Journal of Sedimentary Research

Journal of Sedimentary Research, 2018, v. 88, 385–398
Research Article
DOI: http://dx.doi.org/10.2110/jsr.2018.14

ACID-SALINE-LAKE SYSTEMS OF THE TRIASSIC MERCIA MUDSTONE GROUP, COUNTY ANTRIM, NORTHERN IRELAND

ANNA SOFIA ANDESKIE,[1] KATHLEEN C. BENISON,[1] LYNNETTE A. EICHENLAUB,[1] AND ROBERT RAINE[2]
[1]*Department of Geology and Geography, West Virginia University, Morgantown, West Virginia, 26506-6300, U.S.A.*
[2]*Geological Survey of Northern Ireland, Dundonald House, Belfast BT4 3SB, U.K.*
e-mail: asandeskie@mix.wvu.edu

ABSTRACT: **The Triassic Mercia Mudstone Group of County Antrim, Northern Ireland, is dominated by red beds and evaporites. After only limited study, both marine and continental environments have been proposed previously. Here, we describe these rocks for the first time from core and petrographic observations to interpret depositional environments and conditions, such as water depth, salinity, and aridity. Bedded halite, bedded gypsum, displacive halite, and red siliciclastic mudstone lithologies comprise most (∼ 80%) of the 591.6-m-thick Mercia Mudstone Group in the Gaelectric Carnduff-2 core. Bedded halite consists of chevron and cornet crystals, indicating bottom-growth from shallow surface brines. Bedded-gypsum lithology is composed of halite-replaced pseudomorphs after swallowtail, bottom-growth gypsum crystals. Both bedded halite and bedded gypsum contain dissolution features and are commonly overlain by mud drapes. Bedded-halite and bedded-gypsum lithologies are interpreted to have formed in shallow saline lakes influenced by flooding and evapoconcentration. The displacive-halite lithology is composed of sub-cubic halite crystals, randomly oriented in mudstone, and represents deposition in a saline mudflat. Some mudstones contain ripple cross-lamination, dewatering structures, mudcracks, and rip-up clasts, suggesting shallow surface water and desiccation. Other mudstones are massive (structureless) and may have been deposited by wind. Both of these mudstone units were likely deposited in dry mudflats. Other red mudstones contain soil slickensides, blocky peds, and circumgranular cracks and are interpreted as paleosols. Our observations indicate that the Triassic Mercia Mudstone Group was formed by shallow perennial saline lakes and associated continental environments in an arid climate. Furthermore, lack of carbonates, lack of fossils, and paucity of organic matter suggest acid saline lakes and groundwaters. The Triassic Mercia Mudstone Group is similar to some other Pangean red beds and evaporites. Therefore, we hypothesize that the supercontinent was an arid barren landscape hosting acid-saline lakes.**

INTRODUCTION

Red beds and evaporites are commonly found in mid-Permian to middle Triassic sedimentary strata. However, despite their abundance, their mode of formation is still debated. In general, older studies used the presence of halite and gypsum to argue for marine or marginal marine depositional origin (e.g., Clifton 1944; Campbell 1963; Maughan 1966; Picard and High 1968). In contrast, detailed sedimentological and geochemical data obtained from Permian red beds and evaporites of the mid-continent of North America support continental depositional environments (Benison and Goldstein 2000, 2001; Knapp and Benison 2013; Sweet et al. 2013; Foster et al. 2014). Are ancient red bed and evaporite deposits marine, nonmarine, or a transition of environments? What were the environmental conditions, such as water depth, salinity, aridity, diurnal temperature ranges, and acidity? Answering these questions may resolve the extreme end members of evaporite deposition from natural waters.

The goal of this study is to determine the detailed depositional environments of the Triassic Mercia Mudstone Group of County Antrim, Northern Ireland. Due to limited exposure and poor outcrop quality, there have been no previous detailed petrographic or geochemical studies of the Mercia Mudstone Group in the Larne Basin. Here, by study of a well-preserved, high-recovery core, we describe for the first time the lithology of the Mercia Mudstone Group in Northern Ireland and interpret depositional environments.

BACKGROUND

Permo-Triassic Red Beds and Evaporites

Previous studies reveal that some Permo-Triassic red beds and evaporites were deposited in extremely acid saline ephemeral lakes and by acid saline-inundated mudflats surrounded by dunes and desert soils (Benison et al. 1998). For example, the Permian Nippewalla Group of Kansas and Oklahoma is composed of bedded evaporites, displacive evaporites, red-bed siliciclastics, and rare gray siliciclastics. These rocks formed in an acid ephemeral saline lake and groundwater system (Benison and Goldstein 2001). Bedded and displacive evaporites and red-bed siliciclastics of the Permian Opeche Shale of North Dakota also formed in an acid saline lake and groundwater system with pH values below 1 (Benison et al. 1998; Benison and Goldstein 2000). Both the Nippewalla Group and the Opeche Shale are also characterized by a paucity of fossils and carbonates, as well as eolian features and aridity indicators (Benison and Goldstein 2000, 2001; Sweet et al. 2013; Foster et al. 2014).

Published Online: March 2018

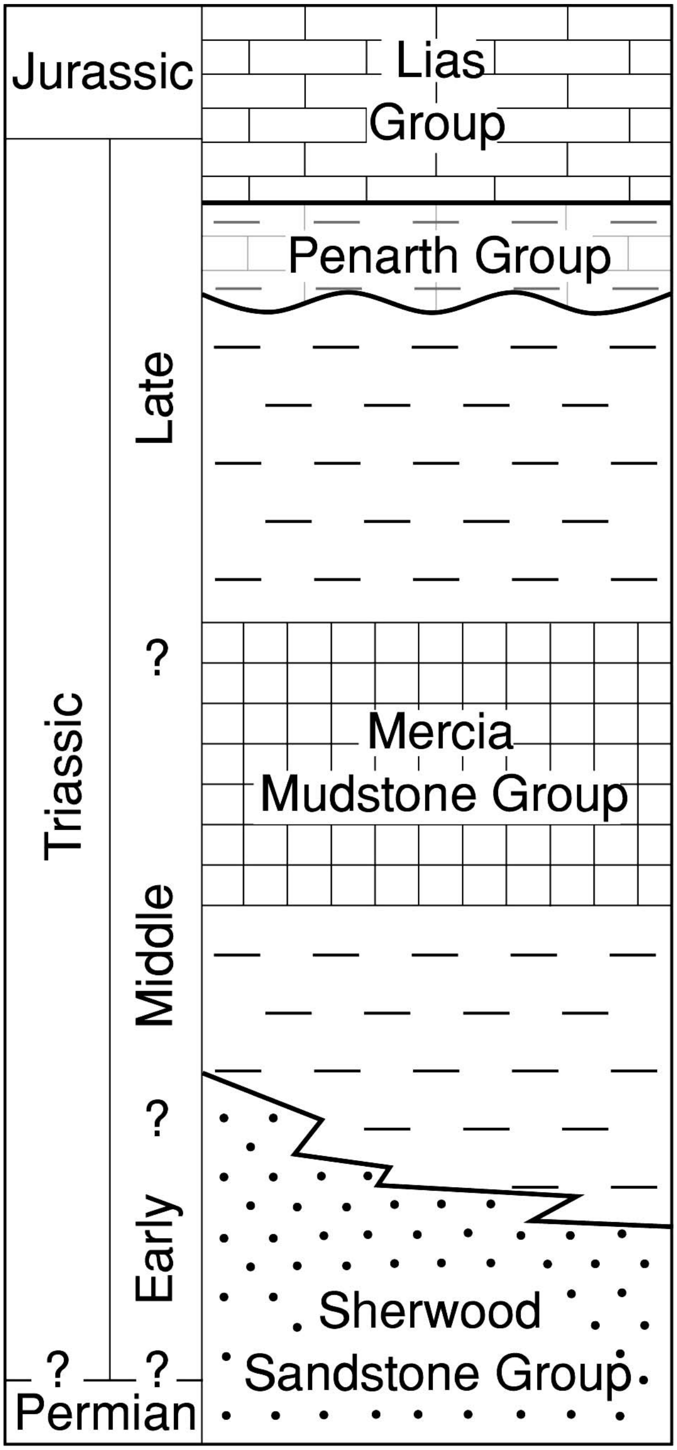


FIG. 1.—General stratigraphic column of Late Permian–Early Jurassic of the United Kingdom. Modified from Benton et al. 2002.

In the United Kingdom, there are multiple prominent rift basins composed of 1–4-km-thick sequences of Permo-Triassic red beds and evaporites. In these basins, there are three Permo-Triassic groups: the Permo-Triassic Sherwood Sandstone, the mid-Late Triassic Mercia Mudstone Group, and the Late Triassic Penarth Group (Fig. 1). These strata have been recognized in both the Larne Basin of Northern Ireland and the Cheshire Basin of England (Fig. 2). In the Cheshire Basin, some of these rocks have been dated with biostratigraphy and magnetostratigraphy (Tresise and Sarjeant 1997; Warrington 1999; Benton et al. 2002). Palynomorphs have been documented and used for dating the Mercia Mudstone Group in England. Warrington (1997) noted miospores dated from the Carnian (Early Triassic) located below the top of the Mercia Mudstone Group to the Norian (?) to Rhaetian (Late Triassic) found in the top of the group. It is important to note that there are distinct lithologic and stratigraphic differences between the Larne Basin and the Cheshire Basin (Griffith and Wilson 1982); therefore, correlating ages between basins should be done with caution. This study focuses on the Mercia Mudstone Group in the Larne Basin of Northern Ireland.

Mercia Mudstone Group in the Carnduff-2 Core

The Carnduff-2 core of the Larne Basin of County Antrim, Northern Ireland, contains a nearly complete section of the Mercia Mudstone Group. In 2014, Gaelectric Energy Storage Ltd. drilled the Carnduff-2 borehole approximately 1 km south of Larne and 28 km NNE of Belfast (Fig. 2). In this core, the Mercia Mudstone Group is found between the depths of 378.4 m and 970 m and has a total thickness 591.6 m. Although the lower contact of the Mercia Mudstone Group was not identified in the core, we consider the base of the well, at 970 m depth, to be close to the bottom of the group, based on the identification of the bottom contact of the Larne Halite Member at $\sim$ 922 m depth. The diameter of the core is 9 cm. Gaelectric Energy Storage Ltd. initially drilled this well to review locations for compressed-air energy storage. To prevent dissolution of the rock, the drilling fluids were fully saturated with a saline solution before reaching the evaporites, resulting in a recovery rate of 92.7%. We interpreted that missing sections of core were likely lost due to misplacement or dropped core boxes rather than any non-recovery during drilling, based on the rare, random disappearance of one to two meters at a time. After drilling, the core was stored in plastic sleeves to prevent dissolution from the moist Northern Ireland air. The Carnduff-2 core is currently housed at the Geological Survey of Northern Ireland (GSNI) core repository in Belfast in sealed plastic sleeves in wooden boxes.

METHODS

Methods for this study include detailed core and thin-section observations. We slabbed the core using a DeWalt D24000S wet tile saw. The saw plumbing was modified to employ a small, focused water stream on the back of the saw blade to minimize wetting of halite. We studied core slabs at the centimeter-scale. Observations were focused on sedimentary textures, mineral composition, color, sedimentary structures, fossils, any notable contacts, diagenetic features, and taste. Core slabs were scanned with a flatbed digital color scanner to document images. Photographs were also taken. Color of dry core slabs was determined with a Konica-Minolta CR-400 chroma meter. A measured section and stratigraphic column were constructed using detailed sedimentologic and stratigraphic observations (Fig. 3). Representative lithologies were identified based on common traits of individual beds throughout the group. These representative lithologies were then sampled at contact intervals and mailed to West Virginia University for laboratory-based work.

Samples for thin-section preparation were sent to Spectrum Petrographics, Inc. and were made with minimal use of water or heat. Thirty-three petrographic sections, including 12 thick (4 mm) sections and 21 thin (0.03 mm) sections, were studied. Of the 33 petrographic sections, 27 were large format (51 mm × 75 mm) and 6 were standard size (27 mm × 46 mm). Petrographic observations included examination of color, sedimentary textures, mineral composition, sedimentary structures, fossils, diagenetic features, and notable contacts. Thin sections were observed with plane transmitted, reflective, and polarized light sources using an

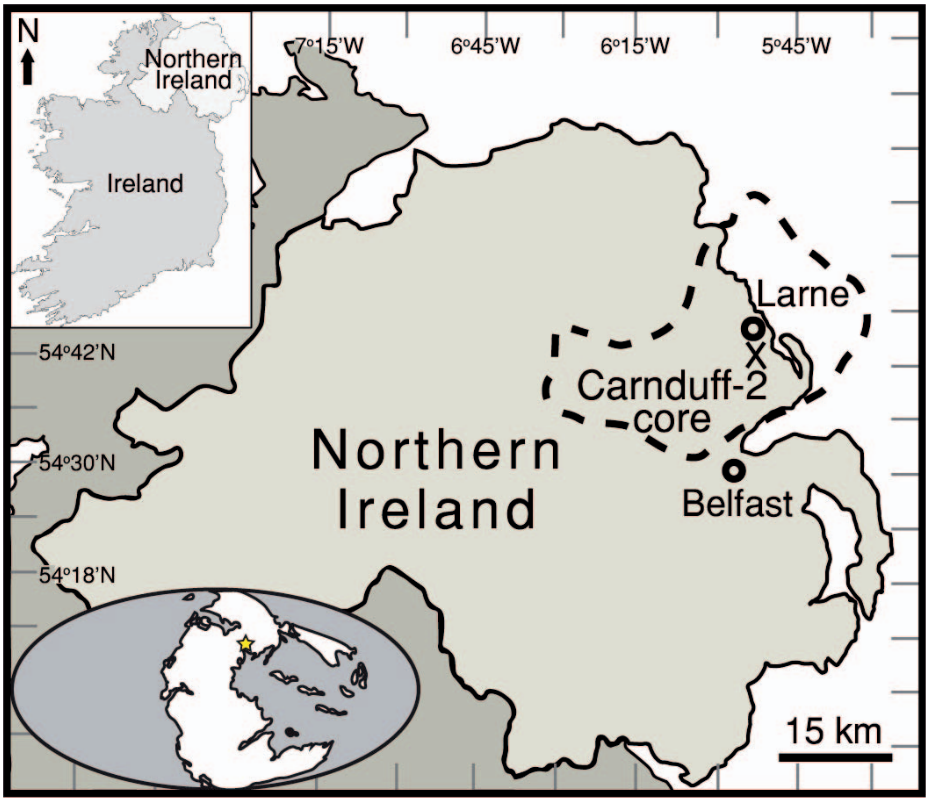


FIG. 2.—Map of Northern Ireland showing the approximate location of the Carnduff-2 core (marked by an X), and the cities of Larne and Belfast. The dashed line indicates the approximate borders of the Larne Basin. Map of Pangea is modified from Colorado Plateau Geosystems.

Olympus SZX10 microscope (20 to 2000× magnification) and an Olympus BX53 microscope (6.3 to 63× magnification). Photomicrographs were taken with a digital camera and SPOT5 digital imaging system.

LITHOLOGIC DESCRIPTIONS AND INTERPRETED FACIES

Throughout the 591.6-m-thick section of Mercia Mudstone Group in the Carnduff-2 core, four main lithologies were observed: bedded halite, bedded gypsum, displacive halite, and mudstone. These four lithologies comprise 474.5 m (or 80.2%) of the interval studied. We were unable to differentiate some halite and gypsum units because they contained both bedded and displacive evaporite textures. Therefore, we categorized them as "undifferentiated evaporites" and did not include them in any of the four lithofacies. Other lithologies present include siltstone, sandstone, mud clast–halite conglomerate, and mafic igneous rock. The Mercia Mudstone Group was tested with HCl, but no reactions occurred. The detailed measured section illustrates the lithologies and their stratigraphic relationships (Fig. 3).

Bedded-Halite and Bedded-Gypsum Lithologies: Saline-Lake Lithofacies

The bedded-halite lithology is glassy pink (5.1YR 2.7/0.5) to dark orange (8.3YR 3.1/0.4), commonly displaying the color of associated muds (Fig. 4A, B). Horizontal beds consist of bottom-growth halite crystals. Typically, the crystals are widest at the bottom and have a pointed tip, in a triangular shape characteristic of chevron halite crystals (Fig. 4C). Other halite crystals have a flat top; these are called cornet crystals (Fig. 4D). Individual crystals range in size from 0.25 to 2.5 cm. In thick and thin sections, primary fluid inclusions are recognized along chevron and cornet growth bands (Fig. 4C). Some chevron tops appear truncated. Some are overlain by mud drapes, 0.1 to 0.5 cm thick, wavy, discontinuous laminae (Fig. 4E). Vertically oriented vugs, filled with clear halite, are found crosscutting growth bands in much of the bedded halite (Fig. 4F). When bedded-halite units were slabbed, clay of tan color (2.7Y 4.1/1.0) and thick consistency accumulated on the saw blade.

The bedded-gypsum lithology is composed of crystal pseudomorphs composed of halite. The pseudomorphs, vertically aligned in beds, have bladed shapes that have a bottom point and widen upward, forming "V" shapes (Fig. 5). Many of the crystals appear to have been twinned, resulting in a swallowtail shape. We observed rare truncated tops on gypsum crystal pseudomorphs that are commonly associated with mud drapes. The crystals range from 0.5 to 2.5 cm in length and are typically reddish brown (9.1YR 3.3/0.9) in transmitted light. When viewed in polarized light, the crystals are isotropic; birefringence is seen along pseudomorph boundaries (Fig. 5C). The crystals tasted salty.

The bedded-halite and bedded-gypsum lithologies compose approximately 16% of the group and are interpreted to have formed in shallow saline lakes. Bottom-growth crystal structures indicate chemical precipitation from a surface saline water body during evapoconcentration. Halite chevrons pointed in the "up" direction indicate that they are *in situ*, not reworked, and precipitated in shallow (< 0.5 m deep) Na–Cl-rich surface brines (Arthurton 1973; Lowenstein and Hardie 1985). The tan clay that accumulated on the saw blade during cutting of bedded halite is likely kaolinite, judging by its color, texture, and similarity to modern analogs (Benison et al. 2007). Swallowtail shapes originally formed as bottom-growth gypsum (Hardie and Eugster 1971; Benison et al. 2007). The gypsum formed at the sediment–water interface in Ca-SO_4-rich surface brines. Truncations at the tops of some halite chevrons and gypsum swallowtails are interpreted as dissolution surfaces. Vugs filled with clear halite in some chevrons likely formed as dissolution pipes (Lowenstein and Hardie 1985). These dissolution features, along with associated mud drapes, mark times of flooding in these shallow saline lakes. There is no clear evidence of desiccation, such as efflorescent microcrystalline halite crusts (Smoot and Castens-Seidell 1994). Bedded halite that includes chevron crystals and dissolution surfaces and pipes, and mud drapes, but

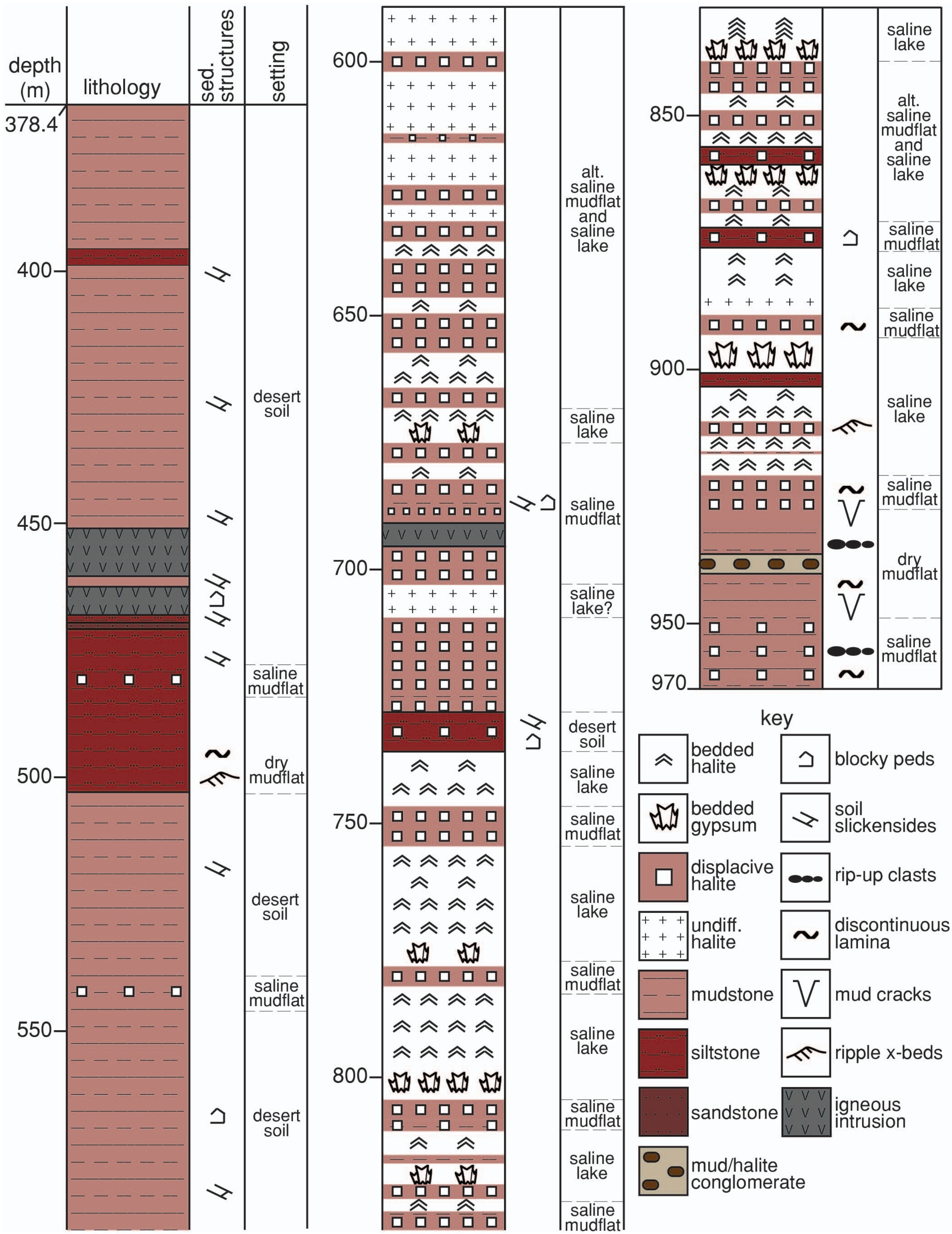


FIG. 3.—Detailed stratigraphic column of the Mercia Mudstone Group in the Carnduff-2 Core of County Antrim, Northern Ireland.

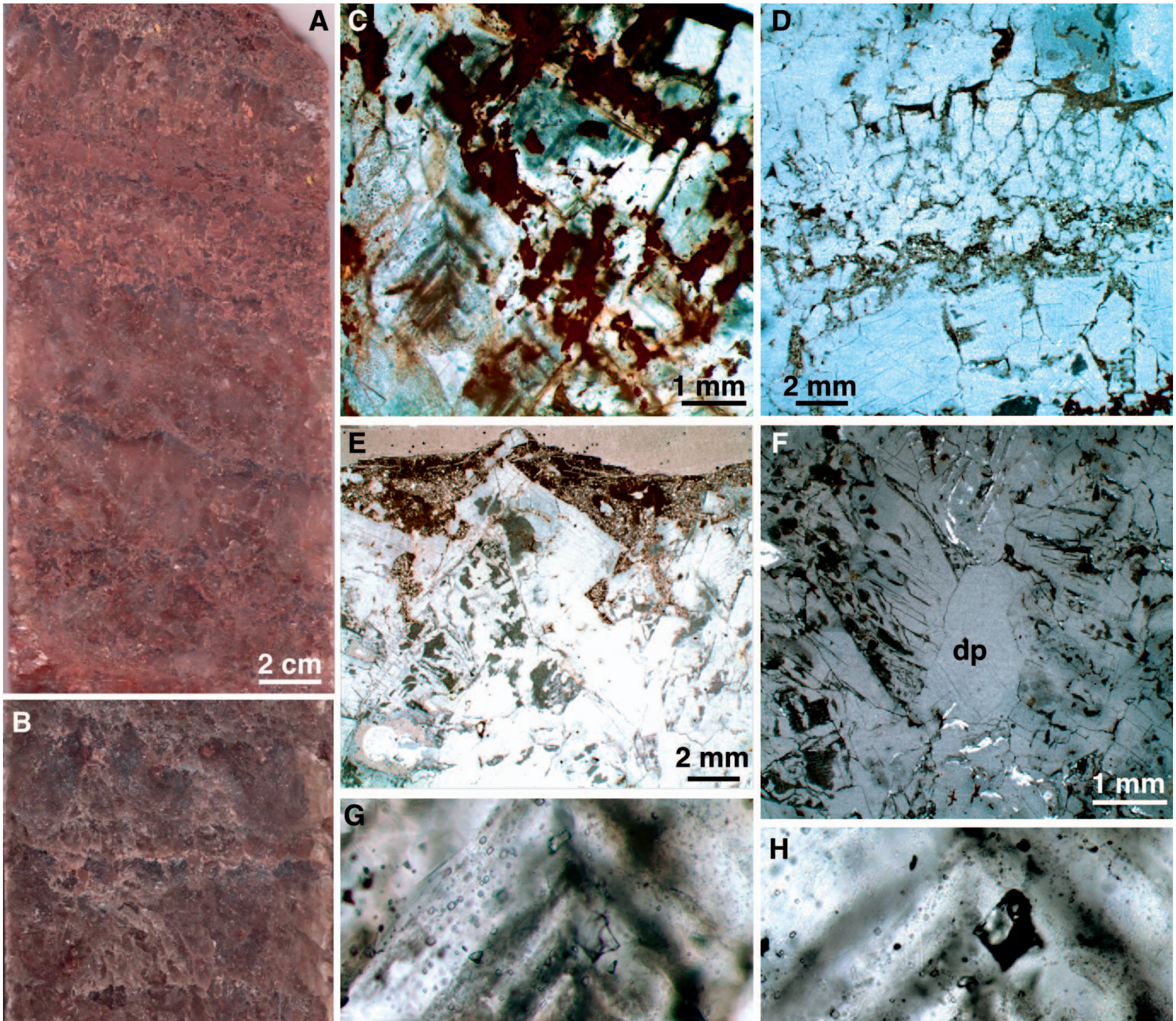


FIG. 4.—Bedded halite in the Mercia Mudstone Group in the Carnduff-2 core. **A)** Core slab from ~ 769.8 m depth. **B)** Core slab from 844.5 m depth. The red color is due to hematite mud. **C)** Thick section from 659.5 m depth, showing chevron crystals and red mud. **D)** Thin-section view of cornet- and chevron-rich halite beds from 844.5 m depth. **E)** Thin-section image of chevrons overlain by siliciclastic sediment at 891.1 m depth. The tan color at top of image is thin-section epoxy. **F)** Thin-section view of chevrons composed of alternating clear and cloudy growth bands, truncated by a dissolution pipe (labeled dp) filled with clear halite cement; from 919.1 m depth. **G**, **H)** Thick sections of cloudy, primary-fluid-inclusion-rich growth bands in single chevron halite crystals from 659.5 m (G) and 919.1 m depth (H). All images are cross sections oriented with respect to stratigraphic up.

no desiccation features, likely formed in shallow saline surface waters that underwent times of evapoconcentration and times of flooding (Schubel and Lowenstein 1997). Gypsum beds composed of bottom-growth gypsum crystals with dissolution surfaces and mud drapes are consistent with this same interpretation. Lake water geochemistry fluctuated amongst saturation with respect to halite, saturation with respect to gypsum, and undersaturation with respect to both halite and gypsum. Therefore, the lakes were most likely perennial, shallow, and saline.

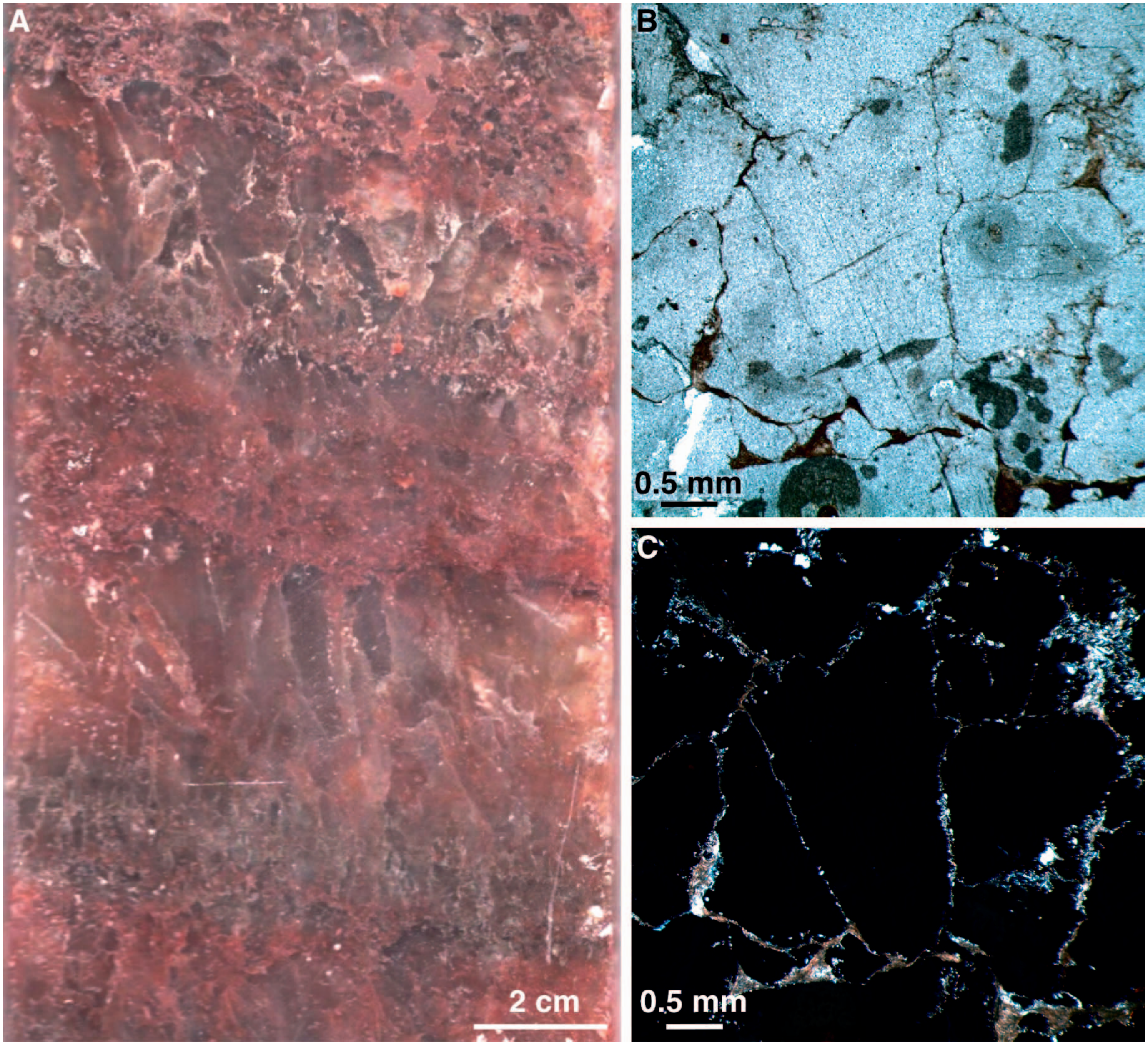


FIG. 5.—Bedded gypsum in the Mercia Mudstone Group in the Carnduff-2 core. **A)** Core slab from ~ 841.5 depth. Bladed vertical crystals are pseudomorphs after bottom-growth gypsum, now composed of halite. **B**, **C)** Thin-section view of swallow-tail bottom-growth gypsum pseudomorph (center of photo) at 844.5 m depth, in transmitted light (B) and cross-polarized light (C). Note that, in Part C, birefringent anhydrite crystals outline boundaries of swallowtail gypsum pseudomorphs, and black areas indicate halite that has replaced the original gypsum. All images are cross sections oriented with respect to stratigraphic up.

Displacive-Halite Lithology: Saline-Mudflat Lithofacies

Displacive halite is one of the most common lithologies found throughout the Mercia Mudstone Group of the Carnduff-2 core, forming approximately 25% of the 591.6 m of the group. Displacive halite crystals are typically cubic to sub-cubic, range from a few millimeters to ~ 3 centimeters long, and make up 10 to 75% of the rock (Fig. 6). The halite crystals are randomly oriented in the mudstone matrix. The mudstone host consists of a combination of clay- and silt-size grains. Most commonly, the matrix is red (5.4YR 3.4/1.7). However, rare gray mudstone exists in some of the displacive-halite units. We observed no sedimentary structures in the displacive-halite lithology.

The displacive-halite lithology is interpreted to have formed in saline mudflats. A saline mudflat is a relatively flat, vegetation-free area located adjacent to a saline lake. Typically, the saline-groundwater table is only centimeters below the surface (Casas and Lowenstein 1989). Displacive halite crystals grow in shallow subsurface sediment that is unconsolidated and saturated with saline groundwater (Smith 1971; Casas and Lowenstein 1989; Smoot and Lowenstein 1991; Benison et al. 2007). The presence of these randomly oriented halite crystals, hosted by siliciclastic sediment,

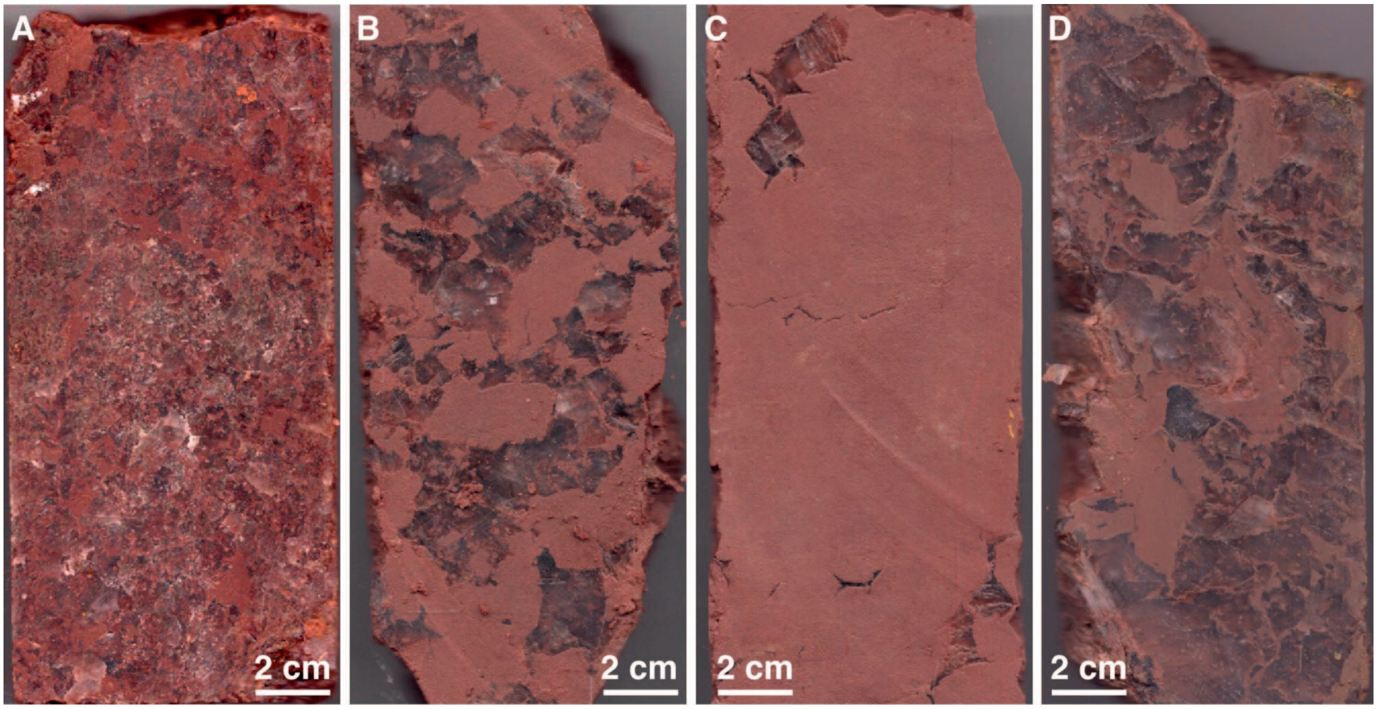


FIG. 6.—Scanned images of core slabs of displacive halite in the Mercia Mudstone Group in the Carnduff-2 core. Note the range in ratio of halite crystals: red mudstone at **A)** 700.6 m depth, **B)** 723.7 m depth, **C)** 728.6 m depth, and **D)** 732.2 m depth. All images are cross sections oriented with respect to stratigraphic up.

indicates that the groundwater must have been saturated with respect to halite.

Red-and Gray-Mudstone Lithologies: Dry-Mudflat Lithofacies

We identified two main types of red and gray mudstones, differentiated by absence or presence of sedimentary structures: 1) massive mudstone (Fig. 7), and 2) mudstone with abundant sedimentary structures (Fig. 8). These two types of mudstone are composed of a mixture of clay- and silt-size grains. The clay-size grains composed ~ 86.5%, and the silt-size grains composed 13.5% of this lithology. The contacts between these grain sizes are gradational with no distinct coarsening- or fining-upward sequences present. These rocks are smooth to the touch, and a thick-consistency, fine, tan material accumulated on the saw while slabbing. Silt is found either disseminated throughout the mudstone or in rare silt-rich lenses (Figs. 7, 8). Silt in these rocks includes quartz, gypsum, and red mud claystone clasts (Fig. 7B). Some of this mudstone is all brick red (5.4YR 4.2/3.1) and chocolate red (3.5Y 5.6/0.9), some is blue-gray (0.7Y 5.0/1.1), and some is a combination of these two colors (Fig. 8A, B). Some of the units of mudstone are massive and very well sorted, with no defined sedimentary structures (Fig. 7). These massive units commonly have pale gray reduction spots (Fig. 7C, D). Other units contain rare, thin (1 to 3 mm thick), wavy, discontinuous laminae and rare climbing-ripple cross lamination. Mudcracks, dewatering structures, and rip-up clasts were observed (Fig. 8). Mudcracks are "V"-shaped cracks that disturbed laminae and were later filled with sediment. Dewatering structures appear as thin, clay-lined and silt-filled vertically oriented lenses (Fig. 8C). Angular granule- and pebble-size rip-up clasts composed of clay-size grains are present as well (Fig. 8D).

Both the massive mudstone and the mudstone with abundant sedimentary structures are interpreted to have been deposited in dry mudflats, but by different processes. A dry mudflat is a relatively flat area with sparse vegetation and a low groundwater table in comparison to a saline mudflat (Lowenstein and Hardie 1985; Benison et al. 2007). We interpret the massive mudstone units to most likely have been deposited on dry mudflats by eolian processes. The well-sorted, massive nature suggests dust storm events. The sedimentary-structure-rich mudstone is interpreted to have undergone repetitive wetting and drying events. Sheet-flood events are interpreted from rare climbing-ripple cross laminae and discontinuous wavy laminae. These structures formed by rapid subaqueous deposition due to an increase in energy from flood waters. Drying, or desiccation events, are interpreted from mudcracks, rip-up clasts, and dewatering structures. The tan clay mineral that accumulates as a sludge on the saw blade is similar to the clay that accumulates when cutting bedded halite and is likely kaolinite.

The siliciclastic sediment in the bedded halite, bedded gypsum, and displacive halite seems similar to that in the massive mudstones and sedimentary-structure-rich mudstones. The main differences are that there is less mud in the bedded displacive evaporites, and that halite and gypsum growth outcompeted the siliciclastic deposition. In the case of the displacive halite, either there was more massive mud, or early diagenetic crystal growth in the subsurface may have disrupted any laminae or other sedimentary structures that may have been in the mud. Therefore, winds and floods were probably the source of much of the mud in the lakes and saline mudflats.

Ped-Dominated-Mudstone Lithologies: Desert-Soil Lithofacies

Another type of mudstone is distinctively different from the dry mudflat lithofacies. This red mudstone is dominated by clay-size grains and three sedimentary structure types. The dominant sedimentary structures in this mudstone are blocky peds. The peds are blocky clumps that are ~ 2 to 3 cm^2 in size. The peds are prismoidal angular to prismoidal subangular in shape. Soil slickensides are commonly found on the outer surfaces of the peds. In hand sample, slickensides appear to be smooth surfaces with some long parallel grooves (Fig. 9). Circumgranular cracks were observed in thin sections of individual peds.

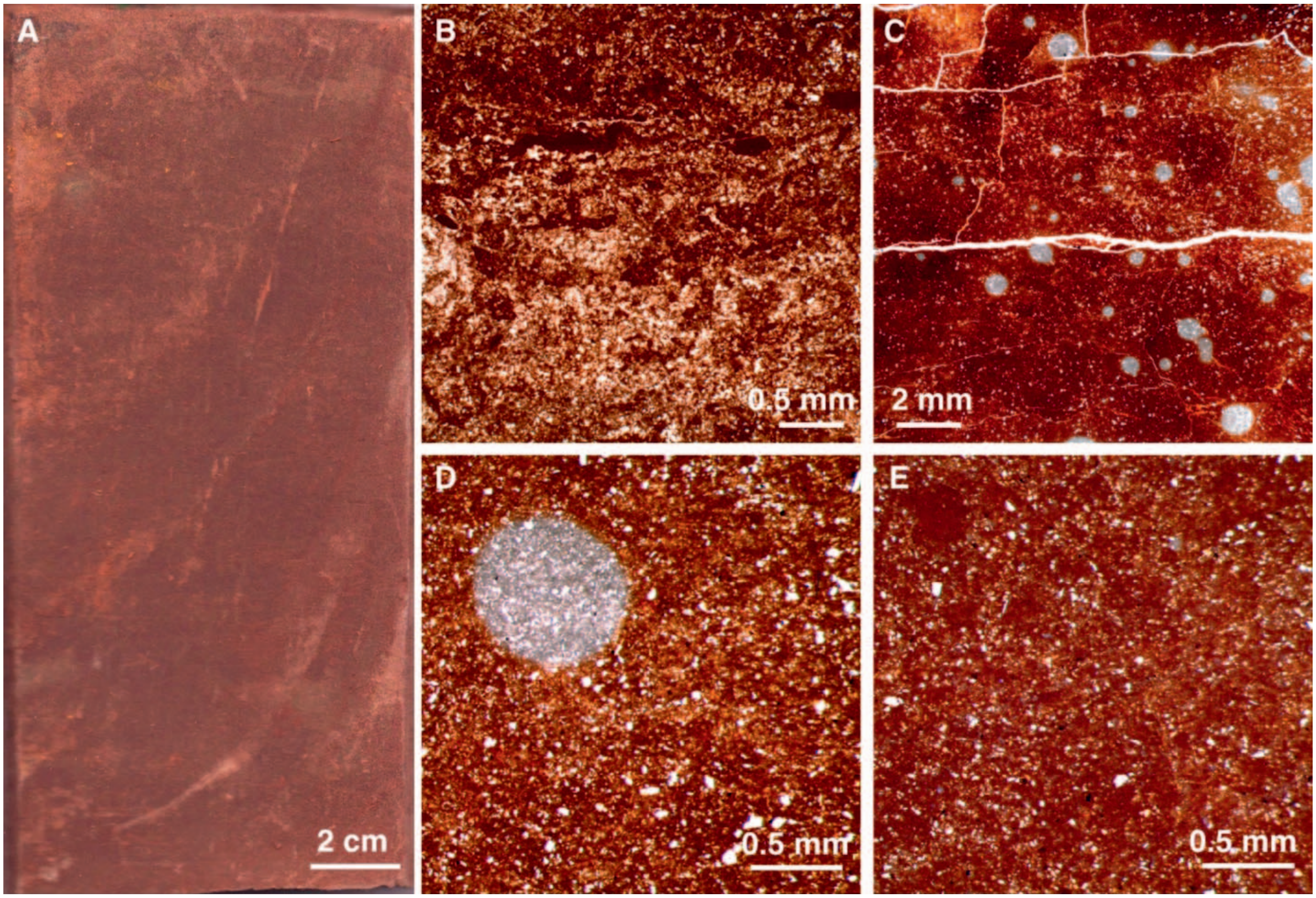


FIG. 7.—Massive red mudstone in the Carnduff-2 core. **A)** Core slab from 965.2 m depth. B–E) Thin-section images. **B)** Mudstone composed of quartz and gypsum silt clasts, dark red rounded to angular silt clasts, and clay-size red grains, at 965.9 m depth. **C)** Red mudstone with reduction spots and horizontal and vertical fractures, at 441.5 m depth. **D)** Closer view of reduction spot from Part C. **E)** Closer view of Part C, showing rounded red mud clasts. All images are cross sections oriented with respect to stratigraphic up.

Blocky peds, soil slickensides, and circumgranular cracks are characteristics of paleosols. Soil slickensides are shear planes that form when clays shrink, swell, and slide from repeated wetting and drying, eventually breaking and forming blocky peds. Circumgranular cracks are found in the peds due to repetitive wetting and drying. Unlike many paleosols, this ped-rich mudstone is noticeably lacking in root features and organic material. These paleosols are interpreted to represent a Triassic desert soil.

Minor Lithologies

Minor abundances of siltstone, sandstone, mud clast–halite conglomerate, and mafic igneous rock compose approximately 4% of the Mercia Mudstone Group in the Carnduff-2 core (Fig. 3). Thin reddish-brown (6.9YR 4.9/3.5) siltstone units contain discontinuous laminae, blocky peds, soil slickenslides, and localized displacive halite crystals. We interpret these siltstones as siltflat deposits, similar to mudflat deposits, that underwent wetting and drying.

One 1.7 m-thick reddish-brown (5.8YR 3.9/3.1) well-sorted massive sandstone bed was observed near the top of the Mercia Mudstone Group. Grains are spherical and subangular to well-rounded coarse silt and fine sand. They are well-sorted with bimodal grain-size distribution in places. The majority of grains are quartz; we also observed gypsum, chert, and rare feldspar grains. We estimate that intergranular porosity was originally ~ 20%, but all pore space is now filled with cements. Grains have thin hematite coatings, followed by thin halite and gypsum meniscus cements, and finally by halite and gypsum epitaxial overgrowth cements (Fig. 10).

We interpret this one sandstone unit as an eolian deposit due to its textures, including some bimodal grain-size distribution. The cement mineralogy and textures suggest that this rock was lithified relatively early and close to the surface by rising saline groundwater.

The mud clast–halite conglomerate, near the bottom of the Mercia Mudstone Group, contains red (2.5 YR 5/2) and gray (2.5 YR 3/2) pebble to gravel-size mudstone clasts (Fig. 11). Halite and some anhydrite crystals form the intergranular cement, which is abundant enough to appear to be the matrix of the rock, supporting the mudstone clasts. An isopachous halite cement surrounds some clasts. This single mud clast–halite conglomerate may be the result of a collapse breccia, or of cementation in a saline lake by clasts derived from autoclastic brecciation.

The igneous rocks are basalt, have sharp contacts with other lithologies, and relate to a period of dike intrusion during the Paleogene (Holford et al. 2009). We noted no obvious signs of contact metamorphism in the host rocks.

Summary of Interpreted Depositional Environments

The Mercia Mudstone Group likely formed in a continental system including saline lakes, saline mudflats, dry mudflats, and desert paleosols

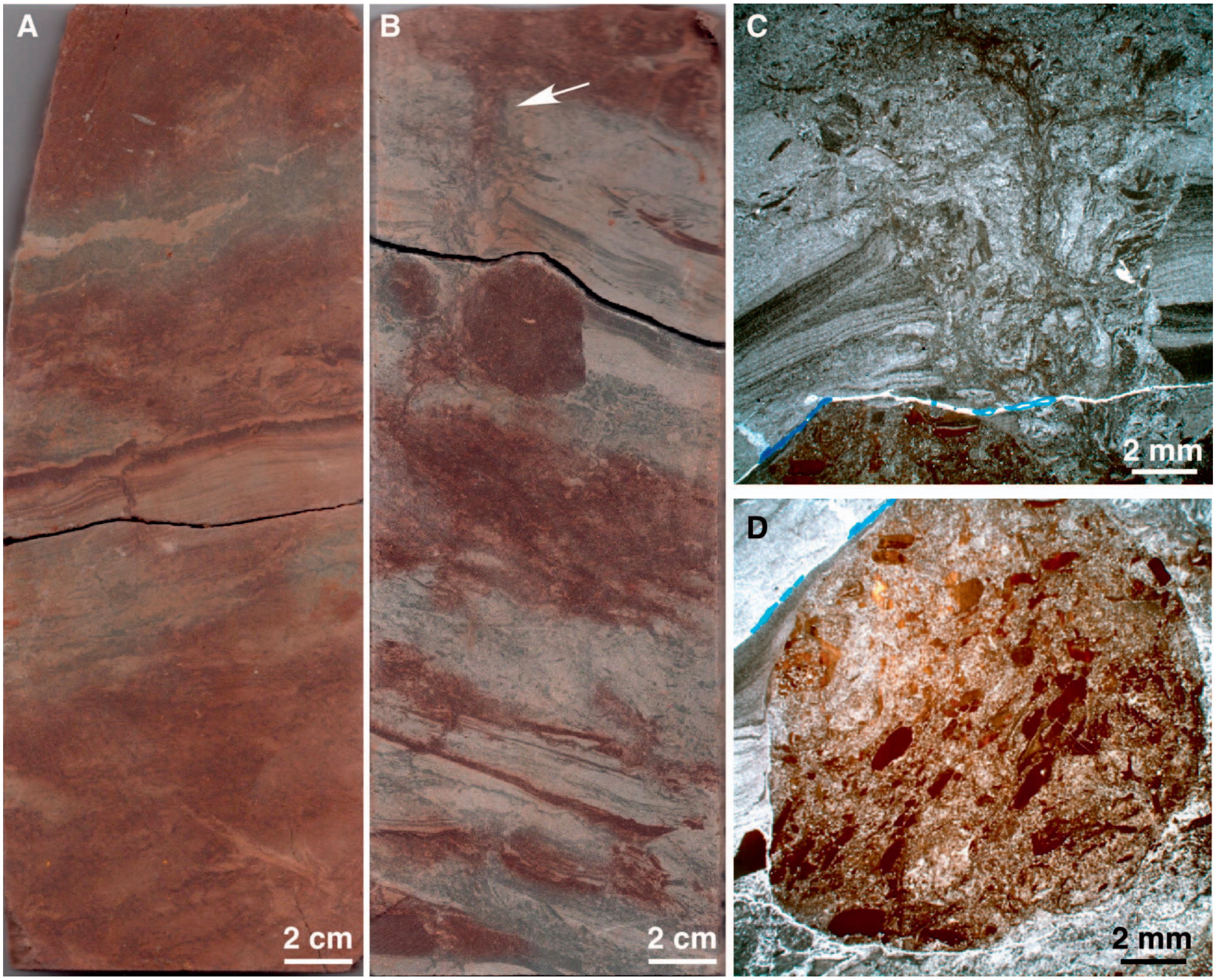


FIG. 8.—Sedimentary-structure-rich mudstones in the Carnduff-2 core. **A)** Core slab from 956.9 m depth with small-scale wave-ripple cross-laminae, discontinuous laminae, mudcracks, and rip-up clasts. **B)** Core slab from 966.1 m depth, with laminae, multiple generations of mudcracks, fluid-escape structures (labeled with arrow), angular rip-up clasts, and rounded clasts of red siltstone. **C)** Thin-section view of fluid-escape structure crosscuts laminae at 966.2 m depth. **D)** Thin-section view of round clast of red siltstone containing angular rip-up clasts, at 966.2 m depth. Note rounded crack around clast. All images are cross sections oriented with respect to stratigraphic up.

(Fig. 12). Flooding, evaporation, and winds played important roles in these Triassic settings. The prevalence of halite and gypsum, in some form in all sedimentary rocks, as well as lack of roots, bioturbation, and fossils, strongly suggest to us that these continental environments were harsh settings for most plants and animals, potentially due to extremes in water chemistry and/or climate.

DISCUSSION

Marine or Nonmarine?

Hardie (1984) addressed the challenging problem of distinguishing marine from nonmarine evaporites. He discussed five specific criteria for making this distinction. These criteria include: (1) fossil types, (2) sedimentology of associated lithofacies, (3) evaporite mineralogy, (4) abundance and trends of evaporites, and (5) evaporite geochemistry (Hardie 1984). The Mercia Mudstone Group presents this geological challenge of determining marine or nonmarine origin.

Typically, fossil assemblages are considered indicators of environmental settings. However, no obvious macrofossils or microfossils were observed in any of the Mercia Mudstone Group lithofacies. No fossils were seen in careful examinations of core slabs and thin sections. If this had been a marine or marginal marine environment, some open or restricted marine fossils would be expected. It is highly unusual to have 591.6-m-thick package of Phanerozoic sedimentary rock without any obvious fossils or organic sedimentary structures. We consider the lack of observed fossils as supporting evidence of an extreme continental environment.

It is notable that the thick Mercia Mudstone Group contains approximately equal abundances of siliciclastics and evaporites, with no carbonates. If these rocks were deposited in a marine-sourced shallow water body in a climate dry enough to precipitate halite and gypsum, there would also be carbonates present. Evapoconcentration of seawater will first

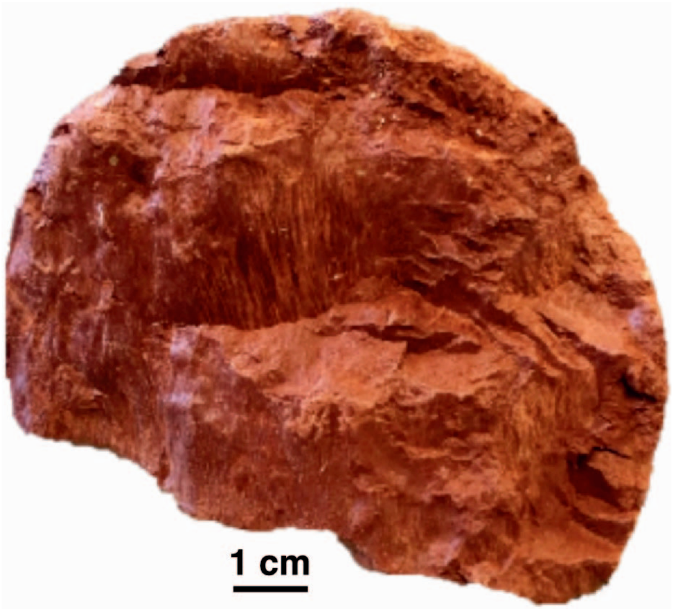


FIG. 9.—Photograph of underside of core fragment of red mudstone with soil slickensides from 449.5 m in Carnduff-2 core.

precipitate calcite or aragonite ($CaCO_3$), followed by gypsum ($CaSO_4$), halite (NaCl), and sylvite (KCl). Even in mixed marine and nonmarine waters, carbonates would be expected (e.g., Hardie and Eugster 1971). We detected no carbonates throughout the 591.6-m-thick unit. The presence of halite and gypsum with siliciclastics, but without any carbonates, suggests saline waters of non-seawater origin.

Marine settings that precipitate evaporites include tidal flats and restricted saline lagoons in arid climates. Saline tidal flats and restricted saline lagoons, besides forming carbonates with evaporites, also have distinct sedimentary structures. Tidal flats can be recognized in the rock record by their tidal bundles (Scholle and Spearing 1982). Tidal bundles are not found in the Mercia Mudstone Group. Saline lagoons are characterized by laminations (Scholle and Spearing 1982; Shinn 1983). However, the Mercia Mudstone Group contains abundant fine-grained siliciclastics that are massive. Typically, the most abundant evaporite morphology in both saline tidal flats and saline lagoons are gypsum and/or anhydrite nodules, which are not present in the Mercia Mudstone Group (Wilson 1975).

Another indicator of nonmarine origin is the relationships of the associated lithofacies in the Mercia Mudstone Group. These lithofacies include saline lake, saline mudflat, dry mudflat, and desert soil. The transitions of interpreted environments, such as upward trends of saline lake to saline mudflat to dry mudflat to soil, is consistent with facies relationships common to modern saline-lake settings. These transitions are not observed in any known marine environments.

Marine-influenced environments commonly deposit rocks that record sea-level change. There is no indication of sea-level rise or fall throughout the 591.6-m-thick Mercia Mudstone Group. Though geologic ages are not well constrained, the overall thickness of the Mercia Mudstone Group and absence of significant unconformities is notable. If this had been a marine or marginal marine environment, it is likely that, in a stratigraphic package this thick, small sea-level changes would have been recorded in cyclic strata and unconformities. We did not recognize any such cyclic strata or unconformities that may suggest a marine influence in the deposition of the Mercia Mudstone Group.

The depositional environment of the Triassic Mercia Mudstone Group is interpreted as a continental-saline-lake system. This was not a marine-sourced environment, such as a marginal-marine or saline-lagoon environment. Two main criteria are absence of carbonates and lack of marine fossils. Other evidence includes thick sequences of fine-grained siliciclastics cemented by halite and gypsum, associated paleosols, and lack of tidal bundles.

Stratigraphic Trends

The Mercia Mudstone Group can be subdivided into two distinct units based on relative abundances of lithologies (Fig. 3). The lower unit is dominated by alternating bedded halite, bedded gypsum, and displacive halite. This unit is interpreted as having formed mostly in shallow saline lakes and mudflats with fluctuating surface water depths. The upper unit is composed of displacive halite, mudstone, siltstone, and sandstone. Rare displacive-halite strata in this upper unit are interpreted as saline mudflats. Mudstone, siltstone, and sandstone strata, more prevalent at the top of this unit, are interpreted as dry mudflat with increasing eolian and pedogenic influences.

There is a general upward trend of bedded evaporites and displacive halite to fine-grained siliciclastics. This is interpreted as a general coarsening-upward sequence. This indicates a transition from saline lakes and saline mudflats to dry mudflats and desert soils. This transition could possibly have formed by increasing aridity that caused the groundwater table to fall.

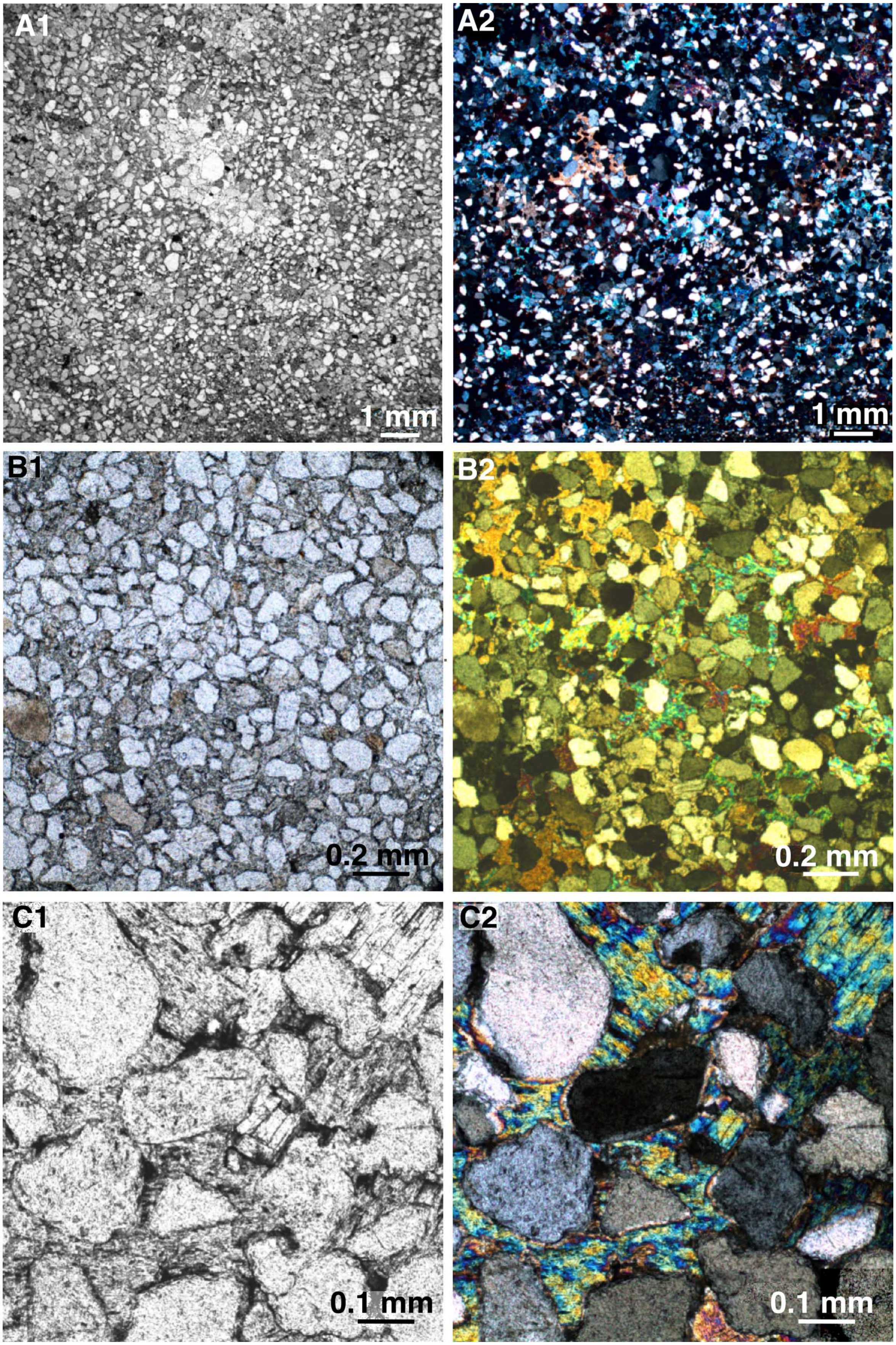
In the Mercia Mudstone Group in the Carnduff-2 core, the finest grains are closely associated with lake deposits. These lake-associated muds may have been deposited by the wind. Another explanation is that these fine grains may have been precipitated directly by lake water, essentially making them chemical sediments disguised as siliciclastics. Both hematite and kaolinite are known to precipitate from some modern acid saline lakes (Benison et al. 2007). Coarser grains (silt- and sand-size) occur in massive strata and are considered eolian. The Mercia Mudstone Group has an overall trend from lake-dominated to eolian-dominated. This trend may represent increased aridity that dropped the groundwater table over time. Chemical precipitation of muds in lakes ceased with lowering of the water table. Eolian deposition dominated the system, allowing coarse-size grains to be the main sediment.

Another explanation for this trend is a lateral migration of environments. In many arid-climate continental systems, saline lakes, saline mudflats, dry mudflats, soils, and dunes coexist. Wind can be the main controller of topographic relief; shallow saline lakes and saline mudflats reside in the lower areas and dry mudflats, dunes, and soils are in the higher areas. However, having one significant trend over 591.6 vertical meters of the Mercia Mudstone Group suggests that lateral migration is likely not the only explanation.

Throughout the Mercia Mudstone Group, there is an abundance of halite present either as bedded-halite crystals, displacive-halite crystals, or halite cement. This significant amount of evaporite minerals indicates that the climate must have been relatively arid throughout deposition. It is important to note that dissolution surfaces are present in bedded-halite sections, effectively erasing previously precipitated halite. The amount of time missing from the dissolution surfaces is unknown, but it is arguable that it was not too extensive because the depositional environments remain consistent. It is also known through comparative sedimentology that some bedded halite can accumulate very rapidly ($\sim$ 10 cm/month; Benison et al. 2007). Therefore, it is very difficult to estimate the amount of time it took for the Mercia Mudstone Group to form.

Can We Correlate the Mercia Mudstone Group in the Larne Basin to Elsewhere in the United Kingdom?

Permo-Triassic red beds and evaporites of the United Kingdom have complex stratigraphy, resulting in a multitude of stratigraphic names (Howard et al. 2008). Some of this data comes from well logs and seismic


A1
1 mm
A2
1 mm
B1
0.2 mm
B2
0.2 mm
C1
0.1 mm
C2
0.1 mm

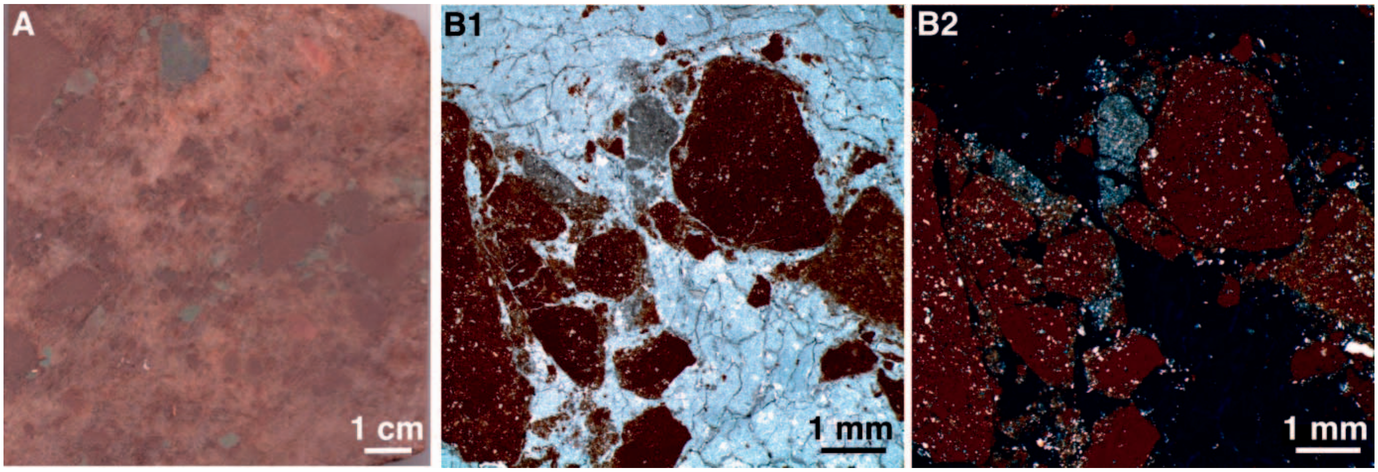


FIG. 11.—Mud clast–halite conglomerate at ~ 944 m depth in the Carduff-2 core. **A)** Core slab of clasts of red and gray mudstone in pink halite matrix. **B)** Thin-section view, in transmitted light (B1) and cross-polarized light (B2). All images are cross sections oriented with respect to stratigraphic "up."

surveys; some comes from outcrops that have likely undergone dissolution and weathering; few represent detailed descriptions of high-recovery core (e.g., Gallois 2001, 2003; Porter and Gallois 2008). The newest nomenclatures for the Mercia Mudstone Group in England differ in stratigraphic names. Howard et al. (2008) includes, from base to top, the Tarporley Siltstone Formation, the Sidmouth Mudstone Formation, the Arden Sandstone Formation, the Branscombe Mudstone Formation, and the Blue Anchor Formation. In contrast, Gallois (2001) lists the Sidmouth Mudstone Formation, the Dunscombe Mudstone Formation, the Branscombe Mudstone Formation, and the Blue Anchor Formation in the Mercia Mudstone. The traditional stratigraphy for the Mercia Mudstone Group in the Larne Basin contains, from base to top, the Glenstaghey Formation, including the Larne Halite Member, the Glenstaghey Formation (undifferentiated), the Knocksoghey Formation, the Pore More Formation, and the Colin Glen Formation (Griffith and Wilson 1982). However, our descriptions of the Carnduff-2 core do not support these formational divisions. We noted two distinct stratigraphic units: the lower halite-rich unit and the upper siliciclastic-rich unit. We consider the lower halite-rich unit in the Carnduff-2 core to consist mainly of the Larne Halite Member. More detailed sedimentological descriptions on intact cores are required to refine stratigraphic relationships across the Triassic rocks of the United Kingdom.

The differences among stratigraphic-unit names and lithologies across the United Kingdom suggest a generally poor correlation. One challenge of attempted correlation of formations and members in the Mercia Mudstone Group from various locations arises from the range of preservation of these red beds and evaporites. Like other evaporite–siliciclastic sequences, the Mercia Mudstone Group is best preserved in moderate depths in the subsurface, where the bedded halite, displacive halite, and halite cements in red beds are not prone to dissolution. In contrast, outcrops and shallow cores of these rocks are likely to be highly altered by halite dissolution by late-stage meteoric groundwaters (Gallois 2001). For example, a study of the Permian Nippewalla Group in outcrops and cores in Kansas showed that displacive halite (early diagenetic halite hosted by red mudstone) was the most common lithology in the subsurface, but its outcrop counterpart consisted of poorly cemented red mudstone (Benison et al. 2015). The Carnduff-2 core represents the high preservation potential of the moderate subsurface depth. In addition, because the Carnduff-2 core was drilled with halite-saturated drilling fluids, little of the core is missing. Only by comparing such high-recovery, well-preserved cores can we truly evaluate whether the units in the Mercia Mudstone correlate across the basins of the United Kingdom.

Recent studies of outcrops of the Mercia Mudstone in the United Kingdom have suggested lacustrine, eolian, and fluvial depositional environments (e.g., Porter and Gallois 2008). Continental deposits are characterized by laterally discontinuous stratigraphic units. This presents another challenge for correlation of lithologies, but it supports the interpretation of the Mercia Mudstone Group as continental deposits.

Interpreting Lake and Groundwater Geochemistry

The lithologies present in the Mercia Mudstone Group contain a variety of information regarding lake and groundwater chemistry. Bedded halite contains chevrons composed of primary fluid inclusions, which are remnants of past lake waters. Fluid inclusions can be used to determine the chemistry of ancient lake water. Displacive halite crystals are viable options to qualitatively determine shallow groundwater chemistry. Intergranular halite cement indicates saline groundwater, as well. The abundant halite is evidence of Na–Cl-rich brines. Halite pseudomorphs after bottom growth gypsum attest to Ca-SO_4-rich lake brines. In addition, hematite and kaolinite in lake and saline mudflat lithofacies may also provide clues regarding water geochemistry.

Modern lake environments that precipitate halite, gypsum, kaolinite, and hematite without the presence of carbonates tend to be acidic (Benison and Goldstein 2002). Acidic saline lakes and groundwaters are typically complex waters rich in Na, Cl, Ca, SO_4, Al, Fe, and Si (Benison and Goldstein 2002; Bowen and Benison 2009). In the Mercia Mudstone Group, acidity is interpreted partly based on the lack of carbonates and the presence of kaolinite ($Al_2Si_2O_5(OH_4)$) and hematite (Fe_2O_3) throughout bedded halite, bedded gypsum, and displacive halite. These minerals could be extrabasinal or intrabasinal. If they formed within the basin by chemical precipitation, the chemical composition of the lake and groundwaters must have been acidic. If these minerals formed outside the basin and were

←

FIG. 10.—Thin-section views of fine sandstone in the Mercia Mudstone from 468.6 m depth in the Carnduff-2 core. **A)** Massive texture, in transmitted light (A1) and cross-polarized light (A2). **B)** Cements include halite and gypsum meniscus cement and epitaxial overgrowths; in transmitted light (B1) and cross-polarized light (B2). **C)** Relatively large, cement-filled intergranular pores, in transmitted light (C1) and cross-polarized light (C2). All images are cross-sections oriented with respect to stratigraphic up. To prevent dissolution of halite, no oil was put on thin sections for viewing.

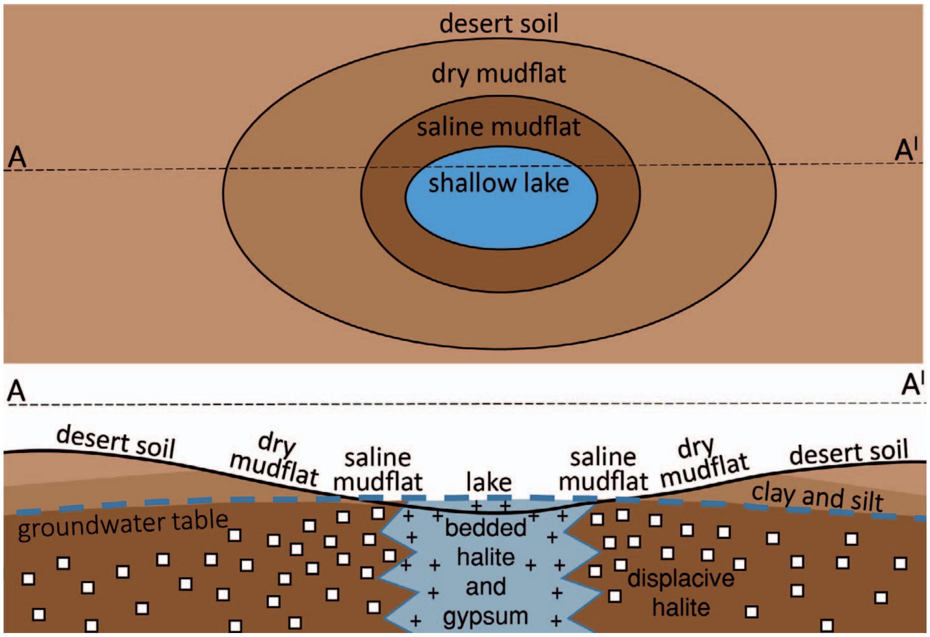


FIG. 12.—Schematic illustration of the Mercia Mudstone Group saline lake and associated facies from **A)** map view and **B)** cross-sectional view.

carried in by wind, then the chemical composition of the lake and groundwaters may not have been acidic. However, relatively homogeneous wind-transported kaolinite and/or hematite is seemingly unlikely. In addition, the lack of carbonates in the Mercia Mudstone indicates that these brines were not alkaline.

Recently, the acidity of the Triassic lake waters was quantitatively determined by laser Raman spectroscopy of primary fluid inclusions in Mercia Mudstone Group bedded halite (Eichenlaub 2016; Eichenlaub et al. 2016). Laser Raman spectroscopy identified aluminum sulfate compounds and bisulfate, suggesting a low pH (< 3). These Raman spectroscopic data, along with sedimentology and mineralogy of the Mercia Mudstone, indicate that the Mercia Mudstone Group was deposited as an acid-saline-lake system (Eichenlaub 2016; Eichenlaub et al. 2016).

How Extensive Were Acid Saline Environments in Pangea?

Past studies indicate that western equatorial Pangea during the mid-late Permian were dominated by acid-saline-lake and groundwater systems (Benison et al. 1998; Benison and Goldstein 2000, 2001). We propose that Northern Ireland was also dominated by similar acid-saline-lake and groundwater systems during the Middle Triassic. Based on the paleographic location of Northern Ireland in the Middle Triassic, the Mercia Mudstone Group was deposited at $\sim 30°$ N (Benton et al. 2002). These extreme terrestrial environments may have covered a large region, from the Equator to 30° N latitude over a distance of at least $\sim$ 8,000 kilometers, perhaps for as long as $\sim$ 30– 40 million years. The spatial and temporal extent of these acid-saline-lake and groundwater environments may have had significant implications for global-scale events such as climate, continent–ocean interactions, and mass extinction.

During the Triassic, Northern Ireland was extremely different from what it is today. There was very low biodiversity of vegetation and macro-invertebrates. Northern Ireland was a stark red landscape of acidic lakes in an arid climate.

CONCLUSIONS

The Triassic Mercia Mudstone Group of the Carnduff-2 core from County Antrim, Northern Ireland, is dominated by bedded halite, bedded gypsum, displacive halite, and mudstone lithologies. Other lithologies were rare and consist of sandstone, mud clast–halite conglomerate, and igneous intrusions. Here, we used detailed hand-sample and thin-section observations to interpret depositional environment and environmental conditions. These strata represent shallow-acid-saline-lake systems surrounded by saline mudflats, dry mudflats, and desert paleosols. Permo-Triassic red beds and evaporite deposits, very much like the Mercia Mudstone Group, are found globally. When compared with other Permo-Triassic red beds and evaporites, we conclude that the Mercia Mudstone Group was deposited as part of a regionally extensive and long-lasting acid saline lake and groundwater system.

ACKNOWLEDGEMENTS

The Gaelectric Energy Storage Ltd. and the Geological Survey of Northern Ireland provided access to the Carnduff-2 core and facilities. National Science Foundation grant EAR-1317138 to KCB provided partial funding. Student grants to ASA from the American Association of Petroleum Geologists, the Geological Society of America, and SEPM (Society for Sedimentary Geology) partially supported this study. We also thank the WVU Geology and Geography Department for logistical and financial support. James Thompson of WVU Division of Plant and Soil Sciences allowed us to use his chroma meter to accurately describe colors. JSR Editor Leslie Melim, Associate Editor Tobi Payenberg, and reviewers Brenda Bown and Elliot Jagniecki are thanked for their time and revisions, which greatly improved our manuscript. Kyle Andrus, Jeremiah Bernau, Tim Carr, Joseph Donovan, Patrick Frier, Jackson Jakeway, Jonathan Knapp, Tim Lowenstein, Stefano Lugli, Natalie Odegaarden, Charlotte Schreiber, Joseph Smoot, and the late Elizabeth Gierlowski-Kordesch are thanked for discussions.

REFERENCES

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., AND GOLDSTEIN, R.H., 2002, Recognizing acid lakes and groundwaters in the rock record: Sedimentary Geology, v. 151, p. 177–185.

BENISON, K.C., AND GOLDSTEIN, R.H., 2001, Evaporites and siliciclastics of the Permian Nippewalla Group, Kansas and Oklahoma: a case for nonmarine deposition: Sedimentology, v. 48, p. 165–188.

BENISON, K.C., AND GOLDSTEIN, R.H., 2000, Sedimentology of ancient saline pans: an example from the Permian Opeche Shale, Williston Basin, North Dakota: Journal of Sedimentary Geology, v. 79, p. 159–169.

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.

Benison, K.C., Bowen, B.B., Oboh-Ikuenobe, F.E., Jagniecki, E.A., LaClair, D.A., Story, S.L., Mormile, M.R., and Hong, B.Y., 2007, Sedimentology of acid saline lakes in southern Western Australia: newly described processes and products of an extreme environment: Journal of Sedimentary Research, v. 70, p. 366–388.

Benison, K.C., Zambito, J.J., and Knapp, J.P., 2015, Contrasting siliciclastic–evaporite strata in subsurface and outcrop: an example from the Permian Nippewalla Group of Kansas, U.S.A.: Journal of Sedimentary Research, v. 85, p. 626–645.

Benton, M., Cook, E., and Turner, P., 2002, Permian and Triassic Red Beds and the Penarth Group of Great Britain: Joint Nature Conservation Committee, Peterborough, no. 24, 337 p.

Bowen, B.B., and Benison, K.C., 2009, Geochemical characteristics of naturally acid and alkaline saline lakes in southern Western Australia: Applied Geochemistry, v. 24, p. 268–284.

Campbell, J.A., 1963, Permo-Triassic red beds, northern Denver Basin, *in* Bolyard, D.W., and Katich, P.J., eds., Geology of the Northern Denver Basin and Adjacent Uplifts: Denver, Rocky Mountain Association of Geologists, 14th Annual Field Conference, Bulletin, p. 105–110.

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.

Clifton, R.L., 1944, Paleoecology and environments inferred for some marginal Middle Permian marine strata: American Association of Petroleum Geologists, Bulletin, v. 28, p. 1012–1031.

Daidu, F., 2013, Classifications, sedimentary features and facies associations of tidal flats: Journal of Paleogeography, v. 2, p. 66–80.

Eichenlaub, L.A., 2016, A fluid inclusion study of acidity in bedded halite of the Larne Halite Member, Triassic Mercia Mudstone Group from the Carnduff-2 core, County Antrim, Northern Ireland [unpublished M.S. thesis]: West Virginia University, 173 p.

Eichenlaub, L.A., Benison, K.A., and Andeskie, A.S., 2016, Acid fluid inclusions in bedded halite of the Triassic Mercia Mudstone, Northern Ireland: Geological Society of America, Annual Meeting, Denver, Colorado.

Foster, T.M., Soreghan, G.S., Soreghan, M.J., Benison, K.C., and Elmore, R.D., 2014, Climatic and paleogeographic significance of aeolian sediment in the Middle Permian Dog Creek Shale (midcontinent U.S.): Palaeogeography, Palaeoclimatology, Palaeoecology, v. 402, p. 12–29.

Gallois, R.W., 2001, The lithostratigraphy of the Mercia Mudstone Group (mid to late Triassic) of the south Devon Coast: Ussher Society Proceedings, v. 10, p. 195–204.

Gallois, R.W., 2003, The distribution of halite (rock-salt) in the Mercia Mudstone Group (mid-late Triassic) in South-West England: Geoscience in South-West England, v. 10, p. 383–389.

Griffith, A.E., and Wilson, H.E., 1982, Geology of the Country Around Carrickfergus and Bangor, Second Edition: Geological Survey of Northern Ireland, 118 p.

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., 1971, The depositional environment of marine evaporites: a case for shallow, clastic accumulation: Sedimentology, v. 16, p. 187–220.

Holford, S.P., Green, P.F., Duddy, I.R., Turner, K.P., Hillis, R.R., 2009, Regional intraplate exhumation episodes related to plate-boundary deformation: Geological Society of America, Bulletin, v. 121, p. 1611–1628.

Howard, A.S, Warrington, G., Ambrose, K., and Rees, J.G., 2008, A formational framework for the Mercia Mudstone Group (Triassic) of England and Wales: British Geological Survey, Research Report RR/08/04, 41 p.

Knapp, J.P., and Benison, K.C., 2013, Rethinking depositional environments of the Permo-Triassic Goose Egg/Chugwater redbeds: preliminary results from outcrops near Rawlins, Wyoming: Geological Society of America, Annual Meeting, Denver, Colorado, Abstracts with Program.

Lowenstein, T.K., and Hardie, L.A., 1985, Criteria for the recognition of salt-pan evaporites: Sedimentology, v. 32, p. 627–644.

Maughan, E.K., 1966, Environment of deposition of Permian salt in the Williston and Alliance Basins: Cleveland, Ohio, Northern Ohio Geological Survey, Second Symposium on Salt, v. 1, p. 35–47.

Picard, M.D., and High, L.R., Jr., 1968, Shallow marine currents on the Early(?) Triassic Wyoming shelf: Journal of Sedimentary Petrology, v. 38, p. 411–423.

Porter, R.J., and Gallois, R.W., 2008, Identifying fluvio-lacustrine intervals in thick playa-lake successions: an integrated sedimentology and ichnology of arenaceous members in the mid-late Triassic Mercia Mudstone Group of south-west England, UK: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 270, p. 381–398.

Scholle, P.A., and Spearing, D., 1982, Sandstone Depositional Environments: American Association of Petroleum Geologists, Memoir 31, 402 p.

Schubel, K.A., and Lowenstein, T.K., 1997, Criteria for the recognition of shallow-perennial-saline-lake halites based on recent sediments from the Qaidam Basin, Western China: Journal of Sedimentary Research, v. 67, p. 74–87.

Shinn, G., 1983, Tidal flat environment, *in* Scholle, P.A., Bebout, D.G., and Moore, C.H., eds., 1983, Carbonate Depositional Environments: American Association of Petroleum Geologists, Memoir 33, p. 171–210.

Smith, D.B., 1971, Possible displacive halite in the Permian Upper Evaporite Group of northeast Yorkshire: Sedimentology, v. 17, p. 221–232.

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.

Smoot, J.P., and Lowenstein, T.K., 1991, Depositional environments of non-marine evaporites, *in* Melvin, J.L., ed., Evaporites, Petroleum, and Minerals Resources: Amsterdam, Elsevier, Developments in Sedimentology, v. 50, p. 189–347.

Sweet, A.C., Soreghan, G.S., Sweet, D.E., Soreghan, M.J., and Madden, A.S., 2013, Permian dust in Oklahoma: source and origin for Middle Permian (Flowerpot–Blaine) redbeds in western tropical Pangaea: Sedimentary Geology, v. 284–285, p. 181–196.

Tresise, G., and Sarjeant, W.A.S., 1997, The Tracks of Triassic Vertebrates: Fossil Evidence from North-West England: Norwich, The Stationary Office, 204 p.

Warrington G., 1997, The Lyme Regis Borehole, Dorset; palynology of the Mercia Mudstone, Penarth and Lias groups (Upper Triassic–Lower Jurassic): Ussher Society, Proceedings, v. 9, p. 152–157.

Warrington, G., Wilson, A.A., Jones, N.S., Young, S.R., and Haslam, H.W., 1999, Stratigraphy and sedimentology in the Cheshire Basin: basin evolution, fluid movement and mineral resources in a Permo-Triassic rift setting: British Geological Survey, Her Majesty's Stationery Office, p. 23–46.

Wilson, J.L., 1975, Carbonate Facies in Geologic History: New York, Springer-Verlag, 470 p.

Received 12 July 2017; accepted 8 December 2017.