Using sedimentology to address the marine or continental origin of the Permian Hutchinson Salt Member of Kansas

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ABSTRACT

The Permian Hutchinson Salt Member of the Wellington Formation of the Sumner Group of Kansas (USA) has multiple scientific and industrial uses. Although this member is highly utilized, there has not been a sedimentological study on these rocks in over 50 years, and no study has investigated the full thickness of this member. Past publications have inferred a marine origin as the depositional environment. Here, this marine interpretation is challenged. The goals of this study are to fully document sedimentological and stratigraphic characteristics of the Permian Hutchinson Salt Member in the Atomic Energy Commission Test Hole 2 core from Rice County, Kansas. This study documents colour, mineralogy, sedimentary textures, sedimentary structures, diagenetic features and stratigraphic contacts in core slab and thin sections. The Hutchinson Salt Member is composed of five lithologies: bedded halite, siliciclastic mudstone, displacive halite, bedded gypsum/anhydrite and displacive gypsum/anhydrite. These lithologies formed in shallow surface brines and mudflats that underwent periods of flooding, evapoconcentration and desiccation. Of note are the paucity of carbonates, lack of marine-diagnostic fossils, absence of characteristic marine minerals and lithofacies, and the stratigraphic context of the Hutchinson with associated continental deposits. The Hutchinson Salt Member was most likely deposited in an arid continental setting. This new interpretation offers a refined view of Pangaea during the middle Permian time.

Keywords Bedded halite, continental, evaporites, Hutchinson Salt, Kansas, Permian.

INTRODUCTION

The 110 m thick Permian Hutchinson Salt Member of Kansas has multiple significant industrial uses, ranging from mined salt, solution-mined storage caverns for liquid petroleum gas, commercial underground storage for humidity-sensitive items and marker beds for petroleum studies (Schulmeister *et al.*, 2019). This salt has also been used to determine Permian seawater composition (Holser, 1966; Claypool *et al.*, 1980; Horita *et al.*, 1991; Lowenstein *et al.*, 2005); however, this interpretation is controversial due

to remaining questions about its depositional origin. The Hutchinson Salt Member was initially proposed as a marine deposit in the 1960s (Tasch, 1960; Dellwig, 1963, 1968; Jones, 1965). Since these initial studies in the 1960s, evaporite sedimentology has made great strides in scientific understanding through the concept of comparative sedimentology (i.e. Lowenstein & Hardie, 1985). In addition, the challenge of distinguishing among marine, marginal marine and continental evaporite deposits has been addressed by Hardie (1984) and Smoot & Lowenstein (1991). This new knowledge needs to be

applied to the Hutchinson Salt to evaluate the depositional history of this well-known evaporite deposit.

Halite deposits can contain specific proxies for past environments, past climate and past life. For example, Schubel & Lowenstein (1997) used comparative sedimentology to develop criteria to recognize ancient shallow-perennial-saline-lake halites. Lowenstein *et al.* (1999) determined palaeoclimatic history of Death Valley for the past 200 kyr from a core of halite and siliciclastics. Fluid inclusions in halite have yielded past surface water and air temperatures (Roberts & Spencer, 1995; Benison & Goldstein, 1999), as well as past atmospheric composition (Blamey *et al.*, 2016). In addition, micro-organisms and organic compounds have been documented in fluid inclusions in halite (Lowenstein *et al.*, 2011). The Hutchison Salt Member most likely contains such proxies for a critical time in Earth history. It also has implications for Permian palaeogeography. However, the depositional conditions which provide the foundation for studies of past environments, past climate and past life are not yet fully understood for the Hutchinson Salt.

The goals of this study are to complete detailed sedimentological and stratigraphic analyses of the Permian Hutchinson Salt Member in the Atomic Energy Commission (AEC) Test Hole 2 core from Rice County, Kansas. This study documents colour, mineralogy, sedimentary textures, sedimentary structures, diagenetic features and bedding contacts on a variety of scales including core slab, thick section and thin section. These observations are used to interpret the depositional environment and diagenetic history. This study of physical features, along with mineralogical and geochemical characteristics, can be used to re-evaluate and test the standing depositional environment interpretation of the Hutchinson Salt Member.

BACKGROUND

Although the Hutchinson Salt is a well-known stratigraphic unit, few sedimentological studies of it have been completed. The only sedimentological or palaeontological descriptions were published in the 1960s (Tasch, 1960; Dellwig, 1963, 1968; Jones, 1965).

Tasch (1960) observed parts of the Hutchinson Salt in mine wall samples. In this study, large blocks of mine salt were dissolved and the residual shale was examined for fossils. In addition

to bacteria and wood fragments, the presence of a single ostracod valve and a red-coloured polygonal-structured object, which was tentatively described as either a fragment of a brackish water bryozoan or a fragment of a marine coral, were noted. Based on this evidence, Tasch (1960) construed that the shale was from a nearby open sea and that the salt was likely from a saline inland basin surrounded by swamps. However, there are potential problems with the interpretations of this study. Ostracods are known from both marine and continental waters. The single ostracod fragment could have been carried by wind into the system. Therefore, Tasch's (1960) observation of a single ostracod fragment provides no diagnostic evidence for depositional environment. In addition, the tentative recognition of one partial fossil as either a bryozoan or marine coral, is not strong evidence of a marine setting. The wood fragments observed by Tasch (1960) would have originated in a continental or marginal marine setting, but could have been transported into a shallow marine environment. In summary, none of these fossil identifications are diagnostic of depositional environment.

Dellwig published two papers (Dellwig, 1963, 1968) that were a part of a larger study that included the most detailed sedimentological description completed on the Hutchinson Salt until now. This author observed samples from salt mine walls, which represent only part of the member, and identified the dominant lithologies as randomly oriented hoppers (cumulates), bottom-growth halite, clay and anhydrite (Dellwig, 1963, 1968). Mudcracks, ripple marks, red salt and polygonal shapes were also observed. From these sedimentary observations, Dellwig (1963) interpreted the depositional setting as a shallow brine with periodic subaerial exposure and occasional addition of brine to the basin. Dellwig (1968) completed chemical analysis on the red salt and noted that it is composed of 23% ferric iron. This red colouration was considered to be ferric iron precipitated by microbial action due to bacteria and other organic forms present in the red halite. There were no potassium minerals identified throughout the entire Hutchinson Salt (Dellwig, 1963, 1968).

Jones (1965) completed a sedimentological study of the Hutchinson Salt on the 94·7 m thick Hutchinson Naval Air Station core. This core was drilled in May, 1958 in Reno County, Kansas. Jones (1965) reported possible remains of blue-green algae, Permophorus-like pelecypods,

and siliceous foraminifera (Serpulopsis), and claimed a restricted marine environment. However, this marine depositional environment interpretation is sceptical because these suspected fossils, major ion ratios, bromide concentration, and sulphur and oxygen isotopes can be found in a range of marine and continental settings.

Since the 1960s, multiple studies have accepted the tentative marine interpretation for the Hutchinson Salt and have used geochemical analyses to evaluate Permian seawater composition. Fluid inclusions in the Hutchinson Salt contain Cl–Na–Mg–K–SO_4 brines (note that elements are listed by abundance; Horita *et al.*, 1991; Lowenstein *et al.*, 2005). Holser (1966) reported 30 to 60 ppm Br and Horita *et al.* (1991) measured 29·2 to 60·4 ppm Br in 15 fluid inclusions in Hutchinson Salt halite. Anhydrite in the Hutchinson Salt has $\partial^{34}S$ of +12·2 to 13·5‰ (Claypool *et al.*, 1980). Some of these studies analyzed isolated or secondary fluid inclusions, which do not represent depositional waters, and some represent whole rock analyses, and, therefore, may contain geochemical data from more than one mineral. These limitations in geochemical analyses cast some scepticism about some of the interpretations. Regardless, none of the geochemical signatures is diagnostic of marine brines. Some modern saline lakes have an overlapping range of these compositions.

There has yet to be a comprehensive modern sedimentological study of the complete thickness of the Hutchinson Salt Member. Previous publications relied on partial cores or salt mine walls that did not include the complete stratigraphic thickness of the member, or relied on geochemical analyses without a full stratigraphic or sedimentological context. Here, the standing marine-interpretation is challenged based on the paucity of stratigraphic and sedimentological observations needed for interpretation of depositional environments and because previous geochemical data is possible in both marine and continental saline systems. There is no independent and diagnostic evidence of marine deposition. A detailed sedimentological study of this famous salt in core is overdue, and is necessary before geochemical proxies for past environments, past climate and past life can be evaluated.

STRATIGRAPHIC CONTEXT

The Hutchinson Salt Member of the Wellington Formation is part of the Sumner Group (Fig. 1; Zeller, 1968; Watney *et al.*, 1988; West *et al.*, 2010). Directly below the Sumner Group lies the 104 m thick Wolfcampian Chase Group. The contact of the Chase Group and Sumner Group defines the Wolfcampian–Leonardian boundary (West *et al.*, 2010). The Chase Group is composed of the Wreford Limestone, Matfield Shale, Barneston Limestone, Doyle Shale, Winfield Limestone, Odell Shale and Nolans Limestone (West *et al.*, 2010). The Chase Group is dominated by grey fossiliferous shale, non-fossiliferous shale and grey/yellow limestone. The Chase Group rocks were likely deposited in alternating marine and continental environments (Miller *et al.*, 1996).

The Leonardian Sumner Group (*ca* 275 m thick) is composed of three formations: the 214 m thick Wellington Formation, the 91 to 137 m thick Ninnescah Shale and the 2 to 30 m thick Stone Corral Formation (Zeller, 1968; West *et al.*, 2010). The Wellington Formation contains six members, from the base: an unnamed member, the Hollenberg Limestone, a second unnamed member, the Carlton Limestone, the

Fig. 1. Stratigraphic column representing context of the Hutchinson Salt Member among Permian rocks in Kansas (not to scale). Modified from West *et al.* (2010) and Foster *et al.* (2014).

Hutchinson Salt and the Milan Limestone. The Hutchinson Salt Member composes approximately 110 m, or about one-third, of the group in the subsurface. There are few publications on the other members of the Wellington Formation due to the thinness and/or the lateral discontinuity of these rocks. Giles *et al.* (2013) studied the Midco and Otoe members of the Wellington Formation in northern Oklahoma, which are equivalents of the Carlton Limestone and shale underlying the Hutchinson Salt in Kansas, and interpreted these as continental deposits, including palaeosols and lakes. It is also important to note that the Sr^{87}/Sr^{86} ratios are inconsistent with Permian marine signatures (Giles *et al.*, 2013). The Ninnescah is a red, siliciclastic shale and the Stone Corral is composed mostly of bedded gypsum/anhydrite. Both the Ninnescah and Stone Corral formations have been interpreted as continental deposits (Watney *et al.*, 1988; West *et al.*, 2010).

The rocks stratigraphically below and above the Hutchinson Salt provide few fossil clues to their past depositional environments. The underlying Carlton Limestone Member contains plant fossils and the insect fossil, *Mecopteroid panorpida* (Beckemeyer & Hall, 2007). The Carlton-equivalent Midco Member of the Wellington Formation, in northern Oklahoma, contains rare fossils. One fossil type was identified as conchostracans, a clam-shrimp considered continental (Giles *et al.*, 2013). In the overlying Milan Limestone Member, Norton (1939) reported brine shrimp fossils, *Estheria*, in its the highest bed (Norton, 1939). This interpretation may not be accurate since brine shrimp are not identifiable in hand sample and there are no photomicrographs present in this publication. However, there are no supplemental studies to confirm the Norton (1939) interpretation. In summary, members of the Wellington Formation stratigraphically below and above the Hutchinson Salt both contain few fossils, one of which is diagnostic of a continental system.

The Sumner Group is overlain by the continental deposits of the Leonardian Nippewalla Group and the Guadalupian Quartermaster Group. The Nippewalla Group is *ca* 150 to 240 m thick and composed of the Harper Sandstone, Salt Plain Formation, Cedar Hills Sandstone, Flowerpot Shale, Blaine Formation and Dog Creek Formation (Zeller, 1968; Benison & Goldstein, 2001; Benison *et al.*, 2013). The Nippewalla Group consists of bedded halite, bedded gypsum/anhydrite, displacive halite and red siliciclastics. It has been interpreted as perennial and ephemeral acid saline lake deposits, palaeosols, mudflats and aeolian dunes (Benison & Goldstein, 2001). Furthermore, some fluid inclusions in Nippewalla Group bedded halites indicate extremely low pH (<1) saline lake water (Benison & Goldstein, 1999). The Quartermaster Group, the youngest Permian rock in Kansas, is composed of red beds and bedded gypsum/anhydrite of the Whitehorse Formation, Day Creek Dolomite and Big Basin Formation (West *et al.*, 2010; Benison *et al.*, 2013).

It is important to note that the Leonardian–Guadalupian rocks of Kansas, the Sumner, Nippewalla and Quartermaster Groups, pose some challenges in their study. Because they contain evaporites, including halite, thicknesses and sedimentological descriptions are best represented in the subsurface; in outcrops, halite has been dissolved and only casts, moulds and pseudomorphs attest to depositional halite (Benison *et al.*, 2015). However, high recovery cores of evaporites are rare. For this reason, most descriptions of the non-evaporite rock units are based on outcrops, and the evaporite units, particularly halite, are best known from cores. Because many of these siliciclastic rocks contain intergranular halite cement and displacive halite crystals, late-stage dissolution near the surface results in outcrops in which the siliciclastics have not retained sedimentary structures well (Benison *et al.*, 2015). Furthermore, the name 'dolomite' has been mistakenly attributed to some gypsum/anhydrite units, presumably because they have a light grey, blocky appearance in outcrop and do not react with HCl. These challenges in the study of mixed evaporite–siliciclastic rocks supports the importance of detailed sedimentological study of the Hutchinson Salt in core.

APPROACH AND METHODS

The Hutchinson Salt Member can be observed in core and salt mines. The majority of past studies were completed on salt mine walls. Salt mines provide easy access to the rocks; however, they only expose portions of the Hutchinson Salt Member. Some cores allow the thickness of the Hutchinson Salt to be observed in its entirety. Although the Hutchinson Salt was observed in walls of the Strataca Mine (old Carey Mine) in Hutchinson, Kansas, throughout this research, this study focuses on the Atomic

Energy Commission (AEC) Test Hole 2 core. In October of 1970, this core was drilled to a total depth of 370·5 m in Rice County, Kansas (Fig. 2). The Hutchinson Salt was identified from 225·5 to 335·2 m. The purpose in drilling this core was to investigate the Hutchinson Salt as a possible repository for radioactive waste. The core was drilled with a salt-saturated brine and low-water-loss starch mud. The diameter of this core is 10 cm. The core is stored in large, wooden boxes at the Kansas Geological Survey (KGS) in Lawrence, Kansas.

As part of an attempt to archive the core, previously to this study, it was slabbed and the two halves were placed in separate boxes and stored in separate parts of the core repository. One half of the core was maintained in its original wooden boxes with bottom and top core section depths labelled in each sample box. The second half was split vertically a second time and the resulting vertical quarter samples were combined into smaller cardboard boxes; during this process, the order by depth of the quarter slabs was not maintained; making it difficult to confirm stratigraphic orientation for individual core quarters. For this study, the core half slabs in the original wooden boxes were used. Each box contained 4·2 m (14 ft) of core. A measured section based on each box of core (*ca* 4·2 m per unit) was created. The measured section focused on colour, mineralogy, sedimentary textures, sedimentary structures,

Fig. 2. Map of Kansas, Oklahoma and north Texas. The star represents the core drilling location and the dashed line represents the Permian Hutchinson Salt Member (modified from Pierce & Rich, 1962; Jones, 1965).

diagenetic features, contacts and any fossils present. Photographs of the core were taken at the KGS. Colours of dry core slabs were determined using a Munsell Soil Chart.

Samples of representative lithologies were slabbed using limited water flow on a wet tile saw at KGS. Approximately 80 core samples were mailed to West Virginia University. Both thin and thick sections were used for petrography. Samples of six mudstone slabs were mailed to Spectrum Petrographics, Inc. (Vancouver, WA, USA) for large-format thin section prepared with minimal use of water or heat. Approximately seven, polished, thick (1 cm or less) bedded halite slabs were also used for microscopy. Bedded halite chips (*ca* 1 mm thick) were sliced from the core slab using a razor blade. The chips were hand polished with various sandpapers and used for fluid inclusion petrography. Petrographic observations were completed using an Olympus BX53 microscope (6·3 to 63× magnification) and an Olympus SZX10 microscope (20 to 2000× magnification) (Olympus Corporation, Tokyo, Japan). Both microscopes are equipped with transmitted, reflective and polarized light sources. A digital camera and SPOT5 digital imaging system were used for photomicrographs of thick sections, thin sections and fluid inclusions.

Mineral identifications were made by X-ray diffraction (XRD), as well as petrographic examination. Select samples of bedded halite and mudstone were crushed by mortar and pestle for XRD analyses. The XRD was conducted on three samples of bedded halite (whole rock analyses) and three samples of mudstone (whole rock and detailed clay analyses) by K-T Geoservices, Inc. (Gunnison, CO, USA). The entire Hutchinson Salt was tested for carbonates by the application of HCl and for salt minerals by taste.

OBSERVATIONS

The Hutchinson Salt Member is composed of five lithologies (in order from most to least abundant): bedded halite, siliciclastic mudstone, displacive halite, bedded gypsum/anhydrite and displacive gypsum/anhydrite. A graphic display of the Hutchinson Salt Member in the AEC-2 core is provided in a stratigraphic column (Fig. 3). The entire Hutchinson Salt Member was tested with HCl (both with and without powdering) and no reactions were observed. The XRD analyses did not detect any carbonates. No
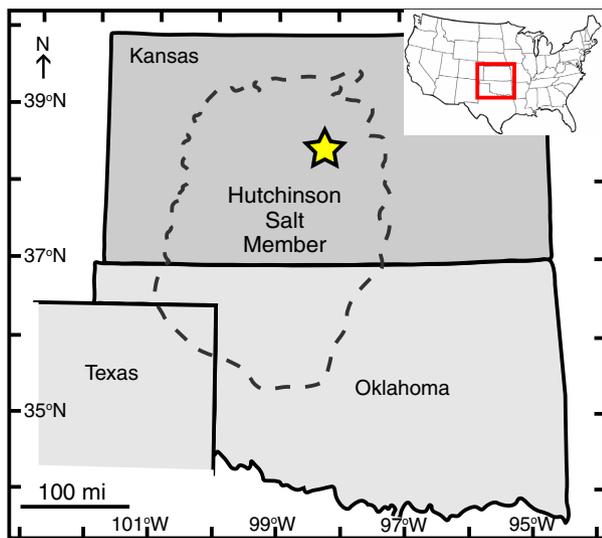
identifiable fossils were observed, either in hand sample or thin section. Detailed sedimentological observations of lithologies are included in the following sections.

Bedded halite

Bedded halite is composed of individual halite laminations varying from 0·5 to 1·0 cm thick (Fig. 4A and B). Most of this lithology ranges in colour from dark grey to light grey (GLEY1 2/5N; 5Y 5/1; GLEY1 5/N; Fig. 4A). However, rare units of bedded halite are pink due to various clast sizes of reddish mud (2·5YR 4/6). Three samples of mud-free bedded halite were used for bulk XRD analyses: (i) the lower unit (294 m) contains 99·6% halite, 0·2% anhydrite and 0·2% quartz; (ii) the middle unit (270 m) contains 99·5% halite, 0·3% anhydrite and 0·2% quartz; and (iii) the upper unit (242 m) consists of 91·2% halite, 8·6% anhydrite and 0·2% quartz. Overall, the bedded halite lithology is dominantly composed of halite, with rare gypsum/anhydrite and quartz.

There are two types of halite crystals within the bedded halite lithology: (i) bottom-growth halite; and (ii) cumulate halite. Bedded bottom-growth halite commonly contains growth bands of primary fluid inclusions arranged in centimetre-scale, upward-oriented chevron halite crystals. (Fig. 4C to F). Some secondary fluid inclusions cross-cut primary inclusion assemblages. The primary fluid inclusions contain trapped brine, gypsum daughter crystals, rare vapour bubbles, rare suspect micro-organisms and pollen (Fig. 4F). In contrast, bedded cumulate halite is observed as beds of millimetre-scale, randomly oriented, cubic halite crystals. Primary fluid inclusions were also observed in cumulate halite crystals. Most halite beds only contain bottom-growth halite. Some beds contain bottom-growth halite and cumulate halite. There are no documented beds consisting solely of cumulate halite crystals. Some bedded halite units contain clear, halite cement-filled vugs that cross-cut growth bands of primary fluid inclusions (Fig. 4C). Commonly, these bedded halite units also contain white (GLEY1 7/N), thin laminations of microcrystalline halite that drape over underlying crystals of cumulates and/or chevrons (Fig. 4C).

Siliciclastic mudstone

Siliciclastic mudstone lithologies consist of clay-sized to silt-sized grains in multiple colours including black, tannish-brown, grey and white (GLEY1 N/4, GLEY1 N/7, GLEY1 N/8, GLEY1 2·5/N, GLEY1 7/N, 5Y 7/1; Fig. 5A to D). Thicker beds of mudstone are grey and black, whereas white mudstone tends to be thin laminae. A variety of sedimentary features can be identified within the mudstone, such as intraclasts, climbing ripple cross-bedding, low-angle ripple cross-bedding, soft sediment deformation, wavy discontinuous lamina, mudcracks, autoclastic breccia, dewatering structures and erosive surfaces (Fig. 5E to K).

Three samples of lithologically-representative mudstone units were analyzed using bulk and detailed clay XRD. One was from a depth of 282 m: 50·4% quartz, 21·9% halite, 10·2% illite and mica, 5·7% plagioclase feldspar, 3·4% potassium feldspar, 2·5% chlorite, 2·0% magnesite, 1·8% kaolinite, 1·3% R1 ordered mixed-layer chlorite/smectite with 50% smectite layers, and 0·8% Fe-rich dolomite were identified. Another sample from a depth of 254 m: 26·5% anhydrite, 25·9% quartz, 13·7% illite and mica, 11·7% halite, 6·9% plagioclase feldspar, 5·1% potassium feldspar, 3·5% chlorite, 2·2% kaolinite, 2·2% R1 ordered mixed-layer chlorite/smectite with 50% smectite layers, 1·4% hematite and 0·9% magnesite. The final sample was at a depth of 235 m: 27·5% quartz, 23·6% illite and mica, 15·6% halite, 7·9% potassium feldspar, 7·8% magnesite, 5·1% chlorite, 4·7% plagioclase feldspar, 3·4% R1 ordered mixed-layer chlorite/smectite with 50% smectite layers, 3·1% kaolinite and 1·3% pyrite. It is noted that the XRD analyses did not detect any primary carbonates.

Mineralogical variations in mudstones are apparent in thin section. Figure 5 shows alternating laminations of black clay-sized grains, grey silt-sized grains and gypsiferous layers. The gypsiferous mudstone laminations are most clearly observed through cross-polarized light. The gypsum crystals are blocky and euhedral in shape and *ca* 0·2 mm^2 in size (Fig. 5K and L). There are a variety of diagenetic features found with the mudstone lithology including intergranular halite cement, anhydrite nodules and patches of red-staining from iron oxide cements.

Displacive halite

Displacive halite is a lithology composed of large (*ca* 1 to 2 cm^2), cubic halite crystals randomly organized in a fine-grained (clay-sized and silt-sized) siliciclastic sediment matrix (Fig. 6A). In the displacive halite lithology,
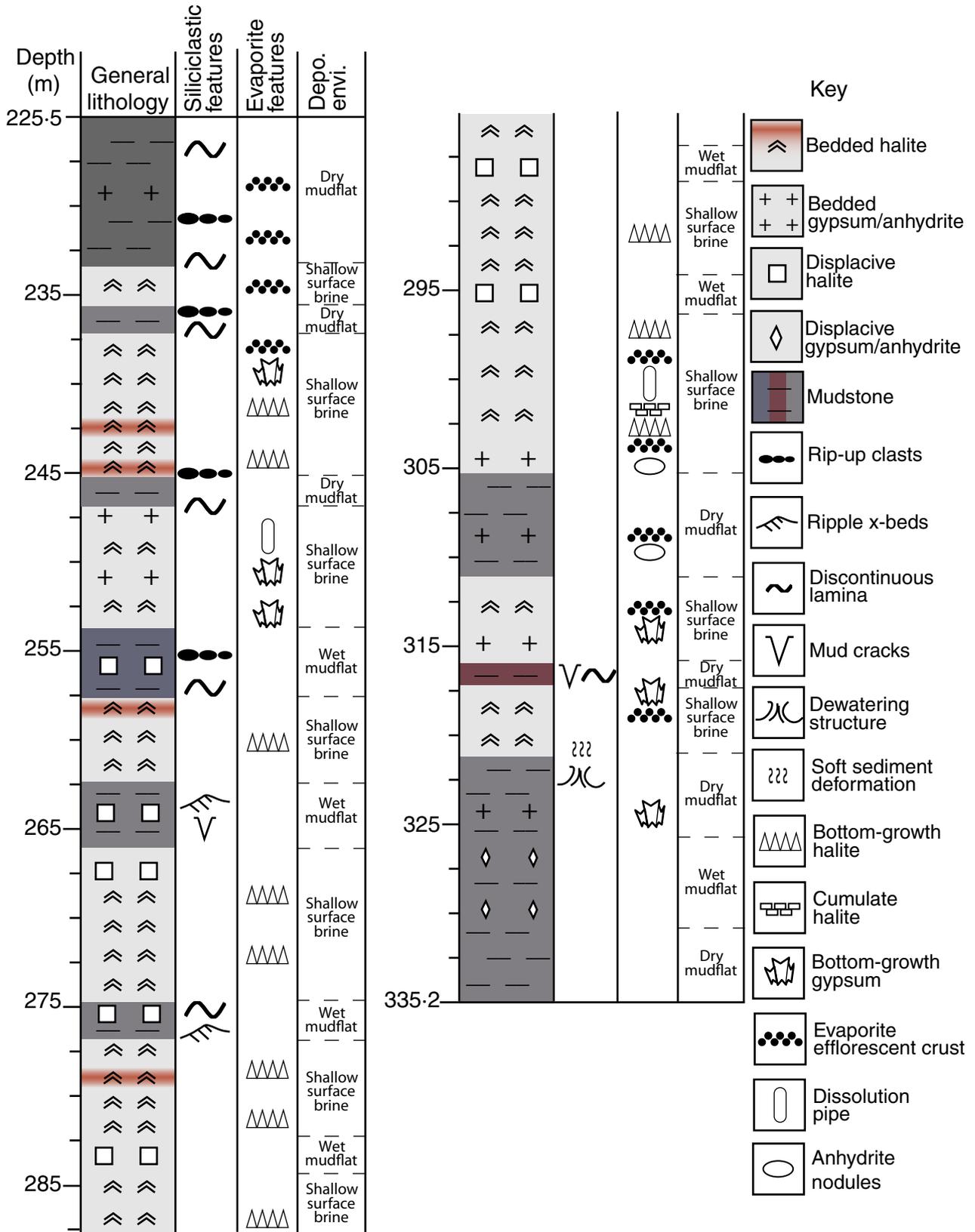
Fig. 3. Stratigraphic column of the Hutchinson Salt Member in the AEC-2 core. Note the distinct colour variations in both bedded halite and mudstone lithologies.
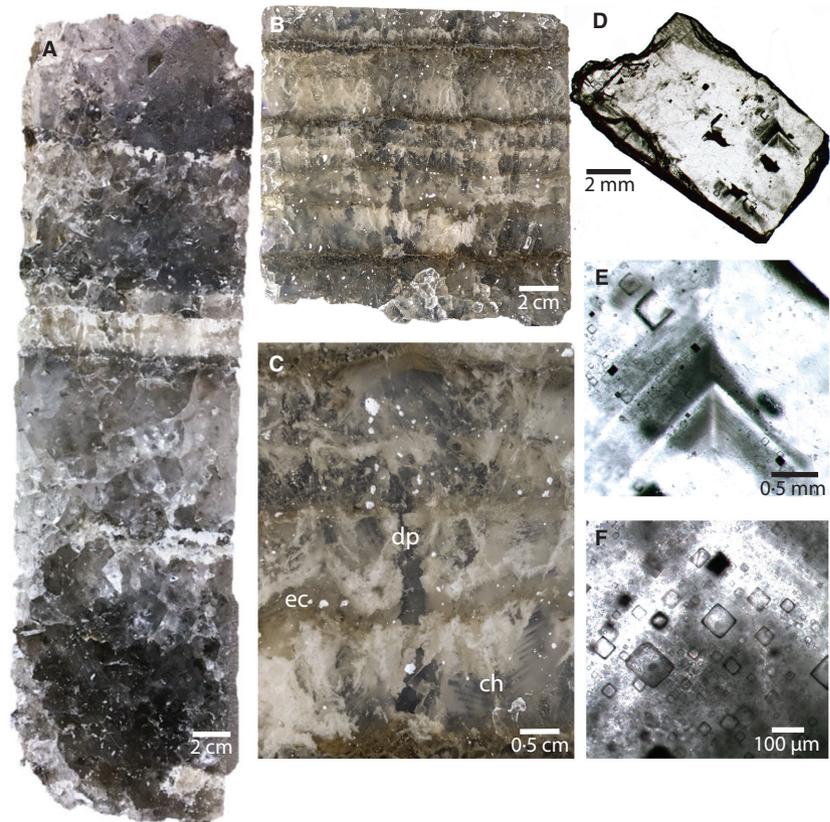
Fig. 4. Bedded halite lithology. (A) Core slab of bedded halite alternating in colour. (B) Thick section (*ca* 0·5 cm) of bedded halite. (C) Close-up of the thick section in (B) with late-stage dissolution pipe (dp) cross-cutting multiple beds of halite with white clay at the base, efflorescent crust (ec) interpreted from fine-grained, tan mud trapped in one lamina and chevrons (ch) composed of primary fluid inclusions labelled. (D) Chip of bedded halite with chevron. (E) and (F) Close-up of chevron and primary fluid inclusions.

halite crystals can range from 15 to 90% and mudstone can range from 10 to 85% of the composition. The mudstone is cemented with halite. The colour of the displacive halite crystals and mudstone range from dark brown to tan (10YR 3·1 and 5YR 6/6). Displacive halite units disrupt rare laminations in the mudstone matrix. Displacive halite is dominantly observed in the middle (253·0 to 298·7 m) of the Hutchinson Salt Member.

Bedded gypsum/anhydrite

Bedded gypsum/anhydrite lithology consists of laminations or beds that are predominantly composed of gypsum/anhydrite mineralogy. This lithology was present in two distinct textures: bottom-growth and cumulate gypsum/anhydrite.

Bottom-growth, swallowtail-shaped, bedded gypsum crystals are oriented upward from a nucleation surface to form a bed (Fig. 7A). The crystals widen at the top, exhibiting competitive crystal growth. The swallowtail-shaped gypsum crystals (GLEY1 N/4) that comprise the beds are approximately 0·5 cm tall and are draped with thick laminations of white, powdery, clay-sized to silt-sized gypsum/anhydrite grains.

Needle-shaped, cumulate gypsum/anhydrite crystals are interbedded with laminations of black mudstone. The cumulate gypsum/anhydrite crystals are tannish-brown (5Y 5/1) and the mudstone is black (GLEY1 2·5N to GLEY1 N/7). This lithology is cemented with halite (Fig. 7B to D).

Displacive gypsum/anhydrite

Displacive gypsum/anhydrite consists of rare, randomly oriented needle-shaped gypsum crystals in black mudstone (Fig. 6B). The gypsum needles range from 0·01 to 0·5 mm long. The composition ranges from 40 to 95% mudstone and 5 to 60% thin gypsum needles. Unlike displacive halite, displacive gypsum/anhydrite is only found within black mudstone in the lowest 10 m of the Hutchinson Salt Member. Some needle-shaped gypsum crystals are twinned and appear as a 'star' or 'burst' shape. These shapes are *ca* 2 mm wide and are suspended in a black mud matrix (GLEY1 2·5N to GLEY1 N/7).

Diagenetic features

There are several different diagenetic features throughout the Hutchinson Salt Member. Most
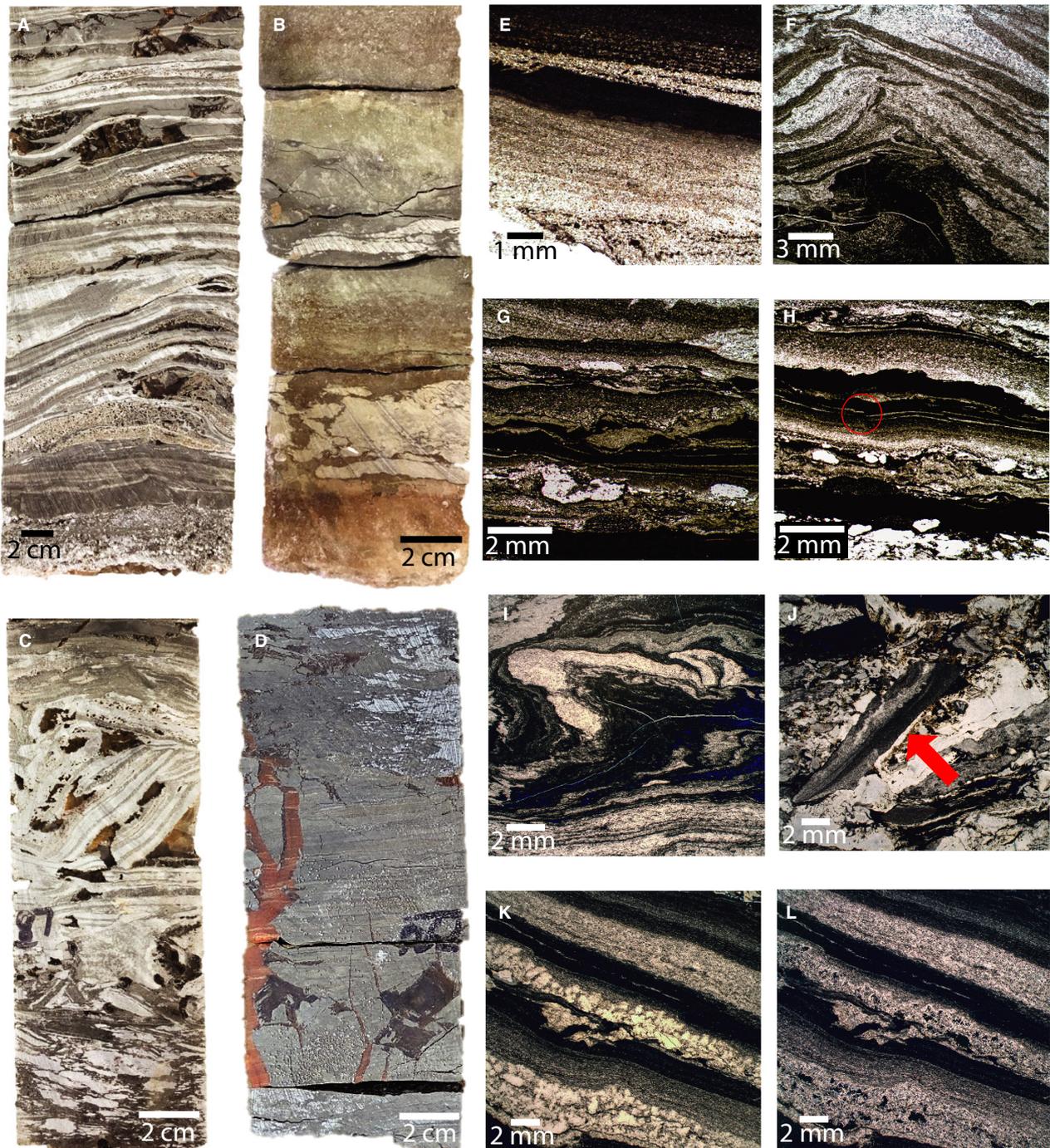
Fig. 5. Mudstone lithology. (A) Dark grey and white laminations of mudstone disrupted by displacive halite crystals in mudstone in core slab. (B) Alternating red and grey graded colouration in mudstone in core slab. (C) Alternating dark grey and white laminations in mudstone brecciated with displacive halite growth in core slab. (D) Grey mudstone core slab with rare displacive halite crystals and Fe-rich halite vein. (E) Climbing ripple cross bedding in silt-sized grains. (F) Dewatering structure (arrow) in mudstone. (G) Discontinuous lamina in mudstone. (H) Faults in laminated mudstone highlighted by a circle. (I) Convolute laminations in black and tan clay-sized and silt-sized sediment. (J) Intraclasts in mudstone highlighted by red arrow. (K) Black mud, gypsum and bottom growth halite in plane light. (L) Same view as (I) in cross-polarized light.
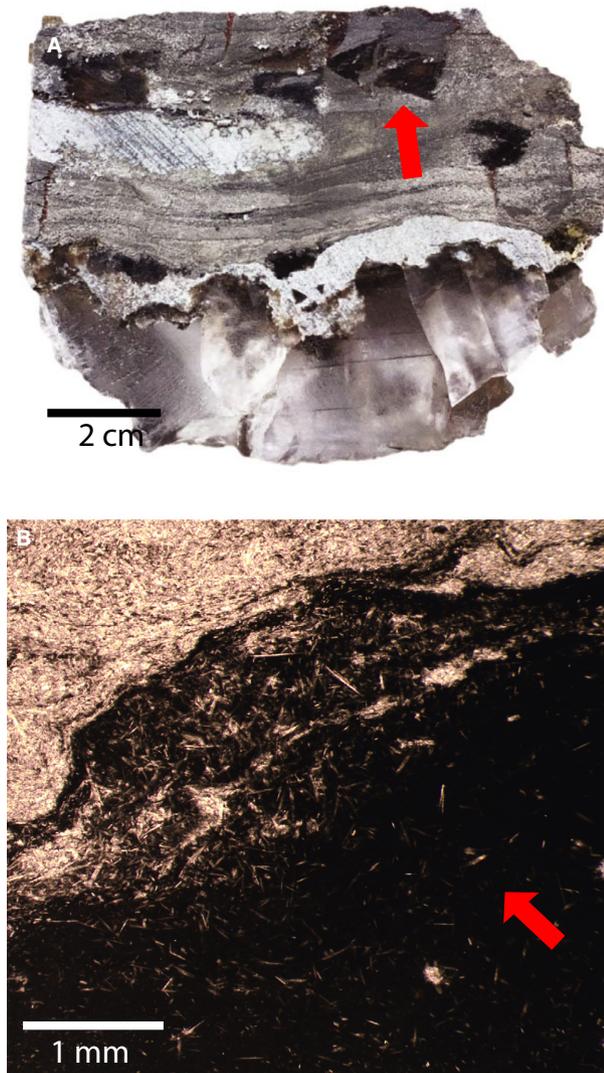
Fig. 6. Displacive halite (A) and displacive gypsum (B) lithologies. (A) Cubic-shaped centimetre-scale displacive halite suspended in mudstone in a conformable contact with underlying bedded halite in core slab. Displacive halite crystals are observed in hand sample and thin section. (B) Thin, needle-shaped, millimetre-scale displacive gypsum crystals suspended in black mudstone in conformable contact with bedded gypsum. Displacive gypsum crystals are only observed in thin section.

of these features are specific to host lithologies, such as intergranular halite cement in mudstone. However, one diagenetic feature, red-coloured halite veins, is not specific to any lithology and cross-cuts all lithologies (Fig. 5D). Although the red colour and lustre resemble sylvite, this is not an accurate identification. Based on the lack of tangy taste and observations from Dellwig (1968), this red mineral is an iron-rich halite.

INTERPRETATION OF LITHOFACIES

The descriptions of the lithologies, including sedimentary features, indicate three environments of deposition. The three environments are: shallow surface brine settings, wet mudflats and dry mudflats.

Shallow surface brine settings

Both bottom-growth and cumulate halite and gypsum/anhydrite crystals form only in surface brines. Therefore, the abundant beds of bottom-growth and/or cumulate crystals in the Hutchinson Salt Member are remnants of past surface brines. These shallow brines had chemistries dominated by Na^+, Cl^-, Ca^{2+} and SO_4^{2-}. No carbonates were observed in the bedded halite or gypsum/anhydrite lithologies, so it is likely that the water chemistry was not HCO_3^--enriched and CO_3^{-2}-enriched. Chevron halite is indicative of shallow surface brines (<0·5 m deep; Shearman, 1978; Lowenstein & Hardie, 1985). Cumulate halite crystals form in surface brines, regardless of depth. However, all beds that contained cumulates also contained chevrons. Therefore, the Hutchinson Salt halite was formed by shallow surface brines.

Some of these shallow brine settings underwent periods of flooding, evapoconcentration and desiccation. Evapoconcentration of surface waters is represented by the precipitation of bedded evaporites, including bottom-growth and cumulate halite and gypsum/anhydrite crystals. Thin laminations of white, microcrystalline halite that drape over some beds of cumulates and/or chevrons are interpreted as efflorescent crusts that formed during desiccation (Fig. 4C; Smoot & Castens-Seidell, 1994). Desiccation is also suggested from mudcracks and intraclasts in mudstones (Smoot & Castens-Seidell, 1994; Benison *et al.*, 2007). Clear, halite cement-filled vugs in some bedded halite is interpreted as early dissolution pipes caused by flooding (Fig. 4C; Lowenstein & Hardie, 1985). In contrast, some bedded halite does not contain flooding and desiccation features, indicating that the shallow saline brines were perennial (Schubel & Lowenstein, 1997). The bedded halite and bedded gypsum/anhydrite lithologies of the Hutchinson Salt Member were deposited by both perennial and ephemeral shallow surface brines.

Wet mudflats

Wet mudflats are interpreted by the presence of the displacive halite and displacive gypsum/anhydrite
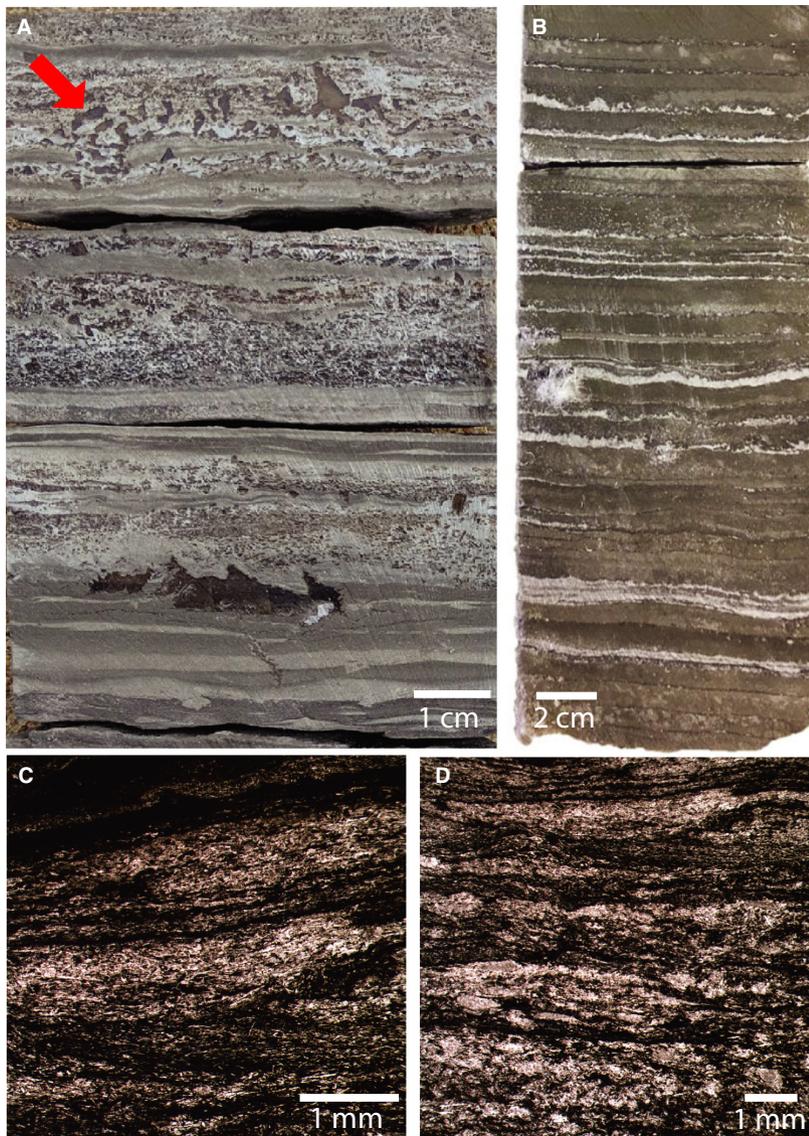
Fig. 7. Bedded gypsum lithology. (A) Core slab of laminated grey and white mud with 'V'-shaped swallow-tail bedded gypsum beds highlighted by red arrow. (B) Core slab of silt-sized, tan-coloured and white-coloured laminations of gypsum/anhydrite crystals. (C) Thin section photograph of interlaminated, aligned, needle-shaped, cumulate gypsum crystals and black mudstone. (D) Thin section photograph of discontinuous laminations of unaligned, unoriented, needle-shaped, cumulate gypsum crystals and black mudstone.

lithologies. These rocks formed in mudflats that were saturated with a shallow saline groundwater that precipitated displacive halite and displacive gypsum/anhydrite in unconsolidated mud (Smith, 1971; Casas & Lowenstein, 1989; Smoot & Lowenstein, 1991). Wet mudflats are dominant throughout the middle unit of the Hutchinson Salt. These mudflats experienced multiple periods of flooding and rare periods of desiccation. This is indicated by climbing ripple cross-bedding and mudcracks, respectively. Displacive halite crystals that crosscut these sedimentary structures document fluctuation of the groundwater table.

Dry mudflats

Siliciclastic mudstone units containing discontinuous lamina, intraclasts and mudcracks formed in dry mudflats. These dry mudflats were vegetation-free areas adjacent to wet mudflats which, at most times, were subaerially exposed and were underlain by a deeper water table. These dry mudflats occasionally experienced periods of flooding. Flooding was most likely activated by rain events, causing sheet floods that deposited wavy discontinuous lamina, climbing ripple cross-bedding and rare soft-sediment deformation. Desiccation followed, forming efflorescent crusts, dewatering structures, mudcracks. autoclastic breccia and intraclasts. Periods of desiccation likely also resulted in deposition of aeolian silt and clay. Erosive surfaces in the mudstone units were likely formed by both flooding events and aeolian processes. X-ray diffraction results indicate that quartz abundance remained relatively consistent

in mudstone lithologies. The quartz abundances are interpreted to indicate that an energy source, such as wind and/or water, carried quartz grains into the system from outside sources, likely including reworking of Chase Group outcrops.

DISCUSSION

Depositional trends of the Hutchinson Salt Member

The Hutchinson Salt Member is composed of five lithologies: bedded halite, mudstone, displacive halite, bedded gypsum/anhydrite and displacive gypsum/anhydrite. These lithologies were found in varying abundances throughout the thickness of this member, creating a natural division of three sections: lower, middle and upper. These stratigraphic divisions were based on the presence or absence of the displacive halite lithology. The middle Hutchinson Salt (253·0 to 298·7 m) predominately contains bedded halite, displacive halite and rare mudstones. The lower (298·7 to 335·2 m) and upper (225·5 to 253·0 m) Hutchinson contain little to no displacive halite beds and are composed of bedded halite, bedded gypsum/anhydrite, displacive gypsum/anhydrite and mudstone.

The middle depths of the Hutchinson Salt in the AEC-2 core do not have as much evidence for flooding, evapoconcentration and desiccation as do the lower and upper depths. The middle Hutchinson likely had higher groundwater levels and more persistent shallow, perennial lake water. This may have been caused by more consistent temperature and humidity levels due to less extreme weather events. Additionally, this groundwater driven system supports the interpretation of a continental depositional environment. In contrast, flooding, evapoconcentration and desiccation cycles observed in the upper and lower Hutchinson Salt may suggest that deposition was strongly influenced by more extreme weather events, such as rainstorms and droughts.

What does Hutchinson Salt Member sedimentology and stratigraphy indicate about marine or continental setting?

The Hutchinson Salt Member is dominated by halite, gypsum and siliciclastics that formed in shallow surface brines adjacent to wet mudflats and dry mudflats. Much of the Hutchinson Salt was subjected to flooding, evapoconcentration and desiccation. These are characteristics of multiple modern environments, including saline lakes, saline lagoons and arid-climate tidal flats. These environments contain similar sedimentary features and may have overlapping chemical signatures, despite the different origins of the parent waters. Deciphering among these environments is challenging (Hardie, 1984).

Revisiting criteria for distinguishing marine versus continental evaporites

Hardie (1984) provided a comprehensive discussion about guidelines to decipher whether ancient evaporites were deposited by a marine or continental environment. Five sedimentological, mineralogical and chemical criteria were recognized: (i) fossil types; (ii) facies associated with unit of interest; (iii) primary mineralogies; (iv) sequence of minerals; and (v) trace element and isotope geochemistry of saline minerals (Hardie, 1984). Other guidelines for recognition of marine versus continental evaporites are overviews of continental evaporites by Smoot & Lowenstein (1991) and marine evaporites by Kendall (2010), as well as detailed case studies of modern evaporite depositional environments (i.e. Eugster & Hardie, 1978; Hardie *et al.*, 1978; Casas & Lowenstein, 1989; Schubel & Lowenstein, 1997; Lowenstein *et al.*, 1999; Benison *et al.*, 2007).

Hardie (1984) suggested the use of fossils to decipher marine or continental settings. Macroscopic body or trace fossils were not observed in hand sample or thin sections in the Hutchinson Salt Member. The only fossils observed were suspect prokaryotes, algae and pollen trapped in fluid inclusions. Although a few publications have mentioned fossils (Tasch, 1960; Jones, 1965), these publications provide little documentation of fossil types. Therefore, the mentions of fossils in past publications are either not diagnostic or too rare within the Hutchinson Salt to be considered diagnostic. No fossils were observed in the current study of the AEC-2 core or supplemental observations of salt mine walls.

The lithofacies associated with the Hutchinson Salt can provide clues to help distinguish environment. Beneath the Wellington Formation lies the Chase Group, which has been interpreted as marine and continental cyclic deposits (Miller *et al.*, 1996). Above the Wellington Formation, there are hundreds of metres of continental deposits (Watney *et al.*, 1988; Benison &

Goldstein, 2001; West *et al.*, 2010; Benison *et al.*, 2013; Giles *et al.*, 2013; Sweet *et al.*, 2013; Foster *et al.*, 2014). In addition, no classic tidal flat features, such as tidal bundles, have been described for any rocks above the Chase Group. Based on these associated lithofacies, the transition from marine to continental settings must stratigraphically occur in either the Chase Group or the Wellington Formation. The stratigraphic position of the Hutchinson Salt Member, as part of the Wellington Formation, plays a key role in transition of marine to continental environments.

Minerals within the Hutchinson Salt Member include halite, gypsum/anhydrite, quartz, illite, mica, potassium feldspar, plagioclase feldspar, chlorite, kaolinite, magnesite, smectite and hematite. These minerals are undiagnostic because they can be found in both marine and continental environments, and some may be diagenetic.

The sequence of minerals throughout the Hutchinson Salt does not show any obvious trends. This suggests that there were not significant changes in brine chemistry. However, it is significant to note the lack of calcite, aragonite and other carbonate minerals in the member, and the presence of iron in some of the halite. Both characteristics are found in some arid continental saline settings (Benison *et al.*, 2007).

This study's application of the Hardie (1984) criteria, supplemented by consideration of Smoot & Lowenstein (1991) and Kendall (2010), highlights the lack of marine fossils and the paucity of carbonates in the Hutchinson Salt Member. Here, it is suggested that continental deposition was more likely than marine deposition.

Investigating the paucity of carbonate minerals

During the sedimentological investigation of this study, carbonate minerals were found to be rare throughout the entire Hutchinson Salt in the AEC-2 core. The only carbonate minerals detected were trace amounts of dolomite and magnesite. One siliciclastic mudstone sample contained *ca* 0·8% Fe-rich dolomite. Three mudstones revealed 0·9%, 2·0% and 7·8% magnesite. No carbonates, including the Fe-rich dolomite and magnesite, were observed in thin section. The absence of calcite or aragonite is interesting because bedded and displacive gypsum and anhydrite reveal that Ca was available in the

saline surface waters and groundwaters. The presence of trace amounts of Fe-dolomite and magnesite may be depositional or diagenetic. Furthermore, it is not known if rare Fe-rich dolomite and magnesite were made within the depositional environments or were transported from another environment.

The rarity of carbonates could be explained by two hypotheses: (i) few, rare carbonate minerals were present at the time of deposition; or (ii) carbonate minerals were present but were later dissolved or altered. The second option is not as viable as the first option due to multiple contradicting observations. Primary halite is still present in the core. It is not feasible to dissolve carbonate minerals and not primary halite because halite is more soluble than carbonate minerals. Another issue is that there are no remnants of carbonate minerals. No shapes, grains, or textures characteristic of carbonate grains or crystals were seen under the microscope. With this reasoning, it is more plausible that calcite and aragonite were never present in the depositional environment and that other carbonate minerals were never in abundance there. This strongly questions the traditional marine model. Typically, marine-sourced waters will initially precipitate carbonates, including calcite or aragonite. As the water chemistry changes through flooding, evapoconcentration and desiccation cycles, carbonates would periodically form and be closely associated with halite and gypsum/anhydrite. If the Hutchinson Salt Member was formed by marine brines, why are only rare and atypical carbonate minerals present?

A case for continental deposition

Although multiple past studies have suggested deposition from a marine environment, diagnostic features confirming this interpretation were not justified well in previous publications and were not identified in this study. Here, the Hutchinson Salt Member is interpreted as a saline lake system with continental parent waters. Supporting evidence for this interpretation is: (i) lack of fossils typically expected in marine-influenced settings; (ii) paucity of carbonate minerals; and (iii) absence of marine-indicative sedimentary lithofacies (for example, tidal bundles and tidal channels). In addition, the Sumner Group is stratigraphically bounded by lithologies that support this interpretation. Therefore, it is likely that the Hutchinson Salt Member was deposited in a continental setting.

CONCLUSIONS

In conclusion, the Hutchinson Salt Member is composed of five lithologies: bedded halite, siliciclastic mudstone, displacive halite, bedded gypsum/anhydrite and displacive gypsum/anhydrite. These formed in shallow surface brines that underwent periods of flooding, evapoconcentration and desiccation with adjacent wet and dry mudflats.

This study proposes that the Hutchinson Salt Member was deposited by a continental environment. This interpretation is supported by the paucity of carbonates, lack of marine-diagnostic fossils, absence of characteristic marine lithofacies and the stratigraphic context. More geochemical analyses are needed to further investigate this interpretation and to use climatic and biological proxies to better understand the Permian of Kansas.

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