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ORIGINAL ARTICLE

Mixed clastic-carbonate lake margin systems: An example from the Triassic of East Greenland

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Abstract

Lake margin deposits are the subject of increased study, but this is often focussed on either clastic or carbonate/microbial dominated end members. This study examines the interaction of clastic and carbonate systems. The Upper Triassic Edderfugledal Formation in East Greenland provides superb exposures through a carbonate dominated lacustrine succession. Fluctuations in lake level, interpreted as a response to cyclic, orbitally forced, climatic variance resulted in a highly mobile lake shore zone. The response of the shore zone environment to these fluctuations in lake level, and the interaction of both clastic and carbonate components, are documented in this study. A general trend from more arid to more humid conditions is recognised through the Edderfugledal Formation. This trend is reflected in a transition from more ephemeral lacustrine conditions with low sediment input to conditions where lacustrine episodes were more prolonged and clastic input was increased. Deposits reflecting more ephemeral conditions are dominated by extensive post-depositional disruption including desiccation, pedogenic processes and evaporite precipitation. These effects increase towards the lake margins where exposure was most common and most prolonged. Increasingly humid conditions and the associated longer-lived lacustrine developments and increased clastic sediment input resulted in a very different form of lake margin. During transgressive phases sediment input was pushed back to the lake margin allowing extensive microbialite development. Ooidal shoals developed in shallow water beyond the extent of clastic input. The lakeward migration of the ooidal shoals and the progradation of clastic systems eventually stifled the microbialites prior to the next transgressive event. In a mixed clastic-carbonate lacustrine setting the interaction of sediment supply and production are key factors in governing facies development and these are in turn predominantly controlled by lake-level change and lake margin bathymetry.

KEYWORDS

clastic-carbonate, cycles, Edderfugledal Formation, lake shore zone, microbialites

[Correction added on 14 March 2025, after first online publication: The affiliation of the second author was incorrect in the original-published version of the article. It has been corrected.]

1 | INTRODUCTION

Lake margin deposits provide an opportunity to examine the delivery and transfer of sediments into lacustrine systems. An increasing number of studies have examined lake margin systems but these have often focussed on either clastic or carbonate-microbial dominated facies associations (Renaut & Owen, 1991; Martel & Gibling, 1991; Andrews & Hartley, 2015; Liao et al., 2024; Platt & Wright, 1991; Moreau et al., 2024). This study provides a rare example of the interaction of clastic and carbonate facies from a dynamic lake margin recorded in the Upper Triassic Edderfugledal Formation in the Jameson Land Basin, East Greenland.

The Edderfugledal Formation lies within the Upper Triassic Fleming Fjord Group (Andrews et al., 2021; Clemmensen et al., 2020; Clemensen, 1978, 1980a, 1980b) and can be traced for over 150 km across the Jameson Land Basin between 70° 20′ and 72° 20′ N on the East Greenland coast (Figure 1). Although dominated by carbonate facies, including microbialites, the Edderfugledal Formation also includes clastic facies, which tend to become more significant up section. The facies recognised form distinct cycles, interpreted to record regular, climatically controlled, fluctuations in lake level within a closed basin (Clemmensen, 1978). These cycles have been attributed to orbital forcing by Clemmensen et al. (2020).

The upward transition from carbonate to clastic facies, alongside the high frequency variations in lake level and superb arctic exposures, have provided the ideal setting to examine the lateral and temporal interaction of a varied range of carbonate and clastic environments which comprised the lake margin sedimentary systems. This study largely draws from the examination of five closely spaced (0.5–1.5 km) sections from Dværgarvedal, which lies towards the northern margin of the Jameson Land Basin (Figure 1). Detailed logging was undertaken of these sections and augmented by thin section, scanning electron microscopy (SEM) and stable isotope analysis on selected samples.

The aim of this study is to characterise hitherto poorly documented clastic-carbonate interactions in lake shore zone settings, and to consider the controls on the observed facies distributions. To achieve this the facies associations are first described, before their vertical relationships are examined in relation to fluctuating lake levels and concomitant transient shore zones. The lateral relationships are then considered and depositional models are proposed.

2 | GEOLOGICAL SETTING

The Jameson Land Basin lies on the western margin of the Greenland-Norway rift between 70°05′ and 73° N (Figure 1). The central portion of the basin, on which this study is focussed, is 200 km long, 70 km wide and is aligned north-south. The basin margins are defined by the Stauning Alper Fault in the west and the Liverpool Land high, on to which the Triassic succession onlaps (Andrews et al., 2021) in the east (Figure 2). A number of NE–SW oriented faults divided the basin during the Early through Mid Triassic but these appear to have had little, if any, control on deposition by Norian times (Andrews et al., 2021). Activity on faults of a similar orientation during the latest Rhaetian—Early Jurassic has been suggested (Andrews et al., 2022).

Rifting in East Greenland occurred over a protracted period, the initiation of which is the subject of some debate, with some workers arguing for post-Caledonian (Devonian) extension resulting from the collapse of the Caledonian Orogen (McClay et al., 1986; Surlyk, 1990) and others suggesting a strike slip origin for these early basins and true extension only beginning after a major Mid Permian hiatus (Friend et al., 1983; Henriksen & Higgins, 1976). Two rift events are suggested to have occurred during the Early Triassic (Seidler et al., 2004) leading to deposition of a thick marine turbidite succession which shallows upwards and is overlain by a continental succession which reaches over 1.5 km in thickness and comprises the rest of the Triassic succession. Initial alluvial coarse clastics of the Pingo Dal Group display distinct thickening into faults (Andrews et al., 2021; Guarnieri et al., 2017) suggesting active faulting during deposition. The overlying succession is dominated by lacustrine units of the Gipsdalen and Fleming Fjord groups which have a more tabular geometry, interpreted to reflect deposition in a post-rift setting (Andrews et al., 2021).

The units which are the focus of this study lie within the Fleming Fjord Group which forms the uppermost unit of the Triassic succession in the Jameson Land Basin (Figure 3) and comprise the lacustrine-dominated Edderfugledal and Malmros Klint formations and the fluvial dominated Ørsted Dal Formation (Clemmensen, 1980a; Clemmensen et al., 2020). The Edderfugledal Formation is split into the lower, microbialite-rich Sporfjeld Member and the overlying sandier Pingel Dal Member (Clemmensen, 1980a; Clemmensen et al., 2020).

3 | METHODS: THIN SECTION, SEM, XRD AND STABLE ISOTOPE ANALYSIS

Thin section analysis was carried out on 38 samples. All samples were first impregnated with blue epoxy in order to highlight the porosity, and stained with a potassium ferricyanide/alizarin red-S solution (Dickson, 1965) to facilitate the distinction of calcite (pink), Fe dolomite (blue) and dolomite. All thin sections were examined using standard transmitted-light petrography.

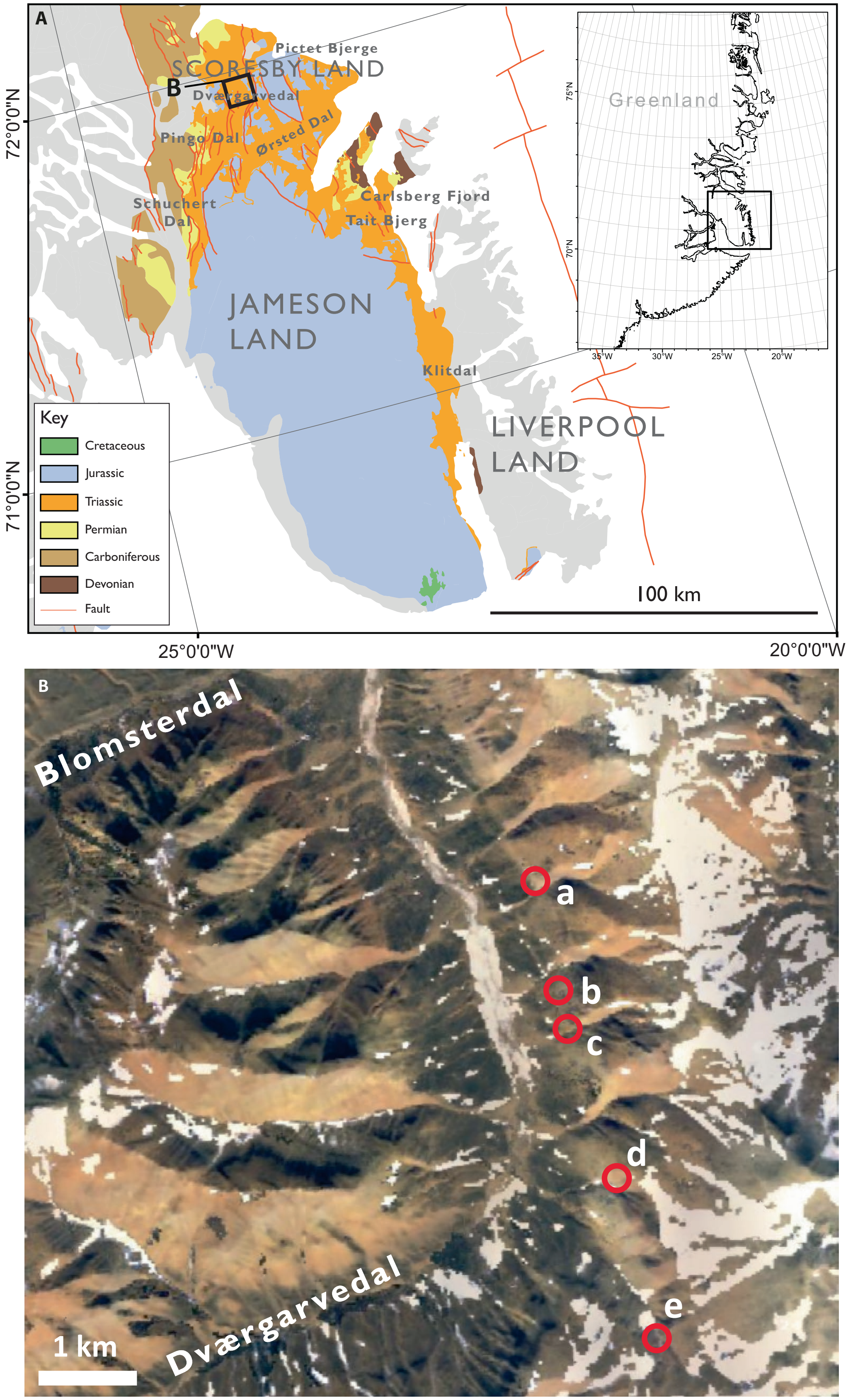


FIGURE 1 (A) Geological map of the Jameson land and Scoresby Land regions of Central East Greenland. Inset map provides the position of the geological map in its wider context. (B) Satellite image of the studied region. The location of the five sections that were logged (Figure 9) along the eastern side of Dværgarvedal (a–e) are also indicated.

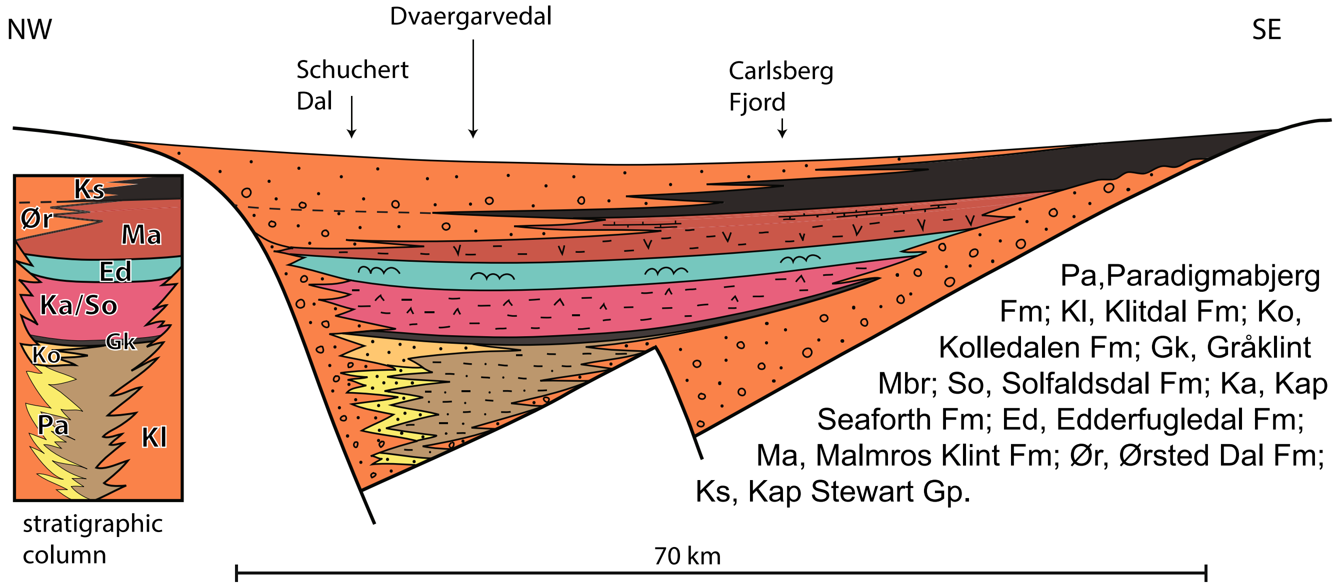


FIGURE 2 Schematic cross section from the north-west to the south-east across the Jameson Land Basin illustrating the gross observed stratigraphic geometries. See Figure 1 for location of areas identified on the cross section. The Edderfugledal Formation was deposited as a widespread tabular unit during post-rift subsidence. See Figure 3 for lithological definition.

Energy dispersive X-ray spectroscopy (EDS) analysis and SEM imaging was performed on a QANTA-650F SEM platform in the Earth Sciences Department, University of Cambridge. Selected samples were highly polished and coated with carbon. High vacuum mode was used. Two Bruker XFlash 6 type detectors were used for EDS analysis. A 20 kV beam, 3 μm spot size and a working distance (WD) of 13 mm were used for EDS analysis.

X-ray diffraction (XRD) was performed on four selected samples to determine mineralogy in the Earth Sciences Department, University of Cambridge. All data were collected in Bragg–Brentano geometry on a D8 Bruker diffractometer equipped with Goebel mirrors for primary CuKα parallel radiation and a Vantec position sensitive detector. Collection conditions were: 3–60° in 2θ, 0.04 step size, 150 s/step divergence slits 0.6 mm. Phase identification was performed with software Eva 10.0 (Bruker) using the PDF2 (Powder Diffraction File) database from 1998.

Stable carbon and oxygen isotope analyses were undertaken on 14 samples at the Godwin Laboratory for Palaeoclimate Research, Department of Earth Sciences, University of Cambridge. Approximately 250 μg of the dried homogenised sample was transferred in to exetainer vials and sealed with silicone rubber septa using a screw cap. The samples were flushed with CP grade helium then acidified, left to react for 2 h at 70°C and then analysed using a Thermo Gas Bench preparation system attached to a Thermo MAT 253 mass spectrometer in continuous flow mode. Each run of samples was accompanied by 10 reference carbonates (Carrara) and two control samples (Fletton). Carrara has been calibrated to VPDB using the international standard NBS19. The results are reported with reference to the international standard VPDB and the precision is better than ±0.08‰ for $^{12}C/^{13}C$ and ±0.10‰ for $^{16}O/^{18}O$.

4 | THE EDDERFUGLEDAL FORMATION

The Edderfugledal Formation lies within a series of lacustrine units which form the Upper Triassic succession of East Greenland. Palynological evidence documented by Andrews et al. (2014) places the Edderfugledal Formation within the Norian. The transition from the gypsum bearing units which lie below (Gipsdalen Group) through the carbonate facies of the Edderfugledal Formation and into the more argillaceous facies of the overlying units (Malmros Klint Formation) has been interpreted to be the result of climate amelioration caused by the northward movement of Pangea (Decou et al., 2017). Recurrent ordered alterations of the facies recognised within the Edderfugledal Formation define sedimentary cycles which have been interpreted as the result of climatically controlled fluctuations in lake level (Clemmensen, 1978). Orbital forcing provides the most probable mechanism for the control of these regular climatic fluctuations (Clemmensen et al., 2020). The evaporative nature of the sedimentation (carbonate), lack of progradational sedimentary packages and the regular fluctuations of lake level are consistent

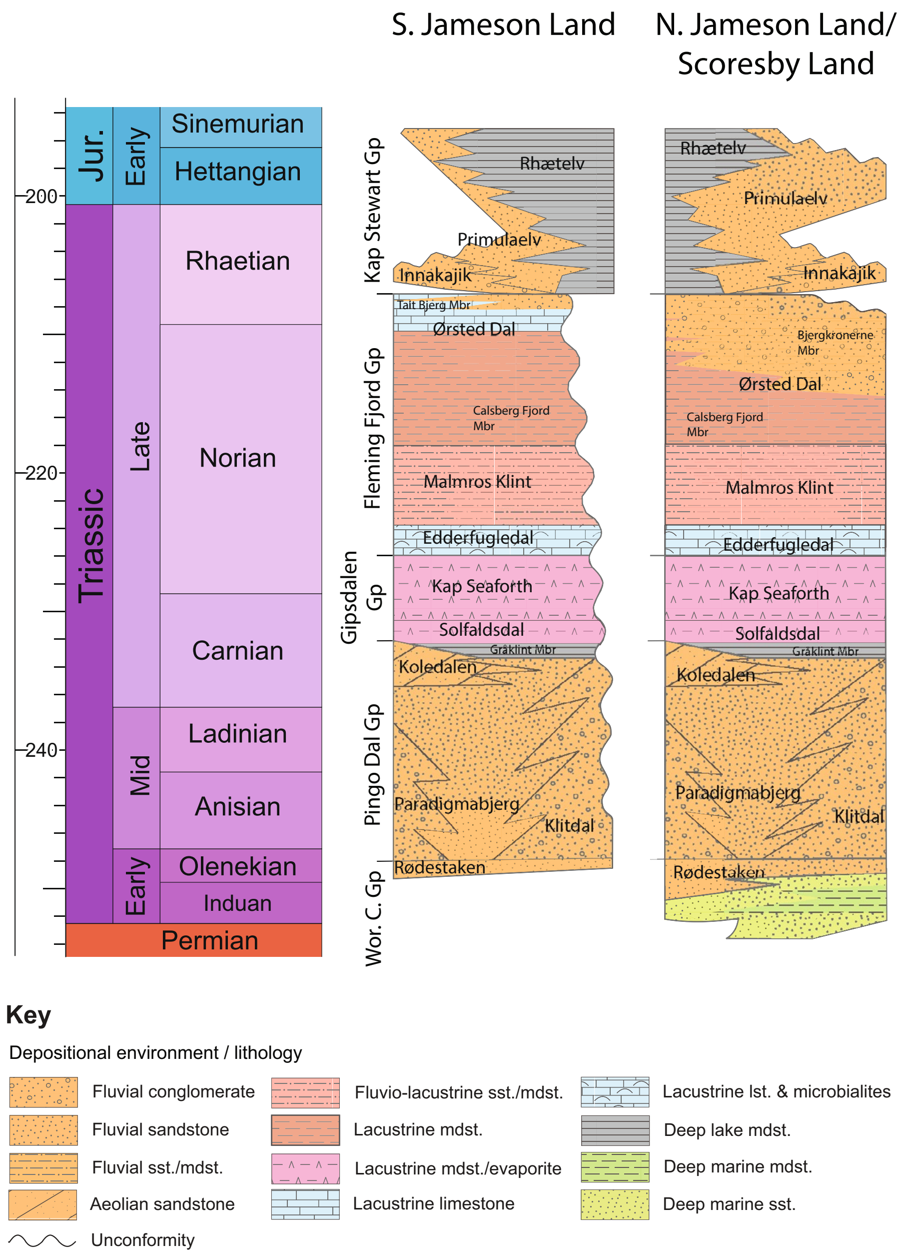


FIGURE 3 Stratigraphy of the Jameson Land Basin after Clemmensen et al. (2020) and Andrews et al. (2021).

with deposition within an under to balanced filled, largely closed, basin.

5 | FACIES ASSOCIATIONS

Six facies associations are recognised in the studied sections though the Edderfugledal Formation: laminated dark grey mudstone; intercalated grey mudstone and sandstone; intercalated desiccated mudstone and sandstone; nodular and brecciated grey-buff dolostone; microbialite; and hummocky cross stratified sandstone and grainstone facies associations. These are described, including additional analysis that was performed and interpreted in turn. A summary of the characteristic features of each facies association, the predominant processes responsible for their formation and the proposed depositional environment is provided in Table 1.

5.1 | Laminated Dark Grey Mudstone Facies Association

5.1.1 | Description

This facies association comprises laminated dark grey mudstones which form intervals up to 2 m thick but more commonly range between 0.2 and 0.4 m (Figure 4A). The mudstones contain significant carbonate content. Lamination ranges from 1 mm to sub-millimetre with rare very fine sandstone laminae up to 2 mm thick. Thicker (0.1 m) limestones which lack internal structure are also

TABLE 1 Summary of the facies associations identified.

Facies association	Grain size	Colour	Composition (mudstone)	Bed characteristics	Sedimentary structures	Process interpretation	Depositional environment
Laminated dark grey mudstone	Mudstone	Dark grey	Carbonate-rich plus up to 0.75% TOC	0.2–0.4 m thick (exceptionally up to 2 m)	1 mm to sub mm lamination. Rare very fine sandstone laminae up to 2 mm thick. Occasional thicker (0.1 m) massive limestones	Low energy sediment settling and anoxic waters	Profundal lacustrine
Intercalated grey mudstone and sandstone	Mudstone/siltstone and very fine sandstone	Grey-dark grey (weather to buff)	Mictritic calcite and dolomite	0.2–2 m thick (sandstones 5–150 mm thick, some with scoured bases)	*Mudstone/siltstone*: 1–3 mm lamination and minor bioturbation *Sandstone*: grading, current ripples and micro hummocky cross stratification *Other*: rare 0.1 m thick chaotic beds (ooids, rounded quartz grains, rounded limestone clasts, elongate microbialite clasts). Occasional massive carbonate mudstones (0.15 m)	Alternating low and high energy with unidirectional and oscillatory flow in oxygenated waters	Shallow lake—deposition at or around wavebase
Intercalated desiccated mudstone and sandstone	Mudstone and very fine sandstone	Grey (buff weathering)	Mictritic calcite and dolomite	0.05–0.4 m thick	*Mudstone*: 10–50 mm lamination, desiccation cracks, rare syneresis cracks and carbonate nodules *Sandstone*: 2–10 mm thick, oscillation and current ripples and possible bioturbation. Plus rare 50–200 mm thick graded sands with loaded bases *Other*: massive carbonate mudstone beds—traces of lamination	Shallow water, at times high energy, deposition with intermittent desiccation and associated salinity changes	Desiccating lacustrine
Nodular and brecciated grey-buff dolostones	Mudstone	Grey-buff	Mictritic calcite and dolomite plus crystalline calcite in fractures	0.1–0.6 m thick	Carbonate nodules (up to 0.2 m in diameter) with diffuse contacts with surrounding carbonate mudstones and in places slickensides. Brecciation of nodule cores with calcite fracture fill. Plus brecciated carbonate mudstone beds with uneven bed tops. Pseudomorphs after gypsum also present	Extensive post-depositional disruption through expansion and contraction through wetting and drying/evaporation	Palustrine

TABLE 1 (Continued)

Facies association	Grain size	Colour	Composition (mudstone)	Bed characteristics	Sedimentary structures	Process interpretation	Depositional environment
Microbialite	Mudstone—fine grained	Grey and buff	Fine grained calcite and dolomite	Up to 0.4 m thick	*Microbialite lamination*: alternating smooth calcite and dolomite laminations (0.5–4 mm thick), with some quartz grains and gypsum crystals included. Laterally linked hemispheroidal forms developed in places. These coat/form the features below: *Sediment cored mounds*: mounds with up to 0.4 m relief. Sediment cores with internal bedding truncated at margins. Often aproned by brecciated microbialite, ooids and oncoids *Ridge and runnel systems*: ridges up to 0. 8 m wide with 0.2 m relief. Runnels up to 0.3 m wide often filled with edgewise breccia, microbialite fragments or laminated carbonate mudstone *Sheets*: 10–20 mm thick with smooth to ruckled surface. Some dolomitic mud drapes between laminations	Microbial mediation of carbonate precipitation and interaction with periods of high energy erosion resulting in variable microbialite forms	Microbialite—shallow water
Hummocky cross stratified sandstone and grainstone	Very fine sandstone/ Coarse to very coarse ooids	Light grey/ Light grey—buff		Up to 3 m think, beds are 5–50 mm thick	Large scale and micro-hummocky cross stratification predominate with some wave ripples. Rare mudstone/ siltstone drapes with desiccation and syneresis cracks. Occasional *Fuersichnus* and vertical burrows Low angle cross stratification and small scale scours are present in the grainstones, which are well-sorted and include some lithoclasts and quartz grains	High intensity oscillatory flow. swash backwash and periods of quiescence with desiccation and salinity changes	Shore zone

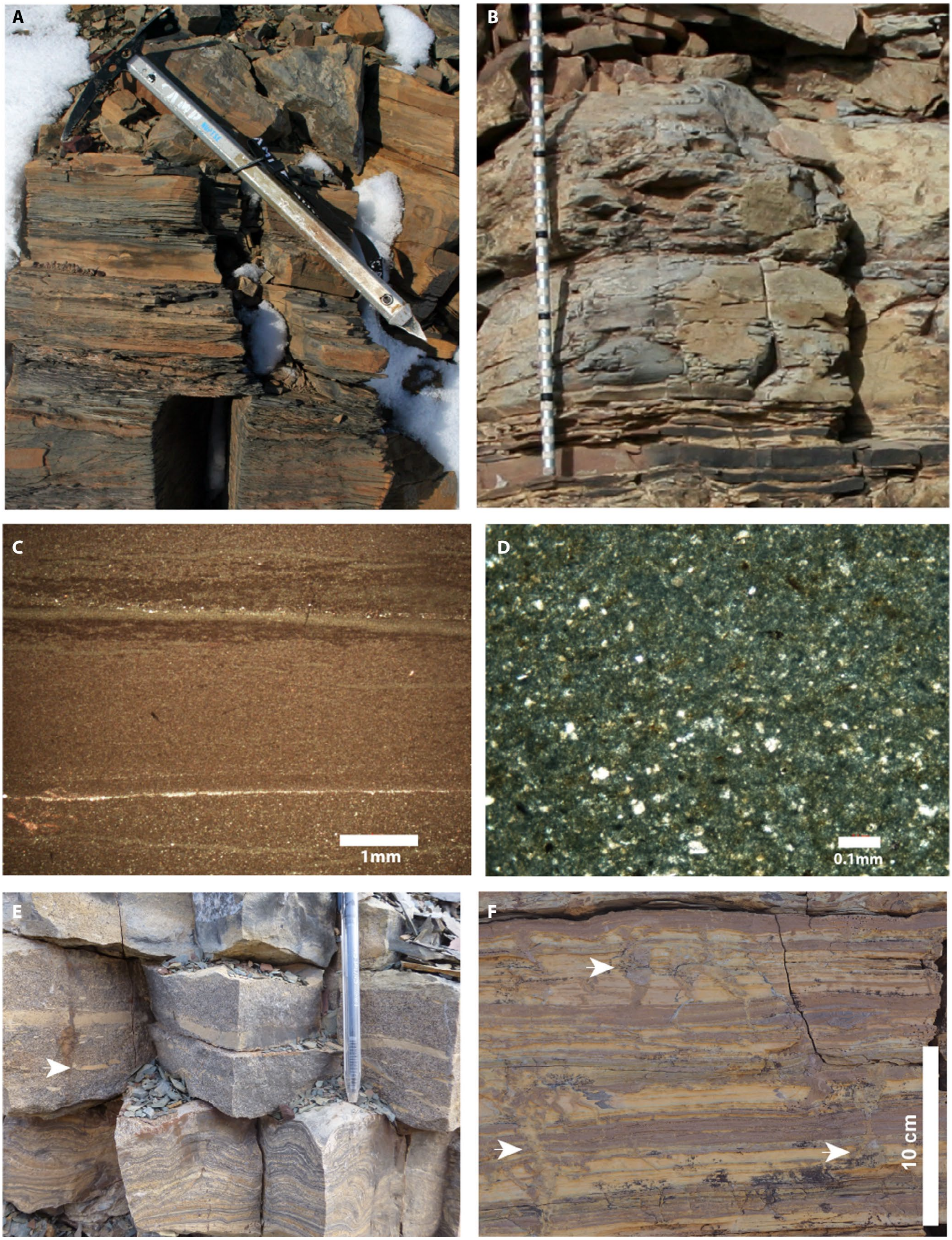

A
B
C
1mm
D
0.1mm
E
F
10 cm

FIGURE 4 Edderfugledal Formation facies associations. (A) Laminated Dark Grey Mudstone Facies Association containing both finely laminated intervals and thicker structureless beds (ice axe is 0.7 m long). (B) Intercalated Grey Mudstone and Sandstone Facies Association with sandstone components concentrated towards the base of the interval (black bands on the measuring stick represent 0.1 m intervals). Photomicrographs of stained carbonate mudstones, (C) micritic and sparry lime mudstone of the Intercalated Grey Mudstone and Sandstone Facies Association with both laminated (top) and more structureless (bottom) intervals illustrated and (D) dolostone consisting of very fine and densely packed dolomite with abundant fine grained quartz. (E) Coarse grained, chaotic, 'storm' bed within the Intercalated Grey Mudstone and Sandstone Facies Association overlying microbialte deposits. Intraclasts, arrowed, are suspended in a matrix of ooids and quartz grains (pen is 0.12 m long). (F) Intercalated Desiccated Mudstone and Sandstone Facies Association. Desiccation cracks, arrowed, are prevalent.

present in some examples. Although little palaeontological material was recognised from this facies association during this study, previous workers have documented a low-diversity assemblage of bivalves, and common conchostracans, from the wider Edderfugledal Formation (see Clemmensen et al., 2020; Clemmensen, 1980a).

5.1.2 | Interpretation

The thin laminae and dark colouration, indicative of the preservation of organic material (up to 0.75% total organic carbon), are interpreted to reflect deposition in a low energy and oxygen poor setting. The restricted fauna and complete lack of a marine faunal assemblage favour a lacustrine interpretation with deposition occurring in oxygen poor bottom waters, below storm wave base. A continental environment was also favoured for the wider Edderfugledal Formation by Bromley and Asgaard (1979) on the basis of the trace fossil assemblage they identified. This facies association can thus be interpreted as a profundal lacustrine depositional environment.

5.2 | Intercalated Grey Mudstone And Sandstone Facies Association

5.2.1 | Description

This facies association is dominated by intercalated grey mudstones/siltstones and sandstones (Figure 4B). The proportion of sandstone shows considerable variability even within individual units (0.2–2 m thick). The mudstones/siltstones are laminated on a 1–3 mm scale and are largely grey to dark grey in colour but commonly weather to buff. Carbonate mudstone samples were subject to thin section analysis from which both micritic calcite and dolomite were recognised (Figure 4C,D, red/pink and blue staining respectively). Confirmation of the presence of dolomite was made by XRD analysis of blue stained material (Figure S2). In some samples, XRD analysis highlighted the presence of dolomite where only calcite is identified through staining and thin section analysis. It seems probable therefore that in some instances the dolomite has remained unstained, as is more characteristic of non-ferroan dolomite. Minor bioturbation is noted within the mudstones but this resulted in little disruption of the lamination. The intercalated sandstones are composed of very fine sand and form beds 5–150 mm thick. Scoured bases are common and internally, grading, current rippling and micro-hummocky cross stratification are recognised. More rarely 0.1 m thick beds containing a chaotic mixture of ooids, rounded quartz grains, rounded calcareous mudstone clasts and angular elongate clasts of microbialite material (2–100 mm) are observed (Figure 4E). Structureless grey limestones and dolomitic mudstones up to 0.15 m thick are also recognised within this facies.

5.2.2 | Interpretation

The presence of micro-hummocky cross stratification suggests deposition in a shallower environment than that of the Laminated Dark Grey Mudstone Facies Association (Allen 1981a, 1981b). The lighter colour and the presence of minor bioturbation further evidences shallower water conditions with more oxygenated bottom waters. Grading, current rippling and scoured bases in the intercalated sandstone beds are interpreted as typical of underflow deposits similar to those described from Lake Brienz by Sturm and Matter (1978). Micro-hummocky cross stratification within these sandstone beds indicates wave reworking of these sediments. The thicker, more chaotic, coarse beds are of a very different provenance with clasts suggestive of derivation from a shallow lake margin. Such a difference in provenance may indicate that these deposits record storm generated density flows washing in coarser material from the lake margins as opposed to the thinner sand intercalations which originated from density currents issuing from a fluvial input.

The prevalent buff colour of the carbonate mudstone components of this facies has previously been interpreted as evidence for a largely dolomitic composition (Clemmensen, 1978, 1980b). However, the petrographic and XRD analysis carried out here has demonstrated that the mudstones are composed of a mixture of micritic calcite and dolomite. The origin of the micritic calcite is likely to be through primary precipitation (Kelts & Hsü, 1978). Primary/penecontemporaneous precipitation of dolomite has been documented from a number of modern lake settings where intense evaporation and recharge play an important role, often in association with microbial activity (Last, 1990; Muir et al., 1980; Warren, 1990; Wright & Wacey, 2005). A similar situation could be envisaged here, and is consistent with other indicators of arid conditions, although later dolomitisation of calcite muds cannot be ruled out. The features described here are consistent with deposition in a shallow lake environment, at or around wave base. The presence of dolomitic laminae further supports this interpretation with this facies association reflecting more arid, evaporative, conditions than prevailed during the deposition of the laminated dark grey mudstone facies association. The intercalation of very fine sandstone laminae, interpreted as gravity driven underflow deposits, are indicative of deposition in a proximal position with respect to the lake margin.

5.2.3 | Intercalated Desiccated Mudstone And Sandstone Facies Association description

The Intercalated Desiccated Mudstone and Sandstone Facies Association consists of grey, buff weathering, mudstones containing 10–50 mm thick lamination which are intercalated with very fine grained sandstones which are 2–10 mm thick. Mud cracks which are 30–100 mm deep with largely straight edges are common (Figure 4F) and more rarely shallower (10–50 mm) mud cracks, often displaying ptygmatic style folding resulting from compaction and carbonate nodules are recorded. The sandstone interlaminations contain oscillation ripples and current ripples. More rarely, thicker (50–200 mm) graded sandstone beds with loaded bases are recorded. Rounded quartz grains are often noted within these beds. Poorly defined traces of bioturbation are recorded throughout this facies. Apparently structureless 0.1–0.2 m thick carbonate beds are also present, although in some instances they contain subtle, 10–30 mm thick laminations defined by thin sandstone interlaminations. Samples examined in thin section contain fine grained carbonates that display both blue and red/pink staining, indicative of the presence of both dolomite and calcite. The XRD results from one sample confirms the presence of dolomite (Figure S3).

5.2.4 | Interpretation

The fine grained nature of this facies association indicates deposition in a largely low energy environment with the presence of oscillation ripples and minor bioturbation suggestive of a relatively shallow standing body of water. The mudcracks identified are interpreted as mostly the product of desiccation, with a few others resulting from syneresis. The abundance of desiccation cracks record periodic evaporation to dryness indicative of ephemerality. The identification of syneresis cracks suggests fluctuations in lake chemistry (Donovan & Foster, 1972; Plummer & Gostin, 1981) which would also be expected in an ephemeral lacustrine setting. The carbonate-rich nature of the mudstones, in some instances forming structureless beds, provides further evidence for evaporative conditions (Kelts & Hsü, 1978; Muir et al., 1980). The thin sandstone intercalations containing current ripples, grading and with loaded bases are interpreted as underflow deposits which were subsequently reworked by wave action, and are similar to those described from the grey mudstone and sandstone facies association. Where these are thicker and overlie desiccation surfaces, a sheet-flow interpretation is made with wave reworking of the bed tops occurring during the subsequent filling of the lake following the flood event.

The micritic carbonate is interpreted to have formed through primary precipitation brought about by changing lake chemistry (Kelts & Hsü, 1978), similar to the Intercalated Grey Mudstone and Sandstone Facies Association. This process has been documented from a number of recent examples (Last, 1990; Muir et al., 1980; Warren, 1990; Wright & Wacey, 2005) some of which were associated with microbial activity. This may be the case in this example and such conditions are consistent with an ephemeral, desiccating lacustrine interpretation.

5.3 | Nodular and Brecciated grey-buff dolostone Facies Association

5.3.1 | Description

This facies association comprises nodular and brecciated grey-buff carbonates that contain a complex suite of disruption fabrics. The nodular forms are up to 0.2 m in diameter and have diffuse contacts with the surrounding carbonate mudstones (Figure 5A). Brecciation occurs towards the nodule centre, with fractures commonly filled with crystalline calcite (Figure 5B). Disruption is also recorded in the surrounding sediments with slickensides often recognised. The brecciated grey-buff carbonates contain more pervasive disruption than the nodular

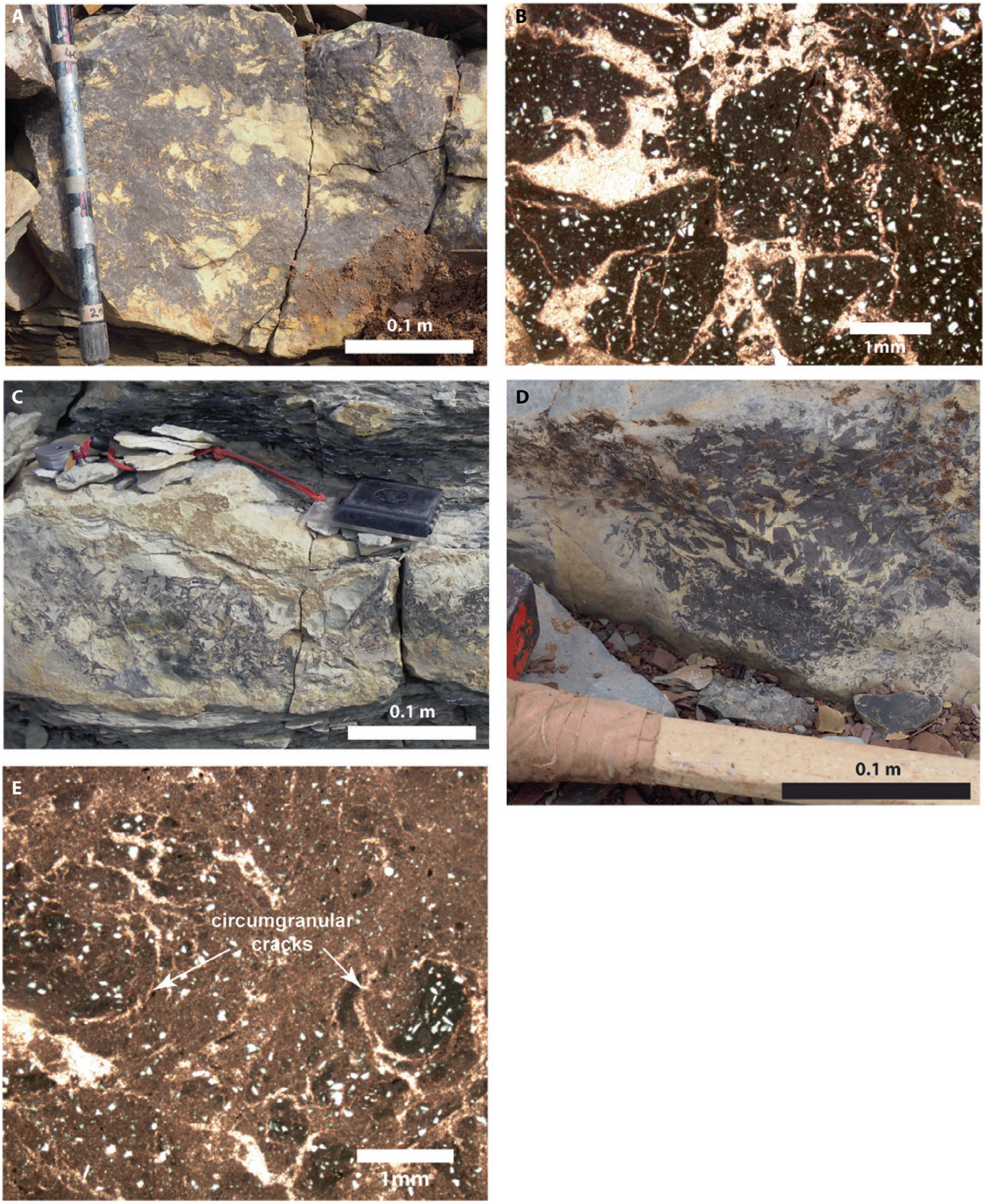


FIGURE 5 Nodular and Brecciated Grey-Buff Dolostone Facies Association. (A) An irregular nodule typical of this facies association. (B) Brecciated lime mudstone with variably sized fractures, some of which have been further enlarged by dissolution. (C) Brecciation associated with nodule development. (D) Pseudomorphs after gypsum? within micritic mudstone. (E) Quartz bearing mottled lime mudstone with circumgranular cracks filled with calcite.

forms and occurs throughout beds up to 0.25 m thick which has led to the development of uneven bed tops. The brecciation is similar in form to that found in the nodular intervals with the development of angular fragments and a crystalline calcite fill of the associated cavities (Figure 5A,C). Pseudomorphs displaying trapezoidal to rhomboidal cross sectional forms (Figure 5D), after gypsum?, are also often found in association with this facies association. These are either found at bed tops or within carbonate mudstones. Thin section analyses of the carbonate mudstones provide evidence for the presence of both calcite and dolomite. This is consistent with XRD analysis (Figure S4). One sample was dominated by dolomite (Figure S3) but a single set of SEM EDX analysis from another samples suggested an absence of dolomite, highlighting the patchy distribution of both calcite and dolomite. Thin section analysis has also allowed the identification of circumgranular cracks (Figure 5E).

5.3.2 | Interpretation

The pervasive brecciated texture which characterises this facies association is interpreted to reflect post—or penecontemporaneous depositional modification of the sediment. The presence of slickensides and carbonate nodules, some containing circumgranular cracks, provides evidence for repeated wetting and drying, alongside incipient calcretisation processes. Such a setting would also be consistent with the formation of evaporites, preserved as pseudomorphs, which grew within the sediment as well as on the sediment surface. The generation of uneven bed tops over which the succeeding units are draped suggests that disruption did occur at the sediment surface. The brecciated and nodular textures recognised are characteristic of palustrine carbonates (Alonso-Zarza, 2003; Freytet & Verrecchia, 2002) which result from the exposure and pedogenesis of lacustrine carbonate-rich mudstones. Some vestiges of features consistent with the intercalated desiccated mudstone and sandstone facies association suggest that a transition between these two associations often occurred, with the former association being overprinted with palustrine features.

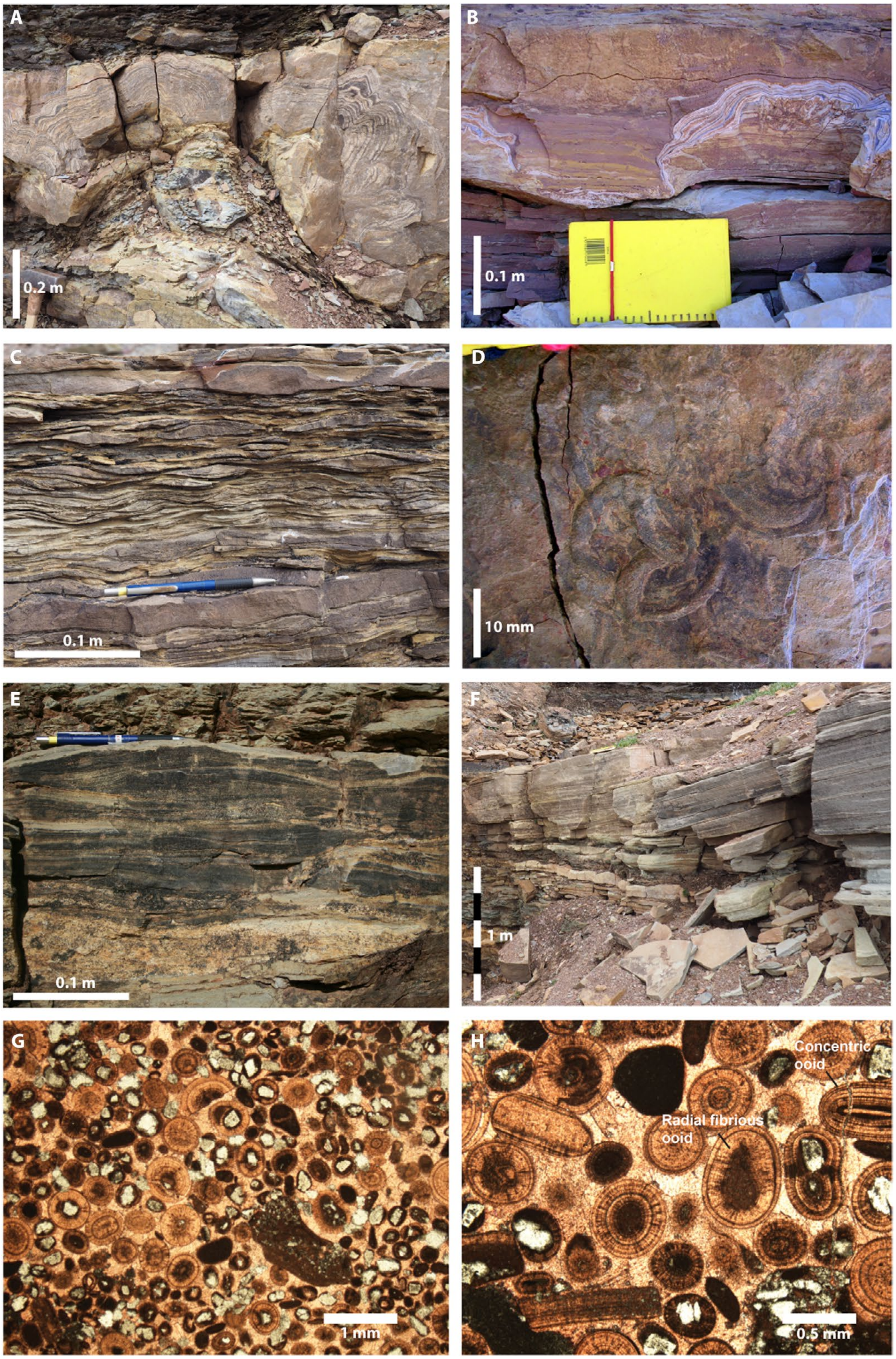
5.4 | Microbialite facies association

5.4.1 | Description

Microbialites are common throughout the Edderfugledal Formation and often occur in association with the Intercalated Grey Mudstone and Sandstone Facies Association. A wide range of microbialite forms are recorded including sediment cored mounds, ridge and runnel systems, and sheets. The sediment cored microbialite mounds form features with up to 0.4 m of relief (Figure 6A) and are often fringed by breccia aprons consisting of brecciated microbialite fragments, ooids and oncoids. The sediment cores commonly contain bedding which is truncated towards the microbialite covering. The microbialites themselves are largely composed of smooth carbonate laminations 0.5–4 mm thick with occasional examples containing quartz grains and gypsum. Laterally linked hemispheroidal forms are also noted in some instances. Of lesser relief and showing a distinct linear arrangement are the ridge and runnel systems. The ridges recognised are up to 0.8 m wide, are sediment cored, display up to 0.2 m relief and are separated by runnels up to 0.3 m wide (Figure 6B). The coating microbialites are similar to those described above and thin into the runnels. The runnel fill is commonly composed of an edgewise breccia of microbialite fragments or laminated carbonate mudstones. In some instances edgewise breccias form the core of the ridges. The most basic microbialite form is the laterally extensive sheets which are 10–20 mm thick and display a smooth, to more ruckled appearance. Lamination is similar to that described above but within the hollows of the ruckled surface dolomitic mud drapes are commonly observed, preceding continued microbialite lamination.

In thin section, the microbialites are composed of alternating layers of fine grained calcite, fine grained dolomite and occasionally include fine gypsum crystals which are often mixed with fragments of reworked microbialite and shell. Vertically aligned, often radiating, calcite crystals up to 3 mm long with a variably defined crystal shape are also recognised within some laminations. These tend to be preferentially developed in the dolomitic layers although they are found elsewhere.

FIGURE 6 Microbialite, and Hummocky Cross Stratified Sandstone and Grainstone Facies Associations. (A) Sediment cored microbialite mounds and (B) ridge and runnel systems—note the Intercalated Grey Mudstone and Sandstone Facies Association infilling the runnel. The ridges are often formed where previous runnels had accumulated edgewise breccias which have subsequently formed resistant ridges on which microbialites have preferentially accumulated. (C) Stacked micro-hummocky cross stratified (base) and wave rippled (middle) sandstones which characterises the Pingel Dal Member. (D) Bioturbation (*Fuersichnus*) on a bed base within the Hummocky Cross Stratified Sandstone and Grainstone Facies Association. (E) Micro-hummocky cross stratification and (F) low angle cross bedding in the ooidal grainstones. Photomicrographs of the ooidal grainstones (stained), (G) moderately to well-sorted ooids with a small amount of lithoclasts and quartz grains and (H) radial fibrous and concentric (tangential) ooids.



5.4.2 | Interpretation

The Microbialite Facies Association is commonly found overlying the Intercalated Grey Mudstone and Sandstone Facies Association which is interpreted to have been deposited in shallow lacustrine conditions. The truncation of bedding within the sediment cored microbialite mounds is interpreted to reflect their erosional origin. Original stabilisation of the sediment surface would have occurred through the growth of microbialite mats. Subsequent erosion would have resulted in elevated patches which would form preferential sites for continued microbialite accumulation and therefore increased stability. This would further focus currents around the bases of these features resulting in increased erosion and truncation of bedding surfaces within the sand cored mounds. The coarse grained nature of the breccia aprons provides further evidence for the high energy setting. Sediment cored microbialite mounds have also been identified from lacustrine environments within the Old Red Sandstone of northern Scotland (Andrews & Trewin, 2013; Fannin, 1969) where they have been interpreted as indicative of environments of elevated energy. The generation of high relief columnular forms described from Shark Bay, Western Australia have also been related to high energy conditions (Hoffman, 1976).

An erosional origin is also suggested for the generation of the ridge and runnel systems identified (Clemmensen, 1978). The edgewise breccia fill of some runnels again illustrates the high energy conditions involved in their formation. Where edgewise breccias form the core of ridges it is suggested that the ridge and runnel system has been abandoned, prior to re-excavation, at which point the edgewise breccias form the resistant ridges favourable for microbialite accumulation. Ridge and runnel structures have been recorded from the Great Salt Lake, Utah (Carozzi, 1962) and Shark Bay, Western Australia (Logan, 1981) where runnels are aligned perpendicular to the shoreline.

The microbialite sheets are interpreted as indicative of lower energy conditions reflecting formation in protected embayments. The episodic nature of microbialite laminae formation and low energy conditions are highlighted by the presence of dolomitic mudstone drapes between some laminae. Microbialite sheets displaying similar features have been described by Hoffman (1976) from Shark Bay and observed in back-beach-pools alongside Kong Oscar Fjord in East Greenland (Andrews & Trewin, 2013).

The fine nature of the lamination identified in all examples described is characteristic of stromatolite forms with episodic accretion (Riding, 2000). Alternations between calcite dominated layers and dolomite dominated layers probably reflect variability in lake water chemistry. Vertically oriented calcite crystals in the dolomitic layers probably represent pseudomorphs after evaporites. The relationship between the vertically oriented pseudomorphs and the dolomitic layers is consistent with more evaporative conditions during their deposition. The trapping of reworked stromatolitic material, gypsum and shell fragments identified within some laminae is characteristic of agglutinated stromatolite forms but are not of sufficient abundance to warrant this classification. These laminae record periods of increased energy, probably related to the erosive events discussed above that are largely responsible for generating the variable stromatolite forms recorded.

5.5 | Hummocky cross stratified sandstone and grainstone facies association

5.5.1 | Description

This facies association comprises a clastic and a carbonate element. The clastic portion is dominated by grey hummocky cross stratified sandstones (Figure 6C) which form well-indurated intervals up to 3 m thick, comprising 5–50 mm thick very fine sandstone beds. Micro-hummocky cross stratification predominates but simpler wave ripples are also recorded. Occasional vertical burrows are noted and *Fuersichnus* is also observed on some bed bases (Figure 6D). Minor mudstone and siltstone intercalations up to 5 mm thick are recorded but are not common. Where these fine grained intercalations are recognised rare large scale and smaller scale contorted mud cracks have also been recorded.

The carbonate component of this facies association comprises coarse to very coarse ooidal grainstones containing hummocky cross stratification (Figure 6E) and low angle cross bedding (Figure 6F) and forms beds up to 0.4 m thick. Small scale scours are also common within these units. Although ooids predominate, a small proportion of lithoclasts and quartz grains are present. The ooids are commonly moderately to well-sorted, range from 0.2 to 0.5 mm in size and are subspherical to spherical in shape. Many ooids have nuclei composed of lithoclasts, peloids or quartz grains (Figure 6G,H). In some cases, ooid cortices exhibit alternating micrite and sparite that are distinguishable where stained. Most ooids are radial-fibrous, but concentric (tangential) ooids also occur. Broken and regenerated ooids are also present. Superficial ooids have a distinctive thin and asymmetric cortex with quartz grains as nuclei and are dominant in some places.

5.5.2 | Interpretation

The presence of micro-hummocky cross stratification is interpreted as evidence for high intensity oscillatory flow, as is often encountered in lacustrine lower shore-face settings (Allen, 1981a, 1981b; Martel & Gibling, 1991; Dam & Surlyk, 1993). Associated low angle cross bedded units, characteristic of upper shore face processes provide further evidence for a shore zone environment of deposition. Minor mudstone and siltstone intercalations record periods of low energy deposition and the occurrence of occasional desiccation and syneresis cracks indicate fluctuations in lake level and salinities. *Fuersichnus* has been interpreted as feeding traces of aquatic origin (Bromley &

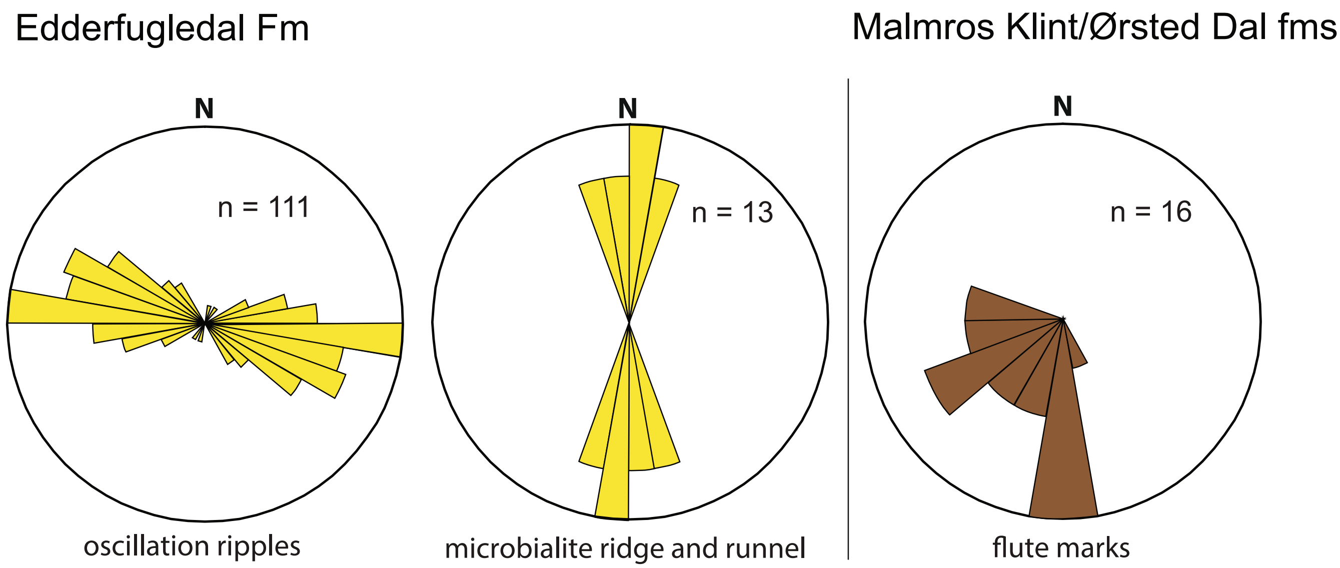


FIGURE 7 Palaeocurrent data collected from the Edderfugledal Formation and the overlying Malmros Klint/Ørsted Dal formations. The north-south orientation of the microbialite ridge and runnel systems along with the predominantly east-west orientation of oscillation rippling favours a north to south palaeoslope orientation. This is confirmed with flute marks from the overlying Malmros Klint/Ørsted Dal formations.

Asgaard, 1979), consistent with a lacustrine shore zone interpretation for this facies association.

The similarity in the structures recorded in the oolitic grainstones to those in their clastic counterpart, suggest a similar lake shore zone depositional setting. The radial-fibrous structure of ooids normally suggests relatively low energy and less turbulent conditions (Flügel, 2004). However, the moderate to well-sorted nature of the grainstone, alongside the sedimentary structures identified, indicate moderate to higher energy levels. The occurrence of broken and regenerated ooids is indicative of multiple periods of reworking and breaking during ooid formation (Flügel, 2004). Superficial ooids with symmetrical cortices are thought to form in quiet water conditions and therefore were probably transported into the shore zone from elsewhere. The absence of fossils suggests that periods of stabilisation were not long enough for shelled organisms to colonise (Feldman et al., 1993), although it is probable that biota were somewhat restricted in what would have been a stressed environment. The relationship between the development of oolitic shore zones and clastic dominated shore zones is discussed below.

6 | PALAEOCURRENTS

Palaeocurrent data were collected from throughout the examined sections and also from sandstones within the overlying Malmros Klint Formation and at the base of the Ørsted Dal Formation (Figure 7). Oscillation ripples are prevalent throughout the Edderfugledal Formation and have a distinct east-west orientation. This closely mirrors the orientation described from throughout the Fleming Fjord Group by Mau et al. (2022), which was attributed to prevailing wind directions during the Late Triassic. The north-south orientation of microbialite ridge and runnel systems, and flute marks, indicative of southerly directed flow recorded at the base of the overlying Malmros Klint/Ørsted Dal formations, suggest a north to south palaeoslope orientation in this locality. Therefore the orientation of the oscillation ripples may also have been impacted by the palaeoslope in this instance. The significance of the defined palaeoslope is that the facies correlated between the five measured sections can then be considered with respect to palaeobathymetry as will be discussed below.

7 | STABLE ISOTOPE ANALYSIS

Stable isotope analysis was carried out on 14 samples from the Edderfugledal Formation. Samples were selected from three separate sections and cover a range of palaeoenvironments as reflected by the facies associations identified. To ensure that as wide a range of facies associations was covered as possible, the samples from Dværgarvedal were augmented with a number of samples from Tait Bjerg (see Figure 1 for its location).

The stable isotope compositions of the main carbonate palaeoenvironments are presented in Figure 8. The $\delta^{18}O$

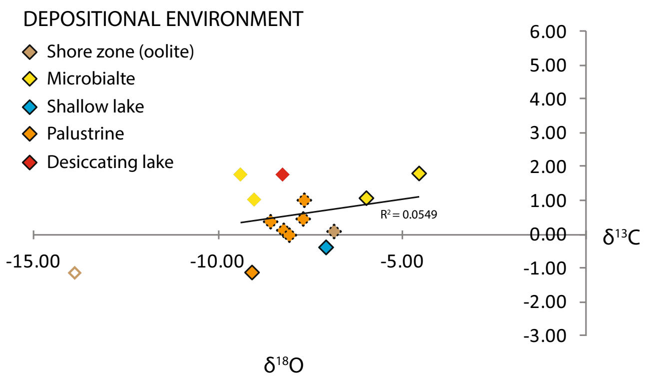


FIGURE 8 Cross plot of $\delta^{18}O$ versus $\delta^{13}C$ values in ‰. The colour of the data points indicate the interpreted depositional environment and the outline indicates the locality: Solid outline, southern Dværgarvedal; dashed line, central Dværgarvedal and no outline, Tait Bjerg. The white cored outlier is thought to be spurious and is not included in the regression.

values show a narrow range from −7.09 to −9.42‰ Vienna-Pee Dee Belemnite (VPDB) in most of the selected samples. The heaviest $\delta^{18}O$ value of −4.56‰ VPDB occurs in the microbialites in Dvaergarvedal. The lightest $\delta^{18}O$ value of −13.92‰ VPDB is somewhat exceptional and was measured from a shore zone oolitic grainstone on Tait Bjerg.

The microbialites have heavy $\delta^{13}C$ values ranging from 1.05 to 1.82‰ VPDB. The rest of the analysed samples from Tait Bjerg and Dvaergarvedal, including lime mudstones, show $\delta^{13}C$ values around −1.13 to 1.79‰ VPDB.

7.1 | Interpretation and discussion

It is known that stable isotope compositions of carbonates in lacustrine environments are influenced by a wide range of variables. The $\delta^{13}C$ values are influenced by complex interlinked environmental factors, such as the inflow water composition, atmosphere CO_2 exchange, gas mixing through microbial activities and water residence time (McKenzie, 1985; Talbot, 1990; Gierlowski-Kordesch, 2010). Variations in $\delta^{13}C$ values can also be indicative of climate, in that the $^{13}C/^{12}C$ ratio changes in response to microbial productivity and atmospheric CO_2 exchange (McKenzie, 1985). In addition, the $\delta^{13}C$ values may also reflect changes in soil productivity. Commonly, variations in $\delta^{18}O$ values are attributed to changes in temperature and/or precipitation/evaporation ratio (Leng & Marshall, 2004). An important factor influencing the $\delta^{18}O$ values is the $\delta^{18}O$ composition of inflow waters and the $\delta^{18}O$ value of water vapour exiting the lake via evaporation (Benson et al., 2013). More negative $\delta^{18}O$ values indicate increased inflow and freshening of the lake water (Carroll et al., 2008). In contrast, the more positive $\delta^{18}O$ values may reflect decreased recharge, a salinity increase and a greater degree of evaporation (Bowen et al., 2008; Frantz et al., 2014). However, it is important to treat the isotope data with caution due to the possibility of diagenetic alteration and the bulk nature of the analysis.

The samples analysed in this study were taken from three different localities, two of which are only separated by 2 km (southern and central Dværgarvedal). If considered geographically, those samples analysed from Tait Bjerg tend to show slightly lighter $\delta^{18}O$ and $\delta^{13}C$ values (Figure 8). More significantly, there seems to be a consistency between the identified palaeoenvironments and the $\delta^{13}C$ values with increasingly light values through shallow lake, palustrine to desiccating lake deposits. As discussed above the potential controls on $\delta^{13}C$ values are complex, however higher values are often interpreted as increased residence time and reduced values to reflect decreased residence time and increased vegetation cover (Talbot, 1990). This is consistent with the palaeoenvironments recorded, with those deposits reflecting more evaporative, closed lake conditions having higher $\delta^{13}C$ values and those reflecting more open, fresher lake conditions having lower $\delta^{13}C$ values. This should be treated with caution as the data set is very limited, and dominated by palustrine and microbialite deposits.

The microbialites show light $\delta^{13}C$ values but greater variability in $\delta^{18}O$ values. This could be explained by the influence of regional variation in inflow (groundwater or overflow), producing local perturbations in the $\delta^{18}O$ values. A similar, but wider, disparity in $\delta^{18}O$ values is recorded from the shore zone oolites and it seems probable that the exceptionally light −13.2‰ value is spurious.

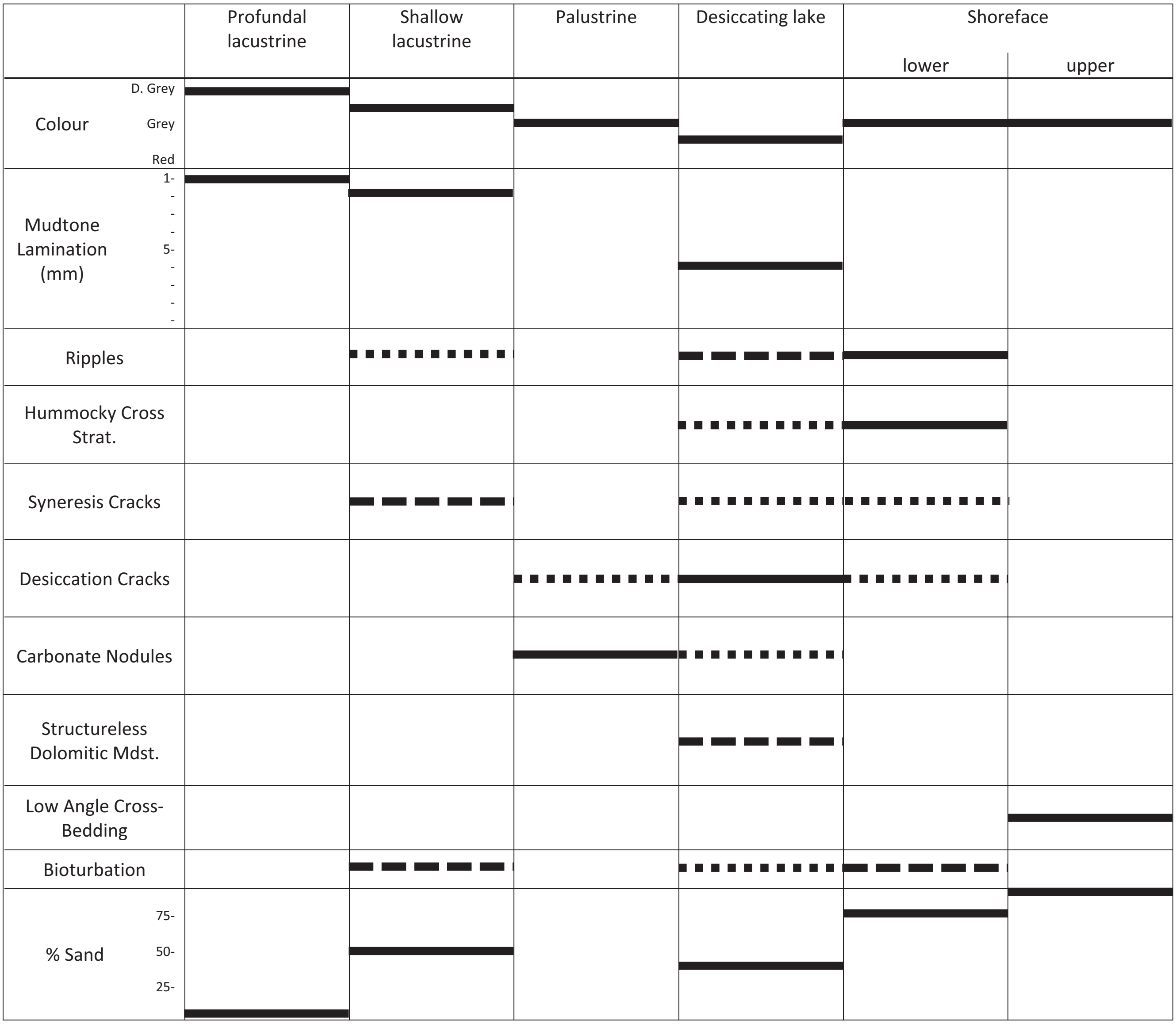
8 | FACIES ASSOCIATION DISTRIBUTION AND LAKE EVOLUTION

The distribution and ordering of the facies associations, and their interpreted environments of deposition, are now considered. Although the tabular nature of the Edderfugledal Formation suggests that relief was limited across the basin during its deposition (Andrews et al., 2021) it is clear that shallower water, more ephemeral environments passed basinward into deeper water, profundal environments. However, it is also the case, given the subdued relief that fairly small fluctuations in lake level could lead to the rapid transit of facies belts over large distances. The vertical distribution of the facies associations will be considered first, with respect to climatic drivers, before the lateral trends that have been identified are discussed.

8.1 | Cyclic sedimentation

Clemmensen (1978) recognised six facies in the Edderfugledal Formation: greenish mudstone—open

TABLE 2 Matrix for the differentiation of depositional environments within the Edderfugledal Formation, forming the basis for a depth rank system. Shoreface is tentatively split into lower and upper divisions.



lacustrine; yellowish mudstone—carbonate flat; flat pebble conglomerate—beach lag; stromatolite—nearshore lacustrine; greyish sandstone—shoreline sandflat and, reddish sandstone and mudstones—alluvial mudflat. It was further recognised that a regular ordering of these facies defined cyclic sequences which were interpreted as the result of fluctuating lake levels. More distinct differentiations have been possible here on the basis of a number of diagnostic features (Table 2) allowing the definition of profundal lacustrine (laminated dark grey mudstones), shallow lake (intercalated grey mudstones and sandstones), desiccating lake (intercalated desiccated mudstones and sandstones), shore zone (hummocky cross stratified sandstones and grainstones), palustrine (nodular and brecciated grey-buff dolostone) and microbialite dominated environments. This has in turn allowed a closer examination of cyclicity within the Edderfugledal Formation. The cycles recorded here are variably developed with complete transgressive successions defined by a transition from palaeoenvironments reflecting desiccating lake to shallow lake, often though microbialitic limestones which show preferential development during transgressive phases (see Andrews & Trewin, 2010), with lake highstand marked by profundal conditions. The regressive elements are more commonly condensed, potentially reflecting the impact of reduced sediment supply, as is discussed more fully below. Cycles comprising more complete transgressive elements are most common in the more distal of the examined sections (Figure 9, section E). Incomplete progressions through the facies associations which depict the cycles occur where transgression does not reach profundal conditions. This is the

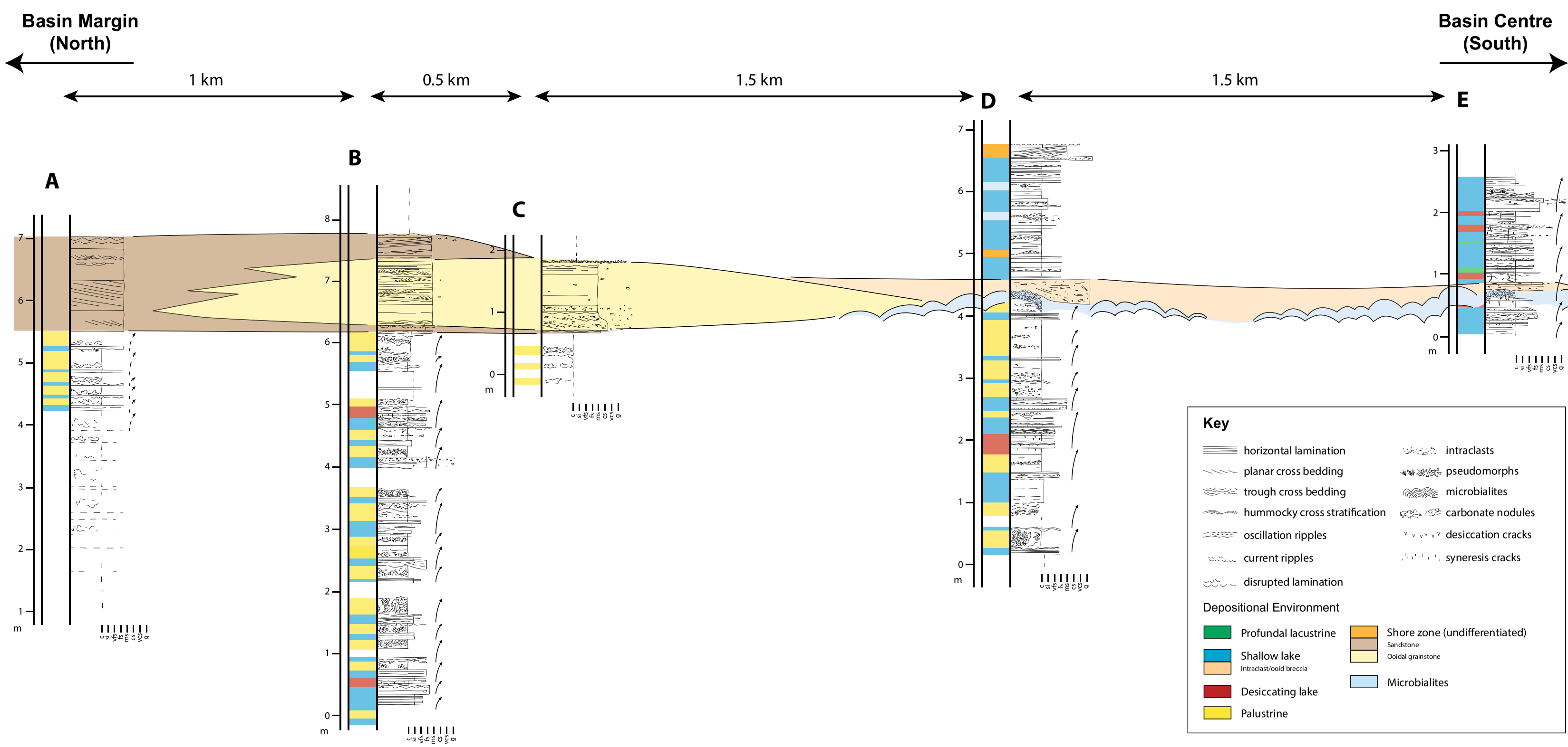


FIGURE 9 Correlation of closely spaced logged sections from Dværgarvedal which allow the shore zone systems, including microbialites to be examined across a 4.5 km transect. See Figure 1 for the position of the illustrated sections. Palaeocurrent indicators (Figure 7) are consistent with this transect being perpendicular to the lake shoreline, which is interpreted to have been aligned east-west in this region. The centre of the basin lay to the south of the examined sections. Interpreted palaeoenvironments are included for clarity. These can be cross referenced with the facies associations summarised in Table 1.

most common situation in the sections which are the focus of this study, and particularly so in the more proximal locations (Figure 9). Although not recorded in this study, sections observed in more distal locations further to the south, in the Carlsberg Fjord region, contain cycles where desiccation is not reached during a lowstand lake phase, truncating the shallower water part of the cycles. These differences in cycle type can be interpreted to record changing climatic conditions or proximal-distal (shallower-deeper) positions within the basin. It is therefore important to have a wider appreciation of the basin configuration and regional climatic trends before interpreting the significance of such variations.

Cyclic successions are commonly identified from ancient lacustrine successions (Olsen, 1986; Pietras & Carroll, 2006; Andrews et al., 2016) and cycles of a closely comparable nature have been reported from the Middle Old Red Sandstone Stromness Flagstones of northern Scotland (Andrews & Trewin, 2013) which, as with those described here, have been attributed to orbitally forced climatic cyclicity (Clemmensen et al., 2020; Clemmensen, 1978).

Cycles in the lower portions of the sections which form the focus of this study are most commonly defined by the alternation of shallow lake and palustrine deposits. The upper part of the sections examined contain cycles comprising alternations of shallow lake and desiccating lake deposits, although some profundal developments are also recorded. These cycles vary between 0.2 and 1 m in thickness (Figure 9). Where dominated by palustrine and desiccating lake deposits, the cycles tend to be thinner, reflecting reduced sediment input during more arid conditions.

The cycles recognised here largely appear to have an asymmetric form (expanded transgression—condensed regression). This may, to some extent, be an artefact of their expression through the alternation of only two facies associations, rather than a regular progression through the full range of depth ranked palaeoenvironments, as is more common elsewhere in the basin. However, this signature can also be interpreted to reflect the dynamics of the lake margin system. As climatic conditions became sufficiently humid to sustain a lake, increased run off would have resulted in elevated sediment supply as is recorded by the thin sandstone beds that often mark the base of the shallow lake deposits. As the lake expanded, the lake margin, and therefore the sediment input point, would have been pushed back, potentially considerable distances in a low gradient setting, restricting the delivery of sediment to the more basinal regions. Progradation of lake margin systems would only be likely to occur if the lake level stabilised, as may be the case if the lake developed open hydrography. With a return to more arid conditions the delivery of coarser sediment would be restricted due to reduced run off, resulting in what would appear to be a fairly simple drying upward motif. Furthermore, the palustrine conditions which often record the more arid phases result in the disruption of underlying deposits, therefore reducing the apparent thickness of the deeper water deposits. The combination of such factors could therefore account for the apparent asymmetric nature of the cycles recorded.

8.2 | Lateral facies trends and lake shore zones

The superb exposures found in Dværgarvedal make it possible to examine the lateral relationships between the facies associations and their interpreted depositional environments across the lake shore zone and speculate as to how these responded to recurrent fluctuations in lake level. The closely spaced nature of the five sections examined has allowed the response and interaction of both clastic and carbonate components of the shore zone environment to be studied. The relationships between the facies associations are first outlined before models are proposed for the development of the facies patterns recognised.

The lower portion of the logged sections are dominated by carbonate-rich facies associations. Drying upward cycles are recorded as alternations between deposits reflecting shallow lake (Intercalated Grey Mudstone and Sandstone Facies Association) and palustrine (Nodular and Brecciated Grey-Buff Dolostone Facies Association) environments (Figure 9). Following periods of shallow lake deposition, regular fluctuations in lake level resulted in extensive post-depositional disruption interpreted to have occurred in a palustrine setting. Disruption is more common in the more northerly sections, as would be expected towards the basin margin where exposure would occur more frequently and for more prolonged periods. To the south, the shallow lake deposits increase in thickness reflecting the more sustained nature of lake conditions away from the lake shore. Desiccation did still occur but was less regular, expressed by the presence of less disrupted desiccating lake deposits. The configuration described demands a fairly simple model (Figure 10A).

Up section, a general trend towards longer-lived lake conditions is recognised and the distribution of facies associations becomes more complex with the development of both clastic and carbonate shore zone deposits (Hummocky Cross Stratified Sandstone and Grainstone Facies Association), and a laterally extensive microbialite unit in the lowermost cycle (Figure 9). The occurrence of profundal deposits (Laminated Dark Grey Mudstone

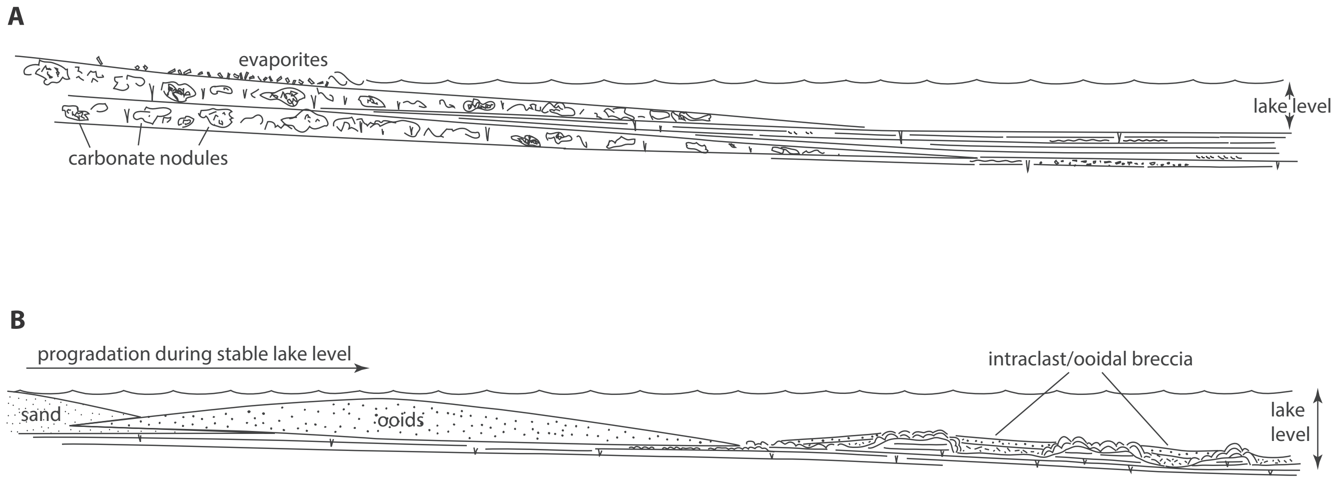


FIGURE 10 Facies models for the two lake margin systems described. (A) Carbonate dominated: Palustrine conditions are prevalent towards the lake margin where wetting and drying are sufficiently regular. In these regions evaporite minerals are precipitated and pedogenic processes are active. During more arid conditions when lake-levels fall palustrine environments stretch far out in to the basin. When lake-level rises these deposits are overlain by desiccating and shallow lake deposits. (B) Mixed carbonate-clastic shore zone: Stromatolites form during the transgressive phase; the initial clastic influx is pushed back towards the basin margin by rising lake levels; oolitic shoals develop in shallow water and later prograde along with clastic shore systems and stifle microbialite growth.

Facies Association) and the greater prevalence of shallow lake deposits (Intercalated Grey Mudstone and Sandstone Facies Association) at this time suggest that lake-level fluctuations were of a higher magnitude and perennial lacustrine conditions were more long-lived. The initial transgression, which marks the change to more long-lived perennial lacustrine conditions, is delineated by the widespread development of microbialites. The positioning of microbialite developments has been noted as commonly characteristic of transgressive conditions in lacustrine settings (Andrews & Trewin, 2013) where sediment input points are pushed back to the basin margins, resulting in reduced sediment supply. A similar interpretation can be made here. In the northernmost sections (sections a, b and c in Figure 9) the initial transgression is marked by a short-lived influx of clastic sediment, probably recording the rejuvenation of fluvial systems as climatic conditions became more humid. These deposits were subsequently reworked by wave action and shore zone processes, reflecting continuing transgression. As the transgression progressed, the delivery of clastic sediment was restricted as a result of the sediment input points being pushed back towards the basin margin, and shore zone ooidal grainstones began to form and accumulate. The development of ooidal grainstones is interpreted to reflect relatively shallow water conditions which support the earlier suggestion of a low gradient lake margin, with shallow water conditions extending over at least 2 km. The grainstones are eventually overtopped by shore zone clastics and the microbialites, which lay farther offshore, are inundated by intraclast/ooidal breccia. This transition is interpreted as the progradation/lakeward migration of both the clastic and carbonate shore zone elements (Figure 10B). Progradation of shore zone systems is indicative of a period of more stable lake level (Andrews & Hartley, 2015) and therefore suggests that the lake may have become open at this time. Falling lake level is then recorded as a transition through shallow lake to desiccating lake deposits in the most distal section prior to continued transgressive-regressive cycles, often containing more restricted developments of shore zone deposits and microbialites.

The key factors which controlled the development and distribution of the described depositional environments and their related facies associations, in this example of a mixed clastic-carbonate lake margin setting, are the interaction of sediment supply and production which govern facies development, and which are in turn predominantly controlled by lake-level changes and lake margin bathymetry.

8.3 | Climate and topography

The dominance of palustrine deposits in the Dværgarvedal sections suggest that arid conditions prevailed at the time of their deposition, leading to more ephemeral lacustrine developments and low sediment input. This is consistent with the prevalence of carbonate within the Edderfugledal Formation which is indicative of arid conditions (Kelts & Hsü, 1978; Muir et al., 1980) as is the relatively low clastic input. The latter is of particular importance for the development of microbialitic limestones. It should also be noted that subdued relief within the basin and its catchments, as a consequence of the basin infilling and the catchments degrading, may have contributed to reduced clastic input (Andrews et al., 2021). However, Clemmensen (1980b) suggested that the increased clastic component recorded in the Pingel Dal Member resulted from tectonic uplift in the north as evidenced by the more sandy nature of the Edderfugledal Formation in the Traill Ø region (Clemmensen, 1978). Sediment sourcing from the north at this time is consistent with the greater abundance of microbialites south of the Pictet Bjerge (Figure 1), however, the largely tabular nature of the Edderfuggledal Formation (51.5–69 m) suggests that subsidence was largely uniform across the basin throughout its deposition.

9 | CONCLUSIONS

The carbonate-rich lacustrine deposits of the Upper Triassic Edderfugledal Formation are superbly exposed in East Greenland. Regular, climatically controlled fluctuations in lake level are interpreted to have produced a cyclic succession within which individual cycles can be traced laterally over several kilometres. This has allowed the response of lacustrine shore zone systems and the relationships between carbonate facies associations, including microbialites and clastic facies associations, to be examined across a 4.5 km transect and the controls on their distribution to be considered.

Two styles of lake shore deposition are dominant in the examined sections. The first is characteristic of more arid conditions during which sediment supply was low and extensive post-depositional disruption occurred with there being evidence for desiccation, pedogenic processes and evaporite precipitation. These effects increase towards the lake margins where exposure was most frequent and most prolonged. The second is characteristic of more humid conditions which led to the formation of longer-lived lacustrine developments and increased clastic sediment input. In these instances sediment input was pushed back to the lake margin during the transgressive phases of individual climatically driven cycles allowing extensive microbialite formation. Ooidal shoals developed in shallow water beyond the extent of clastic supply. The lakeward migration of the ooidal shoals and the progradation of clastic systems eventually stifled the microbialites prior to the next transgressive event. The interaction of sediment supply and production are key factors in governing facies development in these settings and these are in turn predominantly controlled by lake-level dynamics and lake margin bathymetry.

Although only a limited number of samples were subjected to isotopic analysis the results gained are consistent with the facies interpretations made. A general trend towards increasingly light $\delta^{13}C$ values through shallow lake, palustrine to desiccating lake deposits is recognised. This is consistent with increasingly evaporative conditions represented by these facies. However, the data set is very limited and therefore these interpretations are somewhat speculative.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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