Synsedimentary collapse of portions of the lower Blomidon Formation (Late Triassic), Fundy rift basin, Nova Scotia

Rolf V. Ackermann, Roy W. Schlische, and Paul E. Olsen

Abstract: A chaotic mudstone unit within the lower Blomidon Formation (Late Triassic) has been traced for 35 km in the Mesozoic Fundy rift basin of Nova Scotia. This unit is characterized by highly disrupted bedding that is commonly cut by small (<0.5 m) domino-style synsedimentary normal faults, downward movement of material, geopetal structures, variable thickness, and an irregular, partially faulted contact with the overlying unit. The chaotic unit is locally overlain by a fluvial sandstone, which is overlain conformably by mudstone. Although the thickness of the sandstone is highly variable, the overlying mudstone unit exhibits only gentle regional dip. The sandstone unit exhibits numerous soft-sediment deformation features, including dewatering structures, convoluted bedding, kink bands, and convergent fault fans. The frequency and intensity of these features increase dramatically above low points at the base of the sandstone unit. These stratigraphic relations suggest buried interstratal karst, the subsurface dissolution of evaporites bounded by insoluble sediments. We infer that the chaotic unit was formed by subsidence and collapse resulting from the dissolution of an evaporite bed or evaporite-rich unit by groundwater, producing dewatering and synsedimentary deformation structures in the overlying sandstone unit, which infilled surface depressions resulting from collapse. In coeval Moroccan rift basins, facies similar to the Blomidon Formation are associated with halite and gypsum beds. The regional extent of the chaotic unit indicates a marked period of desiccation of a playa lake of the appropriate water chemistry. The sedimentary features described here may be useful for inferring the former existence of evaporites or evaporite-rich units in predominantly clastic terrestrial environments.

Résumé : Une unité de « mudstone » chaotique, dans la Formation de Blomidon (Trias tardif), a été reconnue sur une longueur de 35 km à l'intérieur du bassin mésozoïque du rift de Fundy, en Nouvelle-Écosse. Cette unité est caractérisée par de petites failles normales qui déplacement fréquemment les strates synsédimentaires (<0,5 m) comme des dominos, et en plus par des affaissements de matériaux sédimentaires, des structures géotropes, des épaisseurs variables et un contact avec l'unité sus-jacente irrégulier et partiellement faillé. Cette unité chaotique est recouverte localement par un grès fluvial, qui à son tour est recouvert en discordance par un mudstone. Bien que l'épaisseur du grès varie considérablement, l'unité sus-jacente de mudstone ne montre qu'un faible pendage régional. L'unité de grès exhibe de nombreuses figures de déformation de sédiments mous, incluant des structures d'assèchement, de litage à convolutions, de plis en chevrons, et des éventails de failles convergentes. La fréquence et l'intensité de ces structures augmentent rapidement à l'aplomb des creux à la base de l'unité de grès. Ces relations stratigraphiques suggèrent une zone de karstification située entre des couches sédimentaires, la subsurface de dissolution des évaporites ayant été restreinte par les sédiments insolubles. Nous croyons que l'unité chaotique doit son origine aux phénomènes de subsidence et d'affaissement, résultant de la dissolution par les eaux souterraines d'un lit d'évaporites ou d'une unité riche en évaporites, produisant des structures d'assèchement et la déformation des sédiments dans l'unité de grès sus-jacente, laquelle a comblé les dépressions créées en surface par les affaissements du substratum. Dans les bassins du rift Marocain datés de la même époque, des faciès analogues à ceux de la Formation de Blomidon sont associés à des lits de halite et de gypse. L'étendue régionale de l'unité chaotique indique une période de dessiccation remarquable dans une playa de salinité appropriée. Les structures sédimentaires décrites ici peuvent être utiles pour mettre en évidence d'anciennes unités d'évaporites, ou riches en évaporites, dans les milieux terrestres formés principalement de matériaux clastiques.
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Introduction

Highly disturbed (chaotic) sedimentary units are produced through a variety of mechanisms, including intense synsedimentary faulting and folding (Seilacher 1969), seismic shaking (Seilacher 1984; Plaziat et al. 1990), mass wasting (Collinson and Thompson 1982), and dissolution-related collapse (Stanton 1966; Parker 1967). The dissolution of carbonate or evaporite intervals bounded by insoluble materials can undermine the insoluble units, resulting in collapse and brecciation of the insoluble units as they move downward. This results in a karst or karst-like terrain called interstratal or subjacent karst (Jennings 1985).

Within the lower Blomidon Formation (Late Triassic) of the Fundy rift basin, we have recognized a widespread, highly chaotic, brecciated mudstone interval. This interval lies between undeformed beds, and has presented a conundrum to workers in the region for some time (Olsen et al. 1989). In this paper, we seek to unravel the geologic history and importance of this interval. We argue that a metre-scale evaporite deposit or evaporite-rich unit, possibly along with multiple minor evaporite intervals, once existed in the Blomidon Formation of the Fundy basin and was dissolved by groundwater. Overlying beds were undermined and disturbed, producing the chaotic unit. The chaotic unit has been traced across the basin and several fault blocks, occurs in the same stratigraphic position in all localities, and is in some cases associated with a deposit that partially filled the void created by subsidence of the ground surface. Although minor evaporites and features associated with evaporites have been reported in the Blomidon Formation (e.g., Smoot and Olsen 1988; Mertz and Hubert 1990), the features we describe here indicate the former existence of substantial evaporite bodies, which is consistent with arid paleoenvironmental interpretations of the Blomidon Formation.

Given their solubility, evaporites have the lowest preservation potential of all sedimentary deposits. This is unfortunate because of the paleoenvironmental significance of evaporites, which generally only form in arid settings and are precipitated from restricted water bodies of high salinity (e.g., Kendall 1984; Schreiber 1986). By identifying substantial evaporite-rich deposits that have been previously overlooked, we hope to augment the arid paleoenvironmental interpretations of the Blomidon Formation. Collapse-related features similar to those described here may be used to recognize the former presence of evaporite units within other predominantly clastic continental sequences.

Geologic setting

The Fundy basin is one of a series of synrift basins that formed around the incipient North Atlantic during the Mesozoic breakup of Pangea. In eastern North America (Fig. 1A), these basins are mostly half grabens bounded by normal faults, many of which are reactivated Paleozoic structures (e.g., Plint and van de Poll 1984). The basin fill, known as the Newark Supergroup, consists of exclusively terrestrial sedimentary rocks and tholeiitic igneous rocks (Froelich and Olsen 1984).

The Fundy basin of New Brunswick and Nova Scotia, Canada, consists of three subbasins: the northeast-trending Fundy and Chignecto subbasins and the east-trending Minas subbasin (Fig. 1B). A cross section through the Fundy subbasin, based on seismic reflection data (Fig. 1C), illustrates the half-graben geometry that resulted from northwest–southeast extension along a northeast-striking border-fault system. The same extension produced left-oblique slip on the east-striking Cobequid–Chedabucto fault (Minas fault zone of Olsen and Schlische 1990) (Fig. 1B). Strata of all ages thicken away from the hinge of the Fundy subbasin (Wolfville – Cape Blomidon section, Fig. 2A), and toward the border-fault margin (Chinampas and Cape Spencer wells, Fig. 2A), which is a result of synextensional sedimentation (Olsen and Schlische 1990). Both dip–slip and strike–slip margins were active penecontemporaneously (Olsen and Schlische 1990). All formations within the Minas subbasin are thinner than in the Fundy subbasin; thus, subsidence within the transtensional Minas subbasin was less than in the dip–slip-dominated Fundy subbasin.

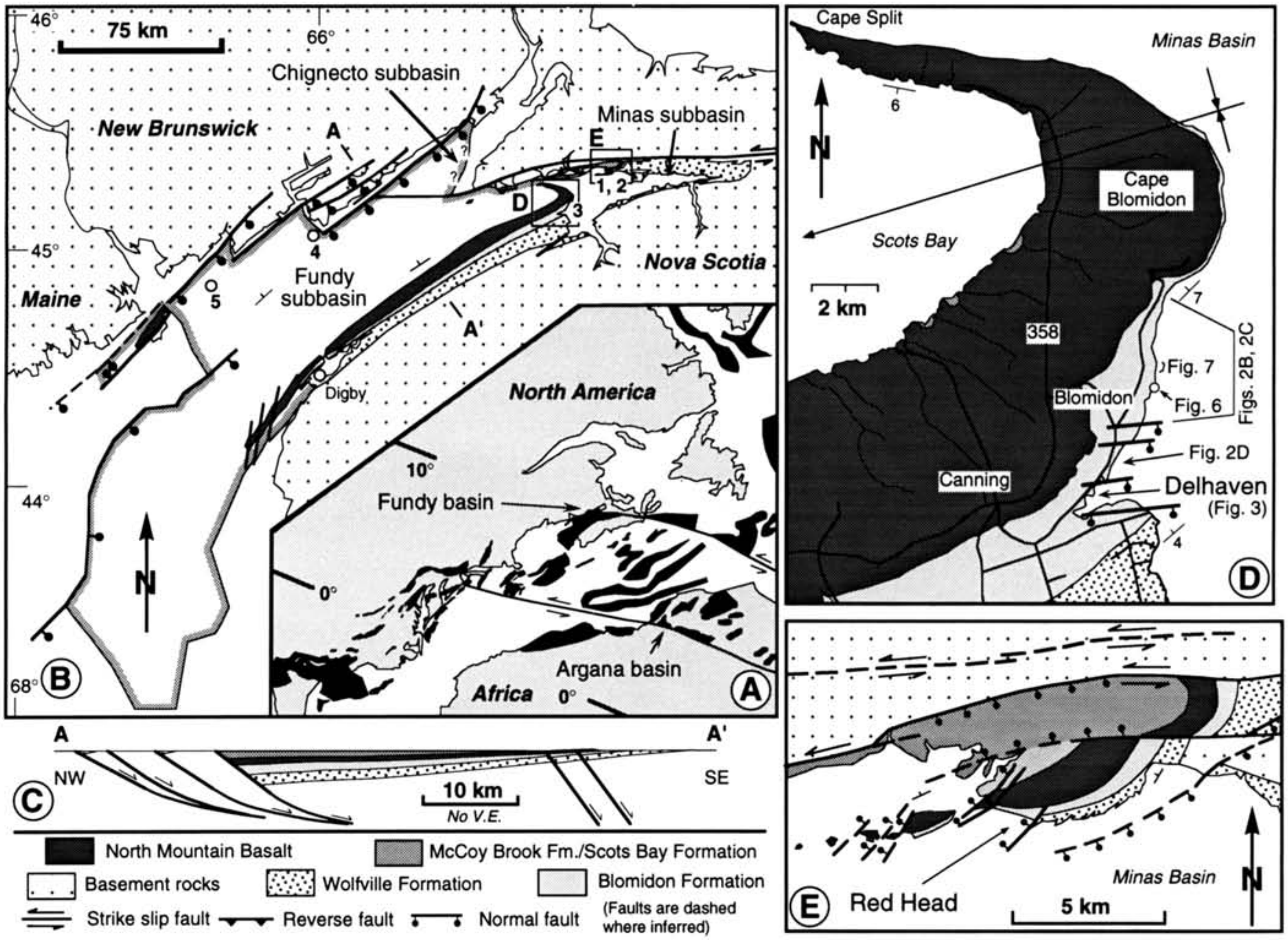
Strata of the Fundy basin are known collectively as the Fundy Group, which is divided into five formations in Nova Scotia (Fig. 2A) (see summary in Olsen et al. 1989). The Middle and Late Triassic age Wolfville Formation is the oldest unit in the basin and consists predominantly of fluvial sandstones and conglomerates, with subordinate eolian sandstones and deltaic–lacustrine deposits (Hubert and Forlenza 1988; Olsen et al. 1989). The overlying Blomidon Formation, which is Late Triassic and earliest Jurassic in age, consists mostly of cyclic lacustrine, playa, sand-flat, and deltaic clastic rocks with minor eolian sandstone and fluvial conglomerate (Hubert and Hyde 1982; Mertz and Hubert 1990; Olsen et al. 1989).

The North Mountain Basalt overlies the Blomidon and consists of multiple quartz-normative tholeiitic lava flows (Stevens 1987; Puffer and Philpotts 1988). U–Pb isotopic dating of the basalt indicates that it crystallized at $\sim 202 \pm 1$ Ma (Early Jurassic) (Hodych and Dunning 1992). The Early Jurassic age McCoy Brook Formation overlies the North Mountain Basalt in most parts of the basin and consists of a wide range of deposits, including fluvial, deltaic, lacustrine, playa, and eolian clastic rocks, with some lacustrine limestones and talus slope deposits (Olsen et al. 1989; Olsen and Schlische 1990; Tanner and Hubert 1991). The Scots Bay Formation is a lateral equivalent of the lower McCoy Brook Formation and consists mostly of lacustrine deposits that fill a series of small sag basins developed on top of the North Mountain Basalt along the coast of Scots Bay (Suchecki et al. 1988; Olsen et al. 1989).

Blomidon Formation

The Blomidon Formation consists of 100+ sandstone–mudstone cycles (Fig. 2B), possibly controlled by Milankovitch forcing (Olsen et al. 1989) or tectonic autocyclicity (Mertz and Hubert 1990). The frequency of mudstone beds in the Blomidon increases basinward (Olsen et al. 1989). Sandstone units of the Blomidon Formation consist of graded beds, climbing-ripple cross-laminations, and eolian deposits with high-angle cross-beds and isolated ripple trains (Mertz and Hubert 1990). The mudstone units contain abundant small lenses of apparently eolian sandstone that make up sand-patch fabric (Smoot and Olsen 1988). Sand-patch fabric is identifiable as irregular pods of sandstone and siltstone within mudstone. The contacts with the mudstones are cuspate, and

Fig. 1. (A) Mesozoic rift basins (black) of the North Atlantic region shown on a predrift continental reconstruction. Paleolatitude data based on paleomagnetic results of Witte et al. (1991). (B) Geologic map of the Fundy rift basin, showing the three subbasins, and the locations of the cross section in (C) and detailed geologic maps in (D) and (E). Numbers indicate locations of sections presented in Fig. 2A. (C) Cross section A−A′ illustrating half-graben geometry of Fundy subbasin. Note the thickening of units toward the border-fault system. (D) Geologic map of the Blomidon peninsula. (E) Geologic map of the Red Head area. (A−C) and (E) are modified from Olsen and Schlische (1990); (D) is modified from Stevens (1987).



the pods may be cut by jagged mudstone-filled cracks and sometimes by burrows.

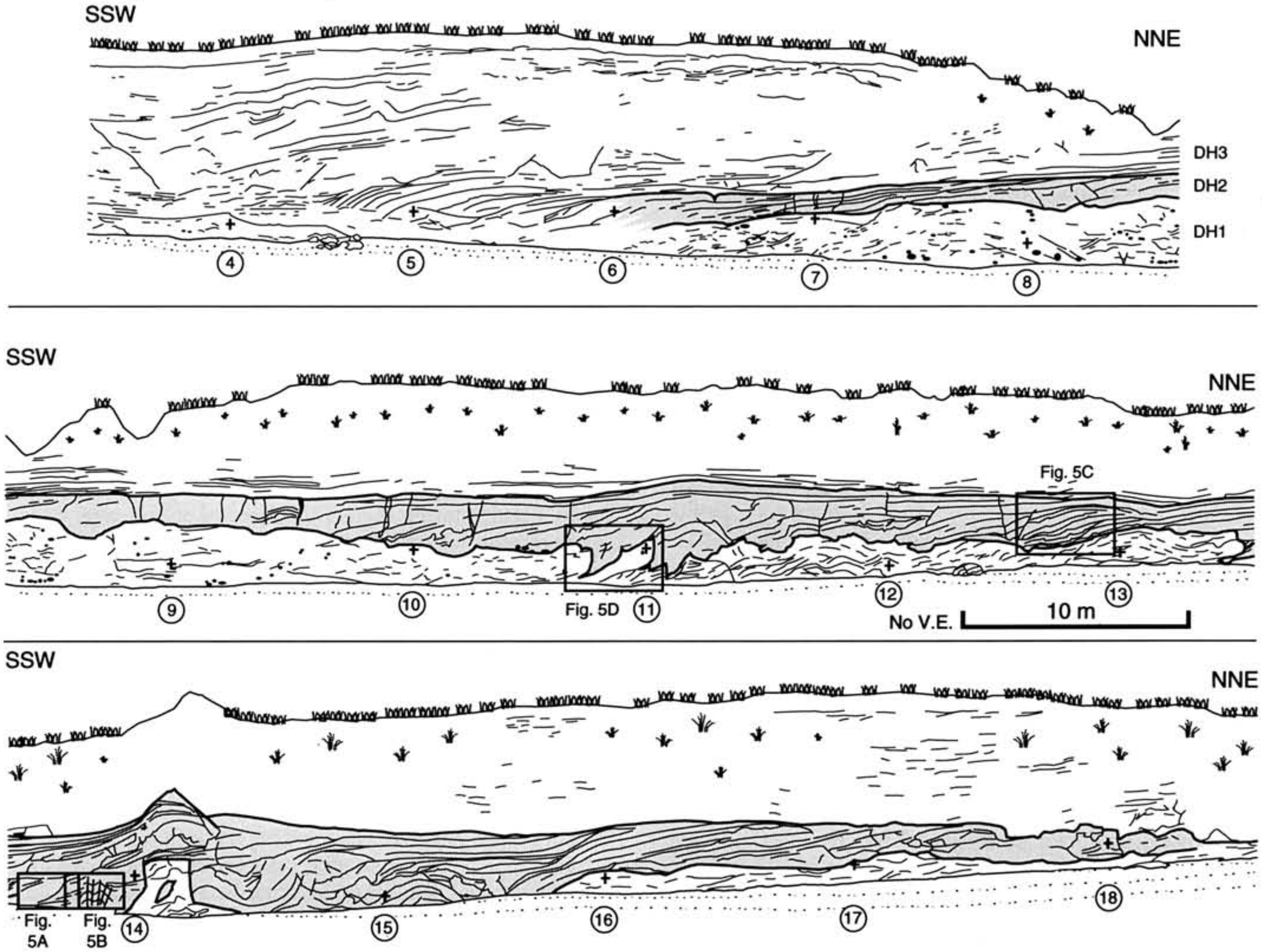
Sand-patch fabrics form on saline mudflats, where eolian and fluvial sand and silt become trapped in depressions in a muddy efflorescent salt (halite) crust; when the salt dissolves, the sand and silt pods become lag deposits within the mud (Smoot and Olsen 1988; Smoot and Kastens-Seidell 1994). Sand-patch cycles (Smoot and Olsen 1988) consist of a massive mudstone or laminated claystone unit, which is overlain by mudstone or sandstone containing sand-patch fabric, in turn locally overlain by ripple-bedded sandstone. Sand-patch cycles account for much of the cyclicity in the Blomidon Formation (Fig. 2B).

Olsen et al. (1989) observed that certain intervals of the Blomidon Formation are riddled with euhedral crystals or pods of gypsum that weather to produce zones of vugs. Mertz and Hubert (1990) reported variable degrees of disruption of sedimentary structures resulting from interstitial precipitation of gypsum. Locally, there are also large (>15 cm) skeletal halite crystal molds. In the Argana basin of Morocco, sand-patch fabrics similar to those in the Blomidon Formation are associated with substantial (metre-scale) evaporite beds of both halite and gypsum (Smoot and Olsen 1988). However, no evaporite beds thicker than a few centimetres are now present in the Blomidon Formation. The evaporite layers that are present are late-stage exhumation features consisting of gypsum, which has precipitated in bedding-plane fractures due to groundwater migration by which deeper sulfate is carried to the near surface (e.g., El Tabakh 1994).

In the northern Fundy basin, the Blomidon Formation lacks thick fluvial deposits. Exceptions are sections located immediately adjacent to syndepositional faults, strata associated with a chaotic unit in the lower Blomidon Formation (described in detail below), and very isolated channels at Digby (Hubert and Hyde 1982; Olsen et al. 1989). The chaotic unit and associated deposits have been recognized in four distinct fault blocks separated by as much as 35 km (Figs. 1, 2). Correlation of sections is based on the lithostratigraphy and biostratigraphy of two laminated claystones containing fish scales, articulated fish fossils, clam shrimp (*Cyzicus*), and

Fig. 2. (A) Regional stratigraphy of the Fundy basin. Locations (see Fig. 1B) are as follows: 1 and 2, Clarke Head – Wasson Bluff and Five Islands area, respectively, along the northern margin of the Minas subbasin; 3, Cape Blomidon area along the hinged margin of the Fundy basin; 4, Cape Spencer well; 5, Chinampas well located in the depocentre of the Fundy subbasin. Vertical bars to the right of columns 2 and 3 indicate sections detailed in (E) and (B), respectively. Modified from Schlische (1990).
(B) Measured section of the Blomidon Formation along the Blomidon peninsula near Delhaven, showing numerous sand-patch cycles. (C) Enlargement of portion of section in (B), showing the stratigraphic position of the lower and upper fish beds (LFB and UFB), the chaotic unit (CU), and strata affected by the bowl-like deformation structures (Fig. 7). (D) Measured section of lower Blomidon Formation located in fault block to the southwest of that depicted in (C). Equivalence of the two sections is based on correlation of the two fish beds. Sections in (B), (C), and (D) are modified from Olsen et al. (1989). (E) Measured section of the lower Blomidon Formation at Red Head. The fish beds allow this section to be correlated with those of the Blomidon peninsula. (F) Measured section of strata affected by domino-style faulting at base of section in (E).

Fig. 3. Sketch of seacliff outcrops near Delhaven (for location see Fig. 1D). Unit DH2 is shaded. Solid black features are dissolution vugs. Sketch based on photomosaic of the cliff face. Numbers indicate control stations.



ostracods (Fig. 2) (Olsen et al. 1989). These units will be informally referred to as the upper and lower fish beds.

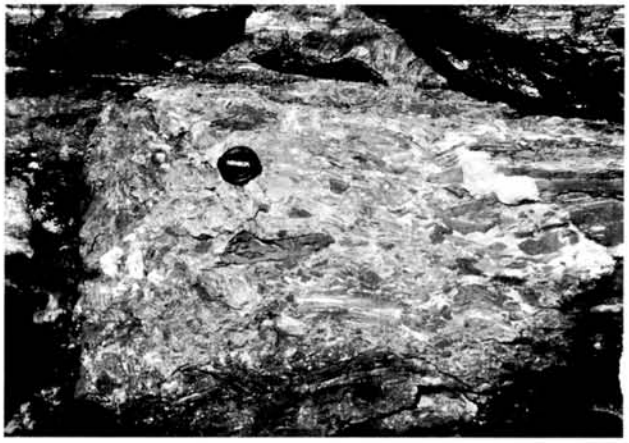
Chaotic units and associated features

Delhaven outcrops

The best exposed section of the chaotic unit and associated deposits is located in the Cape Blomidon region (Figs. 1D, 2D), near the fishing village of Delhaven. The outcrops at the Delhaven locality are mostly red sandstone and mudstone of the lower Blomidon Formation exposed in a wave-cut cliff along the bay.

At Delhaven three distinct units are present, which we have informally designated DH1–DH3 in the upsection direction. These three units form a distinctive association, readily identifiable in the sketch of the cliff face in Fig. 3. DH1 is the chaotic mudstone unit. DH2 unconformably overlies DH1 and is a sandstone with numerous synsedimentary

Fig. 4. Collapse breccia in DH1. Clasts consist of finely laminated, dark red mudstone of the upper fish bed. A relatively coherent block of the laminated mudstone is present on the right.



deformational structures. The DH1 – DH2 contact is irregular. DH2 is overlain conformably by an undisturbed mudstone, designated DH3.

Unit DH1 is a disrupted dark red – brown mottled (buff) mudstone – siltstone – fine sandstone, with distinctive dark red, green, and yellow laminated claystone clasts of the upper fish bed (Fig. 4). Brecciation of the claystone consistently increases downward, with clasts being derived exclusively from beds at the top of DH1. Lenses of the intact upper fish bed are locally present at the top of DH1. Thus coherence and clast size increase upward. Other features of DH1 include geopetal structures, chaotic bedding (in most cases, bedding is not recognizable), domino-style normal faults offsetting the contact with DH2, isolated pods of the overlying sandstone unit (DH2), small mudcracks, and evaporite dissolution vugs. Dissolution vugs are absent to the southwest (Fig. 3). DH1 is only partially exposed at the Delhaven locality.

DH2 is a moderately sorted, medium- to coarse-grained (slightly conglomeratic in places) red–orange sandstone exhibiting the following features: (*i*) alternating bands of red and green- or buff-colored sediments (Figs. 5A–5C); (*ii*) trough cross-beds; (*iii*) shaley interbeds (Fig. 5A); (*iv*) chaotic, disturbed, and convoluted bedding (Fig. 5D); (*v*) dewatering structures (Fig. 5D); (*vi*) convergent normal-fault fans (Fig. 5B); (*vii*) reverse faults (Fig. 5B); (*viii*) kink bands (Fig. 5); and (*ix*) highly variable thickness (0.4–2.0 m) (Fig. 3). (Note that the peak at control point 14 in Fig. 3 is a result of the outcrop projecting out toward the bay.)

The dewatering structures are preferentially aligned with the upward projections of normal faults within DH1. As noted previously, the contact with the underlying DH1 is highly irregular. Deformation in DH2 is most intense at low points along this contact. In some cases, conjugate normal faults dip toward the axis of the low points (Fig. 5B). Reverse faults are likely rotated normal faults (Fig. 5A). The style of faulting strongly resembles that produced in sandbox models (e.g., McClay and Ellis 1987), indicating that the deformation occurred prior to lithification. Near control point 14, the sandstone of DH2 is trough cross-bedded, with the trough azimuth being 105°/285°. DH2 becomes less distinct to the southwest.

The shaley interbeds and color banding are useful for determining stratal geometries. Many of the units at the top of DH2 dip and thicken to the southwest; regional dip is to the northwest (into the cliff face). Individual shale horizons increase in dip to the southwest, with some being disrupted by fluid-escape structures (Fig. 5C) or synsedimentary faults (Fig. 5A). The fanning and thickening of beds to the southwest (Fig. 5C) suggest local asymmetric syndepositional subsidence; this is supported by internal onlap geometries (e.g., Fig. 5C) and a consistent decrease in deformation upward, with the uppermost beds of DH2 being undeformed.

DH3 is an essentially undisturbed red mudstone and shale, at times massive and blocky. Its lower contact is regular and conformable with DH2. DH3 is the stratigraphically highest unit at Delhaven, and is only partially exposed there.

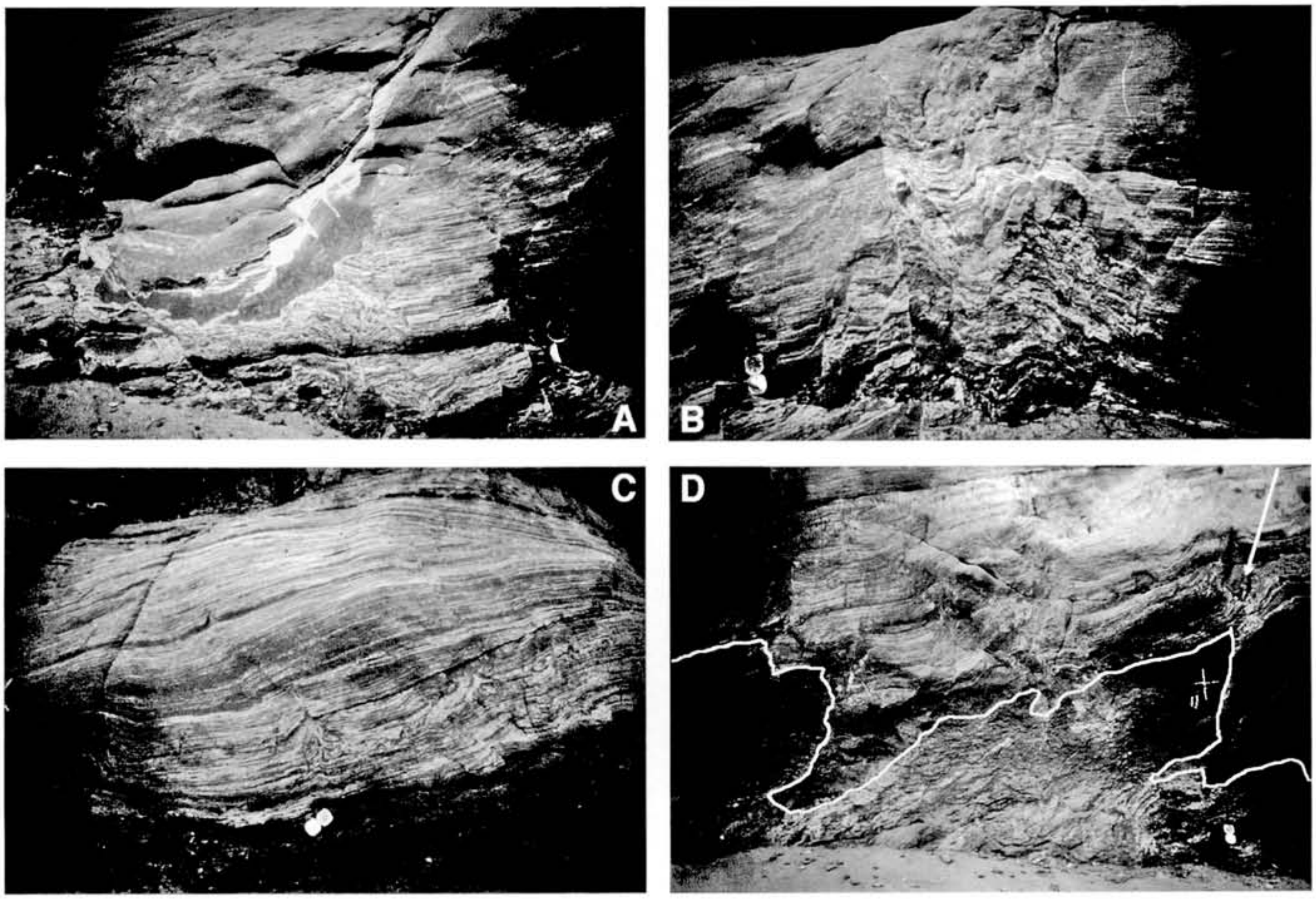
Interpretation of Delhaven section

DH1 has clearly been disturbed; chaotic bedding and domino-style faulting suggest severe disturbance of this unit. Much of DH1 is a breccia, in which clast size increases upward and degree of brecciation increases downward; this is consistent with collapse of DH1 and the subsequent downward movement of material. Evaporite dissolution vugs are present within DH1 as well. Isolated lenses of the overlying sandstone unit (DH2) also occur in DH1. Geopetal structures within these lenses represent voids filled with sand from above.

DH2 is disturbed as well, but not as extensively as DH1. Bedding defined by color banding and shaley interbeds is still recognizable. Deformation is most intense at low points along the DH1–DH2 contact. The reverse faults within DH2 described above probably originally developed as conjugate normal faults during the early phases of subsidence, which were rotated during progressive collapse and loading from sediments deposited above. Soft-sediment deformation features, such as fluid-escape structures, kink bands, and convoluted bedding, indicate that deformation occurred prior to lithification. Evidence of prelithification fluid escape along fault planes is shown in the middle of Fig. 5D. Here the fluid-escape structures in DH2 are rooted in domino-style faults in DH1.

The high degree of disturbance of DH2 strata has destroyed any original small-scale sedimentary structures that would aid in the interpretation of depositional environment. An eolian origin, however, may be ruled out in that the sorting of the grains is too poor, grain sizes are at times too large, and there are mica flakes present. In addition, DH2 does not resemble the other recognized eolian units of the Fundy Group, e.g., the Wolfville Formation at Red Head (Hubert and Mertz 1980, 1984). The presence of a few trough cross-beds suggests that DH2 is fluvial or fluviodeltaic in origin; streams flowed northeasterly off the basement block, shifted with the local axis of subsidence, and then dropped their sediment load into a lake. This would explain the absence of similar sands in neighboring fault blocks to the northeast. Deposition of DH2 occurred while DH1 continued to collapse, based on general thickening and fanning of sediments to the southwest (Fig. 3, control points 10, 12, 13, 16), suggesting either that the axis of subsidence at this locality

Fig. 5. (A) Alternating color bands of same grain size within DH2 sandstone serve as marker horizons to delimit the style of deformation. Large pod or trough is present within DH2. Banded sandstone and shale interbeds are cut by numerous faults, most of which exhibit reverse offset. Intense faulting near lower central part of photograph has resulted in chaotic bedding. Note that the dip of layering within the pod decreases upward. (B) At the centre of the photograph, steeply dipping normal faults have a conjugate geometry. Adjacent faults exhibit reverse offset. This area is located 1 m to south-southwest of control point 14 in Fig. 3, and is immediately adjacent to the section illustrated in (A) (Brunton compass is at the same position as in (A)). (C) Photograph of units DH1, DH2, and DH3 taken near control point 13. DH1 exhibits some brecciation and convoluted bedding. Dewatering structures, kink bands, disturbed bedding, some faulting, and fanning with thickening to the south-southwest (left) are present in DH2. The uppermost part of DH2 and DH3 is undisturbed. (D) Partially faulted contact between DH1 and DH2 (heavy white line). Fluid-escape structures and convoluted bedding are localized near the upward projections of the faults (e.g., arrow). Note dissolution vugs to the left of the Brunton compass. Photograph taken at control station 11.



shifted from northeast to southwest through time, or that the depression caused by subsidence was asymmetric, much like in a half graben. An upward decrease in dip of bedding in DH2 and a conformable contact with the overlying subhorizontal, undisturbed mudstone unit of DH3 (Fig. 3, control points 10–14) suggest that subsidence rates decreased with time, with collapse and settling ceasing by the end of deposition of DH2 and the beginning of deposition of DH3. DH1 and DH2 are most disturbed between control points 13 and 16 in Fig. 3, suggesting that locally this is the zone of maximum subsidence, with the axis of subsidence – depocentre shifting from northeast to southwest through time (from control points 16 to 13).

Collapse features at the hamlet of Blomidon

The outcrops near the hamlet of Blomidon are located in the third fault block to the northeast of Delhaven (Fig. 1D) and have been previously described by Olsen et al. (1989). We have continuously traced the chaotic mudstone unit for ~0.5 km along the length of the cliff face in this fault block. A sketch showing the stratigraphic relations is presented in Fig. 6. The chaotic unit (unit B in Fig. 6; DH1 equivalent) is underlain by a normal-faulted interval of massive mudstone (unit A in Fig. 6), and is characterized by blocks of laminated claystone that become increasingly disrupted and brecciated downward. Lenses and fissures of mudstone to coarse sandstone contain clasts of laminated mudstone derived from overlying beds; this suggests progressive disruption and deposition below the sediment surface, prior to the deposition of the undisturbed overlying laminated mudstone and siltstone (unit C in Fig. 6; DH3 equivalent) (Olsen et al. 1989). The middle unit (B) contains numerous pods and euhedral crystals of gypsum. Many of these are aligned along upward projections of faults in the underlying sand-patch red mudstone. An equivalent to

Fig. 6. Outcrop sketch of collapse features near Blomidon (see Fig. 1D for location and Fig. 2C for position in stratigraphic section). A, B, and C refer to units discussed in the text. Modified from Olsen et al. (1989).

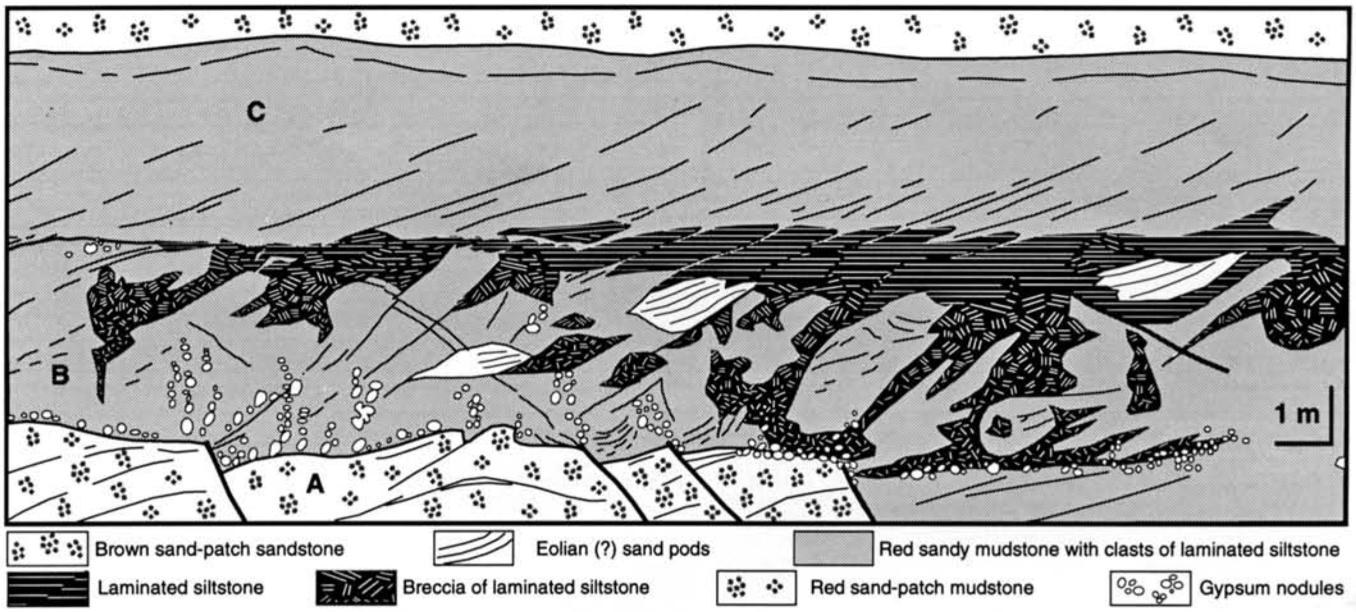


Fig. 7. Bowl-shaped deformation structures near Blomidon (see Fig. 1D for location and Fig. 2C for position in stratigraphic section). Strata thicken toward the centre of the bowls, indicating syndepositional deformation. Note that strata above the bowls are undeformed and those below are essentially undeformed. Cliff is approximately 10 m high.

the DH2 sandstone unit is absent at this locality.

The chaotic unit at this locality (B) is the best developed collapse unit of all outcrops studied. It is also present in the two fault blocks between the Blomidon locality and Delhaven. A measured section of the lower Blomidon Formation (Fig. 2D) in the first fault block to the northeast of Delhaven shows that the stratigraphic position of the chaotic unit is the same as at the Blomidon locality (Fig. 2C). Other features related to collapse in the third fault block to the northeast of Delhaven are metre-scale bowl-shaped structures (sags) that affect the strata (Fig. 7), with strata above and below them being relatively undisturbed. Strata locally thicken toward the centre of the bowls, indicating synsedimentary deformation. These features are likely unrelated to compressive folding in that the units above and below them are relatively undeformed; multiple detachment horizons would be required if the warps were tectonically produced. The bowls likely formed as a result of differential subsidence due to the collapse of underlying units.

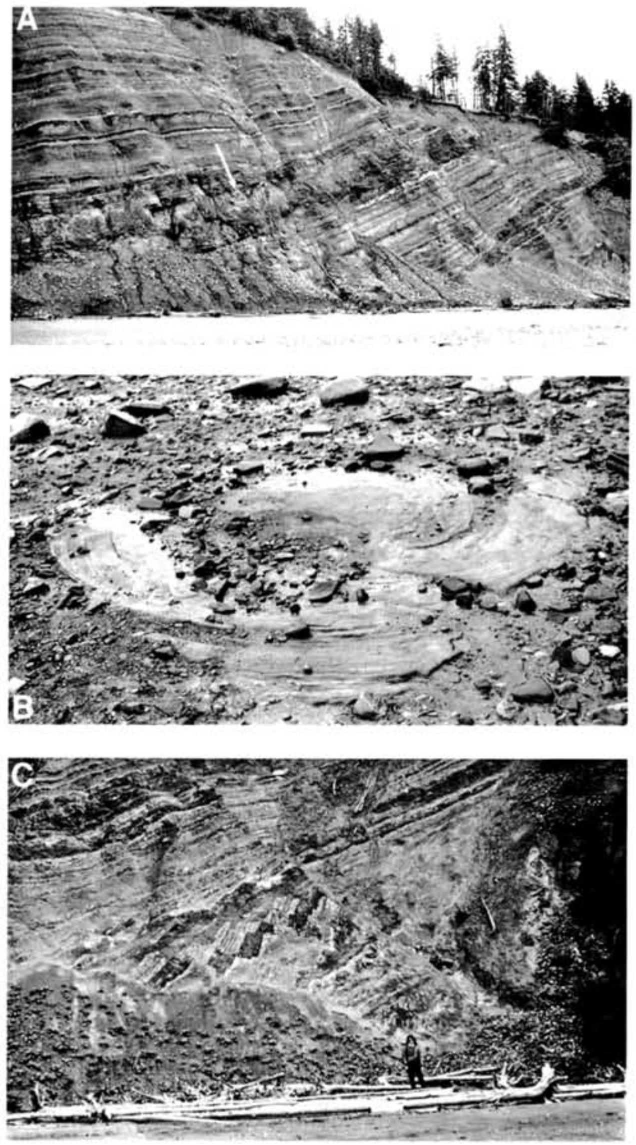
The stratigraphic position of the bowl features is shown in Fig. 2C; they are located ~10 m above the chaotic mudstone unit. The intervening strata are essentially undisturbed. Thus the collapse responsible for the formation of the chaotic unit cannot explain the formation of the bowls, which requires a separate, later collapse event.

Red Head outcrops

A unit equivalent to DH1 at Delhaven can be found in the cliff face at Red Head, 35 km to the east (Figs. 1E, 8A). At this locality, the chaotic unit exhibits many of the characteristics of unit DH1 at Delhaven, including a highly disturbed stratigraphy, with distinct downward movement of material. A sandstone unit equivalent to DH2 is present as well, but here it is thinner; there are no obvious dewatering structures, but some synsedimentary faults are present. Pods of sandstone and conglomerate infill depressions on the top surface of the chaotic unit. Some of the pods have a funnel-like geometry (Fig. 8B), which perhaps served as conduits for transporting sediment into voids in the chaotic unit created by collapse. These structures are remarkably similar to collapse-related funnels described by Hesse and Reading (1978) from the Mississippian Horton Bluff Formation of Nova Scotia (see their Figs. 15 and 16); in their example, collapse was related to upward ejection of liquefied sediments due to seismic shaking. The Red Head DH2 equivalent is not as laterally continuous as DH2 at Delhaven. Overlying units are undisturbed. The top portion of the DH2 equivalent displays erratic thickening and fanning geometries, with strata thickening to the southwest, towards the Delhaven locality. This thickening direction is consistent with that observed at Delhaven.

The collapse features at Red Head, although easily recognized, are not as dramatic as at Delhaven. Those at Red Head are in the same stratigraphic position as those at Delhaven and the other fault blocks along the Blomidon Peninsula, based on the correlation of the upper fish bed (Fig. 2). Domino-style faulting featuring extreme stratal tilting affects the Blomidon Formation 20 m below the chaotic unit at Red Head (Fig. 8C). Units above the domino-faulted interval are undisturbed; the dominoes become smaller downsection until they disappear into the beach. The domino-faulted interval lies below the lower fish bed (Fig. 2E). Similar domino-faulted intervals lie in the lower fish bed in two of the fault blocks along the Blomidon Peninsula (Fig. 2B–2D). The widespread presence of these domino-faulted intervals suggests a basin-wide syndepositional period of disturbance.

Fig. 8. (A) Chaotic unit within lower Blomidon Formation at Red Head (see Fig. 1E for location). Note that bedding is almost completely disrupted within this unit and that pods of sandstone are locally present (arrow). Domino-faulted interval near base of section can be seen at extreme right. (B) Circular sandstone feature exposed on tidal flat. Cross-bedding defines a funnel-like geometry. The sandstone is cut by faults similar in style to those affecting DH2 at Delhaven. Feature is 1.5 m in diameter. (C) Domino-style faults at Red Head, located 20 m below the chaotic unit. Units above the faulted interval are essentially undisturbed.



Discussion

The chaotic unit (DH1 and equivalents) is a highly disrupted mudstone characterized by the downward movement and brecciation of material (Fig. 4). The disturbance observed in the chaotic unit could have been produced by two viable mechanisms; namely collapse or seismic activity, which are not mutually exclusive. Olsen et al. (1989) tentatively proposed that dissolution of a large evaporite bed was responsible for the formation of the chaotic unit near the hamlet of Blomidon. We concur with this interpretation, although we suggest that the now dissolved body may have been evaporite-rich rather than solid evaporite. An evaporite-rich body would have to be thicker than a body of pure evaporites to produce the same amount of subsidence.

Olsen et al. (1989) discounted blowout from seismic activity as the mechanism of collapse in light of the complete absence of evidence for upward movement of material other than groundwater. Sedimentary units affected by seismic shaking are typically associated with clastic dikes and sand volcanoes related to upward movement of liquefied sediment (Hesse and Reading 1978; Obermeier et al. 1985; Talwani and Cox 1985; Plaziat et al. 1990). Clastic dikes are present in the upper Blomidon Formation near Red Head (Withjack et al. 1995), but none are associated with the chaotic units described here. The overwhelming evidence of downward movement is most consistent with collapse. Fissuring associated with the propagation of seismic waves may account for localized collapse, but the large distances over which the chaotic unit is exposed preclude seismic fissuring and collapse. Progressive collapse indicated by the fanning geometry of the DH2 sandstone unit at Delhaven is also not consistent with an abrupt seismic event inducing collapse (e.g., liquefaction). In addition, this is the only unit in the Blomidon section that exhibits these characteristics. If such features had been produced by seismic activity, one would expect them to occur in similar mudstone facies in the section, because the Fundy rift basin presumably formed as a result of numerous earthquake slip events on the border fault system. It is possible, however, that a seismic event was the *trigger* for undermined units to begin subsiding. The domino-style faults exposed at Red Head and several other fault blocks (Figs. 2, 8C) could have been produced by collapse from evaporite dissolution and (or) seismic activity. The structures are similar to those described by Seilacher (1969) and attributed to seismic shaking.

The collapse of the chaotic unit (DH1 and its equivalents) is probably the result of the dissolution of a metre-scale evaporite bed or evaporite-rich unit by groundwater. The presence of clasts derived from the upper fish bed locally at the very top of the chaotic unit, the decrease in brecciation upsection, the overall disturbed nature, and the undulatory and partly faulted contact with the DH2 sandstone at Delhaven are all indicative of collapse. These features are similar to other dissolutional collapse breccias described elsewhere (Stanton 1966; Clifton 1967; James 1984). The fanning geometry of the beds in DH2 at Delhaven and Red Head suggest syncollapse deposition of this unit, with the depocentre shifting to the southwest at Delhaven, towards an axis of subsidence. Syncollapse deposition of DH2 is also suggested by the soft-sediment deformation features, dewatering structures (formed during the expulsion of evaporite-laden groundwater), and presence of faults in the lower portions of DH2. Isolated pods of DH2 surrounded by the chaotic unit may have been deposited below the ground surface.

The dissolution and collapse interpretation is reinforced by the mode of occurrence of the evaporites within the rocks today: nodules are present almost exclusively at the contact between DH1 and DH2, and within equivalent chaotic units as alignments of vugs along projections of underlying fault planes (Fig. 6). The removal of the material that once filled these vugs is not the cause of the collapse. Rather, evaporite-laden groundwater may not have been completely expelled from the chaotic units, allowing evaporites to crystallize at some later time. The vug alignments indicate that evaporite-laden groundwater was expelled along the fault planes as the sediments subsided, with the evaporites then reprecipitating out. The material that once filled the vugs exposed in outcrop has only recently been dissolved. Vugs in large boulders spalled from the cliff contain gypsum infill until it is rapidly removed by weathering.

The generally arid climate suggested by an evaporite body is supported by the presence or absence of several other facies. Eolian deposits are present in all of the exposed sedimentary formations of the Fundy basin in Nova Scotia. The predominance of sand-patch fabrics and cycles within the Blomidon Formation is indicative of a generally, if not continually, arid environment. In addition, dark gray and black lacustrine facies diagnostic of wetter climates, and characteristic of the other Newark Supergroup basins, are almost entirely absent from the exposed Fundy Group. The interpreted arid paleoenvironment most likely reflects the paleolatitudinal setting of the Fundy basin, which was situated at ~10N latitude in Carnian time (~220 Ma BP) and gradually drifted northward (Witte et al. 1991). The other Newark Supergroup basins were considerably farther south, in a more tropical equatorial setting. The Argana basin in Morocco had a similarly arid paleoenvironment and was located at a slightly more southerly paleolatitude than the Fundy basin. Substantial halite and gypsum beds have been documented there (Tixeront 1973; Brown 1980; Lorenz 1988; Smoot and Olsen 1988), and are associated with sand-patch fabrics like those in the Blomidon Formation (Smoot and Olsen 1988).

The former presence of the evaporite body and associated units and features is very important in the context of climate cyclicity. At all of the outcrops of the chaotic mudstone, the disturbed unit is underlain by several metres of mostly sand-patch sandstone, suggestive of arid conditions. The accumulation of the evaporite layer or evaporite-rich unit occurred under similar conditions. Following deposition of the evaporites, conditions became considerably wetter, resulting in the deposition of the upper fish bed. Following the partial lithification of the fish bed, evaporite dissolution by groundwater began. As overlying units were further undermined by the continued dissolution of the evaporites, the mudstones began to collapse and brecciate. Evaporite-laden groundwater was probably expelled during the collapse of units overlying the evaporite body, explaining the presence of the numerous dewatering structures. Fluid movement was likely facilitated along fault zones, thereby accounting for the greater frequency of evaporite vugs and dewatering structures aligned along the upward projections of fault zones. The initiation of collapse may have been *triggered* by a seismic event. At the Delhaven locality, as the mudstone unit collapsed and brecciated, streams flowing off the basement block followed the negative topography produced by subsidence and began to deposit sediments during continued collapse. With continued collapse and subsidence, now aided by loading of fluvial sediments, the fluvial unit itself experienced soft-sediment deformation and was progressively tilted toward the shifting axis of subsidence.

The basin-wide stratigraphic correlations of the collapse features in the Minas subbasin suggest they have a common origin. We propose that the now-dissolved evaporite body was regionally persistent. In fault blocks located closest to the basin margins (e.g., Delhaven, Red Head), the chaotic unit is overlain by a coarse sandstone unit of fluvial or fluviodeltaic origin (DH2) interpreted to have filled depressions created by the collapse. The thickness of DH2 may be used as a proxy for the thickness of the evaporite layer. This value is likely to be a minimum, for the surface depression caused by the dissolution and subsidence of DH1 may not have been completely infilled. The maximum thickness of DH2 at Delhaven is ~2 m (located near control point 14 in Fig. 3). Thus, the minimum thickness of the evaporite layer was 2 m. If an evaporite-rich layer was involved, the thickness of the evaporite component in this unit was 2 m. Unlike the brecciated mudstone unit, the fluvial unit at Delhaven cannot be traced across the Minas subbasin. Although the evaporite body (as evidenced by the brecciated mudstone) was regionally persistent and collapse was basin-wide, syncollapse fluvial deposition was not, most likely because fluvial deposition gave way to playa–lacustrine sedimentation in more basinward settings.

The basin-wide correlation of the chaotic unit (using the upper fish bed) and the domino-style faulted interval below the lower fish bed, as well as the collapse bowls at Lower Blomidon (which are upsection of the chaotic unit), suggest that there may have been at least three evaporite intervals within the lower Blomidon Formation. There may have actually been many more than that, but only those three may have been thick enough (metre scale) to produce significant deformation associated with their dissolution. Any others were likely to have been much thinner (centimetre scale or less), so their dissolution has not caused any recognizable deformation or missing section. Summed together, these units could account for a significant amount of section, which would now be missing. However, in terms of the amount of time that would be missing from the section, this is not significant given the extremely high sedimentation rates for evaporites (Kendall 1988). It is unclear whether this may be a contributing factor to problems encountered in attempts to analyze climatic cycles within the Blomidon Formation (e.g., Olsen et al. 1989).

We suggest that geochemical recycling of weathering products from the Windsor Group to the southeast (Clifton 1967) most likely provided a source for the chemicals that precipitated in the Blomidon playa lake in the Minas subbasin, producing the evaporites (now dissolved) within the

Blomidon Formation. Given the many different evaporites present in the Windsor Group (e.g., halite, anhydrite, sylvite, and carnallite; Bell 1958; Evans 1970), it is difficult to be certain of the composition of the now-dissolved evaporite body or bodies in the Blomidon Formation. However, the widespread presence of sand-patch fabric, which requires halite (Smoot and Kastens-Seidell 1994), and the presence of skeletal halite molds suggest that halite was probably the major salt dissolved.

The idea of geochemical recycling as a source for the evaporites in the Blomidon Formation is consistent with the dissolution of evaporite beds within the Windsor Group of Nova Scotia, currently exposed southeast of the area discussed here (Fig. 1B), as documented by Clifton (1967). Their removal led to internal brecciation and collapse within the Windsor Group. The breccia partially comprises material similar to the sandstones within the middle to upper Wolfville Formation and the Blomidon Formation. The material in the Windsor Group could have been deposited at the same time as the Wolfville and Blomidon formations within the Fundy rift basin. Alternatively, it was derived from uplifted fault blocks along the oblique-slip Minas subbasin margin or erosion of lake margin deposits during lowstands. Clifton (1967) bracketed the time of dissolution and brecciation within the Windsor Group as between the Late Triassic and pre-Pleistocene. Based on limited observations of joints within the fills, we further constrain the timing as Late Triassic (Cretaceous and younger rocks in this region are not jointed). This is consistent with the inferred timing of evaporite deposition and dissolution in the Blomidon Formation (Late Triassic).

The stratigraphic relations described here and mechanisms that formed them are termed interstratal karst—the subsurface dissolution of evaporites or carbonates bounded by insoluble units (e.g., Jennings 1985). Because the features are inactive and lithified, without modern surface expression, they are best described as being buried (e.g., Jennings 1985). Another name given such structures is subjacent karst, which forms by the same mechanism (Jennings 1985). Although the collapse features of the Fundy basin are not karstic in the traditional sense of the term (in that carbonates are not involved), they are most accurately described as buried interstratal karst.

The recognition of now-absent evaporite bodies on the basis of collapse features and associated syncollapse deposits can be useful to augment or enhance paleoenvironmental interpretations. The identification and interpretation of the collapse sequences needs to be assessed in the context of the surrounding stratigraphy and regional setting, and should not be used alone. However, under the proper circumstances, the features discussed in this report can be used to infer the former existence of substantial evaporite units in predominantly clastic continental environments.

Summary and conclusions

(1) The lower Blomidon Formation, a mostly playa and playa–lacustrine deposit associated with saline mudflat fabrics and gypsum, contains a chaotic mudstone unit traceable for 35 km across the Minas subbasin of the Fundy rift basin and through four fault blocks.

(2) Features of the chaotic unit include highly disrupted bedding, nodules of gypsum, geopetal structures, and domino-style faults. The chaotic unit also contains clasts and breccia of a finely laminated fish- and conchostracan-bearing mudstone locally in place at the top of the chaotic unit. Clast size decreases downward, whereas the degree of brecciation increases, suggesting collapse of the chaotic unit due to groundwater dissolution of evaporite beds.

(3) In fault blocks located closest to the basin margins, the chaotic unit is overlain by a coarse sandstone unit of fluvial or fluviodeltaic origin interpreted to have filled depressions created by the collapse. The coarse sandstone is characterized by a highly irregular lower contact, a relatively planar upper contact (indicating that this was not an underground stream deposit), convergent fault fans best developed over localized areas of subsidence, highly disrupted bedding, fanning and thickening of beds, and fluid-escape structures related to the expulsion of evaporite-laden groundwater.

(4) The features described here are indicative of buried interstratal karst, and have been traced across multiple fault blocks of the Minas subbasin. Collapse was likely due to the dissolution of a regionally persistent metre-scale evaporite (or thicker evaporite-rich) body of variable thickness.

(5) The former presence of the now-dissolved unit implies an extended period of arid, playa conditions within the Blomidon Formation. This arid interval was preceded by a fairly dry period, and followed by wetter conditions resulting in the deposition of a fish-bearing laminated claystone.

(6) The recognition of now-absent evaporite bodies enhances the arid paleoenvironmental interpretation of parts of the lower Blomidon Formation, and indicates that portions of the Blomidon section may be missing, although the amount of time missing may be relatively minor.

(7) Features associated with chaotic mudstone units may be useful in documenting synsedimentary collapse and inferring the prior presence of evaporites within mainly clastic continental sequences.

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