SEDIMENTOLOGY OF ANCIENT SALINE PANS: AN EXAMPLE FROM THE PERMIAN OPECHE SHALE, WILLISTON BASIN, NORTH DAKOTA, U.S.A.

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ABSTRACT: **The mid-Permian Opeche Shale of North Dakota consists of bedded evaporites and red-bed siliciclastics. Detailed core and petrographic study has documented sedimentary and early diagenetic features in order to develop a depositional model, and to refine paleoclimatic data and paleogeographic setting for the late Paleozoic of the U.S. midcontinent.**

Lithologies and sedimentary features indicate lacustrine, distal alluvial, and minor eolian deposition, subaerial exposure, and soil formation. Bedded halites consisting of chevron and cumulate crystals, dissolution surfaces and pipes, and mudcracked microcrystalline salt crusts were deposited in a saline pan dominated by flooding, evaporative concentration, and desiccation. Bedded halites containing chevron and cumulate crystals but lacking any dissolution or desiccation features formed in perennial saline lakes. Chaotic halite, composed of red mudstone and siltstone with displacive halite crystals, represents saline mudflat deposits. Red mudstone and siltstone with little or no displacive halite but with abundant cracks and root features suggest deposition in a dry mudflat. Red-bed sandstones and conglomerates, composed of poorly sorted, subrounded quartz grains cemented with halite indicate distal alluvial deposition with possible transport by ephemeral streams, sheet floods, and debris flows. Most deposition took place in halite-dominated shallow perennial and ephemeral saline lakes surrounded by saline and dry mudflats. Evaporation, desiccation, flooding, and wind played significant roles in this environment. Therefore, the Opeche evaporites and red beds are representative of an ancient saline pan system.

An inland playa setting is favored as a depositional model for the Opeche Shale. The abundance of soil features and halite dominance, as well as lack of nearshore carbonates and lack of restricted marine fossils, suggest a closed-basin nonmarine setting for the mid Permian of the U.S. midcontinent.

INTRODUCTION

Paleogeographic, paleoclimatic, and paleoceanographic reconstructions depend upon interpretations of depositional environments. Evaporite deposits can be especially valuable to these reconstructions because they are highly sensitive indicators of localized geographic setting, climate, and water chemistry (i.e., Benison 1995, 1997; Benison and Goldstein 1999; Benison et al. 1998; Hardie and Eugster 1970; Lazar and Holland 1988; Li et al. 1996; Li et al. 1997; Li et al. 1998; Roberts and Spencer 1995; Timofeeff et al. 1998). For paleoenvironmental data from ancient evaporite deposits to be useful, attention must first be paid to interpreting their depositional environments as marine, marginal marine, or nonmarine.

Although evaporites can yield valuable data about earth history, those data can be highly misleading if the depositional setting has not been well documented. For example, many paleogeographic maps have been constructed using the simple presence of bedded evaporites to delineate ancient shorelines of seas (i.e., Maughan 1966), even though modern inland continental evaporites are as common as marine and marginal marine evaporites (see Hardie 1984; Lowenstein and Hardie 1985). Further, nonmarine evaporite deposits are especially good indicators of climate, because saline lakes and saline pans tend to evolve from freshwater and brackish lakes, reflecting continental wet and dry climate trends. The significance of all these data on paleo–global change hinge on the ability to distinguish whether an ancient evaporite formed in a marine or nonmarine setting.

In this paper, we develop a depositional model for the red beds and evaporites of the mid Permian Opeche Shale from the subsurface of southwestern North Dakota. Documentation of sedimentary features, both in bedded halite and in associated siliciclastics, is the main focus. This study shows that the sedimentology of evaporite deposits can be used to distinguish marine, marginal marine, and nonmarine depositional environments of the geologic past, as well as provide insight into the paleogeography and paleoclimatology for the Permian of the northern U.S. midcontinent region.

GEOLOGICAL BACKGROUND

The Permian (Leonardian–Guadalupian; Maughan 1966; Moore 1983) Opeche Shale Formation is composed of bedded halite and red-bed mudstones, siltstones, and rare sandstones and conglomerates. It is present in the subsurface of western North Dakota, eastern Montana, and northwestern South Dakota within the Williston Basin (located mostly in western North Dakota but extending into southwesternmost Manitoba, southeasternmost Saskatchewan, eastern Montana, and northwestern South Dakota; Fig. 1). Surface exposures of Opeche red beds are found in the Black Hills of South Dakota. The Opeche Shale reaches a maximum thickness of 120 m in the Williston Basin and is approximately 40 m thick in the Black Hills.

The Opeche Shale lies unconformably on red-bed sandstones and conglomerates of the Upper Pennsylvanian–Lower Permian Minnelusa Formation. Conformably overlying the Opeche Shale are stromatolitic limestones, dolomites, and minor evaporites of the Upper Permian Minnekahta Limestone (Fig. 2).

Several previous studies of the Opeche Shale were undertaken because of its association with the oil-producing Minnelusa Formation (Moore 1983; Wittstrom and Hagemeier 1979) and economic potential as a mineral resource for halite (Sandberg 1973). Other work focused on the paleogeography of the Permian of the midcontinent region (Maughan 1966, 1967; Mudge 1967).

Limited studies have addressed the depositional environment of the Opeche Shale. Maughan (1966) suggested that the Opeche red beds and halites were deposited in a restricted marginal marine basin connected to the Phosphoria Sea by a broad channel that crossed the Cedar Creek anticline. He based this paleoenvironmental interpretation on the distribution of detrital and evaporite lithologies in the Opeche. An alternative view of a nonmarine origin for the Opeche Shale was proposed by Wilgus and Holser (1984) on the basis of bromide concentrations in Opeche halite. They claimed that the low concentrations of bromide suggest a strong nonmarine influence on precipitation of the halite. Until now, however, no detailed sedimentological study of the Opeche Shale has been used to interpret its depositional environment.

METHODS

This study is based upon data from the Gulf-Romanysyn 2–33–4B core from the subsurface of Billings County in southwestern North Dakota (Fig. 1). In this core, the Opeche Shale is 96 m thick, occurring between depths of 2343 m and 2247 m (Fig. 3). Split cores were described by standard hand-specimen techniques and were further evaluated with petrographic study of 55 thin sections. X-ray diffraction and laser Raman microscopy were used to confirm mineralogy. Staining with alizarin red–S and potassium ferricyanide was used to test for calcite and dolomite (Dickson 1966). Selected samples were stained with bleach in order to identify any organic matter.

Although our study described here focuses on only one core of the Opeche Shale, our analyses of well logs from throughout the Williston Basin show abundant siliciclastics and bedded halite, with no evidence for carbonates or bedded gypsum/anhydrite in the Opeche Shale. Therefore, we suggest that the core we describe is representative of the Opeche Shale throughout the Williston Basin.

LITHOFACIES

Bedded Halite Lithofacies—Saline Lake and Saline Pan Environments

Bedded halite lithofacies are common in the Opeche Shale (Fig. 3). Individual beds of halite are typically 1 to 3 cm thick, but may reach thicknesses up to 8 cm. Halite beds are dominated by chevron and/or cumulate crystals (Fig. 4).

Chevron crystals are centimeter-scale, vertically oriented, elongate halite crystals with fluid-inclusion-rich growth bands (Shearman 1978; Wardlaw and Schwerdtner 1966). Most chevrons are 0.5 to 2 cm tall and 0.1 to 0.8 cm wide. One bed of halite,

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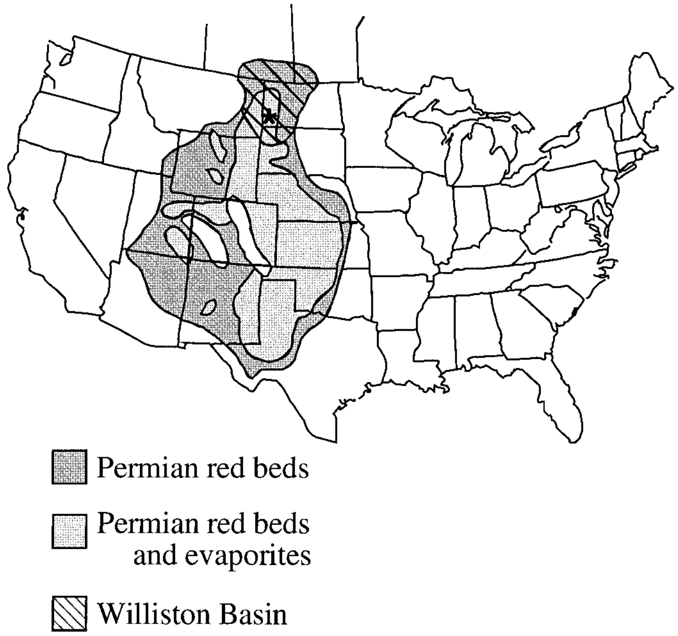


FIG. 1.—Map of the United States showing distribution of Permian red beds and evaporites, as well as approximate location of the Williston Basin. Star marks location of the core of Opeche Shale used in this study, the Gulf-Romanysyn 2–33–4B core from the subsurface of Billings County in southwestern North Dakota. Modified from Walker (1967) and Wilgus and Holser (1984).

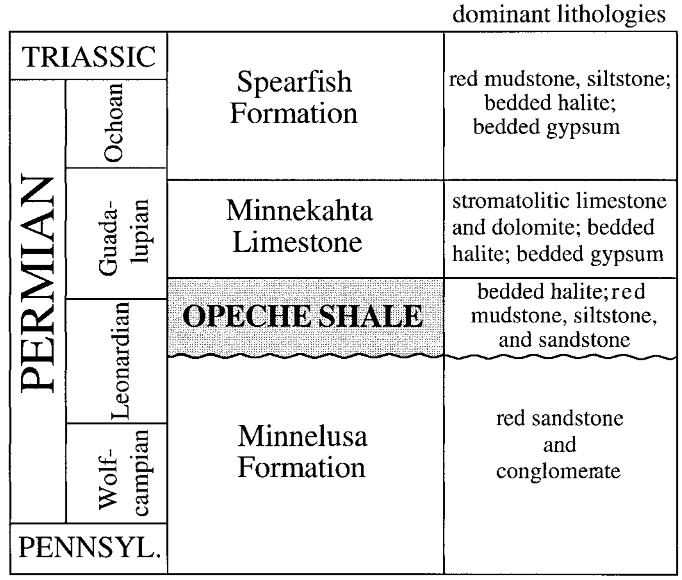


FIG. 2.—Stratigraphic setting and dominant lithologies of the Permian rocks of southwestern North Dakota; modified from Carlson (1993), Maughan (1966), and Sandberg (1973).

however, contains chevron crystals 4 cm tall (Fig. 4B). Most chevron halite crystals have a corner oriented upward. Rare chevron crystals have a crystal face oriented upward. These rare face-up chevrons observed in the Opeche Shale halite are found at the bottoms of halite beds alongside the more common corner-up chevrons, but tend to be edged out by corner-up chevron crystals because of competitive growth. Another feature of competitive growth is widening of chevron crystals upward. Growth bands in the chevrons are defined by alternating cloudy zones rich in primary fluid inclusion, and clear, inclusion-poor zones (Fig. 4B–C). The fluid-inclusion bands are oriented parallel to halite crystal faces. Chevron crystals indicate bottom growth of halite from a substrate upward into the saline water body (Arthurton 1973; Wardlaw and Schwerdtner 1966).

Cumulate crystals are millimeter-scale halite crystals with a random orientation (Fig. 4D). They have been observed in modern brines forming at the air–water interface as floating crystals, and then settling through the water column to accumulate at the bottom (Dellwig 1955). Cumulate crystals typically have cloudy, fluid-inclusion-rich cores and clear, inclusion-poor rims. Primary fluid inclusions may define growth zones, with bands of inclusions situated parallel to crystal faces. Some cumulates have cores that are rich in primary fluid inclusions throughout with no visible inclusion-poor bands (Fig. 4E). Some cumulate crystals are laterally joined together as floating ''rafts'' at the air–water interface before sinking (Arthurton 1973; Shearman 1970). Cumulate crystal corners are rounded in some beds. In many places, a cumulate is found at the base of a chevron or cornet crystal, and probably acted as a nucleus for chevron or cornet growth.

Most halite beds in the Opeche Shale contain chevron and cumulate crystals. Rare beds contain only chevron crystals or only cumulate crystals. Most primary halite contains tiny (tens to hundreds of microns long) anhydrite crystals trapped within the halite crystal or within fluid inclusions in the halite. Traces of red mudstone exist along some halite crystal boundaries and within some halite crystals. Some beds of halite are separated by 0.1–1 cm thick layers of mudcracked microcrystalline material composed of halite, anhydrite, and polyhalite ($K_2MgCa_2(SO_4)_4 \cdot 2H_2O$; Fig. 4B). Less common red mudstone partings, commonly containing tiny (millimeter-scale) anhydrite crystal clumps, separate halite beds. Rare, wavy, thick (1–2 cm) partings of randomly distributed anhydrite crystals separate some halite beds.

Approximately half of the halite beds in the Opeche Shale have dissolution features. Sharp, gently undulating horizontal surfaces (relief of $\approx$ 2–6 mm) that truncate the tops of chevron crystals are found at the tops of many halite beds. These sharp truncation surfaces are commonly overlain by partings of randomly distributed anhydrite crystals. Vertical, rounded dissolution pipes are abundant and commonly truncate fluid-inclusion growth bands in chevron crystals (Fig. 4B). All dissolution pipes are filled with clear, euhedral, inclusion-free halite cement. Some also are lined with a small amount of red mudstone or fringed with anhydrite cement crystals. Halite beds lacking dissolution features include those composed only of cumulates, as well as many beds containing both chevron and cumulate crystals.

Most of the bedded halite in the Opeche Shale is interpreted to have formed in shallow saline water. The presence of both chevron and cumulate crystals (including rafts) in the same bed is a good indication of shallow-water deposition (typically in depths of tens of centimeters; Lowenstein and Hardie 1985; Schreiber, personal communication). Deeper-water evaporite settings tend to be density- and salinity-stratified, producing either surface-growth cumulates or bottom-growth clear (without fluid inclusions) chevron crusts. Therefore, the presence of both chevron and cumulate crystals in the majority of halite beds strongly suggests shallow-water deposition. The rare beds in the Opeche Shale that contain only chevron crystals or cumulate crystals may have formed in a relatively deeper-water setting. Chevron beds probably formed in waters with depths less than approximately three meters. Halite beds composed of only cumulate crystals (with few fluid inclusions) probably formed in perennial, stratified, saline water bodies with depths more than approximately three meters (Schreiber, personal communication).

Associated horizontal truncation surfaces, vertical dissolution pipes, and some rounded halite cumulate crystals indicate dissolution of primary halite due to occasional flooding by lower-salinity water. Red mudstone partings and small amounts of red mudstone between cumulate crystals may have been deposited by flooding events, also. Mudcracked microcrystalline salt crusts and anhydrite and halite cements in dissolution pipes suggest evaporative concentration and desiccation. This evidence of flooding, evaporative concentration, and desiccation found in approximately half of the halite beds indicates that they were deposited in saline pans (Lowenstein and Hardie 1985).

The halite beds lacking dissolution or desiccation features were not greatly influenced by flooding and desiccation, and so were most likely deposited in perennial, yet short-lived, saline lakes. Beds composed of both chevron and cumulate crystals but lacking any dissolution or flooding features are interpreted to have formed in shallow saline lakes. The rare beds consisting only of cumulate crystals or chevron crystals may have formed in slightly deeper saline lakes.

The presence of anhydrite as crystals trapped within depositional halite and within primary fluid inclusions in halite suggest that saline lake waters were supersaturated with respect to both halite and anhydrite much of the time. Less common thin microcrystalline anhydrite partings and early anhydrite isopachous fibrous cement lining dissolution pipes in bedded halite indicates that, at times, the surface waters were supersaturated with respect to anhydrite but not halite. All anhydrite in the Opeche Shale shows optical characteristics of singe crystals and there is no evidence of any pseudomorphs, suggesting that these anhydrite crystals are primary; that is, they do not appear to be the altered remains of gypsum.

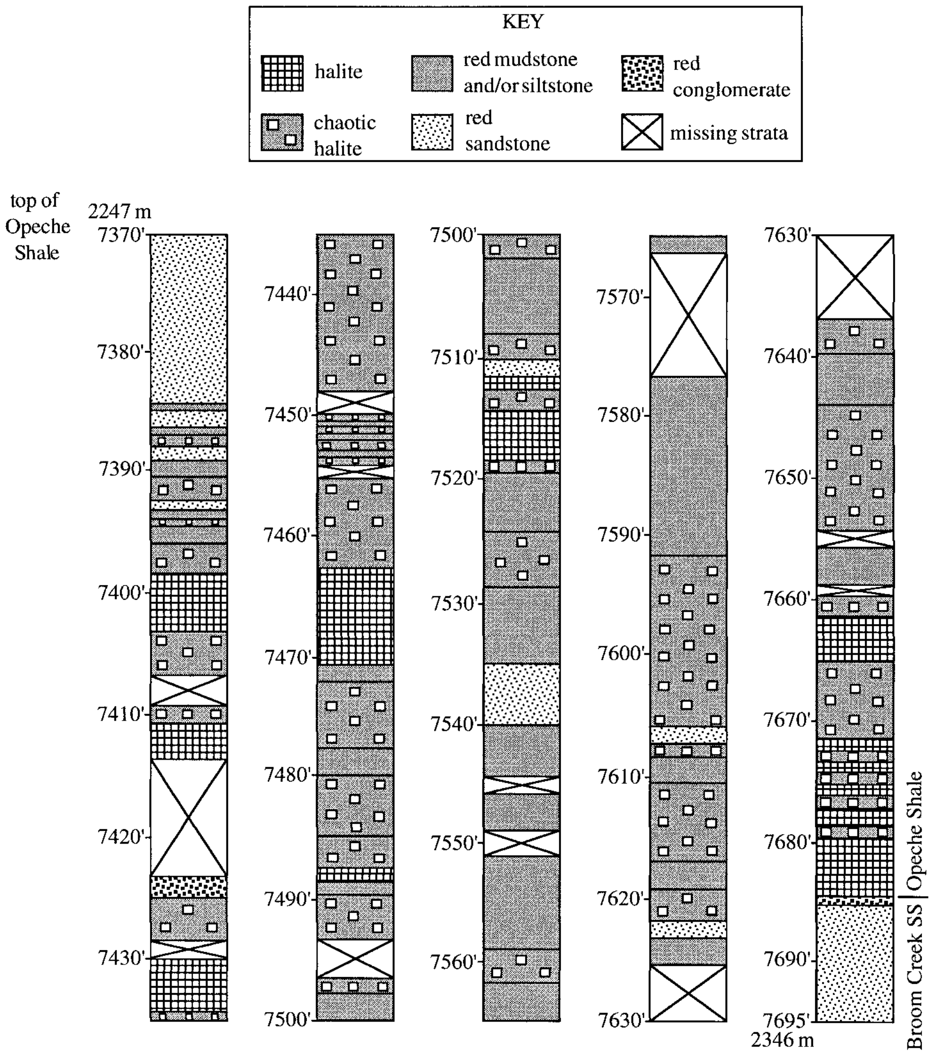


FIG. 3.—Lithological description of the Opeche Shale and underlying Broom Creek Sandstone Member of the Minnelusa Formation from the Gulf-Romanysyn 2–33–4B core, Billings County, North Dakota.

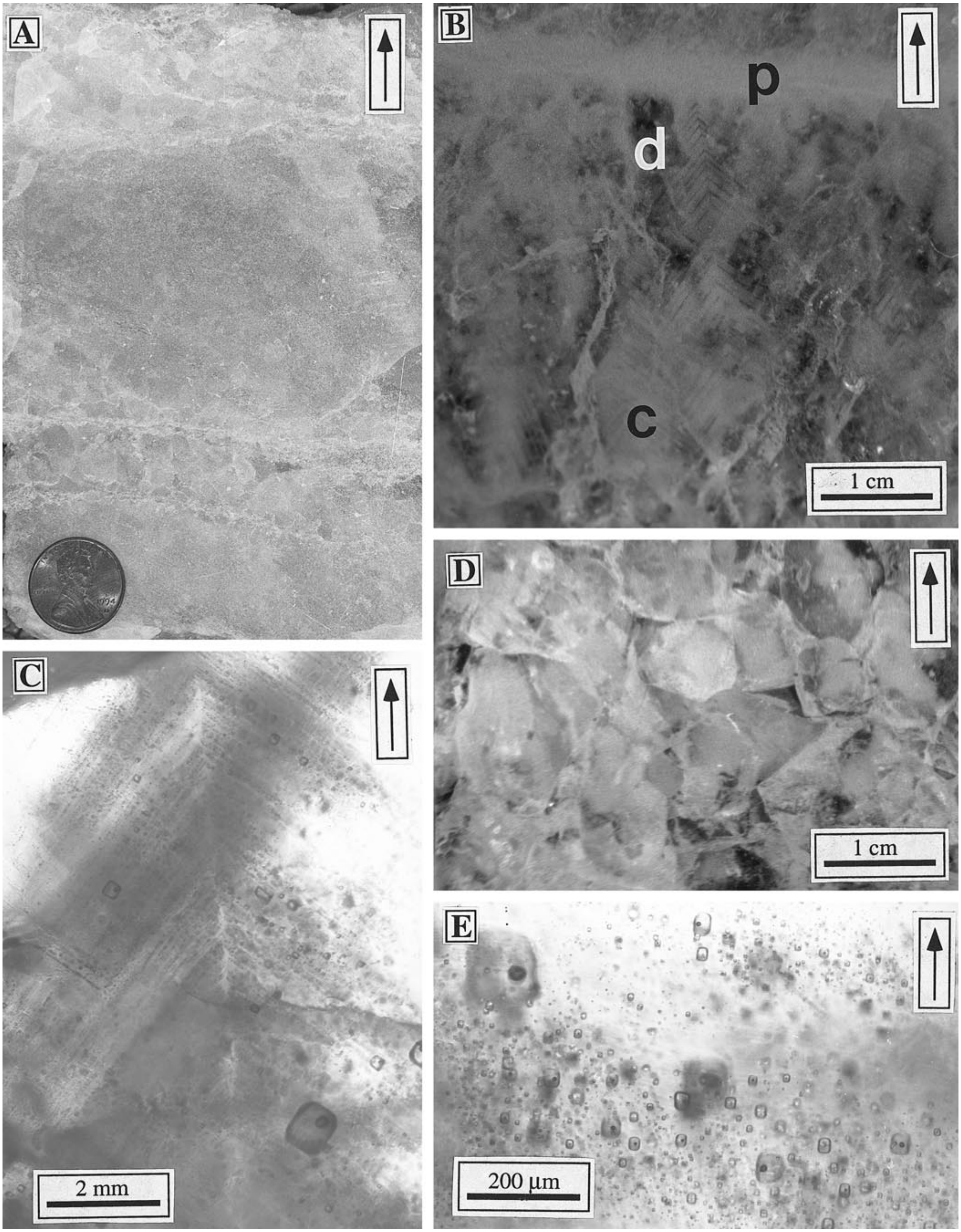
Chaotic Halite Lithofacies—Saline Mudflat Environment

The term ''chaotic halite'' (also called ''haselgebirge'' or ''muddy halite'') has come to describe any mudstone or siltstone that contains abundant displacive halite. In the Opeche Shale, chaotic halite consists of between approximately 30% and 95% halite crystals hosted in red mudstone and siltstone. This is the most abundant lithofacies in the Opeche Shale (Figs. 3, 5A–B).

The red mudstone and siltstone matrix is composed mainly of quartz and some feldspar grains with thin hematite coatings. There is rare stratification composed of alternating planar laminae of light red, coarse siltstone and darker red mudstone and fine siltstone. The bases of the light red laminae are sharp, but the contacts with the bases of the dark red laminae are gradational. Other sedimentary features include poorly developed circumgranular, vertical, and horizontal cracks filled with halite cement, and, less commonly, halite-cement-filled root molds and root casts, root glaebules, clay cutans, and mudcracks. There are some irregularly shaped (centimeter-scale) sand patches and isolated quartz sand grains ''floating'' in a finer matrix. Abundant, small (less than 1 mm), bacillar anhydrite crystals are randomly distributed throughout these red beds. Intergranular halite cement is present in the coarser-grained rocks. Round gray spots are seen in most red beds.

''Chaotic'' halite crystals in the red mudstone and siltstone are blocky, euhedral crystals that range in size from 0.1 to 5 cm (Fig. 5A–B). Within each chaotic halite unit, halite crystal size is relatively uniform. Typically these crystals appear as cubes, but less commonly they have a skeletal ''pagoda'' shape. This halite is interpreted as displacive because: (1) it is clear, without fluid-inclusion growth bands common in subaqueously precipitated halite crystals; (2) halite crystals truncate and disrupt depositional and very early diagenetic features in the host rock, such as laminae and gray reduction spots; (3) abundant grains of silt and sand, and clumps of mud, are included in halite crystals, especially along planes parallel to crystal faces; and (4) halite crystals have random size and distribution throughout thicknesses of each stratigraphic unit (Casas and Lowenstein 1989; Spencer and Lowenstein 1990).

Red-bed mud and silt may have been deposited by sheet floods and then altered syndepositionally by wetting and drying. Laminae that grade upward from siltstone to mudstone suggest deposition from a decelerating water body (Reading 1996). Cracks, clay cutans, and root features are evidence of wetting and drying of a sediment (Goldstein 1988; Klappa 1980; Retallack 1988, 1989). ''Floating'' quartz sand grains and patches of quartz sand in mud may be the remains of wind-blown grains that accumulated on efflorescent salt crusts. When floods dissolved the salt crusts, sand patches and isolated sand grains in massive muds and silts would have been left (Smoot and Castens-Seidell 1994). Mixing of the sand into finer sediment also may be the product of pedoturbation. Gray spots suggest localized reduction around decaying organic material in a previously oxidized setting (Blodgett et al. 1993; Daily and Angino 1990). Blocky displacive halite crystals, small displacive anhydrite crystals, and halite intergranular and crack- and root-mold-filling cements all testify to the presence of saline groundwater. Although there is no petrographic evidence for the timing of the displacive growth of halite and anhydrite except that it was before lithification, it probably formed syndepositionally, or at least very early in the diagenetic history of these rocks. This syndepositional (or very early) interpretation is supported by: (1) observations of displacive evaporite mineral growth just below the surface in modern saline mudflats (Casas 1987; Handford 1982; Lowenstein et al. 1989), and (2) a sharp porosity decrease downward, from 20–50% porosity in the upper meter to approximately 5% porosity at a depth of 10 m in modern and recent saline pans (Casas 1987; Casas and Lowenstein 1989). The observed features suggest that the chaotic halite lithofacies of the Opeche Shale formed in a saline mudflat environment. A saline mudflat is an area adjacent to a saline pan or saline lake characterized by low-relief, subaerially exposed muds and silts that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are deposited by sheetfloods, and are usually saturated with saline groundwater (Lowenstein and Hardie 1985; Smoot and Lowenstein 1991).

Red Mudstone/Siltstone Lithofacies—Dry Mudflat Environment

Red mudstone and siltstone (Fig. 5C–E) is similar to the chaotic halite lithofacies except that: (1) displacive halite is rare or absent, and (2) paleosol features such as cracks are more abundant and better developed. There is a gradation from chaotic halite to red mudstone/siltstone lithofacies, but, for the purpose of classification of lithofacies, we have defined the red mudstone/siltstone lithofacies as those with less than 30% halite observable in hand samples. These rocks are referred to as mudstone and siltstone instead of shale because they lack the fissility attributed to most shales. The great majority of grains are quartz, with some feldspar and rare opaque grains. Clay-size grains composed of hematite and illite act as both a coating and a matrix for the quartz grains. X-ray diffraction of the red mudstone/siltstone also confirm halite, suggesting the presence of halite cement.

There are some alternating thin, planar laminae of light red, coarse siltstone and darker red mudstone and fine siltstone. The bases of the light red laminae are sharp, but the contacts with the bases of the dark red laminae are gradational. There are shallow (less than 0.5 cm) mudcracks at the top of dark red mudstone and fine siltstone laminae (Fig. 5C). Some curled mudchip intraclasts commonly are found directly above these mudcracked laminae. Abundant cracks, including circumgranular (Fig. 5D), vertical, horizontal sheet, and craze plane cracks, as well as deep (up to 7 cm) prismatic cracks, are found throughout the red mudstones and siltstones. Root glaebules, root casts, root molds, and clay cutans are also common (Fig. 5E). There are rare thin lenses of white microcrystalline salt in the red mudstones and siltstones. These rocks are typically poorly sorted. There are some ''floating'' well-rounded, very spherical, quartz and anhydrite sand grains. Some irregularly shaped, centimeter-scale patches of halite-cemented sand grains in the mudstone and siltstone matrix give some of these rocks a mottled appearance. Round gray spots (ranging from <1 mm to 2 cm in diameter) preserve laminae of the red mudstone/siltstone. Halite cement is found filling cracks and root molds. Rare, small (centimeter-scale) anhydrite and halite crystals are randomly distributed in the red mudstones and siltstones. Typically halite cement and rare anhydrite and halite crystals crosscut or truncate the gray spots.

Two thin units (less than 30 cm thick) of red ''breccia'' are associated with the red mudstones and siltstones. These breccias are composed of angular clasts of red siltstone in a matrix of clear, coarse halite cement. The siltstone clasts are of pebble size (1–2 cm) and contain abundant cracks filled with halite cement. The clasts, although separated by coarse halite cement, appear to fit together, suggesting an *in situ*, autoclastic origin and not a transported origin. Solution collapse was considered as a possible origin for these breccias but was dismissed because the clasts appear to fit too tightly together to have formed by even minor collapse. Therefore, these are interpreted as autoclastic breccias that formed by wetting and drying of a previously lithified red siltstone. The siltstone was extensively cracked during desiccation and then the resulting clasts were cemented by halite during a water-table rise.

Red-bed mud and silt may have been deposited mainly by sheet floods and then altered syndepositionally by some wetting and drying. Paleosol features such as circumgranular cracks, autoclastic breccia, clay cutans, and root features are consistent with wetting and drying of a sediment (Goldstein 1988; Klappa 1980; Retallack 1988, 1989). Fragments of microcrystalline salt crusts may be the partially or completely dissolved remains of efflorescent salt crusts. ''Floating'' quartz sand grains and patches of quartz sand may be sand that was originally deposited onto efflorescent salt crusts. When floods dissolve salt crusts on modern mudflats, sand patches and isolated sand grains resulting from windblown sand accumulated on buckled surfaces of efflorescent massive muds and silts are left (Smoot and Castens-Seidell 1994). Gray reduction spots suggest localized reduction around organic material in an otherwise oxidized setting (Blodgett et al. 1993; Daily and Angino 1990). Halite intergranular and crack- and root-mold-filling cements indicate saline groundwater. However, only rare displacive anhydrite and halite crystals suggest that these sediments were more often dry than those of the chaotic halite setting. Deep, abundant mudcracks are evidence for a relatively low water table in this environment. The red mudstone and siltstone lithofacies of the Opeche Shale is interpreted to represent a dry-mudflat depositional environment. A dry mudflat is an environment characterized by low relief with subaerially exposed muds and silts that are not usually inundated with saline groundwater (Lowenstein and Hardie 1985; Smoot and Lowenstein 1991).

Red Sandstone and Red Conglomerate Lithofacies—Distal Alluvial Environments

Red-bed sandstones are uncommon in the Opeche Shale (Fig. 3). These sandstones are composed of poorly sorted coarse-silt-size to medium-sand-size grains. The majority of the grains are quartz, but there are also some feldspar grains and rare opaque grains. These subrounded to subangular, spherical to subspherical grains have a thin coating of hematite. Bedding observed consists of planar and slightly wavy thin and thick laminae, rare convolute laminae, and some climbing ripple cross-laminae. Small-scale (<1 cm), depositional-stoss climbing ripple cross-laminae have drapes of finer-grained sediment (Fig. 5F; see Lindholm 1987). Some well-rounded, very spherical, medium to coarse sand-size quartz grains are found ''floating'' in the finer-grained matrix. There are some small mudcracks, vertical cracks, and circumgranular cracks in these fine-grained sandstones (Fig. 5F). Early diagenetic features include halite intergranular and crack-filling cements, rare anhydrite crystals, and rare, small (0.1–1 cm) halite crystals.

The red sandstones in the Opeche Shale were probably deposited in a distal alluvial–fluvial environment. The sand may have been transported by sheet floods, ephemeral streams, and mudflows in an environment that frequently underwent desiccation. Depositional-stoss climbing ripple cross-strata with finer-grained drapes indicate high rates of deposition in decelerating flows such as the waning stages of floods (Allen 1985; Ashley et al. 1982; Lindholm 1987). The rare convolute laminae may have been produced as water escaped during gravitational collapse of ripples during liquefaction or some other kind of fluid escape (Leeder 1982). The poor sorting of grains, the subrounded to subangular, spherical to subspherical grain shapes, and internal lamination within climbing ripple cross-strata argue against eolian processes as the primary depositional origin of the sandstones (Glennie 1970; Lindholm 1987). Nevertheless, some of the sedimentary features in these sandstones indicate subaerial exposure and eolian action as well as subaqueous deposition. The ''floating'' well-rounded, very spherical quartz sand grains may have been windblown or emplaced by pedoturbation. Small mudcracks, vertical cracks, and circumgranular cracks strongly suggest wetting and drying of this sediment (Goldstein 1988; Klappa 1980). Early diagenetic features such as halite intergranular and crack-filling cements, and rare displacive anhydrite and halite crystals, indicate that this sandy sediment was, at some time, inundated with saline groundwater. Displacive evaporite crystals have been observed in sandy ephemeral streams and sheetflood deposits in arid climates (Mertz and Hubert 1990). Miall's (1996) description of deposits formed in ''flashy, ephemeral, sheetflood sand-bed rivers'' includes absent or very poorly defined channels, lamination, and climbing ripples. Although one core may not provide enough data to make a strong case for depositional environment, such as geometry of the deposits (Pettijohn et al. 1972), we speculate that the red sandstones were deposited in a distal alluvial–fluvial setting.

One bed of red conglomerate 60 cm thick is observed in the Opeche Shale, overlying chaotic halite (Fig. 3). The conglomerate consists of granule-size (2–4 mm) and pebble-size (4–10 mm) clasts of white quartz sandstone supported in a red mudstone and siltstone matrix. The sandstone clasts are rounded to angular and subspherical. This conglomerate is massive. Halite crystals and clumps of radiating anhydrite crystals are found in the mudstone and siltstone matrix.

The rare red conglomerate of the Opeche Shale also may have been formed as a distal alluvial deposit. The granule- and pebble-size clasts of white sandstone were probably reworked and transported. Their rounded to angular and subspherical shape, as well as their white color (in contrast to the red color of the rest of the Opeche Shale siliciclastics) indicates that some of the clasts may have been transported some distance. The poor sorting, matrix support, and lack of bedding in this conglomerate bed may indicate rapid deposition (Lindholm 1987), possibly by a debris flow (Allen 1985; Miall 1996). Displacive halite and anhydrite crystals in the matrix mudstone and siltstone suggest inundation by saline groundwaters after deposition. As with the red sandstones, the geometry of this conglomerate cannot be interpreted from a single core. Nonetheless, we favor an alluvial depositional envi-

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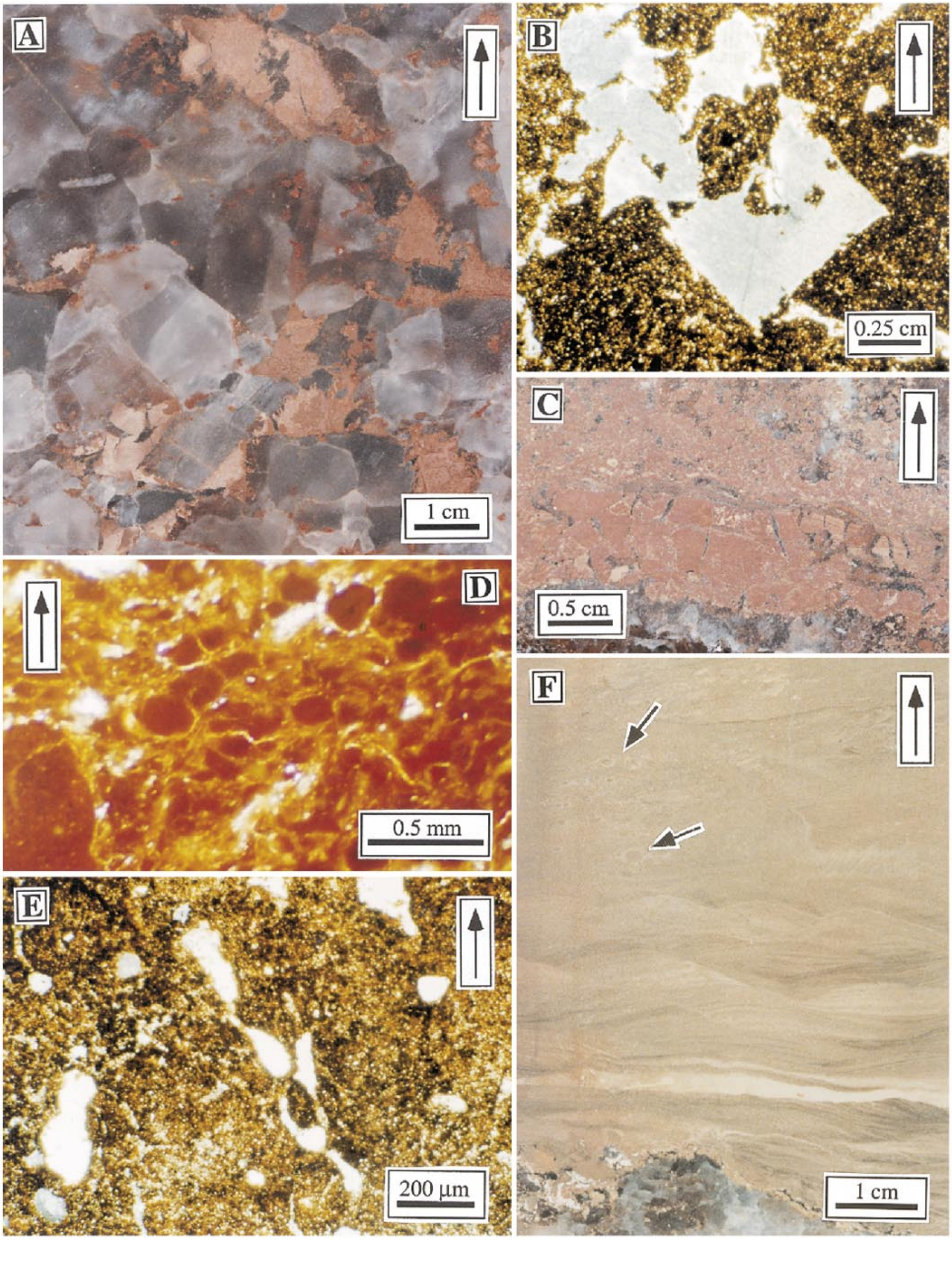
FIG. 4.—Bedded halite of the Opeche Shale. Boxed arrows indicate stratigraphic up. **A)** Photograph of slabbed core sample of bedded halite; coin for scale is 1.9 cm. **B)** Photograph of thin section (placed on black background and photographed with overhead illumination) showing vertically oriented chevron crystals (c) truncated by halite-filled vertical dissolution pipes (d) and white parting (p) composed of microcrystalline halite, anhydrite, and polyhalite. **C)** Photomicrograph of chevron halite crystal; note alternating cloudy, fluid-inclusion-rich bands and clear, inclusion-poor bands. **D)** Photograph of thick section (placed on black background and photographed with overhead illumination) showing cumulate halite crystals; milky white patches are inclusion-rich cumulate crystal cores. **E)** Photomicrograph of primary fluid inclusions in cumulate halite crystal.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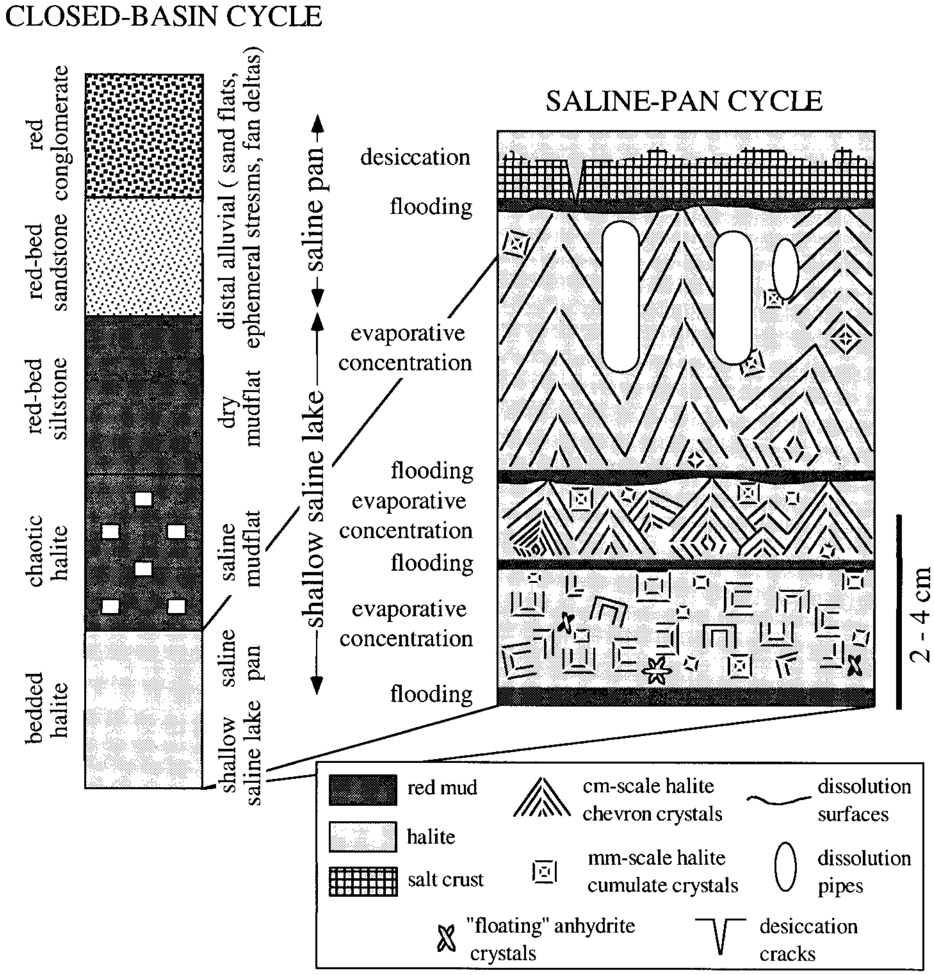

FIG. 6.—Schematic illustration of preferred lithofacies transitions, or idealized closed-basin cycle (shown on the left), and saline-pan cycle (shown on the right), found in the Opeche Shale.

ronment on the basis of poor sorting, massive bedding, and displacive evaporite minerals.

LITHOFACIES TRANSITIONS

Deciphering depositional cycles in ancient saline-pan sequences can be challenging (Kendall 1988; Lowenstein 1988). During deposition of the alternating siliciclastic and bedded halites of the Opeche Shale, this area underwent changes in detrital input, water-table levels, and water salinity. Dissolution and desiccation are common in shallow-water evaporite environments, especially saline pans (Lowenstein and Hardie 1985). Bedded halite can easily be dissolved on the surface. Eolian sands, once deposited, can just as easily be blown away. Therefore, a continuous, uninterrupted record of deposition is typically not preserved.

The Opeche Shale does not have true repeated stratigraphic patterns typically described as cycles (Fig. 3), but there are preferred lithofacies transitions. These preferred lithofacies transitions, or ''idealized cycles'' in the Opeche Shale are vertical successions, from base to top, of: (1) bedded halite, (2) chaotic halite, (3) red mudstones and siltstones, and (4) red sandstones and conglomerates (Fig. 6).

These Opeche ''cycles'' do not follow a regular 1-2-3-4-1-2-3-4 pattern. In some cases, they alternate from one lithofacies to the next and back again in a pattern more like 1-2-1-2-3-2-3-4-3-4. For example, the top of a cycle, a red sandstone or conglomerate, is not commonly overlain by the idealized cycle base of bedded halite. Red sandstones are more typically overlain by red mudstones and siltstones, and then chaotic halite. The best cyclic patterns in the Opeche Shale are at a smaller scale, confined to individual halite units (Fig. 6). These cycles of bedded halite formed by flooding, evaporative concentration, and desiccation events in a saline pan setting (Fig. 7).

Many sedimentary cycles, especially in shallow-water carbonates, represent relative rise or fall of sea level over time. It is more likely that the ''closed basin'' cycles of the Opeche Shale were influenced by a combination of relative rise and fall of water-table level and changes in evaporation, eolian processes, and inflow processes due to seasonal and slight climatic changes (Lowenstein and Hardie 1985; Schubel and Lowenstein 1997).

SUMMARY OF DEPOSITIONAL HISTORY OF THE OPECHE SHALE

The assemblage of sedimentary features observed in core samples indicates that the Opeche rocks were deposited under shallow saline waters, some dilute inflow waters, and subaerial exposure. Sedimentary and early diagenetic features, along with lithologic types, suggest that most deposition took place in halite-dominated, shallow, short-lived perennial and ephemeral saline lakes surrounded by saline and dry mudflats, and distal alluvial-fluvial deposits. Evaporation, desiccation, flooding, and wind played significant roles in the depositional environment. The Opeche red

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FIG. 5.—Red beds of the Opeche Shale. Boxed arrows indicate stratigraphic up. **A)** Photograph of slabbed core sample of ''chaotic halite''; note blocky displacive halite crystals in red mudstone matrix. **B)** Photomicrograph of displacive halite crystals that grew from saline groundwaters in red sediment. **C)** Photograph of slabbed core sample of red siltstone with faint laminae and small mudcracks. **D)** Photomicrograph of circumgranular cracks in red-bed siltstone. **E)** Photomicrograph of halite-filled root molds in red-bed siltstone. **F)** Photograph of slabbed core sample showing red fine sandstone with climbing ripple cross-laminae and circumgranular cracks (arrows).

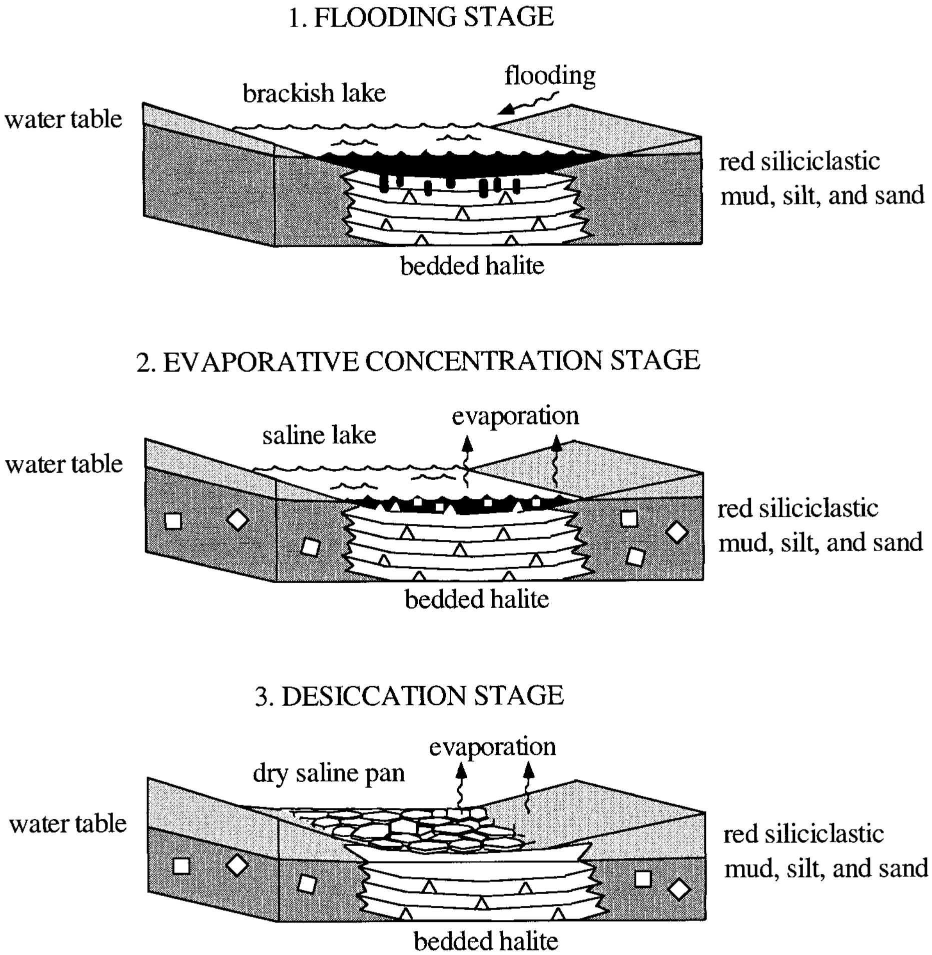

FIG. 7.—Schematic models of saline-pan deposition for the Opeche Shale. Flooding (1), evaporative concentration (2), and desiccation stages (3) are part of the saline-pan cycle. The products of flooding are dissolution surfaces and dissolution pipes in bedded halite and deposition of red mud and silt. During the evaporative concentration stage, there was precipitation of halite in a saline lake and displacive growth of halite and anhydrite in red sediment. The products of the desiccation stage are desiccation cracks in halite and red sediment, microcrystalline salt crust, intergranular and pipe-filling halite cement, and displacive halite and anhydrite crystals. Modified from Lowenstein and Hardie (1985).

beds and evaporites represent a saline-lake and saline-pan system (Lowenstein and Hardie 1985).

A CASE AGAINST MARINE DEPOSITION OF THE OPECHE SHALE

There are two types of saline lake/saline pan systems: inland playas and coastal salinas (Fig. 8). A playa system consists of inland saline lakes/pans surrounded on all sides by saline mudflats, dry mudflats, and sand flats. Alternatively, a salina system is composed of coastal saline lakes/pans or restricted lagoons, bounded on the seaward side by saline mudflats, tidal flats, sand ridges, and possibly reefs, and on the landward side by saline and dry mudflats, sand flats, and sand dunes. Playas are truly nonmarine because they are influenced only by nonmarine waters. Salinas typically have input from both marine and nonmarine waters, so they can be considered marginal marine deposits.

It is difficult to differentiate between these two possible saline lake/pan depositional settings in ancient rocks (Hardie 1984; Lowenstein and Hardie 1985). Both environments are characterized by: (1) cumulate and bottom-growth halites, (2) clear halite cements, and (3) displacive halite growth in the sediment (Figs. 7, 8). Many of the same sedimentary and diagenetic features are observed in both modern playas and salinas. There are some slight differences (Fig. 8). Coastal salinas tend to contain abundant bedded anhydrite/gypsum (Castens-Siedell and Hardie 1983; Schreiber 1988) and carbonate mud (typically magnesite and dolomite; Casas 1987; Handford 1990), even in siliciclastic-dominated shoreline settings (Handford 1988; Schreiber 1986). Besides carbonates, marine or marginal marine evaporite settings commonly, but not always, include microbial mats and stromatolitic laminites (Handford 1990; Hardie and Eugster 1971), flat-pebble conglomerates (Hardie and Eugster 1971), a small assemblage of organisms tolerant of brackish water such as gastropods, some foraminifera, and brine shrimp (Handford 1990; Hardie 1984), and halite ooids and pisoids (Handford 1990, Weiler et al. 1974).

Some modern inland playas have characteristics similar to modern marine and marginal-marine salinas (see Hardie, 1984 for discussion and examples). However, some modern inland playas are significantly different than salinas, especially in terms of general composition, fossil types, and minor evaporite minerals. For example, some modern inland playas may have abundant siliciclastics and little, if any, carbonate minerals (Brown 1995; Casas 1987; Handford 1982; Lowenstein et al. 1989; Roberts et al. 1994; Schubel and Lowenstein 1997). Fewer and less diverse organisms have been reported in playas than in salinas; they include ostracodes, lungfish, and palynomorphs. Evaporite minerals characteristic of nonmarine waters are found in some playa deposits.

Hardie (1984) gave criteria for making distinctions between marine and nonmarine evaporites. These criteria are: (1) kinds of fossils, (2) sedimentology of the associated nonsaline facies, (3) kinds of and association of primary evaporite minerals, and (4) trace-element, isotope, and fluid-inclusion geochemistry of primary evaporite minerals.

Many of the sedimentary features seen in the Opeche Shale are characteristic of both inland-playa and coastal-salina saline pan systems. However, field and petrographic evidence is more indicative of an inland continental playa deposit because of: (1) abundance of halite and absence of bedded anhydrite/gypsum, (2) abundance of well-developed paleosol features in associated red beds, as well as (3) lack of carbonate muds characteristic of modern salina settings and (4) lack of restricted marine fossils found in many modern salinas. The assemblage of sedimentary features in the Opeche Shale argues for perennial saline lakes, saline pans, saline mudflats, and dry mudflats.

Early diagenetic features also support an inland-playa depositional setting over a marginal-marine salina. Cements were more likely precipitated by nonmarine waters than by seawater. Material filling dissolution pipes is composed mostly of halite cement with some anhydrite cement and some red siliciclastic mudstone. No calcite, aragonite, or gypsum cements or magnesite or dolomite mud is found, as might be expected after flooding and evaporation of seawater. No marine carbonate cements have been found. In addition, there is no evidence to support the dissolution of former carbonates. Displacively grown halite and anhydrite crystals and halite cement suggest hypersaline groundwaters typical of modern saline mudflats in closed basins (Casas 1987; Casas and Lowenstein 1989).

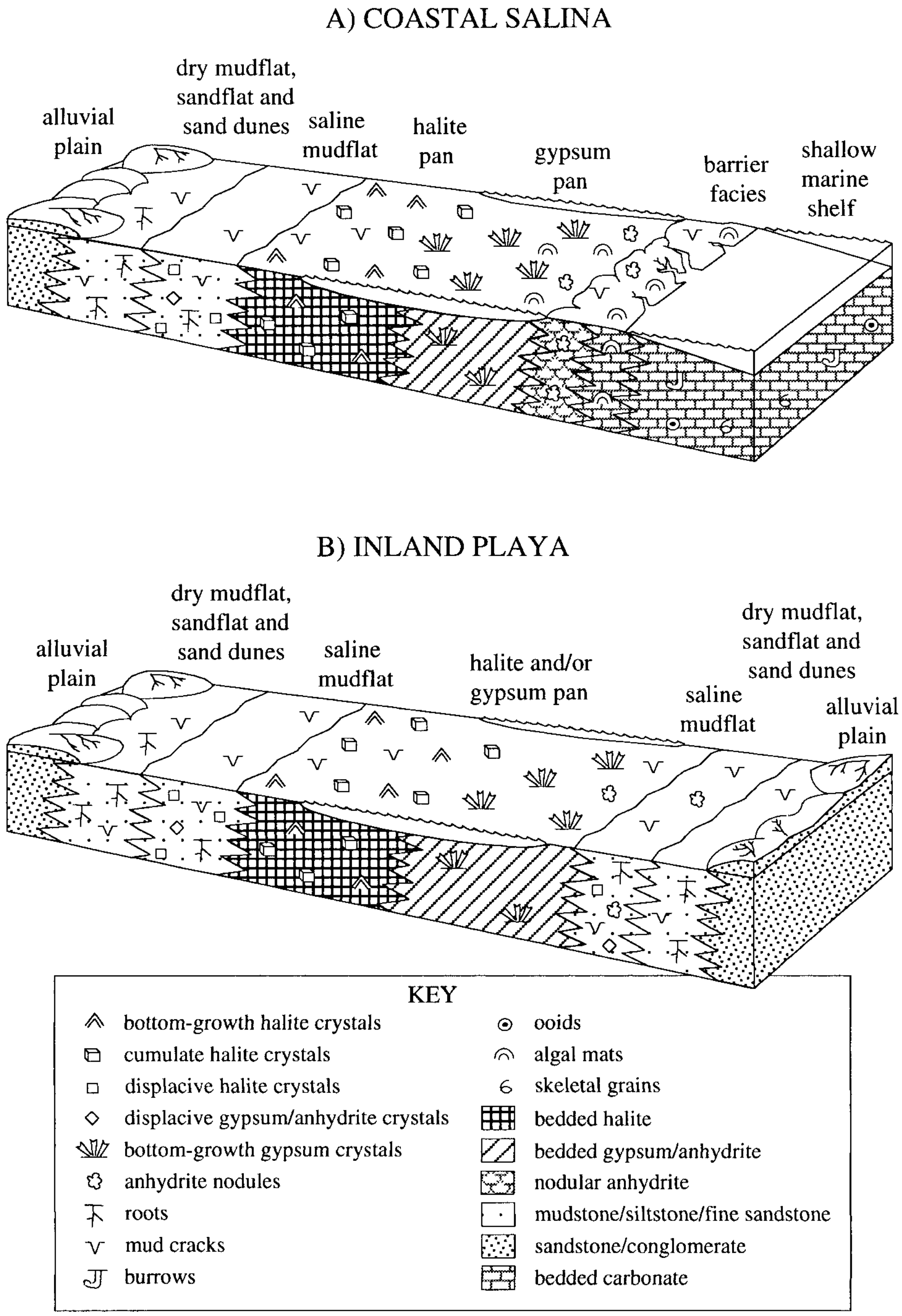

FIG. 8.—Schematic block diagrams of the two types of saline pan environments: **A)** the coastal-salina setting and **B)** the inland-playa setting. These diagrams show generalized subenvironments and their respective lithofacies and key sedimentary and early diagenetic features. This study indicates that the Permian Opeche Shale was deposited in a playa-type saline pan.

Identification of any accessory primary minerals and geochemical analyses of primary evaporite minerals may give valuable information on parent-water geochemistry. Unfortunately for geologists evaluating marine versus nonmarine deposition, some nonmarine waters match seawater and evaporated seawaters in composition. The Opeche Shale contains trace amounts of polyhalite along with halite and anhydrite in salt crusts. However, the salt crusts are microcrystalline, so it is difficult to determine whether the polyhalite is primary or secondary. Regardless, polyhalite is an accessory mineral that forms in both marine evaporite and some nonmarine evaporite settings (Hardie 1984).

Modern settings that may be good analogs for the Permian depositional environment of the Nippewalla Group include Bristol Dry Lake (Handford 1982), Saline Valley (Casas 1987), and Death Valley (Brown 1995; Roberts et al. 1994), all in California, and Qaidam Basin, western China (Casas et al. 1992; Lowenstein et al. 1989; Schubel and Lowenstein 1997). These are all halite-dominated saline pans hosted by siliciclastic sediments. All are situated inland in closed basins and are underlain by up to several hundred meters of bedded salt.

The interpretation of an inland saline-pan depositional setting for the Opeche Shale agrees with Wilgus and Holser's (1984) conclusions. From bromide analysis of the same core, they claimed that these rocks were deposited in a continental, closed basin. Low bromide values ranging from 2 ppm to 70 ppm (average value of 13 samples was 28 ppm) from halite samples suggest either nonmarine precipitating waters or recrystallized halite (Hardie 1984). Because seawater has greater bromide concentrations than do nonmarine waters, marine halites incorporate more bromide and typically have bromide values of 70 ppm to 300 ppm (Holser 1966). Although sampling for bromide analyses was by whole rock and some of the displacive halite may be recrystallized, much of the bedded cumulate and bottom-growth halite documented in this study is well preserved, so the low values for bromide may indeed reflect deposition by nonmarine waters.

Benison et al. (1998) have shown that the primary fluid inclusions in halite from this core have extremely low pH values in the range of 0 to 1. pH values were determined by laser Raman microprobe analyses of fluid inclusions in the Opeche Shale bedded and displacive halite and of standard solutions. Detection of bisulfate (HSO_4^-) in all fluid inclusions analyzed in the Opeche Shale suggests extremely high acidity. Raman spectra for bisulfate could be produced only in standard solutions with pH values less than 1. These analyses appear to represent the original pH of the surface waters and groundwaters responsible for precipitation of the halite. Such low pHs are inconsistent with a marine origin for the fluids. Some nonmarine saline lake and groundwater systems of Australia are good modern analogs for such an acid evaporite setting (Long and Lyons 1990; McArthur et al. 1991). These modern Australian acid systems are characterized by: (1) acid (pH = 2–4), saline lakes and groundwaters hosted by red siliciclastics; (2) precipitation of evaporites (including halite, anhydrite, alunite, and jarosite); and (3) lack of any carbonates.

This core and petrographic study has documented sedimentary and diagenetic features that support a nonmarine, continental-playa depositional model for the Opeche Shale.

CLIMATE DURING OPECHE TIME

Clearly, the presence of evaporites indicates an arid climate in which evaporation was greater than precipitation. The Opeche Shale gives no unequivocal evidence of long-term climate trends, because all lithofacies throughout the core are indicative of the same generally arid conditions. In the Opeche Shale, there are at least 96 meters of saline pan/saline lake bedded evaporites and red beds, recording a relatively long-lived arid climate in the mid Permian of present-day North Dakota (paleolatitude of approximately 7° N; Maughan 1966, 1967; Mudge 1967). By comparison, the Qarhan Salt Plain of the Qaidam Basin, western China, which began evaporite deposition 50,000 years ago, is underlain by 70 meters of interbedded halites and siliciclastics (Schubel and Lowenstein 1997). The 185 meters of bedded evaporites and siliciclastics from Death Valley represent 200,000 years of perennial saline-lake and saline-pan deposition (Ku et al. 1994; Li et al. 1996). Therefore, it can be suggested that the 96 meters of Opeche Shale may represent an arid climate relatively stable on the order of 10^5–10^6 years.

The chemistry of the surface and groundwater brines that deposited and syndepositionally altered the Opeche Shale may have been unusual. The absence of carbonate minerals as muds, cements, displacive crystals, or calcretes is unusual, even for many nonmarine playas. Minor anhydrite as partings and crystals in halite beds, and absence of bedded gypsum and/or anhydrite (or their pseudomorphs), also hint at an unusual brine composition. The anhydrite cements that fringe dissolution pipes in bedded halites suggest that the dilute water promoting dissolution was not just rain water, which one would expect to dissolve the halite and, upon precipitation, fill the pipes with only halite cement. Inflow waters may have had an unusual composition.

GEOGRAPHY DURING OPECHE TIME

The presence of bedded halite in the Opeche Shale has been used as evidence that there were transgressions of the Phosphoria Sea from the west and the Permian basin seas from the south and southwest, which inundated much of the U.S. midcontinent with shallow seawater (Maughan 1966, 1967; Frazier and Schwimmer 1987). Our interpretation of the Opeche Shale as inland playa-type saline-pan deposits suggests an alternative view: that southwestern North Dakota was continental during the mid Permian. Published research on other mid Permian rocks suggests that the nearest marine and marginal marine deposits were far to the south, in Texas and New Mexico (Hovorka 1987; Lowenstein 1988; Presley 1987), and far to the west and southwest, in Utah, northwestern Colorado, and western Wyoming (Maughan 1967; Mudge 1967; Frazier and Schwimmer 1987). We propose that our studies of the Opeche Shale indicate that the northern U.S. midcontinent remained an inland continental area during the mid Permian.

CONCLUSIONS

Detailed core and petrographic observations of the Permian Opeche Shale of North Dakota have yielded sedimentological criteria in support of a saline-pan depositional system. Bedded halites, chaotic halites, and red-bed mudstones, siltstones, sandstones, and conglomerates were deposited in perennial saline lakes, saline pans, saline mudflats, dry mudflats, and distal alluvial deposits.

Most deposition took place in halite-dominated shallow perennial and ephemeral saline lakes surrounded by saline and dry mudflats. These rocks are characterized by cumulate and bottom-growth (chevron) halite crystals, pipe-filling clear halite cements, and displacive halite crystals. Evaporation, desiccation, flooding, and wind played significant roles in this environment. Therefore, the red beds and evaporites of the Opeche Shale are ancient saline-pan deposits.

Two types of saline pans were possible settings for these Permian red-bed-hosted evaporites: (1) a coastal salina or (2) an inland playa. An inland-playa type of saline pan system is the favored depositional model for the Opeche Shale because of its lack of nearshore carbonates and lack of restricted marine fossils. The assemblage of sedimentary features in the Opeche Shale indicates lacustrine and distal alluvial deposition and subaerial exposure, but there is no evidence for marine shoreline features. This sedimentological evidence indicates that, during the mid Permian, the southwestern corner of present-day North Dakota was covered by continental saline pans for at least 10^5–10^6 years.

The complete understanding of an evaporite depositional setting requires the study of its sedimentology, geochemistry, and hydrology. This paper illustrates that sedimentology can be used to distinguish marine, marginal-marine, and nonmarine saline-pan depositional environments.

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REFERENCES

Allen, J.R.L., 1985, Principles of Physical Sedimentology: London, George Allen & Unwin, 272 p.

Ashley, G.M., Southard, J.B., and Boothroyd, J.C., 1982, Deposition of climbing-ripple beds: A flume simulation: Sedimentology, v. 29, p. 67–79.

Arthurton, R.S., 1973, Experimentally produced halite compared with Triassic layered halite-rock from Cheshire, England: Sedimentology, v. 20, p. 145–160.

Benison, K.C., 1995, Permian surface water temperatures from Nippewalla Group halite, Kansas: Carbonates and Evaporites, v. 10, p. 245–251.

Benison, K.C., 1997, Acid water deposition and diagenesis in Permian red-bed hosted evaporites, midcontinent, U.S.A. [unpublished Ph.D. thesis]: University of Kansas, 420 p.

Benison, K.C., and Goldstein, R.H., 1999, Permian paleoclimate data from fluid inclusions in halite: Chemical Geology, v. 154, p. 113–132.

Benison, K.C., Goldstein, R.H., Wopenka, B., Burruss, R.C., and Pasteris, J.D., 1998, Extremely acid Permian lakes and groundwaters in North America: Nature, v. 392, p. 911–914.

Blodgett, R.H., Crabaugh, J.P., and McBride, E.F., 1993, The color of red beds: a geological perspective, *in* Bigham, J.M., and Ciolkosz, E.J., eds., Soil Color: Soil Society of America, Special Publication 31, p. 127–159.

Brown, C.B., 1995, Sedimentology, fluid inclusion geochemistry and paleoclimatic implications from a salt core of Badwater Basin, Death Valley, California [unpublished Master's thesis]: State University of New York at Binghamton, 192 p.

Carlson, C.G., 1993, Permian to Jurassic redbeds of the Williston Basin: North Dakota Geological Survey, Miscellaneous Series 78, 21 p.

Casas, E., 1987, Diagenesis of salt pan halite [unpublished Master's thesis]: State University of New York at Binghamton, 82 p.

Casas, E., and Lowenstein, T.K., 1989, Diagenesis of saline pan halite: Comparison of petrographic features of Modern, Quaternary, and Permian halites: Journal of Sedimentary Petrology, v. 59, p. 724–739.

Casas, E., Lowenstein, T.K., Spencer, R.J., and Pengxi, Z., 1992, Carnallite mineralization in the nonmarine, Qaidam Basin, China: Evidence for the early diagenetic origin of potash evaporites: Journal of Sedimentary Petrology, v. 62, p. 881–898.

Castens-Siedell, B., and Hardie, L.A., 1983, Gypsum–anhydrite deposition in sabkhas: New observations from the Holocene tidal flats of the N.W. Gulf of California, Baja California (abstract): Geological Society of America, Abstracts with Program, v. 15, p. 540.

Daily, M.E., and Angino, E.E., 1990, Origin of green concretions in the redbeds of the Ninnescah Shale, Lower Permian of Kansas: The Compass, v. 67, p. 180–190.

Dellwig, L.F., 1955, Origin of the Salina Salt of Michigan: Journal of Sedimentary Petrology, v. 25, p. 83–110.

Dickson, J.A.D., 1966, Carbonate identification and genesis as revealed by staining: Journal of Sedimentary Petrology, v. 36, p. 491–505.

FRAZIER, W.J., AND SCHWIMMER, D.R., 1987, Regional Stratigraphy of North America: New York, Plenum Press, 719 p.
GLENNIE, K.W., 1970, Desert Sedimentary Environments: Amsterdam, Elsevier, Developments in Sedimentology 14, 222 p.
GOLDSTEIN, R.H., 1988, Paleosols of Late Pennsylvanian cyclic strata, New Mexico: Sedimentology, v. 35, p. 777–803.
HANDFORD, C.R., 1982, Sedimentology and evaporite genesis in a Holocene continental-sabkha playa basin—Bristol Dry Lake, California: Sedimentology, v. 29, p. 239–253.
HANDFORD, C.R., 1988, Depositional interaction of siliciclastics and evaporites, *in* Schreiber, B.C., ed., Evaporites and Hydrocarbons: New York, Columbia University Press, p. 139–181.
HANDFORD, C.R., 1990, Halite depositional facies in a solar salt pond: a key to interpreting physical energy and water depth in ancient deposits?: Geology, v. 18, p. 691–694.
HARDIE, L.A., 1984, Evaporites: Marine or non-marine?: American Journal of Science, v. 284, p. 193–240.
HARDIE, L.A., AND EUGSTER, H.P, 1970, The evolution of closed-basin brines:, *in* Fiftieth Anniversary Symposia: Mineralogy and Petrology of the Upper Mantle, Sulfides, Mineralogy and Geochemistry of Non-Marine Evaporites: Mineralogical Society of America, Special Paper 3, p. 273–290.
HARDIE, L.A., AND EUGSTER, H.P., 1971, The depositional environment of marine evaporites: A case for shallow, clastic accumulation: Sedimentology, v. 16, p. 187–220.
HOLSER, W.T., 1966, Bromide geochemistry of salt rocks, *in* Rau, J.L., ed., 2nd Symposium on Salt: Northern Ohio Geological Society, p. 248–275.
HOVORKA, S., 1987, Depositional environments of marine-dominated bedded halite, Permian San Andres Formation, Texas: Sedimentology, v. 34, p. 1029–1054.
KENDALL, A.C., 1988, Evaporite basin stratigraphy, *in* Schreiber, B.C., ed., Evaporites and Hydrocarbons: New York, Columbia University Press, p. 11–65.
KLAPPA, C., 1980, Rhizoliths in terrestrial carbonates: classification, recognition, genesis, and significance: Sedimentology, v. 27, p. 613–629.
KU, T.L., LUO, S., LOWENSTEIN, T.K., LI, J., AND SPENCER, R.J., 1994, U-series chronology for lacustrine deposits of Death Valley, California: Implications for Late Pleistocene climate changes (abstract): Geological Society of America, Abstracts with Program, v. 26, no. 7, p. A-169.
LAZAR, B., AND HOLLAND, H.D., 1988, Analysis of fluid inclusions in halite: Geochimica et Cosmochimica Acta, v. 52, p. 485–490.
LEEDER, M.R., 1982, Sedimentology; Process and Product: London, Unwin Hyman, 344 p.
LI, J., LOWENSTEIN, T.K., BROWN, C.B., KU, T.L., AND LUO, S., 1996, A 100 ka record of water tables and paleoclimates from salt cores, Death Valley, California: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 123, p. 179–203.
LI, J., LOWENSTEIN, T.K., AND BLACKBURN, I.R., 1997, Responses of evaporite mineralogy to inflow water sources and climate during the past 100 k.y. in Death Valley, California: Geological Society of America, Bulletin, p. 1361–1371.
LI, J., LOWENSTEIN, T.K., AND BROWN, C.B., 1998, A 100 kyr paleotemperature record from fluid inclusions in halite, Death Valley, California: Chemical Geology, v. 150, p. 223–245.
LINDHOLM, R., 1987, A Practical Approach to Sedimentology: London, George Allen & Unwin, 276 p.
LONG, D.T., AND LYONS, W.B., 1990, Aridity, continental weathering, and groundwater chemistry (abstract): Geological Society of America, Abstracts with Programs, p. 295.
LOWENSTEIN, T.K., 1988, Origin of depositional cycles in a Permian ''saline giant'': The Salado (McNutt Zone) evaporites of New Mexico and Texas: Geological Society of America, Bulletin, v. 100, p. 592–608.
LOWENSTEIN, T.K., AND HARDIE, L.A., 1985, Criteria for the recognition of salt-pan evaporites: Sedimentology, v. 32, p. 627–644.
LOWENSTEIN, T.K., SPENCER, R.J., AND PENGXI, Z., 1989, Origin of ancient potash evaporites: Clues from the Modern nonmarine Qaidam Basin of Western China: Science, v. 245, p. 1090–1092.
MAUGHAN, E.K., 1966, Environment of deposition of Permian salt in the Williston and Alliance Basins: Cleveland, Ohio, Northern Ohio Geological Society, 2nd Symposium on Salt, v. 1, p. 35–47.
MAUGHAN, E.K., 1967, Eastern Wyoming, eastern Montana, and the Dakotas, *in* McKee, E.D., and Oriel, S.S., eds., Paleotectonic Investigations of the Permian System in the United States: U.S. Geological Survey, Professional Paper 515, p. 125–152.
MCARTHUR, J.M., TURNER, J., LYOND, W.B., OSBORN, A.O., AND THIRWALL, M.F., 1991, Hydrochemistry on the Yilgarn Block, Western Australia: Ferrolysis and mineralisation in acidic brines: Geochimica et Cosmochimica Acta, v. 55, p. 1273–1288.
MERTZ, K.A., JR., AND HUBERT, J.F., 1990, Cycles of sandflat/playa–lacustrine mudstone in the Triassic–Jurassic Blomidon beds, Fundy rift basin, Nova Scotia: Implications for climatic and tectonic controls: Canadian Journal of Earth Sciences, v. 27, p. 442–451.
MIALL, A.D., 1996, The Geology of Fluvial Deposits; Sedimentary Facies, Basin Analysis, and Petroleum Geology: New York, Springer-Verlag, 596 p.
MOORE, W.R., 1983, The nature of the Minnelusa–Opeche contact in the Halverson Field area, Powder River Basin, Wyoming: The Mountain Geologist, v. 20, p. 113–120.
MUDGE, M.R., 1967, Central midcontinent region, *in* McKee, E.D., and Oriel, S.S., eds., Paleotectonic Investigations of the Permian System in the United States: U.S. Geological Survey, Professional Paper 515, p. 91–123.
PETTIJOHN, F.J., POTTER, P.E., AND SIEVER, R., 1972, Sand and Sandstone: New York, Springer-Verlag, 618 p.
PRESLEY, M.W., 1987, Evolution of Permian evaporite basin in Texas panhandle: American Association of Petroleum Geologists, Bulletin, v. 71, p. 167–190.
READING, H.G., 1996, Sedimentary Environments; Processes, Facies, and Stratigraphy, Third Edition: Oxford, U.K., Blackwell Science, 688 p.
RETALLACK, G., 1988, Field recognition of paleosols, *in* Retallack, G., ed., Paleosols and Weathering through Geologic Time: Geological Society of America, Special Paper 216, p. 1–20.
RETALLACK, G., 1989, Laboratory Exercises in Paleopedology: University of Oregon, 74 p.
ROBERTS, S.M., AND SPENCER, R.J., 1995, Paleotemperatures preserved in fluid inclusions in halite: Geochimica et Cosmochimica Acta, v. 59, p. 3929–3942.
ROBERTS, S.M., SPENCER, R.J., AND LOWENSTEIN, T.K., 1994, Late Pleistocene saline lacustrine sediments, Badwater Basin, Death Valley, California, *in* Lomando, A.J., Schreiber, B.C., and Harris, P.M., eds., Lacustrine Reservoirs and Depositional Systems: SEPM, Core Workshop 19, p. 61–103.
SANDBERG, C.A, 1973, Salt and potash, *in* Noble, E.A., ed., Mineral and Water Resources of North Dakota: North Dakota Geological Survey, Bulletin 63, p. 139–151.
SCHREIBER, B.C., 1986, Arid shorelines and evaporites, *in* Reading, H.G., ed., Sedimentary Environments and Facies: Oxford, U.K., Blackwell, p. 189–228.
SCHREIBER, B.C., 1988, Subaqueous evaporite deposition, *in* Schreiber, B.C., ed., Evaporites and Hydrocarbons: New York, Columbia University Press, p. 183–255.
SCHUBEL, K.A., AND LOWENSTEIN, T.K., 1997, Criteria for the recognition of shallow-perennial-saline-lake halites based on recent sediments from the Quidam Basin, western China: Journal of Sedimentary Research, v. 67, p. 74–87.
SHEARMAN, D.J., 1970, Recent halite rock, Baja California, Mexico: Institute of Mining and Metallurgy, Transactions, v. 79, p. 155–162.
SHEARMAN, D.J., 1978, Halite in sabkha environments, *in* Dean, W.E., and Schreiber, B.C., eds., Marine Evaporites: Society of Economic Paleontologists and Mineralogists, Short Course 4, p. 30–42.
SMOOT, J.P., AND LOWENSTEIN, T.K., 1991, Depositional environments of non-marine evaporites, *in* Melvin, J.L., ed., Evaporites, Petroleum, and Mineral Resources: Amsterdam, Elsevier, Developments in Sedimentology 50, p. 189–347.
SMOOT, J.P., AND CASTENS-SEIDELL, B., 1994, Sedimentary features produced by efflorescent salt crusts, Saline Valley and Death Valley, California, *in* Renaut, R.W., and Last, W.M., eds., Sedimentology and Geochemistry of Modern and Ancient Lakes: SEPM, Special Publication 50, p. 73–90.
SPENCER, R.J., AND LOWENSTEIN, T.K., 1990, Evaporites, *in* McIlreath, I.A., and Morrow, D.W., eds., Diagenesis: Geoscience Canada, Reprint Series 4, p. 141–163.
TIMOFEEFF, M.N., LOWENSTEIN, T.K., BLACKBURN, I.R., AND HARDIE, L.A., 1998, Environmental SEM (ESEM) X-ray EDS chemical analysis of frozen fluid inclusions: Preliminary results from aqueous standards, fluid inclusions in laboratory-grown halite crystals, and Phanerozoic halites (abstract): Pan American Conference on Research on Fluid Inclusions VII, Las Vegas, Nevada, Program and Abstracts, p. 67.
WALKER, T.R., 1967, Formation of red beds in modern and ancient deserts: Geological Society of America, Bulletin, v. 78, p. 353–368.
WARDLAW, N.C., AND SCHWERDTNER, W.M., 1966, Halite–anhydrite seasonal layers in the Middle Devonian Prairie Evaporite Formation, Saskatchewan, Canada: Geological Society of America, Bulletin, v. 77, p. 331–342.
WEILER, Y., SASS, E., AND ZAK, I., 1974, Halite oolites and ripples in the Dead Sea, Israel: Sedimentology, v. 21, p. 623–632.
WILGUS, C.K., AND HOLSER, W.T., 1984, Marine and nonmarine salts of Western Interior, United States: American Association of Petroleum Geologists, Bulletin, v. 68, p. 765–767.
WITTSTROM, M.D., AND HAGEMEIER, M.E., 1979, A review of Little Knife Field: Oil and Gas Journal, v. 77, p. 86–92.

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