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Eustatic control on epicontinental basins: The example of the Stuttgart Formation in the Central European Basin (Middle Keuper, Late Triassic)

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ABSTRACT

The deposition of the Stuttgart Formation ('Schilfsandstein'), commonly considered as a type-example of the Carnian Pluvial Event, was controlled by high frequent 4th order sequences that resulted in pre-, intra- and post-Schilfsandstein transgressions from Tethyan waters into the epicontinental Central European Basin (CEB). The pre-Schilfsandstein transgression flooded the CEB trough gates to the Southeast and resulted in a widespread inland sea that was characterised by increased biological productivity, predominantly oxic conditions and enabled the immigration of euryhaline marine fauna with plankton, ostracodes, fishes, bivalves and the gastropods *Omphaloptychia suebica* n. sp. and *Settsassia stuttgartica* n. sp. The rather short-term intra- and post-Schilfsandstein transgressions flooded the CEB from the Southwest and Southeast and established a shallow brackish inland sea that stretched up to North Germany. Both, the 4th and 3rd order sequences derived from the succession in the CEB correlate well with those derived from successions of Tethyan shelfs. Therefore pronounced circum-Tethyan eustatic cycles are evidenced and may have had considerable impact on prominent middle Carnian events: Reingraben turnover, Carnian Pluvial Event, Carnian Crisis and Mid Carnian Wet Intermezzo. The broad circum-Tethyan evidence of 10^6-year scale cycles suggests glacioeustatic sea-level changes even in the Triassic Greenhouse period.

1. Introduction

The middle Carnian Stuttgart Formation ('Schilfsandstein') is commonly considered as a type-example of the Carnian Pluvial Event. The approximately 50–70 m thick sandy to shaly succession of the Stuttgart Formation occurs sandwiched between shaly and evaporitic Grabfeld and Weser formations ('Lower Gipskeuper', 'Upper Gipskeuper'; e.g. Bachmann et al., 1999; Beutler in DSK, 2005). Deposited within a fluvial channel-floodplain system (Heling, 1979; Duchrow, 1984; Dittrich, 1989; Shukla et al., 2010) the evaporite-free Stuttgart Formation was interpreted to represent a middle Carnian pluvial episode (Simms and Ruffell, 1989, 1990; Simms et al., 1995). This Carnian Pluvial Event was questioned by Visscher et al. (1994) but later contemporaneous environmental changes partly accompanied by faunal turnovers have been recognised from various localities from shelfs of the western Neotethys (e. g. Schlager and Schöllnberger, 1974; Gianolla et al., 1998; Hornung and Brandner, 2005; Keim et al., 2001, 2006; Preto and Hinnov, 2003; Roghi, 2004) and SW Neotethys (e.g. Druckman et al., 1982; Magaritz and Druckman, 1984; Hornung, 2007), Tethyan pelagic or hemipelagic basins (Furin et al., 2006; Hornung et al., 2007a; Rigo et al., 2007) as well as Pangaean continental basins (e. g. Prochnow et al., 2006; Colombi and Parrish, 2008). The illustrious names Reingraben Turnover (Schlager and Schöllnberger, 1974), Carnian Pluvial Event (Simms and Ruffell, 1989, 1990; Simms et al., 1995), Carnian Crisis (Hornung et al., 2007b), and Mid Carnian Wet Intermezzo (Kozur and Bachmann, 2010) demonstrate the general acceptance of global events in middle Carnian times. These have been linked to a number of causes such as short-term humid climate shifts, intensified rifting or oceanographic events.

So far less attention has been paid to middle Carnian sea-level fluctuations although a possible eustatic control on the type-example of the Carnian Pluvial Event was suggested earlier (e.g. Barth et al., 1984; Aigner and Bachmann, 1992; Gehrmann and Aigner, 2002; Shukla and Bachmann, 2007; Franz, 2008). Middle Carnian transgressions from Tethyan waters into the epicontinental Central European Basin (CEB) are rather poorly documented (Wienholz and Kozur, 1970;

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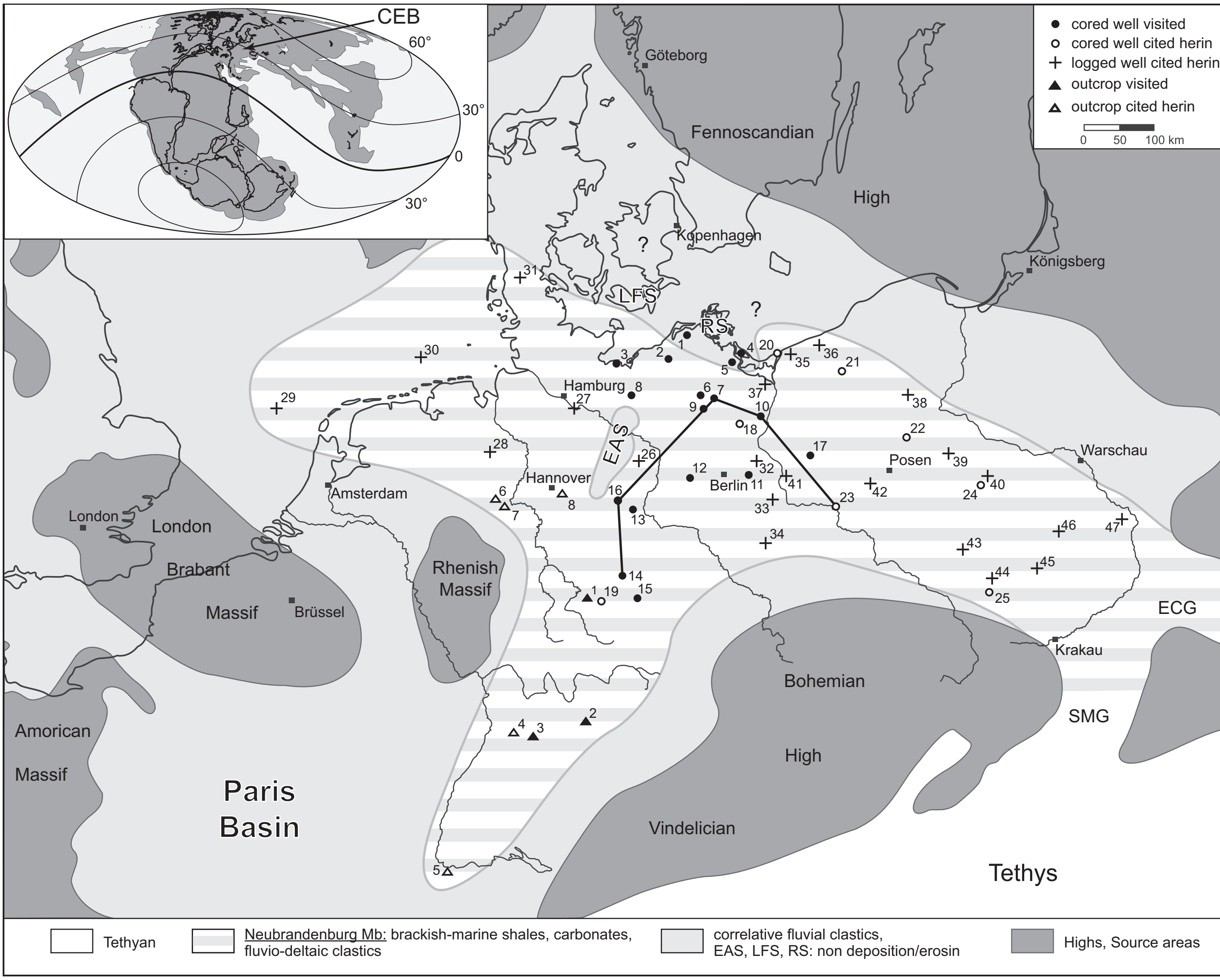
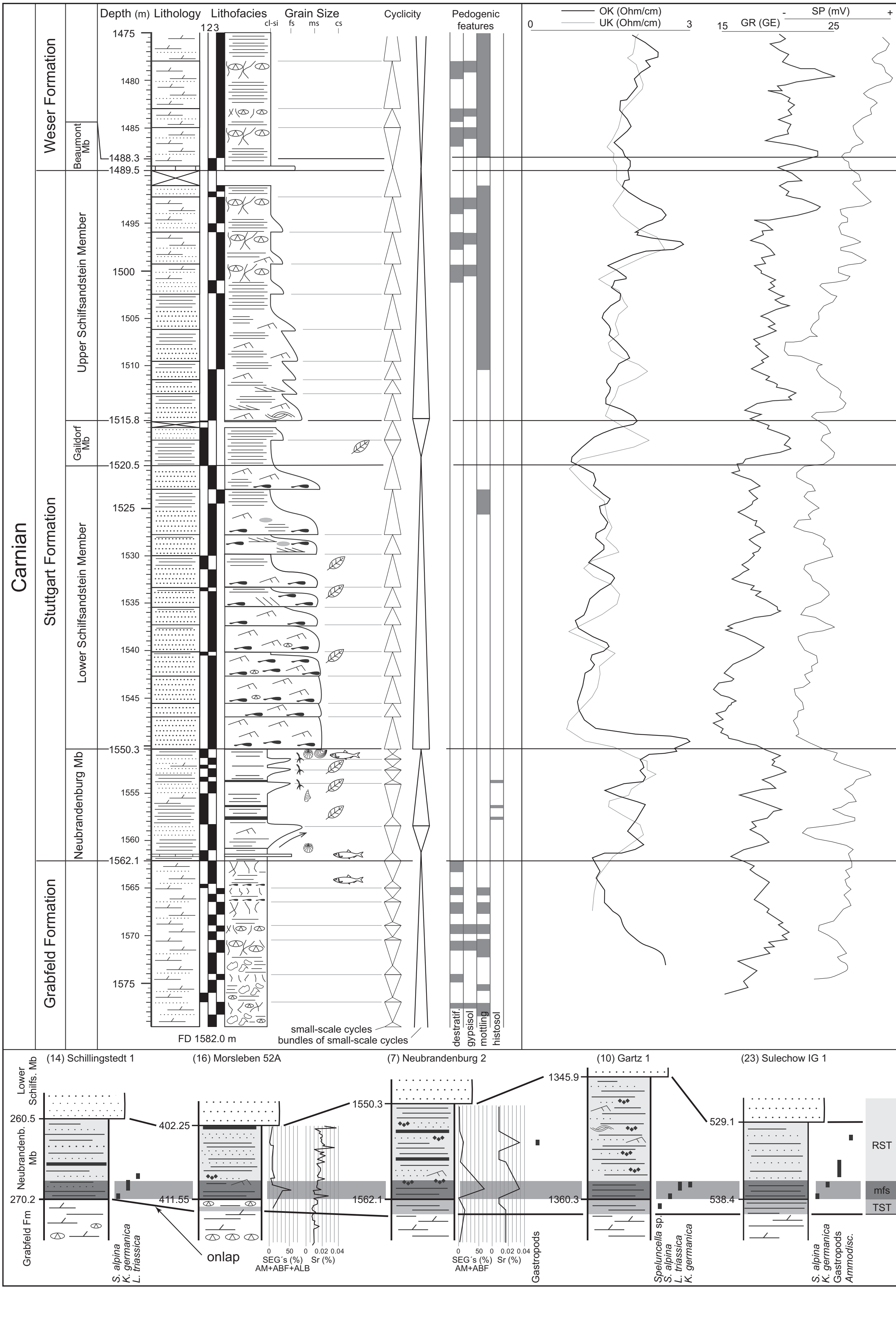


Fig. 1. Upper Triassic palaeogeography of the Central European Basin according to Ziegler (1990) showing the known extension of the Neubrandenburg Member (hatched) and correlative clastics (light grey). Inlet shows late Triassic global palaeogeography (Stampfli, unpublished). Study area and studied cored wells: 1 — Kb Barth 6a/65; 2 — Kb Goritz 1/62; 3 — E Klütz 1/65; 4 — E Lütow 3/66; 5 — Kb Wolgast 1a/64; 6 — Kb Tarnow 1/65; 7 — Gt Neubrandenburg 2/85; 8 — Kb KSS 1/66; 9 — Kb Brustorf 1/62; 10 — Kb Gartz 1/65; 11 — Kb Strausberg 1/63; 12 — Ug Ketzin 38/71; 13 — Kb Burg 2/61; 14 — Kb Schillingstedt 1/64; 15 — Kb Apolda 1/65; 16 — Dp Morsleben 52a/95; 17 — Gorzow Wlkp. IG 1; cored wells cited herein: 18 — Kb Flieth 1/64 (unpublished core report); 19 — Kb Seebergen 1/64 (unpublished core report); 20 — Kamień Pomorski IG 1 (reinterpreted after Gajewska, 1972); 21 — Połczyn Zdroj IG 1 (reinterpreted after Gajewska, 1979); 22 — Wągrowiec IG 1 (reinterpreted after Gajewska, 1973b); 23 — Sulechów IG 1 (reinterpreted after Dembowski, 1972); 24 — Poddębice PIG 2 (reinterpreted after Iwanow, 2012); 25 — Lubliniec IG 1 (reinterpreted after Kotlicki and Siewniak-Madej, 1982); logged wells: 26 — E Meßdorf 1/71; 27 — E Boizenburg 1; 28 — Colnrade Z1 (reinterpreted after Barnasch, 2010); 29 — K 14-1 (reinterpreted after Barnasch, 2010); 30 — J 16-1 (reinterpreted after Barnasch, 2010); 31 — Løggumkloster 1 (reinterpreted after Michelsen and Clausen, 2002); 32 — E Wriezen 1/82 (unpublished core report); 33 — E Grunow 3/69 (unpublished core report); 34 — E Drebkau 105/64 (unpublished core report); 35 — Gostyń IG 1 (unpublished core report); 36 — Gościno IG 1 (unpublished core report); 37 — Trzebież 1 (unpublished core report); 38 — Zabartowo 2 (unpublished core report); 39 — Strzelno IG 1 (reinterpreted after Gajewska, 1973c); 40 — Krośniewice IG 1 (reinterpreted after Gajewska, 1973a); 41 — Ośno IG 2 (reinterpreted after Gajewska, 1983); 42 — Buk IG 1 (unpublished core report); 43 — Male Tyble 1 (unpublished core report); 44 — Dankowice IG 1 (reinterpreted after Grodzicka-Szymanko, 1973); 45 — Pagów IG 1 (reinterpreted after Jurkiewicz, 1976); 46 — Opoczno PIG 2 (reinterpreted after Kuleta and Iwanow, 2006); 47 — Łagów 1 (unpublished core report); outcrops visited: 1 — Am Hohnert, Eisenach; 2 — active clay pit Ansbach/Eyb; 3 — abandoned clay pit Farnersberg; outcrops cited herein: 4 — Scherre (Zweifelberg) near Haberschlacht (Köppen, 1997); 5 — Riedacker (Etzold and Bläsi, 2000); 6 — abandoned clay pit at Brosterberg (T43, Duchrow, 1984); 7 — outcrop Osterhagen (T63, Duchrow, 1984); 8 — outcrop Mittellandkanal Sehnde (Beutler et al., 1996); ECG — East Carpathian Gate, SMG — Silesian Moravian Gate.

Dembowski, 1972; Kannegieser and Kozur, 1972; Kozur, 1975) and need to be further justified in particular concerning their extension up to the northern CEB.

This paper presents detailed reconstructions of circum-Tethyan eustatic fluctuations of middle Carnian times. With an integrated approach of lithofacies, palynofacies and biofacies analyses combined with organic and inorganic geochemistry repeated and short-term transgressions from Tethyan waters into the epicontinental CEB are evidenced and guide to a framework of middle Carnian circum-Tethyan eustatic sequences of 3rd and 4th order.

Fig. 2. Reference section of the Stuttgart Formation in NE Germany: Gt Neubrandenburg 2/85. For legend see Fig. 3. Lower part: Biostratigraphic control and sequence-stratigraphy of the Neubrandenburg Member from W Poland to NE Germany and Central Germany. Range of selected taxa in the well Sulechow 1 according to Dembowski (1972), Gartz 1 and Schillingstedt 1 according to unpublished core reports, Wienholz and Kozur (1970) and Kannegieser and Kozur (1972).


Carnian
Weser Formation
Stuttgart Formation
Grabfeld Formation
Beaumont Mb
Upper Schilfsandstein Member
Gaildorf Mb
Lower Schilfsandstein Member
Neubrandenburg Mb
Depth (m)
Lithology
Lithofacies
123
Grain Size
cl-si
fs
ms
cs
Cyclicity
Pedogenic features
OK (Ohm/cm)
UK (Ohm/cm)
0
3
SP (mV)
-
+
15
GR (GE)
25
1475
1480
1485
1488.3
1489.5
1495
1500
1505
1510
1515.8
1520.5
1525
1530
1535
1540
1545
1550.3
1555
1560
1562.1
1565
1570
1575
FD 1582.0 m
small-scale cycles
bundles of small-scale cycles
destratif.
gypsisol
mottling
histosol
(14) Schillingstedt 1
(16) Morsleben 52A
(7) Neubrandenburg 2
(10) Gartz 1
(23) Sulechow IG 1
Lower Schilfs. Mb
Neubrandenb. Mb
Grabfeld Fm
260.5
270.2
402.25
411.55
1550.3
1562.1
1345.9
1360.3
529.1
538.4
onlap
SEG´s (%) AM+ABF+ALB
Sr (%)
SEG´s (%) AM+ABF
0
50
0.02
0.04
S. alpina
K. germanica
L. triassica
Gastropods
Speluncella sp.
Ammodisc.
RST
mfs
TST

2. Regional setting

In late Triassic times the epicontinental Central European Basin (CEB) was part of the northwestern Peri-Tethyan realm and located around 30°N (Stampfli and Borel, 2001). Surrounded by source areas it extended from today's North Switzerland to South Sweden and East Poland to East UK (Fig. 1). Since its formation in the Latest Carboniferous the CEB underwent significant subsidence through the Permian and Triassic resulting from crustal stretching and thermal subsidence (Bachmann and Grosse, 1989; Littke et al., 2008; and others). Following the retreat of the Middle Triassic Muschelkalk Sea largely terrestrial environments of the Upper Triassic Keuper established for longer times that were replaced not until the transgression of the Rhaetian Sea (Fischer et al., 2012; Franz et al., 2013).

The predominantly terrestrial Keuper comprises several rather thin but distinct marker horizons with a fauna including Tethyan immigrants and reveal repeated short-term transgressions from Tethyan waters through gates to the South and Southeast (Kozur, 1975; Aigner and Bachmann, 1992). Their distribution to the North varies strongly but some of them stretch up to the basin centre in northern Germany and are, therefore, of great stratigraphic importance (Kozur, 1975; DSK, 2005; Franz, 2008; Barnasch, 2010). Three of the marker horizons are detailed herein (Fig. 2).

With its typical variegated and pedogenic shales most of the Keuper strata indicate soil formation characterised by evaporation that strongly exceeded precipitation. Especially the Playa-like to Sabkha-like Grabfeld and Weser formations comprise thick halite deposits and abundant calcisols and gypsisols that suggest deposition under arid to semiarid climate (Nitsch, 2005a). Between these the Stuttgart Formation marks a pronounced change in lithology and is nowadays interpreted meandering channel-floodplain system (Shukla et al., 2010). Large-scale mapping revealed a network of NNE to SSW trending channel belts that tributed towards the South (Wurster, 1964; Gajewska, 1973d; Beutler and Häusser, 1982).

3. Materials and methods

With the aim of a basin-wide reconstruction of transgression horizons that frame the Stuttgart Formation, we concentrate on the transgression at the base of the Stuttgart Formation and integrate methods of classic lithofacies analyses, palynofacies, biofacies, geochemistry and sequence-stratigraphy. A data set that covers larger parts of the CEB is used herein: 17 cored wells, more than 100 logged wells and 3 outcrops. In addition published and unpublished core reports of 7 cored wells and 5 outcrops are included (Fig. 1).

Investigated cored wells and outcrops have been measured in detail, sampled and lithostratigraphically classified following Beutler in DSK (2005) and Franz (2008). The consecutive analysis of lithofacies comprises lithofacies types, facies associations and depositional environments. According to lithologies and physical bedding structures 13 lithofacies types, partly sensu Miall (1996), are established (Table 1), some of them resemble lithofacies types already described by Shukla et al. (2010). From the vertical succession and lateral transitions of lithofacies 7 facies associations (Table 2) are deduced incorporating available information on biofacies (e. g. palynofacies, mircopalaeontology) and geochemistry. Special attention has been paid on their contacts and bounding surfaces. To integrate logged wells the pattern of lithofacies associations identified in cored wells have been used as a rationale for interpretation. The vertical succession of lithofacies associations in neighbouring cored wells and outcrops and their distribution along cross-sections are used to reconstruct regional to basin-wide depositional environments. Depositional geometries and stratal pattern were analysed on cored wells and along cross-sections and tentatively interpreted according to the Transgressive-Regressive Sequence Model of Curray (1964) and Embry (1993, 1995).

For palynological analyses slides from 24 samples from cored well Morsleben 52A, 13 samples from cored well Neubrandenburg 2 and 3 samples from outcrop 'Am Hohnert' were made following the procedure described by Heunisch in Kustatscher et al. (2012). The slides were examined carefully and classified according to Heunisch (1999). For palynofacies analysis the Sporomorph Eco Group (SEG) method established by Abbink (1998) and Abbink et al. (2004a, 2004b) for Upper Jurassic to Lower Cretaceous palynomorph assemblages and recently modified by Heunisch in Kustatscher et al. (2012) for Triassic assemblages was applied. If possible 200 or at least 100 palynomorphs were counted for each slide and, if possible, assigned to Sporomorph Eco Groups.

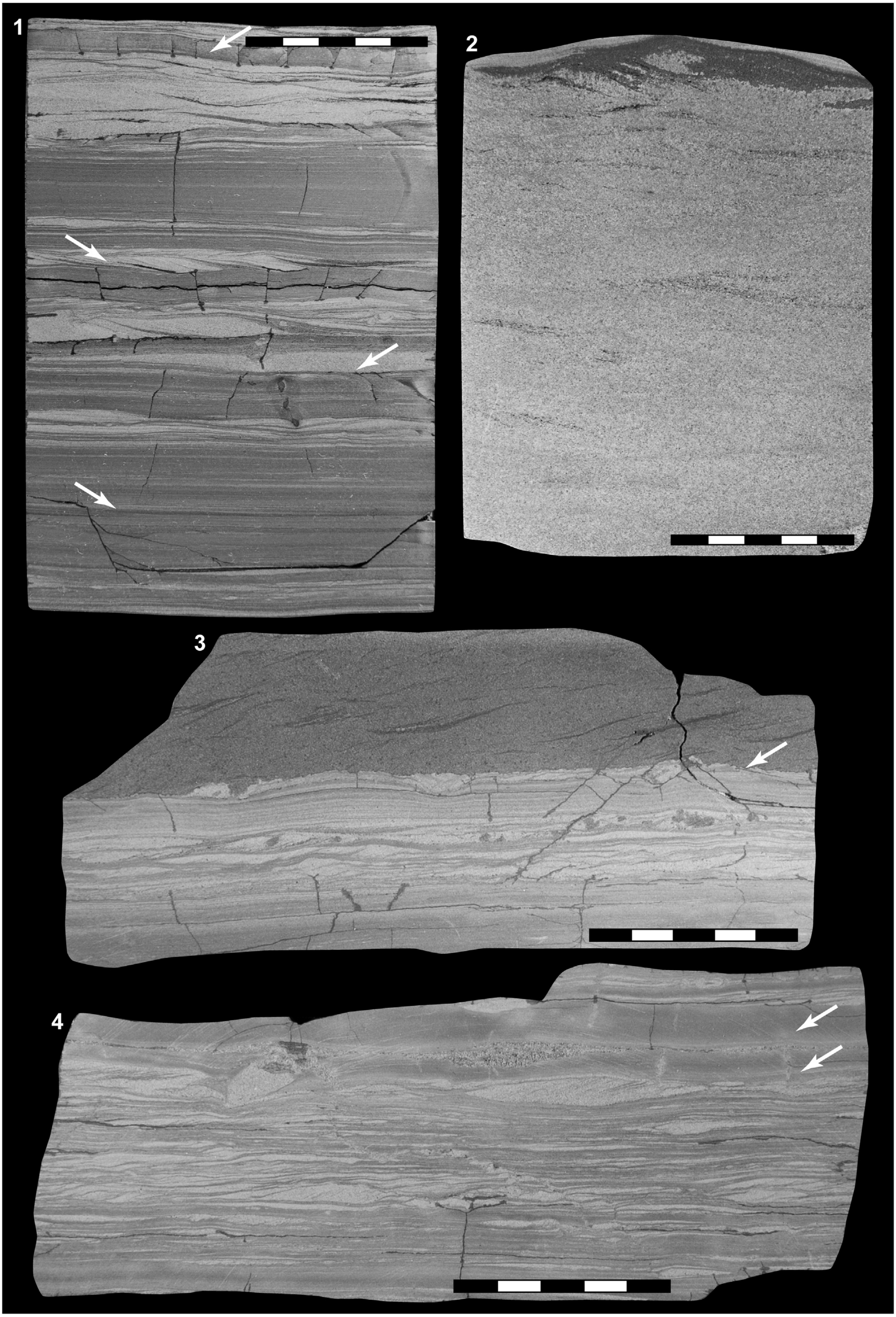
115 samples from cored well Morsleben 52A, 31 samples from cored well Neubrandenburg 2 and 3 samples from outcrop 'Am Hohnert' have been analysed by means of inorganic and organic geochemical methods. Inorganic geochemical methods have been applied to samples from the Morsleben 52A and outcrop 'Am Hohnert' at Federal Institute for Geosciences and Natural resources Hannover (BGR, Hannover, Germany) and to samples from Neubrandenburg 2 at ALS Laboratories Galway (Ireland). At BGR all samples were cleaned, dried at 50 °C for 48 h and pulverised (grain size <100 μm) using 'flying disc' mills. The major and minor element compositions have been analysed by means of XRF methods. 1 g of each pulverised sample was annealed at 1030 °C in a muffle furnace for 10 min. Samples with a weight loss smaller than 25% were supplied with 5 g of $LiBO_2$ and 25 g of LiBr; samples with losses greater than 25% were supplied with 2.5 g of $LiBO_2$, 2.415 g of Li_2B4O_7 and 25 g of LiBr. These mixtures have been homogenized, melted into pellets (i.e. PtAu-crucibles at 1200 °C for 20 min) and analysed using a PANalytical AXIOS (2.7 kW rhodium x-ray anode) and Philips/PANalytical PW2400 (chrome x-ray anode). References and standards have been measured successively to ensure quality control and results were evaluated and corrected using SuperQ 4 software. At ALS Laboratories Carbon and sulphur were determined by combustion furnace and acid digestion, major elements and base metals by ICP-AES ($LiBO_2$ fusion, four acid digestion), trace elements and REE's by ICP-MS ($LiBO_2$ fusion). Selected results of major element concentrations are given as weight percentage of dry rock and minor element concentrations as mg per kg of dry rock (Supplement D).

Organic geochemical methods have been applied to samples from cored well Neubrandenburg 2 and outcrop 'Am Hohnert' at BGR, Hannover (Germany). Total sedimentary sulphur (TS), and total organic and inorganic carbon (TOC, TIC) were determined with a LECO CS-200 elemental analyser (EA) and RockEval pyrolyses were carried out with a RockEval-6 Classic S3 (Vinci-Technologies) following the standard procedure described in Behar et al. (2001). Results of selected organic parameters relevant for the study are given in Supplement D.

4. Results

Natural outcrops of the Stuttgart Formation are limited to the southern parts of the CEB (e. g. Thuringia, South Germany). Hence, detailed

Plate I. Lithologies of the Neubrandenburg Member, scale bar 5 cm; 1 — Sample N2/22/11/2010-15b from cored well Gt Neubrandenburg 2/85, depth 1560.0–1560.2 m, slightly above maximum flooding surface, alternation of dark laminated claystone–siltstone and heterolithic lithofacies (lenticular bedded and flaser bedded siltstone–sandstone), rarely bioturbated, note small-scale normal graded units (lower arrows) and fluid mud layer close to the top (upper arrow); 2 — Sample N2/22/11/2010-17b from cored well Gt Neubrandenburg 2/85, depth 1559.3–1559.4 m, ripple cross-laminated siltstone–sandstone lithofacies of mouth bar facies association; 3 — Outcrop sample 'Am Hohnert'-1 ca. 20 cm above base of Neubrandenburg Member, inverse gradation from laminated claystone–siltstone (lower part) through lenticular bedded siltstone–sandstone and wavy-bedded siltstone–sandstone (middle part) to ripple cross-laminated sandstone (upper part) depicts change from suspension load to bed load, note slightly erosive base of Sr lithfoacies (arrow); 4 — Outcrop sample 'Am Hohnert'-2 ca. 1.4 m above base Neubrandenburg Member, heterolithic lithofacies, lenticular bedded siltstone–sandstone comprises narrow and up to 1 cm thick lentils, fluid mud layers in the upper part show small syneresis cracks (arrows).



descriptions regarding stratigraphy and facies are largely focused on these areas. With respect to remarkable differences from South to North especially concerning the basal part of the Stuttgart Formation we introduce the cored wells Gt Neubrandenburg 2/85 and Dp Morsleben 52A/95 as reference-sections in the northern CEB and central CEB, respectively. For comparison we use the outcrop 'Am Hohnert' northwest of Eisenach (Thuringia).

4.1. Stratigraphic control on the Stuttgart Formation

4.1.1. Lithostratigraphy

The predominantly sandy to shaly Stuttgart Formation is bounded by the shaly and evaporitic Grabfeld and Weser formations to the base and top. The base of the Stuttgart Formation was defined at the base of an up to 20 m thick prominent shaly horizon (Beutler in DSK, 2005) that is herein named Neubrandenburg Member (Fig. 2). The top of the Stuttgart Formation was defined at the base of the up to a few metres thick Beaumont Member (Beutler in DSK, 2005; Etzold and Schweizer in DSK, 2005) also referred to as Dolomie de Beaumont, Dolomie de Elie de Beaumont, Horizont Elie de Beaumont's, Horizont Beaumont, Hauptsteinmergel, Gansingen Dolomite or Beaumont Sulphate (review in Etzold and Schweizer in DSK, 2005). Both, the Neubrandenburg and Beaumont members document transgressions from Tethyan waters up to the northern CEB that pre- and post-dated the fluvial main part of the Stuttgart Formation (Fig. 2). A further transgression up to the northern CEB is documented within the Gaildorf Member (Lang, 1909) by the occurrence of ostracods, gastropods, fishes and marine plankton (Thürach, 1888/1889; Kannegieser and Kozur, 1972; this work, see 4.3). The Gaildorf Member separates the Lower and Upper Schilfsandstein members (Kozur and Bachmann, 2010). Thus, in terms of lithostratigraphy the Lower and Upper fluvial Schilfsandstein members are framed by transgression horizons referred to as Neubrandenburg Member, Gaildorf Member and Beaumont Member (Fig. 2). All these members are well documented within the cored well Neubrandenburg 2 that is considered reference section of the Stuttgart Formation in NE Germany.

4.1.2. Biostratigraphy

Biostratigraphic control of the Stuttgart Formation is provided by palynomorph zonations that are well constrained (Schulz and Heunisch in DSK, 2005). The Stuttgart Formation corresponds to the *Aulisporites astigmosus* zone according to Orłowska-Zwolińska (1983), the *Gibeosporites lativerrucosus*–*A. astigmosus* zone according to Reitz (1985) and Schulz (1976) and the GTr 14 zone according to Heunisch (1999). Most investigated samples of the Stuttgart Formation are characterised by high amounts of *A. astigmosus* — the typical marker species of the Stuttgart Formation.

Further biostratigraphic control is given by the occurrence of *Simeonella alpina* Bunza & Kozur and other Tethyan ostracods occurring within a short interval close to the base of the Stuttgart Formation and the upward change to an assemblage with *Karnocythere germanica* Wienholz & Kozur and other forms but without *S. alpina* (Wienholz and Kozur, 1970; Dembowski, 1972; Kannegieser and Kozur, 1972; Kozur, 1975). The wide-spread distribution of *S. alpina and K. germanica* enables the time constrained-correlation of the basal Neubrandenburg Member from NW Poland (Sulechow IG 1, Dembowski, 1972) to northern Germany (Tarnow 1, unpublished core report) and northern Thuringia (Schillingstedt 1, unpublished core report; Fig. 2).

Based on the occurrence of *S. alpina* and other arguments the Stuttgart Formation was correlated with the upper subzone of the late Julian *austriacum* ammonoid zone (for details see Bachmann and Kozur, 2004; Kozur and Bachmann, 2010). This correlation is modified herein and the range of the Stuttgart Formation is extended up to the early Carnian *dilleri* zone (see 4.7).

4.1.3. Conformities and disconformities

Wolburg (1969) first described the disconformable contact of the Stuttgart Formation to the strata below and later many workers contributed disconformity-based Keuper stratigraphy (DSK, 2005).

However, the unconformity at the base of the Stuttgart Formation (see Bachmann and Kozur, 2004; Nitsch, 2005b; Franz, 2008; Barnasch, 2010; Kozur and Bachmann, 2010) is not supported by the new data from the northern CEB. The uppermost Grabfeld Formation consists of grey to dark grey laminated shales and mudstones forming up to a few metres thick small-scale cycles. Individual cycles comprise dark shales in the lower part, grade vertically into mudstones and are punctuated by palaeosols at the top. To the top stacking pattern of small-scale cycles indicate successive decrease of mudstones, increase of laminated shales and change from mature to rather incipient palaeosols. As the basal part of the Neubrandenburg Member is dominated by laminated dark shales the 'boundary' between both formations appears transitional in the northern CEB (Figs. 3 and 4). This is accompanied by a similar successive change in Sporomorph Eco Groups (SEGs). Both, the transition in lithology and palynomorph assemblages suggest a step-wise facies shift from the Grabfeld Formation to the Stuttgart Formation and exclude a long time gap between both formations. As we have recognised a similar transition in all cored wells from the northern CEB investigated in this study we exclude a disconformity in the central parts of the basin. To the South the boundary between the Grabfeld and Stuttgart formations becomes more distinct in Thuringia and South Germany (Fig. 5). A transition between both formations is missing and therefore this boundary may be considered disconform and associated to a very short time gap in the southern CEB (Fig. 2). In the case of fluvial incision prior to the deposition of the Neubrandenburg Member, for example: outcrop Farnersberg (Kozur and Bachmann, 2010; this work), the disconformable contact of the Grabfeld and Stuttgart formations may be associated to a somewhat longer time gap. Further disconformable contacts of the Stuttgart Formation to the strata below have been reported from basin margins and basin internal swells like the Eichsfeld–Altmark Swell and others (Barnasch et al., 2005; Franz, 2008; Barnasch, 2010).

In contrast the bases of the Lower and Upper Schilfsandstein members are in many cases marked by a sharp change from shaly to sandy lithologies (Figs. 2–5). Substantial erosion is associated to these disconform boundaries if the channel facies of the fluvial members cut into the underlying Neubrandenburg and Gaildorf members or removed them completely (Bachmann and Wild, 1976; Beutler and Häusser, 1982; Nitsch in DSK, 2005; Franz, 2008; Barnasch, 2010).

4.2. The pre-Schilfsandstein transgression: upper Grabfeld Fm to Neubrandenburg Mb

4.2.1. Lithofacies

According to grain size and physically bedding structure 10 types of primary depositional lithofacies of the uppermost Grabfeld Formation and Neubrandenburg Member are described (Table 1). Some of them resemble lithofacies previously described by Shukla et al. (2010). In addition 3 types of secondary lithofacies are described in order to include pedogenic processes. The lithofacies types of the Lower and Upper fluvial Schilfsandstein members are not included here; they will be described elsewhere.

4.2.2. Lithofacies associations

Desiccated salina In North Germany up to several decametres thick halite units C–E (sensu Beutler, 1995) have been cored in Ketzin 12, Ketzin 32 and Ketzin 38 wells; they are further evidenced in numerous logged wells (Franz, 2008; Barnasch, 2010). The halite appears colourless and clear or slightly brownish to intensely reddish, shows up to some centimetres large chevrons or cornets (Beutler, pers. comm.) and forms intercalations with thin beds of dark laminated

Table 1
Lithofacies types of the Upper Grabfeld Formation and Neubrandenburg Member with description and interpretation. Types marked with asterisks are intensely modified by peogenic (secondary) processes. Palaeosols are classified according to Mack et al. (1993).

Lithofacies	Description	Processes — Interpretation
Halite (Hal); examples: Ketzin 38	Up to several decametres thick, colourless and clear or reddish, rarely several centimetres large chevrons; clay lamina interbedded; **Upper Grabfeld Formation**	Precipitation from halite saturated brine
Intraformational breccia (B), examples: Ketzin 38, Neubrandenburg 2	Up to 1.5 m thick, chaotic clast-to-clast fabric of angular mudstones, halite remnants; sharp base/top; cavities filled with shaly matrix; **Upper Grabfeld Formation**	Dissolution of evaporites: collaps breccia
Mud-pebble-bearing mudstone (R), Lf 6 sensu Shukla et al. (2010)	30–100 cm thick, base erosional, top gradational to Ml and Cl; grey elongated clasts of Ml up to 5 cm, black to darkgrey and shaly to clayey matrix, matrix to clast supported; normal gradation; **Upper Grabfeld Formation**	Reworking of desiccated surfaces by traction currents of a sheet flood
Ripple cross-laminated siltstone–sandstone (Sr), Lf 4 sensu Shukla et al. (2010), examples: Plate 1-1, 1-2, 1-3,	<20 cm thick, base slightly erosional, top often gradational to Ml,Cl and Sh; amalgamated sets of current ripples are up to 20 cm thick, isolated trains of current ripples alternate with Het and Cl; Neubrandenburg Member	Migrating ripples, low velocity bed load transport in shallow water
Laminated sandy siltstone (Sh), Lf 7 sensu Shukla et al. (2010), examples: Neubrandenburg 2	Up to 2.5 m thick, base gradational to Cl and Het, top sometimes with Fr or C; sometimes root traces, bedding planes with abundant plant fragments; Neubrandenburg Member	Suspension load, settling from suspension
Laminated claystone–siltstone (Cl), examples: Plate 1-1, Ketzin 38, KSS 1	Up to 2.5 m thick, dark grey to grey, base sharp to L and gradational to R, Sr and Het, top gradational to Het and sometimes with Fr or C; bedding planes with abundant plant fragments and mica; rarely syneresis cracks; variable degrees of bioturbation; Upper Grabfeld Formation and Neubrandenburg Member	Suspension load, settling from suspension in stagnant water
Massive claystone–siltstone (Cm), examples: Plate 1-1,	Max. 2 cm thick, lack of lamination and bioturbation, shap base and top, interbedded with Cl and Het; syneresis cracks; Neubrandenburg Member	Deposition from suspension of buoyant plumes, fluid mud
Laminated mudstone (Ml), Lf 8 sensu Shukla et al. (2010), Neubrandenburg 2, Morsleben 52A	Up to 3.0 m thick, grey, base gradational to Cl and sharp to Fr or C, top gradational to Fr and C, sharp to Cl and erosional to R; silt lamination, minor carbonate content, initial overprint of primary bedding features due to incipient pedogensis, rarely brecciation, colour mottling greenish to reddish; variable degrees of bioturbation; Upper Grabfeld Formation and Neubrandenburg Member	Suspension load, settling from suspension in stagnant water body; upper plane-bed of sheet flows; occasional drying and carbonate precipitation due to evaporation
Heterolithes (Het), examples: Plate 1-1, 1-3, 1-4, Fig. 8a, b	Up to 5.0 m thick, base gradational to Cl, top gradational to Cl, Sh, Sr; two end members with transitions: shale-rich heterolithes comprise isolated silty to sandy lamina and ripples, sand-rich heterolithes appear as horizontal to ripple cross-laminated siltstone–sandstone regularly dissected with thin shale lamina; rarely superimposed by wave ripples and hummocky-cross strat.; in part rich in plant fragments, variable degrees of bioturbation; Neubrandenburg Member	Laminated shales, lenticular, flaser and wavy bedding: repeated fluctuation of sediment input and modulation by waves, storms and currents
Limestone (L), examples: Neubrandenburg 2, Ketzin 38	5–20 cm thick, base and top sharp to Cl and Ml; light grey to grey and massive limestone to dolomitic limestone; partly fossiliferous; Neubrandenburg Member	Precipitation from carbonate saturated water
Siltstone–sandstone with root traces (Fr)*, examples: Morsleben 52A, Am Hohnert	Up to 2.0 m thick partly destratified horizons of Ml and Sh, top sharp to Cl and Ml, gradational to C; vertical to subvertical and branched tubes are filled with black carbonaceous matter; Neubrandenburg Member	Rooting of pioneer vegetation
Coal (C)*, examples: Neubrandenburg 2, Am Hohnert	Up to 20 cm thick, base gradational to Fr, top sharp to Cl and Ml; compacted carbonaceous material (mainly altered plant remnants); in outcrops laterally terminating; Neubrandenburg Member	Histic epipedon of peat soils, histosol
Palaeosol (P)*, examples: Fig. 8a	Single palaeosols up to 1.5 m, stacked palaeosols up to 5.5 m; base always gradational, top sharp; 1) vertisol: variegated to reddish colours, destratified, desiccation cracks, slickensides; 2) calcisol: variegated to reddish colours, calcic subsurface horizon with scattered carbonate nodules; 3) gypsisol: variegated to reddish colours, gypsic subsurface horizon with scattered displacive gypsum nodules; Upper Grabfeld Formation and Neubrandenburg Member	Mature palaeosols, floodplain; 1) vertisol: pedoturbation, repeated shrinking/swelling of clays; 2) calcisol: calcic horizon, evaporative loss of capillary flow; 3) gypsisol: gypsic horizon, evaporative loss of capillary flow;

claystone–siltstone. Laterally and upward halites are associated to intraformational breccias (Fig. 2). Up to decimetre large clasts of laminated mudstones are angular in shape and their clast-to-clast contact indicates dissolution of halite and in-situ fracturing of mudstone beds. The matrix is formed of shaly to sparry dolomite, rarely former halite is still present (e. g. Morsleben 52A).

Comparable layered halite has been described from central Germany (Dockter et al., 1970), South Germany (Beutler and Nitsch in DSK, 2005; Nitsch, 2005c), Poland (Gajewska et al., 1985), England (e.g. Haslam et al., 1950; Arthurton, 1973, 1980; Warrington, 1974) and NE France (e.g. Maubeuge, 1950; Geisler, 1979; Marchal, 1983). A primary marine origin was demonstrated for the halite from Poland, NE France and

Table 2
Facies associations and reconstructed depositional environments of the Upper Grabfeld Formation and Neubrandenburg Member, predominating lithofacies types underlined.

Depositional environment	Facies association (FA)	Lithofacies types (LFT)
Fluvial plain and fluvial deltas	Flood plain	Ripple cross-laminated siltstone–sandstone, horizontal bedded sandy siltstone, laminated claystone–siltstone, laminated mudstone, vertisol
	Delta plain	Laminated claystone–siltstone, laminated mudstone, horizontal bedded sandy siltstone, ripple cross-lamin. siltstone–sandstone, heterolithes, siltstone–sandstone with root traces, coal
	Mouth bar	Heterolithes (lenticular, wavy and flaser bedded), ripple cross-laminated siltstone–sandstone, horizontal bedded sandy siltstone, laminated claystone–siltstone
Shallow inland sea	Marine–brackish	Laminated claystone–siltstone, heterolithes, limestone, ripple cross-laminated siltstone–sandstone, massive claystone–siltstone
Inland sabkha	Shallow lake	Laminated claystone–siltstone, laminated mudstone, mud-pebble-bearing mudstone
	Mudflat	Laminated mudstone, vertisol, gypsisol, calcisol
	Dessicated salina	Halite, intraformational breccia, laminated mudstone

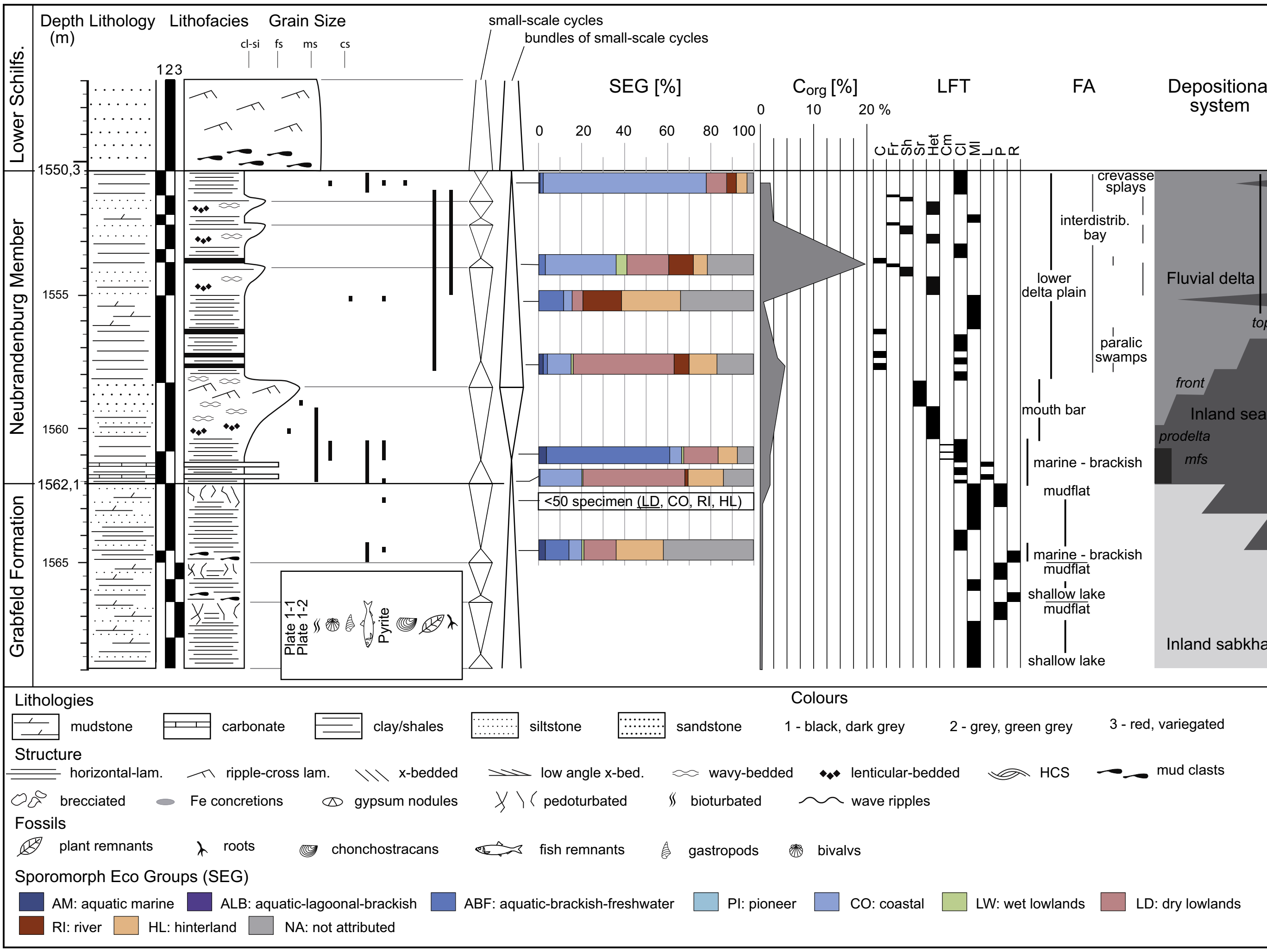


Fig. 3. Detailed litholog of the Neubrandenburg Member in the reference section Gt Neubrandenburg 2/85 with lithofacies types, lithofacies associations, Sporomorph Eco Groups and interpreted depositional systems.

England by means of bromine values between 80 and 230 ppm (Haslam et al., 1950; Geisler, 1979; Gajewska et al., 1985). However, at some locations bromine values are depleted suggesting recycling of primary first-cycle halite (Wardlaw and Schwerdtner, 1966; Gajewska et al., 1985). The structure of layered halite corresponds to successions described from modern salt-pans (Lowenstein and Hardie, 1985) or salinas (Handford, 1991). As the lamination of mudstone lithofacies suggests sedimentation of suspension load (Rouse, 1939; Middleton, 1976) depositional mode varied between precipitation of halite and settling from suspension. This may correspond to the flooding and evaporation stages of the saline-pan cycle described by Lowenstein and Hardie (1985). To the top halites and brecciated horizons are followed by lithologies of the mudflat facies association. This vertical succession of salina and mudflat associations argues for the retreat of the former that enabled the progradation of the latter. Retreat of the salina resulted in large desiccation cracks forming polygonal pattern (Richter-Bernburg, 1980; Marchal, 1983) and corresponds to the desiccation stage of Lowenstein and Hardie (1985). Accordingly we use the term desiccated salina (Maiklem, 1971; Lowenstein and Hardie, 1985).

Mudflat facies association Laminated mudstone lithofacies with features of incipient pedogenesis and mature palaeosols form an association that follows desiccated salina and shallow lake associations in the upper Grabfeld Formation (Figs. 3–5). Due to incipient pedogenesis the lamination of mudstones becomes fuzzy but remains visible. The lamination suggests sedimentation of suspension load (Rouse, 1939; Middleton, 1976) but, especially if silt laminae occur frequently, deposition within the upper plane-bed regime of unconfined sheet flows may also be possible (Bridge, 1978; Handford, 1982; Bridge and Best, 1988; Paola et al., 1989). Regardless the mode of sedimentation incipient pedogenesis evidences short-term subaerial exposure (Retallack, 1986). Longer times of subaerial exposure led to mature palaeosols like vertisols, calcisols and gypsisols (sensu Mack et al., 1993). The mature palaeosols of the Upper Grabfeld Formation argue for repeated drying down to subsurface horizons under hydrologic regimes where evaporation strongly exceeds precipitation and resulted in scattered displacive nodules of calcite or gypsum (Fig. 6b). Repeated changes of wide-spread sedimentation of fine clastics followed by drying, subaerial exposure and pedogensis are typical features of mudflats in terrestrial environments (Smoot, 1983; Flint, 1985; Mertz and Hubert, 1990).

Shallow lake facies association This typical association of the uppermost Grabfeld Formation forms up to a few metres thick successions: mud-pebble-bearing mudstone at the base followed by laminated claystone–siltstone and laminated mudstone to the top (Figs. 3–5). Commonly dark coloured laminated lithofacies types dominate this association and are thought to have been sedimented from suspension load (Rouse, 1939; Middleton, 1976). The dark colours and abundant pyrite probably suggest oxygen deficient bottom waters. Mud-pebble-bearing mudstones comprise rip-up clasts suspended in clayey–silty matrix and represent basal lag deposits of sheet flood traction currents (Hartley, 1993). The often limited thicknesses of lacustrine successions and their rapid transition to the mudflat facies association indicate a temporally rather limited existence of shallow lakes. Despite this lithologies of the shallow lake facies association often comprises abundant fish remnants, conchostracans and bivalves (e.g. *Anoplophora lettica* Quenstedt) of probably brackish ecology, for example in the cored wells Tarnow 1, Flieth 1 and Gartz 1 (Kozur, 1975; unpublished core reports).

Marine-brackish facies association Dark coloured laminated claystone–siltstone lithofacies and heterolithes are typical representatives of the Neubrandenburg Member in the northern and central parts of the basin (Plate 1-1, 1-3, 1-4). Massive claystone–siltstone, thin limestone beds and thin beds of ripple cross-laminated siltstone–sandstone occur only subordinated. Laminated claystone–siltstone represents deposits from suspension load (Rouse, 1939; Middleton, 1976) and heterolithic interbeds with scattered wave rippled surfaces suggest repeated fluctuations in sediment input and modulation by wave action and unidirectional flows (Fig. 5b; Reineck, 1963; Reineck and Singh, 1980). The thin and partly fossiliferous limestone beds recorded in cored wells Morsleben 52A and others as well as in numerous logged wells (e.g. Prenzlau 1, Schilde 1) indicate at least temporally carbonate saturation.

Variations in clastic input produced intercalated units of small-scale fining and coarsening upward grain sizes. Up to a few centimetres thick fining upward units are formed of laminated sandy siltstone that grade into laminated claystone–siltstone and are considered distal deposits of hyperpycnal density underflows (Plate 1-1; Wright et al., 1988; Mulder and Syvitski, 1995). Whereas coarsening upward from laminated claystone–siltstone through heterolithics to ripple cross-laminated siltstone–sandstone is ascribed to discharge variations of a feeder system (Plate 1-3; Bhattacharya, 2006). Up to 2 cm thick layers of massive claystone–siltstone are commonly considered fluid-mud layers rapidly deposited out of buoyant river plumes (Plate 1-1, 1-4; Kuehl et al., 1986; Allison et al., 2000; MacEachern et al., 2005).

The typical features of lithofacies identified to the marine-brackish association are the wide-spread occurrence of a euryhaline marine to brackish fauna with plankton, foraminifera, ostracods, gastropods and bivalves (see 4.2.3). Marine ostracods are described from Poland, NE Germany and Thuringia and enable some biostratigraphic control (Fig. 2). Correspondingly, palynomorph assemblages comprise up to 3.5% marine, 57.5% brackish–freshwater, 5.9% brackish–lagoonal and 19.5% coastal SEGs (Figs. 3, 4, Supplements A, B). The marine influence in the lower part of the Stuttgart Formation most probably extended up to southern Germany as proposed by Köppen (1997).

Mouth bar facies association The upward gradation from laminated claystone–siltstone through heterolithes to finally ripple cross-laminated siltstone–sandstone becomes visible as an overall trend for example in the cored well Neubrandenburg 2 (Fig. 3, Plate 1-1, 1-2). It reflects the successive change from suspension load to bed load as dominant mode of deposition and is accompanied by coarsening from shaly to sandy grain sizes. Both are diagnostic features of prograding mouth bar facies associations of fluvio-deltaic environments (Scruton, 1960; Coleman and Wright, 1975; Elliott, 1986). In individual sections mouth bar facies associations form up to 3 m thick successions that generally translate from marine–brackish associations into delta plain associations (Bhattacharya and Walker, 1992). Internally mouth bar successions are formed of coalesced normal graded units ranging from centimetres to a few decimetres in thicknesses.

Delta plain facies association In NE Germany marine–brackish and mouth bar associations are followed by up to a few metres thick dark laminated claystone–siltstone and laminated mudstone lithofacies that represent deposits from suspension load in stagnant water bodies (Rouse, 1939; Middleton, 1976). These lithofacies comprise a sparse fauna of Unionid bivalves, fish remnants and conchostracans, are generally rich in plant fragments or debris, comprise individual horizons with root traces and up to 20 cm thick horizons of compacted carbonaceous material (Figs. 3–5). High input of plant remains suggest vegetated banks associated to stagnant water bodies and the rooted and

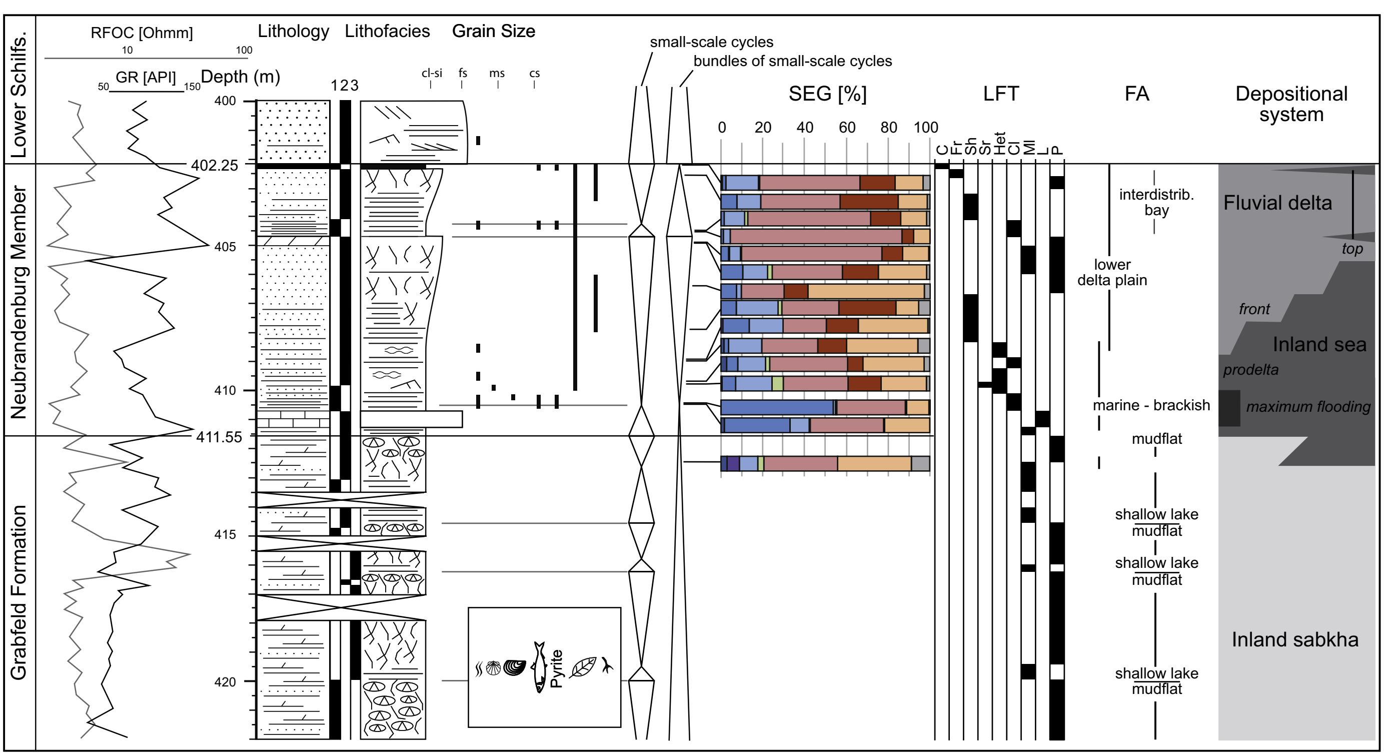


Fig. 4. Detailed litholog of the Neubrandenburg Member in the standard-section Dp Morsleben 52A/95 with lithofacies types, lithofacies associations and interpreted depositional systems. For legend see Fig. 3.

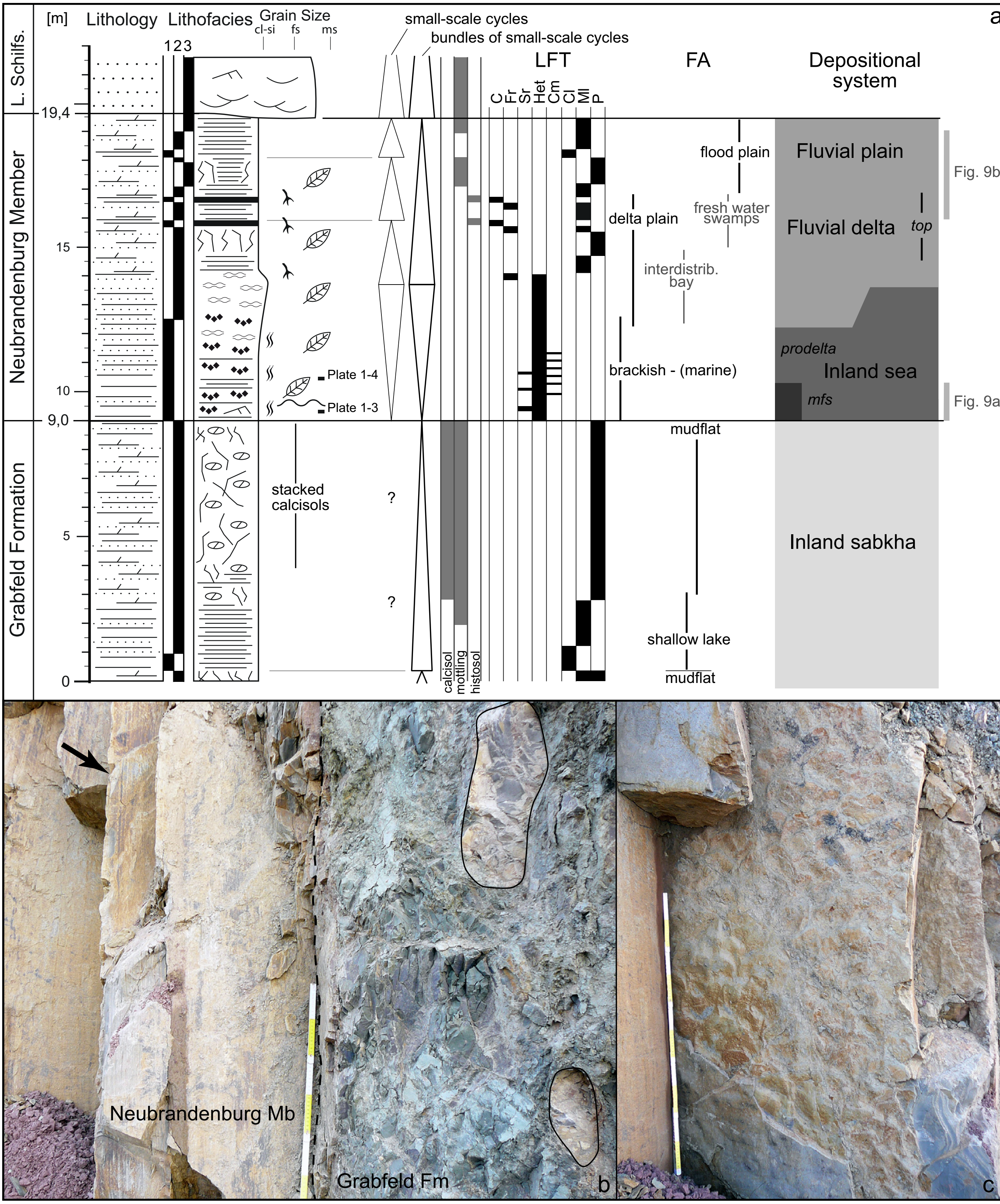


Fig. 5. Neubrandenburg Member in the outcrop 'Am Hohnert' (Thuringia). a — Detailed litholog with lithofacies types, lithofacies associations and interpreted depositional systems. b — Sharp and slighly erosive base of the Neubrandenburg Mb (dashed line) with heterolithes overlying greenish to variegated and destratified mudstones of the Grabfeld Formation. Large dolomite nodules of a petrocalcic horizon are circled (calcisol). The arrow marks the bedding surface shown in c. c — Wave ripples at the top of an about 60 cm thick succession of heterolihtes. Scale is 1 m. For legend see Fig. 3.

carbonaceous horizons their temporal swamping. The described features correspond to interdistributary bays and paralic swamps of modern delta plain environments (Ta et al., 2002; Fielding et al., 2005). In other sections the succession of marine–brackish and delta plain associations corresponds to the transition from prodelta to fluvial delta plain environments without the development of a sandy shoreline (Walker and Harms, 1971; Bhattacharya and Walker, 1991). Delta plain shales and mudstones often comprise up to 1 m thick inverse graded silty to sandy crevasse splays (Fig. 3, Coleman and Prior, 1982). Subaquatic exposure and episodic reworking by oscillatory flows are indicated by scattered hummocky cross stratified horizons in cored wells Tarnow 1 and Gartz 1 (De Raaf et al, 1977). However, as the clear distinction of delta plain sub-environments remains difficult in cored wells we refer to the term delta plain association. The distinction between lower and upper delta plain sensu Coleman and Prior (1982) is enabled by subordinated occurrences of autochthonous marine–brackish SEGs observed in cored wells Neubrandenburg 2 and Morsleben 52A (Figs. 3 and 4). A comparable temporal marine–brackish influence was reported by Köppen (1997) from southern Germany and Heunisch in Beutler et al. (1996) from outcrop Sehnde.

In central Germany and western Mecklenburg the delta plain association comprises laminated mudstones subordinated to laminated claystone–siltstones or as predominating lithofacies (Fig. 5). Root traces and thin carbonaceous horizons occur as well but because laminated mudstones are often colour mottled and contain mud cracks and brecciation, subaerial exposure and pedogensis seem to be prominent features. Accordingly, a marine–brackish influence cannot be demonstrated and therefore the described successions may represent the upper delta plain sensu Coleman and Prior (1982).

Flood plain facies association In the southern and northern parts of the CEB up to 2 m thick successions are dominated by laminated mudstones that comprise thin intercalations of horizontal laminated sandy siltstone and ripple cross-laminated siltstone–sandstone in the lower part. To the top the increase of pedogenesis led to, in part, complete destruction of primary bedding structures. In some cases larger parts of the successions are destratified and comprise immature vertisols at their tops (Fig. 5). Thus the overall nature of these successions appears indicative of coupled drying upward and fining upward trends. The described successions indicate episodic sheet flooding of wide and very gently sloping plains with deposition within the upper plane-bed regime (Bridge, 1978; Handford, 1982; Bridge and Best, 1988; Paola et al., 1989). Following flooding plains dried and longer times of subaerial exposure enabled their modification by pedogenic processes. These pedogenic fining upward mudstone-dominated successions are commonly described from flood plain-like environments (Farrel, 1987; Kraus and Gwinn, 1997; Buatois and Mangano, 2002).

4.2.3. Biofacies

The transgression from Tethyan waters resulted in the establishment of a shallow inland sea and enabled immigration of marine fauna from Tethyan habitats.

4.2.3.1. Palynomorphs. The palynomorph spectrum comprises planktonic taxa, mostly of algal origin ranging from marine up to fluvio-lacustrine environments, which are classified as (par)autochthonous, and dispersed sporomorphs from land plants, classified as allochthonous elements (Supplement A).

Short characteristics of important taxa, based on SEGs

AM: aquatic marine. *Micrhystridium* spp., (acritarcha) and scytinaceae (organic foraminiferal linings) are present in low percentages in the basal and uppermost Neubrandenburg Member, and scytinaceae only in the uppermost Grabfeld Formation (Figs. 3 and 4). Their occurrences point to marine influence from the uppermost Grabfeld Formation to the uppermost Neubrandenburg Member (Supplement B).

ALB: aquatic–lagoonal–brackish. This group comprises prasinophycean algae thought to indicate lagoonal or hypersaline to brackish environments. The present taxa are *Leiosphaeridia* spp. and *Tytthodiscus* spp. that have been recorded in two samples of the cored well Morsleben 52 A where they partly co-occur with acritarchs (Fig. 4).

ABF: aquatic–brackish–freshwater. This group is represented by colonial green algae *Botryococcus* sp., *Plaesiodictyon mosellanum* and accessorily Zygnemataceae and virtually present in all investigated samples of the Neubrandenburg Member (Supplement B). The maximum abundance is recognised in the basal part of the Neubrandenburg Member (Figs. 3 and 4). This maximum abundance coincides with the maximum extension of the inland sea and therefore documents its maximum flooding (Fig. 2).

TI: tidally-influenced. There plants regularly get 'wet feet' by the daily tidal changes. *Densoisporites* spp. belongs to this community.

PI: pioneer. *Protodiploxypinus* spp. and *Cerebropollenites* sp. are assigned to this group that is thought to originate from coastal pioneer plants that grew in the unstable environment in front of the coastal zone (Abbink, 1998). Representatives of this SEG have been recorded in two individual samples only where they occur rarely (Supplement A).

CO: coastal. Representatives of this group are sporomorphs produced by lycophyts: *Aratrisporites* spp. and *Leschikisporis aduncus* (Supplement B). The taxon *Aratrisporites* is considered element of a mangrove-like vegetation (Grauvogel-Stamm and Duringer, 1983). Also spores of Araucariaceae were recorded in low numbers, represented by *Araucariacites australis*. This SEG is recognised throughout the Neubrandenburg Member in cored well Morsleben 52 A (Fig. 4). Contrary its abundance increase towards the top of the Neubrandenburg Member in cored well Neubrandenburg 2 (Fig. 3).

LW: wet lowlands or marshes. *Porcellispora longdonensis*, produced by liverworts, and other spores are tentatively assigned to this SEG. The parent plants are thought to have vegetated freshwater swamps and wet lowlands (e. g. marshes) where they perhaps lived drifty at the water surface. They are also described from sabkha lakes of the Grabfeld Formation (e.g. Hauschke and Heunisch, 1990). Representatives of this SEG occur only subordinated in the uppermost Grabfeld Formation and the Neubrandenburg Member.

LD: dry lowlands. One of the most characteristic taxa of the Stuttgart Formation is *Aulisporites astigmosus* (Supplement B) that was found in situ in *Williamsonianthus keuperianus*, which belongs to cycadophytes (Kustatscher et al., 2012, Table 2). Ferns are represented e.g. by *Deltoidospora* spp. *Ovalipollis pseudoalatus* and other forms are tentatively assigned to this SEG. According to E. Kustatscher (pers. comm.) the producer plant of *Ovalipollis pseudoalatus* (Supplement B) could be a cycadophyte (Reissinger, 1950), a conifer (e.g. Scheuring, 1970) or could belong to the Bennettitales (Schulz, 1967). Those relationships would also match with coastal or hinterland SEGs and suggest that individual taxons may occur in several SEGs and are not restricted to one (Götz et al., 2011). The SEG of dry lowlands forms a substantial part of the total palynomorph spectra throughout the Neubrandenburg Member with highest abundances of up to 80% in its upper parts (Figs. 3 and 4).

RI: river. This SEG is mostly represented by fern spores, e.g. *Punctatisporites* spp. and *Verrucosisporites* spp. as well as equisetites spores (*Calamospora* spp.). Corresponding to the SEG of dry lowlands the abundances of the river bank SEG generally increase towards the top of the Neubrandenburg Member where it makes up almost 30% of the total palynomorph spectra.

HL: hinterland. Bisaccate pollen grains mostly are assigned to this SEG. Besides the big group of bisaccates pollen grains not attributed to specific species like *Triadispora* spp. (Supplement B) and also taeniate pollen grains like *Protohaploxypinus* and *Striatoabieites* are included.

NA: not attributed. The taxa subsumed here cannot be assigned to a specific SEG. Also damaged specimens that could not be attributed to any taxa are included.

4.2.3.2. Gastropods (K. Bandel). So far the occurrence of gastropods was only mentioned from cored well Sulechow IG 1 but not further described (Dembowski, 1972). From a new record in cored well Neubrandenburg 2 more than 100 gastropod shells could be extracted and 52 individuals were documented with the Scanning Electron Microscope (SEM). Among these two new species can be safely recognised and are described below. SEM images and additional descriptions concerning their morphology, ecology and systematic place among *Caenogastropoda* Cox (1959) are provided in Supplement C.

Several individuals are preserved with their protoconch that document the number of whorls but not their original ornament. The presence of larval whorls evidences an ontogenetic stage as free swimming veliger larva during which more than two whorls were secreted. Thus, the documented gastropods represent sea-living forms, which had a larval stage of plankton feeding lifestyle. Their close relationship to gastropod genera described from the S. Cassian Formation suggests immigration of the gastropod fauna as veliger plankton feeding larva from the NE Tethyan shelf into the CEB.

***Omphaloptychia suebica* n. sp**

Diagnosis: The approximately 8 mm long shell is approximately 4 mm wide and consists of 8 whorls, of which 4 belong to the protoconch. Whorls of the teleconch are rounded, their suture is deep and ornament consists of sinuous growth lines with wide low sinus on the upper side and the anterior side. The aperture is oval to egg shaped with a narrower anterior side. Embryonic whorl is 0.2 mm wide and the larval shell is 0.4 mm high (Supplement C).

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Difference: *Omphaloptychia muensteri* has a small pointed egg-shaped shell with narrow protoconch and whorls separated by deep sutures. With approximately 7 whorls it is 3 mm in height and 2 mm in width, thus smaller than *O. suebica*. Ornament consists of fine simple growth lines and narrow umbilicus is surrounded by some spiral lines. The 0.4 mm wide and high protoconch consists of about three whorls, has strong lobe of the outer lip and an embryonic whorl of 0.12 mm width. Thus the more sinuous margin of the larval shell and smaller size of the embryonic whorl differ.

***Settsassia stuttgartica* n. sp**

Diagnosis: The 8 mm long shell is 4 mm. The teleconch comprises 5 evenly rounded whorls that are as wide as high. Ornament of the teleconch consists of 10 to 15 strong rounded axial ribs which increase in number from the first to the last whorl. Ribs are slightly sinuous with weak bend towards the spindle. At the upper part of whorls only axial ribs are developed whereas at the lower part thin spiral ribs are shown often covered by succeeding whorls. The protoconch consists of 4 whorls with a 0.2 mm wide embryonic whorl followed by sinuous larval whorls. The protoconch/teleconch boundary is marked by a narrow ridge (Supplement C).

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Difference: *Settsassia obliquecostata* has a protoconch of only 2.25 whorls and a size of approximately 0.25 mm width and height — thus considerably smaller than *S. stuttgartica*. The whorls of the teleoconch have 12 to 14 axial ribs with slight forward inclination comparable to *Settsassia stuttgartica*.

4.2.3.3. Ostracods. The genus group *Darwinula* occurs in the uppermost Grabfeld Formation and virtually throughout the Stuttgart Formation (Kozur and Bachmann, 2010). *Speluncella* sp. is reported from the uppermost Grabfeld Formation in cored well Gartz 1 (unpublished core report) and from the Neubrandenburg Member in cored well Lubliniec IG 1 (Kotlicki and Siewniak-Madej, 1982). According to Kozur (1968) the genus *Speluncella* has a wide range of salinity tolerance and occurs from brachyhalin marine to brackish and fresh water environments. In a short interval close to the base of the Neubrandenburg Member a Tethyan ostracod assemblage with *S. alpina* Bunza & Kozur, *Lutkevichinella oblonga* Kozur and others species occur contemporaneously from Poland to NE Germany and Central Germany. The records in cored wells Sulechow 1 (Dembowski, 1972), Gartz 1 (unpublished core report), Tarnow 1 (unpublished core report) and Schillingstedt 1 (unpublished core report) indicate wide spread euryhaline marine environments in the CEB (Figs. 2 and 9a; Wienholz and Kozur, 1970; Kozur, 1975; Kozur and Bachmann, 2010). Upwards, an ostracod assemblage with *K. germanica* Wienholz & Kozur, *Limnocythere triassica* Kozur and other species but without *S. alpina* occurs indicating successive freshening up to oligohaline salinities and fresh water (Wienholz and Kozur, 1970; Kozur, 1975; Kozur and Bachmann, 2010).

4.2.3.4. Bivalves. *Palaeoneilo* cf. *elliptica* Goldfuss, *Modiolus* sp. and *Unionites* sp. are reported from cored well Poddębice 2 (Iwanow, 2012). *P. elliptica* has a range from the Triassic to the Jurassic and attained, in particular in the Carnian, a remarkable wide-spread distribution in the Tethyan realm (Bittner, 1895; Patte, 1922; Lerman, 1960; Fürsich and Wendt, 1977; Onoue and Tanaka, 2005). Fürsich and Wendt (1977) described this infaunal deposit feeding bivalve from the S. Cassian Formation. *A. lettica* Quenstedt and *Myoconcha gastrochaena* Dunker are reported from cored well Sulechow 1 (Dembowski, 1972). The former was recently identified as a synonym of *Unionites brevis* Schauroth (Geyer et al., 2005). The latter is commonly described from the Roetian and Muschelkalk of southern Poland where it occurs in assemblages with *Hoernesia socialis* Schlotheim and *Gervilleia mytiloides* Schlotheim. Therefore, *M. gastrochaena* has been interpreted to be a representative of euryhaline marine ecology (Assmann, 1944; Senkowiczowa, 1962; Salamon et al., 2012). Bivalves assigned to the genus group *Unionites* are described from cored wells Morsleben 52A (Barnasch, 2010; this study), Neubrandenburg 2 (this study) and Schillingstedt 1 (Franz, 2008). According to Kozur and Bachmann (2010) *Unionites* species occur from fresh water to fully marine habitats. Further bivalve taxa are reported from outcrops of the Neubrandenburg Member in southern Germany and discussed concerning their taxonomy and palaeoecology (e. g. Thürach, 1888/1889; Linck, 1968; Duchrow, 1984; Warth, 1988; Kozur and Bachmann, 2010).

4.2.3.5. Others. Conchostracans are reported from numerous outcrops and cored wells from South to North Germany (e. g. Thürach, 1888/1889; Reible, 1962; Warth, 1969; Kozur, 1975; Duchrow, 1984; Franz, 2008). Conchostracans are adapted to fresh water to brackish environments and tolerate repeated salinity changes (Retallack and Clifford;, 1980; Lecointre and Le Guyader, 2001; Storch and Welsch, 2004). According to Reible (1962) Triassic conchostracans probably did not tolerate higher salinities.

Remnants of chondrichthyes and osteichthyes (scales, bones, teeth) are reported from outcrops of the Neubrandenburg Member in southern Germany (e. g. Thürach, 1888/1889; Schmidt, 1938; Seilacher, 1943). In particular some described chondrichthyes taxa were not adapted to fresh water environments (Kozur and Bachmann, 2010). In cored wells of northern Germany fish remnants occur virtually throughout the Neubrandenburg Member but are not described in detail here (Kannegieser and Kozur, 1972; several unpublished core reports).

4.2.4. Geochemistry and kerogen analysis

According to Leventhal (1995) sulphur concentrations may indicate whether sediments were deposited in marine or freshwater environments. In clastic sediments sulphur is usually bound to iron sulphides which may form during diagenesis from bacterial processes (Berner, 1978; Berner and Raiswell, 1983; Leventhal, 1983, 1995; Dean and Arthur, 1989; Lallier-Vergès et al., 1991, 1993a, 1993b, 1997; Littke et al., 1991, 1997; Berner et al., 1992; Huc et al., 1992; Gamo et al., 1993; Arthur and Sagemann, 1994; Bertrand et al., 1994; Morse and Berner, 1995; Boussafir and Lallier-Vergès, 1997; Machel, 2001). Sulphide formation depends on iron availability (Lüschen, 2004), and Brumsack (1988, 1989) has determined the amount of reactive iron by correcting the total iron concentration. According to Brumsack (1988, 1989) and Lückge et al. (1999) the amount of reactive iron (Fe*) was calculated:

$$Fe^{*} = Fe–0.25^{*}Al \quad [\text{wt.\%}]. \tag{1}$$

Bacterial sulphate reduction (Lallier-Vergès et al., 1993a, 1993b; Bertrand et al., 1994; Littke et al., 1997; Machel, 2001) in sediments leads to a loss of organic carbon and can be described by three basic steps (cf. Vetö et al., 1994).

$$SO_4^{-2} + 2CH_2O \rightarrow 2HCO_3^{-} + H_2S \tag{2}$$

$$3H_2S + 2FeOOH \rightarrow 2FeS + S^{o} + 4H_2O \tag{3}$$

$$FeS + S^{o} \rightarrow FeS_2. \tag{4}$$

Assuming sulphate reduction is the major process leading to loss of organic carbon, the amount of organic carbon converted by bacterial processes may be estimated by multiplication of measured sulphur concentrations with factor 0.75 (mol ratio 2 × C/1 × S). The amount of originally available C_{org} results from adding calculated values of lost C_{org} and measured C_{org} (cf. Lallier-Vergès et al., 1993a, 1993b).

Salinity Sulphur, total reactive iron (Fe*) and organic carbon are highly variable in samples from cored well Neubrandenburg 2 whereas samples from outcrop Am Hohnert show rather low concentrations

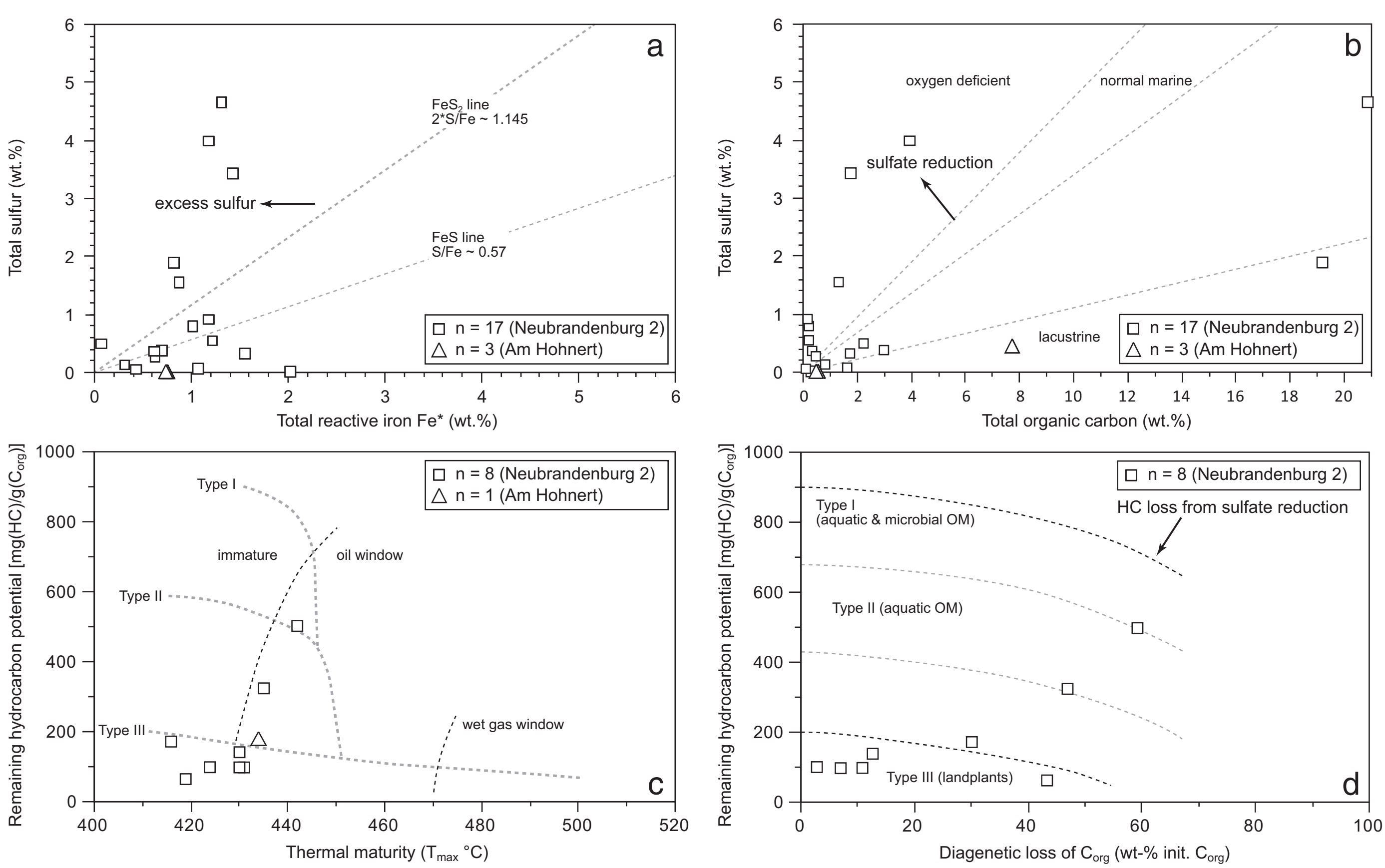

Fig. 6. a, b — Concentrations of sulphur vs. reactive iron (a) and vs. total organic carbon (b). 8c, d — The remaining hydrocarbon potential depends on (c) thermal maturity (classification cf. Peters et al., 2005) and (d) diagenetic sulphate reduction.

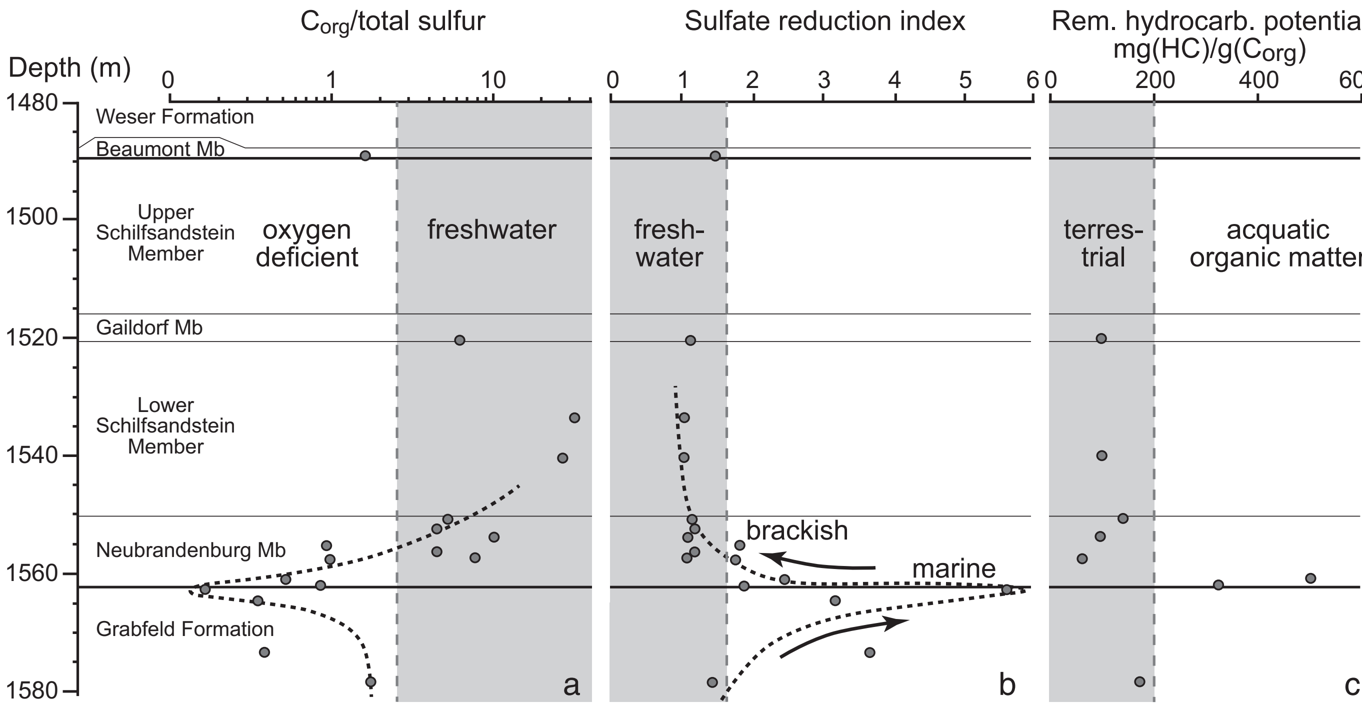

Fig. 7. Organic geochemistry of samples from cored well Neubrandenburg 2; a — ratios of organic carbon and total sulphur indicate palaeoredox conditions, b — restored sulphate reduction index indicate salinity and c — remaining hydrocarbon potential indicate type of organic matter.

(Supplement E). The amount of reactive iron of samples from the Neubrandenburg Member (cored well Neubrandenburg 2) indicates sulphur which is not bound in sulphides as these samples exceed mol ratios of pyrite (Fig. 6a). Sulphur concentrations are generally higher in marine and depleted in freshwater environments (Kelley et al., 1995; Leventhal, 1995). The observed variability of sulphur, total reactive iron and sulphate reduction index (Lallier-Vergès et al., 1993a) in samples from the Stuttgart Formation are in good agreement with results from biofacies analyses. Samples from the euryhaline marine to brachyhaline basal part of the Neubrandenburg Member in cored well Neubrandenburg 2 are characterised by higher values and samples from its oligohaline to freshwater upper part by lowered values. Low sulphur values of samples from the Neubrandenburg Member in Thuringia (Am Hohnert) indicate freshwater environments (Fig. 6a, b). Samples from the Upper Grabfeld Formation and the fluvial parts of the Stuttgart Formation are characterised by rather low sulphur and total reactive iron values as well as sulphate reduction index (Fig. 7b). Accordingly samples with higher sulphur values contain excess sulphur and are shifted away from the normal marine field (Leventhal, 1995) towards lower carbon concentrations which is typically observed for diagenetic processes in oxygen deficient marine environments (Fig. 6a).

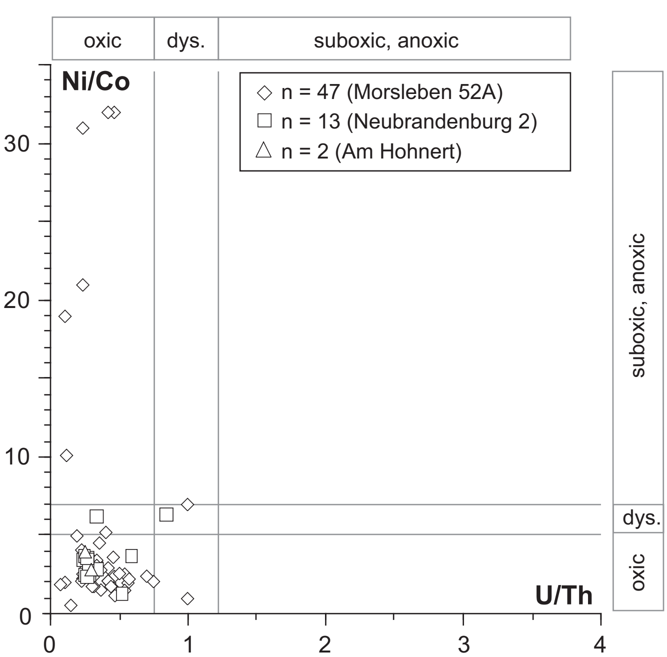

Fig. 8. U/Th and Ni/Co ratios suggest only episodic and local dysoxic to anoxic palaeoredox conditions within the inland sea of the Neubrandenburg Member.

Thermal maturities (given as pyrolysis T_{max}; cf. Peters et al., 2005) are comparatively low with values indicative of immature organic matter or early oil window stage (Fig. 6c). This suggests that a loss of carbon and hydrogen from thermal conversion is minimal and classification of organic matter precursor to remaining organic matter based on the remaining hydrocarbon potential is valid (Supplement E, hydrogen index, cf. Peters et al., 2005). As only sediments with organic carbon concentrations exceeding 0.5 wt.% provide realistic results from pyrolysis (cf. Peters et al., 2005) only a limited number of samples are sufficient. The majority of samples indicate terrestrial and/or inert organic matter (samples below 200 mg HC per g C_{org}). Two samples from the basal part of the Neubrandenburg Member may be related to marine aquatic environments and thus, confirm results of biofacies analyses (Figs. 6d and 7c). Alteration of organic matter from sulphate reduction has been estimated according to Lallier-Vergès et al. (1993a) and Dahl et al. (2004), and theoretical pathways of type kerogens suggest that significant changes may occur. Samples from cored well Neubrandenburg 2 containing type II kerogens may have lost 50 to 60% of their initial organic carbon which translates into losses of hydrocarbon potential between 100 and 200 mg HC per g C_{org} and also one sample comprising organic matter of, most likely, land plants might have lost about 100 mg of its initial hydrocarbon potential.

Palaeoredox conditions Ratios of organic carbon versus sulphur (Leventhal, 1995) of the basal part of the Neubrandenburg Member a

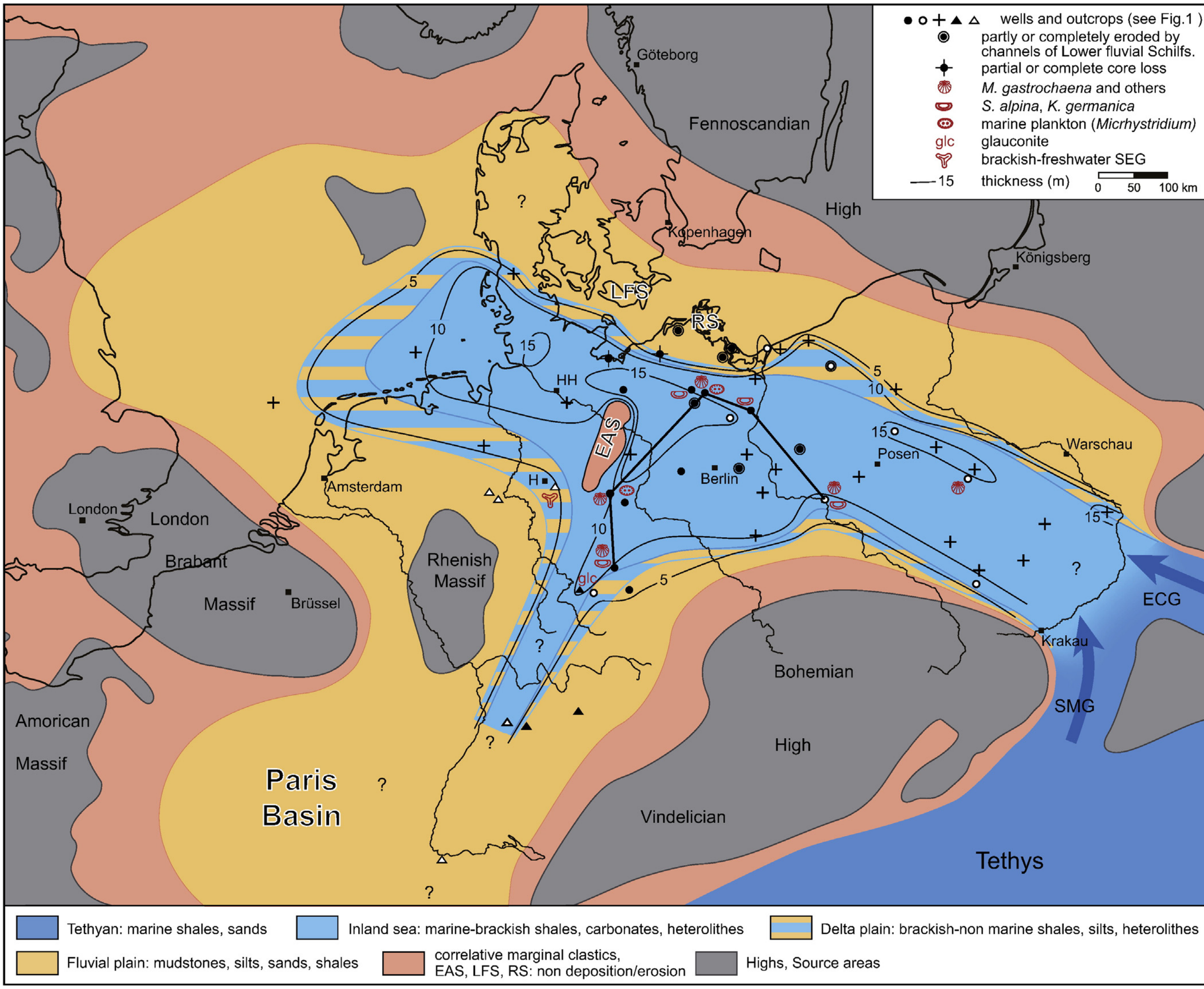

Fig. 9. a: Palaeogeographic reconstruction of the lower part of the Neubrandenburg Member: the pronounced transgression from Tethyan waters via the East Carpathian Gate (ECG) and Sileso-Moravian Gate (SMG) formed a shallow inland sea that covered lager parts of the basin. Thicknesses refer to the complete Neubrandenburg Member, for biostratigraphic control see Fig. 2. EAS — Eichsfeld–Altmark Swell, RS — Rügen Swell, LFS — Lolland-Falster Swell.

indicate that dark shales were partly deposited under oxygen deficient conditions. The strata above were deposited under oxygenated fresh water conditions (Figs. 6b and 7a).

The ratios of U/Th and Ni/Co are thought to reflect palaeoredox conditions (Adams and Weaver, 1958; Rogers and Adams, 1969; Dypvik, 1984; Dill, 1986). Thorium and uranium are relatively immobile in low-temperature environments and fixed to clays or associated with heavy minerals in fine grained sediments (Jones and Manning, 1994). Nickel and cobalt are found in pyrite whose formation in subaquatic sedimentary environments is generally considered to reflect reducing conditions (Raiswell and Plant, 1980; Patterson et al., 1986).

In cored wells Morsleben 52A and Neubrandenburg 2 only a few samples suggest deposition under dysoxic to anoxic conditions, whereas samples from outcrop Am Hohnert do not indicate any oxygen deficiency. Correspondingly, results from kerogen analyses show abundant pyrite (up to 86%) in particular for the basal part of the Neubrandenburg Member (Supplement F). As the majority of measured samples suggest deposition under oxygenated conditions the shallow inland sea of the Neubrandenburg Member has to be considered well oxygenated (Fig. 8). However, episodically dysoxic to anoxic conditions evolved in marginal areas may be evidenced by individual samples. Deposition under oxygen deficient conditions was also a local phenomenon at the delta plains of the upper part of the Neubrandenburg Member for example in brackish swamps and interdistributary bay environments.

Productivity According to the hydrocarbon potential samples from the basal part of the Neubrandenburg Member comprise aquatic organic matter derived from marine environments (Figs. 6d and 7c). The higher concentration of organic matter suggests high nutrient availability and high biological productivity. The enrichment of aquatic organic matter suggests high organic fluxes outcompeting bacterial degradation through sulphate reduction. The samples from below and above comprise organic matter derived from land plants and/or re-worked (inert) organic carbon from terrestrial sediments. This is in good agreement with results from lithofacies as well as biofacies analyses. The low concentrations of organic matter suggest a rather low primary biological productivity and the associated low flux of organic carbon has been outcompeted by diagenetic processes.

b

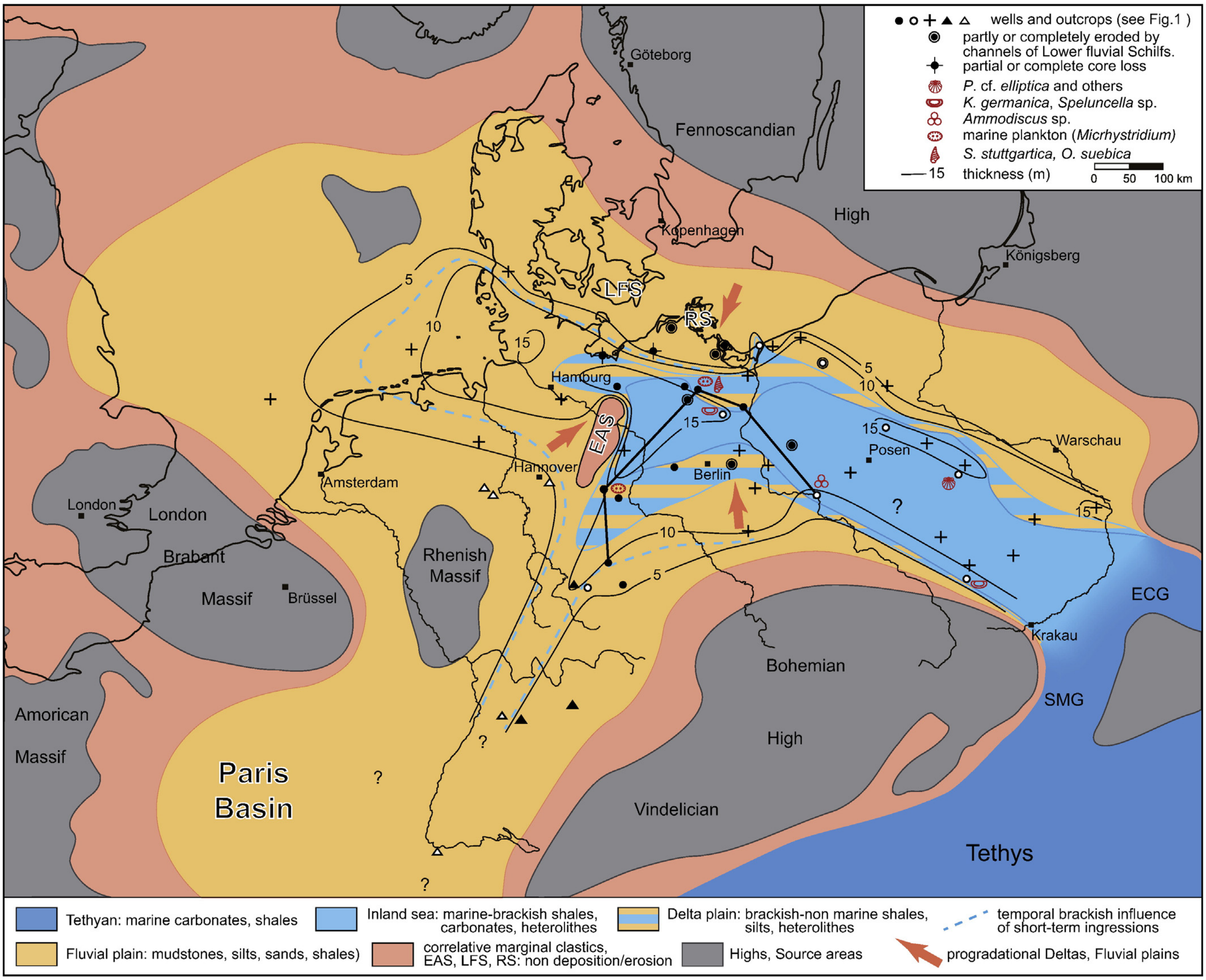

Fig. 9. b: Palaeogeographic reconstruction of the upper part of the Neubrandenburg Member: due to a slight regression the inland sea diminished in size and triggered the progradation of deltaic systems. Thicknesses refer to the complete Neubrandenburg Member, for biostratigraphic control see Fig. 2.

4.2.5. Depositional environments and palaeogeography

Inland sabkha The vertical successions and lateral transitions of desiccated salina, shallow lake and mudflat associations in the upper Grabfeld Formation are best explained within a large continental or inland sabkha system as characterised by Handford (1982) and Cramer (1982) that underwent repeated but short-term flooding from Tethyan waters followed by sedimentation according to the saline pan cycle described by Lowenstein and Hardie (1985).

Flooding from Tethyan waters formed a shallow inland sea and enabled immigration of a brackish fish and bivalve fauna. Resulting laminated siliciclastics of this flooding stage (sensu Lowenstein and Hardie, 1985) point to considerable clastic input. Following this evaporation under arid climate (evaporation > precipitation) resulted in concentration until halite precipitated from saturated brines, for example as syntaxial overgrowth of chevrons (Wardlaw and Schwerdtner, 1966). The halite of this concentration stage (sensu Lowenstein and Hardie, 1985) precipitated in larger and probably connected salt pans corresponding to regional depressions. Both a regressive trend and continued evaporation resulted in desiccation of the former inland sea. The desiccation stage (sensu Lowenstein and Hardie, 1985) was characterised by dense brine that permeated the sediment just below the dry surface in the central part of the pan. This residual brine was fed by groundwater inflow and further concentrated by evaporation (Handford, 1982; Smoot, 1983; Lowenstein and Hardie, 1985; Rosen, 1991). Mudflats lateral to salt pans experienced pedogenic overprint.

A common feature of early flooding stages is dissolution of older halite and formation of brecciated horizons (Lowenstein and Hardie, 1985). As these horizons are common in the northern CEB, today's isolated halite deposits of the Grabfeld Formation (Franz, 2008; Barnasch, 2010) may be the result of marginal dissolution of formerly larger and connected salt deposits (Nitsch, 2005c). Lateral associated mudflats are characterised, in the central parts of the basin, by thin vertisols or incipient calcisols/gypsisols. Towards basin margins, e. g. Thuringia, mature calcisols and gypsisols are common (Figs. 3–5) and finally sandy lithologies of sand flats (not included in this study) become more and more important (Franz, 2008).

Inland sea In the uppermost Grabfeld Formation the inland sabkha was successively replaced by a shallow inland sea. This facies shift becomes visible within a less than 10 m thick interval that comprises alternating lithofacies of both depositional environments (Figs. 2–5). By means of this an incipient marine influence already recognised in the c

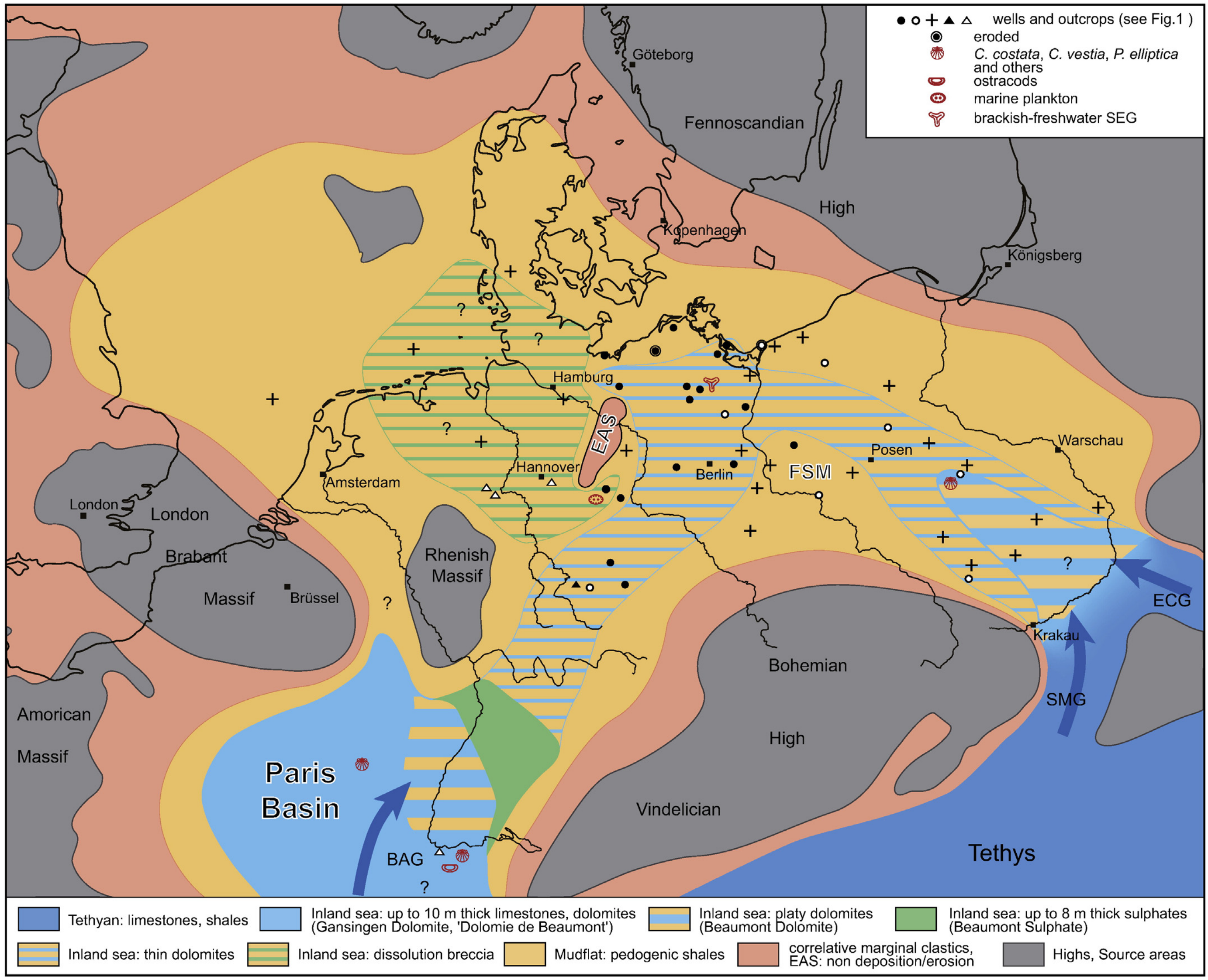

Fig. 9. c: Palaeogeographic reconstruction of the Beaumont Member: the transgression via the Burgundy-Alemannic Gate (BAG) resulted in the Dolomie de Beaumont, Gansingen Dolomite, Beaumont Dolomite and the Beaumont Sulphate in NE France, Switzerland and South Germany. The contemporaneous transgression via the East Carpathian Gate (ECG) and/or Sileso Moravian Gate (SMG) was probably more pronounced and enabled immigration of a macrofauna. The resultant inland sea streched up to North Germany. EAS — Eichsfeld–Altmark Swell, FSM — Forsudetic Monocline.

uppermost Grabfeld Formation increases up to euryhaline marine to brackish conditions in the basal Neubrandenburg Member. The immigration of fauna from Tethyan habitats and their wide-spread distribution in the CEB coincide with the wide-spread distribution of laminated shales, limestone beds and heterolithes. Towards basin margins marine shales and limestones grade into brackish to fresh water shales, silts and sands. The distribution of the euryhaline marine to brackish fauna and associated lithofacies illustrate a transgression from Tethyan waters via the East Carpathian and Sileso–Moravian gates as already suggested by Kozur (1975) and their lack in the southernmost CEB excludes an influence of the Burgundy Alemanic Gate (Fig. 9a).

Subsequent to its maximum flooding the inland sea received variable clastic input supplied by distributary systems. Inflows with high sediment concentrations led to hyperpycnical underflows that formed small-scale fining upward units (Plate 1-1, 1-4; Wright et al., 1988; Mulder and Syvitski, 1995). Buoyant plumes of less concentrated inflows formed fluid mud layers (Plate 1-1; Kuehl et al., 1986; Allison et al., 2000; MacEachern et al., 2005) and stronger discharge variations resulted in inverse graded small-scale units (Plate 1-3; Bhattacharya, 2006). Gradational shifts from marine-brackish to mouth bar and/or delta plain associations translate into progradational stratal pattern of deltaic environments (Figs. 3–5; Köppen, 1997). To the top the marine–brackish association was completely replaced in Thuringia (e.g. outcrop 'Am Hohnert'), southern Germany (Köppen, 1997) and western Mecklenburg (e. g. cored well KSS 1) but persisted in an area between NE Germany and Poland (e.g. cored wells Neubrandenburg, Sulechow IG 1; Fig. 9b). The step-by-step diminished size is accompanied by successive freshening of the inland sea as reported by Kozur (1975). However, marine plankton and *Ammodiscus* sp. from the top of the Neubrandenburg Member argue for at least brackish salinities (Figs. 3 and 4).

Fluvial deltas and fluvial plains Triggered by the retreat of the inland sea the progradation of fluvio-deltaic environments becomes visible either by successions were marine shales are followed by coarsening upward mouth bars followed by shaly to carbonaceous delta plains or successions were marine shales are directly overlain by delta plain lithologies (Figs. 3–5). The transition without the development of a sandy shoreline corresponds to shift from prodelta shales to interdistributary bay silts describe by Walker and Harms (1971) and others. The record of both, mouth bars and interdistributary bays emphasises the significance of fluvial processes on the formation of deltas and are therefore considered diagnostic for the fluvial delta type (Bhattacharya and Walker, 1991).

The progradation of fluvio-deltaic environments is reflected by changes from autochthonous marine–brackish groups to allochthonous terrestrial groups in palynomorph assemblages (Figs. 3 and 4). Delta plains are represented with various sub-environments like brackish interdistributary bays, paralic or fresh water swamps, wetlands and crevasse splays. A subdivision into lower and upper delta plain is enabled by the occurrence of marine–brackish SEGs in the central parts and their lack in marginal parts of the CEB (Coleman and Prior, 1982).

Flood plain environments form the uppermost Neubrandenburg Member in Thuringia and but may built up the complete member in South Germany (outcrop Ansbach/Eyb a. o.). In the palaeogeographic reconstruction of the late Neubrandenburg Member the facies shifts from delta to fluvial plains in the southern parts of the CEB have been taken as analogue for the larger areas to the West, North and East that lack sufficient control by cored wells (Fig. 9b). However, sandy fluvial channels and distributaries have not been exposed in the studied cored wells and outcrops. But sediments of fluvial plains, delta plains and mouth bars that have been bypassed up to several hundreds of kilometres from surrounding sources call for such transport systems.

4.3. The intra-Schilfsandstein transgression: Gaildorf Member

The Gaildorf Member was first recognised in South Germany where it occurs intercalated between the Lower and Upper Schilfsandstein (Thürach, 1888/1889; Lang, 1909). In the type area, the Eisbachtal E of the village Gaildorf, the member is up to a few metres thick and comprises up to a few decametres thick dolomite beds that contain abundant remnants of bivalves (Zeller, 1907; Warth, 1988), and gastropods (Etzold and Schweizer in DSK, 2005). Remnants of chondrichthyes and osteichthyes (teeth, scales, fin rays) were described from a bonebed by Seilacher (1943). The coquina beds are intercalated with clayey, shaly and silty lithologies (Etzold and Bläsi, 2000). Comparable lithologies were described from the vicinity of Basel (e. g. Schmassmann, 1953; Dissler, 1914; Etzold and Bläsi, 2000).

In the northern CEB the Lower and Upper Schilfsandstein are often separated by up to a few metres thick horizon of dark clays or shales and silty lithologies, whereas carbonate beds occur only subordinated. This unit is almost 5 m thick in cored well Neubrandenburg 2 and easily recognisable due to marked lithological contrasts to fluvial members below and above (Fig. 2). If this horizon experienced modification by pedogenic processes, e. g. cored well Morsleben 52A, its recognition may be difficult. Kannegieser and Kozur (1972) described *K. germanica* Wienholz & Kozur and *Omphaloptycha lunzensis* Yen from this horizon of cored well Flieth 1 (Kozur, pers. comm.). Kozur and Bachmann (2010) correlated this horizon with the Gaildorf Member and reconstructed a short-term transgression that extended up to the northern CEB.

This can be confirmed based on the occurrence of the colonial green alga *Botryococcus* sp. recorded in cored well Neubrandenburg 2. This form is identified to the SEG of brackish to freshwater environments (ABF). In addition lycophyte sporomorphs *Aratrisporites* spp., *L. aduncus* and others identified to coastal environments (CO) and *Densoisporites* sp. identified to tidal environments (TI) suggest a brackish influence within the Gaildorf Member in NE Germany. However, palynomorphs identified to aquatic SEGs ABF, CO and TI represent in total only 8% of all counted palynomorphs (Supplement A).

4.4. The post-Schilfsandstein transgression: Beaumont Member

The Beaumont Member forms the prominent base of the Weser Formation and corresponding units in the southern CEB (see Etzold and Schweizer in DSK, 2005 for references). Lutz and Etzold (2003) introduced Gansingen Dolomite, Beaumont Dolomite and Beaumont Sulphate in terms of facies units. In particular the up to 10 m metres thick Gansingen Dolomite, distributed between NE France, southernmost Germany and northern Switzerland, is well recognised as transgression horizon and comprises a marine fauna with *Costatoria goldfussi* Zenker, *Costatoria vestia* Alberti and others (Alberti, 1864; Zeller, 1907; Minoux and Ricour, 1946; Wildi, 1976). Towards NE facies shifts subsequently to almost 10 m thick platy dolomites (Beaumont Dolomite) and up to 8 m thick bedded to nodular sulphates (Beaumont Sulphate); both without marine fauna (Lutz and Etzold, 2003).

In Central and North Germany the base of the Weser Formation is drawn at the base of an up to a few metres thick horizon of variable lithologies. Greyish dolomitic shales and silts are common and may contain thin dolomite beds (e. g. cored wells Neubrandenburg 2, Schillingstedt 1). Towards NW Germany a prominent breccia ('Kühl'sche Brekzie') is evidenced in cored wells (e.g. Morsleben 52A) and outcrops and suggest precipitation of sulphates and/or halites. The correlation of this horizon with the Beaumont Member was demonstrated by Beutler in DSK (2005) and others.

Marine phytoplankton is now evidenced from the Beaumont Member of cored wells Morsleben 52A and Neubrandenburg 2. The prasinophycean algae *Leiosphaeridia* spp. and *Tasmanites* spp. are identified to the Sporomorph Eco Group of brackish lagoonal environments (ALB). As this group forms more than 30% of all counted palynomorphs in cored well Morsleben 52A a brackish influence is clearly demonstrated. The presence of colonial green alga *Botryococcus* sp. (ABF) as well as lycophyte sporomorphs *Aratrisporites* spp. and *L. aduncus* (CO) and the absence of prasinophycean algae in cored well Neubrandenburg 2 suggest freshening towards the North but a brackish influence remains visible (Supplement A).

From cored well Poddębice PIG 2 Iwanow (2012) described about 10 m thick dolomites, shales and silts from the base of the Weser Formation ('Warstwy gipsowe górne') that comprises *Palaeoneilo elliptica* Goldfuss. The occurrence of this Tethyan bivalve (see 4.2.4) in the eastern CEB provides evidence that Tethyan waters entered the CEB also via gates to the SE (in addition to the Burgundy–Alemanic Gate). So far *P. elliptica* is the first record of a Tethyan macrofauna in the eastern CEB and therefore the transgression through gates to the SE needs to be further justified, for example by micropalaeontological investigations. But it is noticeable that *P. elliptica* immigrated much more farther North compared to the macrofauna recorded in southernmost Germany and thus the transgression via gates to the SE was probably more pronounced (Fig. 9c).

4.5. Eustatic control on the Stuttgart Formation

The deposition of the Stuttgart Formation was controlled by pre-, intra-, and post-Schilfsandstein transgressions (Franz, 2008; Kozur and Bachmann, 2010). Basin-wide reconstructions of the pre-Schilfsandstein transgression (Neubrandenburg Member) reveal an inland sea of considerable size comparable to the middle Triassic Upper Muschelkalk Sea (e. g. Franz et al., 2013) and the late Triassic Rhaetian Sea (e. g. Fischer et al., 2012). The maximum extension of the inland sea coincides with a maximum of marine influence and enabled immigration of selected Tethyan taxa (Wienholz and Kozur, 1970; Dembowski, 1972; Kannegieser and Kozur, 1972; Kozur, 1975; Iwanow, 2012; this work). Following this stage the inland sea successively diminished in size and triggered the progradation of fluvio-deltaic systems that culminated with the basin-wide distribution of fluvial environments of the Lower Schilfsandstein (Fig. 9a, b).

The intra-Schilfsandstein transgression (Gaildorf Member) entered the CEB through gates to the South and probably Southeast. Compared to the Neubrandenburg Member this transgression was shorter and less pronounced. However, the brackish influence in the northern CEB that has been concluded by Kannegieser and Kozur (1972) based

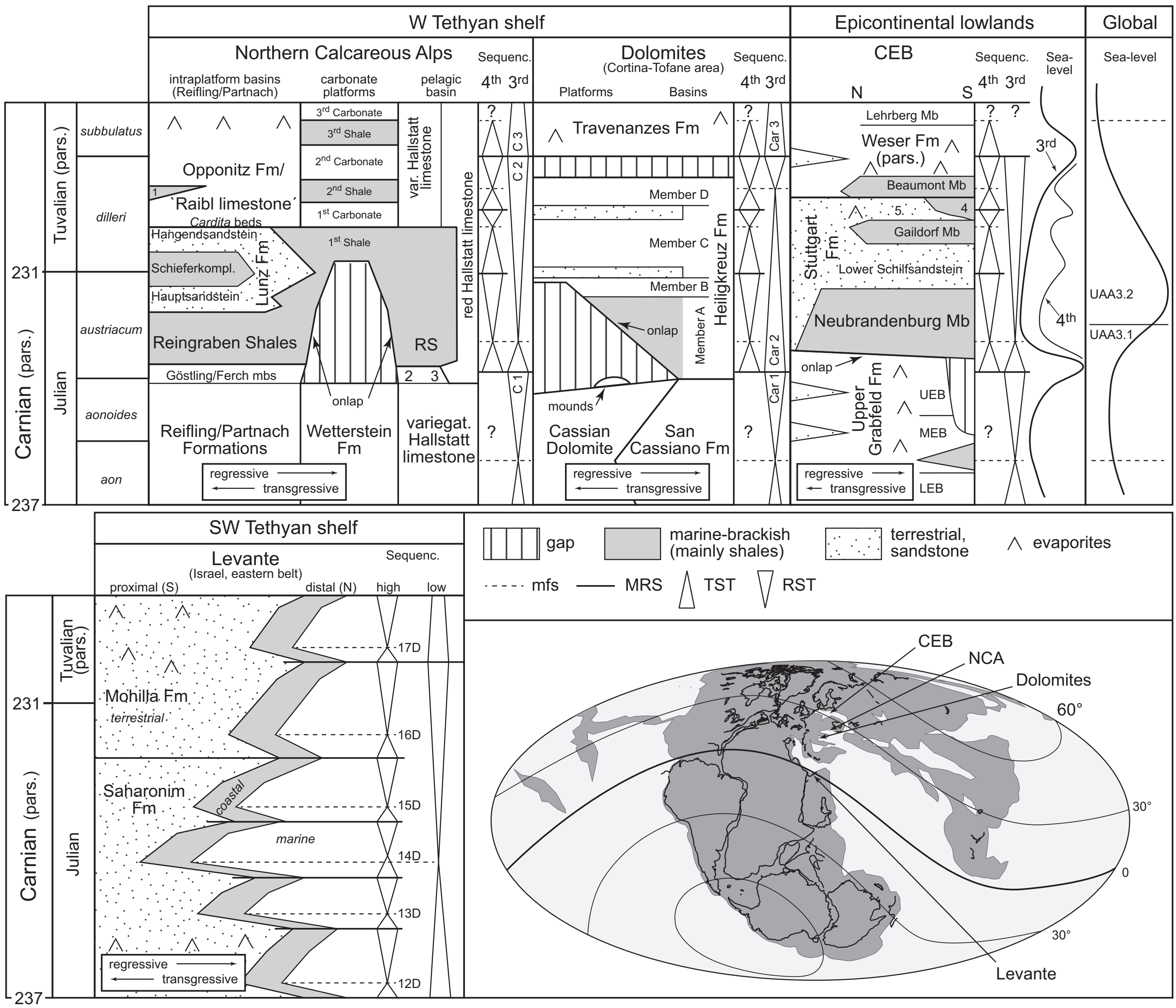

Fig. 10. Correlation of Carnian sequences in the Peri-Tethyan realm. Chronostratigraphy and ages according to Lucas (2013), ammonite zones not to scale, upper Triassic global palaeogeography shows late Julian pre-Schilfsandstein transgression (Neubrandenburg Mb) into the CEB (modified based on Stampfli, unpublished). Lithostratigraphy and sequence-stratigraphic interpretation of the Central European Basin (halites of the Grabfeld Formation not shown), Northern Calcareous Alps modified after Hornung (2007) and Roghi et al. (2010), Dolomites modified after Keim et al. (2001, 2006), Preto and Hinnov (2003) and Levante simplified from well Devora (Korngreen and Benjamini, 2010, 2014). LEB — Lower variegated *Estheria* Beds, MEB — Middle grey *Estheria* Beds, UEB — Upper variegated *Estheria* Beds, RS — Reingraben Shales, 1 — Zementmergel, 2 — Potschen limestone, 3 — ochrish limestone (Hallstatt facies), 4 — 'Dunkle Mergel', 5 — Upper Schilfsandstein.

on gastropods, ostracods and fishes is confirmed herein based on Sporomorph Eco Groups identified to brackish–freshwater, coastal and tidal environments. Following this regressive trends are again indicated by the second basin-wide distribution of fluvial environments of the Upper Schilfsandstein.

The post-Schilfsandstein transgression (Beaumont Member) is evidenced by marine molluscs in the southernmost and eastern CEB (Alberti, 1864; Zeller, 1907; Minoux and Ricour, 1946; Wildi, 1976; Iwanow, 2012) and confirmed herein based on Sporomorph Eco Groups identified to lagoonal–brackish, brackish–freshwater and coastal environments (Fig. 9c). The transgression of the Beaumont Member terminated the fluvial sedimentation in the CEB and segued into shaly and evaporitic lithologies of Playa- to Sabkha-like environments.

The repeated and pronounced transgressive–regressive trends translate into retrogradational and progradational stratal pattern architectures enabling application of the Transgressive–Regressive Sequence Model of Curray (1964) and Embry (1993, 1995). We consider the successive facies shift from the terrestrial Grabfeld Formation to the marine–brackish Neubrandenburg Member that culminates in the wide-spread distribution of an euryhaline marine ostracod assemblage as transgressive system tract (TST) and maximum flooding surface (mfs), respectively (Figs. 2 and 10). Above the brackish to freshwater strata of the upper Neubrandenburg Member and the Lower fluvial Schilfsandstein Member are considered regressive system tract (RST). Comparable couplets of transgressive–regressive stratal pattern architecture are identified with the Gaildorf Member and Upper fluvial Schilfsandstein Member and the Beaumont Member and following strata of the lower Weser Formation, respectively. Maximum regressive surfaces are recognised within the maximum progradation of Lower and Upper fluvial Schilfsandstein members (Fig. 10). As pointed out by Bachmann and Kozur (2004) and Kozur and Bachmann (2010) the Stuttgart Formation represents a rather short time interval.

Therefore, the identified TR Sequences are considered of higher order, most probably of the 4th order. Together they form a sequence of the 3rd order with maximum flooding surface close to the base of the Neubrandenburg Member (Figs. 2 and 10).

4.6. Possible climatic and tectonic controls on the Stuttgart Formation

The pronounced lithological changes from the Stuttgart Formation to the Sabkha- to Playa-like Grabfeld and Weser formations are accompanied by changes of floral (Mader, 1990; Kelber, 1998) and palynomorph assemblages (Scheuring, 1970; Orłowska-Zwolińska, 1976, 1983; Schulz, 1976; Visscher and van der Zwan, 1981; Reitz, 1985; Visscher et al., 1994; Fijałkowska-Mader, 1999; Heunisch, 1999), palaeosols (Mader, 1990; Nitsch, 2005a) and clay mineral assemblages (Simms and Ruffell, 1989) that are controversially discussed concerning their palaeoclimatic implications.

Simms and Ruffell (1989, 1990) evaluated the Stuttgart Formation and corresponding strata in the CEB and based on changes in depositional systems and clay mineral assemblages as well as karstification, they concluded on increasing rainfall/runoff and, in comparison to some contemporaneous changes in other parts of the Triassic world, proposed the so-called Carnian Pluvial Event. Visscher and van der Zwan (1981) and Visscher et al. (1994) rejected the Carnian Pluvial Event and considered the floral change resulting from vegetated banks of a large dryland river-system comparable to today's Nile. However, Mader (1990), Fijałkowska-Mader (1999) and others argued for a climate change based on comparable data. Concerning palynomorph assemblages evaluated herein it is important to note that samples largely dominated by the dry lowlands SEG. Together dry lowlands, river and hinterland SEGs may form up to 95% and the SEG of wet lowlands forms only accessory parts in individual samples (Figs. 3 and 4, Supplement A). Therefore and in accordance with Visscher and van der Zwan (1981), Reitz (1985), Visscher et al. (1994), Kelber (1998) and Heunisch (1999) a shift to more humid climate is not supported.

Based on palaeosols and some general considerations, Nitsch (2005a) and Kozur and Bachmann (2010) favour a slight climate shift. In particular Kozur and Bachmann (2010) provided some comprehensible arguments that are mainly based on earlier works and proposed the so-called Mid Carnian Wet Intermezzo. Apart from names the challenging discussion whether the Stuttgart Formation represents a slight or pronounced climate shift simplifies that a comprehensive data set that evaluates geochemical data, like weathering indices, is still missing.

Kozur and Bachmann (2010) introduced an interesting scenario of a rift shoulder uplift in the area of the western coast of modern day Scandinavia in Carnian times. Within this hypothetic scenario the rift shoulder was considered orographic barrier blocking trade winds and acting as source for the siliciclastics transported by Schilfsandstein rivers. The proposed scenario relies on the assumption that the Scandinavian rift system was active contemporaneously to the Newark rift system in today's eastern United States that was dated active since the early Carnian (see Kozur and Bachmann, 2010). This scenario is supported by micas of Caledonian age reported by Paul et al. (2008) from the Stuttgart Formation of Lower Saxony and Franconia. However, as only samples from these areas have been evaluated by Paul et al. (2008) their conclusion of a source within the Scandinavian Caledonides is not necessarily valid for the Schilfsandstein in NE Germany. Moreover, published petrographic data from the northeastern CEB suggest that at least parts of the Fenno-Scandinavian Shield have to be considered source area (Brotzen, 1950; Häusser and Kurze, 1975; Beutler and Häusser, 1982). Immature Schilfsandstein-type sandstones are also known from the Lower Keuper (e.g. Häusser and Kurze, 1975). Their earliest occurrences in NE Germany have been correlated to the early Ladinian (Franz et al., 2013). Further occurrences of Schilfsandstein-type sandstones in the Grabfeld, Weser and Arnstadt formations of NE Germany and NW Poland (Franz, 2008) suggest that the source (? or sources) of Schilfsandstein-type arenites was already exhumed in early Ladinian times and experienced erosion up to Norian times. By means of this an early Carnian exhumation pulse of the Scandinavian Caledonides is not necessarily excluded but it is emphasised that more detailed age data are needed to draw conclusions on source areas North of the CEB. In particular since the 224 ± 15 Ma zircon FT age of the Schilfsandstein (Köppen and Carter, 2000) is not in agreement with the minimum depositional age of 230.91 ± 0.33 Ma (Furin et al., 2006) of early Tuvalian sediments corresponding to the lower Weser Formation (Kozur and Bachmann, 2008).

4.7. The 3rd and 4th order circum-Tethyan eustatic cycles

In the Northern Calcareous Alps (NCA) the change from carbonate platforms (Wetterstein Formation) with intraplatform basins (Reifling/Partnach formations) to shales and siliciclastics (Lunz Formation, North Alpine Raibl Beds) is accompanied by substantial faunal changes (Reingraben turnover, Schlager and Schöllnberger, 1974). Builtup, growth and demise of Wetterstein platforms and variable lithologies of the Lunz and lower Opponitz formations are subsumed in the 3rd sequences C 1 and C 2 (Rüffer and Zühlke, 1995; Rüffer and Bechstädt, 1998; Hornung et al., 2007b). In particular the stratal pattern architectures of the latter suggest sequences of higher order, most probably the 4th order, that can be correlated with those from the Stuttgart Formation (Fig. 10).

The maximum flooding in the early Carnian *aon* ammonite zone (Rüffer and Zühlke, 1995; Hornung et al., 2007b) can be correlated with the middle grey *Estheria* Beds of the Upper Grabfeld Formation in the southern CEB where an euryhaline fauna occurs (Seilacher, 1943; Linck, 1972; Nitsch, 1996). The brackish influence can be traced up to southern Lower Saxony indicated by prasinophycean algae (Reitz, 1985). The emerged and karstified Wetterstein platforms evidence a pronounced sea-level drop identified to sequence boundary by Rüffer and Zühlke (1995). This lowstand is herein correlated to the upper *Estheria* Beds in the CEB that comprise mature aridisols (Fig. 10; Nitsch, 1996). The following transgression culminated with deposition of up to decametres thick dark Reingraben Shales (e.g. Rüffer and Bechstädt, 1998; Hornung, 2007). From the lower part of the Reingraben Shales Roghi et al. (2010) described abundant acritarchs. According to this and due to onlapping pattern, in particular recognised at emerged Wetterstein carbonate platforms (Hornung et al., 2007b), the Reingraben Shales are herein considered Transgressive System Tract and correlated with the Neubrandenburg Member (Fig. 10). To the top Hauptsandstein and Schieferkomplex indicate progradational stratal pattern of delta front and delta plain environments (Seffinga, 1988; Hornung, 2007) and are herein considered Regressive System Tract comparable to the Highstand System Tract of Bechstädt and Schweizer (1991) and others. The calciferous upper part of the Schieferkomplex and the fossiliferous Hangendsandstein comprise again acritarchs indicating an increasing marine influence (Roghi et al., 2010). This transgressive trend most probably culminated in the '*Cardita*-Bänke' of the basal Opponitz Formation (Hornung, 2007) and can be correlated with the Gaildorf Member (Fig. 10). Above, dolomites and rauhwackes ('Opponitz Liegendrauhwacke') suggest shallower and hypersaline environments. The Lunz and Opponitz formations are biostratigraphically poorly constrained (e. g. Hornung, 2007), however, based on palynological arguments the upper part of the Lunz Formation and the base of the Opponitz Formation have been recently correlated with the Tuvalian (Fig. 10; Roghi et al., 2010). Comparable sequences can be recognised from the strata overlaying emerged Wetterstein carbonate platforms. There, platform tops are disconformably followed by the 1st Shale (sensu Roghi et al., 2010) of the Northern Alpine Raibl Beds. This horizon of dark shales is correlated with the upper Lunz Formation (Hornung, 2007) and palynologically constrained to the Tuvalian (Roghi et al., 2010). On larger scale it shows onlapping pattern, comprise acritarchs

(Hornung, 2007; Roghi et al., 2010) and is therefore considered Transgressive System Tract herein. The following 1st Carbonate interval (sensu Roghi et al., 2010) comprises carbonates and rauhwackes and are considered Regressive System Tract of a transgressive–regressive sequence. The succession 2nd Shale/2nd Carbonate interval forms the next sequence with abundant acritarchs occurring in the 2nd Shale (Roghi et al., 2010).

Comparable Carnian sequences were described from the Dolomites. Builtup followed by progradation and demise of Cassian platforms are subsumed in the 3rd order sequence Car 1 (De Zanche et al., 1993; Gianolla et al., 1998; Stefani et al., 2010). Karstified Cassian platforms are covered by mixed carbonate/clastic lithologies of the Heiligkreuz Formation. Member A of the Heiligkreuz Formation is formed of grey to dark grey marls that onlap onto and partly overlay Cassian platforms (Keim et al., 2001, 2006) suggesting a transgressive trend (Fig. 10). In the Cortina-Tofane area the members B–C of the Heiligkreuz Formation illustrate repeated progradational–retrogradational pattern of a tide-dominated setting that translate into regressive–transgressive trends (Preto and Hinnov, 2003; Gattolin et al., 2013). At the base and top of Member B conglomerates and sandstones are described (Keim et al., 2001; Preto and Hinnov, 2003). To the top the boundary to the Travenanzes Formation is associated to a disconformity and therefore considered sequence boundary of 3rd order sequence Car 2 (De Zanche et al., 1993; Gianolla et al., 1998; Stefani et al., 2010).

From the SW Neotethyan shelf proximal–distal transitions are described from a number of North Arabian Plate localities (e. g. Glennie et al., 1974; Druckman, 1976; Druckman et al., 1982; Sharland et al., 2001; Bandel and Abu Hamad, 2013). From the Anisian to Norian of the eastern belt of Israel, Korngreen and Benjamini (2010, 2014) reconstructed five low-order transgressive–regressive cycles. These low-order cycles are substantiated by a number of high-order transgressive–regressive cycles (Korngreen and Benjamini, 2010, 2014). In terms of stratal pattern both types represent transgressive–regressive sequences. With a range from the early Carnian to early Tuvalian low-order cycle 3 corresponds to sequences L2, C1 and C2 in the northern Alps and corresponding sequences in the Dolomites (parts of La2, Car 1, Car 2). The different ranges may be reasoned with different settings, platforms vs. homoclinal ramp, and/or due to variations in subsidence. But, however, the maximum marine extension within cycles 14D and 15D, identified to the middle part of the Julian, closely corresponds to contemporaneous Wetterstein platforms (NCA) and Cassian platforms (Dolomites). Cycle 16D ranges from the late Julian to early Tuvalian and therefore matches well with C2 (NCA) and Car2 (Dolomites) and the correlative sequence from the CEB (Fig. 10). The transgressive–regressive pattern of cycle 16D can be traced up to surface exposures in Maktesh Ramon (Korngreen and Benjamini, 2014).

The close correlations of the 3rd order sequences derived from successions of Tethyan shelfs as well as epicontinental lowlands confirm circum-Tethyan eustatic cycles (Hirsch, 1992 and others). Sequences C 1, C 3 (NCA) and Car 1, Car 3 (Dolomites) match the global sea-level curve proposed by Haq et al. (1987). However, sequences C 2 (NCA), Car 2 (Dolomites) and the corresponding sequence from the CEB demonstrate that the Haq-curve needs revision (Fig. 10). But the most interesting aspect of the herein presented correlation is the stacking pattern of the 4th order sequences. Already Haq et al. (1987) noted the presence of 10^6-year scale sea-level changes but now the time-constrained circum-Tethyan record provides new evidence for ephemeral ice sheets that triggered end controlled glacioeustatic sea-level changes (Miller et al., 2005).

5. Conclusions

1. The deposition of the Stuttgart Formation (Schilfsandstein) was controlled by high frequent 4th order sequences resulting in pre-, intra- and post-Schilfsandstein transgressions into the CEB.
2. The pre-Schilfsandstein transgression (Neubrandenburg Member) flooded the CEB from the Southeast and resulted in a wide-spread inland sea that enabled immigration of euryhaline marine fauna with plankton, ostracodes, fishes, bivalves and the gastropods Omphaloptychia *suebica* n. sp. and Settsassia *stuttgartica* n. sp.
3. The rather short-term intra-Schilfsandstein transgression (Gaildorf Member) flooded the CEB from the Southwest and established a shallow brackish inland sea that stretched up to North Germany. The post-Schilfsandstein transgression (Beaumont Member) flooded the CEB from the Southwest and Southeast and the resultant inland sea extended up to North Germany.
4. The close correlation of the 4th and 3rd order sequences from Tethyan shelfs and the epicontinental CEB confirm circum-Tethyan eustatic cycles. The broad evidence of 10^6-year scale cycles may be attributed to glacioeustatic sea-level changes.
5. Prominent middle Carnian events referred to as Reingraben turnover, Carnian Pluvial Event, Carnian Crisis and Mid Carnian Wet Intermezzo may have been controlled by pronounced circum-Tethyan eustatic cycles.

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