GEOLOGY OF THE INTERMOUNTAIN WEST
an open-access journal of the Utah Geological Association
ISSN 2380-7601
Volume 4 *2017*

SOURCE WITHIN THE SEAL—DISTRIBUTION AND IMPLICATIONS OF ORGANIC SHALE-BEARING STRINGERS WITHIN THE ONION CREEK DIAPIR, NORTHERN PARADOX BASIN, UTAH

Samuel M. Hudson, Trevor Tuttle, and Matthew Wood

GEOLOGY OF THE INTERMOUNTAIN WEST

an open-access journal of the Utah Geological Association

Volume 4 *2017*

Editors

Douglas A. Sprinkel
Utah Geological Survey
801.391.1977
GIW@utahgeology.org

Bart J. Kowallis
Brigham Young University
801.422.2467
bkowallis@gmail.com

Thomas C. Chidsey, Jr.
Utah Geological Survey
801.537.3364
tomchidsey@utah.gov

Steven Schamel
GeoX Consulting, Inc.
801.583-1146
geox-slc@comcast.net

Production

Cover Design and Desktop Publishing
Douglas A. Sprinkel

Cover

Extensive folding of fractured carbonate and deformed shale beds in the Onion Creek diapir in the northern Paradox Basin near Moab, Utah.

UGA Board

2018 President	Paul Inkenbrandt	paulinkenbrandt@utah.gov	801.537.3361
2018 President-Elect	Peter Nielsen	peternielsen@utah.gov	801.537.3359
2018 Program Chair	Emily McDermott	ekeller@utah.gov	801.537.3389
2018 Treasurer	Zach Anderson	zanderson@utah.gov	801.538.4779
2018 Secretary	Christopher Kravits	ckravitsgeo@gmail.com	
2018 Past President	Bill Loughlin	bill@loughlinwater.com	435.649.4005

UGA Committees

Education/Scholarship	Loren Morton	lmorton@utah.gov	801.536.4262
Environmental Affairs	Craig Eaton	eaton@ihi-env.com	801.633.9396
Geologic Road Sign	Terry Massoth	twmassoth@hotmail.com	801.541.6258
Historian	Paul Anderson	paul@pbageo.com	801.364.6613
Membership	Rick Ford	rford@weber.edu	801.626.6942
Public Education	Paul Jewell	pwjewell@mines.utah.edu	801.581.6636
	Matt Affolter	gfl247@yahoo.com	
Publications	Roger Bon	rogerbon@xmission.com	801.942.0533
Publicity	Paul Inkenbrandt	paulinkenbrandt@utah.gov	801.537.3361
Social/Recreation	Roger Bon	rogerbon@xmission.com	801.942.0533

AAPG House of Delegates

2017-2020 Term	Tom Chidsey	tomchidsey@utah.gov	801.537.3364

State Mapping Advisory Committee

UGA Representative	Jason Blake	blake-j@comcast.net	435.658.3423

Earthquake Safety Committee

Chair	Grant Willis	gwillis@utah.gov	801.537.3355

UGA Website
www.utahgeology.org

Webmasters	Paul Inkenbrandt	paulinkenbrandt@utah.gov	801.537.3361
	Lance Weaver	lanceweaver@utah.gov	801.403.1636

UGA Newsletter

Newsletter Editor	Bob Biek	bobbiek@utah.gov	801.537.3356

Become a member of the UGA to help support the work of the Association and receive notices for monthly meetings, annual field conferences, and new publications. Annual membership is $20 and annual student membership is only $5. Visit the UGA website at www.utahgeology.org for information and membership application.

The UGA board is elected annually by a voting process through UGA members. However, the UGA is a volunteer-driven organization, and we welcome your voluntary service. If you would like to participate please contact the current president or committee member corresponding with the area in which you would like to volunteer.

Utah Geological Association formed in 1970 from a merger of the Utah Geological Society, founded in 1946, and the Intermountain Association of Geologists, founded in 1949. Affiliated with the American Association of Petroleum Geologists.

GEOLOGY OF THE INTERMOUNTAIN WEST
an open-access journal of the Utah Geological Association
Volume 4 **2017**

Source Within the Seal—Distribution and Implications of Organic Shale-Bearing Stringers within the Onion Creek Diapir, Northern Paradox Basin, Utah

Samuel M. Hudson[1], Trevor Tuttle[1], and Matthew Wood[2]
[1]*Department of Geological Sciences, Brigham Young University, Provo, UT 84602, USA; sam.hudson@byu.edu, trevortuttle15@icloud.com*
[2]*School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019, USA; woodmatt52@gmail.com*

ABSTRACT

The Onion Creek diapir is one of the best exposures of a dissected salt diapir in the world, offering a unique opportunity to better understand the internal character of heterolithic diapirs that are common in sedimentary basins worldwide. Large amounts of interbedded shale, carbonate, and evaporites are incorporated into the diapir as stringers or boudins, and excellent three-dimensional exposure allows us to document the nature, size, deformation, and distribution of these stringers. Blocks range in size from single, disaggregated layers of dolomite to several meters of coherent stringers that contain multiple cycles of dolomite-shale-evaporite and are upwards of 20 m thick and more than 100 m in observed length. The largest blocks are most commonly located along the margins of the exposed diapir, though stringers are common throughout the exposed caprock. In areas devoid of large stringers, there is more extensive deformation of the gypsum caprock, suggesting that the presence of stringers leads to a more heterolithic distribution of stress within the salt as it diapirically rises. These observations can help to better characterize similar diapirs elsewhere that are not well exposed at the surface.

Black shale is present in all observed large stringers of the Onion Creek diapir. These shale beds are interpreted to have been deposited in a shallow, restricted marginal marine environment along with the interbedded carbonate and evaporite strata. Pyrolysis analysis of 13 samples from within the stringers shows a range of 2.56 to 60.22% total organic carbon (TOC), with an average value of 16.93%. These strata contain Type I/Type II hydrocarbon source facies, consistent with a restricted shallow marine environment. Tmax data suggest that these source rock facies have been exposed to sufficient thermal energy to generate hydrocarbons (average = 437° C), as evidenced by common hydrocarbon staining of intra-stringer carbonate strata and evaporite beds surrounding the stringers. Twelve additional samples were collected from these stained strata and pyrolysis analysis shows that all are enriched in free oil, as shown by elevated S1 peaks, high production index ratios, and TOC values of 0.64 to 1.66%. This hydrocarbon staining is found around stringers near the center of the exposed caprock, as well as stringers along the margins. Near the margins in particular, extensive alteration can be seen across tens of meters of evaporitic strata, showing that hydrocarbons are effectively generating within and migrating away from stringers fully encased in the anhydrite caprock of the Onion Creek diapir. This has important implications for potential seal integrity of diapiric caprocks, as well as providing a potential mechanism for caprock carbonate formation suggested by other researchers.

Citation for this article.
Hudson, S.M., Tuttle, T., and Wood, M., 2017, Source within the seal—distribution and implications of organic shale-bearing stringers within the Onion Creek diapir, northern Paradox Basin, Utah: Geology of the Intermountain West, v. 4, p. 215–229.

INTRODUCTION

Salt diapirism is an important process in many of the world's sedimentary basins, leading to complex syntectonic sedimentation patterns in surrounding salt withdrawal mini-basins. Whereas much work has focused on the effects of salt on surrounding strata, less has been done to better understand the internal dynamics of diapiric bodies themselves. Important exceptions to this are dominantly from studies of the Zechstein salts of the Netherlands and diapirs in the Gulf of Mexico, both of which commonly have large stringers, rafted blocks, or layered evaporites (Williamson and others, 1997; Callot and others, 2006; Van Gent and others, 2011; Fiduk and Rowan, 2012; Li and others, 2012; Strozyk and others, 2012; Reiche and others, 2014; Strozyk and others, 2014).

The Onion Creek diapir, located near Moab, Utah (figure 1), offers a rare opportunity to study the detailed internal dynamics of a complex salt diapir in surface exposures. It is part of a series of northwest-southeast trending diapiric salt walls originating in the Pennsylvanian Paradox Formation within the Paradox Basin. The Onion Creek diapir is part of the larger Fisher Valley salt wall, and is the only part exposed at the surface. The Fisher Valley salt wall is the most proximal salt wall to the Uncompahgre uplift to the northeast (figure 1, Trudgill and Arbuckle, 2009), and diapirism was initiated by the deposition of the overlying Permian Cutler

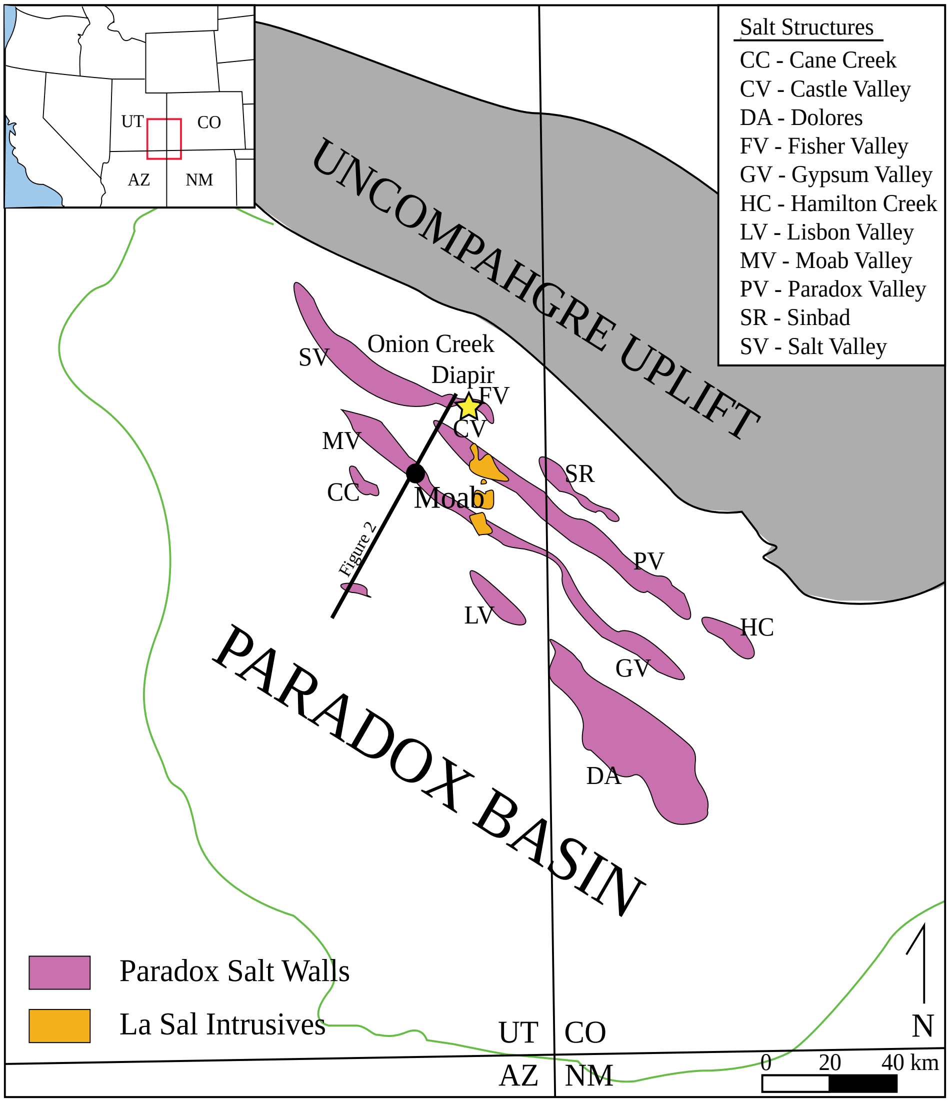

Figure 1. Regional map showing trends of major salt structures associated with the Paradox Basin and Uncompahgre uplift, Utah and Colorado. The Onion Creek diapir (marked with a star) is associated with the Fisher Valley salt wall, located on the northern margin of the Paradox Basin. The location of figure 2 is shown by the black line running from Fisher Towers in the northeast to the Needles District of Canyonlands National Park in the southwest. Modified from Rasmussen and Rasmussen (2009).

Formation, which was shed off from the nearby uplift (Ohlen and McIntyre, 1965; Doelling, 1988; Barbeau, 2003; Trudgill and others, 2004; Kluth and DuChene, 2009; Trudgill, 2011; Venus and others, 2015). The diapir exposes approximately 5 km^2 of highly deformed Paradox Formation (McCalla, 2008).

The Paradox Formation of the Hermosa Group was deposited in the Paradox Basin; a broad, shallow marine basin nearly surrounded by highlands (Ohlen and McIntyre, 1965). Open marine conditions were common, as evidenced by preserved limestone and shale beds (Hite and Buckner, 1981; Handschy and Dyer, 1987; Blakey and Knepp, 1989; Dickinson and Lawton, 2003). However, frequent eustatic sea level changes resulted in complex and cyclic depositional patterns (Hite and Buckner, 1981). This, combined with the semi-arid to arid climate (Guthrie and Bohacs, 2009), led to frequent basin restriction and deposition of appreciable amounts of evaporitic strata (Baker and others, 1933; Rasmussen and Rasmussen, 2009). Originally, there were 29 evaporite-carbonate cycles of interbedded shale, carbonate, and evaporites (halite, gypsum, anhydrite, and potash) identified within the Paradox Formation (figure 2) (Hite 1960; Hite and Buckner, 1981; Trudgill and Arbuckle, 2009); however, as many as 80 stratigraphic sequences (cycles) are now identified (Rasmussen and Rasmussen, 2009).

The exposed Paradox Formation at Onion Creek is dominated by gypsum with minor amounts of anhydrite, but interbedded shales and carbonates of the Paradox are common within the caprock as well. These more competent layers of strata within the diapir (shale and carbonate) are from within the Paradox Formation and thus are identified as stringers. They are differentiated from rafted blocks, which are from older or younger formations that have been entrained into the salt during diapirism (Talbot and Jackson, 1987; Reuning and others, 2009; Fiduk and others, 2014). Stringers within the Onion Creek diapir formed by the rupture and displacement of carbonate- and shale-rich beds as the Paradox Formation was diapirically deformed by sub-regional sediment loading. These stringers are preserved as boudins within the caprock ranging in size and expression from large, competent blocks of strata greater than 100 m in observed length (and possibly longer – exposure is two-dimensional and may be oblique to the longest axis of these bodies), to concentrated layers of cobble-sized clasts of carbonate. Stringers have been observed elsewhere in both outcrop (Jackson and others, 1990) and the subsurface (Talbot and Jackson, 1987; Warren, 2006; Van Gent and others, 2011; Strozyk and others, 2012), and are a common phenomenon in salt bodies worldwide (Fiduk and Rowan, 2012; Reiche and others, 2014). The excellent exposure of the Onion Creek diapir enables detailed description of the character, deformation, and distribution of these stringers within the exposed caprock.

Black shale beds of the Paradox Formation are enriched in preserved organic carbon, with previous studies reporting total organic carbon (TOC) values as high as 20% from nearby wells (Tischler, 1995; Nuccio and Condon, 1996; Van Buchem and others, 2000; Guthrie and others, 2004; Rasmussen and Rasmussen, 2009). Association of evaporites and black shale is common in both shelfal and intracratonic settings such as the Paradox Basin, the Williston Basin (North Dakota), the Eagle-Gypsum basin (Colorado), and the Cretaceous strata along the Gulf Coast (Krumbein, 1951; Sloss, 1953; Zharkov, 1983). The organic-rich shales of the Paradox Formation are incorporated into the stringers of the Onion Creek diapir, and hydrocarbon staining due to the migration of free oil is common within both the stringers and the evaporitic strata surrounding them. This observation has potentially important implications for seal integrity of caprock facies, as well as local implications for hydrocarbon generation and migration on a limited scale, and perhaps on the formation of caprock dolomite.

METHODS

Five transects were described throughout the diapir, and thirteen sections were measured along these transects where stringers were identified (figure 3A). Observations made along these transects include presence or absence of stringers, stringer size, lithologic composition, relative levels of deformation, and their location relative to the edge of the diapir. The location of each observation was recorded using a Trimble differential GPS unit, with sub-meter accuracy for all gathered

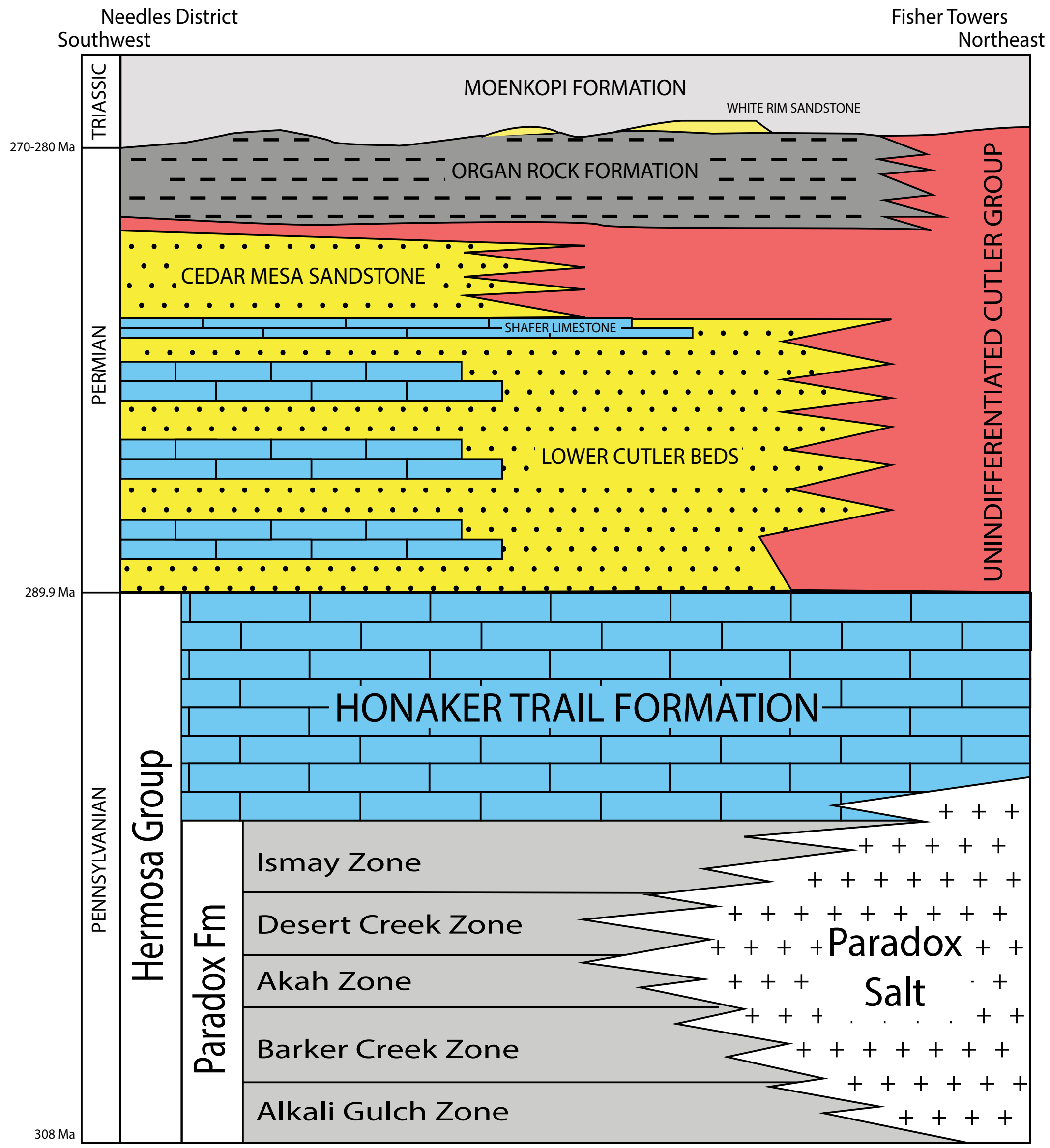

Figure 2. Composite stratigraphic column of Pennsylvanian and Permian strata of the study area, near Moab, Utah. See figure 1 for column location. Modified from Hintze and Kowallis (2009) and Venus and others (2015).

points. A basic geospatial model of surface observations was built using Petrel software. Two Paradox Formation carbonate samples were collected from within the largest two stringers and analyzed for mineralogical content using the Bruker D2 Phasor x-ray diffraction (XRD) instrument. Samples were run for 25 minutes using a Lynxeye Silicon strip detector from 5 to 65° 2-theta at a step increment of 0.02°. A copper-sealed tube was used, and samples were front-loaded for analysis. Quantification was done by Rietveld analysis using the DIFFRAC.TOPAS software package.

Thirteen black shale samples were collected from within the stringers of the Onion Creek diapir, and 12 samples were taken from hypothesized hydrocarbon-stained strata from both the stringers and the gypsum caprock surrounding these stringers. In order to obtain total organic and carbonate carbon, as well as source type and relative maturity, these samples were analyzed by whole-rock pyrolysis and total organic carbon/carbonate carbon (TOC+CC) techniques at Brigham Young University using the Wildcat Technologies HAWK Workstation. A standard pyrolysis+TOC method was used, where the sample was heated from 300^{0} C to 850^{0} C at a rate of 25^{0} C/minute during the pyrolysis stage, and from 300^{0} C to 850^{0} C at a rate of 25 ^{0}C/minute during the oxidation stage (Espitalie and

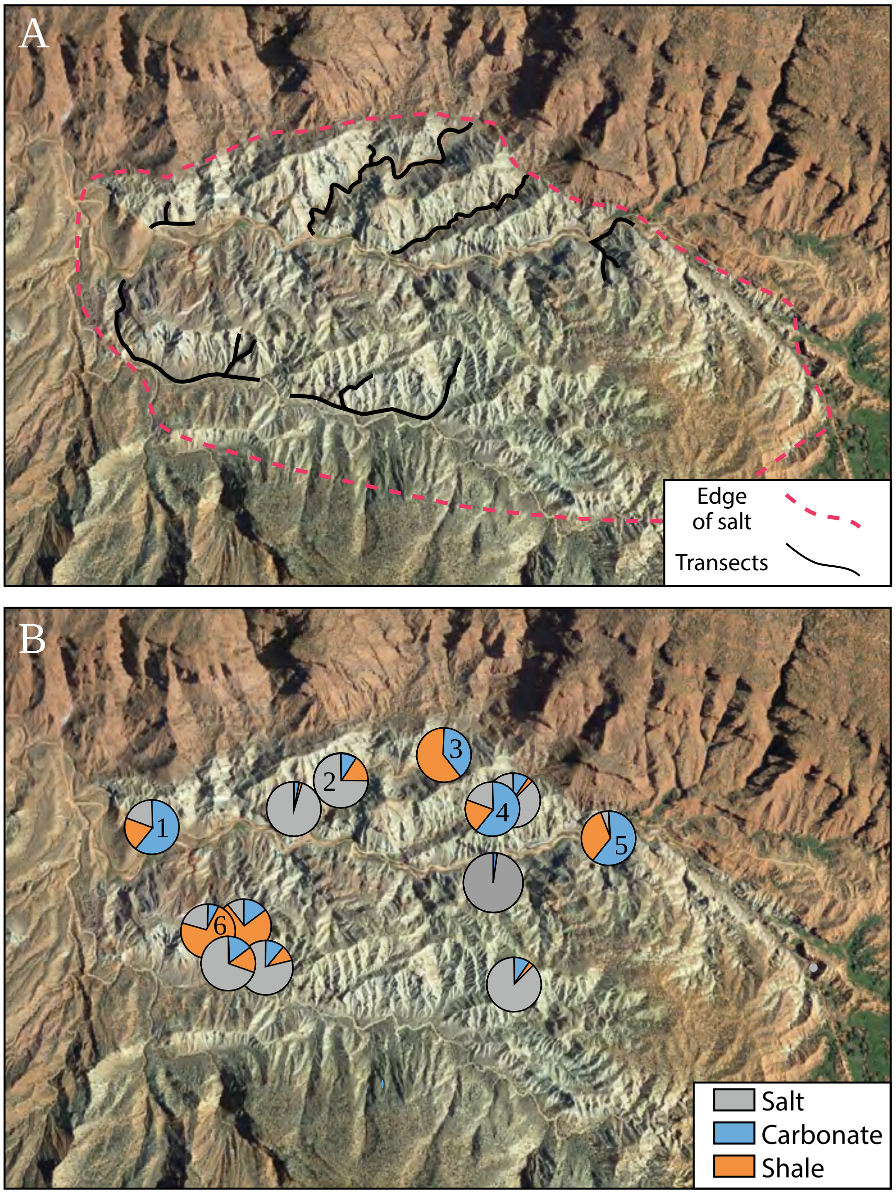

Figure 3. Aerial view of the Onion Creek diapir. (A) Black lines show transects of the Onion Creek diapir that are a part of this study, and the approximate edge of salt is marked (pink dashed line) where it is in contact with younger strata of the dominantly the Permian Cutler Formation. (B) Pie charts represent locations of measured sections along transects, with the relative abundance of evaporite, carbonate, and shale shown. The six large stringers discussed later are marked 1 through 6, with stringer 6 being more interior to the diapir whereas 1 through 5 are at or near the margins of the diapir.

others, 1977; Peters and Cassa, 1994).

OBSERVATIONS

Stringers were identified throughout the Onion Creek diapir from the margins to the center and high in the exposed caprock to the lowest observable point. The stringers observed in the diapir range from concentrated exposures of disarticulated cobble-sized clasts to relatively undeformed interbedded stringers with continuous bedding that are as much as 100 m long and greater than 20 m thick. Six large, intact stringers were identified (figure 3B), with many smaller stringers of interbedded carbonate and black shale throughout the exposed caprock. Stringers with intact bedding planes average between 2 to 3 m thick and 2 to 10 m long parallel to bedding. Some of the stringers are highly folded (figure 4A) whereas others are relatively undeformed, with well-preserved parallel bedding planes (figure 4B).

Throughout the diapir and across the spectrum of stringer sizes, there is common preservation of cyclic packages of shale, carbonate, and gypsum. Carbonate strata are the dominant facies represented in the stringers. The carbonate observed in outcrop is not limestone, as has been reported at depth (Rasmussen and Rasmussen, 2009), but is dolomitic limestone and dolomite (fig-

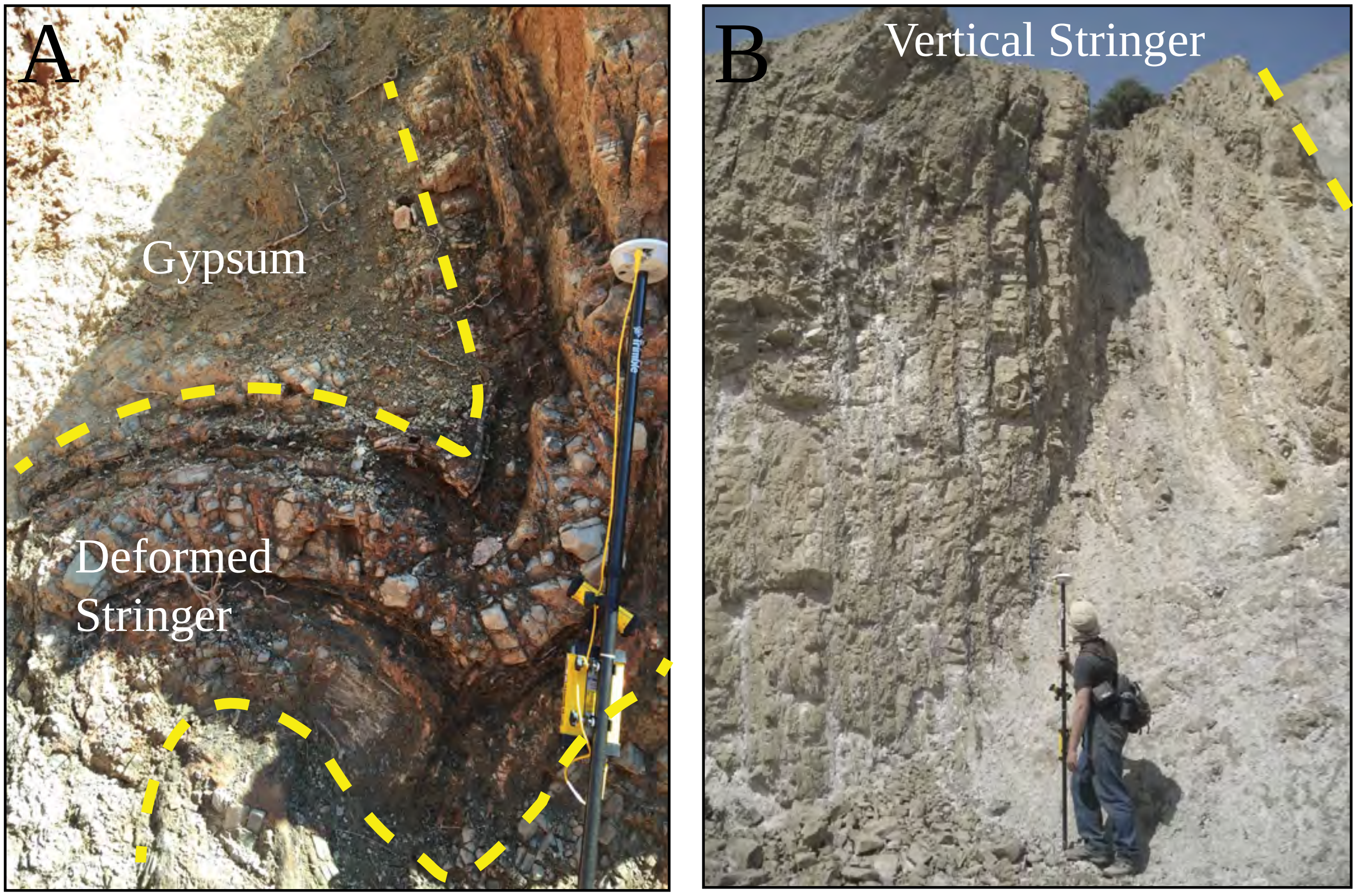

Figure 4. Examples of stringers within the Onion Creek diapir showing: (A) extensive folding of fractured carbonates and deformed shales, and (B) a large carbonate-dominated stringer near the southwest margin of the diapir. GPS antenna shown in the images is 2 m in height.

ure 5A). XRD analysis of two carbonate samples from different stringers show high dolomite content of 63% and 98%, respectively (figure 5B). The sample containing lower dolomite content (63%) also contains clastic material, with 26% orthoclase, 8% muscovite, and 3% quartz. These carbonates are often fractured, but primary bedding is discernable and sedimentary structures can be observed. In multiple stringers, microbial textures are observed, as shown in figure 5C.

Thirteen large stringers (greater than 10 m in length) were measured as part of this study (figure 3B). Of these, six are larger than 50 m in length (figure 3B). Five of the six largest stringers are located along the margins of the diapir, either at the edge of salt or very close to the contact. The only other stringer larger than 50 m in length is located in the southwestern interior of the diapir (figure 3B, section 6). Stringers at or near the edge of the diapir show coherent bedding, and beds are steeply dipping and roughly aligned with the edge of the diapir, though internal folding is often prevalent in these stringers. The very large stringer in the interior of the diapir, in contrast, shows less deformation of beds and is near-horizontal in orientation. Composition varies within the largest six stringers, with four being dominated by carbonate strata and two being dominated by black shale. In general, shale is better preserved in the largest stringers with smaller stringers being dominated by dolomite.

Though stringers of various sizes are common throughout the diapir, there are large sections of the

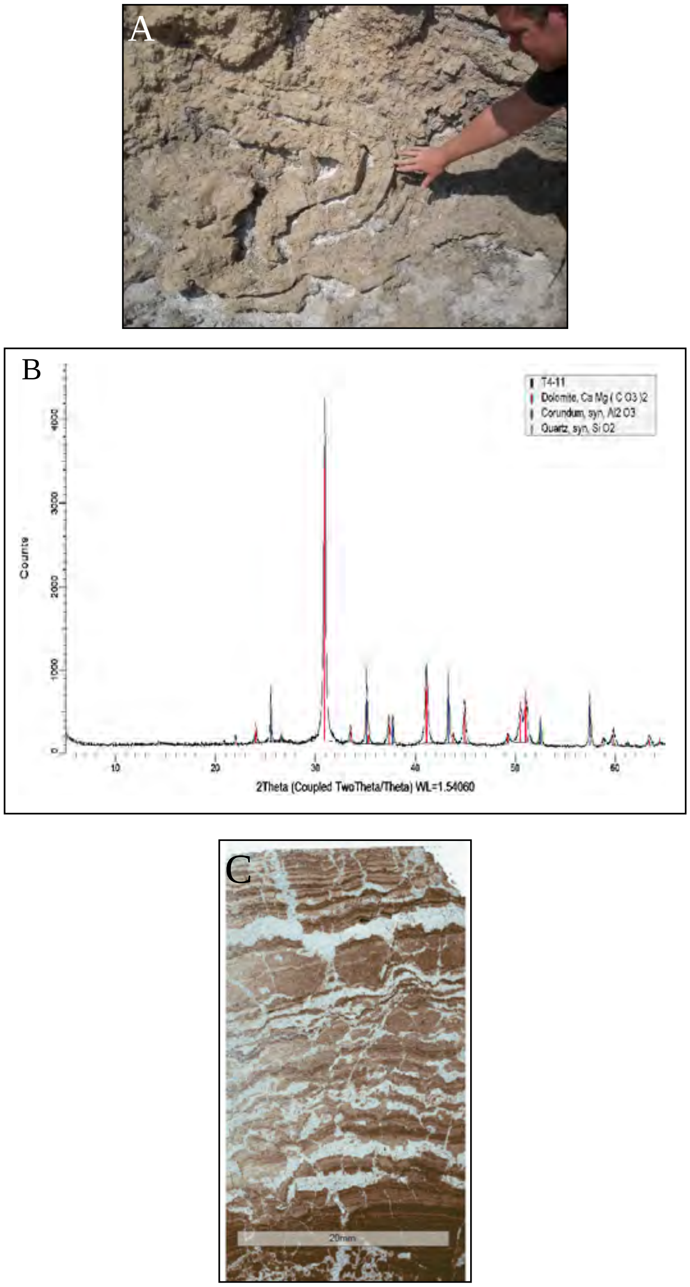

Figure 5. Carbonates within the Onion Creek diapir. (A) Intensely folded bedding of Paradox Formation dolomite. Although diagenetically altered, microbial textures are still preserved. (B) XRD analysis of Paradox Formation carbonate samples within the stringers show dolomitic composition, whereas the Paradox carbonates are limestone at depth nearby, suggesting diagenetic alteration (Rasmussen and Rasmussen, 2009). (C) A thin section from within one of the large stringers shows preserved microbial texture of the dolomite.

exposed caprock that are devoid of significant stringer material. In these areas, it is common to find highly banded and deformed gypsum (figure 6). These sections of gypsum can form resistant outcrops near the margins and within the interior of the exposed caprock. Proximal to the stringers, in contrast, caprock gypsum is commonly more massive to weakly bedded.

It is common to find hydrocarbon staining associated with the preserved Paradox Formation black shales in the Onion Creek diapir. Staining is typically rusty brown to yellow to black and is found both within the stringers and surrounding gypsum caprock. In all large stringers observed, staining and the associated live oil is focused along fractures within dolomite beds, as well as within the surrounding deformed gypsum caprock (figure 7). In smaller stringers, staining of dolomite is common as well, though to a lesser extent. In contrast to the large stringers, staining in small stringers is commonly restricted to fractured dolomite, and does not stain the surrounding gypsum.

Whole-rock pyrolysis analysis was performed on the 12 samples collected from black shale within the large stringers of the Onion Creek diapir. Pyrolysis was also performed on the 13 samples collected from stained carbonates within the stringers and stained caprock gypsum proximal to the stringers. All samples showed appreciable TOC values, ranging from 0.64% to 60.22% (table 1). Samples collected from Paradox black shale within in the large stringers had consistently higher TOC values, ranging from 2.56% to 60.22%, with a mean of 16.93%. Samples collected from the stained beds are easily distinguished based on much lower TOC values, with a range of 0.64% to 1.71% and a mean of 1.06%. Additionally, the two sample sets can be differentiated by the proportionately higher S1 (free oil) signal in the stained beds (table 1). Though the level of preserved organic carbon is lower within the samples of migrated material, the ratio of S1/(S1+ S2), otherwise known as the production index (PI), is much higher for these samples (figure 8).

DISCUSSION

Stringer Character and Distribution

We interpret the observed stringers within the Onion Creek diapir to be intact blocks of Paradox Forma-

Figure 6. Large exposure of highly banded and deformed gypsum. This locality is far from any sizable stringers and is typical of the high level of deformation seen in areas devoid of stringers. GPS pole in image is 2 m tall.

tion strata that have moved as coherent bodies into the diapir. The interbedded nature of strata is interpreted to be the original depositional bedding of the Paradox. Cyclic packages of carbonate, shale, and gypsum are best observed in fresh washes cut into the side of the exposed caprock. In more weathered outcrops, carbonate facies are most easily observed, whereas the interbedded shale and gypsum can be less obvious due to their less resistant nature. Although the carbonate strata observed within the exposed diapir are dominantly dolomite rather than the limestone observed at depth (Rasmussen and Rasmussen, 2009), the interbedded nature and preserved sedimentary structures within these carbonate rocks (figure 5) leads us to conclude that they are altered original Paradox strata. The cause of this alteration to dolomite within the stringers is likely infusuion of meteoric waters due to uplift and exposure of the Onion Creek caprock. These interbedded stringer dolomites are different than the brecciated, structureless lateral caprock dolomite exposed infrequently around the margins of the diapir (figure 9). Lateral caprock dolomite forms at depth in response to hydrocarbon presence and the associated sulfate-reducing bacteria (Giles and others, 2012; Jackson and Lewis, 2012), and has been described along the flanks of the nearby Castle Valley salt wall (figure 1) by Giles and others (2012). A 15-m-long, 1-m-thick lateral caprock dolomite is present along the northern margin of the Onion Creek diapir in direct contact with both the adjacent Permian Cutler strata and the diapiric salt. The absence of primary sedimentary structures or bedding, the high degree of brecciation, and the position along the edge of the diapir are all consistent with what is seen at the Castle Valley salt wall to the south, leading to clear differentiation between primary stringer dolomite and lateral caprock dolomite at the Onion Creek diapir.

Whereas large stringers were identified throughout the diapir, the largest and most continuous stringers are generally located near the margins. Some of these stringers are as much as tens of meters of cohesive, relatively undeformed strata, and can be least 100 m long. The concentration of larger stringers along the margins of the diapir suggest that this part of the diapir may have experienced less extensive deformation as compared to the more highly deformed stringers observed in the interior parts of the diapir. Additionally, the highly deformed, interior stringers appear to be aligned roughly with the edge of salt in many places. Though many of the largest stringers are located at or near the margins of the diapir, one of the larger stringers observed was found approximately 500 m from the edge of the diapir along the southern transect (figure 3B, section 6). This stringer is a large (~95 m in observed length), laterally continuous stringer containing several cyclic packages. This exception points to the fact that stringers of significant size can be present within the interior of a diapir as well. Future work at other diapirs is important to validate these trends.

As previously mentioned, all stringers exhibit deformation; however, there is a wide range in the degree

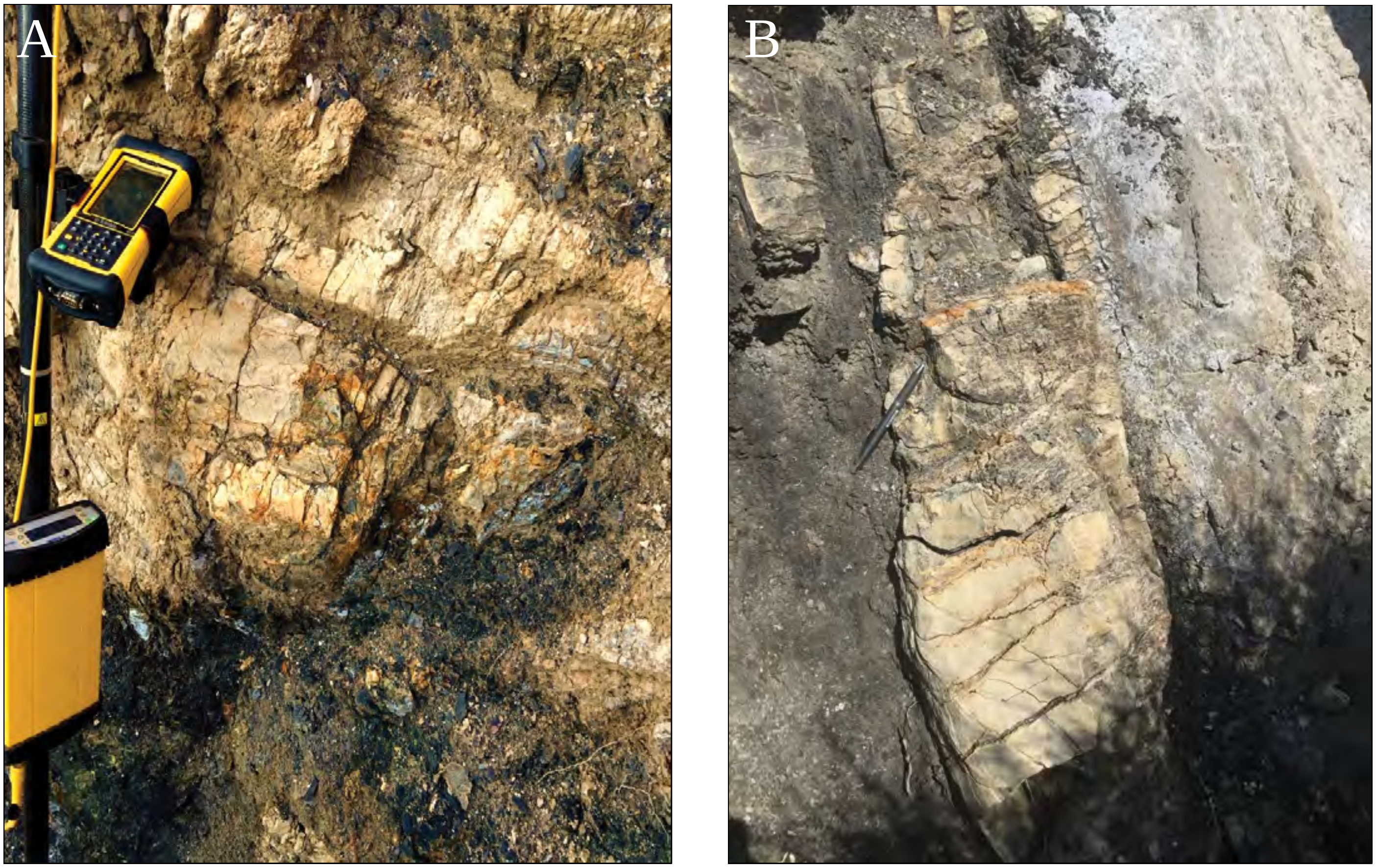

Figure 7. (A) Black to yellow staining associated with migrated hydrocarbons within fractured carbonates of a large stringer near the margin of the Onion Creek diapir (stringer 3), and (B) black to rusty staining resulting from migrated hydrocarbons within the evaporites surrounding a boudin block of dolomite near stringer 2. See figure 3B for stringer locations.

of deformation. The deformation correlates well with stringer size. The smallest identified stringers are discrete clusters of aligned, fist-sized fragments of dolomite. These are common and present throughout the diapir. In contrast, only modest amounts of brittle deformation are seen in the core of larger stringers, with deformation becoming more evident towards the edges. There is a spectrum of intermediate deformation between these two end members, and smaller coherent stringers transitioning laterally into shattered stringers are common in the more central parts of the diapir. Regardless of stringer size, fracturing and destruction of bedding increases towards the edges of all observed stringers. This is consistent with the interpretation that these are boudins of strata that have been stretched and deformed as entrained blocks during diapiric deformation of Paradox strata (Jackson and others, 1990; Warren, 2006; Strozyk and others, 2012).

Lastly, although stringers were identified throughout the diapir, there are large areas within the diapir where stringers are absent. These areas are dominated by banded, highly deformed gypsum that is very different than the often massive, structureless gypsum seen in proximity to the stringers (figure 6). The increased deformation in gypsum-dominated sections suggests that there is heterogeneity of strain within the diapir, driven by the heterogeneity of the lithologies moving upwards during diapirism. This may indicate that the stringers provide added rigidity to the diapir as it rises and may even, to a degree, reduce internal deformation during diapiric rise. Further work, both observational and experimental, can be done to test this hypothesis, which may add to our understanding of the more detailed processes that occur within deforming salt bodies.

Table 1. Whole-rock pyrolysis data for 25 samples collected from the Onion Creek diapir. Thirteen samples were taken from shales within the stringers (primary shale samples), whereas 12 samples were taken from altered carbonates and evaporites (secondary hydrocarbon-stained samples).

Sample ID	TOC-Total Organic Carbon (Weight %)	S1 Free Oil (mgHC/g rock)	S2 Kerogen Yield (mgHC/g rock)	S3 (mgCO_2/g)	Tmax-Maturity (°C)	CC-Carbonate Carbon (Weight %)	GOC-Generative Organic Carbon (Weight %)	NGOC-Non-generative Organic Carbon (Weight %)	PI-Production Index (S1/S1+S2)	HI-Hydrogen Index (mgHC/gTOC)	OI-Oxygen Index (mgCO_2/gTOC)
Primary Shale Samples											
T 4.13	20.26	7.78	125.83	0.45	439	0.63	11.38	8.88	0.06	621	2
T4 S13 C	20.23	6.36	94.90	2.37	435	0.70	8.75	11.48	0.06	469	11
T4 S13 B	19.44	6.92	103.85	1.48	435	0.31	9.48	9.95	0.06	534	7
T4 S13 A	20.32	7.67	122.10	0.71	440	0.19	11.07	9.25	0.06	600	3
T 4.12	10.92	2.81	50.70	0.77	433	0.15	4.58	6.34	0.05	464	7
T 4.7	60.22	17.99	356.31	4.56	437	0.37	32.00	28.22	0.05	591	7
T4.11	2.56	0.33	10.47	0.28	435	12.04	0.93	1.63	0.03	409	11
T 1.2	16.99	2.75	107.39	0.79	438	0.22	9.41	7.59	0.03	632	4
T 4.3	7.25	0.73	45.25	0.25	431	5.64	3.92	3.33	0.02	624	3
T 4.14	18.01	2.80	127.40	0.73	439	0.45	11.09	6.92	0.02	707	4
T 1.1	8.00	0.31	28.09	1.25	439	0.33	2.46	5.53	0.01	351	15
T 4.5	6.14	0.25	20.51	0.61	437	1.80	1.79	4.36	0.01	333	9
T 4.6	9.80	0.38	55.49	0.37	437	2.83	4.77	5.03	0.00	566	3
Secondary Hydrocarbon Stained Samples											
03 SC 15	1.23	0.12	0.40	0.17	374	17.85	0.05	1.17	0.24	32	14
T 1.7	0.64	0.17	0.55	0.20	446	0.20	0.07	0.57	0.23	85	31
T 1.9	1.71	0.10	0.37	0.30	428	2.45	0.05	1.66	0.21	21	17
T 2.1	0.66	0.08	0.34	0.19	439	0.23	0.04	0.62	0.19	51	28
T 1.8	1.12	0.10	0.43	0.13	426	0.36	0.06	1.06	0.19	38	11
T 4.2	1.66	0.09	0.42	0.37	449	0.67	0.06	1.60	0.17	25	22
T 4.1	1.15	0.07	0.35	0.29	442	7.35	0.05	1.10	0.17	30	25
T 1.5	0.65	0.14	0.77	0.25	441	0.26	0.09	0.56	0.16	118	38
T 1.6	0.65	0.11	0.60	0.24	441	0.44	0.07	0.57	0.15	93	37
T 1.10	0.72	0.08	0.50	0.26	453	18.30	0.06	0.66	0.13	70	36
T 1.3	1.59	0.17	1.58	0.30	438	3.47	0.16	1.43	0.10	99	18
T 1.12	0.94	0.08	1.21	0.33	460	0.75	0.13	0.82	0.06	128	35

Hydrocarbon Generation and Migration within the Diapir and Implications

The black shale beds of the Paradox Formation are extremely enriched in organic carbon, as evidenced by high TOC values from samples within the stringers that average nearly 17%. High hydrogen index (HI) values are consistent with the restricted marine depositional environment invoked for the Paradox Formation, with marine microbial preserved organic types (Type I and Type II kerogens) seen in the sample suite (figure 8). Tmax data, while not as accurate as vitrinite reflectance or other thermal indicators, suggest that samples taken from the diapir are within the early oil window, with most values between 435 and 460 °C (Tissot and others, 1987). All samples collected from black shale beds within the stringers are interpreted to be from the Akah or Barker Creek zones of the Paradox Formation (Rasmussen and Rasmussen, 2009), emplaced as part of the Onion Creek diapir during initial diapiric rise. This is consistent with data from subsurface wells and outcrop from within the Paradox Formation. TOC values of Type II marine source rock facies that are consistently above 1%, and occasionally as much as 20%, have been reported at multiple levels and multiple locations at depth within the basin (Tischler, 1995; Nuccio and Condon, 1996; Van Buchem and others, 2000; Guthrie and Bohacs, 2009; Rasmussen and Rasmussen, 2009). Based on the similarity of organofacies, the characteristics of these strata have not significantly changed as the result of stringer emplacement; the black shale within the stringers of the Onion Creek diapir are classified as excellent marine source rock facies capable of generating hydrocarbons in the past.

Within the fractures of all large and many smaller stringers, hydrocarbon staining is interpreted to be ev-

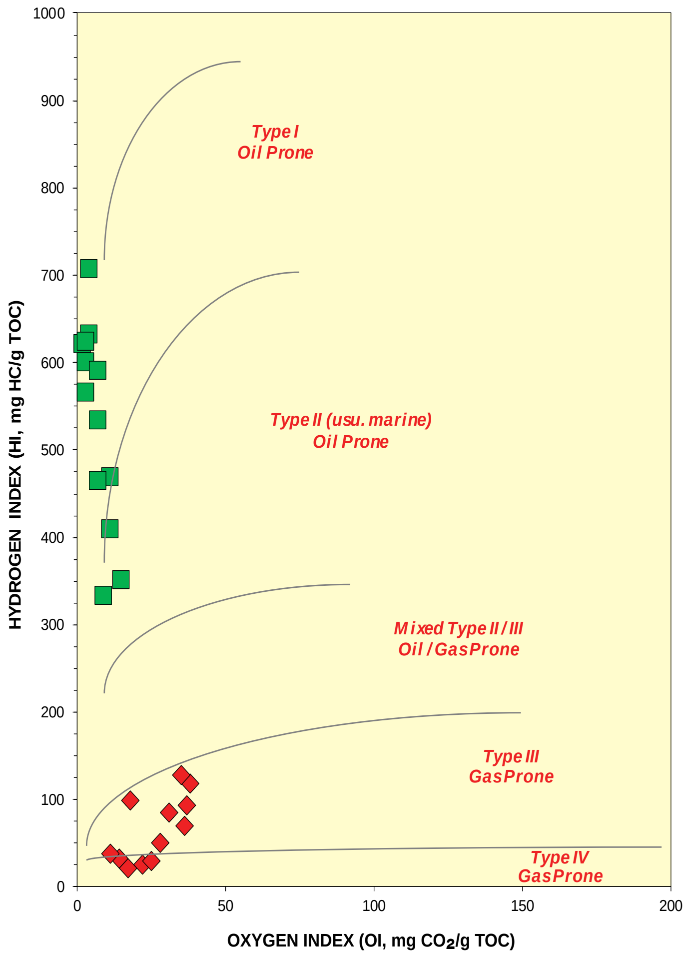

Figure 8. Modified Van Krevelen diagram (van Krevelen, 1950), showing a clear division between primary black shale samples collected from within the stringers of the Onion Creek diapir (green squares) and samples collected from the fractured dolomite stringers and the surrounding evaporite caprock (red diamonds). Samples from stringers of Paradox black shale are classified as Type I/Type II source rock facies, whereas migrated hydrocarbon samples are classified as a Type III/Type IV source rock facies. The low hydrogen index (HI) values for the migrated hydrocarbon samples are not indicative of a terrestrial-rich organic source, as might be the case for a primary source rock, but rather the lean HI is the result of thermal cracking of kerogens, as shown by the high production index (PI) ratio (table 1).

Figure 9. One of several examples of lateral cap rock dolomite observed on the northern side of the Onion Creek diapir. It is characterized by a highly brecciated texture that is in contrast with dolomitic textures that are common within the stringers, such as shown in figure 5.

idence of migrated hydrocarbons. This staining is also prevalent in the gypsum caprock surrounding many stringers, including all large stringers. Staining is black to rusty colored to yellow colored along the fractures of dolomite stringers and within the groundmass of the gypsum caprock (figure 7). Hydrocarbon staining of strata within the Onion Creek diapir is similar in appearance to other instances of hydrocarbon migration associated with salt diapirs, such as documented within and proximal to the La Popa diapir in Mexico (Hudson and Hanson, 2010). TOC values from these stained samples are much lower than values reported from primary black shale within the stringers (table 1), but values are above 0.5%, which is still considered significant source rock potential (Peters and Cassa, 1994), confirming that there are hydrocarbons present. Production index (PI) values (ratio of free oil to total hydrocarbons) in the stained samples are elevated in comparison with the primary black shales. This can be the result of two things: (1) higher relative thermal maturation (the most common use of this indicator), or (2) the presence of migrated hydrocarbons (Tissot and Welte, 1984; Peters and Cassa, 1994). Both interpretations are based on the assumption that primary kerogens have cracked and organic carbon is increasingly being stored in pore space. Tmax results from both the primary shale samples and the stained samples suggest that all samples have experienced a similar thermal history and are within the early oil window. Given the observed field relationships of these samples and the primary Paradox shale they are associated with, we believe that local migration of hydrocarbons from within the black shale beds of large stringers is occurring within the Onion Creek diapir. This is further supported by depletion of HI within secondary stained samples in comparison to primary black shale samples (figure 8).

Evidence that hydrocarbons can be generated locally in quantities sufficient for expulsion and migration has several important implications for exploration around salt bodies. Around other similar salt diapirs, which incorporate organic-rich strata as stringers or rafted blocks, there is a possibility for false indicators of significant hydrocarbon accumulations. This could be as simple as hydrocarbon shows within a juxtaposed reservoir; while these stringers are generating enough free oil for migration to occur, there is insufficient material within even the largest stringers to form an economic accumulation. Less obviously, we propose that local generation of hydrocarbons from stringers within the caprock of a diapir could lead to local precipitation of caprock dolomite. Work by Giles and others (2012) suggests that the presence of anaerobic sulfate-reducing bacteria, commonly associated with hydrocarbons, is necessary for the precipitation of a carbonate caprock, thus implying that the presence carbonates is an indicator of a working petroleum system. If local generation and migration of hydrocarbons occurred in association with stringers along the margin of a diapir, it is possible that this could lead to the precipitation of a carbonate caprock in the absence of a large-scale working petroleum system. Thus, the presence of a carbonate caprock alone could lead to a false characterization of the basin source rock potential or the migration pathways of hydrocarbons within a productive basin if the carbonate caprock formed from local generation and migration rather than regional thermal maturation of a source rock interval.

Lastly, the observation that hydrocarbons are freely migrating through gypsum caprock, similar to what was documented at the La Popa diapir, Mexico, (Hudson and Hanson, 2010), has important implications for the sealing capacity of diapiric caprock, regardless of the inclusion of stringers. Salt is commonly considered to be a near-perfect seal, but evidence is increasingly showing that within the altered caprock of a diapir, the more brittle nature of the salt can lead to banding, fracturing, and potential migration pathways, as seen in the Onion Creek diapir. We interpret hydrocarbon migration within the Onion Creek caprock to happen only at a local scale, but these observations show that vertical migration within diapiric caprock should be considered as a risk in other basins where large quantities of hydrocarbon are being generated at depth, and salt is often called upon to be a lateral and/or vertical seal.

CONCLUSIONS

Cyclic packages of carbonate, shale, and salt are commonly found throughout the Onion Creek diapir. These packages preserve, even after deformation and emplacement into a salt diapir, the original interbedded nature of the Paradox Formation. This suggests that although diapirism is an intense deformational process, more coherent stratal packages can maintain structural integrity in the form of boudins. Banded, highly-deformed gypsum in areas without notable stringers may help to explain the relatively undeformed nature of the large stringers, suggesting that strain is differentially partitioned into less competent evaporite-rich layers. These observations suggest that the internal mechanics of diapirs are perhaps less chaotic than is often assumed, in particular, where interbedded non-evaporitic strata are present. Spatially, there are trends within the Onion Creek diapir that are significant. Larger, less deformed stringers are more common near the margin of the diapir. This implies that either: (1) there was more interbedded material originally in this part of the strata, which is assumed to be the youngest, stratigraphically highest Paradox strata exposed, or (2) that rigid, interbedded strata was concentrated near the margins during the process of diapiric rise and caprock formation. Both hypotheses have different implications for diapiric mechanics, with the latter suggesting a more chaotic diapiric process and the former suggesting a more layered, organized model. The Onion Creek diapir presents an excellent, accessible exposure of a heterolithic diapiric salt body that can serve as an analog for subsurface heterolithic salt bodies elsewhere. Whereas seismic data is capable of imaging large stringers in the subsurface, outcrop observations offer important details at the sub-seismic scale. The frequency of both large and small stringers observed throughout the Onion Creek diapir suggests that stringers should be expected to be present throughout similar salt bodies, even when not detected by geophysical methods. Whereas larger stringers may be more commonly encountered along the margins, significant intervals of non-evaporitic strata are common regardless of relative location within the diapir.

In addition to adding to our understanding of the distribution and character of stringers in diapirs, the inclusion of organic-rich strata in the stringers of the Onion Creek diapir gives us important insight into hydrocarbon resource evaluation. Diapiric salt is considered a near-perfect, impermeable seal; however, within the caprock strata of the Onion Creek diapir, migration of hydrocarbons is associated with every large and many of the smaller stringers of organic-rich shale studied, as evidenced by the presence of hydrocarbon-stained strata within and surrounding the stringers. This has important implications for similar, "dirty salt" diapirs in the Gulf of Mexico and elsewhere. Beyond this, the prevalence of hydrocarbons within the caprock of the Onion Creek diapir suggests that fluid migration through caprock should be a consideration in all diapiric systems, whether stringers are present or not.

ACKNOWLEDGMENTS

The authors would like to acknowledge Kate Giles (University of Texas El Paso), Mark Rowan (Rowan Consulting), Richard Langford (University of Texas El Paso), Thomas Hearon (EOG Resources), and Carl Fiduk (Fiduk Consulting) for discussion that helped to improve this manuscript. Involvement with the Institute of Tectonic Studies at University of Texas El Paso and the opportunity to discuss this work with both the researchers and sponsors of this consortium was invaluable. Comments and suggestions from Frank Strozyk (Aachen University) on an earlier draft of this work were very much appreciated as well. Additional thanks to Brigham Young University for funding this project, and to Sam Hillam (Brigham Young University) and Jason Klimek (Brigham Young University) for their help in the field and the lab.

REFERENCES

Baker, A.A., Dane, C.H., and Reeside, J.B., Jr., 1933, Paradox Formation of eastern Utah and western Colorado: American Association of Petroleum Geologists Bulletin, v. 17, no. 8, p. 963–980.

Barbeau, D.L., 2003, A flexural model for the Paradox Basin—implications for the tectonics of the Ancestral Rocky Mountains: Basin Research, v. 15, p. 97–115.

Blakey, R.C., and Knepp, R., 1989, Pennsylvanian and Permian geology of Arizona, *in* Jenney, J.P., and Reynolds, S.J., editors, Geologic evolution of Arizona: Arizona Geological Society Digest, v. 17, p. 313–347.

Callot, J.P., Letouzey, J., and Rigollet, C., 2006, Stringers evolution in salt diapirs, insight from analogue models [abs.]: American Association of Petroleum Geologists International Conference and Exhibition, Perth, Australia, Search and Discovery Article #90061.

Dickinson, W.R., and Lawton, T.F., 2003, Sequential intercontinental suturing as the ultimate control for Pennsylvanian Ancestral Rocky Mountains deformation: Geology, v. 32, p. 609–612.

Doelling, H.H., 1988. Geology of Salt Valley anticline and Arches National Park, Grand County, Utah, *in* Doelling, H.H., Oviatt, C.G., and Huntoon, P.W., contributors, Salt deformation in the Paradox region: Utah Geological and Mineral Survey Bulletin 122, p. 7–58.

Espitalie, J., Madec, M., Tissot, B., Mennig, J.J., and Leplat, P., 1977, Source rock characterization method for petroleum exploration [abs.]: Proceedings of the Ninth Offshore Technology Conference, Dallas, p. 438–442.

Fiduk, J.C., Clippard, M., Power, S., Robertson, V., Rodriguez, L., Ajose, O., Fernandez, D., and Smith, D., 2014, Origin, transportation, and deformation of Mesozoic carbonate rafts in the northern Gulf of Mexico: Gulf Coast Association of Geological Societies Journal, v. 3, p. 20–32.

Fiduk, J.C., and Rowan, M.G., 2012, Analysis of folding and deformation within layered evaporites in Blocks BM-S-8 & -9, Santos Basin, Brazil: Geological Society of London, Special Publications, v. 363, p. 471–487, doi: 10.1144/SP363.22.

Giles, K.A., Lawton, T.F., Shock, A., Kernen, R.A., Hearon, T.E., and Rowan, M.G., 2012, A halokinetic drape-fold model for caprock in diapir-flanking and subsalt positions [abs.]: American Association of Petroleum Geologists Search and Discovery, article #40956.

Guthrie, J.M., and Bohacs, K.M., 2009, Spatial variability of source rocks—a critical element for defining the petroleum system of Pennsylvanian carbonate reservoirs of the Paradox Basin, SE Utah, *in* Houston, W.S., Wray, L.L., and Moreland, P.G., editors, The Paradox Basin revisited—new developments in petroleum systems and basin analysis: Rocky Mountain Association of Geologists Special Publication, p. 95–130.

Guthrie, J.M., Uribe, R.D., and Bohacs, K.M., 2004, Spatial variability of organic-rich rocks—a critical element for defining the petroleum system of Pennsylvanian carbonate reservoirs of the Paradox Basin, SE Utah [abs.]: American Association of Petroleum Geologists Search and Discovery Article #90026, unpaginated.

Handschy, J.W., and Dyer, R., 1987, Polyphase deformation in Sierra del Cuervo, Chihuahua, Mexico—evidence for ancestral Rocky Mountain tectonics in the Ouachita Foreland of northern Mexico: Geological Society of America Bulletin, v. 99, p. 618–623.

Hintze, L.F., and Kowallis, B.J., 2009, Geologic history of Utah: Provo, Utah, Brigham Young University Special Publication 9, 225 p.

Hite, R.J., 1960, Stratigraphy of the saline facies of the Paradox Member of the Hermosa Formation of southeastern Utah and southwestern Colorado, *in* Olivier, H.E., editor, Geology of the Paradox Basin fold and fault belt: Four Corners Geological Society Third Field Conference, p. 86–89.

Hite, R.J., and Buckner, D.H., 1981, Stratigraphic correlations, facies concepts and cyclicity in Pennsylvanian rocks of the Paradox Basin, *in* Weigland, D.L., editor, Geology of the Paradox Basin: Rocky Mountain Association of Geologists 1981 Field Conference, p. 147–160.

Hudson, S.M., and Hanson, A.D., 2010, Thermal maturation and hydrocarbon migration within La Popa Basin, northeastern Mexico, with implications for other salt structures: American Association of Petroleum Geologists Bulletin, v. 94, no. 3, p. 273–291.

Jackson, M.P.A., Cornelius, R.R., Craig, C.H., Gansser, A., Stöcklin, J., and Talbot, C.J., 1990, Salt diapirs of the Great Kavir, central Iran: Geological Society of America Memoirs 177, 139 p.

Jackson, C.A-L., and Lewis, M.M., 2012, Origin of an anhydrite sheath encircling a salt diapir and implications for the seismic imaging of steep-sided salt structures, Egersund Basin, Northern North Sea: London, Journal of the Geological Society, v. 169, p. 593–599.

Kluth, C.F., and DuChene, H.R., 2009, Late Pennsylvanian and Early Permian structural geology and tectonic history of the Paradox Basin and Uncompahgre uplift, Colorado and Utah, *in* Houston, W.S., Wray, L.L., and Moreland, P.G., editors, The Paradox Basin revisited—new developments in petroleum systems and basin analysis: Rocky Mountain Association of Geologists Special Publication, p. 178–197.

Krumbein, W.C., 1951, Occurrence and lithologic associations of evaporites in the United States: Journal of Sedimentary Research, v. 21, no. 2, p. 63–81.

Li, S., Abe, S., Reuning, L., Becker, S., Urai, J.L., and Kukla, P.A., 2012, Numerical modelling of the displacement and deformation of embedded rock bodies during salt tectonics—a case study from the South Oman Salt Basin: London, Geological Society Special Publications 363, p. 503–520.

McCalla, C., 2008, The Onion Creek salt diapir, Grand County: Utah Geological Survey, Survey Notes Geosights: https://geology.utah.gov/map-pub/survey-notes/geosights/onion-creek-salt-diapir, accessed February 2015.

Nuccio, V.F., and Condon, S.M., 1996, Burial and thermal history of the Paradox Basin, Utah and Colorado, and petroleum potential of the Middle Pennsylvanian Paradox Formation: U.S. Geological Survey Bulletin 2000, p. 57–76.

Ohlen, H.R., and McIntyre, L.B., 1965, Stratigraphy and tectonic features of Paradox Basin, Four Corners area: American Association of Petroleum Geologists Bulletin, v. 49, no. 11, p. 2020–2040.

Peters, K.E., and Cassa, M.R., 1994, Applied source rock geochemistry: American Association of Petroleum Geologists Memoir 60, p. 93–120.

Rasmussen, L., and Rasmussen, D.L., 2009, Burial history analysis of the Pennsylvanian petroleum system in the deep Paradox Basin fold and fault belt, Colorado and Utah, *in* Houston, W.S., Wray, L.L., and Moreland, P.G., editors, The Paradox Basin revisited—new developments in petroleum systems and basin analysis: Rocky Mountain Association of Geologists Special Publication, p. 24–94.

Reiche, S., Hübscher, C., and Beitz, M., 2014, Fault-controlled evaporite deformation in the Levant Basin, Eastern Mediterranean: Marine Geology, v. 354, p. 53–68, doi: 10.1016/j.margeo.2014.05.002.

Reuning, L., Schoenherr, J., Heimann, A., Urai, J.L., Littke, R., Kukla, P.A., and Rawahi, Z., 2009, Constraints on the diagenesis, stratigraphy, and internal dynamics of the surface-piercing salt domes in the Ghaba Salt Basin (Oman)—a comparison to the Ara Group in the South Oman Salt Basin: GeoArabia, v. 14, no. 3, p. 83–120.

Sloss, L.L., 1953, The significance of evaporites: Journal of Sedimentary Research, v. 23, no. 3, p. 143–161.

Strozyk, F., Urai, J.L., Van Gent, H., Keijzer, M., and Kukla, P.A., 2014, Regional variations in the structure of the Permian Zechstein 3 intra-salt stringer in the Northern Netherlands—3D seismic interpretation and implications for salt tectonic evolution: Interpretation, v. 2, no. 4, p. 1–17.

Strozyk F., Van Gent, H., Urai, J.L., and Kukla, P.A., 2012, 3D seismic study of complex intrasalt deformation—an example from the Upper Permian Zechstein 3 stringer, western Dutch offshore: London, Geological Society Special Publications 363, p. 489–501.

Talbot, C.J., and Jackson, M.P.A., 1987, Internal kinematics of salt diapirs: American Association of Petroleum Geologists Bulletin, v. 71, no. 9, p.1068–1093.

Tischler, K.L., 1995, Paradox Basin source rock, southeastern Utah—organic geochemical characterization of Gothic and Chimney Rock units, Ismay and Desert Creek zones, within a sequence stratigraphic framework: Austin, University of Texas, M.S. thesis, 123 p., http://hdl.handle.net/2152/18461.

Tissot, B.P., Pelet, R., and Ungerer, P.H., 1987, Thermal history of sedimentary basins, maturation indices, and kinetics of oil and gas generation: American Association of Petroleum Geologists Bulletin, v. 71, no. 12, p. 1445–1466.

Tissot, B.P., and Welte, D.H., 1984, Petroleum formation and occurrence, 2nd edition: New York, Springer-Verlag, 699 p.

Trudgill, B.D., 2011, Evolution of salt structures in the northern Paradox Basin—controls on evaporite deposition, salt wall growth and supra-salt stratigraphic architecture: Basin Research, v. 23, no. 2, p. 208–238.

Trudgill, B.D., and Arbuckle, W.C., 2009, Reservoir characterization of clastic cycle sequences in the Paradox Formation of the Hermosa Group, Paradox Basin, Utah: Utah Geological Survey Open-File Report 543, 106 p., 3 appendices.

Trudgill, B., Banbury, N., and Underhill, J., 2004, Salt evolution as a control on structural and stratigraphic systems—northern Paradox foreland basin, SE Utah, USA, *in* Post, P.J., editor, Salt–sediment interactions and hydrocarbon prospectivity—concepts, applications and case studies for the 21st century: Gulf Coast Society of Economic Paleontologists and Mineralogists Foundation, 24th Bob F. Perkins Research Conference Proceedings, p. 669–700.

Van Buchem, F.S.P., Houzay, J., and Peniguel, G., 2000, Variation in distribution and quality of organic matter in Pennsylvanian source rock levels of the Paradox Basin (Utah, USA), *in* Homewood, P.W., and Eberli, G.P., editors, Genetic stratigraphy on the exploration and production scales—case studies from the Pennsylvanian of the Paradox Basin and the Upper Devonian of Alberta: Elf Aquitaine Memoir 24, p. 29–69.

Van Gent, H., Urai, J.L., and Keijzer, M., 2011, The internal geometry of salt structures—a first look using 3D seismic data from the Zechstein of the Netherlands: Journal of Structural Geology, v. 33, p. 292–311.

Van Krevelen, D.W., 1950, Graphical-statistical method for the study of structure and reaction processes of coal: Fuel, v. 29, p. 269-284.

Venus, J.H., Mountney, N.P., and McCaffrey, W.D., 2015, Syn-sedimentary salt diapirism as a control on fluvial-system evolution—an example from the proximal Permian Cutler Group, SE Utah, USA: Basin Research, v. 27, no. 2, p. 152–182, doi: 10.1111/bre.12066.

Warren, J.K., 2006, Evaporites—sediments, resources, and hydrocarbons, 2nd edition: Berlin, Springer Verlag, 1035 p.

Williamson, M.D., Murray, S.J., Hamilton, T.A.P., and Copland, M.A., 1997, A review of Zechstein drilling issues: Society of Petroleum Engineers OnePetro, SPE-38483-MS, 8 p., doi:10.2118/38483-MS.

Zharkov, M.A., 1983, Classification of salt-bearing associations according to material composition and patterns of spatial position: International Geology Review, v. 25, no. 2, p. 151–164.