Implications of diapir-derived detritus and gypsic paleosols in Lower Triassic strata near the Castle Valley salt wall, Paradox Basin, Utah

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ABSTRACT

Gypsum-bearing growth strata and sedimentary facies of the Moenkopi Formation on the crest and NE flank of the Castle Valley salt wall in the Paradox Basin record salt rise, evaporite exposure, and salt-withdrawal subsidence during the Early Triassic. Detrital gypsum and dolomite clasts derived from the middle Pennsylvanian Paradox Formation were deposited in strata within a few kilometers of the salt wall and indicate that salt rise rates roughly balanced sediment accumulation, resulting in long-term exposure of mobile evaporite. Deposition took place primarily in flood-basin or inland sabkha settings that alternated between shallow subaqueous and subaerial conditions in a hyperarid climate. Matrix-supported and clast-supported conglomerates with gypsum fragments represent debris-flow deposits and reworked debris-flow deposits, respectively, interbedded with flood-basin sandstone and siltstone during development of diapiric topography. Mudstone-rich flood-basin deposits with numerous stage I to III gypsic paleosols capped by eolian gypsum sand sheets accumulated during waning salt-withdrawal subsidence. Association of detrital gypsum, eolian gypsum, and gypsic paleosols suggests that the salt wall provided a common source for gypsum in the surrounding strata. This study documents a previously unrecognized salt weld with associated growth strata containing diapir-derived detritus and gypsic palesols that can be used to interpret halokinesis.

Keywords: diapirism, Moenkopi Formation, Paradox Basin, gypsum, salt structures, paleosols.

INTRODUCTION

Passive diapirism, or downbuilding, wherein the rise of salt diapirs roughly keeps pace with contemporaneous sediment accumulation, has long been inferred from geometric relations of flanking strata in outcrop and seismic reflection profiles (Barton, 1933; Rowan, 1995) and experimental models (Vendeville and Jackson, 1991). Nevertheless, confirmation of the process requires evidence for diapir-generated topography and possible evaporite exposure, whether subaerial or subaqueous, in the form of detritus eroded directly from the diapir and/or its thin overburden and deposited in flanking strata (e.g., Giles and Lawton, 1999; Rowan et al., 2003).

In this paper we describe diapir-derived detritus and the oldest recorded gypsic paleosols in growth strata of the Moenkopi Formation at the northwest end of the Castle Valley salt wall, one of several elongate salt diapirs in the Paradox Basin of eastern Utah and southwestern Colorado (Fig. 1). The salt walls formed by migration of middle Pennsylvanian evaporite of the Paradox Formation during Late Pennsylvanian, Permian, and Triassic time; minor salt movement continued beyond the Triassic. Evidence for syndepositional salt rise includes thinning of strata and angular unconformities on the flanks of diapiric anticlines (Shoemaker et al., 1958; Elston et al., 1962; Cater and Elston, 1963; Trudgill et al., 2004; Matthews et al., 2004). Elston et al. (1962) described carbonate-clast conglomerate of possible Paradox Formation fragments in Permian strata near the crest of the Salt Valley anticline, and Shoemaker et al. (1958) described gypsum detritus adjacent to the Sinbad Valley anticline in the Lower Triassic Moenkopi Formation. These observations indicate diapir exposure, but their significance to the mechanics of salt rise was not recognized. We present observations here demonstrating that the evaporite of the Castle Valley diapir was subaerially exposed throughout the Early Triassic, confirming that passive diapirism was the primary mechanism of salt rise during that time. We describe the oldest gypsic paleosols known in the rock record and ascribe them to diapiric exposure. These paleosols indicate extreme aridity during the Early Triassic and represent a previously unrecognized type of diapir-sourced material; thus, they are an important indicator of proximity to the salt walls.

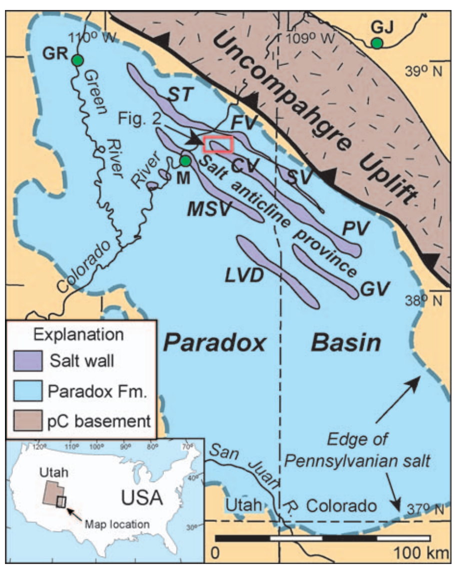

Figure 1. Location map of Paradox Basin and salt anticline province. Salt walls: CV, Castle Valley; FV, Fisher Valley; GV, Gypsum Valley; LVD, Lisbon Valley–Dolores; MSV, Moab–Spanish Valley; PV, Paradox Valley; ST, Salt Valley; SV, Sinbad Valley. Communities: GJ, Grand Junction; GR, Green River; M, Moab. Edge of salt is from Condon (1997); distribution of salt in salt walls is after Shoemaker et al. (1958). Explanation shows distribution of selected geologic features near end of Pennsylvanian. Inset rectangle indicates area of Figure 2.

GEOLOGIC SETTING

The asymmetric Paradox Basin developed in middle Pennsylvanian time adjacent to the northwest-trending basement-cored Uncompahgre uplift (Fig. 1; Baker et al., 1933; Wengerd and Strickland, 1954; Elston et al., 1962). The proximal basin fill constitutes the undifferentiated Cutler Group, a Pennsylvanian–Permian arkosic alluvial wedge ~5 km thick near the uplift; it grades southwestward through a thick section of cyclic middle Pennsylvanian evaporite, shale, and carbonate of the Paradox Formation into middle and Late Pennsylvanian carbonates of the Paradox and Honaker Trail Formations on the southwest flank of the basin (Barbeau, 2003). The strongly progradational Early Permian part of the alluvial wedge grades southwestward into marginal marine, eolian, and fluvial siliciclastic and subordinate carbonate strata of the Cutler Group (Condon, 1997). The Lower Triassic Moenkopi Formation, which unconformably overlies the Cutler Group and was likewise derived from the Uncompahgre uplift, postdated important shortening-related flexural subsidence (Barbeau, 2003), but records con-

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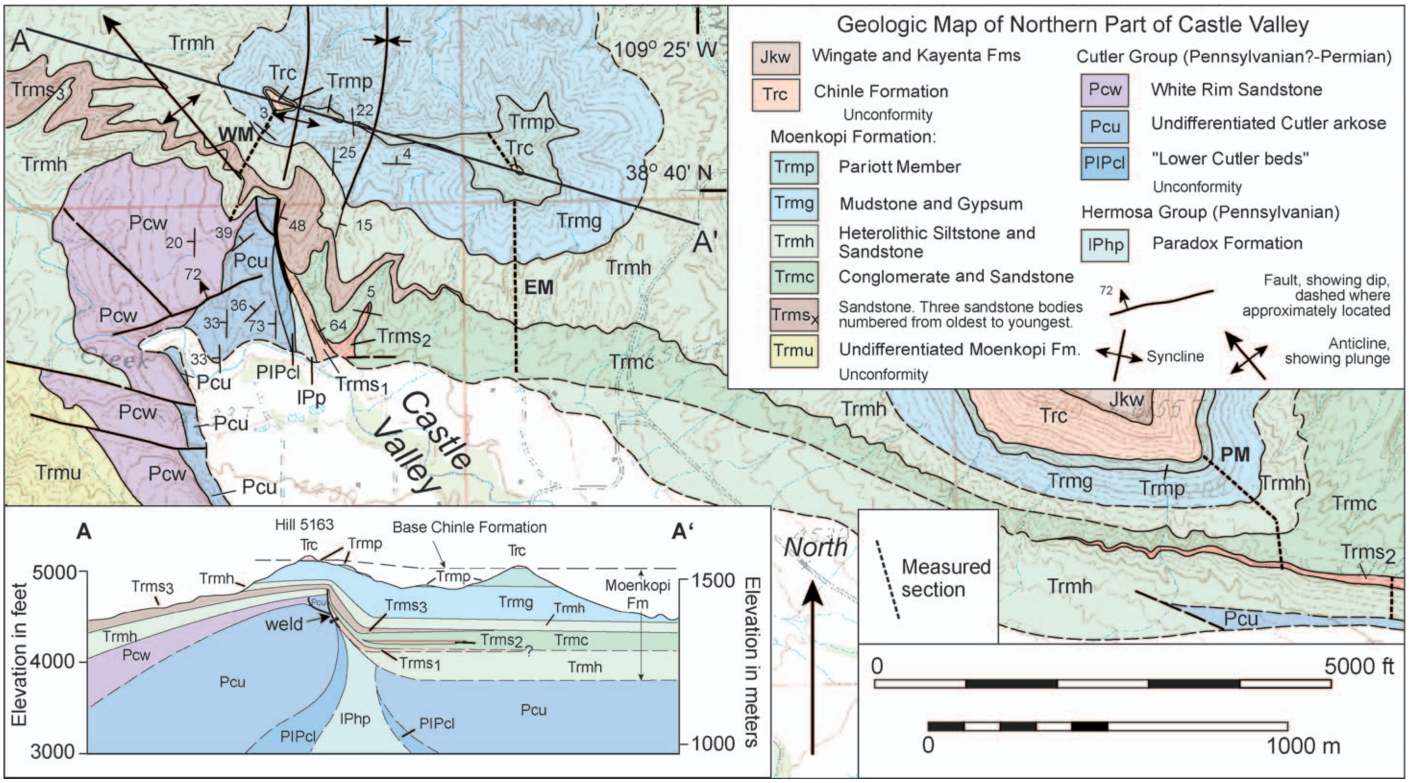

Figure 2. Geologic map and cross section of northwest end of Castle Valley anticline. Plunging crest of anticline is indicated by anticlinal symbol. Locations of measured sections of Figure 3: EM, East monocline; PM, Pariott Mesa; WM, West monocline. Map units of Moenkopi Formation are stratigraphic intervals dominated by lithologic associations (see text for details), except for Pariott Member, which is a formal lithostratigraphic unit (Shoemaker and Newman, 1959). Use of informal "lower Cutler beds" as a lithostratigraphic unit follows the recommendation of Condon (1997).

tinued diapirism in the salt anticline region in the northeastern part of the Paradox Basin (Shoemaker et al., 1958; Shoemaker and Newman, 1959; Trudgill et al., 2004).

The Castle Valley salt wall and associated anticline (Fig. 1) trend 310° from Oligocene intrusions on the southeast to a plunge termination at the Colorado River on the northwest. Gypsum, black shale, and dolostone of the Paradox Formation crop out locally on the flanks and near the middle of the eroded salt wall where not covered by a thin veneer of Neogene surficial deposits. Permian and Triassic strata dip northeast and southwest away from the diapir; dips are steep to overturned near the diapir and decrease away from the diapir and upward through the section, indicating decreasing amounts of halokinetic rotation in progressively younger strata.

Structural and stratigraphic relations at the plunging northwest end of the Castle Valley anticline confirm rapid diapirism during Pennsylvanian and Permian time, with continuing salt-withdrawal subsidence into the Early Triassic (Fig. 2). A previously unrecognized listric secondary salt weld (e.g., Jackson and Cramez, 1989), a fault-like structure formerly occupied by evaporite, juxtaposes Permian and Triassic strata and trends 015°, oblique to the trend of the salt wall. Evidence for the weld interpretation is fourfold: (1) strata on opposite sides of the structure dip steeply and face outward away from the weld; (2) the structure terminates downdip at exposures of Paradox gypsum, shale, and dolostone; (3) strata on both sides of the structure thin toward it; (4) updip Cutler beds adjacent to the structure contain dolostone clasts derived from the Paradox Formation, although the Paradox is no longer present there. The structure loses stratigraphic displacement upward and terminates into the upper hinge of a monoclinal panel of growth strata in the Moenkopi Formation (Fig. 2). Maximum structural relief on the monocline decreases northward from 250 m at its southernmost exposure to ~20 m near the Colorado River (a distance of 1600 m). On the western upthrown block of the weld, laminated dolomicrite and red sandstone that we interpret as upper Pennsylvanian–Lower Permian ''lower Cutler beds'' (e.g., Condon, 1997) underlie a complete but thin section of undifferentiated Cutler arkose and White Rim Sandstone; the latter is overlain by the basal Hoskinnini Member of the Moenkopi Formation. The Cutler Group is not exposed directly east of the weld, where a thick Moenkopi section is present.

LITHOLOGIC ASSOCIATIONS OF MOENKOPI FORMATION

Depositional relations indicate that the Moenkopi Formation in the salt anticline region represents terrestrial strata deposited in a hyperarid basin of low regional relief. On the northeast flank of the Castle Valley anticline, the Moenkopi unconformably overlies arkosic sandstone and conglomerate of the Cutler Formation with ~10° of angular discordance. The basal bed consists of structureless fine- to coarse-grained gypsum-cemented sandstone. This is overlain on both sides of the Castle Valley by a distinctive 0.7–1-m-thick bed of finely crystalline gypsum (Dane, 1935; Shoemaker and Newman, 1959), locally with faint tabular cross-beds as high as 30 cm. We interpret this extensive bed of gypsum as an eolian sand sheet.

Four major lithologic associations are present in the Moenkopi Formation adjacent to the Castle Valley salt wall (Figs. 2 and 3): (1) heterolithic thin-bedded siltstone and sandstone; (2) thick-bedded sandstone; (3) interbedded conglomerate and rippled sandstone; (4) mudstone and gypsum. The dominant heterolithic association consists of thin-bedded siltstone and very fine to fine-grained sandstone with oscillation, current, and combined flow ripples, and desiccation cracks filled with frosted eolian sand. This is a widespread lithologic association in the Moenkopi (e.g., McKee, 1954; Blakey, 1973); in the study area we interpret it as deposits of a continental flood basin or inland sabkha (sebkha of Glennie, 1970)

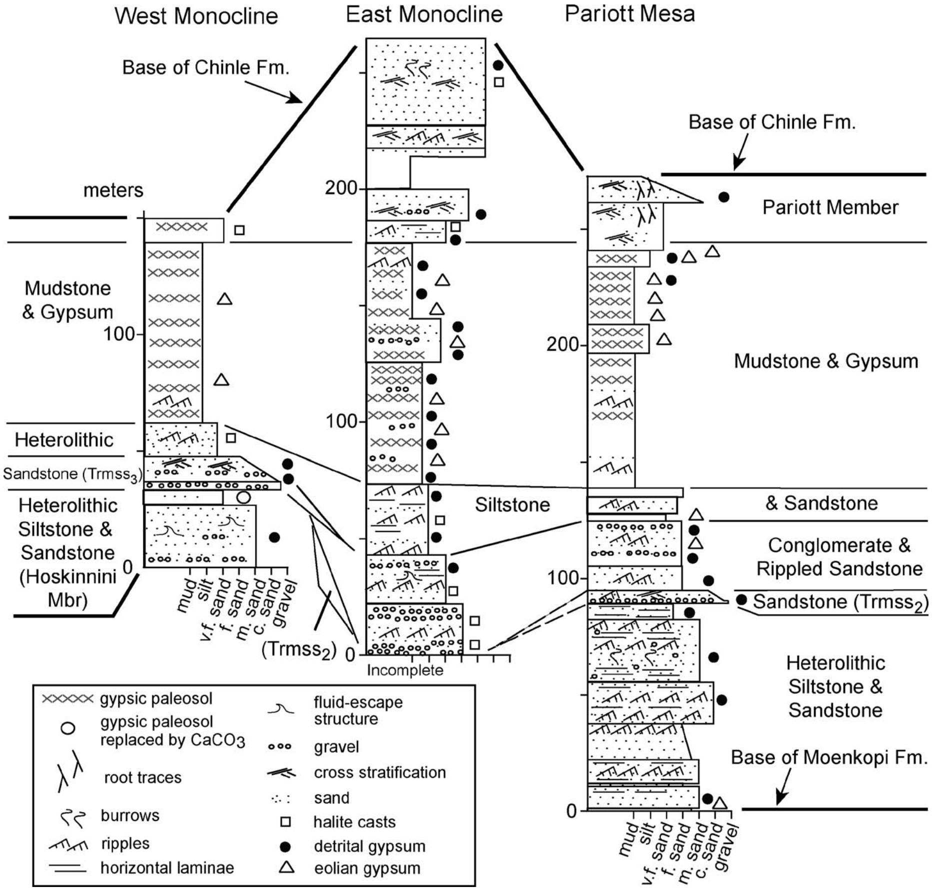

Figure 3. Measured sections of Moenkopi Formation. Section locations are indicated in Figure 2. Datum is base Pariott Member.

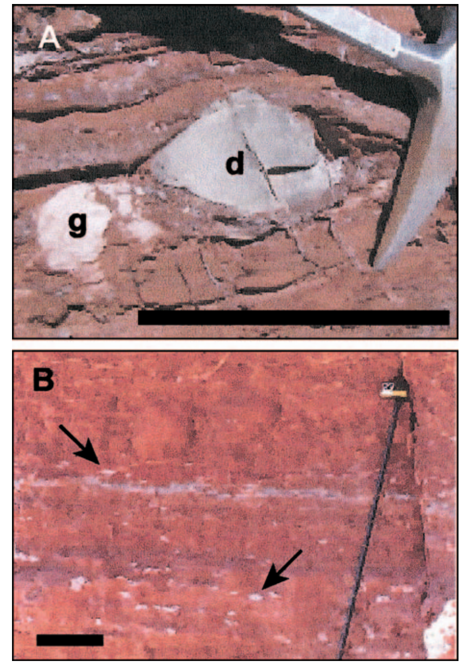

Figure 4. Gypsum in Moenkopi Formation adjacent to Castle Valley salt wall. Scale bars are 20 cm. A: Detrital gypsum clast (g) and dolostone clast (d) derived from Paradox Formation in conglomerate and sandstone association. Photo by Ron Foster. B: Cumulative paleosol with stage II gypsum nodules (1–12 cm; examples indicated with arrows) and variable structure, ranging from moderate to strong, fine to coarse, subangular blocky to columnar, in mudstone and gypsum association.

subject to alternating flooding and desiccation. The oscillation and combined-flow ripples are interpreted to have formed during ephemeral lacustrine (sabkha) deposition. Although the proportion of continental as opposed to marginal marine and tidal deposits in this association of the Moenkopi is debated (e.g., Blakey, 1989), we infer a continental origin in the salt anticline region on the basis of distance to a time-equivalent shoreline (Blakey, 1989) and absence of evidence, other than heterolithic character, for tidal deposition.

The thick-bedded sandstone association consists of poorly to well-sorted, fine- to coarse-grained sandstone in beds 50–100 cm thick, commonly with scour bases overlain by lags containing at least four clast types: (1) rounded quartz; (2) subangular dolostone; (3) angular to subangular intraclastic sandstone and shale; (4) subangular white gypsum as much as 12 cm in diameter. Dolostone clasts include finely crystalline gray Paradox varieties and very light gray laminated lower Cutler varieties. Both dolostone varieties are exposed in the map area (Fig. 2); the Paradox dolostones are in the diapir, and the lower Cutler dolostones are steeply dipping beds adjacent to the diapir. Sandstone bodies fine upward and contain trough cross-beds, horizontal lamination, transverse climbing ripples, halite casts, and occur singly or, less commonly, in multiple stories. Desiccation cracks, adhesion structures, and well-sorted eolian sandstone with compound foresets containing climbing translatent strata are present in the upper parts of some channel-fill successions. This lithologic association records ephemeral and intermittent fluvial systems of a wadi environment (e.g., Glennie, 1970) that impinged upon the inland sabkha. Although the sandstone bodies are stratigraphically adjacent to the heterolithic association, they lack features of tidal influence, notably inclined heterolithic bedsets (e.g., Shanley and McCabe, 1995). Three fluvial sandstone intervals ($Trms_1$–$Trms_3$ in ascending order) are present near the weld, where they onlap the anticline ($Trms_1$ and $Trms_2$) and overlap the weld ($Trms_3$).

The interbedded conglomerate and rippled sandstone association contains 5–40-cm-thick beds of matrix-supported conglomerate with 1–20 cm clasts of dolostone derived from the Paradox Formation and ''lower Cutler beds'' (e.g., Condon, 1997); sugary textured crystalline gypsum (Fig. 4A); and reddish-brown sandstone and siltstone intraclasts. Conglomerate beds are capped by fine-grained sandstone with oscillation, combined-flow and current ripples, adhesion ripples, and halite casts. Uncommon desiccation cracks are restricted to a few horizons in the association. We interpret this association as deposits of debris flows and wave- and/or current-reworked debris flows in the lacustrine (sabkha) setting at the toes of debris cones derived from the topographic high of the diapir.

The mudstone and gypsum association, most common in the upper part of the section (Fig. 3), is dominated by thick reddish-brown mudstone containing repetitive cycles of gypsic paleosols 0.5–1.5 m thick capped by thin (0.1–2 m) tabular beds of gypsum interpreted as eolian sand-sheet deposits. The paleosols range in development from stage I gypsum snowballs (1–3 mm in diameter; Buck and Van Hoesen, 2002), to stage II gypsum nodules (<20 cm), to stage III indurated gypsum (<30 cm) with fine to coarse subangular blocky and/or columnar structure (Fig. 4B). Thin (2–30 cm) rippled sandstone beds with mudcracks and halite casts are also present. The fine grain size and well-developed paleosols in this association indicate reduced rates of deposition in the inland sabkha.

The uppermost interval of the Moenkopi Formation, the Pariott Member (Fig. 3; Shoemaker and Newman, 1959), appears to represent deposits of lacustrine deltas and meandering rivers that record a changing climatic regime. It was not assigned to a lithologic association during our study.

DISCUSSION

A previously unrecognized listric secondary salt weld is associated with growth strata containing diapir-derived detritus and gypsic paleosols in the Moenkopi Formation flanking the Castle Valley in Utah (Fig. 2). The exposed evaporite was an important source for the gypsic paleosols and gypsum eolian sand sheets in the Moenkopi Formation. Proximity of the gypsic paleosols and the detrital gypsum clasts to the salt wall indicates that the diapir was the source of the gypsum. The repeating paleosol–sheet gypsum cycles of the mudstone and gypsum association suggest that paleosols resulted primarily from translocation of eolian gypsum (e.g., Buck and Van Hoesen, 2002), and indicate extreme aridity in the Early Triassic. In addition, eolian deposits in wadi channels imply long dry periods between active discharge events. Abundant salt casts and gypsum cements in fluvial sandstone beds suggest that groundwater was saline.

Clasts of gypsum and dolostone derived from the Paradox Formation and gypsic paleosols adjacent to the weld in diapir-related growth strata of the Moenkopi Formation demonstrate Early Triassic exposure of salt wall evaporite. Exposure of the diapiric cap corroborates a mechanism of passive diapirism that kept pace with sedimentation and created sufficient topography to shed detritus into diapir-flanking deposits. Diapiric topography generated by salt withdrawal in northern Mexico has been explicitly linked to the geometry and facies of strata flanking a passive diapir (Rowan et al., 2003). Coarse-grained diapiric detritus is most abundant in the middle part of the Moenkopi Formation, suggesting comparatively high diapiric topography at that time or fluctuations in climate-driven erosion and sediment supply during the Early Triassic. Extensive paleosol development higher in the Moenkopi section suggests decreased topography along the salt wall, reduced rates of subsidence due to salt withdrawal, and/or climate-induced decreases in erosion and sediment supply resulting in episodic geomorphic stability. The Moenkopi paleosols represent the oldest gypsic paleosols yet known in the rock record, a distinction formerly held by Paleogene gypsic soils (Buck et al., 2003). The persistence of gypsic paleosols in the geologic record thus has significant potential utility for the interpretation of salt tectonics and paleoclimate.

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