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Ammonoid stratigraphy and sedimentary evolution across the Permian–Triassic boundary in East Greenland

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Abstract – East Greenland is a classical area for the study of the Permian–Triassic transition and the succession is one of the most expanded in the world. New ammonoid data from the Wordie Creek Formation have allowed us to better reconstruct the history of the East Greenland basin from semi-isolated basins with an endemic fauna during latest Permian–earliest Triassic *H. triviale*–*H. martini* zones time to well-connected open marine shelf basins during the Early Triassic *M. subdemissum*, *O. commune*, *W. decipiens* and *B. rosenkrantzi* Zone times. The East Greenland zonation can be correlated with Boreal zonations in Arctic Canada, Svalbard and northeastern Asia. It allows precise relative dating and correlation of important events across the Permian–Triassic boundary. The new ammonoid data indicate that deposition was continuous across the Permian–Triassic boundary and developed as a marine mudstone–mudstone contact in basinal areas of Hold With Hope, northern and southern Jameson Land. Correlation of the ammonoid stratigraphy with the FAD of *Hindeodus parvus*, which defines the base of the Triassic in Global Stratotype Section and Point (GSSP) in Meishan, China, suggests that the *Hypophiceras triviale* Zone is to be referred to the uppermost Permian, whereas the *H. martini* Zone is lowermost Triassic. Accordingly, the end-Permian marine and terrestrial extinctions and associated isotope changes as well as the subsequent adaptive radiations in East Greenland took place in latest Permian time. New Boreal faunas and floras were well established and diversified in the *Hypophiceras triviale* Zone prior to the beginning of the Triassic, and the Permian–Triassic boundary, in its present definition, is no longer reflecting major changes in the Earth system. It would have been fortunate if a GSSP were defined in a protracted section at a point of major environmental perturbations, marked by isotope excursions, chemical anomalies and mass extinction, rather than in the strongly condensed section like Meishan at a point which post-dates all significant events.

Keywords: Permian–Triassic boundary, East Greenland, ammonoids.

1. Introduction

The Permian–Triassic boundary is associated with the largest known mass extinction in Earth history, and both the causes and the precise stratigraphical position of the boundary have been and are still the subject of much discussion. East Greenland is a classical area for the study of the marine stratigraphical evolution across the boundary in the Arctic (Nielsen, 1935; Spath, 1935; Trümpy, 1969; Teichert & Kummel, 1976; Perch-Nielsen *et al.* 1974; Surlyk *et al.* 1984, 1986; Stemmerik *et al.* 1997, Stemmerik, Bendix-Almgreen & Piasecki, 2001; Twitchett *et al*. 2001; Wignall & Twitchett, 2002; Seidler *et al.* 2004). The area belongs to the palaeo-biographical Boreal Realm, and biostratigraphical correlations are based mainly on ammonoids. The standard ammonoid zonation of the Early Triassic Boreal Realm was in part established in the Sverdrup Basin, Canadian Arctic Islands, by Tozer (1994). Local zonations have been described from East Greenland (Trümpy, 1969), northeastern Asia (Dagys & Ermakova, 1996) and Svalbard (Weitschat & Dagys, 1989). Due to endemism and to widespread unconformities in the interval spanning the Permian–Triassic boundary, there are, however, still major problems in dating and correlating uppermost Permian–lowermost Triassic successions within the Boreal Realm.

The Permian–Triassic boundary in East Greenland has traditionally been placed at the boundary between the Foldvik Creek Group and the Wordie Creek Formation. In most areas there is a major hiatus between the two units, but successions showing continuous sedimentation have been known for a long time from the deeper, western part of the Jameson Land Basin (Perch-Nielsen *et al.* 1972, 1974; Piasecki & Marcussen, 1986; Oberhänsli *et al.* 1989; Twitchett *et al.* 2001; Stemmerik, Bendix-Almgreen & Piasecki, 2001).

The Global Stratotype Section and Point (GGSP) of the Permian–Triassic boundary in the Meishan section in China has recently been ratified by the Executive Committee of the International Union of Geological Science (Yin Hongfu *et al.* 2001). The boundary is in the Meishan section defined by the first appearance datum (FAD) of the conodont *Hindeodus parvus*, which has been reported from the lowermost part of the

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Wordie Creek Formation in Jameson Land, East Greenland (Twitchett *et al.* 2001; Wignall & Twitchett, 2002).

Six ammonoid zones are recognized in the Wordie Creek Formation and they are, in stratigraphical order: the *Hypophiceras triviale*, *Hypophiceras martini*, *Metophiceras subdemissum*, *Ophiceras commune*, *Wordieoceras decipiens* and *Bukkenites rosenkrantzi* zones (Trümpy, 1969). They are overlain by the *Anodontophora breviformis* and *A. fassaensis* bivalve zones (Spath, 1935).

The aim of this study is to describe the stratigraphical distribution of the key ammonoids and sedimentary evolution across the Permian–Triassic boundary of East Greenland. The study adds to earlier accounts with new lithological and biostratigraphical data from the subbasins of Hold With Hope, Traill Ø, Wegener Halvø and northern Jameson Land (Figs 1, 2), the key areas in East Greenland for understanding the events across the boundary in the Boreal Realm. This is the region where the most expanded and stratigraphically most complete successions are found, both in East Greenland and possibly worldwide. The correlation of the FAD of *Hindeodus parvus* with the ammonoid stratigraphy is still crude, but there is evidence to suggest that the *Hypophiceras triviale* Zone, hitherto considered to mark the base of the Triassic in East Greenland, belongs to the uppermost Permian.

2. Geological setting

The Late Permian–Early Triassic basin of East Greenland is N–S oriented, and the part exposed on land stretches about 400 km in a N–S direction. It is bounded to the west by the Post-Devonian Main Fault–Stauning Alper Fault system, and the Liverpool Land High forms the eastern boundary in the Jameson Land area (Fig. 1). A correlative marine succession offshore Norway suggests that a wide marine gulf extended southwards between Greenland and Norway (Bugge *et al.* 2002; Seidler *et al.* 2004; Stemmerik, Piasecki & Surlyk, unpub. data).

The Middle–Upper Permian Foldvik Creek Group overlies Upper Carboniferous–lowermost Permian continental deposits and older rocks with an angular unconformity. The group comprises, from below, Capitanian alluvial conglomerates with marine influence in the top (Huledal Formation), overlain by marine hypersaline carbonates and evaporites (Karstryggen Formation). In basin marginal areas and over palaeo-highs the Capitanian Karstryggen Formation is overlain by carbonate build-ups, up to 150 m thick (the Wuchiapingian-aged Wegener Halvø Formation), whereas correlative black bituminous mudstones, up to 100 m thick (Ravnefjeld Formation), occur in basinal areas (Surlyk *et al.* 1986; Surlyk, 1990; Piasecki & Stemmerik, 1991; Stemmerik *et al.* 1998). The Changhsingian-aged Schuchert Dal Formation, up to 220 m thick, represents the latest Permian basin fill, where relative sea-level rise caused drowning of the carbonate buildups and deposition of grey-black silty bioturbated mudstone of the Oksedal Member and turbiditic sandstones of the Bredehorn Member (Fig. 3) (Surlyk *et al.* 1986; Stemmerik & Piasecki, 1991; Kreiner-Møller & Stemmerik, 2001; Stemmerik *et al.* 1998). The uppermost part of the Schuchert Dal Formation and the lowermost part of the overlying mainly Griesbachian Wordie Creek Formation include the 24–27 m thick 'Permian–Triassic boundary interval' of Stemmerik, Bendix-Almgreen & Piasecki (2001).

The Permian–Triassic transition coincides in most of East Greenland with an erosional unconformity formed during a fall in relative sea level probably induced by block faulting and tilting. The unconformity is best developed at basin margins and on uplifted intrabasinal fault-blocks. However, in the deeper, down-tilted parts of the northern Jameson Land subbasin, sedimentation appears to have been continuous across the boundary (Perch-Nielsen *et al.* 1972; Piasecki & Marcussen, 1986; Oberhänsli *et al.* 1989; Surlyk *et al.* 1986; Twitchett *et al.* 2001; Stemmerik, Bendix-Almgreen & Piasecki, 2001). The unconformity expands drastically north of Jameson Land and the Schuchert Dal Formation and correlatives are missing in the classical boundary sections at Hold With Hope.

The Wordie Creek Formation is 70–850 m thick and was deposited during overall relative sea-level rise punctuated by several falls. The formation varies markedly in facies and thickness, reflecting a strong tectonic control on deposition (L. Seidler, unpub. Ph.D. thesis, Univ. Copenhagen, 2000; Seidler, 2000; Seidler *et al.* 2004). The overall facies development in the study area begins with marine shales and mudstones, with sandy and conglomeratic turbidites in the lower part (*H. triviale*–*O. commune* zones). On Wegener Halvø these deep marine sediments onlap the basin margin towards the east against the Liverpool Land High (Grasmück & Trümpy, 1969; Surlyk *et al.* 1986; Seidler *et al.* 2004). The overlying strata (*W. decipiens*–*B. rosenkrantzi* zones) consist of marine mudstones, shoreface sandstones and a fluvial conglomerate (Fig. 4) (Svinhufvuds Bjerge Member) (Clemmensen, 1980*b*). Locally, a succession of thrombolitic carbonate bioherms, up to 19 m thick, occurs in the uppermost part of the formation (Ødepas Member: Clemmensen, 1980*a*). The bioherms are laterally associated with small stromatolite mounds and calcareous shoreface storm sandstones. The uppermost part of the Wordie Creek Formation consists of tidally influenced shallow marine sandstones. The overlying Middle–Upper Triassic succession is up to 1400 m thick and is mainly continental with a marine intercalation in the Middle Triassic (Clemmensen, 1980*a*, *b*).

3. Stratigraphy of the Permian–Triassic boundary strata

The presence of Lower Triassic marine deposits in East Greenland on the north coast of Hold With Hope was first recognized by Wordie (1927) and the succession

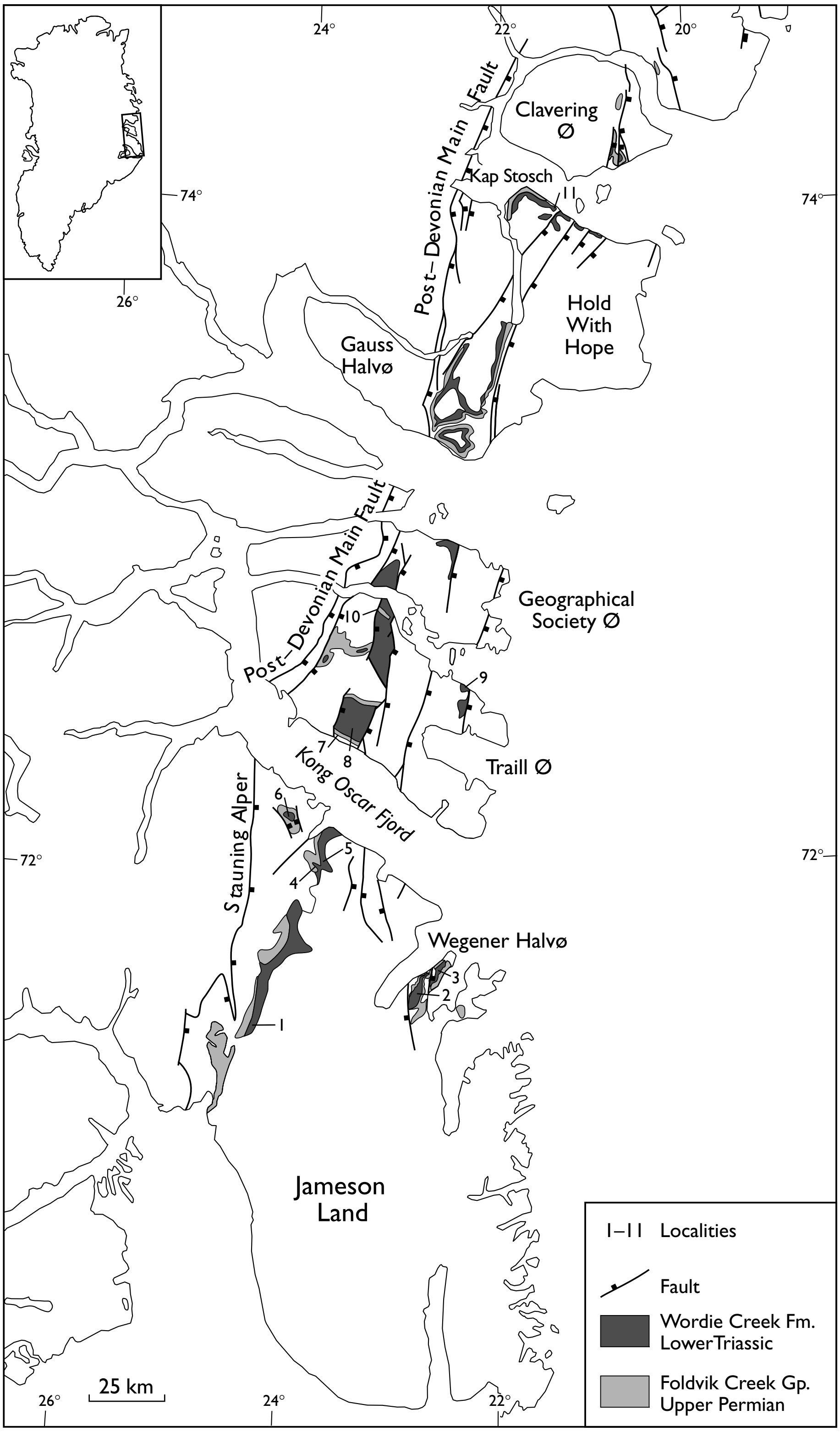

Figure 1. Map showing outcrop of the Upper Permian Foldvik Creek Group and uppermost Permian–Lower Triassic Wordie Creek Formation in East Greenland basin together with the main faults; Localities: 1 – Fiskegrav; 2 – Lille Cirkusbjerg; 3 – Paradigmabjerg; 4 – Aggersborg; 5 – Oksedal; 6 – Korsbjerg; 7 – Svinhufvud Bjerge, coastal section; 8 – Svinhufvud Bjerge, Ødepas; 9 – Mols Bjerge; 10 – Rold Bjerge, Månedal; 11 – Hold With Hope. Modified from Callomon, Donovan & Trümpy (1972) and Larsen *et al.* (1998).

was termed the Wordie Creek Formation by Koch (1929, 1931). Subsequent studies in the area described the general lithostratigraphy and fish faunas (Nielsen, 1935, 1961; Stensiö, 1932), ammonoid faunas (Spath, 1930, 1935), palynostratigraphy (Balme, 1979) and the stratigraphical development across the Permian–Triassic boundary (Teichert & Kummel, 1976). Mapping and description of Upper Permian–Triassic strata

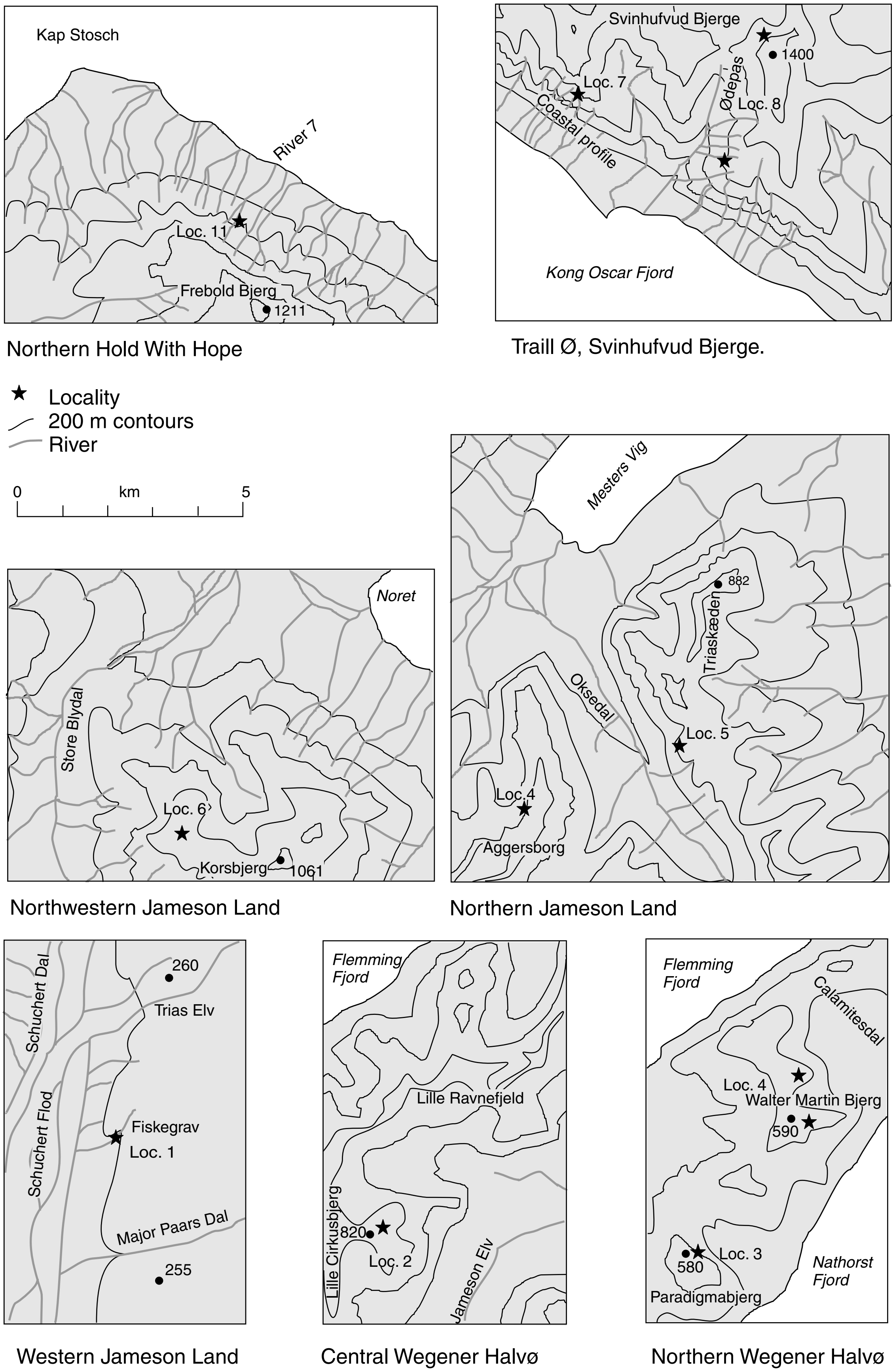

Figure 2. Maps of localities 1–8 and 11. Locality numbers as in Figure 1.

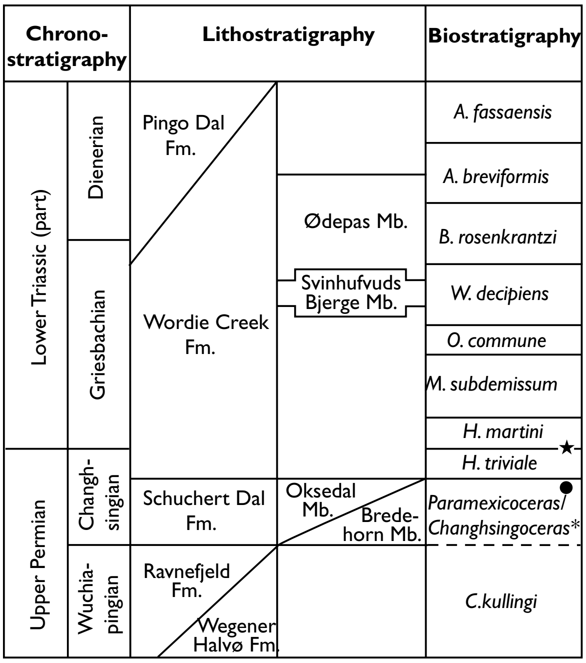

Figure 3. Upper Permian–Lower Triassic lithostratigraphy and ammonoid zonation. Vertical scale arbitrary. Based on Perch-Nielsen *et al.* (1974), Stemmerik, Bendix-Almgreen & Piasecki (2001), Yin Hongfu *et al.* (2001), and this study. Asterisk – material does not allow definite determination; star – FAD of *H. parvus*; solid circle – δ^{13}C spike.

from Traill Ø and northern Jameson Land was undertaken by Frebold & Noe-Nygaard (1938), Stauber (1942), Putallaz (1961) and Grasmück & Trümpy (1969), and the Lower Triassic ammonoid fauna and zonation based mainly on material from Wegener Halvø was described by Trümpy (1969).

A lithostratigraphical scheme covering the Lower Triassic of Jameson Land and Traill Ø was presented by Perch-Nielsen *et al.* (1974) and updated by Clemmensen (1980*a*, *b*). More recently the Upper Permian–Lower Triassic succession has been dealt with in connection with petroleum geological investigations (Piasecki, 1984; Surlyk *et al.* 1984, 1986; Stemmerik *et al.* 1997; Larsen *et al.* 1998). A sedimentological and sequence stratigraphical interpretation of the Wordie Creek Formation was presented by Seidler (2000; L. Seidler, unpub. Ph.D. thesis, Univ. Copenhagen, 2000), while the Permian–Triassic boundary interval was studied by Twitchett *et al.* (2001), Stemmerik, Bendix-Almgreen & Piasecki (2001) and Wignall & Twitchett (2002).

This study adds to earlier accounts with new lithological and biostratigraphical data from Hold With Hope, Traill Ø and northern Jameson Land, including the Wegener Halvø area. The fossils were collected bed-by-bed and the generic names of the ammonoids follow Tozer (1981, 1994) and Dagys & Ermakova (1996). A thorough revision of the taxonomy of Spath (1930, 1935) and Trümpy (1969) with an evaluation of synonymy (intraspecific variations, ontogenetic variations) and subgeneric ranks would be useful. However, the preservation of the collected material is too poor and the total number of ammonoids from single beds is too scarce to allow such a revision to be undertaken. Specimens are therefore assigned to the morphotypes of Spath (1935), except where these have been revised by Tozer (1994) or Dagys & Ermakova (1996).

4. Biostratigraphical zonation

The Upper Permian cyclolobid ammonoid stratigraphy of East Greenland comprises a Wuchiapingian *Cyclolobus* assemblage and a Changhsingian *Changhsingoceras?/Paramexicoceras* assemblage, but this is not

Figure 4. Wordie Creek Formation at Ødepas in Svinhufvud Bjerge, looking east (loc. 8 in Figs 1, 2). Fluvial conglomerates of Svinhufvuds Bjerge Member (Sv Mb), shallow marine mudstone sandstone and carbonates of Ødepas Member (Ød Mb), sandstone turbidites (T), shoreface sandstones (SFS), Tertiary dykes (D) and sills (S).

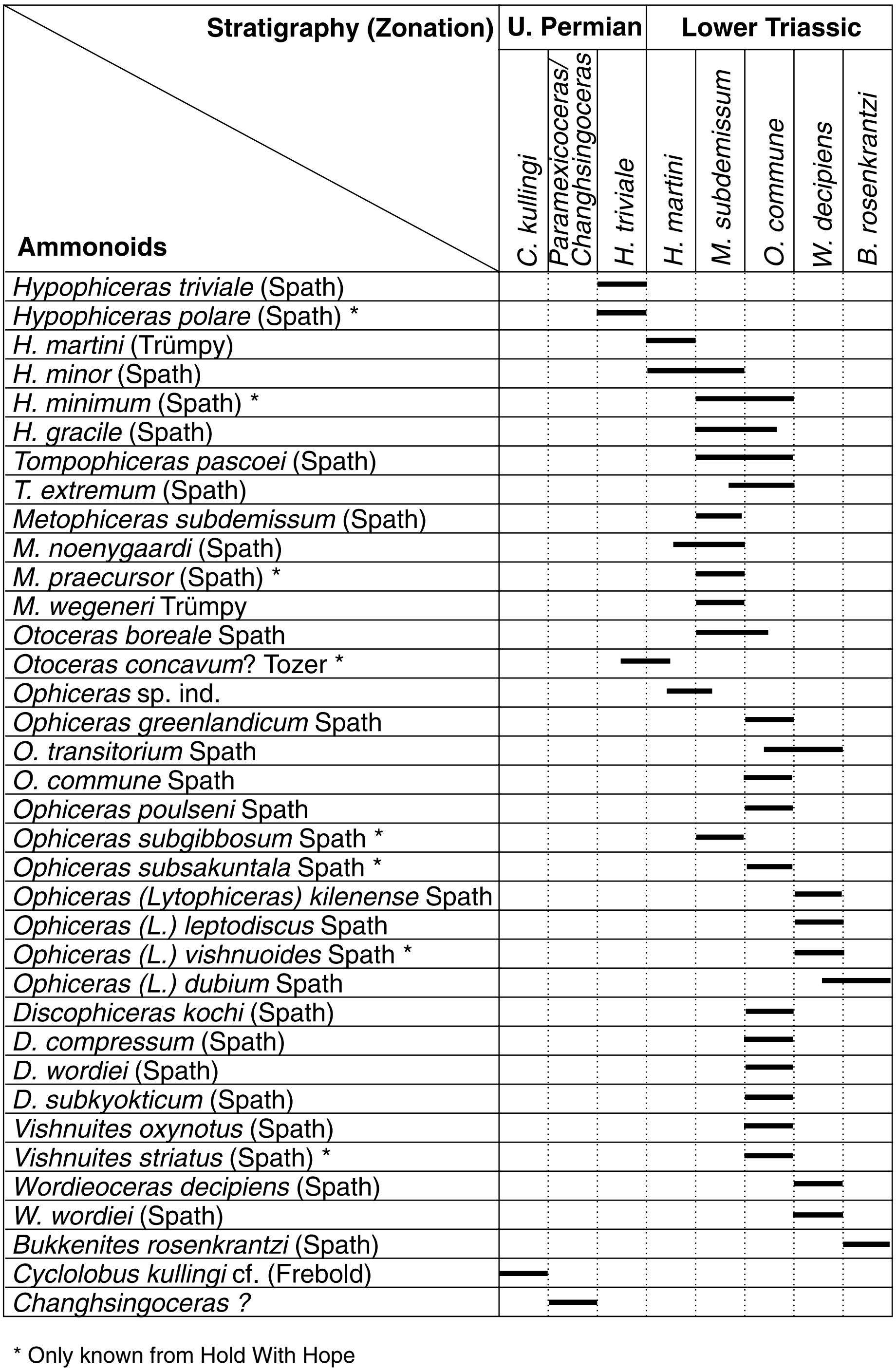

Figure 5. Ammonoid range chart mainly based on fossil collections from northern Jameson Land and Traill Ø. The species marked with an asterisk are only known from Hold With Hope (Spath, 1935).

dealt with in further detail. The Changhsingian age of the strata containing the ammonoids tentatively referred to *Changhsingoceras*? is indicated by palynological data (Stemmerik, Bendix-Almgreen & Piasecki, 2001). The ammonoid zonation of the uppermost Permian–Lower Triassic is based on Spath (1935) and Trümpy (1969) and the terminology is updated after Tozer (1994) and Dagys & Ermakova (1996). A range chart based on ammonoid collections from northern Jameson Land and Traill Ø and a correlation scheme of boreal ammonoid zonations are presented in Figures 5 and 6. Key specimens of the generally poorly preserved and poorly documented ammonoid fauna of northern Jameson Land and Traill Ø are illustrated in Figures 7 and 8, whereas the rich and mainly well-preserved Hold With Hope fauna has been documented by Spath (1930, 1935). The six ammonoid zones recognized in the Wordie Creek Formation of

		East Greenland (Trümpy 1969, this paper)	Arctic Canada, Sverdrup basin (Tozer 1994)	Svalbard (Weitschat & Dagys 1989)	Northeast Asia (Dagys & Weitschat 1993, Dagys & Ermakova 1996)
Lower Induan	Dienerian				*Kingites(?) korostelevi*
					Vavilovites turdigus: *V. umbonatus* / *V. subtriangularis*
			Vavilovites sverdrupi		*Vavilovites sverdrupi*
			Proptychites candidus		
	Griesbachian	*Bukkenites rosenkrantzi*	*Bukkenites strigatus*	*Bukkenites rosenkrantzi*	*Wordieoceras decipiens*
		Wordieoceras decipiens	*Ophiceras commune*		
		Ophiceras commune		*Otoceras boreale*	*Tompophiceras morpheus*
		Metophiceras subdemissum	*Otoceras boreale*		*Tompophiceras pascoei*
					Otoceras boreale
		Hypophiceras martini	*Otoceras concavum*		*Otoceras concavum*
C.		*Hypophiceras triviale*			

Figure 6. Correlation of ammonoid zonations from East Greenland, Arctic Canada (Standard Zonation of the Boreal Realm), Svalbard and Northeast Asia (eastern Verkhoyansk). The Griesbachian and Dienerian are equivalent to the Induan, which is used in northeastern Asia. C. – Changhsingian. Modified from Dagys & Weitschat (1993) and Dagys & Ermakova (1996).

Hold With Hope, the *Hypophiceras triviale, Hypophiceras martini, Metophiceras subdemissum, Ophiceras commune, Wordieoceras decipiens* and *Bukkenites rosenkrantzi* zones and the overlying *Anodontophora breviformis* and *A. fassaensis* bivalve zones, can be used for regional correlation in the East Greenland basin. The *H. martini* to *B. rosenkrantzi* zones are widely distributed in the area, whereas sediments included in the *H. triviale* Zone have a more limited occurrence. The bivalve zones are only known from the northern part of the basin. The East Greenland ammonoid zonation has a relatively high stratigraphical resolution and its use is therefore preferred here; the zones are correlated with the Canadian, Svalbard and Siberian zonations of the Boreal Realm in Figure 6.

4.a. *Hypophiceras triviale–Hypophiceras martini* zones

The zones are characterized by a few species only, and specimens are rare and normally not well preserved. The zones are therefore combined in this description. The combined thickness of the two zones is up to 260 m. The *H. triviale* Zone contains *H. triviale* (Spath) and *H. minor* (Spath), whereas the *H. martini* Zone contains *H. martini* Trümpy, *H. minor, Metophiceras noenygaardi* (Spath) and *Ophiceras* sp. ind. Species of *Otoceras* are not recorded from these zones in Jameson Land and Traill Ø, but fragmented specimens assigned to *Otoceras* sp. ind. showing a rather inflated whorl section with flat sides have been described from Hold With Hope (Spath, 1935). These specimens occur stratigraphically many tens of metres below the level with abundant *Otoceras boreale* and they probably belong to *Otoceras concavum* Tozer of Dagys & Ermakova (1996). *Hypophiceras polare* (Spath) has also been described from the *H. triviale* Zone at Hold With Hope (Spath, 1935). The index species of the two zones have not been found elsewhere in the Boreal Realm, suggesting a relatively high level of endemism at that time.

4.b. *Metophiceras subdemissum* Zone

The diversity of the ammonoid assemblage in this zone has increased to five genera and about 15 species. The specimens are abundant and commonly well preserved in concretions. The zone is 15–100 m thick. The recorded species are *H. minor, H. gracile* (Spath), *T. extremum* (Spath), *Tompophiceras pascoei* (Spath), *Otoceras boreale* Spath, *Metophiceras subdemissum* (Spath), *M. noenygaardi, M. wegeneri* Trümpy and rare *Ophiceras commune* Spath. *Tompophiceras serpentinum* (Spath), *T. subextremum* (Spath), *T. nielseni* (Spath), *Metophiceras praecursor* (Spath), *Ophiceras* sp., *Ophiceras ligatum* (Spath) and *Ophiceras chamunda* Diener have also been recorded from this zone at Hold With Hope (Spath, 1935).

The *M. subdemissum* Zone can be correlated with the *O. boreale* Zone of Arctic Canada (Sverdrup Basin), where *Hypophiceras gracile* (Spath) and *Otoceras boreale* Spath are common. Correlation with the Tethyan Realm can be made on the genus level by the probably cosmopolitan *Otoceras* and *Ophiceras* (Teichert, 1990; Dagys, 1988; Hallam & Wignall, 1997).

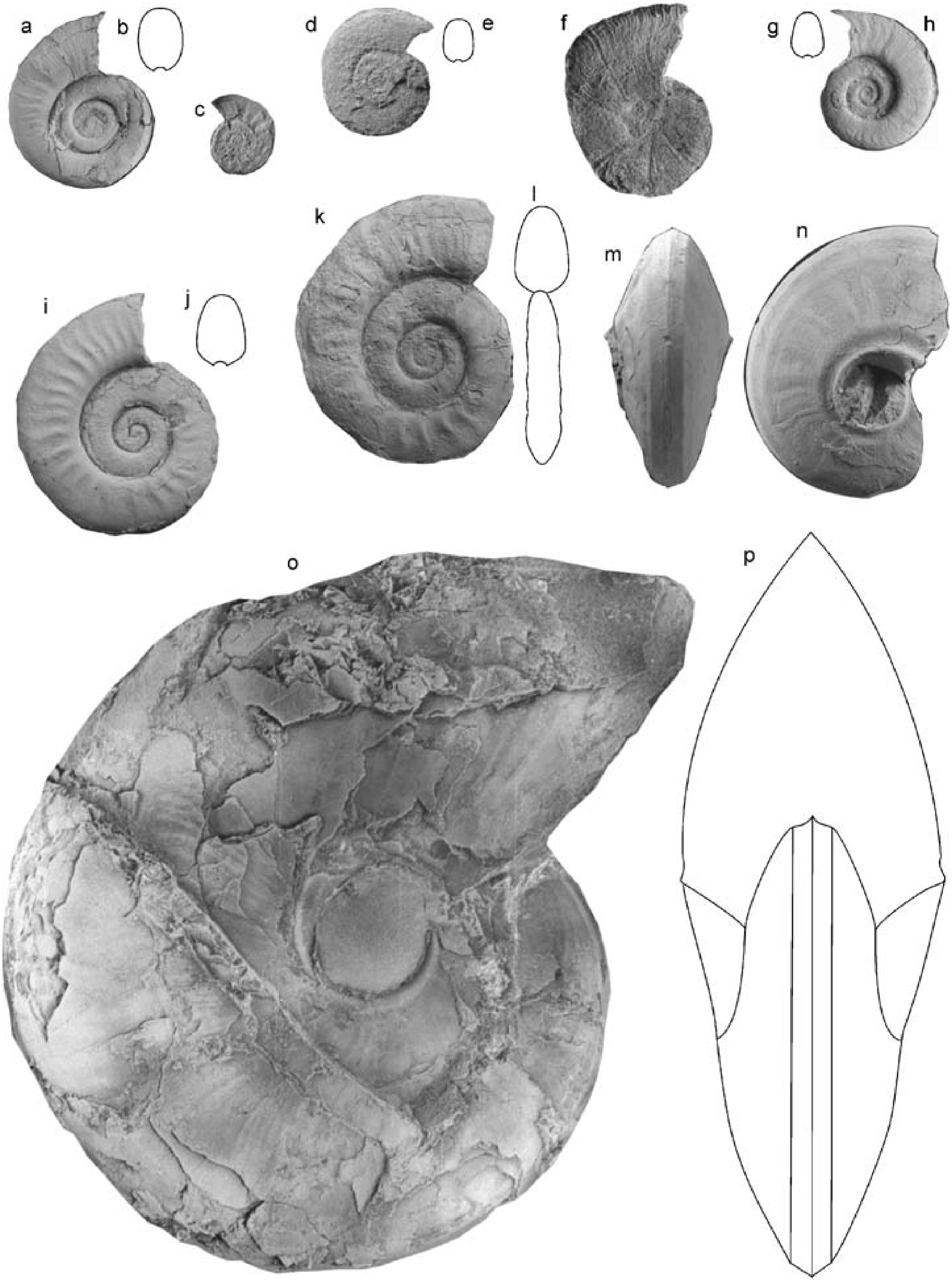

Figure 7. Ammonoids from Permian and *H. triviale–O. commune* zones of East Greenland (all in natural size). (a, b) *Hypophiceras minor* (Spath), adult specimen, *O. commune* Zone, Aggersborg, northern Jameson Land (GGU 423887); (c) *Hypophiceras triviale* (Spath), imprint in shale, *H. triviale* Zone, Oksedal, northern Jameson Land (GGU 423841); (d, e) *Hypophiceras martini* (Spath), *H. martini* Zone, Svinhufvud Bjerge, Traill Ø (GGU 443068); (f) *Changhsingoceras*? sp., cast of mould, juvenile specimen, Svinhufvud Bjerge, Traill Ø (GGU 423822); (g, h) *Metophiceras subdemissum* Spath, juvenile specimen, *M. subdemissum* Zone, Walter Martin Bjerg, Wegener Halvø (GGU 449614); (i, j) *Hypophiceras gracile* (Spath), adult specimen, combined *M. subdemissum–O. commune* Zone, Walter Martin Bjerg, Wegener Halvø (GGU 449622); (k, l) *Tompophiceras pascoei* (Spath), adult specimen, *O. commune* Zone, Paradigmabjerg, Wegener Halvø (GGU 423941); (m, n) *Otoceras boreale* Spath, juvenile specimen, *M. subdemissum* Zone, Walter Martin Bjerg, Wegener Halvø (GGU 449615); (o, p) *Otoceras boreale* Spath, *M. subdemissum* Zone, Paradigmabjerg, Wegener Halvø (GGU 423925).

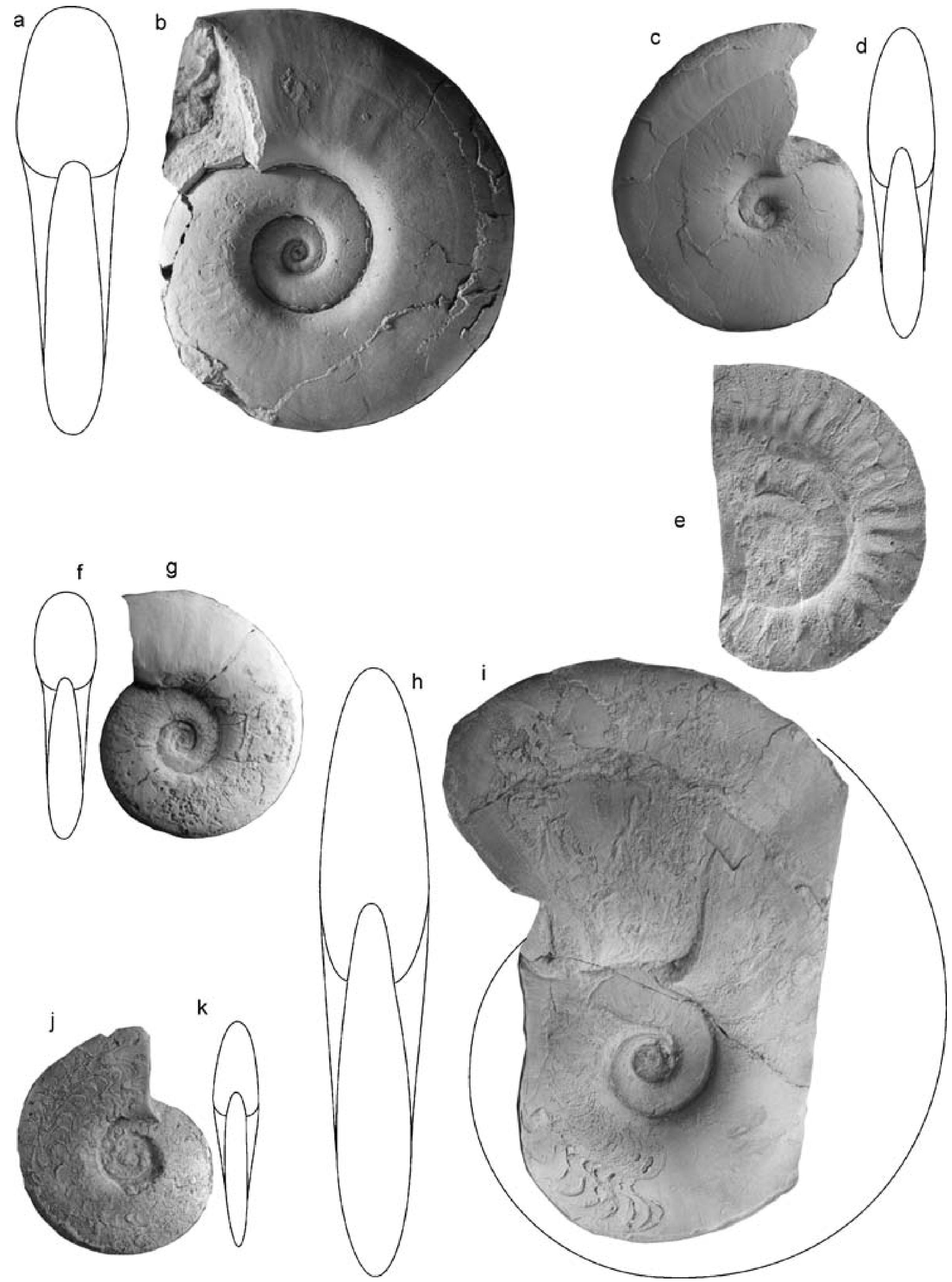

Figure 8. Ammonoids from the *M. subdemissum–W. decipiens* zones of East Greenland (all in natural size). (a, b) *Ophiceras commune* Spath, adult specimen, *O. commune* Zone, Lille Cirkusbjerg, Wegener Halvø (GGU 423971); (c, d) *Discophiceras subkyokticum* (Spath), *O. commune* Zone, Oksedal, northern Jameson Land (GGU 423868); (e) *Tompophiceras pascoei* (Spath), mould, *O. commune* Zone, Paradigmabjerg, Wegener Halvø (GGU 423950B); (f, g), *Metophiceras noenygaardi* Spath, *M. subdemissum* Zone, Aggersborg, northern Jameson Land (GGU 423904); (h, i) *Discophiceras wordiei* (Spath), *O. commune* Zone, Aggersborg, northern Jameson Land (GGU 423880); (j, k) *Wordieoceras decipiens* (Spath) juvenile with the ventral area slightly weathered, *W. decipiens* Zone, Lille Cirkusbjerg, Wegener Halvø (GGU 423983).

4.c. *Ophiceras commune* Zone

This zone is widely distributed, 20–150 m thick, and contains the most diverse ammonoid assemblage with seven genera. *Ophiceras commune* is by far the most abundant species. Other common species include *Ophiceras greenlandicum* Spath*, Tompophiceras pascoei, Discophiceras wordiei* (Spath) and *D. subkyokticum* (Spath). Rare species are *Otoceras boreale, H. minor, H. gracile, H. serpentinum* (Spath)*, D. kochi* (Spath)*, D. compressum* (Spath)*, Ophiceras (Acanthophiceras) poulseni* Spath*, Vishnuites oxynotus* (Spath) and *Wordieoceras decipiens* (Spath). In addition, *Ophiceras subsakuntala* (Spath)*, Ophiceras L. kilenense* (Spath)*, Vishnuites striatus* (Spath) and *Hypophiceras minimum* (Spath) have been recorded from Hold With Hope (Spath, 1935).

Ophiceras commune Spath, *Ophiceras greenlandicum* Spath*, Discophiceras wordiei* (Spath) and *Wordieoceras decipiens* (Spath) are also found in Arctic Canada. *W. decipiens* was included in *W. wordiei* by Tozer (1994) but we consider it as a separate species. On a genus level, *Ophiceras* and possibly *Tompophiceras* are in common with the Tethyan Realm (Teichert, 1990; Dagys, 1988; Hallam & Wignall, 1997).

4.d. *Wordioceras decipiens* Zone

The ammonoid diversity is reduced compared to the two underlying zones and the specimens are commonly less well preserved and relatively rare. The zone is up to 350 m thick and widely distributed, but the original three-fold subdivision of the zone into lower, middle and upper beds (Spath, 1935) is not substantiated by this study. The recorded species include *Wordieoceras decipiens, W. wordiei* (Spath)*, Ophiceras transitorium* Spath*, Ophiceras (L.) kilenense* Spath and *Ophiceras (L.) leptodiscus* Spath. Rare species are *Ophiceras commune* and *Ophiceras (Lytophiceras) dubium* Spath. *Bukkenites grandis* (Spath) and *B. subdiscoides* (Spath) are also recorded from the zone at Hold With Hope. *Bukkenites* possibly includes species referred to as *Proptychites* by Tozer (1994).

The *W. decipiens* Zone is also recognized in Siberia with the same index species. It can probably be correlated with the *B. strigatus* Zone in the Sverdrup Basin as both zones contain *W. wordiei* and species assigned to *Bukkenites* (Spath, 1935; Tozer, 1994; Dagys & Ermakova, 1996).

4.e. *Bukkenites rosenkrantzi* Zone

The zone marks the top of the ammonoid-bearing part of the Triassic succession in East Greenland; it is up to 80 m thick. At Svinhufvud Bjerge on Traill Ø the zone is represented by *Ophiceras (L.) dubium.* According to Waterhouse (1994), the species should possibly be assigned to the genus *Mesokantoa* Waterhouse, but firm generic designation awaits further taxonomic studies. The index species *Bukkenites rosenkrantzi* (Spath) and other species of *Bukkenites* are common at Hold With Hope but rare further south. Only two localities on Traill Ø (Månedal and Svinhufvud Bjerge) have yielded a few specimens of this genus (Putallaz, 1961). The *B. rosenkrantzi* Zone is also present on Svalbard (Weitschat & Dagys, 1989). In East Greenland the zone clearly characterizes an interval above the *W. decipiens* Zone and it may correlate with the upper part of the *B. strigatus* Zone of the Sverdrup Basin, or more likely with an interval above this zone. The base of the *B. rosenkrantzi* Zone corresponds to the base of the palynologically defined *Densoisporites* assemblage zone at Hold With Hope, which correlates to Assemblage O in the Barents Sea (Hochuli, Colin & Vigran, 1989).

4.f. *Anodontophora breviformis* Zone

This zone is defined by the presence of the bivalve *Anodontophora breviformis* Spath; it is up to 150 m thick. It has not yielded any ammonoids and is confined to Svinhufvud Bjerge on Traill Ø and Hold With Hope. It has not been identified outside East Greenland.

4.g. *Anodontophora fassaensis* Zone

This zone is also a bivalve zone and has not yielded any ammonoids. It has only been described from Hold With Hope, where it is up to 100 m thick. It contains *A. fassaensis* (Wissmann) and *Myalina kochi* Spath (Spath, 1930, 1935). Strata belonging to the *A. breviformis–A. fassaensis* zones are included in the *Densoisporites* assemblage zone at Hold With Hope.

5. Structural and sedimentological evolution

Deposition of the Upper Permian–Lower Triassic succession took place in the connected marine Hold With Hope, Traill Ø, northern Jameson Land and Wegener Halvø subbasins (Seidler *et al.* 2004). The subbasins are half-grabens showing greatest subsidence towards the western basin margin formed by the Post-Devonian–Stauning Alper Fault System. Two rift events took place during deposition of the Wordie Creek Formation and are dated to the *H. martini* and *W. decipiens* Zone times, respectively (Seidler *et al.* 2004).

5.a. Hold With Hope subbasin

The main outcrops on the north coast of Hold With Hope occupy a central position on a westward tilted fault block on which the Wordie Creek Formation thickens towards the west to more than 650 m. The upper part of the Foldvik Creek Group, the Schuchert Dal Formation and correlative strata are missing at Hold With Hope, and the Wordie Creek Formation

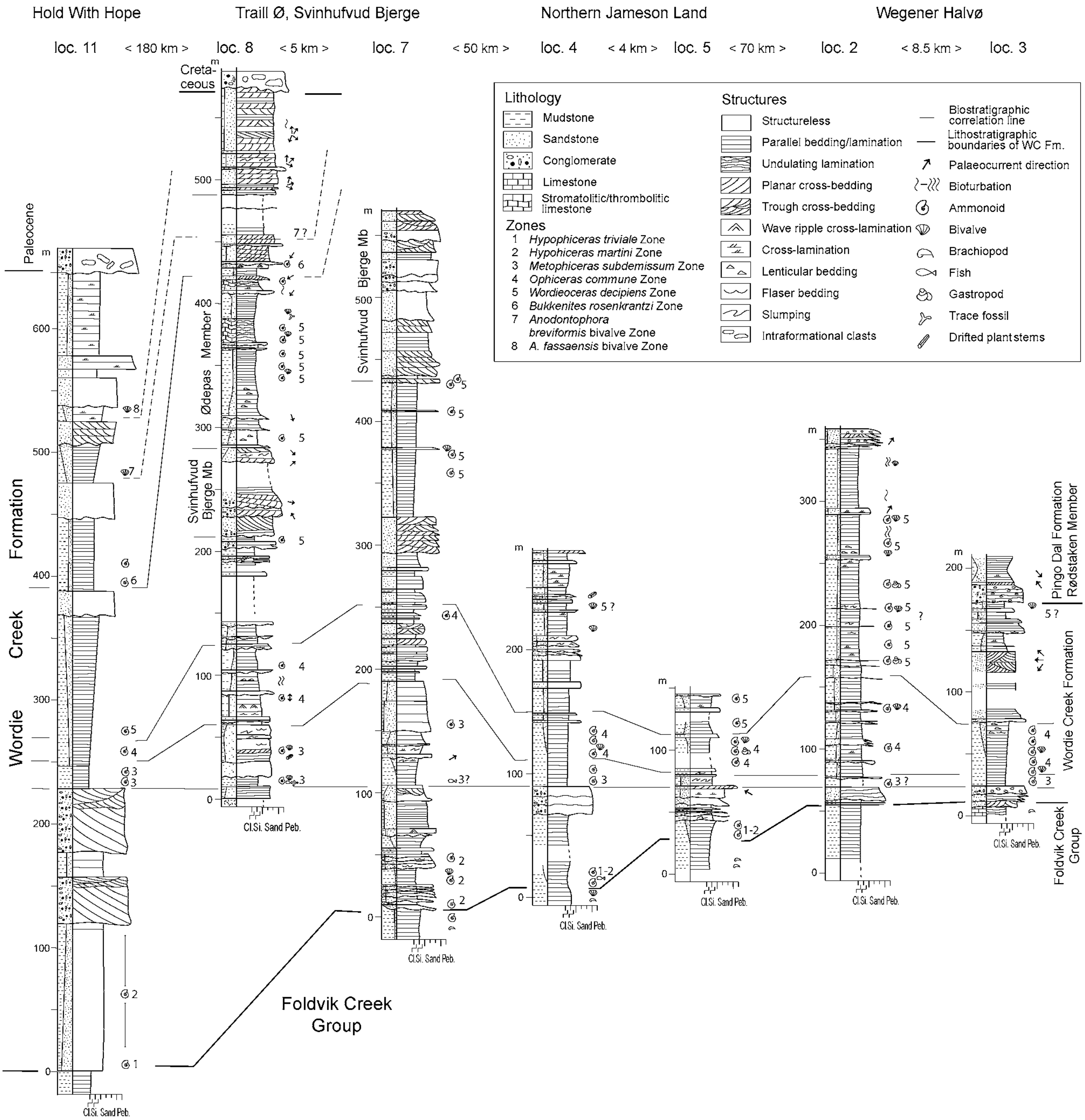

Figure 9. Sections through the 'Permian–Triassic boundary interval' of Stemmerik, Bendix-Almgreen & Piasecki (2001) and the Wordie Creek Formation. The profile is hung on the base of the *M. subdemissum* Zone, which corresponds to a major flooding surface. Note the thickness variations in the *H. triviale–H. martini* zones and in the *W. decipiens* Zone. The *A. fassaensis* Zone is only known from Hold With Hope.

rests directly on black mudstones of the Ravnefjeld Formation (Fig. 9). The top of the Ravnefjeld Formation is reddish due to weathering, reflecting prolonged latest Permian subaerial exposure. It is overlain by greenish silty mudstones and fine-grained sandstones with *Hypophiceras triviale*.

5.a.1. Hypophiceras triviale–H. martini *zones*

At Hold With Hope the combined zones form a wedge-shaped unit of fine-grained sandstones and mudstones thinning from west to east from more than 250 m to 140 m. The upper part of the succession is characterized by two prograding fan delta conglomerates, each 30–40 m thick.

5.a.2. Metophiceras subdemissum–Ophiceras commune *zones*

The base of the combined zones is marked by a sharp boundary between fan delta conglomerates and sandstones and black marine mudstones. Upwards the mudstones gradually pass into interbedded silty mudstones and thin turbidite sandstones. Ammonoids are mainly preserved in concretions in the lower part of the succession and as filled body chambers in sandstone beds higher in the succession. The total thickness of the combined *M. subdemissum–O. commune* zones is approximately 40 m.

5.a.3. Wordieoceras decipiens *Zone*

This zone is represented by offshore mudstones and thin sandstone turbidites in the lower part and a prominent unit of canyon-filling marine density flow sandstones in the upper part. The zone varies from 100 to 150 m in thickness.

5.a.4. Bukkenites rosenkrantzi *Zone*

This zone is also represented by a lower fine-grained unit of mainly offshore mudstones overlain by a thick nearshore sandstone-dominated unit. Ammonoids are restricted to the basal part of the mudstones.

5.a.5. Anodontophora breviformis–A. fassaensis *zones*

These zones reflect a gradual transition from offshore mudstones and sandy turbidites to more shallow marine siltstones and sandstones. The combined zones are up to 210 m thick. The *A. fassaensis* Zone is erosionally overlain by Cretaceous and Palaeogene sediments.

5.a.6. Permian–Triassic transition

The Permian–Triassic boundary at Hold With Hope has been much debated due to the occurrence of supposedly reworked Permian fossils in the lower part of the Wordie Creek Formation. The redefinition of the period boundary means that the important hiatus between the Ravnefjeld Formation and the Wordie Creek Formation is of latest Permian, intra-Changhsingian age, and that the basal part of the Wordie Creek Formation is of latest Permian age. The basal Wordie Creek Formation was deposited during block faulting and westward tilting of the Hold With Hope–Clavering Ø block and a rise in relative sea level over the hangingwall. Shelf mudstones and fine-grained sandstones were deposited during the early *Hypophiceras* zones times, and coarse-grained fan deltas prograded southward due to falls in relative sea level during late *Hypophiceras martini* Zone time. The subbasin deepened at the onset of *M. subdemissum* Zone time, and deposition of offshore mud and thin sandy turbidites characterized the subbasin to the end of *A. breviformis* Zone time. Marine Early Triassic deposition continued longer at Hold With Hope than anywhere else in central East Greenland, and shallow marine sandstones and red siltstones characterize the *A. fassaensis* Zone (Fig. 10).

5.b. Traill Ø subbasin

The sections at Svinhufvud Bjerge along the south coast of Traill Ø occupy a central position in the subbasin (Fig. 1) and the Wordie Creek Formation is about 850 m thick. Two sections were measured 3 km apart. The western coastal section contains the Permian–Triassic transition, whereas the Triassic middle and upper parts of the Wordie Creek Formation are exposed at Ødepas (Figs 1, 4, 9). The fossils recorded from the two localities are listed in Table 1. The lowest part of the Wordie Creek Formation is exposed at Rold Bjerge, northern Traill Ø.

At Svinhufvud Bjerge the Upper Permian is represented by black mudstones of the Ravnefjeld Formation, gradually passing upward into grey silty mudstones of the Oksedal Member (Schuchert Dal Formation), of which 35 m are preserved. Juvenile specimens possibly referred to a cyclolobid ammonoid *Changsingoceras* were found 3 m below the top of the member (Figs 7, 9). The Wordie Creek Formation erosionally overlies the Oksedal Member, and the boundary is marked by the base of a 6 m wide and 1.5 m thick turbidite channel-fill sandstone that is overlain by mudstone with *Hypophiceras* sp. of the *Hypophiceras* zones.

5.b.1. Hypophiceras triviale–H. martini *zones*

At Svinhufvud Bjerge these zones consist of basinal mudstone with three intervals of turbidite sandstone forming an approximately 100 m thick succession with scattered occurrences of poorly preserved ammonoids and other fossils (Figs 9, 10). At Rold Bjerge only the top part of the zones is present and consists of a succession of yellow turbidite sandstones that is 30 m thick. The *H. triviale* Zone has not been identified and is probably missing in the studied Traill Ø sections.

5.b.2. Metophiceras subdemissum–Ophiceras commune *zones*

The base of the combined zones at Rold Bjerge and Svinhufvud Bjerge is characterized by dark grey to black mudstones, which pass upwards into greenish mudstones and include intercalations of turbidite sandstones, the total being up to 40 m thick. Ammonoids are preserved in concretions, especially in the lower part of the succession, as imprints on mudstone bedding planes, and as filled body chambers with compressed phragmocones in turbidite sandstone beds. At Rold Bjerge the lowest 6 m of the mudstones contain imprints of the ammonoids *Hypophiceras minor, Hypophiceras* sp., *Metophiceras noenygaardi, Metophiceras* sp. and *Ophiceras* sp. The total thickness of the combined *M. subdemissum–O. commune* zones is 100 m in in this area.

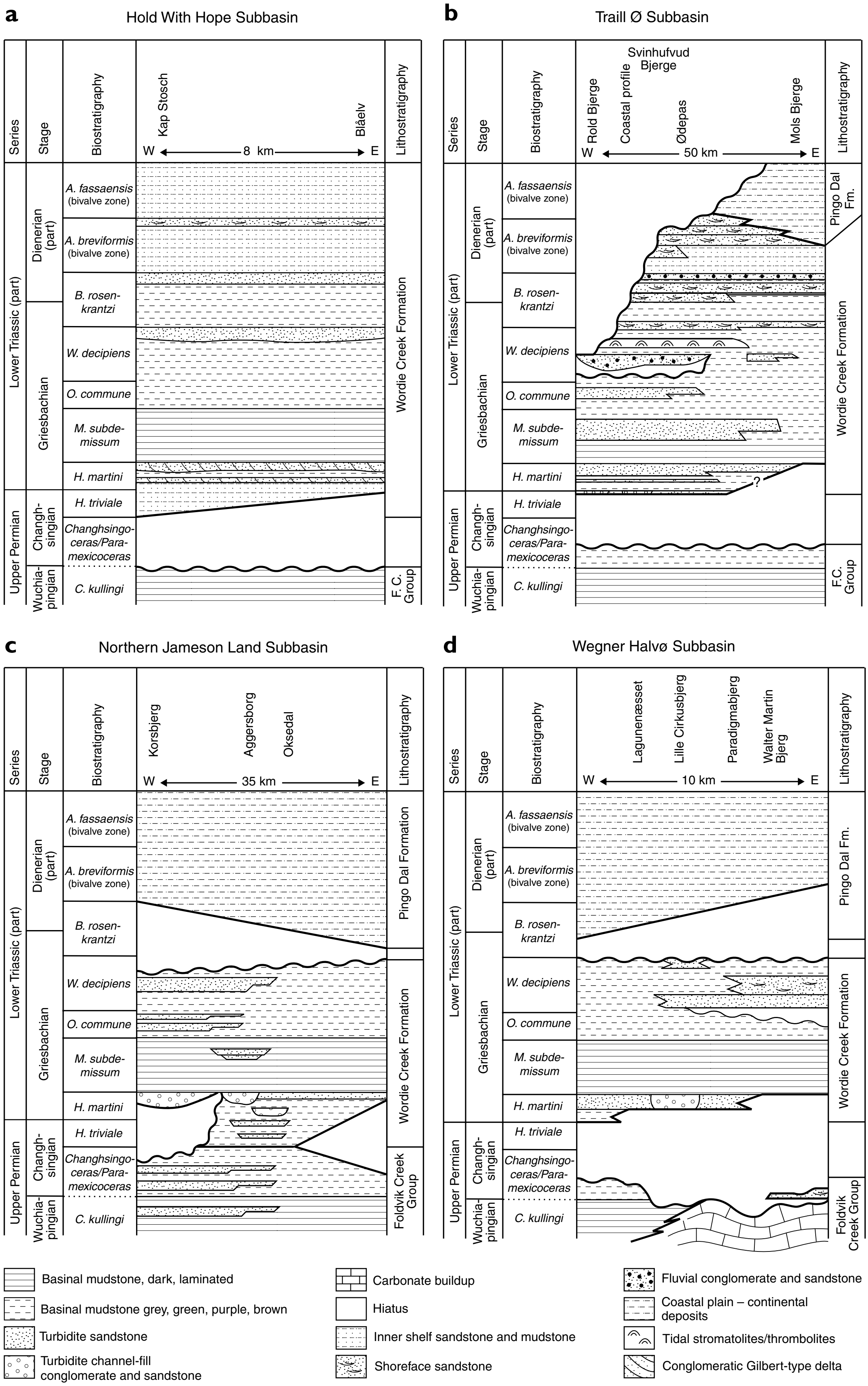

Figure 10. Stratigraphy and depositional environments across the upper Permian–lower Triassic boundary in the East Greenland subbasins. (a) Hold with Hope subbasin; (b) Traill Ø subbasin; (c) Northern Jameson Land subbasin; (d) Wegener Halvø subbasin.

5.b.3. Wordieoceras decipiens *Zone*

At Svinhufvud Bjerge the base of the zone is represented by a 100 m thick interval of greenish grey mudstones erosionally overlain by a 125 m thick fluvial conglomerate, belonging to the Svinhufvuds Bjerge Member. The conglomerate is overlain by greenish-grey marine mudstones interbedded with up to 19 m of stromatolitic mound-forming carbonates and thrombolitic biostromes associated with calcareous shoreface sandstones of the Ødepas Member (Fig. 4). Ammonoids occur in the marine parts of the interval as imprints or as filled body-chambers.

5.b.4. Bukkenites rosenkrantzi *Zone*

At Svinhufvud Bjerge the zone consists of about 25 m of tidally influenced upper shoreface sandstones and shallow marine mudstones. At Månedal the zone is represented by shallow marine mudstones (Putallaz, 1961). Svinhufvud Bjerge is the southernmost location in the basin where *B. rosenkrantzi* has been recorded.

5.b.5. Anodontophora breviformis *Zone*

At Svinhufvud Bjerge this zone is represented by 100 m of predominantly tidally influenced shallow marine sandstones with very few fossils. At Månedal *A. breviformis* occurs in grey shallow marine mudstones overlain by 20 m of pebbly sandstones. The zone marks the top of fully marine Lower Triassic deposits in the Traill Ø subbasin. At Svinhufvud Bjerge the zone is erosionally overlain by Cretaceous conglomerates with clasts up to 5 m across.

5.b.6. The Permian–Triassic transition

The Permian–Triassic boundary in the Traill Ø subbasin is developed as an important unconformity, spanning the upper part of the Upper Permian Changhsingian Stage, including the *H. triviale* Zone. Offshore basinal mudstones and turbidite sandstones were deposited during the time of the *H. martini* Zone, and the base of the *M. subdemissum* Zone is represented by a prominent flooding surface (Figs 9, 10). Deposition of offshore mudstones with intercalated intervals of turbidite sandstone continued through *O. commune* Zone time with a gradually shallowing-upward transition into the *W. decipiens* Zone. The fluvial interval of *W. decipiens* Zone age marks an important tectonic event in the subbasin (Seidler *et al*. 2004). The shallowing-upward trend continued through *B. rosenkrantzi* and *A. breviformis* Zone times with deposition of the shallow marine stromatolitic carbonate mounds and sandstones.

The thickest succession of the Wordie Creek Formation in East Greenland occurs in the Svinhufvud Bjerge area, reflecting high rates of subsidence and sedimentation. The western coastal section is situated in a more proximal setting than the Ødepas section, as indicated by thicker turbiditic sandstone beds and greater thickness of the fluvial Svinhufvuds Bjerge Member (Fig. 9).

5.c. Northern Jameson Land subbasin

The Oksedal and Aggersborg sections are situated in the western central part of the subbasin where the Wordie Creek Formation is up to 280 m thick (Figs 1, 9, 10). The Aggersborg section is located 3.5 km west of Oksedal. Korsbjerg is situated closer to the western basin margin and here the Wordie Creek Formation is 170 m thick. The fossils recorded from these localities are listed in Table 1. The Oksedal section was probably measured at the same location as the OK 3 section of Wignall & Twitchett (2002).

In the central part of the basin the Upper Permian is represented by dark-grey bioturbated mudstone with thin fine-grained sandstone beds of the Oksedal Member (Schuchert Dal Formation). At Oksedal, the base of the Wordie Creek Formation is placed at the transition from dark-grey mudstone to greenish grey and brown mudstones with abundant sandstone beds. A fine-grained turbidite, 20 cm thick, occurs approximately 6 m above the base of this unit and the FAD of *H. triviale* is situated 5 m higher in the section.

At the Aggersborg section, the Permian–Triassic transition shows a similar development. The first appearance of *Hypophiceras* sp. followed by *H. triviale* occurs within 5 m of a slightly upward-coarsening succession from grey to grey-green mudstone (Fig. 9). At Korsbjerg the Upper Permian grey mudstones of the Oksedal Member are overlain erosionally by a 30 m thick conglomerate with ammonoids of the *H. martini* Zone in the uppermost part.

5.c.1. Hypophiceras triviale–martini *zones*

At Oksedal and Aggersborg, the *H. triviale* Zone consists of a slightly upward-coarsening interval of basinal dark grey mudstones passing into green and brown mudstones with thin sandstone turbidites (Fig. 9). Ammonoids are preserved as imprints on mudstone bedding planes. The top part of the *H. martini* Zone is marked by incised valleys or canyons filled with conglomeratic density flow deposits, which mark the base of the Triassic at Korsbjerg. The thickness of the combined zones varies from 30 m at the basin margin to 80 m in the basinal settings.

5.c.2. M. subdemissum–O. commune *zones*

The base of the *M. subdemissum* Zone is sharp and marked by dark grey to black mudstones, which over an interval of 25 m pass upwards into grey and greenish

Table 1. Fossils recorded from the studied localities

Zonation	Ammonoids	Other fossils
Svinhufvud Bjerge, Traill Ø, localities 7, 8 in Figure 1		
B. rosenkrantzi	*Ophiceras (Lytophiceras) dubium* Spath *Wordieoceras* sp.	*Myalina* aff. *schamarae* Bittner
W. decipiens	*Wordieoceras decipiens* (Spath) *W. wordiei* (Spath) *Wordieoceras* sp.	*Claraia* sp. *Myalina* sp. *Myalina* aff. *schamarae* Bittner
O. commune	*Ophiceras commune* Spath *O. commune* var. *evolvens* Spath	
M. subdemissum	*Hypophiceras* sp. *Tompophiceras pascoei* (Spath) *Metophiceras noenygaardi* (Spath) *M. subdemissum* (Spath)	*Lingula borealis* Bittner *Laugia groenlandica* Stensiö *Glaucolepis arctica* Stensiö
H. martini	*Hypophiceras martini* (Spath) *H. minor* (Spath) *Metophiceras noenygaardi* (Spath)	*Claraia* sp.
Paramexicoceras/Changhsingoceras	*Changhsingoceras?*	*Martinia greenlandica* Dunbar
Oksedal, northern Jameson Land, locality 5 in Figure 1		
W. decipiens	*Wordieoceras* sp.	*Claraia* sp.
O. commune	*Ophiceras commune* Spath *Discophiceras subkyokticum* (Spath) *D. wordiei* (Spath) *Hypophiceras gracile* (Spath)	*Naticopsis arctica* Spath *Claraia* sp.
M. subdemissum	*Hypophiceras* sp. *Tompophiceras pascoei* (Spath) *Metophiceras noenygaardi* (Spath) *M. subdemissum* (Spath)	*Lingula borealis* Bittner *Laugia groenlandica* Stensiö *Glaucolepis arctica* Stensiö
H. martini	*Hypophiceras minor* (Spath)	
H. triviale	*Hypophiceras minor* (Spath) *H. triviale* (Spath)	*Claraia* sp.
Paramexicoceras/Changhsingoceras		*Martinia greenlandica* Dunbar
Aggersborg, northern Jameson Land, locality 4 in Figure 1		
W. decipiens	*Ophiceras commune* Spath	*Claraia* sp.
O. commune	*Discophiceras wordiei* (Spath) *D. kochi* (Spath)	*Claraia* sp.
M. subdemissum	*Hypophiceras minor* (Spath) *Metophiceras subdemissum* (Spath) *M. wegeneri* Trümpy *Ophiceras commune* Spath	*Lingula borealis* Bittner *Glaucolepis arctica* Stensiö *Broughia perleididoides* Stensiö
H. martini	*Hypophiceras minor* (Spath)	
H. triviale	*Hypophiceras minor* (Spath) *H. triviale* (Spath)	*Claraia* sp. *Laugia groenlandica* Stensiö
Paramexicoceras/Changhsingoceras		*Lisotella* sp.
Korsbjerg, northern Jameson Land, locality 6 in Figure 1		
W. decipiens		*Claraia* sp.
O. commune	*Ophiceras commune* Spath *O. commune* var. *aperta* Spath *Discophiceras wordiei* (Spath) *D. kochi* (Spath) *D. subkyokticum* (Spath) *Hypophiceras gracile* (Spath) *H. minor* (Spath) *Vishnuites oxynotus* Spath *Wordieoceras* cf. *wordiei* (Spath)	*Claraia* sp.
M. subdemissum	*Otoceras boreale* Spath *Hypophiceras gracile* (Spath) *Tompophiceras pascoei* (Spath) *Ophiceras commune* Spath	*Claraia* sp. *Bellerophon borealis* Spath
H. martini	*Hypophiceras* cf. *martini* (Spath)	*Claraia* sp.
Paramexicoceras/Changhsingoceras		*Lisotella* sp.

Table 1. (*Contd.*)

Zonation	Ammonoids	Other fossils
Paradigmabjerg, Wegener Halv Ø, locality 3 in Figure 1		
W. decipiens	*Wordieoceras* sp. juv.	*Claraia* sp.
O. commune	*Ophiceras commune* Spath *O. poulseni* (Spath) *Discophiceras wordiei* (Spath) *D. kochi* (Spath) *D. subkyokticum* (Spath) *Wordieoceras decipiens* (Spath) *Hypophiceras gracile* (Spath) *H. minor* (Spath) *Tompophiceras extremum* (Spath) *T. pascoei* (Spath)	*Claraia* sp. *Perleidus stoschiensis* Stensiö
M. subdemissum	*Otoceras boreale* Spath *Hypophiceras minor* (Spath)	 *Claraia* sp.
C. kullingi		*Pleurohorridonia scoresbyensis* Dunbar
Lille Cirkusbjerg, Wegener Halv Ø, locality 2 in Figure 1		
W. decipiens	*Wordieoceras decipiens* (Spath) *W. decipiens* var. *discoidea* (Spath) *W. wordiei* (Spath) *Wordieoceras* sp. juv. *Ophiceras (Lytophiceras) dubium* Spath	*Claraia* sp. *Myalina* aff. *schamarae* Bittner *Myalina* sp. *Naticopsis arctica* Spath *Bellerophon borealis* Spath
O. commune	*Ophiceras commune* Spath *O. poulseni* (Spath) *Discophiceras wordiei* (Spath) *D. kochi* (Spath) *D. subkyokticum* (Spath) *O. greenlandicum* Spath *Wordieoceras decipiens* (Spath) *Hypophiceras gracile* (Spath)	*Claraia* sp.
M. subdemissum	*Otoceras boreale* Spath *Hypophiceras minor* (Spath)	*Claraia* sp.

mudstones of the *O. commune* Zone. Abundant concretions at several levels contain well-preserved ammonoids, bivalves and occasional fish. The combined thickness of the two zones varies between 50 and 100 m.

5.c.3. W. decipiens *Zone*

The zone consists of a shallowing-upward succession of grey, green to brown mudstones with metre-thick sandstone beds and a prominent conglomerate, 25 m thick. The zone marks the upper part of the marine Wordie Creek Formation in this subbasin and is overlain by reddish coastal plain and continental sandstones of the Pingo Dal Formation with an angular unconformity (Fig. 10). Only a few ammonoids preserved as imprints in mudstones or as partly filled body chambers were collected in the Wordie Creek Formation.

5.c.4. The Permian–Triassic transition

The sections studied in the Jameson Land basin represent a transition from a position relatively close to the basin margin (∼ 5 km) represented at Korsbjerg to more basinward settings at Aggersborg and Oksedal (20–30 km). Sedimentation was continuous across the Permian–Triassic boundary at Oksedal and Aggersborg and the localities show a similar development to the Fiskegrav section at the eastern side of Schuchert Dal (Fig. 11) (Stemmerik, Bendix-Almgreen & Piasecki, 2001; Twitchett *et al.* 2001). The conglomerate forming the base of the Triassic at Korsbjerg can be traced further out into the basin and represents a period of faulting and uplift of basin margins (Wignall & Twitchett, 2002; Seidler *et al.* 2004). The base of the *M. subdemissum* Zone is interpreted as a marine flooding surface where black bituminous mudstones overlie grey siltstones. The succession shallows upward through grey and greenish grey mudstones of the *O. commune* and *W. decipiens* zones and is topped by a marked tectonically induced erosion surface probably formed during *W. decipiens* Zone time. The Wordie Creek Formation is unconformably overlain by coastal plain to continental deposits of the Pingo Dal Formation.

5.d. Wegener Halvø subbasins

The Wegener Halvø area is situated at the southeastern basin margin (Fig. 1), and the succession there is bounded by faults, which controlled the Early Triassic sedimentological development (Seidler, 2000; Seidler *et al.* 2004). The Paradigmabjerg section is located in a structurally stable area within the subbasins and the Wordie Creek Formation is only 150 m thick, whereas

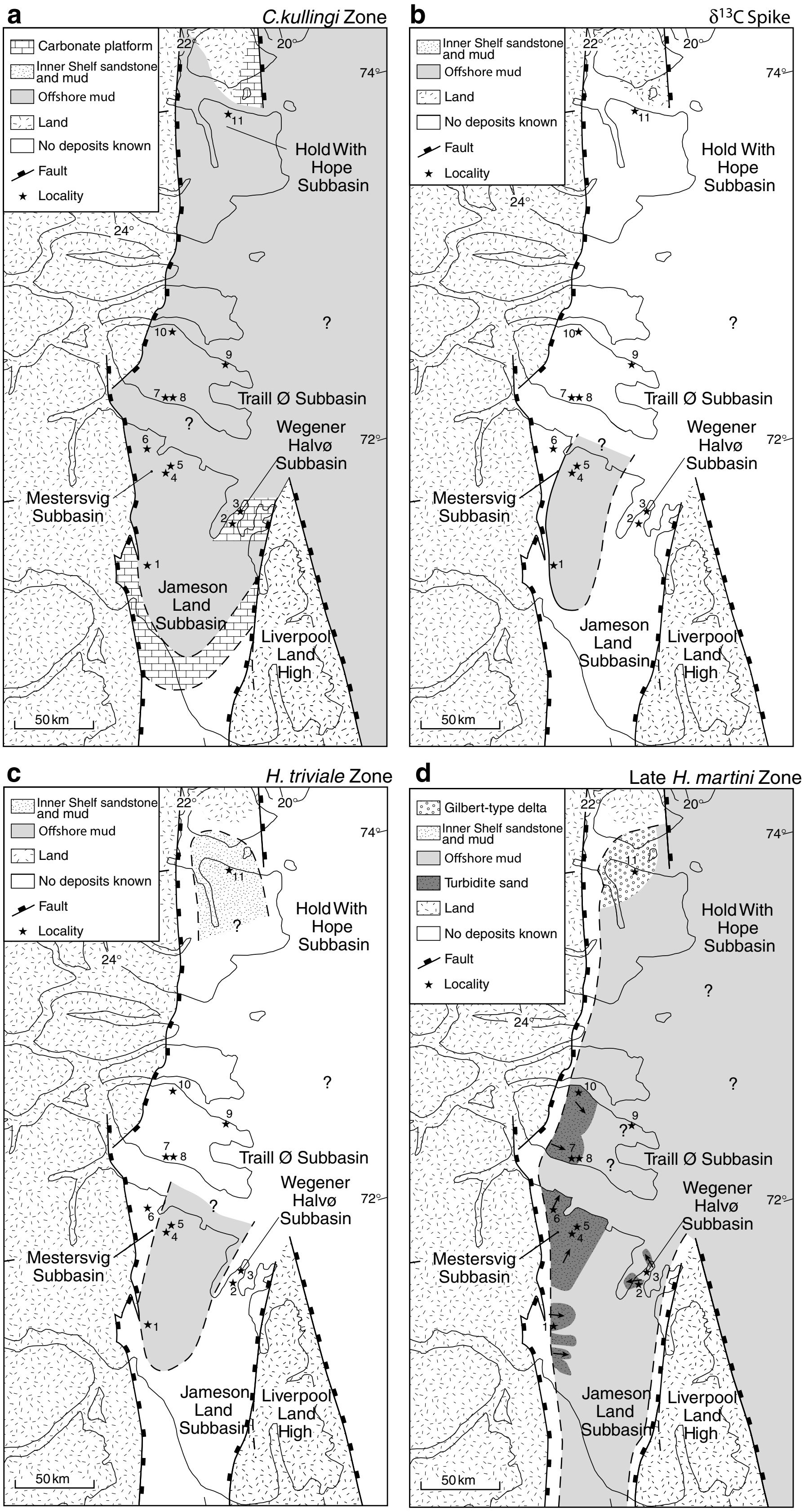

Figure 11. Palaeogeographical maps of (a) late Permian Wuchiapingian *C. kullingi* Zone time, (b) $\delta^{13}C$ spike, (c) *H. triviale* Zone time, and (d) early Triassic late *H. martini* Zone time. Locality numbers as for Figures 1 and 2.

it is 300 m thick at the more basinal Lille Cirkusbjerg section. Fossils recorded at the localities are presented in Table 1.

At Paradigmabjerg, the Upper Permian comprises reef-associated carbonates of the Wegener Halvø Formation, up to 150 m thick, erosionally overlain by shallow marine, calcareous shoreface sandstones, 6 m thick, of the Bredehorn Member (Schuchert Dal Formation) (Figs 2, 10, 11). The erosional top of the Bredehorn Member coincides with the Permian–Triassic boundary and is overlain by a 13 m thick density flow conglomerate, containing clasts of the Wegener Halvø Formation and forming the basal part of the Wordie Creek Formation.

At Lille Cirkusbjerg the Upper Permian succession consists of reef limestones of the Wegener Halvø Formation interfingering with and overlain by black mudstones of the Ravnefjeld Formation or in some places by dark grey silty mudstones of the Oksedal Member (Schuchert Dal Formation). The Permian–Triassic boundary is developed as an erosional unconformity overlain by 20 m of conglomerate interbedded with mudstone in the lower part. This succession forms the basal part of the Wordie Creek Formation and passes laterally into a conglomerate, up to 40 m thick, which in some places directly overlies the Wegener Halvø Formation with an erosional unconformity.

5.d.1. Hypophiceras triviale–martini *zones*

No ammonoids of the *H. triviale* Zone have been recorded from Wegener Halvø. The *H. martini* Zone is present in the most basinal settings in the area and is represented by turbidite sandstone and offshore mudstone (Grasmück & Trümpy, 1969; Seidler, 2000; L. Seidler. unpub. Ph.D. thesis, Univ. Copenhagen, 2000). Prominent conglomerate beds, forming the lowermost part of most of the Lower Triassic sections on Wegener Halvø, probably belong to the top of the *H. martini* Zone.

5.d.2. M. subdemissum–O. commune *zones*

The basal part of the *M. subdemissum* Zone consists of black mudstone, overlying the conglomeratic interval at the base of the Triassic succession in the area. The mudstone contains concretions with well-preserved ammonoids and other fossils and passes upward into greenish silty mudstones of the *O. commune* Zone. At Paradigmabjerg and Lille Cirkusbjerg the total thicknesses of the combined zones are about 50 m and 100 m, respectively.

5.d.3. W. decipiens *Zone*

At Paradigmabjerg the zone is 100 m thick and is represented by a yellow and grey, sandstone-dominated, erosionally based turbiditic succession. Two mudstone intervals occur containing a few imprints of fossils. The upper part of the zone is erosionally overlain by alluvial-fan conglomerates of the Pingo Dal Formation. At Lille Cirkusbjerg the greenish grey mudstone of the *O. commune* Zone passes gradually upwards into a *W. decipiens* Zone succession of dark grey, green and brown mudstone with common erosionally based sandy turbidites that are up to 10 m thick. The zone is 170 m thick, and ammonoids and other fossils occur as imprints in mudstones and as shell-rich layers in sandy turbidites.

5.d.4. The Permian–Triassic transition

The Wegener Halvø sections show different developments, depending on their structural position, and the Late Permian reefs and tectonic movements exerted a strong control on deposition. The Permian–Triassic boundary is developed as an erosional unconformity (Fig. 10). The widespread conglomeratic interval at the base of the Wordie Creek Formation is most prominent over structural highs and at basin margins and correlates with the conglomerate at the base of the Korsbjerg section. It represents the filling of incised valleys and/or submarine canyons eroded during latest Permian–earliest Triassic time (Seidler, 2000). In more basinal settings the *H. martini* Zone is represented by offshore mudstones and turbidite sandstones (Grasmück & Trümpy, 1969; Seidler, 2000).

The base of the *M. subdemissum* Zone is also marked by an abrupt shift towards black mudstones on Wegener Halvø, interpreted as a flooding surface. Similarly, there is an upward gradual shift to grey and greenish grey mudstone of the *O. commune* Zone. Shallow marine mudstone and subordinate sandy and conglomeratic density flow deposits characterize the *W. decipiens* Zone. Shallow marine tidally influenced sandstones occur in the middle part of this zone at Paradigmabjerg, close to the eastern basin margin.

6. Discussion

Upper Permian–Lower Triassic ammonoids of East Greenland are of outstanding importance for biostratigraphical subdivision and correlation of the Wordie Creek Formation and for identification of the Permian–Triassic boundary. The Upper Permian ammonoids from the Oksedal Member at Svinhufvud Bjerge and in western Jameson Land are quite different from *Cyclolobus kullingi* from Hold With Hope and are referred to *Changhsingoceras* and *Paramexicoceras*, (W. W. Nassichuk, 1995 and pers. comm. 2001; Zakharov, Oleinikov & Kotlyar, 1997; Zhou *et al.* 1996; Glenister, Furnish & Zhou, unpub. data). The *Hypophiceras triviale* Zone and the overlying *H. martini* Zone can probably be correlated with the *O. concavum* Zone of Arctic Canada and northeast Siberia

(Dagys & Weitschat, 1993; Tozer, 1994). The Permian–Triassic boundary GSSP at Meishan is defined at the FAD of the conodont *Hindeodus parvus* (Yin Hongfu *et al.* 2001), but correlation with the ammonoid stratigraphy is still rather crude. The base of the *H. triviale* Zone is situated 7 m above the base of the Wordie Creek Formation at Oksedal, northern Jameson Land. The FAD of *H. parvus* occurs 23.5 m above the base of the Wordie Creek Formation in the Fiskegrav section, southern Jameson Land (Twitchett *et al.* 2001), where the lowermost ammonoids belonging to the *H. martini* Zone are found 28 m above the base of the formation, that is, above the FAD of *H. parvus* (Stemmerik, Bendix-Almgreen & Piasecki, 2001). Yin Hongfu *et al.* (2001, table 1) referred both the *H. triviale* and the *H. martini* zones to the Permian. Our data show that this cannot be substantiated. The *H. triviale* Zone is clearly of latest Permian, Changhsingian age, whereas most or all of the *H. martini* Zone belongs to the lowermost Triassic. In the Fiskegrav section there is a pronounced palynological shift in the uppermost part of the Schuchert Dal Formation, 0.5 m below the base of the Wordie Creek Formation (Stemmerik, Bendix-Almgreen & Piasecki, 2001; Twitchett *et al.* 2001). The $\delta^{13}C$ of organic material drops by 8 ‰ in the topmost metre of the Schuchert Dal Formation to reach its most negative value of −32 ‰ PDB at the base of the Wordie Creek Formation. The negative $\delta^{13}C$ spike in the Permian–Triassic boundary interval thus pre-dates the FAD of *H. parvus* in Jameson Land with an interval corresponding to a 23.5 m thick succession (Stemmerik, Bendix-Almgreen & Piasecki, 2001). It is possible that the FAD of *H. parvus* in East Greenland post-dates the FAD at the GSSP at Meishan, and the immediately underlying strata (lowermost Wordie Creek Formation) at Fiskegrav may thus still belong to the lowermost Triassic.

The *H. triviale* Zone is for the first time documented in northern Jameson Land. Together with the conodont data of Wignall & Twitchett, (2002) this strongly indicates that a continuous mudstone succession across the Permian–Triassic boundary occurs in the basinal localities at Oksedal and Aggersborg in northern Jameson Land (Figs 9, 10). The section at Fiskegrav, southwestern Jameson Land, described by Stemmerik, Bendix-Almgreen & Piasecki (2001) and Twitchett *et al.* (2001), clearly indicated the existence of a continuous succession.

At Hold With Hope, the classical and most disputed boundary locality in East Greenland, the new boundary definition means that the basal Wordie Creek Formation is of youngest Permian age (*H. triviale* Zone) and that sedimentation was continuous across the Permian–Triassic boundary in the western, deepest part of the half-graben.

In most other areas in East Greenland the Permian–Triassic boundary is developed as an erosion surface, and the Schuchert Dal Formation and its correlatives are missing. The strata containing the $\delta^{13}C$ spike and the FAD of *H. parvus* do not show sedimentological signals indicative of sea-level changes. The claim by Twitchett *et al.* (2001) and Wignall & Twitchett (2002) that 'conformable shale contacts are present throughout the basin' (the Jameson Land subbasin) and implicitly that there was continuous sedimentation across the boundary is not substantiated by field evidence from the other subbasins of East Greenland. Rather, the ammonoid and palynological zonations from the whole region indicate that the interval recording the $\delta^{13}C$ anomaly and the extinction event is missing in most areas (Fig. 10).

The uppermost Permian–lowermost Triassic deposits of the *H. triviale–H. martini* zones are dominated by basinal mudstone and sand- and conglomerate-dominated turbidites in basinal and down-tilted areas. At Hold With Hope the succession is dominated by shelf sandstones and siltstones, and in the upper part two prominent fan delta conglomerate units occur. An erosional unconformity is overlain by prominent conglomerate- or sand-dominated turbidite units, the top of which mark the top of the *H. martini* Zone throughout the Jameson Land subbasin, including Wegener Halvø (Fig. 9). The hiatus includes the Permian–Triassic boundary at basin margins at Korsbjerg and Paradigmabjerg and over intrabasinal highs at Lille Cirkusbjerg and is interpreted to represent a prominent but local tectonically induced relative sea-level fall. Erosion and incision took place at the Permian–Triassic transition and/or in late *H. martini* Zone time.

The base of the *M. subdemissum* Zone coincides with a basin-wide change in deposition from siltstone to black bituminous mudstone and is interpreted as a drowning surface, probably of eustatic nature. The black mudstone passes upward into greenish-grey silty mudstone of the *O. commune* Zone. This Early Triassic sea-level rise was associated with the evolution of diverse ammonoid faunas in the *M. subdemissum* and *O. commune* zones, reflecting the filling of vacant niches after the end-Permian mass-extinction. The number of ammonoid genera thus increases from three in the *H. triviale* and *H. martini* zones to seven in the *O. commune* Zone (Fig. 5).

The *W. decipiens* Zone is characterized by shallow marine mudstone and subordinate coarse-grained turbidites in the Traill Ø and Jameson Land subbasins, and by mudstones and turbidite sandstones in the Hold With Hope subbasin. The number of ammonoid genera is greatly reduced to four, combined with a gradual shallowing-upward trend in the succession. A distinct fluvial interlude represented by the Svinhufvuds Bjerge Member, possibly of relatively short duration, occurred within *W. decipiens* Zone time, reflecting a tectonic event in the Traill Ø subbasin. The Svinhufvuds Bjerge Member cannot be traced out into the basin but is probably time-equivalent to turbidite sandstones at

Aggersborg and Lille Cirkusbjerg and to the coastal tidally influenced sandy succession at Paradigmabjerg.

Marine deposition in northern Jameson Land and Wegener Halvø ceased in *W. decipiens* Zone time but continued at Svinhufvud Bjerge and Hold With Hope. At Hold With Hope deep-water deposition continued during *B. rosenkrantzi* and *A. breviformis* Zone times, whereas the Svinhufvud Bjerge area was characterized by shallow marine stromatolitic build-ups and associated carbonate mudstones and sandstones of the Ødepas Member. The lower part of the continental basin-marginal Pingo Dal Formation is probably contemporaneous with the uppermost shallow marine part of the Wordie Creek Formation at Traill Ø (Perch-Nielsen *et al.* 1974). The ammonoid fauna is further reduced to only two genera in the *B. rosenkrantzi* Zone, and the correlation potential to other parts of the Boreal Realm is limited. This level marks a major regression in East Greenland and the transition to more widespread shallow marine–continental deposition.

7. Conclusions

Ammonoids are important in determining the Permian–Triassic boundary and for the stratigraphical subdivision and interpretation of the marine uppermost Permian–Lower Triassic of East Greenland. Six ammonoid zones are recognized in the uppermost Permian–Lower Triassic, and the zonation can be correlated with the standard ammonoid zonation of the Boreal Realm (Sverdrup Basin) and other Boreal regions (Svalbard, Northeast Siberia). The lowest of the East Greenland zones, the *H. triviale* Zone, most likely belongs to the uppermost Permian, following the recent definition of the Permian–Triassic GSSP at Meishan in China, but more integrated studies of conodonts and ammonoids are needed to correlate precisely the Boreal and Tethyan sections. The proposed correlation indicates that the end-Permian marine and terrestrial extinctions and associated isotope changes, as well as the subsequent adaptive radiations in the Boreal Realm, took place in what is now defined as latest Permian time. New Boreal faunas and floras were well established and diversified prior to the beginning of the Triassic, and the Permian–Triassic boundary in its present definition is not reflecting major changes in the Earth system. It would have been fortunate if a GSSP was defined in a protracted section at a point of major environmental perturbations, marked by isotope excursions, chemical anomalies and mass extinction, rather than in the strongly condensed section like Meishan at a point which post-dates all significant events.

New ammonoid data from Jameson Land, Wegener Halvø and Traill Ø allow us to better reconstruct the latest Permian–Early Triassic evolution of the East Greenland Basin. The *H. triviale* and *H. martini* zones are characterized by endemic faunas reflecting deposition in small and semi-isolated basins. Diverse and widespread Boreal ammonoid faunas occur in the *M. subdemissum* and *O. commune* zones. This interval corresponds to an overall transgressive development, including a maximum flooding interval, which resulted in better marine connections to the Boreal Sea towards the north. The overlying *W. decipiens–B. rosenkrantzi* zones mark a change into a higher degree of endemism associated with onset of relative sea-level fall and regression in the basin. This was associated with regional rifting, causing large-scale incision and erosion over structural highs and at basin margins and deposition of sand and conglomerate in the basins (Seidler *et al*. 2004).

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References

Balme, B. E. 1979. Palynology of Permian–Triassic boundary beds at Kap Stosch, East Greenland. *Meddelelser om Grønland* **200**(6), 1–37.

Bugge, T., Ringås, J. E., Leith, D. A., Mangerud, G., Weiss, H. M. & Leith, T. L. 2002. Upper Permian as a new play model on the Mid-Norwegian continental shelf; Investigated by shallow stratigraphic drilling. *American Association of Petroleum Geologists Bulletin* **86**, 107–27.

Callomon, J. H., Donovan, D. T. & Trümpy, R. 1972. An annotated map of the Permian and Mesozoic formations of East Greenland. *Meddelelser om Grønland* **168**(3), 1–35.

Clemmensen, L. B. 1980*a*. Triassic rift sedimentation and palaeogeography of central East Greenland. *Bulletin Grønlands Geologiske Undersøgelse* **136**, 1–72.

Clemmensen, L. B. 1980*b*. Triassic lithostratigraphy of East Greenland between Scoresby Sund and Kejser Franz Josephs Fjord. *Bulletin Grønlands Geologiske Undersøgelse* **139**, 1–56.

Dagys, A. S. 1988. Major features of the geographic differentiation of Triassic Ammonoids. In *Cephalopods present and past* (eds J. Weidmann and J. Kullmann), pp. 341–9. Stuttgart: E. Schweizerbart'sche Verlagsbuchhandlung.

Dagys, A. & Ermakova, S. 1996. Induan (Triassic) ammonoids from north-eastern Asia. *Revue de Paléobiologie* **15**, 401–47.

Dagys, A. & Weitschat, W. 1993. Correlation of the Boreal Triassic. *Mitteilungen aus dem Geologisch-Paläontologischen Institut der Universität Hamburg* **75**, 249–56.

Frebold, H. & Noe-Nygaard, A. 1938. Marines Jungpalaeozoikum und Mesozoicum von der Traill-Insel (Ostgrönland). *Meddelelser om Grønland* **119**(2), 1–37.

Grasmück, K. & Trümpy, R. 1969. Triassic stratigraphy and general geology of the country around Fleming Fjord (East Greenland). *Meddelelser om Grønland* **168**(2), 3–76.

Hallam, A. & Wignall, P. B. 1997. *Mass extinctions and their aftermath*. New York: Oxford University Press, 320 pp.

Hochuli, P. A., Colin, J. P. & Vigran, J. O. 1989. Triassic biostratigraphy of the Barents Sea area. In *Correlation in Hydrocarbon exploration* (ed. J. D. Collinson), pp. 131–53. London: Graham & Trotman for the Norwegian Petroleum Society.

Koch, L. 1929. Stratigraphy of Greenland. *Meddelelser om Grønland* **73**(2), 205–320.

Koch, L. 1931. Carboniferous and Triassic stratigraphy of East Greenland. *Meddelelser om Grønland* **83**(2), 1–100.

Kreiner-Møller, M. & Stemmerik, L. 2001. Upper Permian lowstand fans of the Bredehorn Member, Schuchert Dal Formation, East Greenland. In *Sedimentary Environments Offshore Norway – Palaeozoic to Recent* (eds O. J Martinsen and T. Dreyer), pp. 51–65. NPF Special Publication no. 10.

Larsen, M., Piasecki, S., Preuss, T., Seidler, L., Stemmerik, L., Therkelsen, J. & Vosgerau, H. 1998. Petroleum geological activities in East Greenland in 1997. *Geology of Greenland Survey Bulletin* **180**, 35–42.

Nassichuk, W. W. 1995. Permian ammonoids in the arctic regions of the world. In *The Permian of the Northern Pangea 1: Paleogeography, Paleoclimates, Stratigraphy* (eds P. A. Scholle, T. M. Peryt, and D. Ulmer-Scholle), pp. 210–35. Berlin: Springer-Verlag.

Nielsen, E. 1935. The Permian and Eotriassic vertebrate-bearing beds at Godthaab Gulf (East Greenland). *Meddelelser om Grønland* **98**(1), 1–111.

Nielsen, E. 1961. On the Eotriassic fish faunas of central East Greenland. In *Geology of the Arctic 1* (ed. G. O. Raasch), pp. 255–7. Toronto University Press.

Oberhänsli, H., Hsü, K. J., Piasecki, S. & Weissert, H. 1989. Permian–Triassic carbon-isotope anomaly in Greenland and in the Southern Alps. *Historical Biology* **2**(1), 37–49.

Perch-Nielsen, K., Birkenmajer, K., Birkelund, T. & Aellen, M 1974. Revision of Triassic stratigraphy of the Scoresby Land and Jameson Land region, East Greenland. *Bulletin Grønlands Geologiske Undersøgelse* **109**, 1–51.

Perch-Nielsen, K., Bromley, R. G., Birkenmajer, K. & Aellen, M. 1972. Field observations in Palaeozoic and Mesozoic sediments of Scoresby Land and northern Jameson Land. *Rapport Grønlands Geologiske Undersøgelse* **48**, 39–59.

Piasecki, S. 1984. Preliminary palynostratigraphy of the Permian–Lower Triassic sediments in Jameson Land and Scoresby Land, East Greenland. *Geological Society of Denmark Bulletin* **32**, 139–44.

Piasecki, S. & Marcussen, C. 1986. Oil geological studies in central East Greenland. *Rapport Grønlands Geologiske Undersøgelse* **130**, 95–102.

Piasecki, S. & Stemmerik, L. 1991. Late Permian anoxia of central East Greenland. In *Modern and ancient shelf anoxia* (eds R. V. Tyson and T. H. Pearson), pp. 275–90. Geological Society of London, Special Publication no. 58.

Putallaz, J. 1961. Géologie de la partie médiane de Traill Ö (Groenland Oriental). *Meddelelser om Grønland* **164**(2), 1–84.

Seidler, L. 2000. Incised submarine canyons governing new evidence of Early Triassic rifting in East Greenland. *Palaeogeography, Palaeoclimatology, Palaeoecology* **161**, 267–93.

Seidler, L., Steel, R. J., Stemmerik, L., & Surlyk, F. 2004. North Atlantic marine rifting in the Early Triassic – new evidence from East Greenland. *Journal of the Geological Society, London* **161**, 584–92.

Spath, L. F. 1930. Eotriassic Invertebrate Fauna of East Greenland. *Meddelelser om Grønland* **83**(1), 1–90.

Spath, L. F. 1935. Additions to the Eo-Triassic Invertebrate Fauna of East Greenland. *Meddelelser om Grønland* **98**(2), 1–115.

Stauber, H. 1942. Die Triasablagerungen von Ostgrönland. *Meddelelser om Grønland* **132**(1), 1–325.

Stemmerik, L., Bendix-Almgreen, S. E. & Piasecki, S. 2001. The Permian–Triassic boundary in central East Greenland: past and present views. *Bulletin of the Geological Society of Denmark* **48**, 159–67.

Stemmerik, L., Clausen, O. R., Korstgård, J., Larsen, M., Piasecki, S., Seidler, L., Surlyk, F. & Therkelsen, J. 1997. Petroleum geological investigations in East Greenland: project "Resources of the sedimentary basins of North and East Greenland". *Geology of Greenland Survey Bulletin* **176**, 29–38.

Stemmerik, L., Dam, G., Noe-Nygaard, N., Piasecki, S. & Surlyk, F. 1998. Sequence stratigraphy of source rocks in the Upper Permian and Jurassic of Jameson Land, East Greenland. *Geology of Greenland Survey Bulletin* **180**, 43–54.

Stemmerik, L. & Piasecki, S. 1991. The Upper Permian of East Greenland – A Review. *Zentralblatt für Geologie und Paläntologie* **1**(4), 825–37.

Stensiö, E. 1932. Triassic fishes from East Greenland. *Meddelelser om Grønland* **83**(3), 305 pp.

Surlyk, F. 1990. Timing, style and sedimentary evolution of Late Palaeozoic-Mesozoic extensional basins of East Greenland. In *Tectonic Events Responsible for Britain's Oil and Gas Reserves* (eds R. F. P. Hardmann and J. Brooks), pp. 107–25. Geological Society of London, Special Publication no. 55.

Surlyk, F., Piasecki, S., Rolle, F., Scholle, P. A., Stemmerik, L. & Thomsen, E. 1986. The Permian of the western margin of the Greenland Sea – A future exploration target. In *Future Petroleum Provinces of the World* (ed. M. T. Halbouty), pp. 629–59. American Association of Petroleum Geologists, Memoir no. 40.

Surlyk, F., Piasecki, S., Rolle, F., Stemmerik, L. & Thomsen, E. & Wrang, P. 1984. The Permian basin of East Greenland. In *Petroleum geology of the North European margin* (eds A. M. Spencer *et al.*), pp. 303–15. London: Norwegian Petroleum Society (Graham and Trotman).

Teichert, C. 1990. The Permian–Triassic boundary revisited. In *Extinction Events in Earth History* (eds E. G. Kaufmann and O. H. Walliser), pp. 99–238. Berlin: Springer-Verlag.

Teichert, C. & Kummel, B. 1976. Permian–Triassic boundary in the Kap Stosch area, East Greenland. *Meddelelser om Grønland* **197**(5), 1–54.

TOZER, E. T. 1981. Triassic Ammonoidea: classification, evolution and relationship with Permian and Jurassic forms. In *The Ammonoidea: the classification, mode of life and geological usefulness of a major fossil group* (eds M. R. House and J. R. Senior), pp. 66–100. Systematics Association, Special Volume no. 18.

TOZER, E. T. 1994. Canadian Triassic ammonoid faunas. *Geological Survey of Canada Bulletin* **467**, 1–663.

TRÜMPY, R. 1969. Lower Triassic ammonites from Jameson Land (East Greenland). *Meddelelser om Grønland* **168**(2), 77–116.

TWITCHETT, R. J., LOOY, C. V., MORANTE, R., VISSCHER, H. & WIGNALL, P. B. 2001. Rapid and synchronous collapse of marine and terrestrial ecosystems during the end-Permian biotic crisis. *Geology* **29**, 351–4.

WATERHOUSE, J. B. 1994. The Early and Middle Triassic ammonoid succession of the Himalayas in western and central Nepal, Part 1. Stratigraphy, classification and Early Scythian ammonoid systematics. *Palaeontographica Abteilungen* **232**, 1–83.

WEITSCHAT, W. & DAGYS, A. 1989. Triassic biostratigraphy of Svalbard and comparison with NE-Siberia. *Mitteilungen aus dem Geologisch-Paläontologischen Institut der Universität Hamburg* **68**, 179–213.

WIGNALL, P. B. & TWITCHETT, R. J. 2002. Permian–Triassic sedimentology of Jameson Land, East Greenland: incised submarine channels in an anoxic basin. *Journal of the Geological Society, London* **159**, 691–703.

WORDIE, J. M. 1927. The Cambridge expedition to East Greenland in 1926. *Geographical Journal* **75**, 225–65.

YIN HONGFU, ZHANG KEXIN, TONG JINNAN,, YANG ZUNYI, & WU SHUNBAO 2001. The Global Stratotype and Point (GSSP) of the Permian–Triassic Boundary. *Episodes* **24**, 102–14.

ZAKHAROV, Y. D., OLEINIKOV, A. & KOTLYAR, G. V. 1997. Late Changxingian ammonoids, bivalves and brachiopods in South Primorye. In *Late Palaeozoic and Early Mesozoic Circum-Pacific events and their global correlation* (eds M. Dickens, Zunyi Yang, Hongfu Yin, S. G. Lucas and S. K. Acharyya), pp. 142–6. Cambridge University Press.

ZHOU, Z., GLENISTER, B. F., FURNISH, W. M. & SPINOSA, C. 1996. Multiepisodal Extinction and Ecological Differentiation of Permian Ammonoids. *Permophiles* **29**, 52–62.