The Permian–Triassic boundary in central East Greenland: past and present views

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The latest Permian, Changhsingian fauna in East Greenland is a typical northern cool-water fauna, dominated by a low diversity assemblage of boreal brachiopods and lacking fusulinids, small foraminifers and fish. Continuous sedimentation across the Permian–Triassic boundary is recorded at the Fiskegrav locality, southwestern Jameson Land but the precise location of the boundary is disputable within an interval covering the uppermost few metres of the Schuchert Dal Formation and the lowermost 23.5 m of the Wordie Creek Formation. Based on palynological data the boundary is best placed 50 cm below the top of the Schuchert Dal Formation at Fiskegrav, in a monotonous interval of bioturbated, grey offshore marine siltstone characterised by a marked drop in the $\delta^{13}C$ of organic carbon. $\delta^{13}C$ of carbonate from brachiopods shows a temporary drop of 2‰, 4–5 m below the top of the Schuchert Dal Formation, while the $\delta^{13}C$ of whole rock carbonate reaches a minimum in the lowermost part of the Wordie Creek Formation. Comparisons to the $\delta^{13}C$ carbonate curves from the boundary stratotype section at Meishan, China are therefore highly subjective and allow the boundary to be placed within a 24–27 m thick interval in the topmost Schuchert Dal Formation and the lowermost Wordie Creek Formation, – here termed as the Permian–Triassic boundary interval. The lower part of this interval, below the palynological boundary includes a low diversity Permian-type fauna of two brachiopod and four agglutinated foraminifer genera. Above the palynological boundary, in the uppermost 50 cm of the Schuchert Dal Formation remains of the Triassic-type fish *Bobasatrania* occur together with agglutinated foraminifers, and at the base of the Wordie Creek Formation a more diverse, Triassic-type fish fauna with five genera is present. In the stratotype section at Meishan the first Triassic-type faunal elements appear above the negative $\delta^{13}C$ anomaly in what is regarded as a topmost Permian mixed fauna interval. A similar situation may possibly exist in East Greenland so the old East Greenland issue of faunal mixing with Permian-type fauna in the Triassic may turn out to be a matter of having Triassic faunal elements in the Permian.

Keywords: Permian–Triassic boundary, East Greenland, $\delta^{13}C$ variations, faunal changes.

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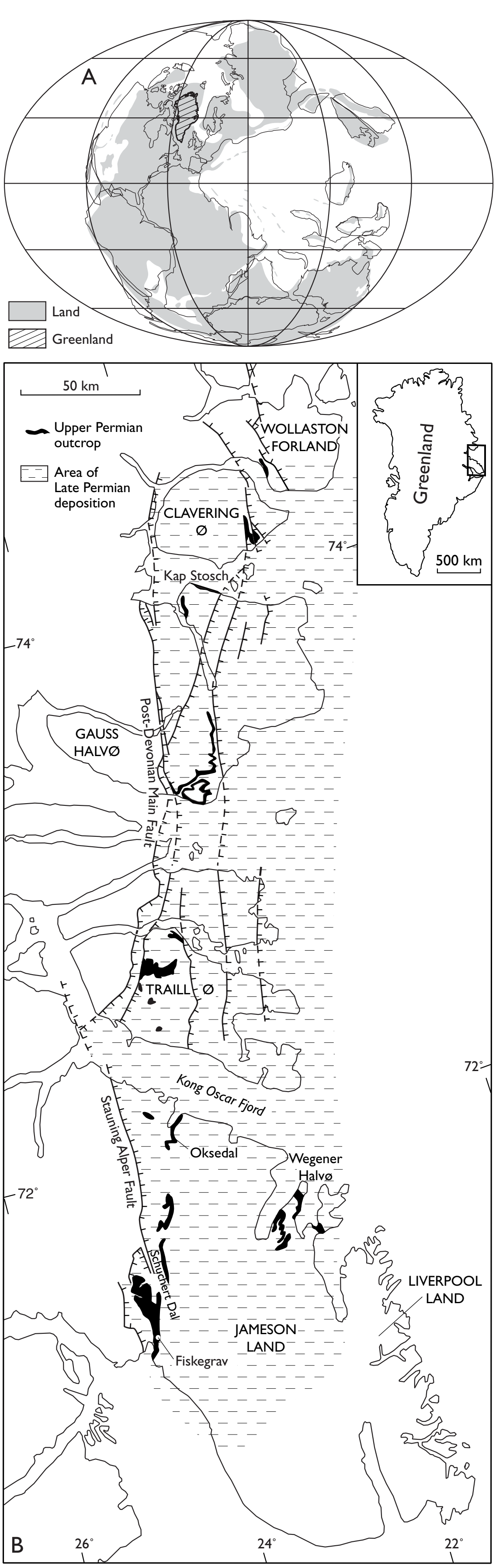
The end-Permian mass extinction was the most severe biotic crisis in the Earth's history. It has been estimated that nearly 85% of marine species and 70% of terrestrial vertebrate genera became extinct, apparently in less than 1 million years during the latest Changhsingian (Stanley & Yang 1994; Bowring et al. 1998). Historically, the East Greenland boundary localities have played an important role in the mass extinction debate since the first reports of an apparently mixed fauna with clearly Permian faunal elements associated with ophiceratid ammonoids and *Otoceras* above the Permian–Triassic boundary at Kap Stosch (Figs 1, 2; Spath 1930). The apparently mixed fauna soon divided the geological community into those believing that the Permian fossils were reworked into the Triassic and those arguing that some Permian genera had survived into the earliest Triassic (e.g. Koch 1931; Maync 1942). The pre-war debate was resumed by Trümpy (1960) after visits to Kap Stosch and Wegener Halvø from where he described *Hypophiceras* and *Otoceras* associated with large numbers of Permian-type brachiopods, bryozoans and crinoids, which in his opinion supported survival of Permian genera into the earliest Triassic (Trümpy 1960; Grasmück & Trümpy 1969). This view was contradicted by Teichert & Kummel (1976) who based on



field work at Kap Stosch concluded that the Permian-age fossils in the Triassic succession were redeposited. This conclusion is supported by later researchers based on the presence of a major hiatus, spanning the entire Changhsingian in the sections at Kap Stosch and elsewhere in the area north of Kong Oscar Fjord (Stemmerik et al. 1993).

Recently, most studies of the end-Permian mass extinction and environmental changes at this time have focussed on localities in the equatorial, warm-water, Tethys province with a highly diverse marine fauna, and on non-marine, peri-Gondwana sections of Australia and Antarctica (Retallack et al. 1996; Bowring et al. 1998; Jin et al. 2000). Less attention has been paid to the high latitude cool-water sections in East Greenland and elsewhere along the northern margin of Pangea.

The uppermost Permian of East Greenland includes the Wegener Halvø, Ravnefjeld and Schuchert Dal Formations of the Foldvik Creek Group while the lowermost Triassic forms the Wordie Creek Formation (Figs 1, 3; Perch-Nielsen et al. 1972; Surlyk et al. 1986). Traditionally, the Permian–Triassic boundary is placed at the lithostratigraphical boundary between the Schuchert Dal Formation and the Wordie Creek Formation, but biostratigraphical and geochemical data from an apparently continuous section at Fiskegrav, southern Jameson Land raise the possibility that the boundary could be in the topmost Schuchert Dal Formation or as high as 23.5 m above the base of the Wordie Creek Formation (Oberhänsli et al. 1989; Piasecki 1990; Twitchett et al. 2001). The practice of regarding the Schuchert Dal Formation – Wordie Creek Formation boundary as equivalent to the Permian–Triassic boundary is retained until further biostratigraphical and geochemical data have been obtained to allow firm correlation with the global stratotype at Meishan, China (Hongfu et al. 2001). The topmost Schuchert Dal Formation and the lowermost Wordie Creek Formation is here be described as the "Permian–Triassic boundary interval" (Fig. 4).

The present paper gives a general overview of faunal and floral changes in the "Permian–Triassic boundary interval" in East Greenland utilising all available biostratigraphical and geochemical data. The Permian succession of East Greenland clearly reveals a two-step change in the marine fauna and ter-

Fig. 1. A: Late Permian palaeogeographic reconstruction showing the position of Greenland (cross-hatched) at the western edge of the seaway connecting the northern boreal ocean with the Zechstein basin of NW Europe. Modified from Ziegler et al. (1997). B: Map of central East Greenland showing distribution of Upper Permian sediments and the proposed outline of the Late Permian depositional basin.

Fig. 2. The classical Permian–Triassic boundary section at Kap Stosch seen from the northeast. The dark Upper Permian (Wuchiapingian) Ravnefjeld Formation (Ra) is directly overlain by the Wordie Creek Formation (W) which is disconformably overlain by Tertiary basalts forming the top of the approximately 1300 m high mountains. The prominent red unit in the lower part of the section is the Upper Permian Huledal Formation (Hu).

restrial microflora. The first marked change occurs at the transition from the Wegener Halvø and Ravnefjeld formations to the overlying Schuchert Dal Formation, at or near the Wuchiapingian–Changhsingian boundary. The second occurs in the topmost metres of the Schuchert Dal Formation and marks the palynological shift from a Permian- to a Triassic-type flora.

Regional and palaeogeographical setting

The Late Permian depositional basin in East Greenland was an elongate, approximately 400 km long and up to 80 km wide, north-south orientated embayment bounded to the west by the post-Devonian Main Fault – Stauning Alper Fault and landlocked towards the south (Fig. 1) (Surlyk et al. 1986). Towards the southeast it was separated by the Liverpool Land High from the rift basins that formed the main seaway connecting the Zechstein Basin of northwest Europe with the Permian basins of North Greenland and the Barents Sea along the northern margin of Pangea (Fig. 1; Stemmerik 1995). During latest Permian time, East Greenland was located in a northern palaeolatitudinal position at approximately 35°N in a climatically sensitive area near the confluence of the equatorial and mid-latitude atmospheric circulation cells (Scholle et al. 1993). There is a marked change in depositional style from the warm-water carbonates of the upper Wuchiapingian Wegener Halvø Formation to the cool-water carbonates in the overlying Schuchert Dal Formation, suggesting a cooler palaeoclimate in East Greenland during the latest Permian.

The Upper Permian Foldvik Creek Group is widely distributed from the Wollaston Forland in the north to southern Jameson Land in the south (Fig. 1) (Surlyk et al. 1986). The lowermost Triassic marine succession in central East Greenland is included in the Wordie Creek Formation of Griesbachian to earliest Dienerian age based on the ammonite fauna (Grasmück &

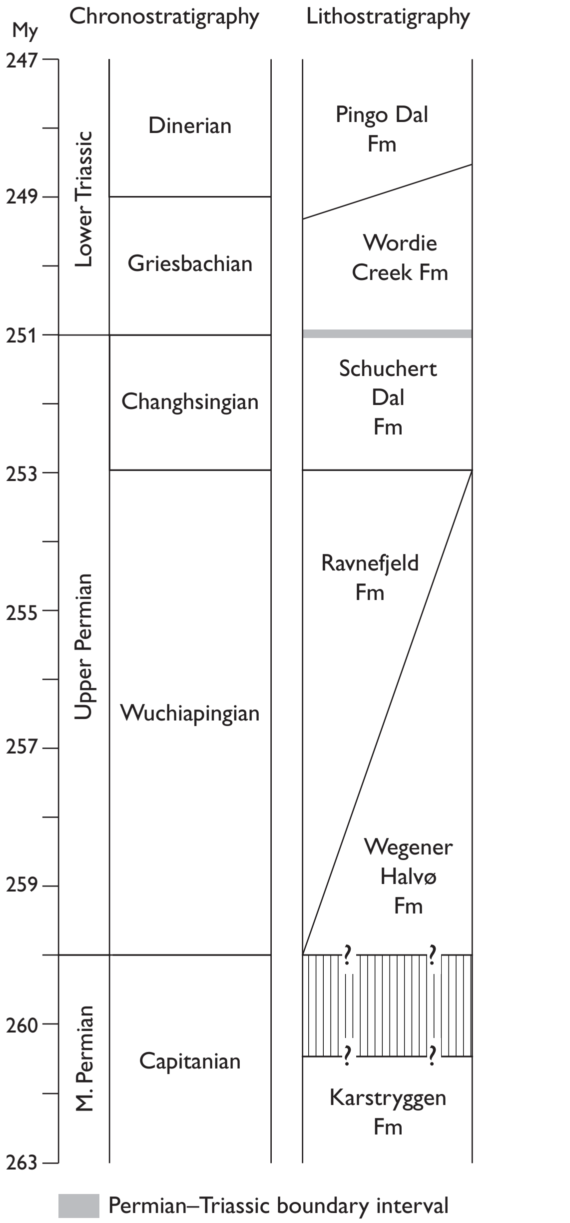


Fig. 3. Upper Permian – Lower Triassic lithostratigraphic scheme of East Greenland.

Trümpy 1969). The formation is exposed in the same general area as the Foldvik Creek Group, and well exposed outcrops of the Permian–Triassic boundary succession can be studied at the classical sections from Kap Stosch in the north (Nielsen 1935; Teichert & Kummel 1973, 1976) to Schuchert Dal near the southwestern edge of the basin (Fig. 1) (Perch-Nielsen et al. 1972). Generally, the most complete Permian sections occur south of Kong Oscar Fjord. The uppermost Permian Schuchert Dal Formation and equivalents are missing in the northern part of the basin and there is a marked late Permian hiatus, spanning the Wuchiapingian in the classical boundary section at Kap Stosch (Balme 1980; Stemmerik et al. 1993). Sections with continuous sedimentation across the boundary are limited to basinal settings in Jameson Land to the south, and include localities in southeastern Schuchert Dal and Oksedal (Fig. 1) (Perch-Nielsen et al. 1972; Piasecki 1990; Surlyk 1990; Twitchett et al. 2001).

Stratigraphy

The Upper Permian Foldvik Creek Group consists of a poorly dated alluvial to marginal marine part, the Huledal and Karstryggen Formations of mid-Permian (?Capitanian) age and an upper, fully marine part, the Ravnefjeld, Wegener Halvø and Schuchert Dal Formations (Fig. 3) (Surlyk et al. 1986). The shallow marine, carbonate-dominated Wegener Halvø Formation and the partly time-equivalent basinal, shale-dominated Ravnefjeld Formation are dated to the latest Wuchiapingian based on the presence of a low diversity conodont fauna of *Mesogondolella (Neogondolella) rosenkrantzi*, *Merrillina divergens* and *Xaniognathus abstractus* (Rasmussen et al. 1990; Henderson & Mei 2000). The age of the uppermost Permian Schuchert Dal Formation is less well-constrained. Palynologically, the basal part of the formation is characterised by a rapid transition from a *Vittatina*-dominated assemblage to an assemblage dominated by bisaccate pollen of Late Permian affinity (Fig. 4; Piasecki 1984; Utting & Piasecki 1995). In the uppermost part of the formation at Fiskegrav, southwestern Jameson Land detailed palynostratigraphical studies reveal a gradual appearance over a few metres of small trilete spores that heralds the floral changes at the Permian–Triassic boundary (Piasecki 1990; Utting & Piasecki 1995; Twitchett et al. 2001). Based on palynological data the Permian–Triassic boundary is best placed 50 cm below the top of the Schuchert Dal Formation at Fiskegrav, in a monotonous interval of bioturbated, grey shelf siltstone (Figs 1, 3, 4; Oberhänsli et al. 1989; Piasecki 1990). Recently, this view has be challenged by Twitchett et al. (2001) who preferred the boundary to be located in the lowermost Wordie Creek Formation. Correlation between the boundary stratotype at Meishan, China and the Fiskegrav section based on the negative $\delta^{13}C$ excursion is problematic because several different isotope curves exist both from China and East Greenland (Bowring et al. 1998; Jin et al. 2000; Oberhänsli et al. 1989; Twitchett et al. 2001). In the Meishan stratotype section the negative $\delta^{13}C$ event is located below the most commonly accepted boundary at the base of bed

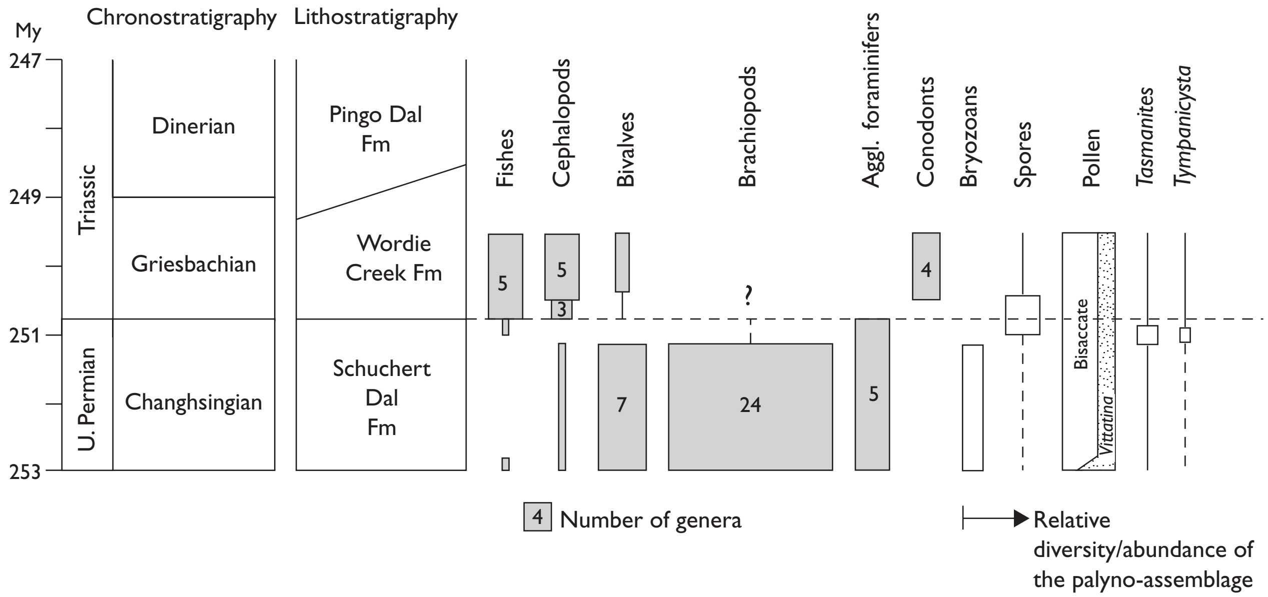


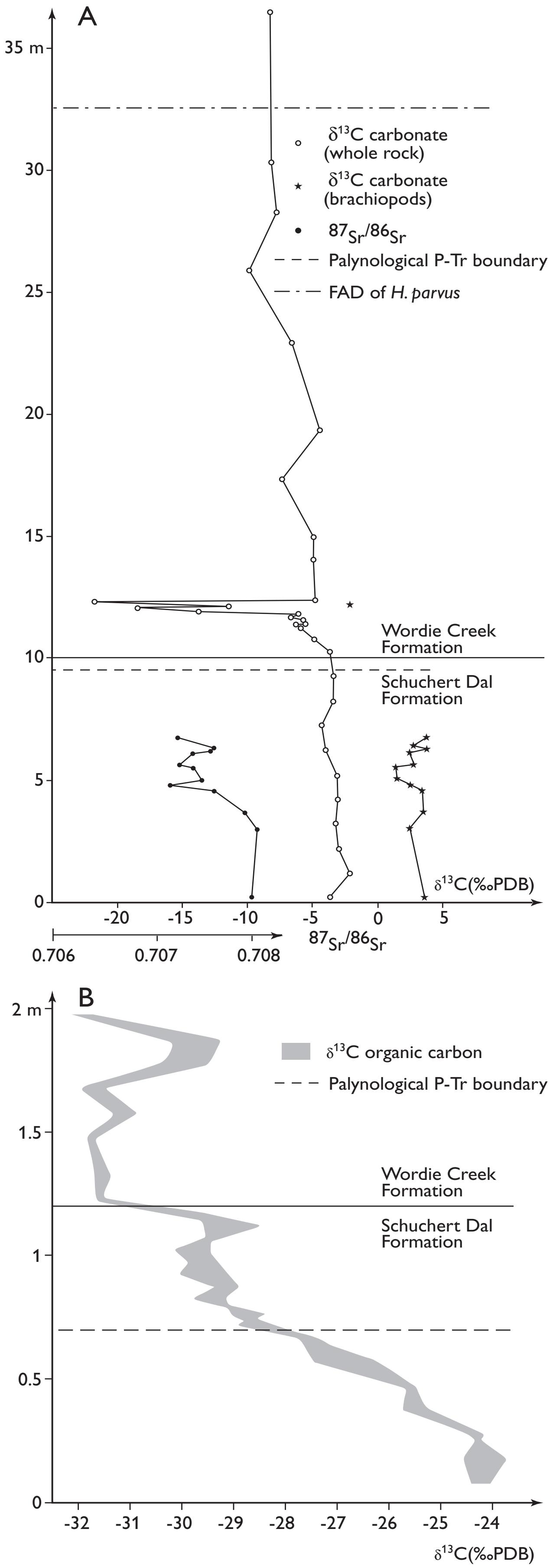
Fig. 4. Palaeontological changes across the Permian–Triassic boundary in East Greenland. Faunal abundance is given as number of genera except for the bryozoans. The microfloral data show shifts in relative abundance. Data from Newell (1955), Dunbar (1955), Grasmück & Trümpy (1969), Sweet (1976), Oberhänsli et al. (1989), Nassichuk (1995), Pattison & Stemmerik (1996), and unpublished data of the authors.

27c and is thus regarded of latest Permian age (Bowring et al. 1998; Jin et al. 2000). In East Greenland we have recorded a 2‰ shift towards more negative $\delta^{13}C$ carbonate values of brachiopod shells in the interval 4–5 m below the top of the Schuchert Dal Formation (Fig. 5). Oberhänsli et al. (1989) and Twitchett et al. (2001) recorded an interval with negative $\delta^{13}C$ carbonate values based on whole rock samples in the lowermost 2 m of the Wordie Creek Formation (Fig. 5). Our data show a shift towards negative $\delta^{13}C$ values of organic material starting 75 cm below the top of the Schuchert Dal Formation reaching a minimum in the lower 50 cm of the Wordie Creek Formation and a new minimum 80 cm above the base of the formation (Fig. 5). Comparison between the $\delta^{13}C$ carbonate curves from the proposed stratotype section in China and the curves from Fiskegrav are therefore highly subjective and allows the boundary to be placed in a wide interval from c. 4 m below the top of the Schuchert Dal Formation (brachiopod data) to 5-10 m above the base of the Wordie Creek Formation (whole rock data).

Palaeontological data

The upper Wuchiapingian Wegener Halvø and Ravnefjeld Formations are characterised by a moderately diverse marine fauna including brachiopods, bivalves, cephalopods, bryozoans, nodosariid and miliolid foraminifers, crinoids, corals, conodonts and 15 genera of marine vertebrates (Dunbar 1955; Newell 1955; Fedorowski 1982; Pattison & Stemmerik 1996).

The Changhsingian Schuchert Dal Formation is characterised by a low diversity marine fauna lacking several of the groups described from the underlying Wegener Halvø and Ravnefjeld formations including nodosariid and miliolid foraminifers, crinoids, conodonts and rugose corals (Fig. 4). The number of cephalopods and marine vertebrates is drastically reduced as only one ammonoid genus (*Paramexicoceras*) and one marine vertebrate genus, the fish *Fadenia* have been described from the formation. *Fadenia* is restricted to the basal 2 m of the formation at Triaselv, southwestern Jameson Land. The number of brachiopod genera is only slightly reduced, from 26 to 24 (Dunbar 1955), and the fauna is dominated by brachiopods and bryozoans. Systematic description of the East Greenland Permian bryozoan fauna is lacking but field observations reveal the immigration of at least three new forms, two fenestrate and one trepostome in the Schuchert Dal Formation (Fig. 4). The formation also contains siliceous sponges and a relatively low diversity bivalve fauna (seven genera; Newell 1955). The terrestrial microflora is dominated by pollen (Piasecki 1984; Utting & Piasecki 1995). There is a marked shift in composition in the basal part of the formation from the dominance of *Vittatina* to dominance of bissacate pollen, and in the



uppermost part of the formation there is a gradual appearance of trilete spores.

Due to stratigraphical incompleteness of most uppermost Permian shallow marine successions it is difficult to judge when the final decline of the Permian fauna started. In the stratigraphically complete basinal sections at Fiskegrav and Oksedal, the upper 10–15 m of the Schuchert Dal Formation include agglutinated foraminifers, the brachiopods *Lisotella* and *Martinia* and the ammonoid *Paramexicoceras*. It is in this part of the formation that trilete spores start to appear, and at Fiskegrav the topmost 50 cm of the formation is characterised by the presence of a spore-dominated microflora e.g. *Uvaesporites imperialis*, *Lundbladispora obsoleta*, *Densoisporites playfordii* and *Densoisporites nejburgii* of Triassic affinity. *Tasmanites* and *Tympanicysta* are also common in this interval together with a highly impoverished fauna of agglutinated foraminifers and disarticulated remains of the Triassic fish *Bobasatrania*. The overlying Wordie Creek Formation holds a more diverse fauna in its lower part; at the base of the formation at Fiskegrav typical Lower Scythian (Griesbachian) fishes like the actinopterygiids *Bobasatrania, Boreosomus, Pteronisculus* and *Australosomus* occur together with the coelacanth ?*Whiteia* and remains of the elasmobranch ?*Parahelicampodus*. The first bivalve, *Claraia*, appears 5 m higher in the section. Ammonites, belonging to the basal Triassic *Hypophiceras triviale* Zone have been reported 7 m above the base of the formation at Oksedal, northern Jameson Land (Bjerager 1999) and ammonites of the overlying *Hypophiceras martini* Zone occur 28 m above the base of the formation in the Fiskegrav and Triaselv sections.

Discussion

Sedimentological data from the upper Wuchiapingian Wegener Halvø Formation indicate deposition under overall warm-water, semiarid conditions interrupted by more humid periods during sea-level lowstand and subaerial exposure of the carbonate platform (Scholle et al. 1993; Stemmerik 1997, 2001). The overall warm

Fig. 5. Changes in $\delta^{13}C$ in the Permian–Triassic boundary interval at the Fiskegrav section, southern Jameson Land. A: Variations in $\delta^{13}C$ carbonate. Whole rock analyses from Oberhänsli et al. (1989). Lower stippled line marks the palynological boundary of Piasecki (1990), upper dash-dot line marks the lowermost find of *Hindeodus parvus* by Twitchett et al. (2001). B: Variations in $\delta^{13}C$ organic carbon in the topmost Schuchert Dal Formation – lowermost Wordie Creek Formation. Note different vertical and horizontal scales compared to A.

and semiarid setting of the depositional basin at this time is supported by the Subangara affinity of the microflora and the presence of pollen grains derived from specialised Zechstein-type desert and semi-desert vegetation (Meyen 1987; Utting & Piasecki 1995).

The uppermost Permian, Changhsingian carbonates of the Schuchert Dal Formation are typical Late Palaeozoic cool-water carbonates dominated by brachiopod and bryozoan wackestones and packstones suggesting a shift towards cooler climate near the Wuchiapingian– Changhsingian boundary (cf. Beauchamp & Desrochers 1997; Stemmerik 1997). This is in accordance with the bissacate-pollen-dominated terrestrial microflora recorded in the formation which is believed to reflect a humid temperate climate (Utting & Piasecki 1995). The marine fauna of the uppermost Permian Schuchert Dal Formation is dominated by a low diversity assemblage of cool-water forms like brachiopods, bivalves and bryozoans and is less diverse than that of the underlying Ravnefjeld and Wegener Halvø Formation (Fig. 4).

High-resolution stratigraphic data from the "Permian-Triassic boundary interval" only exist for the microflora and $\delta^{13}C$ of organic carbon where variations have been recorded from samples at 5 cm intervals in the topmost Schuchert Dal Formation – basal Wordie Creek Formation at Fiskegrav. The microflora shows a gradual increase of trilete spores in the upper Schuchert Dal Formation followed by a rapid shift towards complete dominance of spores associated with abundant *Tympanicysta stoschiana* in the uppermost 50 cm of the formation. The change in flora is accompanied by a rapid shift in $\delta^{13}C$ of organic carbon across the palynological boundary from latest Permian values around –24‰ PDB to –29‰ PDB in the topmost 50 cm of the Schuchert Dal Formation to –32‰ PDB in the basal part of the Wordie Creek Formation (Fig. 5B). The only marine fossils occurring in the topmost Schuchert Dal Formation are agglutinated foraminifers, abundant acritarchs and *Tasmanites*, together with the Triassic-type fish *Bobasatrania*. The low diversity remains unchanged during a time interval corresponding to deposition of the topmost 50 cm of the Schuchert Dal Formation but then the fish fauna apparently diversified rapidly since five different genera occur in the basal Wordie Creek Formation.

Summary and conclusions

1. The uppermost Permian succession in Jameson Land is characterised by a low diversity brachiopod-dominated fauna. The end-Permian extinction event is less well constrained due to erosion of the uppermost Permian platform successions in most of the region; two brachiopod genera and one ammonoid occur in the upper Schuchert Dal Formation at Fiskegrav together with five genera of agglutinated foraminifers. The first Triassic-type marine vertebrate (*Bobasatrania*) occurs 50 cm below the top of the formation at a shift towards a spore-dominated assemblage and 25 cm above the start of a marked negative excursion of $\delta^{13}C$ of organic carbon. A new fish fauna evolved rapidly and five new genera occur in the lowermost Wordie Creek Formation.
2. Precise correlation of the East Greenland boundary sections to the stratotype section of Meishan, China is disputable and location of the Permian–Triassic boundary in the continuous section at Fiskegrav has to await further investigations. However, the Boreal flora and fauna in East Greenland show a well-defined appearance of Triassic-type assemblages suitable for local correlation.
3. The present consensus of placing the boundary at the base of bed 27c in the Meishan section means that the global mass extinction and the geochemical anomaly are latest Permian events and that the Permian–Triassic boundary itself is less significant. In the proposed stratotype section the first Triassic-type faunal elements appear above the $\delta^{13}C$ isotope anomaly in a mixed-fauna interval in the topmost Permian below bed 27c. A similar situation exists in East Greenland if the correlation proposed by Twitchett et al. (2001) is correct. Thus, given the proposed re-definition of the boundary the old East Greenland issue of faunal mixing may turn out to be a matter of Triassic faunal elements appearing in the latest Permian instead of a Permian-type fauna surviving into the Triassic.
4. The first occurrence of *Otoceras* in what generally is regarded the uppermost Permian of China opens the possibility that the basal Wordie Creek Formation is of Permian age so that complete boundary sections may occur further north in East Greenland than previously acknowledged. However, continuous sedimentation across the Permian–Triassic boundary in East Greenland is restricted to downtilted basinal areas and has so far been documented only in the southern part of the basin. The uppermost Permian Schuchert Dal Formation is missing in the classical boundary section at Kap Stosch in the northern part of the basin.
5. The negative $\delta^{13}C$ spike appears to be global and is an important marker for the dramatic global changes at the end of the Permian, and we find that this event has the best potential defining the Permian–Triassic boundary.

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