Controls on the structural and stratigraphic evolution of the megaflap-bearing Sinbad Valley salt wall, NE Paradox Basin, SW Colorado

Jessica Ann Thompson Jobe1,2,*, Katherine A. Giles1, Thomas E. Hearon IV1,2, Mark G. Rowan4, Bruce Trudgill2, C. Evelyn Gannaway Dalton1, and Zane R. Jobe2

1Institute of Tectonic Studies, Department of Geological Sciences, The University of Texas El Paso, El Paso, Texas, USA
2Department of Geology and Geological Engineering, Colorado School of Mines, Golden, Colorado, USA
3ConocoPhillips Company, Houston, Texas, USA
4Rowan Consulting, Inc., Boulder, Colorado, USA

ABSTRACT

The interplay between sedimentation and salt rise around a diapir results in distinct geometries that can be used to determine the structural and stratigraphic history within a basin. Using new geologic mapping, measured stratigraphic sections, and subsurface interpretations of seismic and well logs, we describe circum-diapir stratal geometries and deformation at the Sinbad Valley salt wall in the proximal, northeastern Paradox Basin, southwest Colorado (USA). We interpret these geometries in the context of newly recognized halokinetic features and salt-associated deformation (megaflaps, counterregional faults, intrasalt inclusions), present a revised stratigraphic and salt tectonic history of Sinbad Valley diapir, and compare these proximal features to those at the distal Gypsum Valley diapir and infer local versus regional controls on their formation. The deposition of conglomerates within the Paradox Formation, now preserved as intrasalt inclusions in the center of Sinbad Valley, record early elevation of the Uncompahgre Uplift. Subsequent differential sedimentary loading resulted in initiation of passive diapirism during the late Pennsylvania through the latest Triassic/Early Jurassic, facilitated by movement on a NE-dipping, listric, counterregional fault that extends for >22 km southeast of the diapir. Exposures of a steeply dipping stratigraphal panel of late Pennsylvania-aged Honaker Trail Formation along the southwestern flank of Sinbad Valley are interpreted as a megaflap, a preserved remnant of the diapir roof that was folded into a vertical position by drape-folding during passive salt rise. Significant lateral changes in the surface geometry and depositional facies of the megaflap define four structural domains that may result from a combination of radial faulting and varying degrees of folding via limb rotation or limb rotation with minor hinge migration. Using key differences between Sinbad Valley and Gypsum Valley salt walls in regard to the megaflap facies, timing of megaflap formation, and the presence of a Paradox Formation conglomeratic intrasalt inclusion, we conclude that salt wall position (i.e., proximal versus distal) within a basin influences the characteristics of some of these features, whereas the timing of other features (e.g., megaflap formation) appears to be similar throughout the basin suggesting a more regional control.

INTRODUCTION

Salt walls are linear salt diapirs that have a discordant relationship with the surrounding minibasin strata (Jackson and Hudc, 2017; Trusheim, 1960). As a salt diapir passively rises, halokinetic features and stratigraphic geometries near the salt-sediment interface record the complex intersections between the relative rates of sediment accumulation and salt rise (Giles and Lawton, 2002; Giles and Rowan, 2012). However, recent studies of salt walls typically focus on only one aspect of the salt wall history: the depositional facies or single-channel systems directly adjacent to the salt walls (e.g., Gee and Gawthorpe, 2006; Matthews et al., 2007; Banham and Mountney, 2013; Venus et al., 2015; Doughty-Jones et al., 2017), broader minibasin-scale facies and stratigraphic geometries (e.g., Oluboyo et al., 2014; Ribes et al., 2015; Rojo and Escalona, 2018), or the structural or deformational kinematic analysis of salt movement (e.g., Trudgill and Rowan, 2004; Stewart, 2006; Trudgill 2011; Rowan et al., 2016). There are few studies that integrate both structural and stratigraphic histories adjacent to salt walls (e.g., Adam et al., 2012; Teixell et al., 2017; Martin-Martin et al., 2017), which is the only way the halokinetic history of salt walls and the geometries of strata in the surrounding basins can be assessed (e.g., Alsop et al., 2018). Moreover, the along-strike lateral variability of salt diapirs and associated stratigraphic geometries as well as the kinematics of salt wall growth remain an active avenue of research (e.g., Jackson et al., 2014). Although high-resolution 3-D seismic data now provide the opportunity to study lateral variability at the seismic scale, there are limited studies that integrate outcrop and seismic data to examine the near-salt lateral variability of facies and geometries.
In the Paradox Basin, southwest USA (Fig. 1A), excellent outcrop exposures and an abundance of subsurface data have facilitated the reinterpretation of stratal geometries and structures adjacent to the salt walls, sparking renewed interest in understanding the salt tectonic and stratigraphic history of the basin (Lawton and Buck, 2006; Trudgill, 2011; Banham and Mountney, 2013; Venus et al., 2015; Rowan et al., 2016; Hartley and Evenstar, 2017; Escosa et al., 2018). For example, the stratal architecture adjacent to salt walls in the northwestern part of the Paradox Basin, including the Salt Valley, Castle Valley, and Moab Valley salt walls, has revealed patterns of fluvial-alluvial deposition in response to salt movement during the Permian through Triassic (Matthews et al., 2007; Banham and Mountney, 2013, 2014; Venus et al., 2015; Hartley and Evenstar, 2017) and the identification of steeply dipping strata adjacent to the salt walls (Trudgill, 2011) that are now interpreted as megaflaps (i.e., Giles and Rowan, 2012). Moreover, new mapping and reinterpretation of stratal geometries along the Gypsum Valley and Castle Valley salt walls has identified a number of newly recognized and interpreted halokinetic and near-diapir features, including megaflaps, counterregional faults, salt shoulders, radial faults, secondary welds, and lateral caprock (Fig. 2; Lawton and Buck, 2006; Shook, 2012; Lehmann, 2015; McFarland, 2016; Rowan et al., 2016; Escosa et al., 2018), that have facilitated a reinterpretation of the relationship between salt tectonics and sedimentation within the basin.

In this study, we focus on the Sinbad Valley diapir, an oval-shaped salt wall in the proximal, northeastern Paradox Basin (Fig. 1B). Because of the excellent outcrop exposure and nearby subsurface data, the Sinbad Valley salt wall provides an opportunity to document the lateral variability in facies and stratal and salt wall geometries and kinematics. We first describe the structural and stratal geometries around the diapir from new field mapping, measured sections, and subsurface interpretation, and then classify these geometries as halokinetic and near-diapir features. Next, we discuss a revised general salt tectonic and stratigraphic evolution of the Sinbad Valley salt wall, including lateral variations in the stratal geometries and the folding kinematics. In addition, we compare the observations at Sinbad Valley to recently described halokinetic and near-diapir features at Gypsum Valley and discuss differences in these features between sediment-source proximal (Sinbad Valley) and distal (Gypsum Valley) salt walls. Finally, we briefly discuss the impact these differences in basin position may have on the petroleum system.
**GEOLOGIC SETTING**

The Paradox Basin is an intracratonic flexural foreland basin (Barbeau, 2003) that formed adjacent to the Ancestral Rocky Mountains (ARM) basement-cored Uncompahgre Uplift (Blakey and Knepp, 1989; Dickinson and Lawton, 2003). Well and seismic data across the region indicate 8–10 km of dip slip movement along NE-dipping reverse faults (Moore et al., 2008), which, along with the consequent crustal loading and salt evacuation, created accommodation that was subsequently filled by as much as ~7 km of upper Paleozoic to Mesozoic sediments (Figs. 3, S1, S2; Barbeau, 2003). Low-temperature thermochronology data from the Uncompahgre Uplift show that exhumation began in the Pennsylvanian and continued through the Early Permian, with zircon fission-track ages of 390–280 Ma and zircon (U-Th)/He ages between 309 and 34 Ma (Thomson et al., 2012; Ronnevik et al., 2017). Upper Triassic strata overlap the Uncompahgre Uplift, indicating it was no longer a topographic high and sediment source at that time (Bears and Doelling, 1987; Doelling, 1988).

The initial mid-Pennsylvanian fill of the foreland basin was dominated by evaporite deposition. During the late Pennsylvania, sediment shed off the Uncompahgre Uplift created differential loading of the evaporites, leading to salt inflation over pre-salt basement normal faults (Elston et al., 1962; Kluth and DuChene, 2009; Trudgill, 2011). Passive diapirism in the Permian resulted in a series of northwest-southeast–trending linear salt walls, which initiated earlier in the proximal, northeastern part of the basin and later in the distal, southwestern part of the basin (Kluth and DuChene, 2009; Trudgill, 2011). The salt walls separate minibasins containing 3–7 km of Paleozoic through Mesozoic strata. Passive diapirism continued through the Triassic, and likely ended by mid-Jurassic or Cretaceous time at the distal, southwestern salt walls (Trudgill, 2011; Rowan et al., 2016). During the Laramide Orogeny (ca. 75–40 Ma), minor shortening caused upwarping of the strata near the diapirs, and regional exhumation during the Cenozoic removed much of the Cretaceous and younger strata in the northeastern Paradox Basin (Fig. 3; Baars and Stevenson, 1981; Kluth and DuChene, 2009). During the late Eocene through the Oligocene, Laramide-associated volcanism lead to the emplacement of the La Sal and Abajo Mountains in the center of the Paradox Basin (Ronnevik et al., 2017). In the late Cenozoic, minor extension, evaporite dissolution, and collapse of the salt walls created their present-day geomorphology (Gutiérrez, 2004).

---

**Figure 2.** Generalized descriptions of halokinetic and near-diapir features described in text. Schematic sketches and descriptions modified from Rowan et al., 2016—megaflap; Rowan et al., 1999—counterregional fault; Guiterrez et al., 2004—collapse faults. LES—layered evaporite sequence.
Stratigraphy

The upper Pennsylvanian Paradox Formation (Fig. 3) is a cyclic, layered evaporite sequence of mixed evaporites (mostly halite with gypsum, anhydrite, and potash) as well as carbonates, black shales, and coarser-grained siliciclastics (Baker et al., 1933; Hite and Buckner, 1981) and is the source for the salt walls of the Paradox Basin. The Paradox Formation exposed at the surface in the salt walls (Fig. 4) has created a modern caprock of mostly gypsum and anhydrite, which forms due to the dissolution of salt. The Paradox Formation is overlain by the upper Pennsylvanian Honaker Trail Formation (Fig. 3), a succession of limestones, sandstones, shales, and siltstones of mixed fluvial and shallow-marine affinity (Elston et al., 1962; Condon, 1997; Williams, 2009). The Honaker Trail Formation transitions from siliciclastic fluvial and fan-delta systems adjacent to the Uncompahgre Uplift to carbonate shoals and shoreface siliciclastics in the distal southwestern part of the basin (Gianniny and Mickel-Gerhardt, 2009). Where exposed adjacent to the salt walls, the Honaker Trail Formation is commonly thinned relative to the thickness preserved in wells in the adjacent minibasins due to syndepositional salt movement (Fig. 5; Trudgill, 2011; Rowan et al., 2016; Escosa et al., 2018).

Overlying the Honaker Trail Formation is the Permian Cutler Group, composed of interbedded arkosic conglomerates, sandstones, siltstones, and mudstones, with subordinate carbonates (Loope, 1984; Condon, 1997). The Cutler Group exhibits considerable thickness and facies variations in the northern Paradox Basin due to sediment routing and salt movement (Trudgill, 2011). Cutler Group deposition likely began early in the Uncompahgre Uplift history as a series of alluvial fans in the proximal part of the basin along the southwestern margin of the uplift (Barbeau, 2003; Moore et al., 2008). The Cutler Group in the distal southwestern Paradox Basin has more varied depositional
Figure 4. Geologic map of the Sinbad Valley salt wall, southwest USA, created from previous [Shoemaker, 1955, 1956; Carter et al., 1958; Williams, 1964; Doelling, 2002] and new geologic mapping. Cross-section locations shown, along with locations of wells and detailed geologic maps of key features. Structural domains A–D correspond to cross-sections A–D. Down-dropped Jurassic fault blocks described in text located near structural domain D and between structural domains A and B. Red faults mark faults interpreted as counterregional faults, black faults are other normal faults. Inset map shows the relative locations of the halokinetic and near-diapir features on the diapir. The line W-W’ marks the extent of the seismic line (Fig. 8A) that overlaps with the detailed geologic map.
Figure 5. Generalized cross-section of Sinbad Valley integrating previous and new field mapping, and well log (1 Altex Sinbad and 2 Husky Huber) and 2-D seismic reflection data interpretation (cross-section modified after Shoemaker, 1955; Maret and Coe, 1960). Location shown in Figures 1B and 4. TD—total depth. To view Figure 5’s annotation layer in the PDF version of this paper, open the PDF in Adobe Acrobat or Adobe Reader. To view the layer while reading the full-text version of the paper, click http://doi.org/10.1130/GES02089.f5 to download a PDF of the figure.
environments and is subdivided into four formations, which in ascending order are: lower Cutler, Cedar Mesa Sandstone, Organ Rock Formation, and the White Rim Sandstone (Condon, 1997; Barbeau, 2003, Gradstein et al., 2004).

In much of the northeastern Paradox Basin, the Cutler Group is not divided in outcrop or in well logs due to a lack of correlative marker horizons (Trudgill, 2011). However, a regionally extensive mid-Cutler Group unconformity recognized in well logs (Rasmussen, 2014), and also imaged on seismic data (e.g., DuChene et al., 2009; Rowan et al., 2016), separates lower and upper Cutler strata throughout most of the Paradox Basin.

The Cutler Group is separated from the Lower Triassic Moenkopi Formation by a regional unconformity (Orgill, 1971; Condon, 1997). In general, the Moenkopi has significant thickness variations and facies changes across the basin, ranging from 0 to ~760 m thick in the subsurface (Trudgill et al., 2004; Trudgill, 2011; Banham and Mountney, 2013), with mixed lacustrine, fluvial, and marine depositional environments (Doelling, 1988; Banham and Mountney, 2013). Another regional unconformity separates the Triassic Moenkopi and Chinle formations (Shoemaker and Newman, 1959; Hazel, 1994). The Chinle Formation has significant regional facies variations, with depositional environments including lacustrine, fluvial, and eolian (Baars and Doelling, 1987; Hazel, 1994). Regionally, the Chinle thickens southwestward into the Paradox Basin, but locally thins over the diapirs, with local intraformational angular unconformities adjacent to salt walls (Hazel, 1994; Matthews et al., 2007; McFarland, 2016; Hartley and Evenstar, 2017).

Jurassic strata (including the Wingate, Kayenta, and Navajo formations) that comprise the Glen Canyon Group and the Entrada, Summerville, and Morrison formations) and Cretaceous strata (including the Burro Canyon and Dakota formations) are dominated by fluvial and eolian depositional facies, with local facies variations and thickness changes. These units record waning salt wall growth throughout the Paradox Basin (Trudgill, 2011).

Sinbad Valley Salt Wall

The Sinbad Valley salt wall, located in the proximal part of the Paradox Basin (Fig. 1), was originally studied and mapped in the 1950s (Carter et al., 1958; Shoemaker, 1955, 1956) as the target of several oil and gas exploration wells (Maret and Coe, 1960). It is ~10 km long by 5 km wide and trends northwest-southeast (Fig. 1B). It has a structural relief of over 3 km, with a topographic relief of ~700 m from the rims on the flanks of the salt wall to the valley floor (Figs. 4 and 5). The center of Sinbad Valley is characterized by limited exposures of modern Paradox Formation caprock, primarily gypsum, surrounded by Quaternary alluvium. An active oil seep exists along the northeastern flank, near Salt Creek (Fig. 4). Two minibasins flank the Sinbad Valley diapir: the thicker Salt Creek minibasin to the northeast, and the thinner Roc Creek minibasin to the southwest (Figs. 4 and 5). Strata thin and contain local angular unconformities toward the Sinbad Valley salt wall, indicating that the salt wall was a topographic high and passively rising during deposition (Shoemaker and Newman, 1959) (Fig. S1 [footnote 1]). Along strike to the southeast, the Roc Creek diapir is connected to the Sinbad Valley diapir through a system of listric normal faults (Fig. 1B), described in more detail below.

METHODS

Field data included regional mapping from U.S. Geological Survey (USGS) quadrangles (1:24,000 and 1:100,000 scale), new detailed structural mapping at key areas (~15,000 scale), and three new measured stratigraphic sections, including facies descriptions and thin section analyses. Previous maps (Shoemaker, 1955, 1956; Carter et al., 1958; Williams, 1964; Doelling, 2002) were combined with new mapping to create a revised geologic map of Sinbad Valley (Fig. 4). To augment field mapping, a drone was used to collect high-resolution aerial photos of inaccessible areas and to build a 3-D surface model to verify the structure and stratigraphy and extract approximate strikes and dips. The 3-D surface model was constructed in Agisoft Photoscan using GPS-tagged photos, which enabled georeferencing. The location and general strikes and dips from the model were checked against GoogleEarth imagery and field measurements, where possible, to verify accuracy. These areas were primarily located at the northwestern end of the valley.

Subsurface data included nine key wells and 60 km of proprietary 2-D seismic reflection data, interpreted in time (Fig. 1B). All well data are publicly available (Table 1), but older (pre-1980s) well logs and tops are often incomplete (Tables DR1 and DR2). Seismic data were provided by and converted to depth by ConocoPhillips using a simple four-interval velocity model that followed interpreted horizons (Table DR3). Interval velocities were assigned based on checkshot data and velocities from the Burkholder #1 well near Castle Valley, Utah, ~40 km west. Due to the proprietary nature of the seismic data, only line drawing interpretations are shown, but seismic data quality is similar to or better than those shown in Trudgill and Paz (2009).

SOUTHWEST FLANK OF SINBAD VALLEY

Along the southwestern flank of Sinbad Valley, there is a ~7-km-long and 0.5-km-wide, moderately dipping to overturned stratal panel composed of uppermost Paradox, Honaker Trail, and Cutler strata (Figs. 5–7). In the following sections, we describe first the surface structure, which is divided into four structural domains, then the subsurface geometry, and finally the panel stratigraphy before providing an interpretation.

Outcrop Observations

The stratal panel is divided into four structural domains (SD A–D) corresponding to cross-sections A–D (Figs. 4 and 6–8; Table 2), described below.
In map view, the panel of moderate to steeply dipping older strata curves to form several salients and reentrants in the edge of the diapir; this curvature is also reflected in the faults bounding the down-dropped Jurassic block (Fig. 4). SD D is located along a salient in the salt edge, SD A is along a reentrant, and SD B and C have less obvious relationships. We also observed small (<2 to ~100 m offset) faults that cut the stratal panel. These faults commonly originate at the salt-sediment interface and do not extend into the Jurassic strata. They strike to the southwest and appear to be nearly vertical. Locations of faults were defined through offset stratigraphy and fault surfaces observed in the field had >1 m gouge or fractured zones. The largest faults appear to separate the different structural domains.

### Structural Domain A

The Honaker Trail strata dip ~40–50° SW near the diapir but dips generally steepen to over 60° SW away from the diapir into the lower Cutler strata. Above an angular unconformity within Cutler strata, dips decrease progressively from ~50° to 28 SW° (Figs. 6A, 6B, and 7A), with another angular unconformity beneath Chinle strata that dip ~10° SW (Fig. 9). Strata curve to strike northeast at the northwestern lateral termination of the panel (Fig. 6B). At the southeastern end of SD A, Triassic Chinle and Jurassic Glen Canyon strata are juxtaposed along strike against Cutler strata (Figs. 6A and 6B). This relationship may be explained either by a radial fault or by an unconformity with localized erosion of the Cutler with onlapping younger strata. Several normal faults have been previously mapped separating different Triassic and Permian strata (Williams, 1964), and there is a down-dropped block of Jurassic strata inboard of the Honaker Trail Formation (Fig. 4).

### Structural Domain B

To the southeast, the strata increase in dip away from the diapir, thereby defining SD B (Figs. 6B and 7B). Whereas Honaker Trail strata dip ~30° SW, the youngest Cutler strata dip ~40–50° SW (Fig. S4). Northeast of the Honaker Trail Formation outcrops, modern caprock of the Paradox Formation at the diapir margin is juxtaposed across a fault with down-dropped Jurassic Wingate Formation. However, due to lack of access, we were unable to map this structural domain in detail, and relied on previous USGS mapping (Carter et al., 1958).

### Structural Domain C

To the southeast of SD B, the maximum Honaker Trail Formation dip increases again to 50° SW, defining SD C (Figs. 6A and 7C; S6). Stratal dips gradually decrease to 20° away from the diapir and up-section through the Cutler Group. The overlying Triassic Chinle and Jurassic strata dip gently (5–10°) to the southwest.

### Structural Domain D

At the southeastern end of the steeply dipping panel (SD D), uppermost Paradox, Honaker Trail, and Cutler strata dip between ~70° SW and 70° NE (overturned) over a strike length of ~1 km (Figs. 6A, 6C, and 7D). The stratal panel is juxtaposed across a steep fault against down-dropped Jurassic Wingate Formation above Paradox Formation modern caprock. Dips in the Cutler Group progressively decrease upsection, the uppermost Cutler to Chinle strata.

### Table 1. Key Wells from the Northeast Paradox Basin

| Common well name          | API      | Latitude (°N) | Longitude (°W) | TD (ft, TVD) | TD (m, TVD) | Notes                                                                 |
|---------------------------|----------|---------------|----------------|--------------|-------------|----------------------------------------------------------------------|
| Husky Huber 2             | 05-077-40018 | 38.5094       | 108.9641       | 9215         | 2809        | Paradox Fm. target. Dry hole (very minor shows in Cutler).             |
| 1 Altex Sinbad            | 05-077-07372 | 38.5044       | 108.9950       | 10,316       | 3144        | Drilled in center of Sinbad Valley with Mississippian/Devonian target. TD 10,316 ft (3144 m) in Paradox Salt. |
| Federal Sinbad Ridge 14-1 | 05-085-06111 | 38.4099       | 108.9413       | 9124         | 2781        | Objective was Cutler/Honaker Trail formations. Very minor gas shows at 6440–6470 ft (1963–1972 m) in Honaker Trail Fm., gas kicks and dead oil stain in the Paradox Fm. (>8500 ft or >2991 m). |
| 1 Moon Mesa               | 05-085-06009 | 38.4627       | 108.7005       | 14,268       | 4349        | N.A.                                                                   |
| Uravan Unit               | 05-085-05032 | 38.3882       | 108.7161       | 18,354       | 5594        | Dry hole (no shows)                                                  |
| Martin Mesa Federal #33-3 | 05-085-06013 | 38.3550       | 108.8397       | 7289         | 2222        | Dry hole (no shows)                                                  |
| Haukelid #35-1            | 05-085-06033 | 38.3774       | 109.0533       | 15,785       | 4811        | N.A.                                                                   |
| Pace State                | 4301910830  | 38.5637       | 109.1081       | 16,237       | 4949        | Devonian target. Dry hole (no shows)                                  |
| Taylor Creek              | 4301931157  | 38.5550       | 109.1146       | 16,810       | 5124        | Mississippian target. Dry hole (no shows)                              |
| Geyser Creek              | 4303731174  | 38.4394       | 109.2048       | 15,405       | 4695        | Dry hole (no shows)                                                  |

Abbreviations: API—American Petroleum Institute; TVD—true vertical depth; Fm.—Formation; TD—total depth. N.A.—not applicable.
are not exposed, and Jurassic strata are in contact with Cutler strata and dip gently to the southwest.

Subsurface Observations

Two 2-D seismic lines cross the Sinbad Valley-Roc Creek trend (Fig. 1B); the first (W-W’) crosses the Sinbad Valley diapir approximately at cross-section A-A’ (Fig. 8A) and the second (Y-Y’), located ~10 km to the southeast, crosses closer to the Roc Creek diapir (Fig. 8B). Chaotic, discontinuous reflectors near the center and southwestern sides of the seismic lines are interpreted to be Paradox salt. On seismic line W-W’ (Fig. 8A), semi-continuous reflectors in the Salt Creek minibasin characterize a stratal package that thickens toward the diapir and an apparent downlap or rotated onlap geometry onto the salt and primary weld, compatible with sediment progradation and a southwestward migrating depocenter. Southwest of the Sinbad Valley diapir (i.e., in the Roc...
Figure 7 Cross-sections of the surface and shallow subsurface geometry of the older stratal panel, based on field mapping data. Locations shown in Figures 4 and 6. Topographic profiles extracted from 10-m NASA Shuttle Radar Topography Mission digital elevation map. (A) Northwestern section (structural domain [SD] A) measured Section 1 is shown as yellow rectangle; (B) Structural domain B; (C) Structural domain C; (D) Southeastern end (SD D); measured Section 2 is shown as yellow rectangle. Pc-unconf.—mid-Cutler Group unconformity.
Figure 8. Line drawings across Sinbad Valley–Roc Creek diapirs, southwest USA, based on vintage 2-D seismic reflection data, interpreted in time and converted to depth. Locations of seismic lines are shown in Figure 1B. (A) Uninterpreted (top) and interpreted (bottom) regional line W-W' across northwestern part of Sinbad Valley. Line drawing corresponds to cross-section A-A' from field mapping. This line is part of the regional line shown in Figure S1 (see text footnote 1). Arrows represent southward migrating depocenters in response to sediment progradation driven by slip on the counter-regional fault. (B) Uninterpreted (top) and interpreted (bottom) regional line Y-Y' across Roc Creek diapir southeast of Sinbad Valley. This line is part of the regional line shown in Figure S2. The counterregional (CR) fault interpreted on the seismic line is the same as fault F3 mapped at the surface. To view the seismic line drawing and interpretation layers of Figure 8's A and B sections in the PDF version of this paper, open the PDF in Adobe Acrobat or Adobe Reader. To view the layers while reading the full-text version of the paper, click http://doi.org/10.1130/GES02089.f8 to download a PDF of the figure.
TABLE 2. CHARACTERISTICS OF THE MEGAFLAP STRUCTURAL DOMAINS

| Structural domain | Average Honaker Trail Fm. Dip | Average Cutler Group Dip | Notes |
|-------------------|-------------------------------|--------------------------|-------|
| A                 | 50–67°                        | 50°                      | Thicker, coarser clastic Honaker Trail Fm. section. Seismic may show steeper dips at depth than at surface. Unconformity between Cutler and Honaker Trail strata. |
| B                 | 30°                           | 40–50°                   | Gentle dips at surface. Not mapped in detail. |
| C                 | 50°                           | 20–30°                   | Poor exposure. Fossiliferous, resistant marker beds in Honaker Trail Fm. section. |
| D                 | 70–70° OT                     | 50–70°                   | Paradox Formation exposed at base of measured section 2. Thin, carbonate-rich Honaker Trail Fm. section. |

OT—overturned; Fm.—Formation.

Figure 9. (A) Orthophoto of northwestern area of Honaker Trail Formation stratal panel. Outline shown in Figure 6. (B) Oblique view of megaflap, illustrating steeper dips of Honaker Trail and Cutler strata. Measured Section 1 and White Rim Sandstone (top of Cutler) shown in both panels. (C) Uninterpreted and (D) interpreted field photo of the Permian and Mesozoic strata. Photo location shown in Figure 6.
Creek minibasin), in contrast, the reflectors thin and turn up toward the diapir, with a relief of ~2 km and maximum dips of 70–80° SW. In the Roc Creek minibasin, the Cutler strata thicken to 1–3 km away from the diapir over 2–5 km, based on seismic and well data from Federal Sinbad Ridge 14–14, Geyser Creek, and Taylor Creek (Fig. 1B).

Seismic line Y-Y’, between Sinbad Valley and Roc Creek diapirs (Fig. 8B) displays a similar asymmetry, albeit with two key differences. First, a counterrregional fault (discussed below) and its corresponding footwall salt roller separate the two minibasins. Second, the strata on the southwestern side of the salt roller have lower upturn relief and are not as steep as they are adjacent to the Sinbad Valley diapir.

**SW Panel Stratigraphy**

To characterize the oldest strata exposed on the southwestern flank of the Sinbad Valley diapir, two stratigraphic sections were measured from the northwestern and southeastern ends of the salt wall (Figs. 9 and 10). The northwestern section (Section 1) and southeastern section (Section 2) are 220 and 96 m thick, respectively, and correspond to SD A and SD D, respectively. In general, the northwestern Section 1 has significantly more siliciclastic material than Section 2, although the presence of poorly exposed faults oriented oblique to the section may have removed or duplicated beds. At the base of Section 2, the Paradox Formation is cut by a normal fault that juxtaposes it against the Jurassic Wingate Formation.

**Facies Descriptions and Interpretations**

The SW panel strata is composed of seven lithofacies subdivided based on lithology, sedimentary structures, fossils, and interpreted depositional environments. In general, the stratigraphy represents deposition in terrestrial to shallow marine environments. Siliciclastic facies (CL-I and CL-II) are characterized by their grain size, bed thickness, composition, and sedimentary structures (Table 3; Figs. 10 and 11A–11D) and represent fluvial channel and overbank environments. Carbonate facies (CA-I through CA-V) were characterized based on their texture (Dunham, 1962), composition, fossil content, and bed thickness (Table 4; Figs. 10 and 11E–11I), and represent deposition in shallow marine environments.

CL-I is composed of multistory packages of pebble conglomerates with a medium- to coarse-grained sandy matrix and granite, quartz, and feldspar clasts. The conglomerates are interbedded with horizontally and cross-stratified, rippled sandstones, and laminated siltstones (Figs. 10, 11A, and 11B). CL-I is interpreted to be channel-related deposits in an alluvial environment. CL-II is an interbedded succession of reddish-brown or tan, micaceous, horizontally and cross-stratified, fine- to medium-grained sandstones, and laminated siltstones (Figs. 10, 11C, and 11D), interpreted as overbank or floodplain deposits in an alluvial environment.

CA-I is composed of recrystallized limestone and dolomite that do not contain visible fossils or “ghosts” of fossils (Figs. 10, S3A–D [footnote 1]). Crystalline limestones in the upper Hermosa Group (equivalent to the Honaker Trail Formation) are interpreted as deposition under open marine conditions (Herman and Barkell, 1957). Petrographic analysis indicates some beds are recrystallized dolomite with local baroque dolomite and pressure solution along grains that together indicate brine hydrothermal fluids (Spötl and Pitman, 1998) once moved through the rocks (Fig. S3A–D). Furthermore, iron sulfides may be indicative of dead oil in the fractures (Fig. S3A; Sassen, 1980) consistent with observations from nearby well data (Federal Sinbad Ridge 14-1; Daily Drilling Report for Sinbad Ridge [1974]). CA-II is a fossiliferous carbonaceous mudstone to wackestone (Figs. 10, 11E, and 11F) that contains abundant phylloid algae with bivalves and crinoids and is interpreted to have been deposited in a shallow, normal marine shelf setting below wavebase (Gianniny and Miskell-Gerhardt, 2009). CA-III is a skeletal (phylloid algal) wackestone to packstone (Figs. 10, 11G, 11H, S3E–F) with echinoderm, fenestrate bryozoan, brachiopod, and bivalve grains indicating deposition in a shallow, normal marine shelf setting above wavebase. CA-IV is a dolomitized carbonate mudstone to wackestone, with minor quartz sand grains and no visible fossils, interpreted to represent deposition in a supratidal to restricted lagoonal environment (Figs. 10 and 11I). CA-V is a micritic mudstone without visible fossils (Fig. 10), whose depositional environment is interpreted to be lagoonal mud banks.

In summary, the stratigraphic sections are interpreted to be shallow marine and fluvial facies of the Paradox Formation, Honaker Trail Formation, and Cutler Group, which corroborates previous work at Sinbad Valley (Maret and Coe, 1960) and other localities in the broader Paradox Basin (Fig. 10; Herman and Barkell, 1957; Gianniny and Miskell-Gerhardt, 2009; Rasmussen and Rasmussen, 2009). These facies record relative sea-level fluctuations throughout the late Pennsylvanian and Permian (Goldhammer et al., 1991). The abundance of clastic material with poorly sorted and subangular granite and feldspar grains in the Honaker Trail and Cutler strata indicate the nearby Uncompahgre Uplift was the likely source area (Kluth and Coney, 1981). This overall coarsening-upward sequence, from shallow marine to fluvial facies, likely represents the overall uplift of the region in response to ARM tectonics (Barbeau, 2003; Cain and Mountney, 2009). The lateral variations observed in the Honaker Trail strata are not uncommon, and well data indicate significant facies variations over short distances (Clair, 1958). In addition, the lenticular shapes of limestone beds (Clair, 1958) indicate that they may be local features and thus not observed over long (>5 km) distances.

**Interpretation**

Based on observations from surface mapping data, the stratal panel on the southwestern flank of the Sinbad Valley diapir is defined as a megaflap (Fig. 2) in SD D due to overturned dips of the oldest suprasalt strata, structural relief of ~1.7 km, and a folding width of ~2 km (see Rowan et al., 2016). Lower
Figure 10. Stratigraphy of the megaflap sections. Section 1, the northwestern section, was ~300 m thicker than Section 2, at the southeastern end of the megaflap. Note the significant differences in stratigraphy between the two exposed sections. Strat—stratigraphic.
maximum surface dips to the northwest (SD A-C) might suggest that the mega-
flap is confined to a small area in the southeast. However, the northern seismic
profile W-W’ (Fig. 8A), across the diapir in the vicinity of SD A, demonstrates
the panel has similar relief and maximum dips of ~80° at depth, despite sur-
face dips of only 50–60°. Thus, the megaflap is interpreted to extend along the
total length of the stratal panel, a topic we will return to below.
The Honaker Trail and lower Cutler strata in the megaflap, although thin-
ner than at the base of the flanking minibasin, show relatively little internal
thickness or dip variations. In contrast, overlying strata of the upper Cutler
and Moenkopi formations progressively become gentler updip and thin more
dramatically toward the diapir. We infer that the oldest strata represent the
thinned roof of early inflated salt, and that the mid-Cutler unconformity marks
the breakthrough of salt and the onset of passive diapirism and associated
drape folding. This evolution is very similar to that of the Gypsum Valley diapir
(Rowan et al., 2016), as discussed below.

### FAULTS

#### Northwestern Termination

At the northwestern termination of Sinbad Valley, two faults intersect the
end of the salt wall at high angles (Figs. 4 and 12). These faults extend for
8–10 km to the northwest and offset the Cretaceous Burro Canyon Formation,
the youngest strata exposed (Figs. 4 and 12), defining a graben (Fig. 12B).
However, the structure is asymmetric: fault F2 is visible on a seismic line
(not shown), detaches in the Paradox salt, offsets all post-salt strata, has
~1.1 km of maximum offset, and the Moenkopi and Chinle formations thicken
across it; whereas fault F1 has ~270 m of offset, is not visible on the seismic
data, and has no stratal growth at exposed levels. The strata in the graben
shift from dipping gently to the north, to dipping gently northwest around
the end of the diapir.

#### Southeastern Termination

At the southeastern end of Sinbad Valley, numerous faults extend away
from the end of the salt wall (Figs. 4 and 13). The largest fault, F3, is a down-
to-the-northeast fault that has a surface expression for at least 22 km, and up
to 34 km, to the southeast, intersects the Roc Creek diapir (Figs. 1B, 4, and
13), and is visible on 2-D seismic data (Fig. 8B). At the surface, the fault offsets
Jurassic strata, with ~200 m of offset measured in the Navajo Formation. In
the subsurface, the Cutler is offset ~1 km and the top Honaker Trail Formation
is offset up to ~1.8 km (Fig. 8B).

Permian and Triassic strata have significant thickness variations across F3,
visible on seismic data and in wells in the adjacent minibasins. In the hanging

### TABLE 3. CLASTIC FACIES DESCRIPTIONS

| Facies                | Grain size | Bedding thickness/geometries | Interbedded with | Composition                                                                 | Sedimentary structures                                           | Interpreted depositional environment                      |
|-----------------------|------------|------------------------------|------------------|---------------------------------------------------------------------------|-----------------------------------------------------------------|----------------------------------------------------------|
| CL-I conglomeratic sandstones | Medium to granule size matrix, pebble clasts | 5–20 cm thick/multistory packages with uncommon channelized, erosional scours at base, uncommon fining-upward sequences | Fine- to coarse-grained sandstones and siltstones | Clast composition: subangular granites and feldspars matric micaeous quartz sandstone | Cut and fill structures, horizontal and cross-stratification and ripples in sandstones, planar laminations in siltstones | Channel deposits in an alluvial environment? |
| CL-II sandstones      | Fine- to medium-sandstones | 1–20 cm thick/planar | Laminated siltstones | Micaceous to arkosic sandstones | Horizontal and cross-stratification in sandstones, planar laminations in siltstones | Overbank/distal deposits in an alluvial environment? |
| PCL-I cobble conglomerates | Fine sand limestone matrix, pebble-cobble (1–30 cm diameter) clasts | 20 cm to 1 m/uncommon fining upward sequences | PCL-II, fine- to medium-grained calcareous sandstones | Clast composition: subangular to subrounded fossiliferous limestones, dolomitized limestone, chert, and uncommon sandstone matric sandy limestone | Massive, clasts poorly sorted and no imbrication or sedimentary structures | Debris flows initiated on steep local slopes |
| PCL-II calcareous sandstones | Fine- to medium-sand | 1–10 cm/planar | PCL-1 | N/A | Laminated or massive siltstones, laminated calcareous sandstones | Shallow marine facies? |

Note: N/A—not applicable.
CA-I: Fossiliferous mud-supported wackestone with phylloid algae (Honaker Trail Fm.)

CL-I: pebble conglomerates with granitic and feldspar clasts, interbedded with medium-grained sandstones in the Honaker Trail Fm.

CA-III: Fossiliferous grain-supported packstone, crinoid-rich bed near top of the Honaker Trail Fm.

CL-II: Laminated siltstones and fine-grained sandstones in the lower Cutler

CA-II: Fossiliferous mud-supported wackestone with crinoids (Honaker Trail Fm.)

CLA: Fossiliferous mud-supported wackestone with phylloid algae (Honaker Trail Fm.)

Figure 11. Facies photos of older stratal panel. (A) and (B) CL-I; (C) and (D) CL-II; (E) and (F) CA-II; (G) and (H) CA-III; (I) CA-V. Fm.—Formation; Strat—stratigraphic.
TABLE 4. CARBONATE FACIES DESCRIPTION

| Facies                  | Rock type (Dunham, 1962) | Bedding            | Facies associations                      | Grain types, grain sizes         | Sedimentary structures | Fossils                  | Interpreted depositional environment |
|-------------------------|---------------------------|--------------------|------------------------------------------|----------------------------------|------------------------|--------------------------|--------------------------------------|
| CA-1 crystalline limestone | Finely to coarsely crystalline limestone (dark gray) | 5–20 cm thick, some nodular and dolomitized | Fine-grained sandstones (CL-IV) | Few reworked sand to silt quartz grains, baroque dolomite sometimes present | None                  | No visible fossils | Open marine conditions? |
| CA-II fossiliferous mud-supported limestones | Wackestones-packstones with micrite matrix, (gray) | <2 m thick, beds may be locally richer in phylloid algae or crinoids | Fine-grained sandstones (CL-IV) | In situ and reworked skeletal grains | Shell lag | Crinoids, phylloid algae, bivalves, bryozoans, and brachiopods | Subtidal within storm wave base |
| CA-III fossiliferous grain-supported limestones | Packstones to grainstones with micrite matrix, (gray) | <2 m thick, beds may be locally richer in phylloid algae or crinoids | Underlain by crystalline limestone (CA-I) and fossiliferous mud-supported limestones (CA-II), Overlain by siltstones (CL-IV) | In situ and reworked skeletal grains | Beds of fossils and fossil fragments | Crinoids, phylloid algae, bivalves, bryozoans, echinoderms and brachiopods | Shallow tidal to intertidal, under moderate energy |
| CA-IV dolomitic wackestone mudstone | Dolomitized mudstone and wackestone (dark gray) | 1–2 m thick | Fine-grained sandstones (CL-IV) | Minor quartz clasts | Micrite | No visible fossils | Supratidal, possibly in a lagoon. |
| CA-V micritic mudstone | Mudstone (blueish grey) | 10–30 cm thick | Conglomeratic sandstone (CL-III) and fine-grained sandstones (CL-IV) | Micrite | Wavy laminations | No visible fossils | Lagoon mud banks |

Note: Modified after Gianniny and Miskell-Gerhardt, 2009; Dunham, 1962; Wright, 1992.

wall, thicknesses from the Husky Huber 2 well are ~315 and ~1000 m for the Moenkopi and Cutler units, respectively (Table DR2); in the footwall, the Federal Sinbad Ridge 14-14 well records ~170 and ~690 m for the Moenkopi and Cutler units, respectively. Seismic data tied to wells suggest corresponding thicknesses of ~2500 and ~1500 m (Fig. 8B) in the hanging wall and footwalls, respectively, of combined Moenkopi and Cutler strata. The seismic data show similar thickness variations in the Honaker Trail Formation.

Salt Wall Flanks

Whereas the northeastern flank of the diapir is relatively unfaulted, the southwestern flank is cut by numerous small, diapir-parallel normal faults similar to those at the southeastern end of the salt wall (Fig. 4). Some of these drop Jurassic strata down onto the diapir top inboard of the megaflap (e.g., Fig. 6C), whereas others offset growth strata and the megaflap panel. In addition, there are several possible faults that separate the different structural domains on the southwestern flank. One, between SD C and SD D, is postulated due to the abrupt change in dip along strike in Honaker Trail and lower Cutler strata (Fig. 6C). Another possible fault is even less certain, but may explain the lateral juxtaposition of Cutler and Triassic strata between SD A and SD B (Fig. 6B).

Interpretation

We interpret fault F3 to be a counterregional fault (Fig. 2), following the terminology used for faults with a similar geometry in the Gulf of Mexico (Schuster, 1995; Rowan et al., 1999). Counterregional means landward-dipping, or dipping toward the proximal sediment source (i.e., the Uncompahgre Uplift), with thicker syndepositional strata in the hanging wall than the footwall. Counterregional faults typically extend away from, and often link, diapirs (e.g., Sinbad to Roc Creek linkage, Fig 1B; Rowan et al., 1999). The hanging walls typically contain expulsion rollover structures, which is a series of basinward-shifting depocenters (Ge et al., 1997; see also “heel-toe” structures of Kluth and DuChene, 2009). Counterregional faults in the Gulf of Mexico typically curve and are tangential to the proximal edge of the diapir (Trudgill and Rowan, 2004), which is not evident for fault F3 at the surface but may be the case at depth. Moreover, fault F3 dips toward the Uncompahgre Uplift, has thicker growth strata forming an expulsion rollover in its hanging wall, and connects the Sinbad Valley and Roc Creek diapirs. Based on the offset growth strata across the fault, it was active from the late Pennsylvanian through the Jurassic.

Faults F1 and F2 are more enigmatic. Fault F2 is likely another counterregional fault because of its geometry and position, with F1 therefore simply an antithetic fault similar to some of the minor faults in the hanging wall of F3. The strata in the hanging wall appear to fold into the counterregional fault around the end of the diapir, an expected geometry given that the displacement...
Figure 12. (A) Detailed geologic map of the faults on the northwestern end of Sinbad Valley, Colorado, USA, modified from Doelling (2002) with new mapping. Map symbols and lithologic unit colors are the same as Figure 3. (B) Cross-section illustrating the shallow subsurface interpretation of the faults and apparent thickness changes across faults, from field mapping and well data. (C) Aerial photo of the southwestern fault; note poor exposure of fault in field. (D) Photo of the northwestern end of Sinbad Valley; both faults appear to dip steeply (Fault F1 is an apparent dip). F2 (red) is interpreted as a counterregional fault; F1 (black) is an antithetic normal fault. Note extensive vegetation cover masks exposure of the faults.
Alternatively, faults F1 and F2 may have originated as radial faults (Stewart, 2006) that formed due to roof doming during passive salt rise. In this case, they would have been reactivated and propagated along strike during a later extensional event, since they have lengths of multiple kilometers and drape folding is typically more localized close to the diapir margin (Rowan et al., 2003). A third possibility is that faults F1 and F2 are collapse faults, formed by late stage evaporite dissolution.

The smaller normal faults around the diapir, especially along the southwestern flank and at the southeastern end, may have multiple causes. Those bounding the blocks of Jurassic strata dropped down onto the top of the diapir probably formed due to evaporite dissolution and consequent roof collapse (collapse faults, Fig. 2). Others, however, are outside the edge of the diapir and may have formed due to bending of strata during megaflap formation.

PARADOX FORMATION CONGLOMERATES

In the center of Sinbad Valley is a unit of interbedded gypsum, calcareous sandstones and mudstones, and pebble-boulder conglomerate (Fig. 14). This unit was originally mapped as the Honaker Trail Formation, with a faulted relationship with the surrounding Paradox Formation modern caprock (Shoemaker, 1956); however, these facies are not consistent with regional Honaker Trail Formation observations or the Honaker Trail strata exposed in the Sinbad Valley.
megaflap. Areas with different attitudes suggest folds and/or faults within the anomalous unit (Fig. 14), although in general, the strata in the eastern, western, and northern exposures dip 30–40° to the northwest, 60–70° to the southwest, and 50–80° to the northeast, respectively. Limited field exposure and alluvial cover mask the contacts between these different structural domains.

Stratigraphic Facies Observations

A measured section (Fig. 15) documents well-bedded, laminated gypsum, calcareous siltstones and sandstones, and pebble-boulder conglomerate (facies PCL-1; Table 2). The conglomerates contain poorly sorted, subangular to sub-rounded clasts 1–30 cm in diameter within a calcareous sandstone matrix, and are commonly matrix-supported but occasionally clast-supported (Figs. 15; S5). Locally, the matrix contains detrital material, including quartz, chert, and carbonate grains. The carbonate conglomerate grades upward into a very coarse-grained sandstone/granule conglomerate with uncommon larger clasts (5–10 cm in diameter) of carbonate and fossiliferous limestone. Clast compositions include tan partially dolomitized limestone, chert, fossiliferous limestone, ooid packstone, dolomitized and silicified chaetted sponges, and uncommon fine-grained sandstone and quartzite clasts. The fossiliferous limestones (sample 11-7-16-1A; Fig. 15; Fig. S6) are echinoderm packstones to grainstones, and contain abundant crinoid columnals and other echinoderm material, and uncommon fine-grained sandstone and quartzite clasts. The fossiliferous limestones are echinoderm, crinoid, and fenestrate bryozoans and ooid packstones are lithologies characteristic of the Mississippian Leadville Formation (Cooper, 1955).

At different outcrop locations along strike of the measured section, we observed lateral facies variations, with the conglomerates, siltstones, sandstones, and limestones changing thicknesses of <50 cm laterally over distances of <100 m. Subsurface data on these strata is limited, thus its spatial extent and relationship with the surrounding Paradox Formation evaporites is unclear. The Huber Sinbad Valley Unit No. 1 well (also called 1 Altex Sinbad), drilled in the center of Sinbad Valley ~2.6 km to the northwest of the measured section (Fig. 4), encountered coarse-grained clastics described as greywacke or arkosic in character (Maret and Coe, 1960). A core recovered from depths of 2800–2808 m displays contorted bedding in halite, black shale, siltstone, dolomite, and anhydrite (Maret and Coe, 1960).

Stratigraphic Interpretation

The ungraded, matrix-supported, granule-to-boulder conglomerates are interpreted as subaqueous debris flow deposits (see Horton and Schmitt, 1996), and the lack of observed scour or clast imbrication suggests deposition under laminar flow conditions (see Talling et al., 2012). The graded granule-to-boulder conglomerates that grade upwards into a sandstone are interpreted to be subaqueous transitional flow deposits that were deposited under temporally and spatially variable flow rheology (see Talling et al., 2012). The calcareous...
Figure 15. Measured section through the carbonate-rich facies in the center of Sinbad Valley, Colorado, USA. Discontinuous, poor exposures prevented a more detailed and complete stratigraphic analysis. Location shown in Figure 14.
sandstones are interpreted to be calcareous turbidite deposits (see Horton and Schmitt, 1996). Overall, the assemblage of ungraded and graded matrix- and clast-supported conglomerates, interbedded with horizontally stratified sandstones and granule conglomerates and massive sandstones and mudstones, represents deposition in a subaqueous or subaerial fan-delta system, formed when an alluvial fan meets a standing body of water (see Nemec and Steel, 1988). Deposition was dominated by subaqueous debris-flows, interbedded turbidites, wave-influenced, shallow water sediments, and hemipelagic deposits (see Horton and Schmitt, 1996).

**Structural Interpretation**

We interpret these strata to be a conglomerate and sandstone intrasalt inclusion (Fig. 11). An intrasalt inclusion, also called a stringer, is a non-evaporite, more competent lithology originally deposited within the layered evaporite sequence, which was subsequently broken up and deformed within the salt during salt wall growth (e.g., Strozyk et al., 2012; Jackson et al., 2014). Salt inclusions can reveal information about depositional environments during the time of evaporite deposition and the internal dynamics of the salt diapir (e.g., Jackson et al., 2014; Alsop et al., 2016; Hudson et al., 2017) as well as the regional sediment routing during salt deposition (Fig. 16; also see below discussion).

**EVOLUTION OF THE SINBAD VALLEY SALT WALL**

Proximal to the Uncompahgre Uplift, a prograding sediment wedge of the upper Pennsylvanian Honaker Trail Formation through the Permian Cutler Group drove lateral salt withdrawal and initiated diapirism in the northeastern part of the basin (Trudgill, 2011; Figs. 17, S1, S2 [footnote 1]). However, the Honaker Trail and lower Cutler strata are conformable and do not show significant growth, thus passive diapirism had not yet initiated. The Sinbad Valley salt wall, given its proximity to the Uncompahgre Uplift, initiated during the late Pennsylvanian. At this point along the Uncompahgre Uplift, the Honaker
Trail Formation overlaps the early thrusts on the margin of the basin. This observation suggests these thrusts were not reactivated but instead were buried when the central Uncompahgre uplifted and provided abundant clastic material that buried the frontal thrusts. The Honaker Trail Formation within the megaflap stratal panel thins across the top of the inflated salt and thickens into the adjacent Roce Creek and Salt Creek minibasins, from seismic and well data. On the northeastern margin, Salt Creek minibasin strata are separated from the roof of the inflated salt by a counterregional fault located over and extending off the ends of a single-flap active diapir (Fig. 17). Eventually, the salt broke through the thin roof, initiating passive salt wall rise and megaflap formation. Although we show this happening during Cutler Group deposition (Fig. 17), it is difficult to determine exactly when it occurred.

The Permian through Triassic stratigraphy around the margins of the Sinbad Valley salt wall record at least three major unconformities, with several minor local, near-diapir unconformities within the Moenkopi Formation. The major unconformities include (1) ca. 290 Ma, in the mid-Cutler Group between the lower Cutler (Rico Formation) and upper Cutler strata, (2) ca. 251 Ma, at the top of the Cutler Group/base Moenkopi Formation, and (3) ca. 200 Ma, at the top Moenkopi Formation/base Chinle Formation. These are consistent with regional unconformities (Orgill, 1971; Hazel, 1994; Condon, 1997; Rasmussen, 2014) identified in subsurface data throughout the Paradox Basin (e.g., Kluth and DuChene, 2009; Rowan et al., 2016; this study), with the first (mid-Cutler) interpreted to mark the time of salt breakthrough. In contrast, the minor, local intra-Moenkopi and Chinle unconformities are observed only in outcrops adjacent to certain salt walls (Shoemaker and Newman, 1959; Hazel, 1994; Lawton and Buck, 2006; Matthews et al., 2007; Trudgill, 2011; Heness, 2016; Hartley and Evenstar, 2017) and probably represent local halokinetic-sequence unconformities generated during passive diapirism (see Giles and Rowan, 2012).

The base-Moenkopi unconformity likely eroded into the growing megaflap on the southern side of the Sinbad Valley salt wall, which was probably an emergent island in an otherwise shallow-marine setting. Moreover, the contact between the Tenderfoot and Ali Baba members of the Moenkopi is an unconformity (Shoemaker and Newman, 1959), suggesting that the diapir was inflating during this time. The gradational contact between the Ali Baba Member and the overlying Sewemup Member is characterized by granules and lumps of gypsum in Sinbad Valley (Shoemaker and Newman, 1959), which represent diapir-derived detritus and an emergent diapir at that time (e.g., Lawton and Buck, 2006; Ribes et al., 2015). Furthermore, the regional unconformity at the base of the Chinle Formation eroded into both the Moenkopi and Cutler strata such that the Moenkopi and uppermost Cutler strata to the southwest of the megaflap are no longer exposed. Chinle strata unconformably overlie lower Cutler strata. Although Kluth and DuChene (2009) suggest that most of the salt growth and related unconformities near Sinbad Valley occurred during the Permian, the beveling of Triassic strata on the diapir flanks indicates that salt growth persisted at least into the early Mesozoic. Thickening toward the diapir of Chinle strata on the proximal side and thinning on the distal side (Fig. 5) also show continuing growth. However, the lack of apparent growth in Jurassic strata suggests that passive diapirism ceased roughly by the end of the Triassic.

Regional field data show slight upwarping and folding of the Cretaceous strata on both flanks of the salt wall over a distance of ~2 km from the diapir (Figs. 4, 5, and 7). This upwarping probably reflects minor diapir rejuvenation during the Laramide and Sevier orogenies in the early Cenozoic (Baars and Stevenson, 1981). Finally, collapse faulting on the margins of the salt wall (Figs. 6C and 11) occurred during the late Cenozoic. This collapse faulting may have occurred as the region experienced uplift, erosion, and salt dissolution (Gutiérrez, 2004; Guerrero et al., 2015). However, the presence of such faults away from the diapir, both off the ends and outside the edges, suggest that minor regional Cenozoic extension may have contributed to diapir collapse as well. In any case, these faults, usually striking parallel to the salt wall, control the present-day geomorphology of the valley and may mask some of the key salt-sediment features. For example, the collapse faults along the southwestern flank overprint the terminations of the megaflap to the northwest and southeast.
DISCUSSION

Integrating new and existing subsurface, field, and remote sensing data permitted identification of a series of diapir-related features (megaflaps, counterregional faults, and conglomeratic intrasalt inclusions) at Sinbad Valley salt wall, forming the basis for revision of interpretation of its origin and growth history. We first discuss the limitations of the data, then the extent and nature of the megaflap and compare the observations at the proximal Sinbad Valley diapir to those at the more distal Gypsum Valley diapir.

Limitations of the Data

Pre-1980s well log and 2-D seismic data were used for the subsurface interpretation, and these data sets may introduce uncertainties into our interpretations. First, older well logs are incomplete, and tops were picked inconsistently between wells based on lithofacies without absolute or relative age control. For example, the top of the Honaker Trail Formation is inconsistently picked in well logs (Clair, 1958); in some wells, it is described as the first anhydrite or limestone bed, but new research indicates limestone and anhydrite beds may be present in the younger Cutler Group and locally in the Moenkopi and Chinle formations (Gianniny and Miskell-Gerhardt, 2009; Rasmussen, 2014). Thus, we consider many of the older well tops for the top Honaker Trail Formation/Hermosa Group to be unreliable and used them in a qualitative sense to guide the seismic interpretation. In addition, not all formation tops were picked in all wells (Table DR1), and it is unclear if the formation was not present or a top simply was not picked, thus complicating the comparisons of regional depths and thicknesses for the strata.

Second, the vintage 2-D seismic reflection data are noisy, and the interpretations near diapir edges are especially challenging. In addition, the depth conversion may have introduced some uncertainty in the dips of faults and strata that were measured at depth. Inaccurate velocities will steepen or flatten the apparent dips on the seismic data. For example, velocities that are 10% too slow would result in a measured dip change of <~5°.

Regional Sediment Routing: Paradox Formation Conglomeratic Intrasalt Inclusion

Sinbad Valley has intrasalt conglomerate inclusions that may reflect early unroofing of the Uncompahgre Uplift or syndepositional recycling of Paradox lithofacies in the proximal part of the basin. In fact, conglomerates similar to the Paradox Formation conglomeratic intrasalt inclusion at Sinbad Valley salt wall are present at Salt Valley salt wall (Rasmussen, 2014), another proximal diapir located ~60 km to the northwest of Sinbad (Fig. 1). The Salt Valley conglomerates contain boulders of limestone and chert as large as 38 cm in diameter, in a yellow sandstone matrix, and are also interpreted to be fan-delta deposits (Rasmussen, 2014). The boulder compositions include fossiliferous limestones that contain Mississippian-age fossils (Baker et al., 1933). In Salt Valley, these carbonate conglomerates were assigned to the Akah and Barker Creek stages of the Paradox Formation, deposited prior to the first massive arkosic sandstone influx and the initial stages of salt movement (Rasmussen, 2013). Furthermore, the presence of chaotedid sponges, a diagnostic fossil for Desmoinesian age strata in the Paradox Basin (Clair, 1952), in the conglomerate clasts supports the idea that these strata are part of the Paradox Formation. Hermosa-age conglomerates are also present at the Onion Creek diapir located along strike to the northwest of Sinbad Valley diapir (Baker et al., 1933), although with a different clast composition (granitic and carbonate clasts at Onion Creek versus primarily carbonate clasts at Sinbad Valley), so these conglomerates may belong to the Honaker Trail Formation (Grisi, 2018). In addition, abundant black shale and sandstone inclusions are exposed in the center of the Onion Creek diapir (Hudson et al., 2017).

The presence of conglomerates containing reworked Paleozoic carbonate rocks within the Paradox Formation suggests a response to early development of the Uncompahgre Uplift. Previous studies of the Salt Valley Paradox Formation conglomeratic facies invoked derivation from a local Desmoinesian uplift to the northeast of Salt Valley (Rasmussen, 2013; Ritter et al., 2016). However, the presence of similar conglomerates more than 60 km to the southeast along the Uncompahgre front at the Sinbad salt wall supports more widespread early uplift of the range, providing a local source of coarse-grained sediment (Fig. 16). Importantly, none of the conglomerates at Salt Valley contain clasts of igneous or metamorphic rocks, as would be expected if the source area were the Uncompahgre Precambrian basement rocks, unlike the Honaker Trail and Cutler strata at Onion Creek and Sinbad Valley that contain granitic clasts associated with the Uncompahgre Uplift (Baker et al., 1933; Elston et al., 1962; Grisi, 2018; this study, Fig. 11). Instead, clasts are likely derived from Cambrian through Pennsylvanian strata originally deposited on top of the Precambrian rocks of the Uncompahgre Uplift area, but later stripped off during exhumation. This interpretation is supported by the presence of abundant fossils and ooid packstone clasts, which are common to the Mississippian in this region (Cooper, 1955), and abundant detrital glauconitic grains, which may have been derived from the Upper Devonian Elbert Formation (Cooper, 1955). Following Pennsylvanian thrust uplift and erosion of older Mississippian and Devonian strata in the frontal Uncompahgre Uplift, further uplift and/or erosion of the central part of the Uncompahgre Uplift near the end of Paradox evaporite deposition generated arkosic and granitic material, as coarse-grained as boulders, interbedded with the evaporites (Elston et al., 1962). Thus, an Uncompahgre Uplift unroofing sequence is preserved in the Paradox intrasalt inclusions and the overlying clastic units (e.g., Honaker Trail Formation and Cutler Group), and early thrusts on the basin margin were inactive and buried by the subsequent unroofing sequence.

Importantly, these conglomeratic units have only been documented in salt walls that are adjacent to the Uncompahgre Uplift (Fig. 16), suggesting that coarse-grained detritus being shed off of the emergent local uplifts was...
restricted to the most proximal salt basins, and never reached the distal salt walls (e.g., Gypsum Valley; Figs. 1 and 16).

Megaflap Lateral Variations and Terminations

The surface geometry of the stratal panel that forms, at least locally, a megaflap along the southwestern flank of the diapir changes along strike. Rowan et al. (2016) proposed two end-member styles of megaflap formation, by limb rotation or hinge migration, and Escosa et al. (2018) presented models for the termination of megaflaps along strike. Here we expand on these ideas and propose three possible explanations for the observed changes at Sinbad Valley (Figs. 18 and 19): (i) varying degrees of folding via limb rotation, (ii) varying degrees of folding via hinge migration and preservation of the remnant roof, and/or (iii) radial faults separating different dip panels. Below we discuss the styles and the evidence supporting each mechanism.

Folding via Limb Rotation

One possible interpretation for the lateral changes in maximum observed dip is varying degrees of folding via limb rotation, which creates an undulating salt-sediment interface along strike if the lower hinge of the monoclinal drape fold is parallel to the deep edge of the diapir (Figs. 18A and 19A). In this case, steeper strata (90°) should occur where the diapir is the widest, and more gently rotated strata should correspond to a narrower part of the salt wall. The amount of rotation, in turn, may be related to the relationship between original roof length (width of roof across the diapir) and deep salt thickness (Rowan et al., 2016; Escosa et al., 2018).

The surface map pattern at Sinbad Valley appears to match this interpretation. At the southeastern end of the Pennsylvanian-Permian stratal panel, in SD D, the diapir is wider and the megaflap strata are the steepest. In SD C, the dips become gentler and the diapir margin curves inward. In this scenario, only the southeastern part of the stratal panel is a megaflap. However, the seismic data, which show steep dips in the subsurface at the northwestern section (SD A), do not support this interpretation.

Varying Preservation of Roof during Folding via Hinge Migration

If the megaflap formed by hinge migration, then part of the roof that never passed through the upper fold hinge may still be preserved as gently dipping strata, even though steeper dips exist at depth (Figs. 18B and 18B). In this scenario, SD A to SD C are interpreted to preserve a part of the roof that never completely passed through the fold hinge, leaving a short zone of eroded, more gently dipping strata at the surface and a larger, vertically dipping panel of strata at depth. To the southeast, in SD D, either the entire roof passed through the hinge, such that all strata are now dipping steeply, or the remnant gently dipping roof panel was eroded. This interpretation is compatible with the apparent steeper dips on seismic data in SD A (Fig. 8A) and, like the limb rotation model, can also explain the curvature in the edge of the diapir (Fig. 19B). If this interpretation is correct, the megaflap at Sinbad Valley extends for ~7 km along the southwestern flank of the diapir rather than being confined to the southeastern portion of the old stratal panel.

Radial Faults

Lateral changes in stratal geometries may be gradual or may be more abrupt and accommodated by radial faults (Fig. 19C). We have suggested that two radial faults might separate the different observed dips between SD A and SD B and between SD C and SD D (Fig. 18). Whether they juxtapose different degrees of limb rotation, different amounts of roof preservation during hinge migration, or even different styles of limb formation is uncertain due to the lack of subsurface data adjacent to the edge of the salt wall.

Comparison to Gypsum Valley

The new salt-associated faults and halokinetic features identified at Sinbad Valley, namely the counterregional faults and megaflap, were first specifically identified in the Paradox Basin at Gypsum Valley salt wall (Rowan et al., 2016; Escosa et al., 2018), although analogous structures were also shown in the northwestern Paradox Basin by Trudgill (2011). The Gypsum Valley salt wall is located in the distal, southeastern region of the Paradox Basin, and stretches for ~35 km in a northwest-southeast trend. The salt wall was a topographic high from the Pennsylvanian through the Jurassic/Cretaceous, based on stratal thickness changes adjacent to the diapir (Escosa et al., 2018). On its northeastern side, the Dry Creek minibasin contains thick and deeply buried Honaker Trail and Cutler strata (Amador et al., 2009; Rowan et al., 2016). In contrast, the Disappointment minibasin on the southwestern side has concordant Honaker Trail and Paradox strata that gradually thin toward the diapir, forming a vertical megaflap on the southeastern end of the diapir (figure 4 in Rowan et al., 2016; figure 3 in Escosa et al., 2018). The megaflap terminates against two radial faults on the southeastern end of the diapir, which intersect the diapir margin at a high angle and extend <5 km away into Cretaceous strata (Escosa et al., 2018). Also at the southeastern end of the diapir, a counterregional fault extends for >5 km off the end of the salt wall and offsets Pennsylvanian and Permian strata by more than 1.5 km (Escosa et al., 2018).

Overall, the salt-associated faults and halokinetic features are remarkably similar at the Gypsum Valley and Sinbad Valley salt walls (Table 5), suggesting a basin-wide control on the formation of these features, but there are distinct differences between the proximal (Sinbad) and distal (Gypsum) diapirs.
Varying degrees of folding laterally

Remnant roof preserved except at southeastern end

Figure 18. Schematic along-strike variations in megaflap geometries assuming formation by limb rotation (left) or limb rotation plus hinge migration (right). Locations of cross-sections A–D are in Figures 4 and 6, and near-surface geometries are shown in Figure 7. Fm.—Formation.
Figure 19. End-member models of lateral variations in megaflap geometries, modified from Escosa et al. (2018) and Rowan et al. (2016). (A) Folding of megaflap via limb rotation. In this scenario, the steeper dipping strata occur where the megaflap limb has rotated to a near-vertical position, and the diapir is wider at the surface. The gentler dipping strata occur where the megaflap has rotated to a lesser degree, with remnant salt at depth, and a narrower diapir at the surface. (B) Folding of megaflap via hinge migration. In this scenario, the steeper dipping strata occur where the megaflap has passed completely through the hinge to a near-vertical position, and the diapir is wider at the surface with no remnant roof. The gentler dipping strata occur where the megaflap panel hasn’t fully passed through the hinge, leaving a remnant roof at the surface with gentler dips and a steeply dipping panel at depth, and a narrower diapir at the surface. (C) Steep radial faults may occur in either scenario separating different panels of strata with different dips. When radial faults do occur, they are located at the highest curvature points between the different panels. To view Figure 19’s annotated map view and block models layer and “Step 1”, “Step 2”, and “Step 3” layers in the PDF version of this paper, open the PDF in Adobe Acrobat or Adobe Reader. To view the layers while reading the full-text version of the paper, click http://doi.org/10.1130/GES02089.f19 to download a PDF of the figure.
Both Gypsum and Sinbad valleys have megaflaps on their southwestern flanks (Table 5). The megaflap panel at Gypsum Valley is composed of uppermost Paradox, Honaker Trail, and Cutler strata, similar stratigraphic units to the southeastern section of the megaflap at Sinbad Valley. Furthermore, both diapirs have a counterregional fault extending for >5 km off the southeastern ends of the salt wall. Thus, the presence or absence of a megaflap or counterregional fault, and the formations involved in the megaflap panel do not appear to be influenced by the proximal or distal location of the diapir within the basin.

**Differences in the Geometry and Strata of the Megaflap**

There are distinct differences in the lateral changes in stratal geometries of the megaflaps at Gypsum Valley and Sinbad Valley salt walls. The megaflap at Gypsum Valley decreases in dip and structural relief toward the northwest on seismic lines (Rowan et al., 2016; Escosa et al., 2018), with the Honaker Trail strata no longer exposed at the surface. At Sinbad Valley, however, the Honaker Trail Formation is continuously exposed at the surface, and although it dips only 40–70° SW at the surface, seismic data indicate the same strata steepen at depth and maintain their megaflap geometry along the length of the salt wall. Furthermore, the stratal geometries suggest possible differences in the folding kinematics that created the megaflap; Gypsum Valley formed primarily via limb rotation (Rowan et al., 2016), whereas Sinbad Valley likely formed primarily via limb rotation but with a contribution from hinge migration.

Moreover, the same formations form both megaflap panels, but the facies vary between the proximal and distal parts of the basin. In the distal part of the basin, the megaflap at Gypsum Valley involves uppermost Paradox through lower Cutler strata. The Gypsum Valley megaflap strata have abundant carbonate facies, with fossiliferous carbonate beds, black shales, and dolomites (Mast, 2016; Deatrick et al., 2015). These strata are broadly similar to the strata described at the southeastern Section 2 in Sinbad Valley, which are composed of dolomites and fossiliferous limestones interbedded with sandstones (Fig. 10). However, there is considerably coarser-grained siliciclastic material in both sections at Sinbad Valley, and fewer beds of carbonates or dolomites, reflecting its more proximal position in the basin where deposition was heavily influenced by material eroded off the Uncompahgre Uplift.

**Differences in the Timing**

Although the geometries are similar at a first order, there is a difference in the timing of minicell fill between the proximal and distal settings. In the Salt Creek minibasin northeast of Sinbad, prograding packages of Honaker Trail and Cutler strata thicken toward the diapir (Kluth and DuChene, 2009; this study). In the Dry Creek minibasin northeast of Gypsum Valley, the Honaker Trail Formation has a nearly constant thickness, and it is the Cutter Group that is characterized by basinward-shifting depocenters (Rowan et al., 2016; Escosa et al., 2018). This difference may simply reflect the gradual southwestward progradation of depocenters sourced by the Uncompahgre Uplift.

Despite these differences in timing in the proximal minibasin (northeastern side) of each diapir, both distal minibasins (southwestern side) have gradual thinning and rotation of all uppermost Pennsylvanian to Triassic strata. These stratal thicknesses show that megaflap initiation was synchronous at both locales, marked by growth strata above the mid-Cutter Group unconformity. Moreover, both diapirs appear to have switched from single-flap active diapirism to passive diapirism at the same time, probably triggered by roof erosion by the mid-Cutter Group unconformity.

Although the onset of diapirism was effectively the same, the cessation of passive diapirism differed between the proximal and distal diapirs. Growth geometries show that diapirism continued through the Jurassic and possibly into the Cretaceous at the Gypsum Valley diapir (Escosa et al., 2018). At Sinbad Valley, the lack of growth strata in Upper Jurassic and Cretaceous strata indicates that passive diapirism at Sinbad Valley had largely ceased by the Early Jurassic. The offset of Jurassic and Cretaceous strata along the counterregional faults may have resulted from later extension and/or evaporite dissolution; these offsets cannot be used to constrain the timing of passive diapirism.

**Implications for Hydrocarbon Exploration**

Andy’s Mesa field, located on the northeastern side of the Gypsum Valley salt wall, produces oil and gas from Honaker Trail Formation and Cutter Group sandstone reservoirs within faulted structural-stratigraphic traps (Amador et al., 2009; DuChene et al., 2009; Coalson, 2014) sourced from the Paradox
Formation organic-rich shales. In contrast, the well on the northeastern side of Sinbad Valley (Husky Huber #2) was a dry hole with only minor shows in the Cutler Group (Table 1; Maret and Coe, 1960). Combined with observations of an oil seep in Cutler strata at the northeastern margin of the diapir (Fig. 4), there is likely a leaky trap on the northeastern side of Sinbad Valley. Two factors may account for this difference in sealing capacity, even though both the field and the dry hole are in similar settings. First, although there are facies variations between the proximal and distal Honaker Trail and Cutler strata, the few measured porosities and permeabilities of proximal (Hamilton Creek) and distal (Andy’s Mesa) producing Honaker Trail Formation reservoirs are similar (Amador et al., 2009; Coalson, 2014; Davis, 2014). However, in a regional sense, the proximal strata have an abundance of coarser-grained clastic material (Clair, 1958) and may have higher overall connectivity, with a relative lack of more shale- and carbonate-rich strata that may serve as seals or baffles to flow in the distal (i.e., Andy’s Mesa) setting. Second, there is an important difference in the adjacent minibasin geometries between the proximal and distal salt walls. At Andy’s Mesa, the Honaker Trail and lower Cutler strata are upturned and truncated against the salt wall (Amador et al., 2009; DuChene et al., 2009). Moreover, the overlying unconformity is locally marked by a salt wing (Amador et al., 2009), which may have served as a seal. At Sinbad Valley, however, the equivalent strata display apparent downlap (or rotated onlap) onto a primary salt weld and are structurally higher closer to the Uncompahgre; the gentle dip away from the diapir served as a probable hydrocarbon migration pathway. Only the younger Cutler strata, where there were minor gas shows and the oil seep, are upturned against the salt wall. Moreover, faulting near the edge of the diapir at Sinbad Valley may have also served as a migration pathway and a seal for hydrocarbons in the Cutler strata. On the southwestern side of the diapir-parallel faults, the Cutler strata are bleached, whereas the strata on the northeastern side of the fault were not bleached. Thus, the minibasin geometry and fill history and near-diapir faulting will affect whether or not the hydrocarbons can migrate to the trap and the trap will remain sealed.

CONCLUSIONS

Integrating new and existing field mapping, measured sections, well and 2-D seismic interpretation, we describe salt-sediment geometries at the Sinbad Valley salt wall in the proximal northeastern Paradox Basin. Previously unrecognized features, including a megaflap, counterregional faults, and conglomeratic intrasalt inclusions, allow for a revision of the structural and stratigraphic evolution of the Sinbad Valley salt wall and flanking minibasins. Moreover, our observations and interpretations illuminate the lateral variations in facies, stratal geometries, and kinematics along salt walls. In the center of Sinbad Valley, conglomerates within the Paradox Formation record early uplift of the Uncompahgre. Differential loading of the salt resulted in passive diapirism during the late Pennsylvanian through the latest Triassic/Early Jurassic. Exposures of a steeply dipping panel of the oldest suprasalt strata (Honaker Trail Formation) along the southwestern flank of Sinbad Valley are interpreted as a megaflap, a preserved remnant of the original diapir roof that was folded into a near-vertical position. Significant lateral changes in the surface geometry and depositional facies define four structural domains that may result from a combination of radial faulting and variations of strike-parallel folding via limb rotation or limb rotation plus minor hinge migration with minor roof preservation. Counterregional faults extend off the ends of Sinbad Valley and, along with the diapir, form the distal boundary of southwestward-prograding-sediment fill and associated salt expulsion from the late Pennsylvanian through the Triassic.

The halokinetic and near-diapir features at Sinbad Valley have similar geometries to features at the more distal Gypsum Valley salt wall, with both diapirs exhibiting megaflaps on their southwestern flanks and counterregional faults off the northwestern and southeastern ends. However, there are key differences in intrasalt non-evaporite lithologies, megaflap facies, minibasin stratall fill, and timing of diapirism, which indicate that the position of the salt wall (proximal or distal) within the basin has an effect on the development and characteristics of these features.

ACKNOWLEDGMENTS

ConocoPhillips generously provided access to the subsurface data used in this study and also provided funding to Thompson Jobe. Additional funding from the Salt-Sediment Interaction Research Consortium (S-SIRC) sponsors BP, BHP Chevron, ConocoPhillips, ExxonMobil, Hess, and Repsol also supported this work. This work benefitted from discussions with Craig Schneider and J. Clark Gilbert, field assistance from Cheryl Fountain, Elizabeth Wilson, and Polly Polaris, as well as technical support from Terry Martin and Nila Matser. We thank the editor Shanaka de Silva, associate editor Francesco Mazzarini, Pablo Granado, and an anonymous reviewer for comments that improved the manuscript.

REFERENCES CITED

Adam, J., Ge, Z., and Sanchez, M., 2012, Salt-structural styles and kinematic evolution of the Jequitinhonha deepwater fold belt, central Brazil passive margin: Marine and Petroleum Geology, v. 37, no. 1, p. 101–120, https://doi.org/10.1016/j.marpetgeo.2012.04.010.
Alsop, G.I., Weinberger, R., Levi, T, and Marco, S., 2016, Cycles of passive versus active diapirism recorded along an exposed salt wall: Journal of Structural Geology, v. 84, p. 47–67, https://doi.org/10.1016/j.jsg.2016.01.008.
Amador, C.M., Miller, B.L., and Schurger, S.G., 2009, Andy’s Mesa Unit, San Miguel County, Colorado, in Houston, W.S., Wray, L.L., and Moreland, P.G., eds., The Paradox Basin Revisited: New Developments in Petroleum Systems and Basin Analysis: Denver, Colorado, Rocky Mountain Association of Geologists Special Publication, p. 497–618.
Baars, D.L., and Doelling, H.H., 1987, Moab salt-intruded anticline, east-central Utah, in Beus, S.S., ed., Rocky Mountain Section of the Geological Society of America: Geological Society of America, Geology of North America, Centennial Field Guide, v. 2, p. 275–280, https://doi.org/10.1130/0-8137-5402-X.275.
Baars, D.L., and Stevenson, G.M., 1981, Tectonic Evolution of the Paradox Basin, Utah and Colorado, in Wiegand, D.L., eds., Geology of the Paradox Basin: Denver, Colorado, Rocky Mountain Association of Geologists, Field Conference Guidebook, p. 23–31.
Baker, A.A., Dane, C.H., and Resside, J.B., 1933, Paradox Formation of eastern Utah and western Colorado: AAPG Bulletin, v. 17, p. 963–980.
Banham, S.G., and Mountray, N.P., 2013, Controls on fluvial sedimentary architecture and sediment-fill state in salt-walled mini-basins: Triassic Moenkopi Formation, Salt Anticline Region, SE Utah, USA: Basin Research, v. 26, p. 709–733, https://doi.org/10.1111/bre.12022.
Rojo, L.A., and Escalona, A., 2018, Controls on minibasin inflow in the Nordkapp Basin: Evidence of complex Triassic synsedimentary deformation influenced by salt tectonics: AAPG Bulletin, v. 102, no. 7, p. 1791–1800, https://doi.org/10.1306/09281711524316523.

Ronnevik, C., Kriek, A.K., Fossen, H., and Jacobs, J., 2017, Thermal evolution and exhumation history of the Uncompahgre Plateau (northeastern Colorado Plateau), based on apatite fission track and (U-Th)-He thermochronology and zircon U-Pb dating: Geosphere, v. 12, p. 518–537, https://doi.org/10.1130/GES01148.1.

Rowan, M.G., Jackson, M.P., and Trudgill, B.D., 1989, Salt-related fault families and fault welds in the northern Gulf of Mexico: AAPG Bulletin, v. 83, p. 1454–1484.

Rowan, M.G., Lawton, T.F., Gilles, K.A., and Ratliff, R.A., 2003, Near-salt deformation in La Popa basin, Mexico, and the northern Gulf of Mexico: A general model for passive diapirism: AAPG Bulletin, v. 87, p. 733–756.

Rowan, M.G., Gilles, K.A., Hearon, T.E., and Fiduk, J.C., 2016, Megafaults adjacent to salt diapirs: AAPG Bulletin, v. 100, p. 1723–1747, https://doi.org/10.1306/05241616009.

Sassen, R., 1980, Biodegradation of crude oil and mineral deposition in a shallow Gulf Coast salt dome: Organic Geochemistry, v. 2, p. 153–166, https://doi.org/10.1016/0146-6380(80)90006-6.

Schuster, D.C., 1995, Deformation of allochthonous salt and evolution of related structural developments in eastern Louisiana Gulf Coast, in Jackson, M.P., Robertson, D.G., and Snelson, S., eds., Salt Tectonics: A Global Perspective: American Association of Petroleum Geologists Memoir 65, p. 177–198, https://doi.org/10.1130/M6504C.1.

Shock, A.L., 2012, Origin and implications of Permian and Triassic diagenetic carbonate caprock adjacent to diapirc salt walls, Paradox Basin, Utah [M.S. thesis]: Las Cruses, New Mexico State University, 105 p.

Shoemaker, E.M., 1951, Preliminary geologic map of part of the Sinbad Valley-Fisher Valley Anticline, Colorado and Utah: U.S. Geological Survey, scale 1:24,000.

Shoemaker, E.M., 1956, Geology of the Roc Creek quadrangle, Colorado: U.S. Geological Survey Map G-81, scale 1:24,000, https://doi.org/10.3133/gq81.

Shoemaker, E.M., and Newman, W.L., 1959, Moenkopi formation (Triassic?) in salt antcline region, Colorado and Utah: AAPG Bulletin, v. 43, p. 1835–1851.

Shoemaker, E.M., Cather, F.W., and McKay, E.J., 1955, Geologic of the Juanita Arch quadrangle, Colorado and Utah: U.S. Geological Survey Geologic Quadrangle Map GQ-81, scale 1:24,000, https://doi.org/10.3133/gq81.

Spötl, C., and Pitman, J.K., 1999, Saddle (baroque) dolomite in carbonates and sandstones: A reappraisal of a burial-diagenetic concept, in Morad, S., ed., Carbonate Cementation in Sandstones: Distribution Patterns and Geochemical Evolution: Cambridge, UK, Wiley, v. 2, p. 437–460, https://doi.org/10.1002/9781114430489.ch19.

Steward, S.A., 2006, Implications of passive salt diapir kinematics for reservoir segmentation by radial and concentric faults: Marine and Petroleum Geology, v. 23, p. 843–853, https://doi.org/10.1016/j.marpetgeo.2006.04.001.

Strozyk, F., Van Genti, H., Urai, J.L., and Kukla, P.A., 2012, 3D seismic study of complex intra-salt deformation: An example from the Upper Permian Zechstein 3 stringer, western Dutch offshore, in Alisop, G.I., Archer, S.G., Hartley, A.J., Grant, N.T., and Hodgkinson, R., eds., Salt Tectonics, Sediments and Prospectivity: Geological Society of London Special Publication 363, p. 489–501, https://doi.org/10.1144/SP363.23.

Talling, P.J., Masson, D.G., Sumner, E.J., and Malgesini, G., 2012, Subaqueous sediment density flows: Depositional processes and deposit types: Sedimentology, v. 59, p. 197–203, https://doi.org/10.1111/j.1365-3091.2012.01353.x.

Teixell, A., Barnolas, A., Rosales, I., and Arboleya, M.L., 2017, Structural and facies architecture of a diapir-related carbonate minibasin (lower and middle Jurassic, High Atlas, Morocco): Marine and Petroleum Geology, v. 81, p. 334–360, https://doi.org/10.1016/j.marpetgeo.2017.01.003.

Thomson, S.N., Soreghan, L.S., and Eccles, T.M., 2012, Elevated Cenozoic geothermal gradients and the last 8-9 Ma incision of the Uncompahgre Plateau and Unaweep Canyon (western Colorado) revealed by low temperature thermochronology: Geological Society of America Abstracts with Programs, v. 44, no. 6, p. 18.

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, p. 208–238, https://doi.org/10.1111/j.1365-2117.2010.00478.x.

Trudgill, B.D., and Paz, M., 2009, Restoration of mountain front and salt structures in the northern Paradox Basin, SE Utah, in Houston, W.S., Wray, L.L., and Moreland, P.G., eds., The Paradox
Basin Revisited: New Developments in Petroleum Systems and Basin Analysis: Denver, Colorado, Rocky Mountain Associations of Geologists Special Publication, p. 132–177.

Trudgill, B.D., and Rowan, M.G., 2004, Integrating 3D seismic data with structural restorations to elucidate the evolution of a stepped counter-regional salt system, Eastern Louisiana Shelf, Northern Gulf of Mexico, in Davies, R.J., Cartwright, J.A., Stewart, S.A., Lappin, M., and Underhill, J.R., eds., 3D Seismic Technology: Application to the Exploration of Sedimentary Basins: Geological Society of London Memoir 29, p. 169–176.

Trudgill, B.D., Banbury, N., Underhill, J., and Post, P.J., 2004, Salt evolution as a control on structural and stratigraphic systems: Northern Paradox foreland basin, southeast Utah, USA, in Post, P.J., Olson, D.L., Lyons, K.T., Palms, S.L., Harrison, P.F., and Rosen, N.C., eds., Salt-Sediment Interactions and Hydrocarbon Prospectivity Concepts, Applications and Case Studies for the 21st Century: Gulf Coast Section SEPM (Society for Sedimentary Geology), Houston, Texas, December 5–8, Annual Bob F. Perkins Research Conference: SEPM (Society for Sedimentary Geology), v. 24, p. 669–700, https://doi.org/10.5724/gcs.04.24.0669.

Trusheim, F., 1960, Mechanism of salt migration in Northern Germany: AAPG Bulletin, v. 44, p. 1519–1540, https://doi.org/10.1306/0BDA61CA-16BD-11D7-864500102C1865D.

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, p. 152–182, https://doi.org/10.1111/bre.12066.

Williams, M.R., 2009, Stratigraphy of Upper Pennsylvanian cyclic carbonate and siliciclastic rocks, western Paradox Basin, Utah, in Houston, W.S., Wray, L.L., and Moreland, P.G., eds., The Paradox Basin Revisited: New Developments in Petroleum Systems and Basin Analysis: Denver, Colorado, Rocky Mountain Association of Geologists Special Publication, p. 381–435.

Williams, P.L., 1964, Geology, structure, and uranium deposits of the Moab quadrangle, Colorado and Utah: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-360, https://doi.org/10.3133/i360.

Wright, V.P., 1992, A revised classification of limestones: Sedimentary Geology, v. 76, p. 177–185, https://doi.org/10.1016/0037-0738(92)90082-3.