Triassic lithostratigraphy of the Wandel Sea Basin, North Greenland

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Published in:
Bulletin of the Geological Society of Denmark

DOI:
10.37570/bgsd-2019-67-06

Publication date:
2019

Document version
Publisher’s PDF, also known as Version of record

Citation for published version (APA):
The Wandel Sea Basin in eastern North Greenland forms the northern continuation of the offshore Danmarkshavn Basin and the conjugate margin to the western Barents Shelf south of Spitsbergen. The Triassic succession of eastern North Greenland, up to 700 m thick, spans the Induan (Dienerian) – Norian. The Triassic sediments rest unconformably on Upper Carboniferous and Upper Permian sediments, and are unconformably overlain by Upper Jurassic – Lower Cretaceous deposits. Based on recent fieldwork in the Wandel Sea Basin, five new and revised Triassic formations are described and included in the Trolle Land Group (revised). The Lower Triassic (Induan) Parish Bjerg Formation (revised) consists of marine sandstones, fluvial conglomerates and sandstones, and muddy flood-plain deposits. It is conformably overlain by Lower Triassic (Dienerian – lower Spathian) offshore mudstones with minor sand-dominated intervals of the Ugleungernes Dal Formation (new). The upper Spathian to Ladinian Dunken Formation (revised) is represented mainly by marine sandstones. A marked erosional unconformity characterises the base of the overlying Upper Triassic (Carnian – Norian) Storekløft Formation (new) composed of marginal marine to marine, massive sandstones and conglomerates as well as cross-bedded and biomottled marine sandstones and minor mudstone units. The Isrand Formation (mainly Middle Triassic) consists of laminated mudstones with minor thin sandstone units that were deposited in slope and basin floor settings in the eastern deeper part of the Wandel Sea Basin in Kronprins Christian Land. The Triassic succession of the Wandel Sea Basin represents a well-constrained shallow shelf to deep shelf / basin floor transect and thus forms an excellent outcrop analogue to the time-equivalent intervals in the western Barents Sea basins and the Danmarkshavn Basin offshore North-East Greenland.

Keywords: Triassic, Arctic, Greenland, sedimentology, lithostratigraphy, palaeogeography, Peary Land, Kronprins Christian Land.

The Triassic of the greater Barents Sea area as represented by the Kara Sea, Barents Sea, Timan Pechora, Franz Josef Land, Svalbard and eastern North Greenland areas, is considered to have been deposited in a relatively shallow shelf setting (Mørk et al. 1989). Numerous studies have dealt with the depositional evolution and petroleum geological potential, especially based on exposures on Svalbard (e.g. Mørk et al. 1989; Lundschien et al. 2014; Vigran et al. 2014). In contrast, the Wandel Sea Basin in the eastern part of North Greenland, where Triassic sediments are exposed in Herlf Trolle Land in the eastern part of Peary Land, Kronprins Christian Land and Amdrup Land (Fig. 1), has been neglected in regional Triassic palaeogeographic reconstructions, most likely due to the very limited amount of published data (e.g. Glersted-Clark et al. 2010, Klausen et al. 2015).

The first report of Triassic sediments in North Greenland came from the Danish Peary Land Expedition 1948–49 (Troelsen 1950). The collected ammonoids were described by Kummel (1953), and the remaining macrofossils including bivalves, brachiopods, fish
Fig. 1. A: Geological map of eastern North Greenland (Peary Land to Amdrup Land). B: Detailed geological map of Herluf Trolle Land (eastern Peary Land) with localities 1–10 indicated. Modified from Zinck-Jørgensen (1994). C: Geological map of the Galadriel Fjeld area in Kilen (Kronprins Christian Land) with locality 11 indicated. From Alsen et al. (2017).
remains and vertebrates were briefly listed in Peel et al. (1974). Until recently, Triassic sediments were not considered to occur outside Peary Land (Fig. 1). A discovery of ammonoids and halobiid bivalves in a shale succession in Kronprins Christians Land and a revision of ammonoid findings from Amdrup Land now extend the Triassic distribution to include these eastern areas (Alsen et al. 2017).

The Triassic Parish Bjerg and Dunken Formations were provisionally described by Håkansson (1979) and later formalised by Stemmerik & Håkansson (1989) (Fig. 2). The biostratigraphy of the Triassic strata was based on limited palynological and macrofossil data. Palynological data from the Parish Bjerg Formation indicated a Triassic age for parts of the formation (Håkansson 1979). Ammonoids from two stratigraphic levels in the Dunken Formation were documented and referred to the Smithian and Lower Anisian, respectively (Kummel 1953; Håkansson et al. 1991; Molgaard et al. 1994). The major part of the Triassic succession remained undated and the boundary between the Parish Bjerg and Dunken Formations was not known (Stemmerik & Håkansson 1989). At Kilien in the northern part of Kronprins Christian Land, a new Triassic mudstone-dominated succession was discovered in 2013 and assigned to the Isrand Formation (Fig. 1; Alsen et al. 2017).

This study presents a revised and new lithostratigraphic subdivision of the Triassic in the Wandel Sea Basin in eastern North Greenland, framed in a regional context of the greater Barents Sea area. Lithostratigraphic data were collected during field campaigns in North Greenland in 2012–2013 and 2016. Key localities were sedimentologically logged and systematically sampled for macrofossils and palynomorphs in order to provide biostratigraphic constraints and information on the depositional environment. The succession is now known to range from the Lower Triassic (Induan) to the Upper Triassic (Norian) (Figs 2–4), based on biostratigraphic correlation to the Boreal Triassic ammonoid zonation of Dagys & Weitschat (1993), the Arctic Canadian ammonoid zonation of Tozer (1994) and the palynological composite assemblage zones of Svalbard and Barents Sea of Vigran et al. (2014).

## Wandel Sea Basin

The Upper Palaeozoic – Lower Cenozoic Wandel Sea Basin forms a structurally complex basin configuration combining a NW–SE oriented structural regime between Peary Land in eastern North Greenland and Spitsbergen in Svalbard, and with a transition and junction to the N–S trending rift regime in Kronprins Christian Land and Amdrup Land that is related to the Caledonian trend between Greenland and Norway (Fig. 1; Håkansson & Stemmerik 1989). NW–SE trending structural lineaments controlling basin configuration and formation of grabens and half-grabens are linked to the Tolle Land Fault Zone in eastern North Greenland (Håkansson & Stemmerik 1989). N–S trending structural lineaments are associated with the northward continuation of the onshore basins in North-East Greenland and the offshore Danmarkshavn Basin (Hamann et al. 2005; Fyhnn & Hopper, in press). The latter trend continues northwards into the western Barents Sea area (Glørstad-Clark et al. 2010).

In a depositional context, the Triassic of the Wandel Sea Basin forms the south-western part of a series of inherited Late Palaeozoic connected intracratonic basins in the Greater Barents Sea area (Stemmerik & Worsley 2005; Glørstad-Clark et al. 2010; Henriksen et al. 2011). Sediments were sourced from uplifted Caledonian domains on the conjugate Greenland and Norwegian margins and from the Uralide Orogen farther to the east (e.g. Riis et al. 2008; Klausen et al. 2017; Eide et al. 2018).

In Peary Land, the Triassic sediments rest unconformably on Upper Permian carbonates and siliciclastics of the Midnatfjeld Formation (Figs 3, 5; Håkansson 1979) and are erosionally overlain by Upper Jurassic – Lower Cretaceous siliciclastics of the Ladegårdsåen Formation. The succession is exposed in fault-bounded blocks trending NW–SE and dipping slightly towards the east, forming an inverted structural complex as a result of a post-Mesozoic, N–S oriented compressional component (Zink-Jørgensen 1994; Pedersen & Pedersen 1999; von Gosen & Piepjohn 2003; Svennevig et al. 2016).

### Triassic lithostratigraphy of the Wandel Sea Basin

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<tr>
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Fig. 2. Previous and present Triassic lithostratigraphy in the Wandel Sea Basin.
Fig. 3. Correlation panel with lithostratigraphic type sections and reference sections for the Triassic sediments in the Wandel Sea Basin.
Triassic lithostratigraphy of the Wandel Sea Basin, North Greenland

Lithology and environment

Legend

- Fluvial conglomerate and sandstone
- Flood plain mudstone
- Marine channel sandstone and conglomerate
- Shallow marine sandstone
- Offshore to Offshore transition mudstone and sandstone
- Marine carbonate
- Basinal – offshore mudstone
- Concretion
- Apatite nodules

Sedimentary structures

- True cross-stratification
- Planar lamination/bedding
- Asymmetric ripple cross-stratification
- Ripple cross-lamination

Fossils

- Shell fragment
- Logs
- Brachiopods
- Bivalves

Miscellaneous

- Wavy bedding
- Structureless
- Biomottled fabric
- Large scale slump structure
- Slump and contorted bedding
- Hummocky cross-stratification
- Plant fragments
- Ammonite
- Gastropod

Palaeocurrent direction

- Current lineation

Bioturbation

Dunken Main, Loc. 3

Isrand Fm

Dunken-X, Loc. 4

Kilen, Loc. 11

Legend

- Fluvial conglomerate and sandstone
- Marine channel sandstone
- Marine channel mudstone
- Marine mudstone
- Marine mudstones and sandstones
- Marine channel mudstone and sandstone
- Marine channel mudstones
- Bioclastic mudstone
- Bioclastic mudstones
- Bioclastic mudstones and sandstones
- Bioclastic mudstone and sandstone

Direction

0° 30° 60° 90°

W
N
E
S

Cl Si

Sand Pebble

Vf F FGM MC CVc

1 A 2 B 2 C 4 A 4 C

2A 2B 2C 4A 4C
Snadd Fm

Triassic

Lower Middle Upper

Palynological composite assemblage zones

Vigran et al. (2014)

Changhsingian

R. tuberculatus
L. lundbladii
Rhaetogonyaulax spp.
A. astigmosus
E. iliacoides
P. decus
T. obscura
A. spiniger
J. punctispinosa
P. disertus
N. striata
Maculatasporites spp.
P. pococki
R. chalastus
U. imperialis

Griesbachian

Dienerian

Smithian

Upper

lower

Spathian

Olenekian

Induan

Ladinian

Rhaetian

Norian

Upper Carnian

Middle Carnian

Lower Carnian

Upper Anisian

Middle Anisian

Lower Anisian

Chronostratigraphy

Svalbard

Peary Land

Wandel Sea Basin

Kronprins Christian Land

West

East

Lithostratigraphy

Fruholmen Fm
Steinkobbe Fm
Klappmyss Fm
Havert Fm
Flatsalen Fm

Alaska

Dunken Fm
Kilen Fm
Storekløft Hjulspordalen

Loc. 8–10
Loc. 1, 2
Loc. 7
Loc. 6
Loc. 5
Loc. 4
Loc. 3
Loc. 11
Loc. 1

H. Parish Bjerg Fm
Ugleungernes Dal Fm
Dunken Fm
Isrand Fm
Storekløft Fm

10-20 km
200 km
NWSE

Fluvial conglomerates and sandstones
Floodplain mudstones
Shallow marine sandstones
Base of slope
Marine channel conglomerates and sandstones
Offshore to Offshore transition mudstones and heteroliths
Deep shelf - basinal mudstones with thin sandy turbidites
Regional to Offshore transition mudstones and heteroliths

Palynomorph sample/ammonoid zones

Ammonoid zones, North Greenland (This study)

W. tardus
L. caurus
Daonellaeformis
Pterosirenites
E. romunderi
M. maclaerni/F. sutherlandi
M. meginae
T. varius

Parish Bjerg Fm
Ugleungernes Dal Fm
Dunken Fm
Isrand Fm
Storekløft Fm

200 km
1.0-20 km
Door Land
Kronprins Christian Land
SE
Wandel Sea Basin

NW

Chronostratigraphy

Tertiary

Cretaceous

Jurassic

Triassic

Upper

Middle

Lower
In Amdrup Land, newly reassigned Triassic deposits (previously inferred to be Jurassic) occur as small outcrops overlying Upper Carboniferous carbonates of the Foldedal Formation (Alsen et al. 2017). In the northern part of Kronprins Christian Land, a deeper-water mudstone succession assigned to the Isrand Formation (Alsen et al. 2017) is exposed in an oblique fold structure. The lower boundary of the succession is probably situated beneath the adjacent Flade Isblink glacier, and the top of the formation is fault-bounded against Cretaceous mudstone (Fig. 1).

Lithostratigraphy

The here presented lithostratigraphy is revised from Stemmerik & Håkansson (1989) (Fig. 2). The Triassic succession is assigned to the Trolle Land Group (sensu Stemmerik et al. 1996) and divided into the Parish Bjerg (revised), Ugleungernes Dal (new), Dunken (revised) and Storekloft (new) formations in Peary Land and the Isrand Formation in Kronprins Christian Land. The upper part of the Parish Bjerg Formation (sensu Stemmerik & Håkansson 1989) is now included in the Ugleungernes Dal, Dunken and Storekloft Formations, and the Dunken Formation (sensu Stemmerik & Håkansson 1989) is now subdivided to be included in the Ugleungernes Dal, Dunken and Storekloft Formations based on new lithological and stratigraphical data. Overall, the Triassic succession is widely distributed but poorly exposed in eastern Peary Land, and the subdivision presented here is based on improved understanding of the distribution of genetically related sedimentary units in the area, combined with a greatly improved biostratigraphy.

Trolle Land Group

Revised group

History. The group is named after Herluf Trolle Land, which defines the eastern part of Peary Land (Fig. 1). The unit was provisionally erected by Håkansson (1979) and formally described by Stemmerik & Håkansson (1989) to include the Upper Permian – Triassic, mainly siliciclastic succession in the Wandel Sea Basin. The Permian Midnatfjeld Formation was later suggested reassigned to the Mallemuk Mountain Group due to its genetic and conformable relationship with the underlying Kim Fjelde Formation (Stemmerik et al. 1996). This reassignment is followed here; hence, the Trolle Land Group now solely represents the Triassic succession of the Wandel Sea Basin (Fig. 2).

Type area. Herluf Trolle Land in the eastern part of Peary Land.

Thickness. More than 350 m thick at Henry Parish Bjerg (upper boundary not known); more than 550 m thick and possibly up to 700 m thick in Dunken mountain area (lower part not exposed); > 400 m thick in Kronprins Christian Land (lower part not exposed and upper part not known). A thickness of about 1 km of the Triassic succession was estimated by Håkansson et al. (1991) and Stemmerik et al. (2000), but was based on combined thicknesses of measured sections with inadequate biostratigraphic control, which would have demonstrated partial repetition of strata across major faults.

Lithology. Mainly reddish-brown conglomerates and mudstones of the Parish Bjerg Formation, dark grey to black mudstones of the Ugleungernes Dal Formation, shallow marine sandstones of the Dunken Formation, and interbedded massive sandstones, bioturbated and cross-bedded sandstones of the Storekloft Formation. Black and very dark grey shales dominate the Isrand Formation.

Fossils. The fauna comprises few to common ammonoids and bivalves. Minor to rare occurrences of brachiopods, crinoids, fish and vertebrate remains are recorded. Trace fossils are common to abundant in the marine units. Floral occurrences include silicified wood and plant remains as well as spores, pollen and dinoflagellate cysts from several levels.

Depositional environment. Shallow marine and fluvial in the lower part and marine offshore to shallow marine in the middle and upper parts in Peary Land, marine basin floor and lower slope in Kronprins Christian Land.

Fig. 4. Stratigraphic scheme of the Triassic in the Wandel Sea Basin, showing the inferred transition from shallow shelf in Peary Land to deep shelf in Kronprins Christian Land. Green vertical lines mark the stratigraphic range of measured sections. Lithostratigraphic correlation is shown to adjacent Arctic areas, Svalbard and Barents Sea (Vigran et al. 2014; Rossi et al. 2019) and Alaska (Parrish et al. 2001).
Boundaries. The lower boundary has a slight angular unconformity where marine sandstones of the Parish Bjerg Formation overlie fossiliferous and dark grey calcareous shales of the Upper Permian Midnatfield Formation (Stemmerik et al. 1996). The upper boundary is generally poorly exposed. Where present, it is represented by an erosional unconformity overlain by Upper Jurassic – Cretaceous siliciclastics of the Ladegårdåsåen Formation.

Distribution. The group was originally confined to Herluf Trolle Land in eastern Peary Land, but new discoveries in the southern part of Kilen in Kronprins Christian Land, and re-dating of outcrops in Amdrup Land in the eastern part of North Greenland (previously assigned to the Jurassic, Stemmerik et al. 1998, 2000) have extended the distribution (Alsen et al. 2017; Fig. 1).

Chronostratigraphy. Induan–Norian, based on ammonoids and palynomorphs.

Subdivisions. The group comprises the Parish Bjerg, Ugleungernes Dal, Dunken, Storekløft and Isrand Formations as defined in this paper.

Key references. Håkansson (1979); Håkansson & Stemmerik (1984, 1989); Stemmerik & Håkansson (1989); Håkansson et al. (1991); Stemmerik et al. (1996, 2000); Alsen et al. (2017).

Parish Bjerg Formation

Revised formation

History. The formation was provisionally erected by Håkansson (1979) and formally described by Stemmerik & Håkansson (1989). It was named after the mountain Henry Parish Bjerg in Herluf Trolle Land (Fig. 1), where it originally included a succession about 350 m thick and comprised markedly different lithological units. The succession was assigned to the Lower Triassic based on a very limited biostratigraphic dataset (Håkansson 1979). The formation is here revised to represent the lowermost, mainly reddish interval of conglomerates, sandstones and mudstones with well-defined lower and upper boundaries. This interval is easily recognised in the field in moderate to well-exposed areas. The overlying succession at Henry Parish Bjerg is now included in the Ugleungernes Dal, Dunken and Storekløft Formations based on new biostratigraphical data and lithological characteristics. A fault-bounded sliver of sandstones and minor mudstones in the southern part of Henry Parish Bjerg was previously assigned to the Parish Bjerg Formation; it is now included in the Cretaceous Ladegårdåsåen Formation based on new biostratigraphic data.

Type area and section. The western part of Henry Parish Bjerg (Loc. 1) in Herluf Trolle Land (Figs 1, 3, 5); the base of the section is located at 82°44.4053’N, 021°58.9517’W, elevation 495 m.

Reference section. The section Hjulsordalen in the southern part of Herluf Trolle Land (Figs 1, 3, Loc. 10).

Thickness. The formation is at least 25 m thick at the type locality and about 20 m thick at Hjulsordalen.

Lithology. The basal part of the formation consists of greyish yellow, fine-grained sandstones with hummocky cross-bedding and planar bedding. Trace fossils of Gyrocorte, Helminthopsis, Nereites and Planolites are common in the fine-grained sandstones. The sandstones are erosionally overlain by two couplets of characteristic reddish-brown conglomerates, and pebbly sandstones with trough cross-bedding succeeded by reddish-brown mudstones (Figs 3, 5B). The clast assemblage of the conglomerates comprises mainly extraformational sedimentary clasts of greenish sandstones, quartzite and chert.

Fossils. Some bedding surfaces contain abundant fossil wood fragments, and plant remains are present in the muddy sediments overlying the conglomerates. Palynological assemblages are poorly preserved, only Verrucosisporites spp., Densoisporites sp., Lunatisporites sp., Alisporites sp. and a possible specimen of Uvaesporites sp. could be positively identified.

Depositional environments. Shallow marine in the lower part and succeeded by coarse-grained fluvial and muddy flood-plain deposits.

Boundaries. The base is a slightly angular erosional surface in calcareous shales of the Upper Permian Midnatfjeld Formation (Stemmerik & Håkansson 1989), which is overlain by shallow marine sandstones of the Parish Bjerg Formation. A prominent internal erosional boundary occurs at the base of the fluvial conglomerates. The upper boundary represents a flooding surface where the red flood plain mudstones are conformably overlain by shallow marine biomottled muddy sandstones of the Ugleungernes Dal Formation in Hjulsordalen.

Distribution. Henry Parish Bjerg, Hjulsordalen and presumably Ladegårdåsåen area. It is probably scattered and poorly exposed in the shallow plain north-east of the Dunken mountain in Herluf Trolle Land.
**Chronostratigraphy.** Lower Triassic, based on sparse and poorly constrained spore-pollen assemblages. Presumably restricted to the Induan based on diagnostic palynomorphs in overlying sedimentary units in the Hjulspordalen area.

*Key references.* Håkansson (1979); Stemmerik & Håkansson (1989); Håkansson *et al.* (1991).

**Ugleungernes Dal Formation**

New formation

*History.* The formation is a fairly easily recognisable, mappable unit of mudstone-dominated strata that corresponds to the lower muddy interval of the Dunken Formation sensu Håkansson (1979) and Stemmerik &

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**Fig. 5.** A: Triassic succession 350 m thick in the western part of Henry Parish Bjerg (Loc. 1), and type locality of the Parish Bjerg Formation, unconformably overlying Permian carbonates of the Midnatfjeld Formation. B: Fluvial conglomerates with trough cross bedding, Parish Bjerg Formation at the type locality.
Håkansson (1989). It is also represented by a similar lithological unit in Hjulsprøden previously assigned to the Parish Bjerg Formation in Stemmerik & Håkansson (1989). New biostratigraphical data show that these mudstone units are age-equivalent and hence they are combined in a new formation with a

![Image of geological succession](image)

**Fig. 6.** Triassic succession about 600 m thick in Dunken mountain; the lower boundary of the Triassic is not exposed. The yellow circles mark the same snow patch on both figures (Photos by Kristian Svennevig). Dotted lines mark the location of logs in Fig. 3. A: Northern part of Dunken representing the type locality of Ugleungernes Dal Formation (Loc. 3). B: Eastern part of Dunken representing the type locality and section of the Dunken Formation (Loc. 4).
Triassic lithostratigraphy of the Wandel Sea Basin, North Greenland

The upper boundary is an erosional surface in muddy bioturbated sand overlain by a thin conglomeratic or pebbly sandstone bed and bioturbated sandstones of the Dunken Formation.

Type area. The north-eastern part of Dunken with the Dunken Main sections 1a–d, 4, 5 (Loc. 3; Figs 1, 3). The base of the section is located at 82°41.8909’N, 021°10.4232’W, elevation 123 m.

Reference sections. Hjulspordalen (Loc. 9), Dunken-2 borehole (Loc. 5).

Thickness. More than 125 m is recorded in the north-eastern part of Dunken, more than 100 m in the Dunken-2 drill core (lower boundary not reached in the hole), and about 65 m at Hjulspordalen.

Lithology. The lower part is characterised by laminated to weakly laminated dark grey to black mudstones with common thin beds of ripple and planar laminated fine sand. The middle part is dominated by dark grey biomottled sandy mudstones and muddy sandstones, fine heterolithic mudstone-sandstone intervals (Fig. 7A), and a few thin conglomeratic beds. The top of the formation is characterised by biomottled grey to light-grey muddy sandstones. Slump structures are common in several intervals. Trace fossils include Thalassinoides, ?Scolicia, Rhizocorallium, Planolites and Chondrites. Diverse and well-preserved palynofloral assemblages are recorded in the muddy sediments in the southern localities. The formation is slightly calcareous with a carbonate content of 2–6%.

Fossils. Ammonoids and bivalves are recorded in the upper part of the formation. Ammonoids occur at few levels and are mainly represented by Arctoceras blomstrandi, but a single specimen of a possible Radioceras is also recorded. The Smithian part is dominated by spores of mainly Densoisporites, Pechorosporites, Kneuselisporites and Punctatisporites fungosus, while the Spathian is dominated by bisaccate pollen of Lunatisporites novialensis and Protohaploxypinus samoilovichii along with common spores of Rewanispora foveolata.

Depositional environment. Mainly offshore to lower shoreface environments in an overall shallowing-upward succession with several minor transgressive-regressive intervals.

Boundaries. The base is exposed at Hjulspordalen and corresponds to a flooding surface where bioturbated muddy sand conformably overlies muddy flood-plain deposits of the Parish Bjerg Formation (Fig. 3). The

Fig. 7. A: Sandy mudstones and ripple laminated sandstones in the upper part of the Ugleungernes Dal Formation at Dunken. Camera lens cap for scale, 5 cm. B: Biomottled shallow marine sandstones with abundant apatite nodules, Dunken Formation in Storekløft (Loc. 6). Length of hammer 32 cm. C: Bedding-parallel surface of a shallow marine sandstone with abundant Rhizocorallium trace fossils, Dunken Formation in Storekløft (Loc. 6). Length of pencil 14 cm.
Fig. 8. Upper shoreface planar-bedded and cross-bedded sandstones of the Dunken Formation, Loc. 6. The hammer is located at level 53 m in the Storekloft-1 section in Fig. 3. Height of exposed section is about 8 m.
Distribution. The formation is well exposed in Dunken mountain and at Hjulspsordalen; it is probably present although poorly exposed at Henry Parish Bjerg, south of Storekloft and in the Ladegårdsåen area (Fig. 1). Similar, age-equivalent deposits occur in Amdrup Land (Alsen et al. 2017), extending the distribution of the formation to this area (Fig. 1).

Chronostratigraphy. Upper Induan (Dienarian) – Olenekian (Smithian–Spithian) based on palynology and ammonoids (Lindström et al. 2019). The palynological assemblages are correlated with the four consecutive zones: the Maculatasporites, the Naumovaspora striata, the Pechorospites disertus, and the Jerseyaspora punctispinosa Composite Assemblage Zones of Vigran et al. (2014). The recorded ammonoids are characteristic of the Smithian Euflemingites romunderi and Wasatchites tardus Zones in Canada (Tozer 1994) and occur together with palynological assemblages of the Naumovaspora striata Composite Assemblage Zone (Fig. 4).

Key references. Kummel (1953); Håkansson (1979); Stemmerik & Håkansson (1989); Håkansson (1979); Stemmerik & Håkansson (1991); Stemmerik et al. (2000); Alsen et al. (2017).

Dunken Formation

Revised formation

History. The formation was provisionally erected by Håkansson (1979) and formally described by Stemmerik & Håkansson (1989) to represent the Triassic succession at the Dunken mountain. New lithological and biostratigraphic data and a better understanding of the regional context form the basis of a revision of the formation. The formation is now restricted to the sandstone-dominated interval in the middle part of the Triassic succession at Dunken (Stemmerik & Håkansson 1989) and the lower part of the Storekloft section in Mølgaard et al. (1994). The formation is thus lithostratigraphically separated from the underlying mudstone-dominated succession of the new Ugleungernes Dal Formation, and from the overlying Upper Triassic sandstones and conglomerates of the new Storekloft Formation (see below, Fig. 8). Despite the present revision to a restricted and well-defined stratigraphic interval, the formation is more widely distributed in the region than previously anticipated. It now includes the middle part of the Triassic succession on Henry Parish Bjerg and Hjulspsordalen that earlier was mapped as part of the Parish Bjerg Formation by Stemmerik & Håkansson (1989). The formation represents a shallow marine equivalent to the Isrand Formation at Kilen (Alsen et al. 2017).

Type area and section. The Dunken mountain area (Loc. 4, Fig. 1) with several sections measured in the northeastern slopes (Figs 3, 6A, B). Section 1d (Loc. 3, Fig. 1) shows the base and lower part of the formation, and section Dunken-X (Loc. 4) represents the main part of the formation including the upper boundary. The base of the section is located at 62°41.3289N, 021°08.2579W, elevation 200 m. The Dunken-2 drill core (Loc. 5) additionally records the lower boundary.

Reference sections. The formation is well exposed in Storekloft (Loc. 6). Part of the formation and especially the lower and upper boundary intervals are exposed at Hjulspsordalen in the southern part of Herul Trolle Land (Loc. 8).

Thickness. The formation is about 230 m in type area, 80 m thick in Hjulspsordalen, and possibly >130 m thick at Henry Parish Bjerg, where the formation is poorly exposed.

Lithology. The formation is dominated by biomottled light grey to yellowish grey fine-grained sandstones, slightly muddy sandstones and planar and trough cross-bedded, medium-grained sandstones (Figs 7B, 7C, 8). Minor interbedded units of very dark grey mudstones, sandy mudstones and heterolithic sandstone-mudstones occur. Subordinate thin beds of pebbly sandstones and conglomerates are present at certain levels. Apatite nodules are common throughout the formation (Fig. 7B). Highly diverse trace fossil assemblages are recognised including Rhizocorallium, Diplocraterion, Skolithos, Planolites and Chondrites. The trace fossil assemblages are commonly superimposed on an intensely biomottled fabric (Fig. 7C).

Fossils. Ammonoids occur at several levels and include typical Anisian taxa: Lenotropites caurus, Lenotropites tardus, Groenlandites cf. nielseni and Pearylandites aff. troelseni, as well as Ladinian forms such as Indigrirites sp., Indigrirites cf. stolleyi, Zestoceras sp. and Natherstites sp. Bivalves are rare. Plant remains, spores and pollen and marine acritarchs of various degrees of preservation are predominantly recorded in the muddy sediments. The spore-pollen floras are mostly dominated by bisaccate pollen, including taeniate and non-taeniate forms. Age diagnostic taxa for the late Spithian include the first occurrences of Cyclothelleites oligogranifer, Jerseyaspora punctispinosa, Illinites chitonoides and Striatooabietes balmei, and the last occurrences of Rewanispora foveolata and Pechorospites disertus. Taxa typical for the Anisian include the first occurrence of Eresinia spinellata and the first common occurrence of Antapiculatisporites spiniger, as well as the last occurrences of Densoisporites nebjurgii and J.
punctispinosa in the lower and upper Anisian, respectively. The first occurrences of Echinitosporites iliacoides, Schizaeisporites worsleyi, and Staurosaccites quadrifidus occur in the lowermost Ladinian strata.

Depositional environment. Mainly shallow marine lower to upper shoreface with minor offshore intervals representing several transgressive–regressive cycles.

Boundaries. The base is marked by a pebble lag and medium- to coarse-grained sandstones that erosionally overly bioturbated muddy sandstone of the Ugleungernes Dal Formation. The upper boundary is a major erosional boundary in fine- to medium-grained bioturbated sandstones or trough cross-bedded, medium-grained sandstones overlain by prominent massive sandstones with an occasionally conglomeratic basal part of the Storekloft Formation.

Distribution. The formation was previously restricted to the Dunken mountain – Storekloft area (Håkansson 1979). The new data presented herein shows that the revised formation is much more widely distributed in the region, e.g. at Henry Parish Bjerg and Hjulsوردalen (Fig. 1), and possibly also in the Ladegårdssåen area in eastern Peary Land.

Chronostratigraphy. Upper Olenekian (Spathian) – Ladinian based on ammonoids and palynomorphs. The palynological assemblages in the lower part of the formation are correlated with the upper Spathian – lower Ladinian Composite Assemblage Zones, while the upper part of the formation belongs to the Ladinian Echinitosporites iliacoides Composite Assemblage Zone of Vigran et al. (2014) (Fig. 4). The recorded ammonoids are characteristic of the lower Anisian Lenotropites caurus Zone, and the upper Ladinian Meginoceras maginae and Mclarnoceras maclearni – Frankites sutherlandi Zones in Canada (Tozer 1994).

Key references. Kummel (1953); Håkansson (1979); Stemmerik & Håkansson (1989); Håkansson et al. (1991); Mølgaard et al. (1994).

Storekloft Formation

New formation

History. The unit encompasses the upper sandstone-dominated part of the Dunken main section previously included in the Dunken Formation of Stemmerik & Håkansson (1989) and the upper part of the Storekloft section in Mølgaard et al. (1994). The base of the new formation is identified as a prominent unconformity with increasing hiatal magnitude towards the basin margin, e.g. from the Dunken area to Hjulsوردalen (Figs 4, 9). The lower part comprises a characteristic and easily mappable interval of channelised massive sandstones with varying thicknesses (Fig. 3). The deposits of this unit are for the first time dated to encompass the Upper Triassic, which together with the diagnostic deposits in the basal part justify the separation of a new formation.

Type area and section. The formation is well exposed in both sides of the Storekloft valley (Storekloft is Danish for ‘large gorge’), which accordingly serves as the type area (Figs 1, 9). The type section is Storekloft (Loc. 6), with the base located at 82°39.4684’N, 021°09.0173’W, elevation 195 m. The lower and middle part of the formation is well-exposed in the type area, and the upper part is mainly present at Dunken.

Reference sections. The Dunken-X section (Loc. 4) in Dunken mountain and the western part of Henry Parish Bjerg (Loc. 1, Fig. 3). Hjulsوردalen in the southern part of Herluf Trolle Land (Loc. 8) represents a proximal and very coarse-grained example of the formation.

Thickness. Minimum 130 m at Storekloft and Dunken, and about 50 m at Henry Parish Bjerg. At Hjulsوردalen the formation is represented by 25 m.

Lithology. In the Dunken area, the lower part consists of massive sandstones, occasionally with a conglomeratic base comprising intraformational mudclasts and extraformational Palaeozoic rock types. The massive sandstones comprise amalgamated lenticular bodies commonly separated by thin bioturbated sandy mudstones (Figs 3, 9). It is overlain by interbedded massive sandstones and bioturbated sandstones with an interval of mudstone and heterolithic mudstone and sandstones in the middle part. Phosphatic nodules occur occasionally in the lower and middle part of the formation in the Dunken area. At Hjulsوردalen the formation is represented by a prominent conglomerate unit up to about 12 m thick, with large intraclasts of sandstones and mudstones and extraformational clasts of quartzite and chert (Fig. 10). The conglomerate is overlain by a few metres of pebbly sandstones and in turn well-sorted medium-grained sandstones with cross-bedding. At Henry Parish Bjerg the formation comprises massive, planar-bedded and trough cross-bedded sandstones with a few conglomeratic beds. Trace fossils of Rhizocorallium, Diplocraterion, Skolithos and Planolites are common in the biomottled intervals. Lockeia occurs occasionally in abundance on
Fig. 9. Type locality of Storekloft Formation at Storekloft (Loc. 6). A: Massive sandstones at the base of the Storekloft Formation (dashed line) at Storekloft. Person for scale to the left. B: Erosional conglomerate at the lower boundary of the Storekloft Formation (dashed line). Note dispersed black mudstone clasts in the conglomerate. Length of hammer 32 cm.
Fig. 10. Conglomerates of the Storekleft Formation in Hjulspordalen (Loc. 8).
sandstone bedding surfaces especially in the upper part of the formation.

Fossils. A few ammonoids that are relatively poorly preserved and tentatively assigned to cf. Brouweritès maclearni occur at Dunken mountain. Palynological assemblages from primarily mudstones and heteroliths are of variable preservation, but are generally diverse and dominated by acritarchs and bisaccate pollen. Palynological events used for recognition of the Carnian include: the first occurrences of Enzonalasporites spp., Patinaasporites densus and Vallasporites ignacii in the lowermost Carnian, with the last occurrences of Echinitosporites iliacoides and Triadispora verrucatus in the lower and middle Carnian, respectively. Upper Carnian to Norian strata contain the first occurrences of poorly preserved dinoflagellate cysts assigned to Shublikodinium spp. and Suessia swabiana. The top of the Carnian is marked by the last occurrences of Illinites chitonoides, Podosporites amicus, Protodiploxypinus gracilis and Staurosaccites quadrifidus.

Depositional environment. The conglomerates in the basal part of the formation at Hjulsproldalen represent proximal fluvial to marine marginal deposits in an incised valley. In the Storekløft area, the prominent channelised and erosional massive sandstones with thin interbedded bioturbated sandy mudstones were deposited from episodic gravity flows in a marine environment. The biomottled sandstones and cross-bedded sandstones represent marine lower to upper shoreface environments. The muddy interval probably represents an offshore transition environment. Several transgressive–regressive cycles are recorded in the formation.

Boundaries. In Storekløft the base is a prominent erosional surface incised into biomottled sandstones of the Dunken Formation and overlain by massive sandstones with or without a conglomeratic basal part (Fig. 9). In Hjulsproldalen the base is a steep and undercutting erosional surface associated with a considerable hiatus (Fig. 4) and overlain by conglomerates (Figs 3, 10). The upper boundary is generally poorly exposed but probably represents a major erosional unconformity overlain by mudstones and sandstones of the Upper Jurassic – Cretaceous Ladegårdsåen Formation.

Distribution. Storekløft, Dunken mountain, south of Storekløft, Henry Parish Bjerg, Hjulsproldalen, possibly Ladegårdsåen area in eastern Peary Land.

Chronostratigraphy. Carnian–Norian, based mainly on palynomorphs and on a few ammonoids. The palynomorph assemblages are correlated with the Carnian Aulisporites astigmosus and Rhaetogonyaulax spp. Composite Assemblage Zones of Vigran et al. (2014) (Fig. 4). The assemblages assigned to the Rhaetogonyaulax spp. Composite Assemblage Zone may also correlate with the Protodiploxypinus Assemblage from Hopen island, Svalbard (Paterson & Mangerud 2015).

Key references. Troelsen (1950); Kummel (1953); Håkansson (1979); Stemmerik & Håkansson (1989); Håkansson et al. (1991); Mølgaard et al. (1994).

Isrand Formation

History. The Isrand Formation was described and named by Alsen et al. (2017). It comprises an outcrop of a Triassic mudstone succession that was discovered during GEUS’s Expedition to North Greenland 2012–2013 along both sides of the Sølverbæk river, which drains melt water from the Flade Isblink glacier in the western central part of Kilen in Kronprins Christian Land (Fig. 1). The unit had previously been mapped as part of the Upper Jurassic Kuglejet Formation (Pedersen 1989). The retreat of the ice sheet has increased the exposure during the last decades as seen from comparison of aerial orthophotos and recent oblique photogrammetry (Svennevig et al. 2016). Macrofossils include bivalves and ammonoids collected from an interval in the middle part of the formation and indicate a Middle Triassic age (Alsen et al. 2017). The name ‘Isrand’ is the Danish word for the glacial margin that delimits the outcrop towards the west.

Type area and section. The western central part of Kilen between the flanks of the Sølverbæk river and the glacier margin constitutes the type area (Loc. 11, Figs 1, 11). The type section is combined from three sub-sections (Figs 3, 11) with base of the section located at 81°13.2453’N, 013°56.2115’W, elevation 117 m.

Thickness. The combined sections in the type area record a thickness of 400 m. The base of the succession is not exposed as the lower part is presently still covered by the ice sheet of the Flade Isblink glacier (Figs 1C, 11A).

Lithology. The formation consists of black laminated mudstones with prominent bedding-parallel cretationary horizons and lenses (Figs 11–12). Thin planar, wavy and ripple laminated sand beds occur frequently, and slumped sandstone beds and lenses are common in the upper part of the succession. Abundant bivalve shell accumulations occur commonly on bedding surfaces.
**Fossils.** Abundant halobiid bivalves of *Daonella subarctica* occur throughout the formation. Ammonoids are recorded at several levels and include in the lower part *Aristoptychites euglyphus* and further up in the succession *Nathorstites cf. macconnelli*. Wood and plant fragments are present in certain intervals in the upper part of the formation. Due to the thermal maturity of the organic material, the palynological samples were either barren or contained very few unidentifiable fragments of bisaccate pollen grains and unidentifiable spores. Only a single specimen of the long-ranging spore taxon *Gordonispora fossulata*, which first appears in the early Spathian *Pechorosporites disertus* Composite Assemblage Zone of Vigran et al. (2014), has been identified in the samples from the Isrand Formation.

**Depositional environment.** Lower slope and basin floor in oxygen deficient environments.

**Boundaries.** The lower boundary is not exposed. The upper boundary is constituted by a fault against Lower Cretaceous mudstones of the Galadriel Fjeld Formation (Hovikoski et al. 2018).

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**Fig. 11.** A: Overview of the Triassic succession at Kilen (Loc. 11) showing the positions of measured type sections 1–4 in the Isrand Formation, view towards the north-west. B: Lower part of the Isrand Formation showing dark grey mudstones and shales and bedding-parallel light brown concretionary horizons (Section Isrand-1), view towards the south-east.
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**Chronostratigraphy.** The recorded ammonoid zones include the Ladinian *Tsjevkovites varius* Zone, *Megaloceras meginae* Zone, *Mclearnoceras maclaerni* Zone and *Frankites sutherlandi* Zone. The middle levels with halobiid bivalves belong to the Ladinian *Daonella subarctica* bivalve zone. The lowermost 30 m and uppemost 100 m of the formation remains presently undated, and most likely the formation reaches downwards into the Anisian and upwards into the Carnian. Stratigraphy from palynomorphs remains unsolved due to poor preservation and a high maturity level in the mudstones.

**Key references.** Svennevig et al. (2016); Alsen et al. (2017).

**Discussion and Arctic correlation**

The stratigraphy and depositional evolution of the Triassic in North Greenland has hitherto been essentially unknown. It was tentatively and provisionally described as two coarsening-upward lithostratigraphic units with a few biostratigraphic data suggesting a lower to middle Triassic age (Håkansson et al. 1991). This study presents a coherent Triassic lithostratigraphy of the Wandel Sea Basin in a robust biostratigraphic framework that represents a near-complete Triassic succession from the Induan to the Norian (Fig. 4). The lithostratigraphic framework represents a geological transect with an overall basin marginal setting in Peary Land to a deeper water basinal setting in Kronprins Christian Land (Figs 4, 13).

The base of the Triassic succession is only exposed in Peary Land, where it forms an erosional unconformity against Upper Permian marine carbonates and mudstones of the Midnatfjeld Formation. The basal Triassic deposits belong to the Induan Parish Bjerg Formation, which is up to 25 m thick. It consists of a thin veneer of shallow marine storm-influenced sandstones that is erosionally overlain by fluvial conglomerates and muddy flood-plain deposits. Time-equivalent deposits are not presently exposed in Kronprins Christian Land. The Parish Bjerg Formation is probably time equivalent to the shallow marine deposits in the lower parts of the Vardebykta Formation on Svalbard (Vigran et al. 2014), and the depositional facies belts were probably parallel aligned in the palaeogeographic context (Fig. 13A). The Parish Bjerg Formation is also considered time equivalent to the deltaic Tana fan of the Havert Formation in the south-western Barents Sea (Eide et al. 2018).

The base of the overlying Ugleungernes Dal Formation represents a Dienerian transgressive surface. The deposits consist of a thin unit of shallow marine
Fig. 13. Regional palaeogeographic maps of the western Barents Sea and Wandel Sea Basin. The Barents Sea area is based on Eide et al. (2018) in A, Glørstad-Clark et al. (2010) in A–B, and on Klausen et al. (2015) in C–F. Dashed lines in A and B show the western limit of the study area in Glørstad-Clark et al. (2010), as represented by the Late Mesozoic – Cenozoic tectonic deformation boundary. DB: Danmarkshavn Basin. KCL: Kronprins Christian Land. WSB: Wandel Sea Basin.
sandstones followed by an offshore mudstone-dominated interval about 150 m thick and encompass the Dienerian – Spathian. A thin, prograding shallow marine unit in Peary Land marks a regressive coarse-grained interlude in the lower Spathian. The recently discovered marine Triassic deposits in Amdrup Land belong to this interval, which extends the deposition of the marine deposits to these areas (Fig 13B; Alsen et al. 2017). The Ugleungernes Dal Formation correlates with the Urd Formation on Bjørnøya where a similar depositional trend is recorded (Mørk et al. 1990), and with the upper part of the Vardebukta and Vikinghøgda Formations on Svalbard (Fig. 4; Vigran et al. 2014).

The Spathian – Ladinian Dunken Formation in Peary Land represents shallow marine sandy shelf deposition that experienced several flooding episodes as represented by condensed organic biomottled mudstone deposits in the lower Anisian and two such intervals in the Ladinian (Figs 3, 4). The formation correlates with the lower to middle part of the Isrand Formation at Kronprins Christian Land, which is dominated by offshore organic-rich mudstones with alternating minor amounts of distal, thin, low-density gravity-flow sandstones. The latter show depositional characters similar to the time-equivalent Botneheia Formation at Svalbard (Krajewski 2008, 2013; Vigran et al. 2014) and the Steinkobbe Formation in the Barents Sea (Mørk & Elvebakk 1999).

A marked erosional unconformity occurs at the base of the Carnian in Peary Land, with associated marine channel deposits of massive sandstones and conglomerates up to about 50 m thick, which belong to the lower part of the Storekløft Formation. The possible equivalent interval in the deeper part of the basin in Kronprins Christian Land is represented by a slumped base of slope succession, 35 m thick, of mudstones and gravity-flow sandstones in the upper part of the Isrand Formation (Figs 3, 4, 13D). The interval is time-equivalent to deltaic mudstones and sandstones with abundant channelised sandy units in the lower part of the De Geerdalen Formation in the eastern part of Svalbard (Edgeøya, Barentsøya and Hopen; Vigran et al. 2014; Lord et al. 2014), and to channelised sandstones in the Snadd Formation in the Barents Sea (Klausen & Mørk 2014). In Peary Land the channelised marine sandstones are succeeded by mainly shallow marine sandstones of the Storekløft Formation with two intervals of offshore organic-rich mudstones that probably correlate to black and dark grey deep shelf – basin floor mudstones in the uppermost part of the Isrand Formation (Figs 3, 4, 13E), as well as to Carnian maximum flooding intervals described from the Barents Sea by Klausen et al. (2015). The Storekløft Formation extends well into the Norian and has a total thickness of up to 130 m. A prominent channelised unit, 25 m thick, comprises marginal marine conglomerates and sandstones of inferred Norian age at Hjulsordalen (Figs 3, 4). It may correlate with shallow marine coarse clastic units of the Svenskøya Formation on Svalbard (Hopen) and Fruholmen Formation in the Barents Sea (Sentralbanken and Nordkapp Basin, Lundschiehen et al. 2014; Lord et al. 2014).

Conclusions

The Wandel Sea Basin represents a nearly complete Triassic succession with an estimated combined thickness of 700 m. The basal part of the Induan is fluvial, and the remaining Triassic is marine, representing a sand-dominated basin marginal succession in Peary Land to the west and a marine basinal mudstone succession in Kronprins Christian Land to the east. The Wandel Sea Basin formed the western continuation of the basins in the western Barents Sea and the northern continuation of the Danmarkshavn Basin offshore North-East Greenland and thus represents a key area for the understanding of the depositional evolution from the western Barents Sea area and into the north-east Atlantic basins in Triassic times. Major depositional sequences in the Wandel Sea Basin correlate genetically well with time-equivalent units especially onshore Svalbard, but also on a regional scale in the greater Barents Sea area.

Acknowledgements

The study was conducted as part of GEUS’s petroleum-geological activities in the region, with Jørgen Bojesen-Koefoed as expedition leader. Station Nord served as base camp, with Klaus Bidstrup and Mari-anne Vestergaard. Harald Brekke, Hans I. Sjulstad and Hilde Krogh from the Norwegian Petroleum Directorate shared geological information from their field work in Peary Land. Stefan Plasecki and Peter Frykman are thanked for companionship in the field and for geological input to the study. Christopher McRoberts is thanked for his biostratigraphic remarks on the collected halobiid bivalves. Kristian Svennevig and Erik Vest Sørensen provided 3D photo-geological data and Jette Halskov conducted the graphic work. Constructive reviews by Atle Mørk and Christian Eide are gratefully acknowledged.
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