB	δ ^{18}O VPDB
RRR12 A	Poikilotopic	Calcite	-6.40	-17.40
RRR12 B	Poikilotopic	Calcite	-5.95	-16.94
RRR12 C	Poikilotopic	Calcite	-5.02	-15.61
RRR12 E	Poikilotopic	Calcite	-6.72	-18.15
RRR12 F	Poikilotopic	Calcite	-5.96	-17.30
RRR12 G	Poikilotopic	Calcite	-6.76	-17.73
RRR12 H	Poikilotopic	Calcite	-6.01	-17.26
RRR12 J	Poikilotopic	Calcite	-5.98	-17.21
RRR15 A	Poikilotopic	Calcite	-6.10	-16.58
RRR15 B	Poikilotopic	Calcite	-6.68	-17.03
RRR15 C	Poikilotopic	Calcite	-6.60	-17.06
RRR15 D	Poikilotopic	Calcite	-6.29	-17.13
RRR15 E	Poikilotopic	Calcite	-6.60	-16.91
RRR15 F	Poikilotopic	Calcite	-6.58	-17.01
RRR15 G	Poikilotopic	Calcite	-6.44	-16.70
RRR15 H	Poikilotopic	Calcite	-6.35	-16.81
RRR15 I	Poikilotopic	Calcite	-6.50	-16.78
RRR15 J	Poikilotopic	Calcite	-6.53	-16.90

UGS GRN Core 184



Stratigraphic column and isotopic data was collected by G.A. Ludvigson, R.M. Joeckel, and J. Davis at the Utah Geological Survey in July of 2004. This stratigraphic column includes only the section of the core utilized for isotopic analysis and is limited to the Poison Strip Sandstone and the underlying Yellow Cat member.