Climatic and eustatic controls on the development of a Late Triassic source rock in the Jameson Land Basin, East Greenland

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Abstract: Complex environmental controls have influenced deposition of the Gråklint Beds, a prospective oil and gas prone Late Triassic (Mid Carnian) source rock in the Jameson Land Basin, East Greenland. The identification of a Late Triassic source rock is significant for hydrocarbon exploration in the North Atlantic region. Detailed sedimentological analysis, biostratigraphy and geochemical analysis provide insights into the controls on source rock development and have wider implications for palaeoclimatic trends and palaeogeographic reconstructions of the North Atlantic at this time.

The Gråklint Beds were deposited in a predominantly lacustrine setting during a phase of climatic cooling which can be ascribed to the ‘Mid Carnian pluvial event’. This further extends the evidence for the global effect of such climatic perturbations and furthermore highlights the potential for the use of climatic events for global and regional correlation between varying environmental settings. Evidence for marine ingression is also recorded, which resulted in the precipitation of magadiite ($NaSi_7(OH)_3 \cdot 3H_2O$) and the brief influx of a marine fauna. This provides the most southerly record of marine influence from the Boreal Ocean at this time and has important implications for palaeoenvironmental reconstructions and correlation in the region.

Keywords: Triassic; lacustrine; East Greenland; source rock; Carnian; Jameson Land Basin.

The Gåklint Beds form an enigmatic unit in the largely continental Triassic succession of East Greenland and has previously been suggested to form a source rock in the region (Perch-Nielsen *et al.*, 1974; Christiansen *et al.*, 1992), although no data has been published on its quality, distribution or controls thereon. Confirmation of a Triassic source rock in East Greenland provides the potential for a new petroleum play both in East Greenland and the adjacent offshore basins.

The Gråklint Beds have been interpreted as reflecting a restricted marine, lagoonal setting (Clemmensen, 1980a) however, we suggest a more complex origin on the basis of detailed sedimentological, palaeontological and geochemical studies. Biostratigraphic revisions presented here place the Gråklint Beds within the Carnian, a time when significant environmental perturbations occurred both locally and globally. During the Carnian, sea level reached their Triassic highstand (Haq *et al.*, 2008; Haq *et al.*, 1987) resulting in the southward penetration of the boreal ocean at least as far as the Halten Bank, offshore Norway (Jacobsen *et al.*, 1984). Furthermore, there is increasing evidence for a global climatic perturbation, the Mid Carnian Pluvial Event (eg. Stefani *et al.*, 2010; Mutti *et al.*, 1996; Hochuli *et al.*, 2010; Simms *et al.*, 1989; Kürschner *et al.*, 2010; Prochnow *et al.*, 2006), at this time which has been linked to the Wrangelia large igneous province (Dal Corso *et al.*, 2012). Evidence for the influence of these factors has significant implications for North Atlantic palaeogeographies at this time and further reinforces the global impact of climate forcing events. This study investigates the relative influence of these factors on the deposition and distribution of the Gråklint Beds and furthermore characterises the source rock properties of this unit.

Geological Setting

The Jameson Land Basin is located in East Greenland between 70˚05' and 73˚ N (Fig. 1). The continental, Mid to Late Triassic, strata are largely confined to the Jameson Land, Scoresby Land and Liverpool Land regions (Fig. 1) with minor outcrop recorded further north in the Mols Bjerge, on Traill Ø, and on Geographical Society Ø. Aligned broadly north-south the Jameson Land Basin is approximately 280 km long and 80 km wide and contains in excess of 1.5 km of Mid to Late Triassic fill. During the Mid Triassic, Jameson Land was positioned in the northern arid belt, 15˚-30˚ north of the equator (Kent *et al.*, 1996), resulting in an arid to semi-arid climate. By the Early Jurassic Jameson Land had drifted to around 40˚N.

The Mid to Late Triassic succession of East Greenland consists of the coarse, predominantly alluvial, clastics of the Pingo Dal Formation which are overlain by the lacustrine, and subordinate fluvial, mudstones and sandstones of the Gipsdalen and Fleming Fjord formations. Dating of the succession is poor, as is often the case in continental deposits. However, palaeontological work presented here has significantly improved dating constraints and allowed revision of the stratigraphy (Fig. 2). The lithostratigraphic scheme erected by Clemmensen (1980b) is broadly followed here (Fig. 2).

The Gråklint Beds lie at the base of the Gipsdalen Formation and thicken from the south in Carlsberg Fjord (≈10m, Fig. 3a) to the north, on Sporfjeld (≈54m, Fig. 3b). An intrabasinal high existed between these areas at this time dividing the Jameson Land Basin. The Gråklint Beds were first described, as the *Myalina* limestone, by Grasmück and Trümpy (1969) who regarded the interval to reflect a marine ingression on the basis of its wide extent and the presence of a marine fauna. This interpretation was followed by Perch-Nielsen *et al.* (1974) and Clemmensen (1980b) who suggested that the complex facies pattern was also characteristic of a marine setting with beach barriers developed isolating lagoonal regions.

These interpretations are not wholly consistent with the observations and analysis which are described herein.

Sedimentology

Detailed sedimentological analysis of the Gråklint Beds has been undertaken throughout the Jameson Land Basin. Four main facies are recognised within the Gråklint Beds; black to dark grey mudstone and limestone facies; grey to light grey mudstone, siltstone and limestone facies; cross bedded grey calcareous sandstone facies with associated bioturbated buff sandstones and, of very restricted occurrence, sandy limestone breccia facies. These facies are described and their distribution discussed below.

Black to dark grey mudstone and limestone facies

The black to dark grey mudstone and limestone facies are dominated by black and dark grey, finely laminated mudstones with variable carbonate content. Lamination is variably developed across the basin with 1 to sub-millimetre lamination recorded to the south east in the Carlsberg Fjord region and less consistent sub-millimetre to 10 mm lamination observed further north. Where well defined in Carlsberg Fjord, thin section analysis reveals a regularly ordered arrangement of silt, calcite and organic elements composing each lamina (Fig. 4a). In some instances this sequence is curtailed to silt-calcite or silt-organic couplets. TOCs up to 6.3% have been measured making this facies the main component of the prospective source rock. Intervals of less well defined lamination tend to contain more poorly developed calcite laminae and disseminated organic components. Rare silt and very fine sand laminae up to 5 mm are recorded, some containing current ripples. Thicker graded grey sandstone beds up to 0.35 m thick, some of which display loaded and erosive bases, have also been recorded. Where silt/very fine sand laminae are present rare syneresis cracks tend to be preserved. The relationship of syneresis cracks and the silt/sand laminae may be an artefact of preservation, which was only possible in places where sand was available to provide a crack fill. The limestones recorded in this facies occur in two forms; black limestone beds 5-20 mm thick and more rarely grey carbonate nodules. The carbonate nodules range 0.05-0.5 m in scale and are round to vertically elongate in form. Larger nodules tend to have a vertically elongate form. Distinctive black chert nodules are recorded in this facies in the Carlsberg Fjord region where they occur directly overlying the sandy limestone breccia facies to which they seem genetically linked. These nodules are therefore described alongside the sandy limestone breccia facies.

The fine grained nature and development of fine lamination in the black to dark grey mudstone and limestone facies is indicative of a low energy environment. The absence of bioturbation, preservation of organic material (up to 6.3% TOC) and lack of wave ripples indicate that deposition took place within a largely anoxic setting below the influence of surface waves, possibly in a stratified water body. The couplet/triplet arrangement of the individual laminae identified in the Carlsberg Fjord region is characteristic of non-glacial varves, which form in lacustrine settings (eg. Anderson *et al.*, 1988; Glenn *et al.*, 1991; Andrews *et al.*, 2010). The alternation of silt, calcite and organic components of the non-glacial varves are interpreted as reflecting seasonal variance in lake conditions. The largely structureless nature of the silt component suggests deposition from the gradual settling of sediment introduced to the lake by interflows and overflows during cooler, wetter seasons. Similar silt components have been reported from modern lake sediments which contain non-glacial varves, eg. Loch Ness (Cooper *et al.*, 1998; Cooper *et al.*, 2000) and Lake Brienz (Sturm *et al.*, 1978). Carbonate precipitation in lakes is stimulated by increasing water temperatures and pH (Brunskill, 1969; Kelts *et al.*, 1978). Therefore the calcite component is interpreted as reflecting warmer, drier conditions. The micritic nature of the calcite suggests high nucleation rates which would be expected with elevated water temperatures and related increases in carbonate saturation. The organic component is interpreted as the result of algal blooms as is suggested to be the origin of similar laminae components present in annually laminated deep lake deposits in the Middle Old Red Sandstone of northern Scotland (Andrews *et al.*, 2010; Rayner, 1963; Donovan, 1980; Trewin, 1986). Similar increases in organic content during summer deposition have been reported from modern lakes (Håkanson *et al.*, 1983; Dean *et al.*, 1999). The less well developed lamination recognised in more northern regions suggests less stable conditions within a similar deep water setting. The thin sandstone beds with occasional current ripples and the thicker graded grey sandstones, some of which display loaded and erosive bases, are interpreted as small scale turbidite units. Sturm and Matter (1978) described similar turbidite beds from Lake Brienz which were attributed to catastrophic flooding and landslide events.

Grey to Light Grey Mudstone, Siltstone and Limestone Facies

The mudstones and silts of the grey to light grey mudstone, siltstone and limestone facies are typically poorly consolidated and therefore little sedimentological detail can be ascertained. Thin sandstone intercalations (2-20 mm) are common containing current and oscillation ripples. Plant fragments are also recorded and, in some instances, the sand intercalations aid in the preservation of syneresis cracks. Minor occurrences of slump beds are noted up to 0.1 m thick displaying overturned folding and disrupted lamination. Minor disruption is also recorded where bioturbation is present. Grey to light grey limestones are common and rare black limestones are also recorded which are of bioclastic origin, composed of monospecific assemblages of disarticulated bivalves (Fig. 4b) which form beds up to 0.15 m thick. The lighter coloured limestones show parallel lamination/bedding ranging from 1 mm to 10 cm scale. Mudstone and siltstone partings are common. Where examined in thin section the limestones can be seen to comprise clotted/pelleted? muddy dolomitic material forming laminae which are often punctuated by thin spreads of silt grade quartz. Dolomite rhombs have grown within the muddy matrix and any further porosity has been filled with ferroan calcite. Thin microbialite developments (up to 2 cm thick) are recorded which tend to be brecciated but show little sign of transport. Galena mineralisation is associated with microbialite development.

The reduced organic content, presence of oscillation ripples and the occurrence of microbialites within the grey to light grey mudstone, siltstone and limestone facies suggest deposition in shallower, oxygenated water, within the photic zone. Low energy conditions predominated as indicated by the fine grained nature of the facies. However, periods of elevated energy are indicated by the presence of oscillation ripples which evidence deposition above storm wave base. The identification of current rippling suggests an origin of the thin sandstone beds as underflows which were in some instances reworked by wave action. The undamaged nature of the disarticulated bivalves also favours a largely low energy regime. The presence of a low diversity fauna suggests a predominantly fresh water or stressed marine environment of deposition as does the paucity of bioturbation. The limestones are interpreted as the combination of a biogenic source, faecal pellets similar to those described from Lake Urmia (Kelts *et al.*, 1986), and abiogenic precipitation stimulated by elevated salinities and pH within shallow, more concentrated waters. The production of these carbonate components would increase during warmer summer conditions and therefore the presence of punctuating silt laminae may reflect flood or storm sediment input during a cooler, winter season, similar to the pattern of deposition seen in the relatively shallow Lake Balaton (Müller *et al.*, 1978).

Cross Bedded Grey Calcareous Sandstone Facies

The cross bedded grey calcareous sandstone facies with associated bioturbated buff sandstones show considerable variance across the basin but do form a coherent facies. The cross bedded grey calcareous sandstones are composed of fine to granule grained sub rounded sand and include variable amounts of carbonate material. The carbonate component is dominated by rounded shell fragments up to 1 mm thick and 4 mm long. Some examples of more complete shell material are recorded and rare ooidal dominated beds are also noted. In some instances the carbonate material is dominant resulting in limestone beds 0.1-0.2 m thick, within which stylolites have been recorded. Bedding in the sandstones varies between 0.1 and 0.4 m. The thinner bedded units (including the bioclastic limestones) commonly contain simple wave rippling and more complex wave knitted rippling. Rare cubic, carbonate filled pseudomorphs after halite up to 7 mm are also recorded. Low angle cross bedding and hummocky/swaley cross stratification are noted in the thicker bedded sandstones. Of limited geographical distribution are thick cross sets, up to 3.5 m (Fig. 4c), containing abundant re-activation surfaces which form prominent units up to 7.5 m thick. Subordinate intercalations of grey mudstones, some of which contain desiccation cracks, and pebbly planar cross bedded sandstones with erosive bases are also recorded. Associated with these cross bedded grey calcareous sandstones, and more common in northern regions of the basin, are bioturbated buff sandstones which are composed of fine to very fine sand intercalated with green grey silt and clay and are characterised by an intensely bioturbated texture (Fig. 4d). A horizontal fabric is commonly developed (Fig. 4d) which may reflect the retention of original structure or the more likely dominance of horizontal verses vertical disruption. However, some intervals do display a more chaotic, mottled texture. On better defined bed interfaces a number of horizontal traces can be recognised (Fig. 4e, f & g). Straight, 30-50 mm wide traces, which display an asymmetric pinch and swell over their >0.6 m length (Fig. 4e) are recognised on the base of the thick sandstone beds containing large scale cross bedding. These traces form troughs up to 10 mm deep and in some instances seem to display a meniscate back fill. A more complex assemblage is recognised where visible within the more intensely bioturbated examples, including; traces similar to those described above but having a branching form comparable to *Thalassinoides* (Fig. 4f), probable *Fuersichnus* and a single, *Cruziana* type trace, up to 60 mm wide and 10 mm deep, containing two sets of back-swept lineations divided by a central groove. These latter traces form cross cutting networks (Fig. 4g). Bioturbation commonly obscures bed boundaries resulting in composite ‘beds’ up to 1.3 m thick. Traces of ripples and small scale cross bedding are discernable in sections where bioturbation is less complete. Plant material and occasional cubic vugs (after halite?) are also recorded.

The coarse, sub-rounded character of the arenaceous component and the rounded and fragmented nature of the bioclastic material which comprise the cross bedded grey calcareous sandstone facies are indicative of high energy conditions within which regular reworking of sediment was common. The identification of ooidal limestones contribute evidence for such an interpretation and furthermore suggest formation in shallow, warm, carbonate rich waters. Rare cubic pseudomorphs are interpreted as evidence for evaporite (halite) formation. Common oscillation rippling and hummocky cross stratification indicate the dominance of wave action and alongside low angle cross bedding, formed through swash and backwash in the breaker zone (Allen, 1981a), characterise a shore zone setting. A similar assemblage of structures has been reported from lacustrine shore zone facies (Link *et al.*, 1978; Renaut *et* *al.*, 1991; Allen, 1981b; Dam *et al.*, 1993). These are also similar to what would be expected in a marine setting. Intercalations of desiccated mudstones are interpreted as evidence for fluctuations in lake level and the erosively based pebbly sandstones as evidence for the interaction of fluvial systems with the shore zone environment. The large scale cross bedded unit appears to coincide with the intra-basinal high located in the Devondal region (Fig. 1). The formation of such large scale cross-sets with regular re-activation surfaces is indicative of a large scale bar form subject to regular changes in currents. This feature appears to separate a northern and southern depositional domain during the deposition of the Gråklint Beds and is therefore interpreted as a barrier complex. It seems likely that this formed across the intrabasinal high through the reworking of the underlying Klitdal Member and the addition of abundant fragmented shell material. Further study is required to fully understand the genesis of this feature.

Associated with these cross bedded grey calcareous sandstone facies are bioturbated buff sandstones which are restricted to the area north of the intra-basinal high. The disruption of most, if not all, original structure makes interpretation of the depositional setting problematic but the presence of both sands and muds suggests regular fluctuations in energy. Furthermore, the intensity of bioturbation is indicative of relatively low sedimentation rates/sediment reworking and high degrees of biogenic activity. Therefore with comparison to the closely associated cross bedded grey calcareous sandstones it is suggested that the bioturbated buff sandstones reflect deposition in deeper but still oxygenated waters, probably below wave base. The presence of *Thalassinoides* and *Cruziana* suggests a marine influence, as does the increased diversity of traces (Bromley, 1996) which is perhaps the most compelling evidence for a marine influence as similar traces have been recorded from continental settings.

Sandy Limestone Breccia Facies

The sandy limestone breccia facies is of restricted occurrence forming a single unit which can be correlated over 13 km in the Carlsberg Fjord region where it divides an upper and lower unit of the black to dark grey mudstone and limestone facies (Fig. 5a). A broad thinning from 30 cm in the north to 5 cm in the south is noted. The facies itself is composed of moderately to poorly sorted, medium to very coarse grained sandstone with moderately abundant rounded quartz granules also present. When examined in thin section rounded carbonate clasts of probable bioclastic origin can also be identified. In the north, rounded and more elongate dolomitic microbialite fragments up to 10 cm and more rarely oncolites are incorporated within the medium to coarse grained matrix. In the more southern examples angular massive limestone clasts up to 10 cm are present, which in the Buch Bjerg (N) (Fig. 5a) example are derived from the underlying bed with displacements in some instances of only a few centimetres. Where transported further these large clasts tend to ‘float’ in the upper portion of the bed (Fig. 5a). Soft sediment deformation is also recorded in some examples. Distinctive black chert nodules are recorded immediately overlying the sandy limestone breccia facies. The chert occurs in both nodular and bedded forms (Fig. 5a). The nodules range from 10-50 mm in diameter, are of irregular shape and are draped by the overlying sediment. Deformation of the surrounding sediment has also occurred during compaction. Where bedded, the chert is up to 20 mm thick, often latterly discontinuous and contains lamination on a 1-3 mm scale. Internally the chert is composed of inclusion rich microcrystalline quartz (Fig. 5b). A patchy rectilinear extinction pattern (Fig. 5c) can be observed in the bedded chert when a first order red plate is inserted and polars crossed. Inclusions are common but tend to become less abundant towards the nodule margins. Well preserved palynomorphs are present within the chert (Fig. 5b) as well as very rare foraminiferans (a single example) and possible ostracods (Fig. 5d). The nodule margins are irregular and commonly have a rind of calcite up to 1 mm thick composed of 50-100 μm calcite crystals (Fig. 5e). Towards the margins of the calcite rind are large, 70-250 μm, pale green to yellow crystals which show little birefringence and are of broadly hexagonal form (Fig. 5e). Pyrite nodules up to 500 μm occur out-with the calcite rind. Cracking is also a common feature in the nodular and bedded cherts. Cracks, some of which branch, tend to penetrate from the margins of the nodules reaching up to 5 mm in length and 1-2 mm in width. The cracks contain an initial micro-chalcedonic fill which is succeeded by a more thickly developed chalcedonic phase, in some cases occluding the crack system. Where open crack systems were retained a further micro-chalcedonic phase was formed before calcite filled the remainder. A second phase of cracking is represented by smaller scale, up to 1.75 mm long, cracks containing a two stage calcite fill (Fig. 5e) which cross-cut the larger, chalcedony filled, cracks. An early ferroan calcite phase is succeeded by non ferroan calcite precipitation. This sequence is, however, reversed where carbonates fill the remaining portions of the larger cracks. Cracking within the bedded chert tends to be less well developed with the cracks defined by the inclusion rich nature of their margins, the fill consisting of microcrystalline quartz. A further common feature of the bedded chert is the presence of pseudomorphs up to 0.5 mm. The pseudomorphs are largely rectangular in form and in hand specimen these can be seen to be prismatic. More complex blocky forms are also recognised.

The coarse grained nature of the sandy limestone breccia facies and its largely poorly sorted nature is characteristic of high energy conditions and rapid deposition. A general absence of erosive features may be accounted for by the early lithification of the underlying strata. This can be deduced from the brecciation and inclusion of angular clasts from underlying limestone beds within which the development of diastasis cracks has also been recognised. The floating nature of the limestone blocks provide further testament to the rapid nature and high density of the depositional event. The presence of rounded quartz grains up to 3 mm in diameter and bioclasts is suggestive of derivation from facies similar to those interpreted above, as of a shore zone origin. This facies is therefore interpreted to reflect a density flow entering the basin during a flooding event.

The features present within the chert which directly overlie the sandy limestone breccia facies are consistent with Magadi-type cherts (Eugster, 1969; Parnell, 1986; 1988; Krainer *et al.*, 1998). Schubel & Simonson (1990) suggested that the presence of a rectilinear extinction pattern is diagnostic of Magadi-type cherts. Magadiite ($NaSi_7(OH)_3 \cdot 3H_2O$) forms as a precursor to Magadi-type cherts, the transformation resulting from dehydration and the leaching of Na (Eugster, 1969) and has only been recorded in lacustrine settings. Precipitation of magadiite occurs from alkaline brines with high silica concentrations, either through intense evaporation or when a reduction in pH occurs leading to supersaturation (Sebag *et al.*, 2001). The latter can occur when brines come into contact with more dilute/acid waters. The widespread, correlatable occurrence of the chert suggests that the conditions leading to the precipitation of magadiite occurred basinwide. It seems unlikely, given the position within deep water calcareous mudstones, that the precipitation of the magadiite could have been caused by intense evaporation such as that leading to the formation of magadiite in shallow water settings around the margins of Lake Chad (Sebag *et al.* 2001). It is therefore suggested that stratification was present within the lake and that mixing across a chemocline between silica saturated alkaline brines and overlying more acid waters occurred. The close association with the underlying bed, interpreted as reflecting a flooding event, and the presence of a foraminiferan within the chert nodules suggest that the introduction/evolution of brines to the lake may be related to a marine flooding episode. This would therefore be the first time Magadi-type cherts have been recorded to form where a marine influence has been present.

The thickening of the sandy limestone breccia facies to the north in the Gråklint Beds implies that the incursion was from this direction which is consistent with the source of marine influence postulated by Clemmensen (1980a). Analogues for such a facies are few, however, a 'pebbly mudstone' unit, bearing some similarities to the facies described here is documented from the Pleistocene succession of the Black Sea (Gillet *et al.*, 2007; Ross *et al.*, 1978). This unit overlies shallow water stromatolitic limestones and is interpreted similarly to the 'flood bed' described here.

Distribution

Marked thickness variations are recognised in the Gråklint Beds between the SE and NW of the Jameson Land Basin. Evidence for an intrabasinal high in the Devondal region, with significant thinning in the underlying Pingo Dal Formation, has been recognised. Regional facies analysis suggests that the intrabasinal high acted as hydrological barrier during the deposition of the Gråklint Beds. To the SE of Devondal the Gråklint beds characteristically form a unit up to 10 m thick dominantly composed of black finely laminated mudstone source rock facies which form two upward shallowing packages separated by a 5 to 30 cm coarse grained 'event' bed (Fig 3a & 6). Magadi-type cherts have been identified overlying the 'event' bed and are interpreted to reflect a significant geochemical anomaly resulting from marine flooding. Non-glacial varves have been recognised within the black mudstones and the fauna collected in this region has been very limited, both of which are suggestive of a lacustrine setting.

In the Devondal region thick, cross bedded calcareous sandstones (containing cross sets up to 3.5 m) are interpreted as shore zone facies which developed on the intrabasinal high. To the NW of Devondal the Gråklint Beds comprise a succession up to 56 m thick of intercalated dark grey to black mudstones and very fine to coarse grained, commonly heavily bioturbated shore zone sandstones (Fig 3b). The intense bioturbation, often completely obscuring original sedimentary textures, alongside a more diverse fauna than that seen in the SE, is suggestive of a greater marine influence.

Palaeontology

Macropalaeontological samples were collected from throughout the basin and mudstone samples were prepared for palynological analysis. These analyses have helped constrain the dating of the Gråklint Beds and furthermore, aid in environmental interpretation. Evidence for both a fresh water environment and a marine influence have been recognised.

Biostratigraphy

Palynological analysis has yielded assemblages dominated by *Ovalipollis pseudoalatus* with accessory forms such as *Granuloperculatipollis rudis*, *Classopollis/Corollina* spp., *Chasmatosporites* spp. and *Perinopollenites elatoides* which suggest a Late Triassic age. The presence of *Chasmatosporites* spp. precludes a pre-Carnian age whilst the predominance of *O. pseudoalatus* is more reminiscent of the Mid Carnian. Records of forms such as *Classopollis/Corollina* spp. are more typical of Norian-Rhaetian assemblages but do occur into Late Carnian assemblages (eg. Hochuli *et al.*, 2010). The palynological data obtained from this unit generally indicates a consistent Carnian or younger age in most of the sections analysed. Assemblages gained from samples analysed from Sporfjeld, including significant numbers of *Ovalipollis pseudoalatus* in association with large numbers of *Calamaspora* *mesozoica*, favour comparison with Hochuli *et al.*'s (1989) Association D which implies a Mid Carnian age, providing a slightly refined age.

Despite locally abundant bivalves in the Gråklint Beds, macropalaeontological collection has proved less useful in constraining the dating of the Gråklint Beds than the palynology. However, *Halobia* cf. *moussoni* Merian, was recorded by Defretin-Lefranc *et al.* (1969), from Profil Bjerg, Wegener Halvø, to which they attributed an Anisian-Ladinian age. If correctly identified as *Halobia*, then this unit must be no older than Carnian age, because that genus ranges from Early Carnian to Mid Norian (McRoberts, 2010). This is consistent with palynological evidence for a Mid Carnian age for the Gråklint Beds.

Although originally named '*Myalina* Limestone' by Grasmück and Trümpy (1969), the most abundant bivalves within the Gråklint Beds are in fact a species of *Modiolus*. Towards the north of the basin, *Modiolus* aff. *sodburiensis* Vaughan (Fig. 4b) is the dominant taxon, and locally *Modiolus* cf. *minimus* (J. Sowerby) is common. Also present are locally common *Pteromya* spp. (formerly identified as *Anodontophora*, e.g. Spath 1930) and the annelid *Spirorbis valvata* (Goldfuss) with small numbers of a nuculoid bivalve, *Bakevellia* sp. and a bryozoan. A trigonioid bivalve *Costatoria* aff. *goldfussi* Alberti occurs in small numbers, eg. at Carlsberg Fjord and on Sporfjeld.

Further biostratigraphic constraints have allowed the fuller revision of the stratigraphic scheme illustrated in figure 2. The co-occurence of *Ovalipollis pseudoalatus* with *?Aratrisporites* spp. and *Chasmatosporites* spp. at Kap Seaforth demonstrates an age of no older than Carnian for the Kolledalen Member. The lower unit of the Edderfuggledal Member, the Sporfjeld Beds, has also been better constrained by a palynological assemblage including very common *Classopollis/Corollina* spp. with *Quadraeculina anellaeformis, Chasmatosporites* spp. and *Kyrtomisporis* spp. Collectively these occurrences reflect a Norian – Rhaetian age. The numbers of *Classopollis/Corollina* spp. might be further considered to favour a more restricted age within the Rhaetian. The overlying Pingel Dal Beds, the uppermost unit of the Edderfugledal Member, have provided bivalves (*?Trigonodus* sp.) and conchostracans (*Euestheria forbesi)*, alongside non-marine trace fossils which were dated as ?Carnian by Clemmensen (1980a). However, the majority of the palynological samples we have analysed from the Edderfugledal Member in this study yield assemblages that are consistent with an age in the range Norian – Rhaetian, although the possibility that it may be extended into the Late Carnian exists in some instances.

This biostratigraphic refinement is consistent with the magnetostratigraphically constrained cyclostratigraphic dating of the base of the Malmros Klint Member, which was placed within the Norian (Clemmensen *et al.*, 1998).

Environmental significance

Palaeontological specimens are often concentrated in high abundance, low diversity shall beds with much of the succession being barren. Articulated valves of the *Modiolus* species are common within shell beds and suggest little or no post-mortal movement under low energy conditions however, elsewhere disarticulated and fragmented shell material is recorded.

The paleontological data provide evidence for both restricted marine and freshwater environments. The modiolid-dominated macrofauna is one of high abundance and low diversity, typical of a lacustrine or brackish environment, or of variable salinity conditions within a temporary marginal marine environment. The presence of common conchostracans (Defretin-Lefranc, 1969 and CASP collections) provides good evidence for lacustrine conditions. The presence of low abundance halobiid, trigonioid, nuculoid and pterioid bivalves, bryozoans, together with one identified foraminifera is indicative of marine influence. *Halobia* cf. *moussoni* Merian and *Costatoria* aff. *goldfussi* Alberti are marine bivalves. In contrast palynological analysis reveals a somewhat impoverished palynomorph suite but abundant organic material, dominated by sapropel (algal?) and humic (woody derived) components are recognised. Such characteristics are typical of a lacustrine setting and no evidence for a marine influence has been identified within the palynological data.

Source Rock Evaluation

Samples were collected from four sections through the Gråklint Beds in the Carlsberg Fjord region (Fig. 1). These were collected at metre intervals through one section and as representative samples from both the upper and lower black mudstone units of the other sections examined. Samples were largely from the black to dark grey mudstone and limestone facies. In all, 17 samples were submitted for Rock Eval pyrolysis analysis using standard techniques. The geochemical evidence indicates that the Gråklint Beds represent a significant source rock in this region. The results are presented in Table 1. Total Organic Carbon (TOC), source potential (S_2) and Hydrogen Index (HI) values show considerable variation from which a number of observations can be made. The most prospective samples (SSA0015, 30, 32 and 42) are organically rich dark grey/black shales (TOC 3.1-6.3%) with very good-excellent source potential (S_2 11.1-29.4kg/tonne) and a Type II oil and gas -prone source rock quality (measured HI 338-464mgS_2/gTOC) derived from kerogen assemblages dominated by a dark brown dense-opaque groundmass of amorphous organic matter. Further interpretation of the source rock quality is given by the cross plot of TOC versus S_2 (Fig. 7a), from which the dead-carbon free or corrected Hydrogen Index value (HI 563mgS_2/gTOC) is indicative of good Type II oil and gas prone potential. Although spores were not observed, the visual appearance of the kerogen, combined with its lack of fluorescence suggests that these samples are at least mid-mature for oil generation, with an estimated equivalent Spore

Colour Index of SCI 7-8 and an estimated equivalent vitrinite reflectance of Ro 0.8-1.0%. This, together with the observation of lattice structures within the kerogen network and traces of suspected bitumen, suggests that thermogenic hydrocarbon generation had already commenced at the time of reaching maximum maturity and that the original Hydrogen Index of the immature source rock possibly extended into the Type I range. Other significant source rock samples consist of organically rich dark grey shales (TOC 1.5-2.8%) with moderate-very good source potential (S_2 2.1-5.8kg/tonne) and a predominantly Type II oil and gas-prone source rock quality (HI 139-267 $mgS_2/gTOC$) (Fig. 7b). A relationship between source rock quality and depositional environment is given by the cross plot of S_2 versus HI (Fig. 7c), from which the progressively flatter trend encountered at HI values of c.400$mgS_2/gTOC$ and S_2 values in excess of 10kg/tonne suggests that optimum conditions were attained for the preservation of source rock organic matter. A variation in TOC relative to the coarse-grained event bed, which divides the two mudstone units, can be correlated through the sections examined and shows a repeated trend from high to low TOC values (Fig. 6). This suggests increasing oxic conditions and therefore provides further evidence for two shallowing upward cycles, as supported by the results of sedimentological analysis.

Discussion

Source rock analysis has shown that the Gråklint Beds represent significant source rocks in the Jameson Land Basin. This provides evidence for the potential for a previously unrecognised Mid to Late Triassic petroleum play in the region with adjacent aeolian or alluvial reservoir sands and sealing lacustrine mudstones (Fig. 2). Grasmück and Trümpy (1969) interpreted the Gråklint Beds to reflect a marine ingression on the basis of its wide extent and the presence of a marine fauna. However, the wide extent of this unit does not preclude a lacustrine setting, with many modern and ancient examples covering much larger areas than the Jameson Land Basin. Furthermore, although elements of a marine fauna have been found these are relatively rare and concentrated towards the north of the basin. The biota collected indicates sources from contrasting environments. The palynology indicates a non-marine environment and the conchostracans suggests a lacustrine to brackish setting. The tripartite seasonal lamination identified within the mudstones and the development of Magadi-type cherts are also characteristic of lacustrine deposition. Furthermore, the impoverished molluscan fauna, consisting of rare occurrences of high abundance/low diversity assemblages, is consistent with a fresh to brackish water setting.

Evidence for intermittent marine influence is recorded with rare units containing a more diverse molluscan fauna, some of which do have marine affinities. The presence of heavily bioturbated units, again containing a diverse range of traces, is also suggestive of a marine influence. The restriction of these marine indicators to the regions north of the intrabasinal high, discussed above, during the deposition of the Gråklint Beds suggests that the marine influence was reaching south from the Boreal Sea. Intermittent marine flooding of the northern regions of the basin was only occasionally accompanied by flooding into the southern sub-basin as evidenced by the sandy limestone breccia facies event bed and associated Magadi-type cherts, indicative of the geochemical perturbations caused by a marine ingression. It is believed that the marine influence was of a more intermittent nature than that previously suggested (Clemmensen, 1980b).

Grasmück and Trümpy (1969) considered the Gråklint Beds to be Anisian in age due to the presence of the bivalve *Halobia* and this was followed by Clemmensen (1980b). However, *Halobia* is here considered to reflect an early Carnian to mid Norian age (McRoberts, 2010) and is therefore consistent with our palynological and macro-palaeontological analysis which suggest a mid Carnian age.

The Gråklint Beds lie between coarse alluvial clastics and gypsum bearing playa and minor fluvial deposits both of which contain short lived lacustrine/playa episodes. Therefore the appearance of organic rich mudstones with features characteristic of lacustrine deposition is most simply accounted for by a period of relatively wet conditions which would allow the formation of a deep lake which persisted for several thousands of years. Similar periods of climatic cooling, termed the Mid Carnian Pluvial Event, have been described from Europe (Stefani *et al.*, 2010; Mutti *et al.*, 1996) and more locally from southern Britain (Simms *et al.*, 1989) and the Barents Sea (Hochuli *et al.*, 2010). The deep lake phases of the Newark Basin in the north east US also lie within the Carnian (Olsen, 1997). Dal Corso *et al.* (2012) suggested the Wrangelia large igneous outpouring was responsible for climatic cooling at this time and this study presents further evidence for the global effect and pervasive record of such climatic events in varied sedimentary settings. Furthermore the widespread nature of this event suggests that it may prove a powerful tool for correlation on a local and global scale, particularly in poorly constrained continental successions.

The Carnian age gained for the Gråklint Beds also coincides with the Triassic marine highstand (Haq *et al.*, 1987). This may have influenced climatic conditions at this time but it is also clear that the marine influence recorded in the Gråklint Beds is likely to be related to this highstand period. Identifying a mechanism for the intermittent flooding recognised is problematic with possibilities ranging from storm surges to tsunami events. However, it can be said that the main flooding event was high energy and that marine connection was only temporary. This is the southernmost evidence of the Boreal Ocean during the Mid to Late Triassic and has significant implications for palaeogeographic reconstructions at this time.

Conclusions

The Gråklint Beds were deposited in a deep lake setting with intermittent marine influence. The strata above and below the Gråklint Beds reflect more arid conditions compared to the more humid setting required for the development of a deep lake environment. Palaeontological analysis has better constrained the dating of the Gråklint beds, providing a Mid Carnian age. The identification of a humid phase at this time can be correlated with the Mid Carnian Pluvial Event and provides further evidence for the global effect of such climatic perturbations. The global recognition of this event through numerous depositional settings suggests that such events can be extremely useful in both local and more regional correlation, especially in poorly dated continental settings.

Evidence for periodic marine flooding is also recognised within the Gråklint Beds with the introduction of short lived marine faunas and geochemical perturbations which resulted in the precipitation of Magadi-type cherts. A marine influence at this time corresponds with the Triassic highstand and can be correlated with marine evaporites described from the Halten Bank (Jacobsen *et al.*, 1984). Thus Jameson Land provides the southernmost record of the influence of the Boreal Ocean during the Mid to Late Triassic and has important implications for previously poorly constrained palaeoenvironmental reconstructions and northward correlation in the North Atlantic region.

This study has proven the presence of a Late Triassic source rock and therefore the potential for a Mid to Late Triassic petroleum play in East Greenland and more widely in the North Atlantic. Deposition occurred in a deep lake environment, in relatively close proximity to a marine setting. The deep lake environment provided conditions suitable for source rock deposition. Evidence for the relationship of this unit to a global climatic event, the Mid Carnian Pluvial Event, and the Triassic marine highstand implies that the development of continental and potentially marine source rocks may be more widespread at this time.

This work was undertaken as part of the continuing work of CASP in East Greenland. The sponsoring companies are thanked for their continued support of this work. Help in the field by Tim Kinnaird and useful discussions with Andrew Whitham are gratefully acknowledged. The reviews of Lars Clemmensen and a further anonymous reviewer, and the input from Stuart Jones led to improvements to the original manuscript.

Captions

Figure 1. A geological map of the Jameson Land Basin with key localities labelled. (a) Klitdal; (b) Carlsberg Fjord; (c) Devondal; (d) Kap Seaforth; (e) Sporfjeld.

Figure 2. Revised stratigraphy for the Triassic of East Greenland (timescale of Gradstein et al. 2012; Gk - Gråklint Beds).

Figure 3. (a) Gråklint Beds, forming the base of the Solfaldsdal Member, exposed in the Carlsberg Fjord region (Buch Bjerg) where they form a 10 m thick succession of black bituminous lacustrine mudstones separated by a coarser grained flooding bed. Figure 5 provides a sedimentary log through this section. (b) A well exposed section through the Gråklint Beds at Sporfjeld, illustrating the northward thickening of the unit and the increasing proportion of sandstone.

Figure 4. Sedimentary structures and fauna in the Gråklint Beds: (a) Seasonal silt-carbonate-organic triplets within the laminated mudstones of the Gråklint Beds; (b) Bedding surface containing a monospecific assemblage of abundant *Modiolus* aff. *sodburiensis* Vaughan; (c) Large scale cross bedding (3.5 m) in sandy limestones, the NW end of Devondal. d) Intensely bioturbated texture in green grey silty sandstone, Sporfjeld; (e) straight traces on the bed bases of the large scale cross bedded unit figured in c; (f) Branching, *Thalassinoides*?, type burrows and *Cruziana* type traces (g - bottom left) on bed bases from Kap Seaforth. The increments on the scale bar provided in d, f and g are 1 cm.

Figure 5. (a) Sandy limestone breccia facies with black chert nodules, after magadiite, draped by the overlying black mudstones; (b) inclusion rich microcrystaline quartz of the

chert nodules containing palynomorphs; (c) patchy rectilinear extinction pattern (aligned at 45° to horizontal), characteristic of Magadi-type chert (crossed polars and first order red plate inserted) ; (d) a probable foraminiferan and ostracod within the chert; (e) cracking from the nodule margins with two stage calcite fill which also forms a rind to the nodule. Also note the green-yellow crystals around the margins of the rind.

Figure 6. Sedimentological log of the Gråklint Beds from Buch Bjerg north, Carlsberg Fjord, with environmental interpretations (FB - flood bed) and a composite plot of TOC with depth taken from correlatable sections.

Figure 7. (a) Plot of TOC vs S_2 from which a corrected HI of 563mgS_2/gTOC indicates a good type II source rock quality (white diamonds contain negligible Organic Carbon; light grey diamonds define the trend and the black diamonds are suggestive of a lower HI trend . (b) TOC vs S2 for samples from the Gråklint Beds (Solfaldsdal Member) exposed along the west shore of Carlsberg Fjord. Note, not all data plot within the defined area. (c) HI vs S_2, illustrating that optimum conditions for preservation of source rock organic matter were attained.

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Table 1. Rock Eval Pyrolysis data from the Gråklint Beds, the Jameson Land Basin, East Greenland

Sample	Location	Free Oil Yield S_1 (kg/tonne)	Source Potential S_2 (kg/tonne)	Thermal Maturity Tmax (deg.C)	Oil Production Index (OPI)	Active/Total Organic Carbon Ratio AOC/TOC (%)	Total Organic Carbon Content TOC (% wt)	Hydrogen Index HI ($mgS_2/gTOC$)
SSA0015	Buch Bjerg N	0.72	11.09	448	0.06	30	3.28	338
SSA0017	Buch Bjerg N	0.36	4.09	447	0.08	13	2.80	146
SSA0018	Buch Bjerg N	0.01	0.03	*451*	*0.25*	*17*	0.02	*150*
SSA0025	Nordenskiold Bjerg	0.51	2.14	449	0.19	14	1.54	139
SSA0024	Nordenskiold Bjerg	1.44	5.78	440	0.20	22	2.67	216
SSA0026	Nordenskiold Bjerg	0.02	0.12	453	0.14	4	0.32	38
SSA0030	Buch Bjerg S	0.33	12.42	441	0.03	34	3.07	405
SSA0032	Buch Bjerg S	0.61	15.22	440	0.04	35	3.72	409
SSA0033	Buch Bjerg S	0.39	5.18	437	0.07	24	1.94	267
SSA0034	Buch Bjerg S	0.01	0.02	*390*	*0.33*	*8*	0.03	*67*
SSA0035	Buch Bjerg S	0.06	0.23	435	*0.21*	*27*	0.09	*256*
SSA0036	Buch Bjerg S	0.03	0.11	452	*0.21*	*19*	0.06	*183*
SSA0037	Buch Bjerg S	0.01	0.11	442	0.08	3	0.32	34
SSA0038	Buch Bjerg S	0.00	0.06	*358*	0.00	3	0.19	32
SSA0039	Buch Bjerg S	0.00	0.05	*334*	0.00	1	0.39	13
SSA0041	Tait Bjerg	0.00	0.04	-	0.00	4	0.09	44
SSA0042	Tait Bjerg	0.29	29.36	442	0.01	39	6.33	464

Note: values given in italics are regarded as anomalous results

Figure 1.

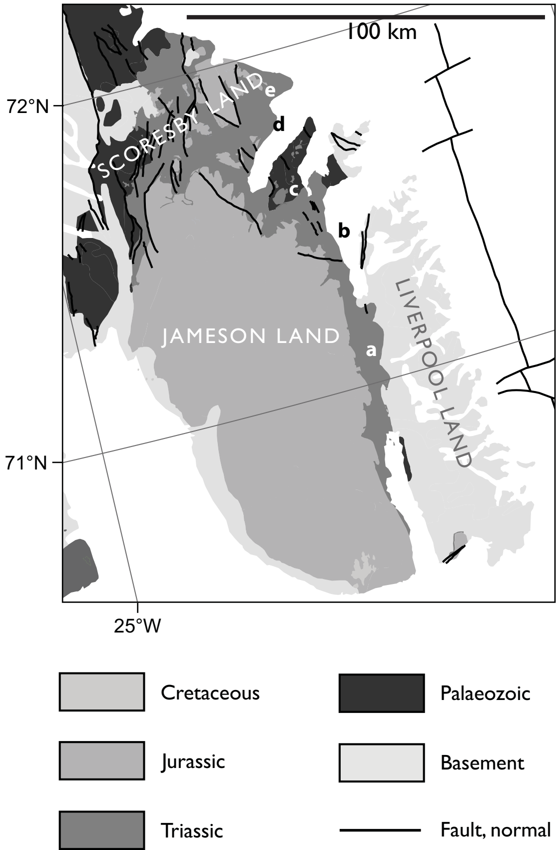

100 km
72°N
SCORESBY LAND
e
d
c
b
a
JAMESON LAND
LIVERPOOL LAND
71°N
25°W
Cretaceous
Jurassic
Triassic
Palaeozoic
Basement
Fault, normal

Figure 2.

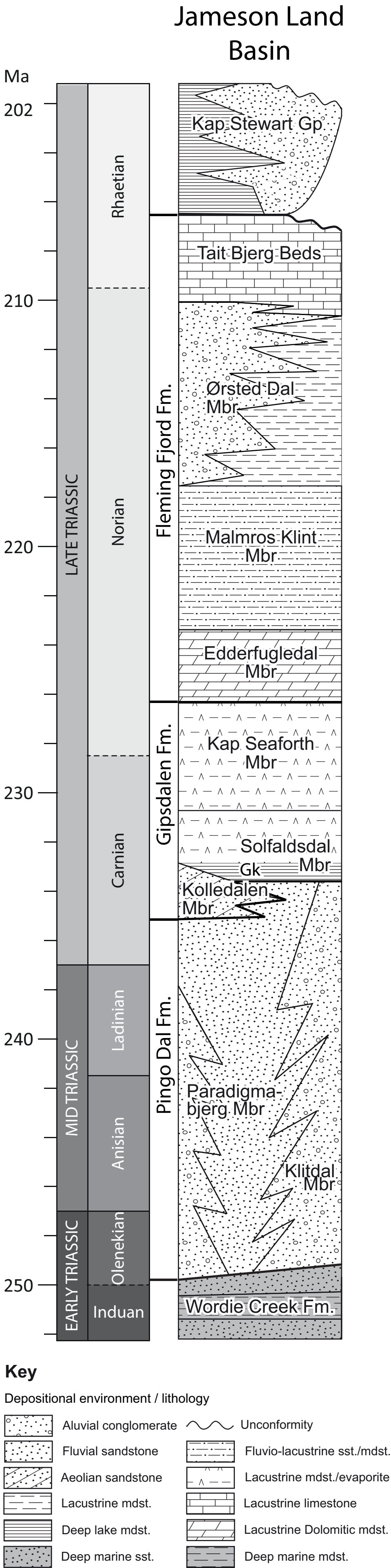

Jameson Land Basin
Ma
202
210
220
230
240
250
LATE TRIASSIC
MID TRIASSIC
EARLY TRIASSIC
Rhaetian
Norian
Carnian
Ladinian
Anisian
Olenekian
Induan
Kap Stewart Gp
Tait Bjerg Beds
Fleming Fjord Fm.
Ørsted Dal Mbr
Malmros Klint Mbr
Edderfugledal Mbr
Gipsdalen Fm.
Kap Seaforth Mbr
Solfaldsdal Mbr
Gk
Kolledalen Mbr
Pingo Dal Fm.
Paradigma-bjerg Mbr
Klitdal Mbr
Wordie Creek Fm.
Key
Depositional environment / lithology
Aluvial conglomerate
Fluvial sandstone
Aeolian sandstone
Lacustrine mdst.
Deep lake mdst.
Deep marine sst.
Unconformity
Fluvio-lacustrine sst./mdst.
Lacustrine mdst./evaporite
Lacustrine limestone
Lacustrine Dolomitic mdst.
Deep marine mdst.

Figure 3

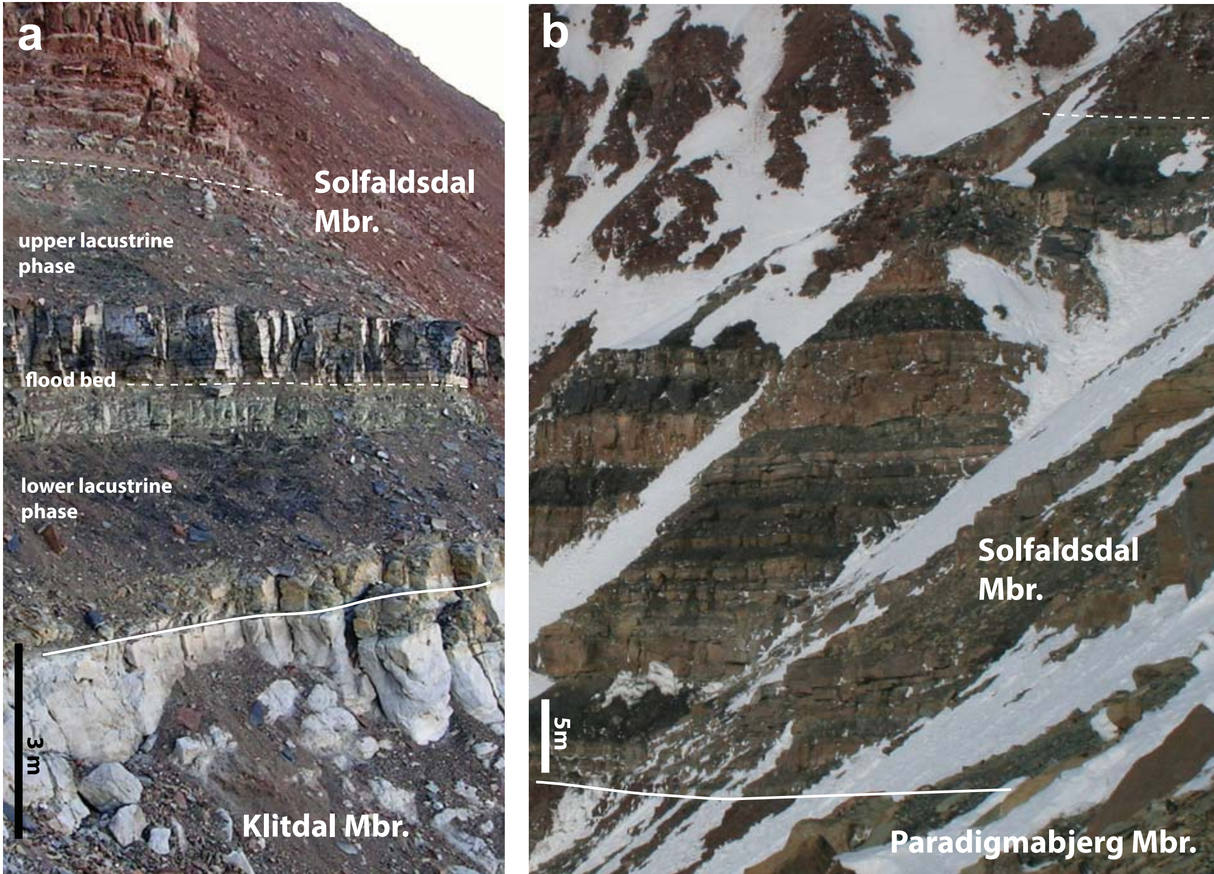

a
Solfaldsdal Mbr.
upper lacustrine phase
flood bed
lower lacustrine phase
3 m
Klitdal Mbr.
b
Solfaldsdal Mbr.
5m
Paradigmabjerg Mbr.

Figure 4.

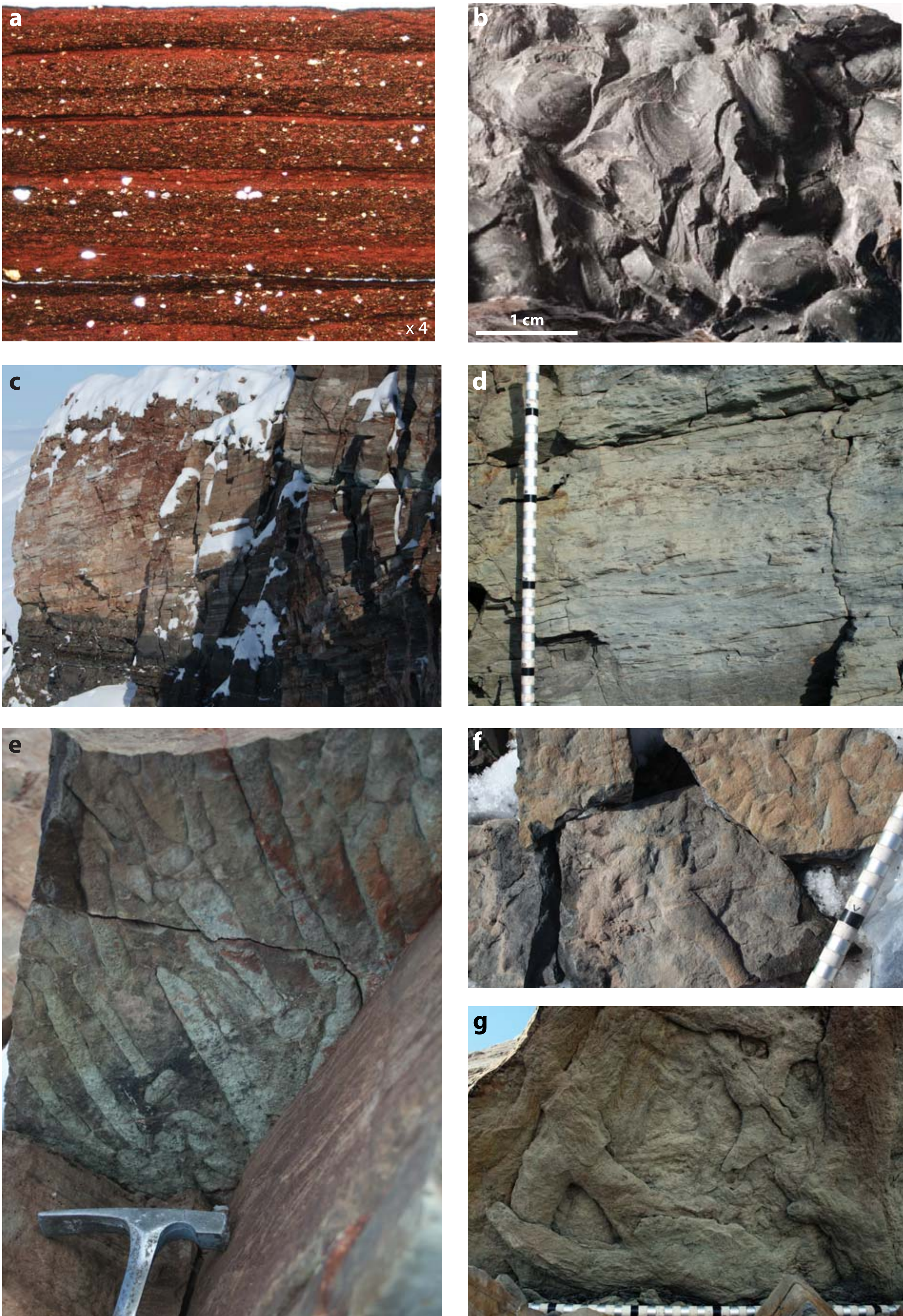


Figure 5.

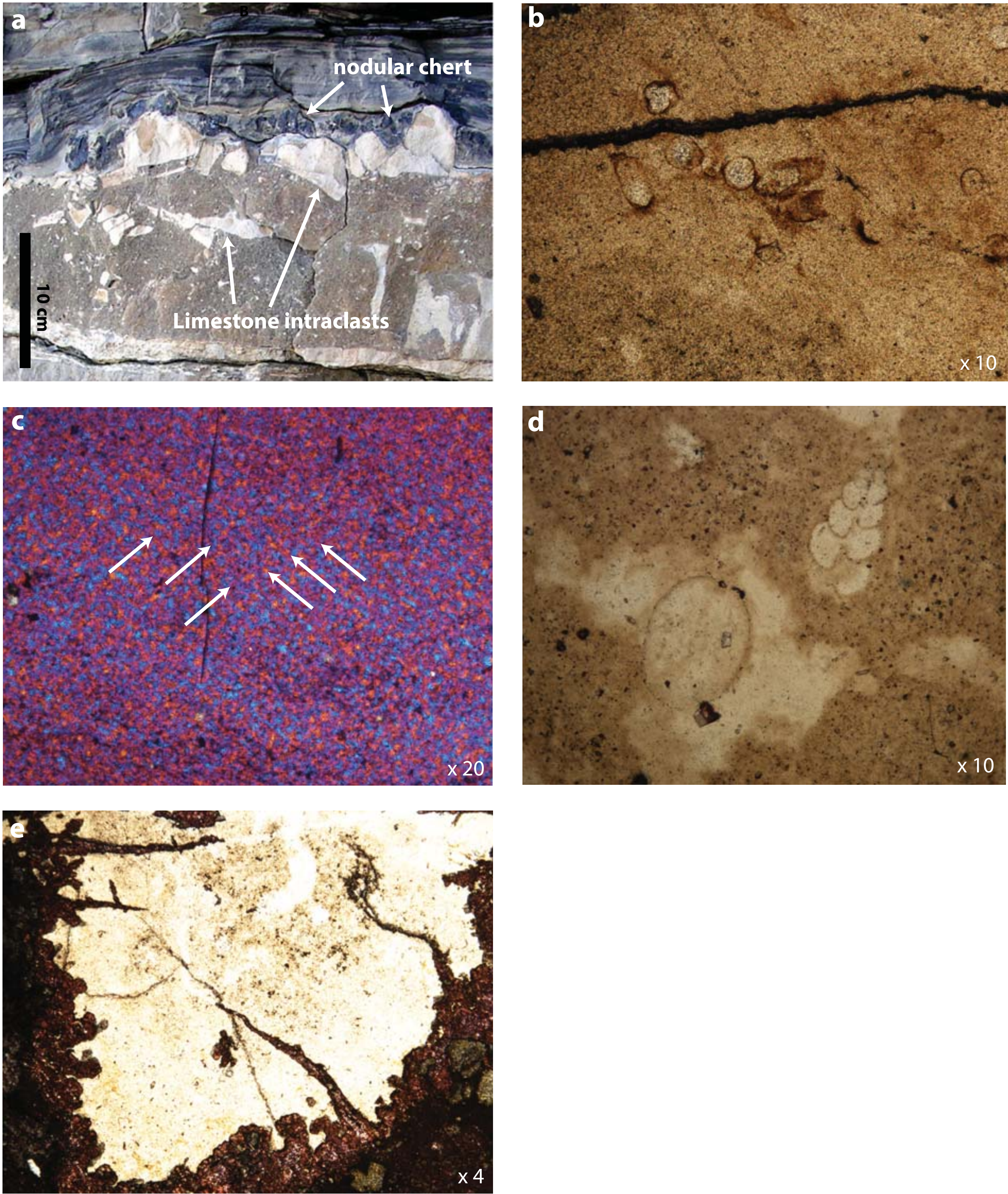

a
nodular chert
Limestone intraclasts
10 cm
b
x 10
c
x 20
d
x 10
e
x 4

Figure 6.

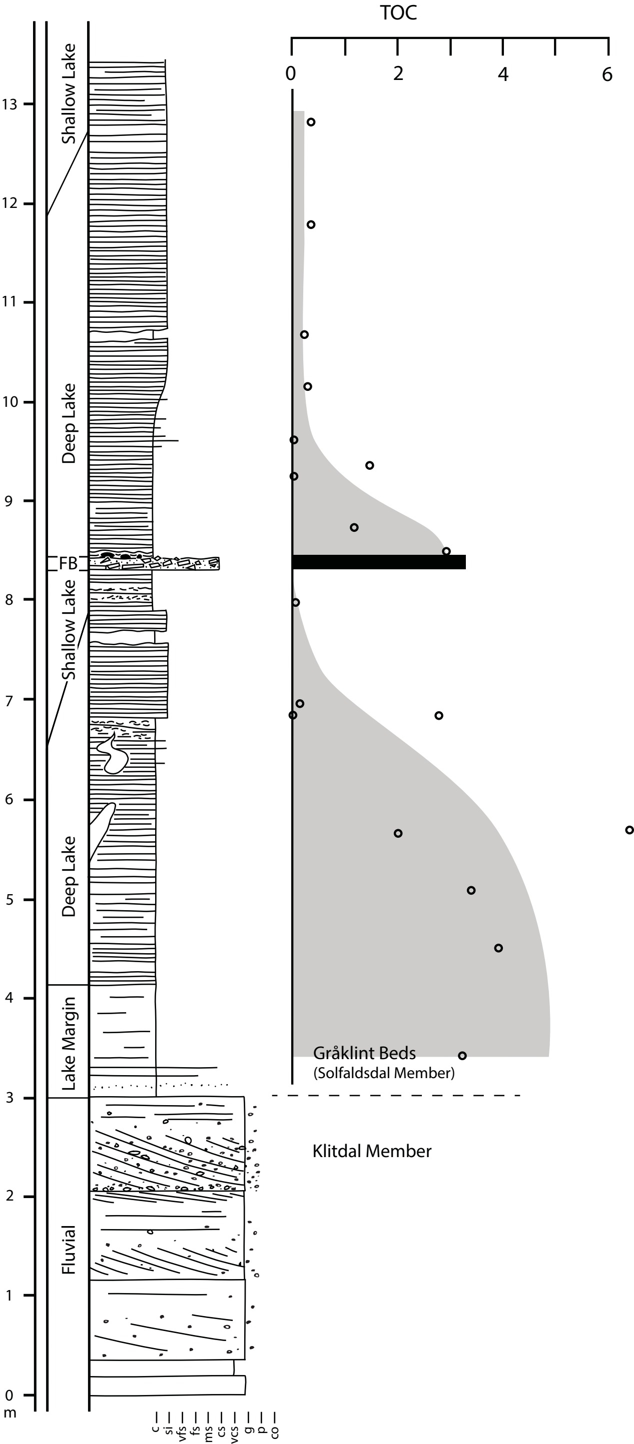
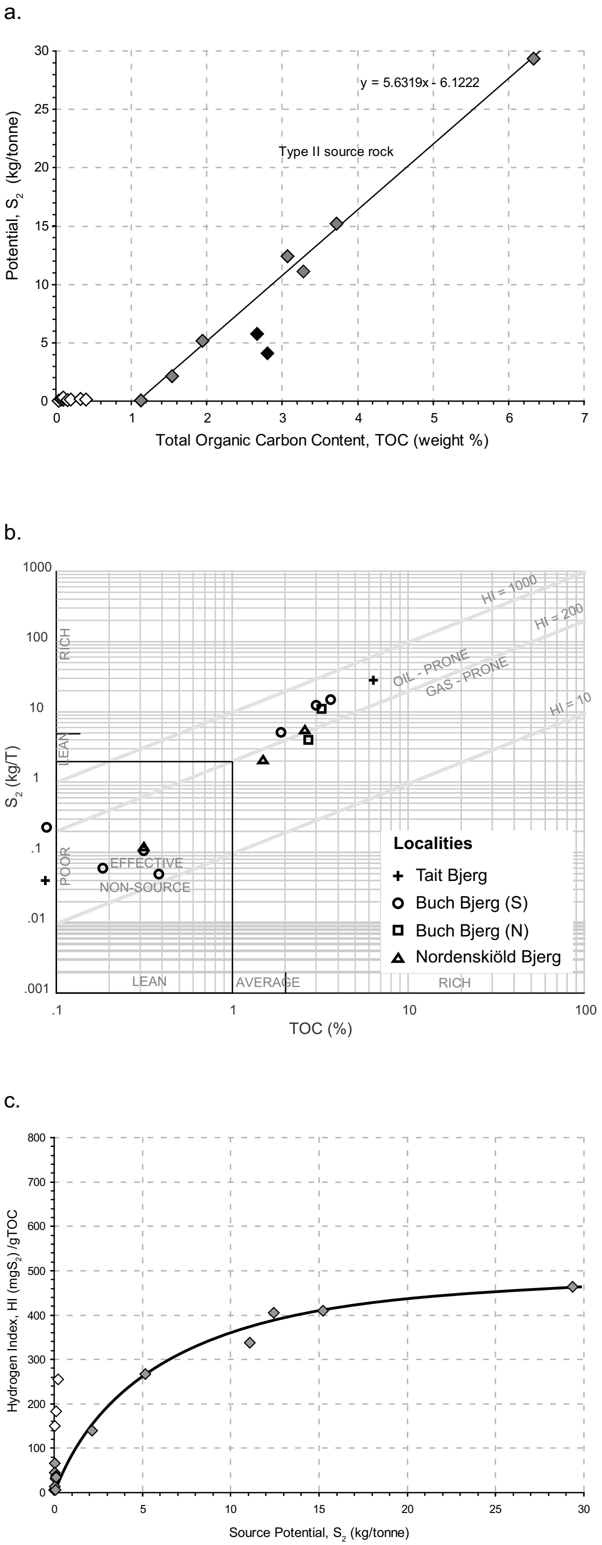

TOC
0
2
4
6
Shallow Lake
Deep Lake
FB
Shallow Lake
Deep Lake
Lake Margin
Fluvial
13
12
11
10
9
8
7
6
5
4
3
2
1
0
m
c
si
vfs
fs
ms
cs
vcs
g
p
co
Gråklint Beds
(Solfaldsdal Member)
Klitdal Member

Figure 7.


a.
y = 5.6319x - 6.1222
Type II source rock
Potential, S_2 (kg/tonne)
0
5
10
15
20
25
30
0
1
2
3
4
5
6
7
Total Organic Carbon Content, TOC (weight %)
b.
1000
100
10
1
.1
.01
.001
.1
1
10
100
S_2 (kg/T)
TOC (%)
RICH
LEAN
POOR
HI = 1000
HI = 200
HI = 10
OIL - PRONE
GAS - PRONE
EFFECTIVE
NON-SOURCE
LEAN
AVERAGE
RICH
Localities
+ Tait Bjerg
○ Buch Bjerg (S)
□ Buch Bjerg (N)
△ Nordenskiöld Bjerg
c.
Hydrogen Index, HI (mgS_2) /gTOC
0
100
200
300
400
500
600
700
800
0
5
10
15
20
25
30
Source Potential, S_2 (kg/tonne)