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New advances in the stratigraphy and geochemistry of the German Turonian (Late Cretaceous) tephrostratigraphic framework

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ABSTRACT:

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The lowest of the five bentonites in the German Turonian tephrostratigraphic framework, T_C, can be correlated for the first time from the Rotpläner (red limestone) standard section in the Söhlde-Loges Quarry (Lower Saxony) to highly condensed, near-swell successions of the nearby Woltwiesche Quarry and the Hoppenstedt Quarry (Saxony-Anhalt). A second bentonite, T_{C2}, only recently recognised at Söhlde-Loges, is now identified at Woltwiesche and in the distal/expanded white limestone successions of the Salzgitter-Salder Quarry and the Flöteberg road-cutting (both Lower Saxony). T_{C2} can easily be located a short distance above a major lithofacies change (herein termed the Basal Upper Turonian Facies Turnover), making it an isochronous marker permitting correlation between condensed near-swell and expanded basinal sections. On this basis, a bentonite, previously identified as T_C at Hoppenstedt must be re-assigned as T_{C2}. Examination of the major, trace, and rare-earth element (REE) data of all the five bentonites identified in Lower Saxony and Saxony-Anhalt shows that it is possible to discriminate between them to some extent. Bentonites T_C and T_{C2} are geochemically similar and separable from T_D, which is itself distinct from T_E and T_F.

Key words: Bentonite, Tuff, Upper Cretaceous, Turonian, Lower Saxony, Saxony-Anhalt, Rare-earth elements, Trace elements.

INTRODUCTION

Two vulcanogenic clays (bentonites) were first identified in the Turonian limestone successions of Lower Saxony by DORN & BRÄUTIGAM (1959) in the Woltwiesche Quarry and the Kraus'sche Quarry near Söhlde. These were designated Tuff horizons A and B, and identified as tuffs on the basis of their montmorillonitic composition and petrographic characters, notably the apparent presence of volcanic glass. BRÄUTIGAM (1962) subsequently recognised additional bentonites, which he designated Tuff horizons 0, C, D, E, F and G, in ascending stratigraphical order. Although BRÄUTIGAM (1962, enclosure 16), satisfactorily correlated his Tuff horizons C, D, E, F and G between continuous sections in the Flöteberg road-cutting and on the Kahnstein (also in Lower Saxony), he was unable to correlate his A and B horizons to other sections.

Later expansion of the working quarries near Söhlde and the Salzgitter-Salder Quarry enabled the establishment, inspired largely by the late Gundolf Ernst, of a standard tephrostratigraphic scheme that was applicable throughout Lower Saxony. Geochemical studies in northern Germany over many years have identified four bentonites in sediments of mid to late Turonian age (WRAY 1995; WRAY & WOOD 1995; WRAY & *al.* 1995, 1996). These are, in ascending order, bentonites T(uff)$_C$, T_D, T_E and T_F, BRÄUTIGAM's "tuffs" T_0 and T_G being detrital marls. Bentonite T_B of Woltwiesche Quarry was inferred largely on biostratigraphical evidence to be bentonite T_E (see below). The correctness of this interpretation is reviewed in this paper.

Parallel investigations in eastern England (Lincolnshire and Yorkshire) and the Anglo-Paris Basin demonstrated the presence of five bentonites in coeval sediments (predominantly coccolith chalks), as well as a sixth bentonite at the base of the Middle Coniacian (WRAY & WOOD 1998; WRAY 1999). Four of the five Turonian bentonites have been satisfactorily correlated on biostratigraphical evidence between the UK and northern Germany, thereby establishing a tephrostratigraphic framework of isochronous events that is applicable over an area of the order of several 100 km^2 (WRAY 1999, text-fig.7; MORTIMORE & *al*. 2001, text-fig. 1.12). However, the apparent absence in northern Germany of the second of the five Turonian bentonites identified in the UK remained puzzling, in view of the fact that this was one of the best developed and thickest of the five. Using stable isotope stratigraphical correlation in an attempt to locate its possible position, WRAY & WOOD (2002) successfully identified the missing bentonite in the Söhlde-Loges Quarry in Lower Saxony, as a thin marl seam close to the top of a succession of red limestones (Rotpläner Facies) In view of its position between bentonites T_C and T_D, the bentonite was given the designation T_{C2}.

WRAY & WOOD (2002) noted that Söhlde-Loges Quarry was apparently the only section in Germany where bentonite T_{C2} was represented. They suggested that the apparent absence of T_{C2} across the region was probably a reflection of primary transportation processes, principally wind direction; its occurrence at Söhlde might simply represent a chance concentration of relatively distal ash due to current action. However, we will show that bentonite T_{C2} is represented throughout the study area, the reason that it was not observed previously being that it is generally very thin (less than one centimetre in some sections) and inconspicuous.

Bentonite T_{C2} at Söhlde-Loges Quarry is located closely above a significant lithofacies change from predominantly nodular, flaser-bedded, intraclastic limestones to predominantly massive-bedded limestones. Knowing the position of bentonite T_{C2} at Söhlde-Loges in relation to this facies change enabled the recognition of its approximate position in the lithological column at other localities in Lower Saxony (Salzgitter-Salder Quarry, Flöteberg road cutting) and showed that the identification of the conspicuous bentonite near the top of the Rotpläner at the abandoned Hoppenstedt Quarry (Saxony-Anhalt) as T_C (HORNA 1995) was incorrect and required to be reassessed. This lithofacies change will be shown to be entirely independent of the development of the Rotpläner facies, which is largely controlled by the depositional setting within a distal – proximal intra-shelf transect.

As the stratigraphic positions of bentonites T_D, T_E and T_F can be readily identified in sections throughout the study area, (except for the localities Woltwiesche and Hoppenstedt; see below), we will concentrate in this contribution mainly on bentonites T_C and T_{C2}, which were deposited during a period when the depositional area underwent rapid vertical and lateral facies changes due to synsedimentary tectonic/halokinetic movements, hindering fine-scale lithostratigraphic correlation on a regional scale.

Finally, it must me emphasised that this contribution is intended to bring current knowledge of the Turonian tephrostratigraphic framework in Lower Saxony and Saxony-Anhalt up to date and documents the results of our most recent investigations. In order to aid understanding, it is necessary to include a summary of the development of ideas in this field and to provide a detailed review of the lithostratigraphical framework of the relevant parts of the sections in question. This has led, unavoidably, to a rather complex structure for the body of the paper, in which observations cannot always be clearly separated from interpretation. So far as possible we have attempted to rectify this in the discussion section and in the summary of conclusions.

GEOLOGICAL SETTING AND SECTIONS

The study area is located in north-west Germany (Lower Saxony and Saxony Anhalt; Text-fig. 1). The Turonian successions are developed as limestones (traditionally termed Pläner), which represent a pelagic biosedimentary carbonate system; deposition is inferred to have taken place in an open oceanic intra-shelf setting at comparatively shallow water depths between ca. 150 m and near storm wave base, the latter being indicated by deposits of tempestitic origin (KOTT 1985). Lithologically, the Pläner limestones can be broadly described as bioclastic pelagic coccolith/calcisphere sediments (for more lithological details see WIESE & *al.*, this volume).

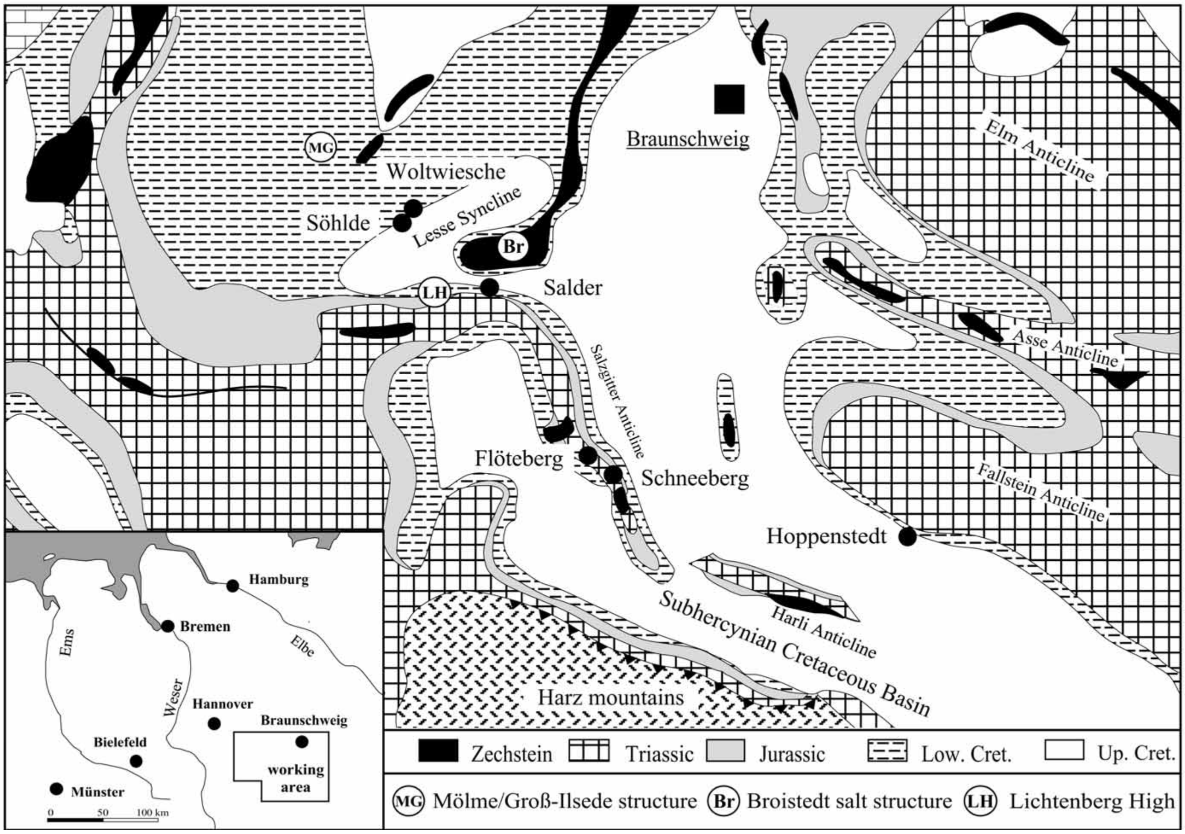

Fig. 1. Generalised geological map of the study area showing localities considered in the text

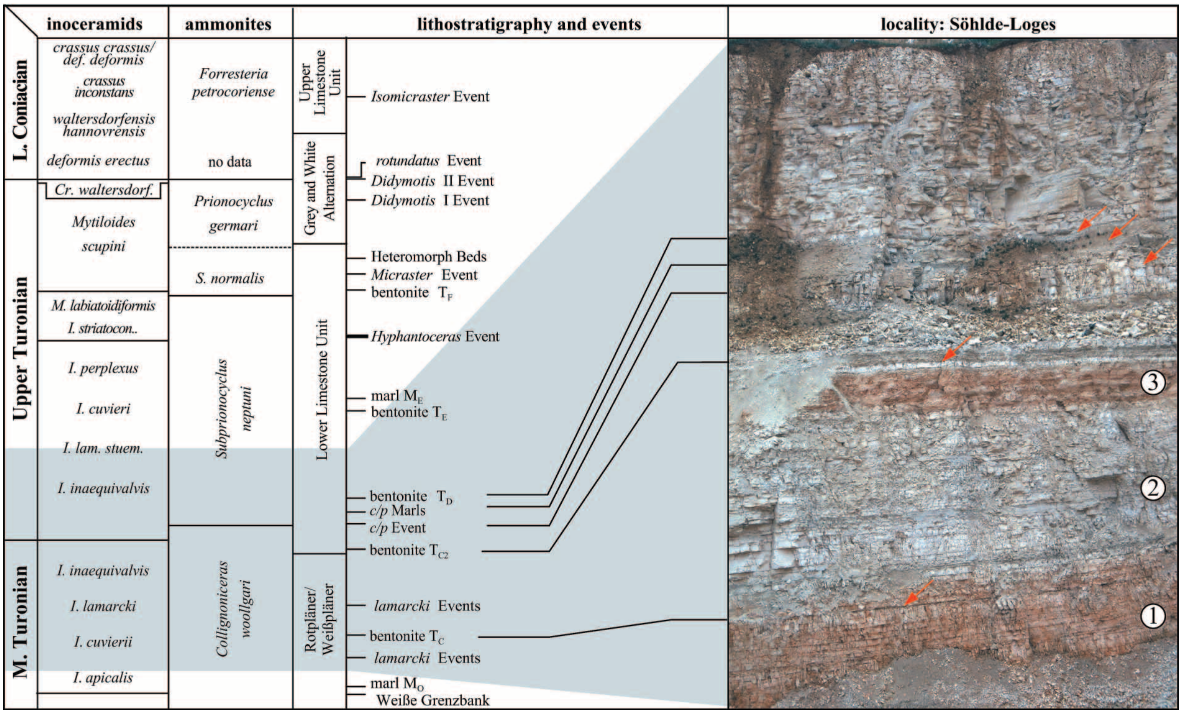

Fig. 2. Stratigraphy and events in the Middle Turonian to Lower Coniacian in the Salzgitter area. The grey box marks the interval in question. Lithostratigraphy and bio/eventstratigraphy exemplified by the Söhlde-Loges quarry. 1) Middle Rotpläner, 2) Weißpläner, 3) Upper Rotpläner. Red arrows: position of the indicated events in the lithological column

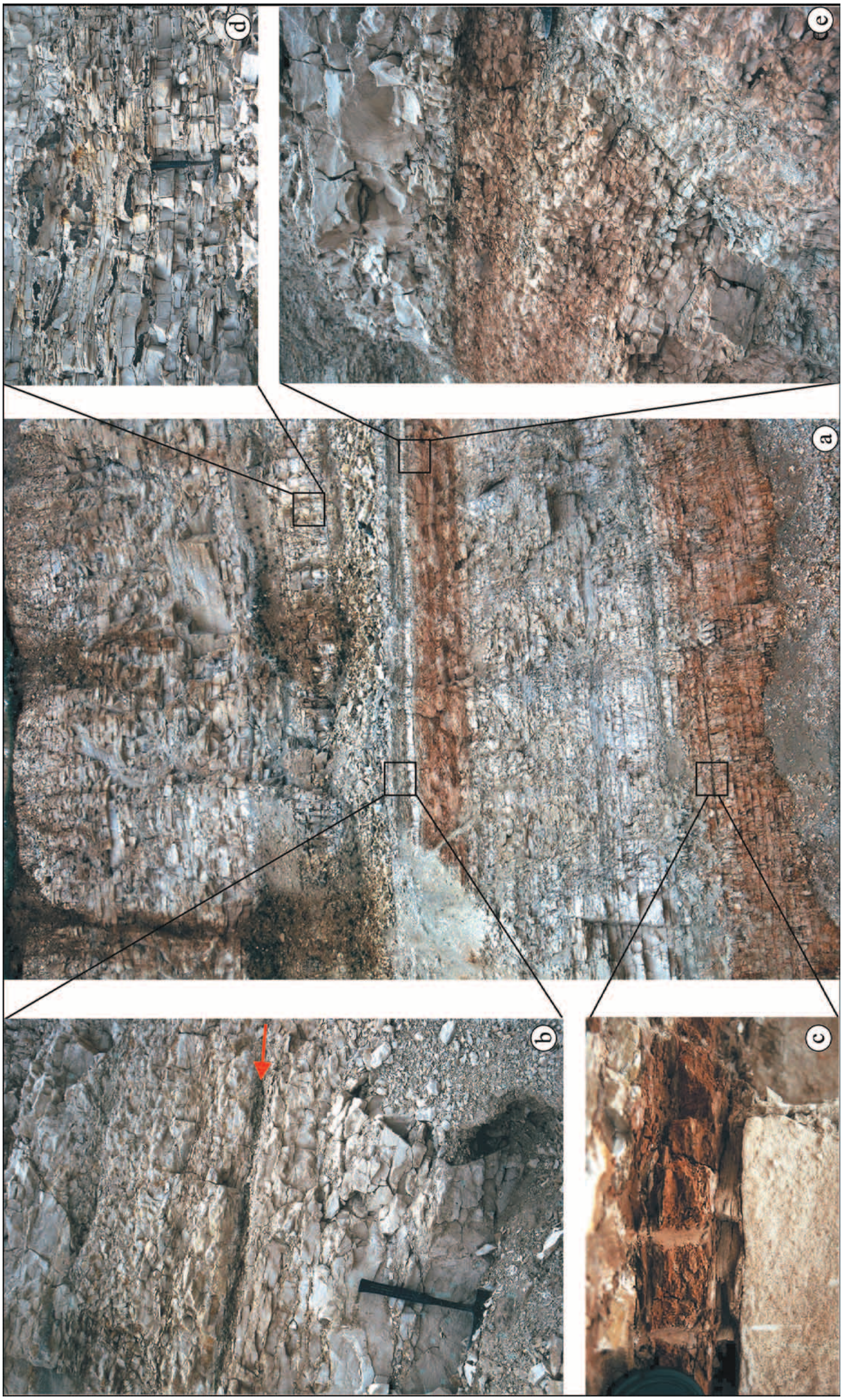

Fig. 3. Lithological details of the Söhlde-Loges succession. a) Overview of the stratigraphic interval from the Middle Rotpläner until above the *costellatus*/*plana* Event (see also Text-fig. 2), b) first white compact limestone above the Basal Turonian Facies Turnover with bentonite T_{C2} in its upper part, weathering as a distinct dark marl seam, c) close-up of bentonite T_C showing its bipartite nature, d) level around flint F_{23}; with platy and nodular flints (hammer for scale), e) upper part of the Upper Rotpläner with the terminal flasery marl seam, sharply overlain by a white compact limestone. The contact between the two marks the Basal Upper Turonian Facies Turnover

In the study area, the entire setting is characterised by structural differentiation into closely-spaced swell areas and more subsiding parts (here referred to as "basinal"), resulting in facies differentiation within distances of only a few hundred metres. The more distal settings are characterised by white/grey flaser-bedded to partly massive-bedded (Weißpläner: white Pläner) limestones, whereas the concomitant near-swell settings are characterised by intercalating red and white lithoclastic/bioclastic to griotte-like limestones (Rotpläner: red Pläner; Text-figs 2 & 3). The conspicuous colour changes from red to white limestones within the lithological column have traditionally been used for the establishment of the Rotpläner and Weißpläner as mapping units (e.g. ERNST & *al*. 1983, WOOD & *al*. 1984).

The sections selected for this investigation represent both distal settings (Flöteberg road-cutting and Salzgitter-Salder Quarry), intermediate to near-swell setting (Söhlde-Loges Quarry) and near-swell/on-swell settings (Hoppenstedt and Woltwiesche quarries) (Text-fig. 1). These localities were chosen because they have been investigated in detail in respect of bio-, litho- and event stratigraphy, and have previously been sampled for REE analysis.

We concentrated mainly on the interval from bentonite T_C to bentonite T_{C2}. Only at Woltwiesche Quarry, the investigation was expanded up-section to the inferred position of T_D, a bentonite that had not previously been identified there. As noted above, a significant facies change at the base of the possible Middle/Upper Turonian boundary interval (Text-fig. 2; see Wiese & Kaplan 2001 for discussion) facilitates estimation of the approximate positions of the two bentonites within the lithological column: Bentonite T_C is located well below, T_{C2} just above this facies change (see Text-fig. 3). Recent biostratigraphic studies (WIESE & KAPLAN 2001) in context with stable isotope correlations ($\delta^{13}C$, VOIGT & HILBRECHT 1997) have suggested that the facies change, rather than the traditional *costellatus/plana* Event, higher up-section, could be taken as the marker for the base of the Upper Turonian in northern Germany. This is suggested by interbasinal stable isotope correlation (see discussion in WIESE & KAPLAN 2001). This interpretation is supported by the correlation of bentonite T_{C2} with the Southerham 1 and Melton Ross marls (both bentonites) in the lower part of the Upper Turonian in the UK (see discussion in WRAY & WOOD 1998; MORTIMORE & *al.* 2001). Owing to its position in the Middle/Upper Turonian boundary interval, this facies change is termed herein the "Basal Upper Turonian Facies Turnover". It is well developed in all sections considered here, although its development in individual sections varies with the depositional setting (see also Text-figs 4-5).

GEOCHEMICAL METHODOLOGY, REE DATA AND RESULTS

From the sections considered, numerous clay beds have been sampled for geochemical analyses. The methodology adopted for the preparation and geochemical analysis of data presented in this work is similar to that previously reported (WRAY & WOOD 1998). All samples were ground using an agate ball mill and, after drying at 105°C overnight, were fused with lithium metaborate at 1000°C in graphite crucibles. Dissolution was achieved by pouring the molten bead into a vessel containing 2.3% nitric acid. Major- and some trace elements were determined using inductively coupled plasma-optical emission spectroscopy while the remaining trace elements were determined using an inductively coupled plasma-mass spectrometer (ICP-MS). In previous studies on Upper Cretaceous marl seams, e.g. WRAY (1995, 1999), a separate sample dissolution protocol employing a hydrofluoric- and perchloric acid ($HF/HClO_4$) digestion was also undertaken. Use of the latter procedure enables a more concentrated sample solution to be presented to the ICP-MS, and was required due to the relatively low levels of many of the lanthanide elements in the samples under investigation. The recent purchase of a new, more sensitive ICP-MS (Thermo X7) has negated the need for this acid digestion procedure and all data reported in this study have been determined from the fusion-derived solutions. Fusion preparations are preferred as they enable the quantification of silicon and, furthermore, some heavy minerals are not fully dissolved by $HF/HClO_4$ attack (e.g. see TOTLAND & *al.* 1992). An evaluation has been made between earlier, acid digest derived bentonite data and those derived from fusion preparations and no discernable differences have been observed.

Following a similar approach to previous work, differentiation of beds into those that are detrital and those that are volcanogenic was achieved using shale-normalised rare-earth element (REE) profiles.

For this study, we sampled several marl seams in each of the following localities: Söhlde-Loges working quarry, Woltwiesche Quarry, Salzgitter-Salder Quarry, Flöteberg road-cutting and Hoppenstedt Quarry (Text-fig. 1). Samples were taken from an interval well below the suspected position of bentonite T_C up to an interval well above the suspected position of bentonite T_{C2}. This interval could be safely determined by the regional bio- and lithostratigraphic framework (Text-fig. 2). Only at Woltwiesche, the type-locality of tuffs A and B, was the sampling extended to higher parts of the succession, since these remained poorly understood in a tephrostratigraphic context. The REE profiles for all beds collected during this study which are considered to be bentonites are shown in Text-figs 6-9. All these beds are characterised by

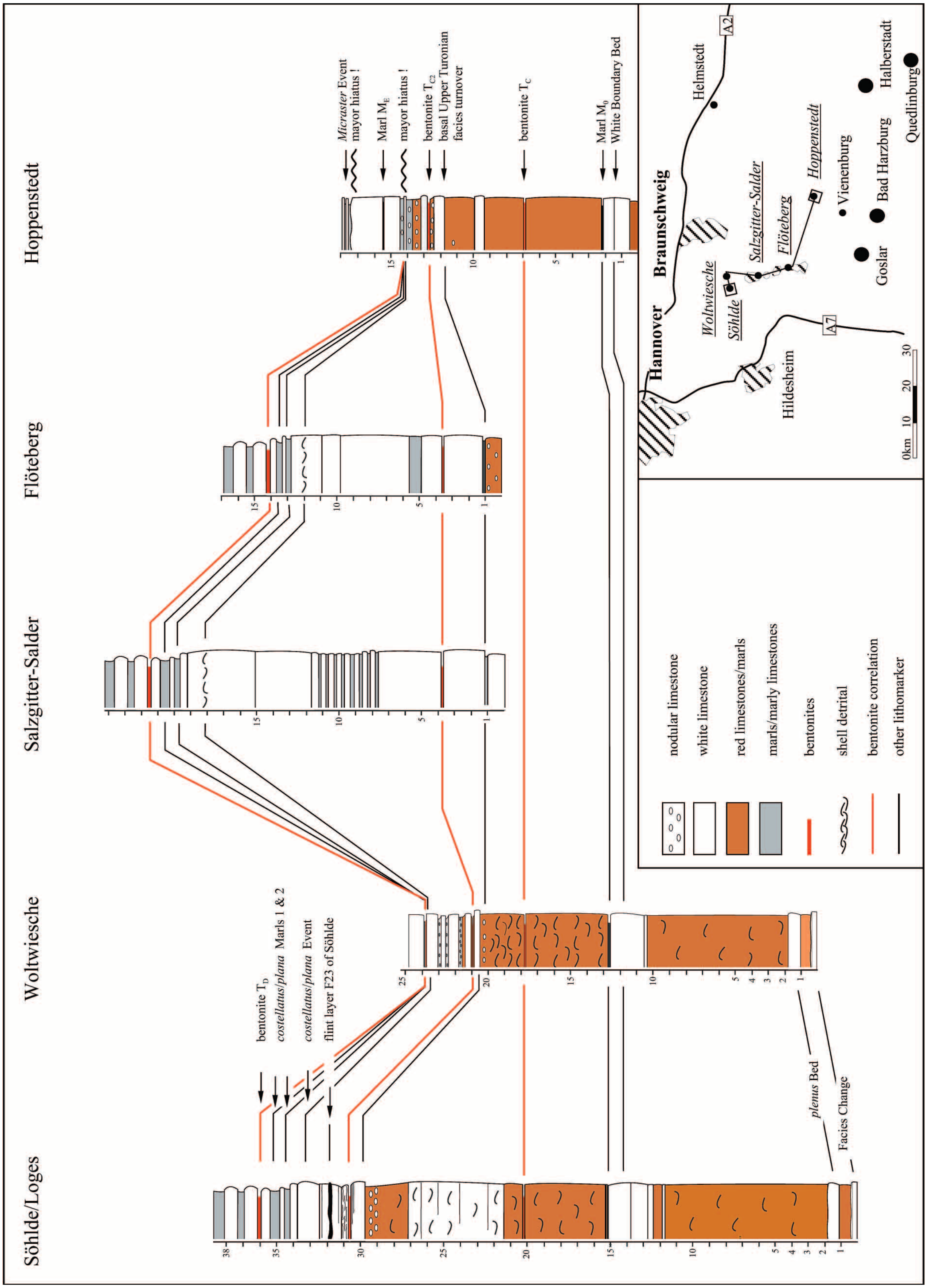

Fig. 4. correlation of the interval from the Lower Turonian to lower Upper Turonian between Söhlde-Loges in the west and Hoppenstedt in the east. Important lithomarkers and events are indicated. Bentonite T_C is used as a datum line. For details on Turonian bioevents see also WIESE *et al.* (this volume), for details on the Facies Change and *plenus* Bed (Upper Cenomanian) see WILMSEN (2003)

a negative europium anomaly and also often display a slight depletion in the heavy REE (data for all bentonites introduced as part of this study are presented in Table 1 in the appendix).

DETAILS OF STUDIED SECTIONS AND TEPHROSTRATIGRAPHIC INTERPRETATION

Söhlde-Loges working Quarry

The quarry exposes a superb section from the white, carbonate-rich Upper Cenomanian "poor *rhotomagense* limestones", through the entire Rotpläner (red limestone) succession, up to a level in the overlying Weißpläner, some distance above bentonite T_D. It is a key section for the investigation of the lowest two bentonites, T_C and T_{C2} of the standard tephrostratigraphic scheme (Text-figs 2-3).

The Söhlde-Loges Quarry is the type-section for the conspicuous white limestone bed (Weiße Grenzbank or White Boundary Bed) that separates the Lower Turonian Lower Rotpläner from the remainder of the Rotpläner. It is also the type-section for flint F_{23}, which is locally developed in the interval between bentonites T_{C2} and T_D here (Text-fig. 3d) and in the immediately adjacent quarries (compare ERNST & WOOD 1995, 1997).

Recent extension of the quarry to the south in a down-dip direction has exposed new Middle and Upper Turonian sections from the White Boundary Bed upwards. These new section have enabled access to bentonite T_C in a deep part of the quarry (Text-fig. 3a, c), and also to the succession at the top of the Rotpläner succession that includes bentonite T_{C2}. (Text-fig. 3a, b).

The Rotpläner: The Rotpläner here is readily divisible into three parts, for which reason the quarry was also designated the type-section for their tripartite subdivision of the Rotpläner (ERNST & WOOD 1995; ERNST & *al*. 1998) into Lower, Middle and Upper Rotpläner. The variable upper limit of the red coloration marking the Middle Rotpläner lies about one metre above bentonite T_C (Text-figs 2-3). The Upper Rotpläner overlies a unit of partly nodular and partly more massive limestones that exhibit no red coloration (see ERNST & *al*. 1998, fig. 62a; Text-figs 2-3). The red coloration of the Upper Rotpläner is relatively weakly developed and its absolute upper limit is laterally variable, inconspicuous and difficult to define. However, the main up-section loss of coloration lies some distance below this upper limit, at a marl seam immediately beneath a conspicuous, 50-cm unit of massive-bedded white limestones (see WRAY & WOOD 2002; Text-fig. 4). The top of the marl seam marks the level of the Basal Upper Turonian Facies Turnover (Text-fig. 3a, e).

The tripartite subdivision of the Rotpläner recognised in the centre of the Lesse Syncline is essentially applicable only to Söhlde-Loges Quarry and the immediately adjacent sections, as well as to a newly discovered section near Dörnten, the Schneeberg section (Text-fig. 1). In more proximal settings, e.g. the highly condensed Rotpläner succession in the Woltwiesche Quarry (Text-figs 1, 4, 5), the unit of limestones without any red coloration separating the Middle and Upper Rotpläner cannot be recognised and falls presumably into an expanded hiatus, indicated by a well developed, sharp and undulating erosional unconformity with an overlying pebble bed that has now been recognized for the first time. In an increasingly distal direction within

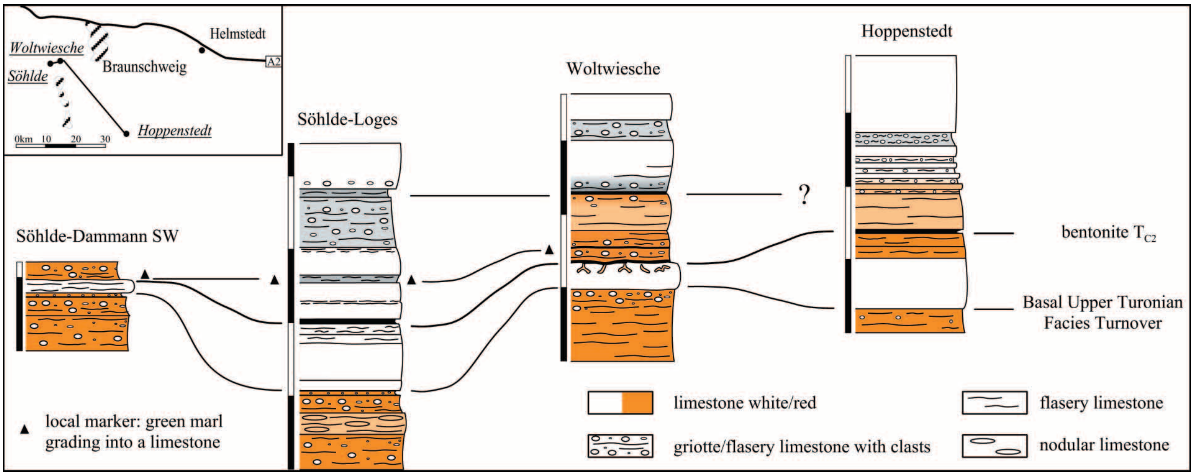

Fig. 5. detailed correlation of the interval around the basal Upper Turonian Facies Turnover and bentonite T_{C2} between Söhlde, Woltwiesche and Hoppenstedt. Black triangle indicates a local marker horizon that enables correlation between the quarries: a marl grading up into an argillaceous limestone. Note that towards Söhlde-Damman SW Quarry, bentonite T_{C2} is cut out due to the synsedimentary development of small-scale relief, and the marker marl come to rest immediately above the white limestone

the Lesse Syncline, i.e., to the west of Söhlde-Loges Quarry, the succession becomes progressively more argillaceous and only the Lower Rotpläner is recognisable.

Bentonite T_C

Presumably the originally small, shallow quarry that has since become the Söhlde-Loges Quarry provided the original reference section (Ernst & *al*. 1983) for bentonite T_C However, the later geochemical studies (Wray & Wood 1995) on T_C were based on samples collected from a bentonite in the abandoned Müller-Nord Quarry, nearly one km to the west. Our subsequent investigations have revealed that the true stratigraphical position and identity of the bentonite in the Müller-Nord quarry are uncertain because of the considerable synsedimentary tectonism, resulting in major lateral facies changes at distances of only tens of metres. Trace element studies (see below) indicate that the bentonite is likely to be either T_C or T_{C2} but further discrimination is not possible due to the impossibility of correlating between Müller-Nord and Söhlde-Loges. For this reason, the Söhlde-Loges Quarry is now to be regarded as the type section for bentonite T_C.

Bentonite T_C is represented at Söhlde-Loges Quarry by the lower marl seam of a conspicuous pair of closely-spaced red marl seams; the upper of which is a thin detrital marl (Text-fig. 3a, c). These two red marl seams are located close to the top of the so-called Middle Rotpläner. Rare-earth element analysis of the clay component of the lower marl seam revealed the negative europium anomaly that is characteristic of a bentonite (Text-fig. 6). Bentonite T_C, with its typical buttery texture, can be traced for only a few metres before it thins, loses its buttery texture, and becomes indistinguishable from the upper marl seam, which also thins laterally and locally disappears altogether.

Bentonite T_{C2}

As recently documented (Wray & Wood 2002; for REE profile see Text-fig. 6), bentonite T_{C2} immediately overlies the conspicuous unit of massive white limestones above the lithofacies change from predominantly nodular, flaser-bedded limestones to predominantly massive-bedded limestones (Basal Upper Turonian Facies Turnover; Text-fig. 3e).

Bentonite T_{C2} itself is overlain by a 0.48 m tripartite unit comprising nodular limestone, a detrital marl and nodular limestone (Text-figs. 3b, 4, 5). This is followed by a thin marl seam grading up into a 0.2 m bed of argillaceous limestone. This upward-grading marl seam is of particular significance for correlation within the Lesse Syncline, because it can be identified in the quarries adjacent to Söhlde-Loges as well as in the condensed section at Woltwiesche Quarry (Text-fig. 5).

The higher part of the succession between bentonite T_{C2} and bentonite T_D is currently inaccessible in Söhlde-Loges Quarry but generalised logs of the lower part are given in Text-fig. 4. There are no accurately measured logs available for this interval, which includes the locally developed flint F_{23}, the *costellatus/plana* Event and the *costellatus/plana* Marls (Text-fig. 2).

The succession that includes bentonite T_{C2} is laterally extremely variable within the Söhlde-Loges Quarry due to the above-mentioned synsedimentary tectonism: the section logged in the current investigation is generally similar, but differs somewhat in detail from that presented earlier (Wray & Wood 2002, fig. 4). In the section exposed in the enormous, and recently hugely expanded, Dammann SW Quarry, southwest of the road junction, the succession is significantly condensed and bentonite T_{C2} is difficult to identify. Here, the conspicuous unit of massive white limestone immediately above the Basal Upper Turonian Facies Turnover is fragmented into separate blocks, resulting in a coarse griotte-like fabric. Bentonite T_{C2} is only locally recognisable; elsewhere in the section, the thick greenish-grey detrital marl seam grading upwards into argillaceous limestone that is located some distance above the bentonite at Söhlde-Loges Quarry comes to rest on the limestone griotte, completely occluding the intervening strata, including the bentonite (Text-fig. 5).

Woltwiesche Quarry

This abandoned quarry is located towards the eastern margin of the Lesse Syncline and currently exposes a highly condensed Rotpläner succession, overlain by a discontinuously exposed Weißpläner succession that extends up to bentonite T_E. For a detailed log of the succession formerly visible see Bräutigam (1962, enclosure 12).

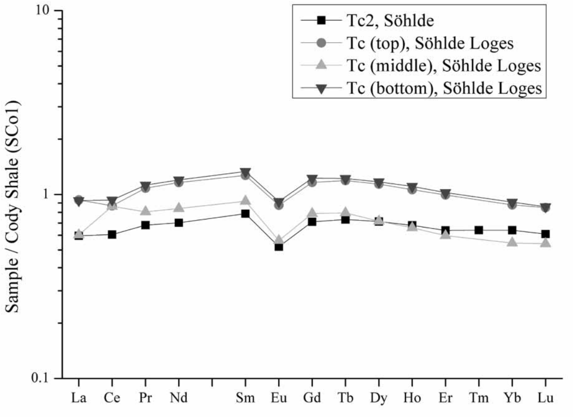

Fig. 6. REE profiles of T_C and T_{C2} at Söhlde-Loges Quarry

It is particularly unfortunate that this was DORN & BRÄUTIGAM's (1959) and BRÄUTIGAM's (1962) original type-locality for the two tuff horizons A and B, which were identified as such petrographically by the apparent presence under the microscope of volcanic glass. Not only were the geochemical methods, such as REE analyses, that were employed in later investigations not available at the time of their study, but their identifications were heavily reliant on optical techniques with no supporting probe analyses.

The two tuff horizons are, respectively, near the base and just below the top of the section. Tuff horizon A has not been subsequently recognised, but its possible identity is discussed further below; tuff horizon B corresponds to bentonite T_E of the standard tephrostratigraphic scheme.

Bentonite T_C

The lower marl of a pair of red marls within the Rotpläner corresponds to bentonite T_C, as indicated by the REE data (Text-fig. 7). This is identical to the situation at Söhlde-Loges Quarry.

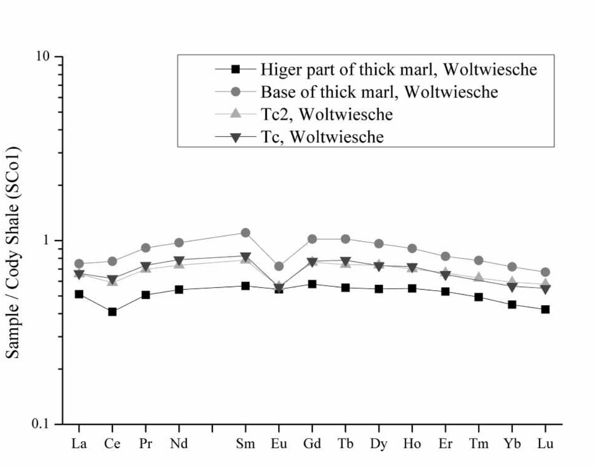

Fig. 7. REE profiles of T_C, T_{C2} and the thick marl of Woltwiesche Quarry. Note that the thick marl exhibits a bipartite signal: the base is volcanogenic and the top is detrital. Its lithostratigraphical position suggests that the base of the thick marl equates with bentonite T_D

Bentonite T_{C2}

T_{C2} can easily be identified due to its position in relation to the Basal Upper Turonian Facies Turnover as a thin green marl seam overlying a conspicuous bed of white limestone, some distance below the top of the Rotpläner. The section here is more condensed than at Söhlde-Loges Quarry and the white limestone has red marl piped down into it. The distinctive unit comprising a marl seam grading up into an argillaceous limestone that was noted in the Söhlde-Loges and Dammann SW quarries is also present but here it is dark pink instead of greyish-green, and lies only 0.15 m above the bentonite.

Tuff horizon A

Higher in the succession, well above T_{C2}, BRÄUTIGAM's log (1962, enclosure 12), shows a 0.10 m marl seam (Tuff horizon A), situated 0.70 m beneath a thick (0.25 m) marl seam. He described this marl seam as comprising a lower (0.08 m) yellowish-green montmorillonitic layer overlain by a (0.02 m) pale grey glass ash layer. Although what appears to be his thick marl seam is conspicuous and readily identifiable, the distinctly coarse-grained marl seam that would then correspond to his Tuff horizon A is only 0.45 m beneath it, rather than 0.70 m, and the REE profile shows no sign of the negative europium anomaly considered diagnostic of vulcanogenic clays in other localities of similar age. Furthermore, this latter marl seam does not match the description of a two-component vulcanogenic marl seam given by DORN & BRÄUTIGAM (1959, p. 2) and BRÄUTIGAM (1962, p. 16). However, detailed sampling of the thick marl seam has revealed that, whilst the upper portion displays a detrital REE profile, the basal six centimetres exhibits an REE profile that is suggestive of a bentonite (Text-fig. 7). Since it is the next bentonite above the positively identified bentonite T_{C2}, it can probably be safely inferred that it corresponds to bentonite T_D (Text-fig. 4). The trace element and REE composition differs from that normally expected of T_D because of contamination from the detrital horizon which directly overlies it. This is an unusual preservation of a bentonite and it is not one that has previously been encountered in either the German or English successions.

Bentonite T_E

The bentonite at the top of the quarry has always been identified on biostratigraphical grounds as T_E because it is located a short distance above the entry of *Micraster*. The same relationship between the entry of *Micraster* and bentonite T_E is observed in the Söhlde-Dammann SE Quarry, where the complete event-bundle comprising bentonite T_E and the overlying detrital marls, M_E and $M_{E'CHEN}$ forms a conspicuous marker. In addition, there are *Conulus* occurrences at the latter locality between bentonite T_D and the entry of *Micraster*, a parallel situation to that at Woltwiesche. There is depositional support for the correlation, in that the interval measured by BRÄUTIGAM (1962) between his thick marl (our inferred T_D) and T_E at Woltwiesche is of the same order of magnitude (circa 16 m) as the interval between the inferred T_D and T_E at Söhlde. This is only to be expected, as this is an interval in which the effects of syndepositional tectonism are negligible and the depositional setting is one of transgression.

Salzgitter-Salder Quarry

This intermittently working quarry lies in a structurally complex position at the junction of the southeasternmost margin of the Lesse Syncline and the Broistedt salt structure in the north (Text-fig. 1). It exposes a continuous succession, dipping at ca.70º NNE, from near the top of the Middle Turonian to the Lower Coniacian (WOOD & ERNST 1997). A conspicuous thick marl seam near the base of the section was considered incorrectly by earlier authors (WOOD *et al.* 1984) to be the Middle Turonian bentonite T_C. However, stable isotope stratigraphical evidence (VOIGT 1997) shows unequivocally that this bentonite lies beneath the base of the section. Recent and better exposures, on the other side of the quarry from the original section, have revealed that the top of the thick marl actually marks the position of the Basal Upper Turonian Facies Turnover, which is well developed here. Bentonite T_{C2} was readily identified in this new section (for REE profile see Tex-fig. 8). In contrast to the development at Söhlde-Loges Quarry, bentonite T_{C2} falls here within a 3 m package of white massively bedded limestones.

The top of the Rotpläner facies that is developed at this level in the more proximal Söhlde-Loges and Woltwiesche quarries is absent here because of the depositional setting in a stronger subsiding area, as indicated by higher accumulation rates.

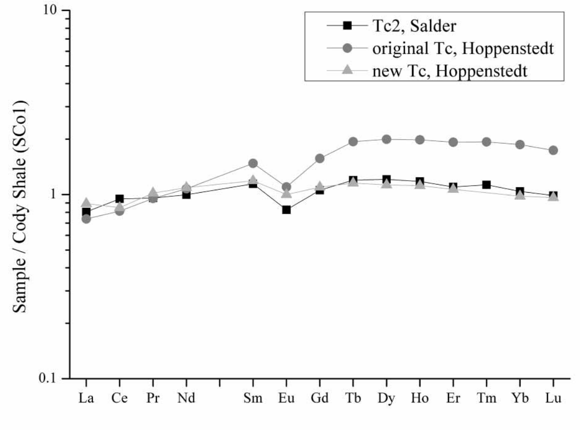

Fig. 8. REE profiles of bentonite T_C at Hoppenstedt Quarry and bentonite T_{C2} at Salzgitter-Salder Quarry

Flöteberg road-cutting section

The Flöteberg road-cutting (Text-fig. 1) near Othfresen exposes a highly instructive section from the Upper Albian to the Lower Coniacian. A detailed log of the Turonian and Lower Coniacian parts of the succession was presented by BRÄUTIGAM (1962, enclosure 16). The presence of bentonite T_C was previously been confirmed by WRAY *& al.* (1996) The development of the basal Upper Turonian Facies Turnover is similar to that at Salzgitter-Salder Quarry, albeit the Flöteberg section – located in the Salzgitterer Höhenzug - reflects a slightly shallower depositional setting as expressed by the higher amount of macrofossil debris and lithoclasts, the stronger nodularity of the Rotpläner and the smaller thickness of the interval from the Basal Turonian Facies Turnover up to the *costellatus/plana* Event. The marl below the Basal Upper Turonian Facies Turnover is also present, but here is only poorly developed. Within this lithostratigraphic framework, bentonite T_{C2} (for REE plot see Text-fig. 9) was found to be located in a package of massively bedded limestones above the Basal Upper Turonian Facies Turnover, as at Salzgitter-Salder.

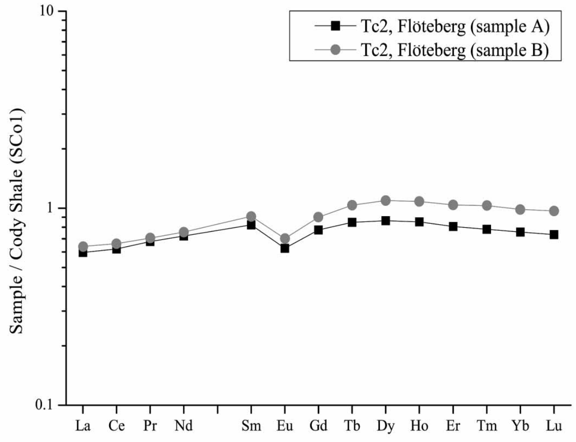

Fig. 9. REE profile of bentonite T_{C2} at Flöteberg road cutting

Hoppenstedt (abandoned) Quarry

The quarry is situated on the southern flank of the Fallstein anticline, Saxony-Anhalt (Text-fig. 1). So far, only bentonite T_C was believed to have been identified (HORNA 1995). However, correlation of the supposed bentonite T_C of Hoppenstedt to sections with T_C in Lower Saxony presented severe stratigraphic problems. Having recognised the Basal Upper Turonian Facies Turnover in the Hoppenstedt section, it was apparent that the supposed bentonite T_C was located in the

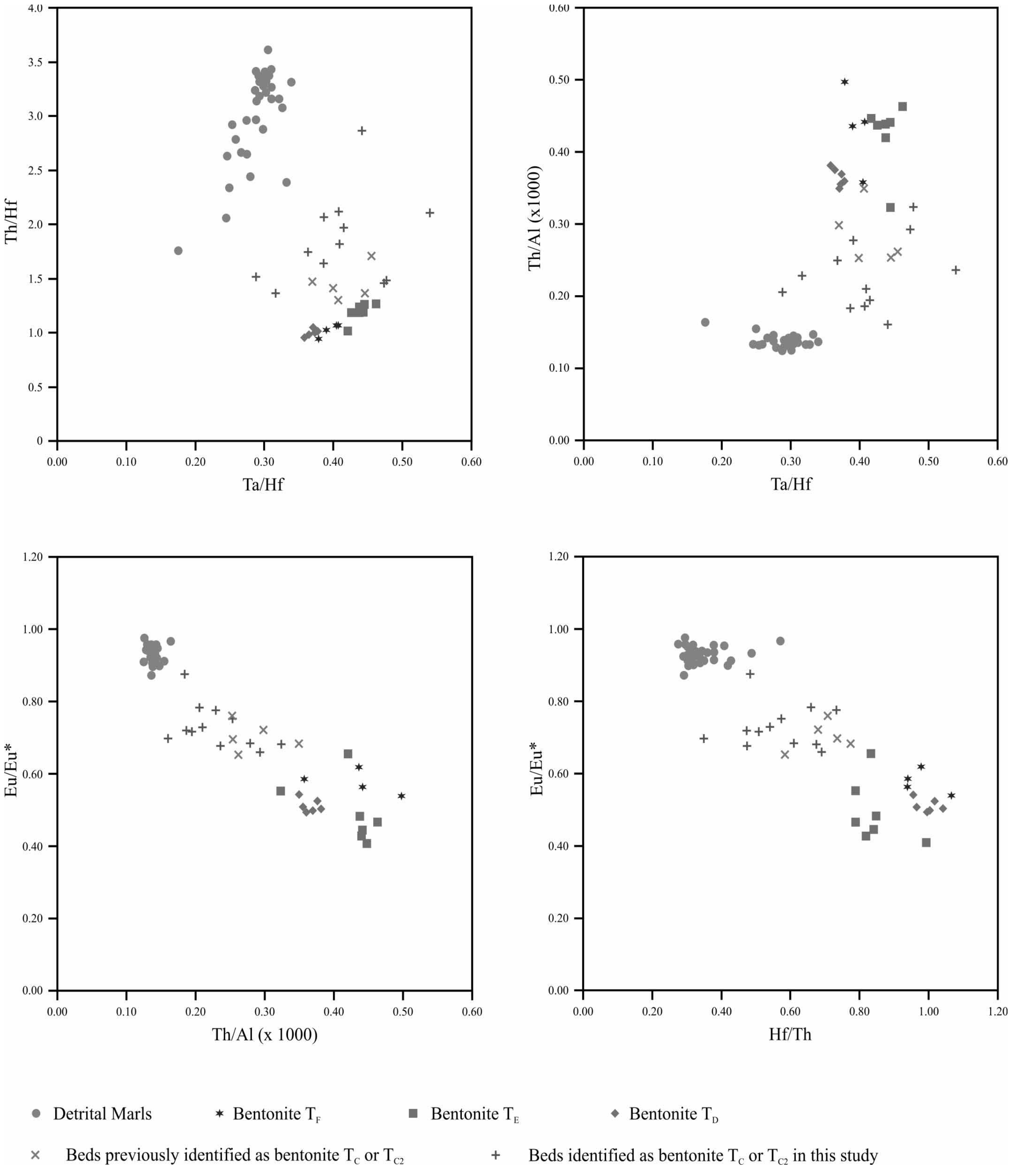

Fig. 10. selected REE crossplots of detrital marls and bentonites T_C, T_{C2}, T_D, T_E and T_F

lithostratigraphic position of T_{C2} as observed in Lower Saxony. Consequently, the Hoppenstedt section was reinvestigated. Bentonite T_C was readily identifiable within the Rotpläner (top of Middle Rotpläner) succession as the lower of the paired red marl seams seen at Söhlde-Loges Quarry, and within the undivided Rotpläner succession at Woltwiesche Quarry. Its bentonitic character is confirmed by REE analysis (Text-fig. 8). Given that this marl-seam had now been positively identified both stratigraphically and geochemically as bentonite T_C, it followed that the supposed bentonite T_C, higher up-section (HORNA 1995, HORNA

& WIESE 1997), needed to be reassessed. Its REE profile (Text-fig. 8) is similar to that of the true T_C at this locality. In view of the fact that bentonites T_C and T_{C2} are geochemically broadly similar and readily distinguishable from the remaining Turonian bentonites, the supposed bentonite T_C is most probably T_{C2}. This interpretation is also supported by its lithostratigraphic position immediately above the Basal Upper Turonian Facies Turnover.

The succeeding bentonite, $T_{D,}$ has not so far been recognized at Hoppenstedt. However, owing the very condensed succession here, it is most probable that the interval around T_D, including the *costellatus*/*plana* Marls, falls into an hiatus (see also Text-fig. 4 of WIESE *et al.*, this volume).

BENTONITE DISCRIMINATION USING TRACE- AND RARE-EARTH ELEMENT DATA

As mentioned above, it is impossible to distinguish individual bentonites on their REE profile alone, leading in the structurally and sedimentologically complex study area to the confusion of bentonites T_C and $T_{C2,}$ which possess similar REE profiles. In an attempt to differentiate the two bentonites, an investigation of their trace element composition was undertaken. An expanded dataset was used for this study; it included results from all other previously collected north German bentonites (T_C, T_{C2}, T_D, T_E and T_F) and representative detrital beds. An extensive number of element ratios were investigated. Selection of the ratios presented in this work was based on their ability to differentiate between well characterised, previously collected bentonites. The following ratios proved most effective: Th/Hf, Ta/Hf, Th/Al and Eu/Eu*. Eu/Eu* was calculated using the shale normalised values as follows: $Eu_{SN}/\sqrt{(Sm_{SN}.Gd_{SN})}$. Cross-plots of paired ratios are presented in Text-fig. 10.

The data presented in Text-fig. 10 demonstrate that it is possible to reliably separate detrital and volcanogenic beds on the basis of their trace element chemistry. Furthermore, examination of data from well characterised bentonites indicates that it is possible to distinguish individual bentonites from one another with a reasonable degree of confidence. Bentonites T_D, T_E and T_F can be readily characterised using a combination of these trace element ratios. Likewise it is possible to separate T_C and T_{C2} from the remaining bentonites and detrital beds but unfortunately none of the ratios examined was able to distinguish these two bentonites from each other. Consequently, an unequivocal identification/discrimination of the two bentonites T_C and T_{C2} is only possible in context with lithostratigraphic data.

DISCUSSION

Use of the bentonites to establish isochronous time planes within the laterally extremely variable Pläner limestones succession in Lower Saxony and Saxony-Anhalt demonstrates that – contrary to previous interpretations – the Rotpläner lithofacies is highly diachronous, with its upper limit extending progressively higher – with respect to the position to offshore swells – in a distal to proximal transect within the intra-shelf setting. The upper limit of the Rotpläner in the study area lies in the Upper Turonian, but even younger (Coniacian) red limestones are known from shallow water settings in Westphalia (VOIGT 1962).

In addition to enabling interbasinal correlation, the isochronous nature of the bentonites aids in the understanding of lateral facies relationships. While in subsiding areas bentonite T_{C2} is located well within massively bedded limestones (Salzgitter-Salder Quarry, Flöteberg road-cutting), in near-swell sections (Woltwiesche Quarry, Hoppenstedt Quarry) it is located in griotte-like sediments. This demonstrates that a concomitant, closely-spaced lateral facies variation occurs between massively bedded limestones and griottes as end-members and facilitates the reconstruction of the (bio)sedimentation dynamics of the anactualistic Pläner limestone biosedimentary system.

The new data establish the correlation of the five Turonian bentonites between the UK and Lower Saxony/Saxony-Anhalt in northern Germany. However, in Westphalia, where bentonites T_C, T_D, T_E and T_F are also recorded (WRAY & *al.* 1995), bentonite T_{C2} has not yet been identified. Since this bentonite can be traced from the UK to the study area, it is probable that it is also represented in Westphalia. In the UK, the equivalent of T_{C2} is one of the thickest and best developed of the Turonian bentonites (Southerham Marl 1/Melton Ross Marl), whereas it is relatively thin and inconspicuous in the study area and even locally disappears. Recognition in Westphalian sections of the equivalent of the Basal Upper Turonian Facies Turnover may provide the key to the location of this bentonite.

Arising from the correlation of bentonite T_C with one of the Glynde marls (cf. MORTIMORE & *al.* 2001, text-figs 1.12 and 2.9), the lithofacies change in southern England from the essentially marly chalks of the New Pit Chalk Formation to the nodular chalks of the Lewes Nodular Chalk Formation approximates to the Basal Upper Turonian Facies Turnover as identified in Lower Saxony and Saxony-Anhalt. The succeeding bentonite, Southerham Marl 1 and the correlative bentonite $T_{C2,}$ are located a short distance above the base of the Lewes Nodular Chalk and the Basal Upper Turonian Facies Turnover respectively.

SUMMARY OF CONCLUSIONS

1. Bentonite T_C has been correlated for the first time from the type section in the Söhlde quarries to condensed near-swell sections in the abandoned Woltwiesche and Hoppenstedt quarries.
2. In the Söhlde-Loges Quarry, where it was first identified, bentonite T_{C2} is a thin, inconspicuous marl seam located a short distance above an up-section change from nodular limestones to massive limestones, herein termed the Basal Upper Turonian Facies Turnover. This lithofacies change is marked by a marl seam, which is followed by a conspicuous bed of massive white limestone.
3. Recognition of the position of bentonite T_{C2} at Söhlde-Loges Quarry relative to the Basal Upper Turonian Facies Turnover provided a lithostratigraphic/tephrostratigraphic template enabling the location of this bentonite for the first time in other sections, notably in near-swell settings (Woltwiesche and Hoppenstedt quarries) and in distal settings (Salzgitter-Salder Quarry, Flöteberg road-cutting).
4. Problems still arise in relation to the correct identification of Brautigam's tuff-horizon A at Woltwiesche Quarry. However, in view of the identification of bentonite T_{C2} at this locality, it is likely that tuff-horizon A is bentonite T_D.
5. In the highly condensed Hoppenstedt Quarry succession, the conspicuous bentonite previously identified as T_C is located in griotte-like facies within the Rotpläner, a short distance above the Basal Upper Turonian Facies Turnover, and is consequently reinterpreted as bentonite T_{C2}.
6. The new data establish the correlation of the five Turonian bentonites between the UK and Lower Saxony/Saxony Anhalt in northern Germany. However, in Westphalia, where bentonites T_C, T_D, T_E and T_E are also recorded, bentonite T_{C2} has not yet been identified. It is likely that bentonite T_{C2} is also represented in Westphalia and that recognition of the Basal Upper Turonian Facies Turnover will enable this bentonite to be identified.
7. Use of the bentonites to establish isochronous time planes within the laterally extremely variable Pläner limestones succession demonstrates that – contrary to previous interpretations - the Rotpläner lithofacies is highly diachronous, with its upper limit extending progressively higher in a distal to proximal transect within the intra-shelf setting. The upper limit of the Rotpläner in the study area lies in the Upper Turonian, but even younger (Coniacian) red limestones are known from shallow water settings in Westphalia.
8. The previous distinction, above the Lower Turonian Lower Rotpläner and the overlying White Boundary Bed, of two Middle Turonian red limestone units (Middle and Upper Rotpläner), separated by nodular white limestones, is shown to apply only to particular depositional settings. In a distal direction, the red coloration of the higher two units may be lost altogether, whereas in more proximal settings (intra-shelf swells) the middle and upper red limestones fuse together and the intercalated white limestone either falls into an hiatus or time-equivalent strata are also developed as Rotpläner.
9. The geochemical fingerprints of individual bentonites in Lower Saxony have been elaborated using Th/Hf, Ta/Hf, Th/Al and Eu/Eu crossplots. It showed that bentonites T_D, T_E and T_F can be discriminated by one or more of the ratios, as can T_C/T_{C2}. The latter, however, are indistinguishable from each other.

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Appendix

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3(t)	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
Tc$_2$ Söhlde	28.96	0.306	9.19	2.99	0.027	1.80	28.40	0.113	0.87	0.07
Tc (top), Söhlde Loges	24.05	0.362	9.82	2.41	0.020	1.03	30.76	0.166	1.54	0.22
Tc (middle), Söhlde Loges	38.46	0.419	13.67	4.23	0.027	2.44	19.22	0.119	0.81	0.09
Tc (bottom), Söhlde Loges	28.18	0.421	11.28	3.28	0.023	1.19	27.56	0.177	1.76	0.23
Tc$_2$, Salder	38.08	0.535	15.74	2.61	0.023	1.79	22.27	0.190	1.72	0.10
original Tc Hoppenstedt	38.78	0.573	16.04	2.85	0.021	1.76	17.81	0.187	2.11	0.16
new Tc, Hoppenstedt	29.40	0.491	12.68	4.19	0.026	1.21	24.08	0.213	2.20	0.25
Tc$_2$ Flöteberg (sample A)	19.52	0.301	8.00	1.79	0.037	0.93	36.04	0.155	1.37	0.11
Tc$_2$ Flöteberg (sample B)	27.16	0.421	11.28	2.46	0.031	1.25	29.24	0.177	1.75	0.11
higher part of thick marl, Woltwiesche	19.21	0.228	4.80	2.02	0.041	0.81	38.31	0.155	0.90	0.41
base of thick marl,Woltwiesche	27.18	0.319	8.17	1.69	0.032	1.55	32.60	0.164	1.09	0.33
Tc$_2$ Woltwiesche	18.05	0.235	5.74	1.67	0.021	0.96	39.95	0.132	0.87	0.15
Tc Woltwiesche	25.70	0.382	9.44	3.29	0.020	0.97	30.33	0.183	1.72	0.23

	Ba	Co	Cr	Cs	Ga	Hf	Nb	Ni	Rb
Tc$_2$ Söhlde	107.9	14.6	21.7	2.8	15.6	9.1	31.6	42.2	39.1
Tc (top), Söhlde Loges	178.2	6.5	42.1	5.1	13.1	4.6	28.3	32.6	70.9
Tc (middle), Söhlde Loges	125.0	11.5	17.2	2.3	23.8	14.6	70.7	47.7	33.6
Tc (bottom), Söhlde Loges	209.5	11.1	46.4	5.9	15.7	5.9	34.0	42.1	81.6
Tc$_2$, Salder	242.8	13.1	42.2	5.7	21.4	12.1	30.1	49.6	76.9
original Tc Hoppenstedt	5655.0	31.8	57.2	8.9	20.5	17.2	52.9	62.3	99.1
new Tc, Hoppenstedt	2604.0	11.1	59.2	7.4	15.4	6.0	30.6	53.8	100.0
Tc$_2$ Flöteberg (sample A)	144.3	16.0	31.5	5.3	10.4	5.8	25.7	43.1	63.8
Tc$_2$ Flöteberg (sample B)	175.7	30.5	38.6	7.2	14.3	10.0	40.5	62.5	83.6
higher part of thick marl, Woltwiesche	388.0	23.2	26.6	3.2	6.1	1.3	6.9	54.4	40.3
base of thick marl,Woltwiesche	111.7	19.0	40.4	5.4	16.3	7.5	18.2	42.3	62.8
Tc$_2$ Woltwiesche	77.8	11.1	25.3	3.0	8.8	3.5	16.0	31.2	42.3
Tc Woltwiesche	162.2	8.3	45.1	6.0	11.5	2.8	15.7	44.2	83.3

	Sc	Sr	Ta	Th	U	V	Y	Zr
Tc$_2$ Söhlde	3.5	504.6	4.0	12.3	0.5	44.6	17.5	268.2
Tc (top), Söhlde Loges	6.3	439.7	1.9	9.7	1.0	60.7	29.9	130.6
Tc (middle), Söhlde Loges	3.2	375.8	6.9	21.1	0.4	40.1	16.3	421.2
Tc (bottom), Söhlde Loges	6.6	382.6	2.5	11.6	1.0	79.3	29.2	169.4
Tc$_2$, Salder	7.2	453.8	4.4	21.1	1.7	77.7	29.9	354.7
original Tc Hoppenstedt	7.8	599.5	6.4	25.3	2.1	109.0	50.9	581.6
new Tc, Hoppenstedt	8.1	745.2	2.3	12.3	1.3	82.5	30.1	180.5
Tc$_2$ Flöteberg (sample A)	5.3	654.8	1.7	8.7	0.9	58.7	24.1	164.8
Tc$_2$ Flöteberg (sample B)	6.6	502.9	3.2	13.7	1.2	82.4	30.2	282.8
higher part of thick marl, Woltwiesche	3.5	622.7	0.7	4.22	0.9	46.2	19.9	51.49
base of thick marl,Woltwiesche	5.7	524.8	2.9	12.1	1.4	60.4	21.5	177.6
Tc$_2$ Woltwiesche	3.5	507.1	1.4	6.4	1.2	55.2	17.6	93.9
Tc Woltwiesche	6.6	331.5	1.2	8.0	0.8	78.8	22.2	79.7

	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Tc$_2$ Söhlde	19.4	35.8	5.05	19.5	4.03	0.64	3.29	0.52	2.97	0.61	1.62	0.24	1.53	0.22
Tc (top), Söhlde Loges	30.3	51.4	8.03	32.2	6.51	1.07	5.38	0.85	4.74	0.96	2.53	n.d.	2.11	0.30
Tc (middle), Söhlde Loges	19.6	51.0	5.97	23.3	4.71	0.69	3.65	0.57	2.98	0.60	1.52	n.d.	1.31	0.19
Tc (bottom), Söhlde Loges	30.1	55.2	8.35	33.3	6.83	1.12	5.68	0.87	4.88	1.00	2.61	n.d.	2.18	0.30
Tc$_2$, Salder	26.1	56.1	7.10	27.6	5.85	1.01	4.88	0.85	5.03	1.07	2.80	0.42	2.50	0.35
original Tc Hoppenstedt	23.9	48.1	7.06	29.8	7.57	1.35	7.26	1.38	8.30	1.79	4.89	0.71	4.48	0.62
new Tc, Hoppenstedt	29.0	50.3	7.55	30.2	6.08	1.23	5.07	0.82	4.70	1.01	2.71	n.d.	2.35	0.34
Tc$_2$Flöteberg (sample A)	19.4	36.7	5.02	20.0	4.21	0.77	3.58	0.60	3.59	0.77	2.06	0.29	1.82	0.26
Tc$_2$ Flöteberg (sample B)	20.8	39.1	5.22	21.0	4.66	0.86	4.16	0.74	4.56	0.98	2.64	0.38	2.36	0.34
higher part of thick marl, Woltwiesche	16.5	24.2	3.7	15.0	2.90	0.62	2.68	0.39	2.27	0.50	1.34	0.18	1.08	0.15
base of thick marl,Woltwiesche	24.3	45.7	6.77	27.0	5.65	0.89	4.71	0.73	4.00	0.82	2.09	0.29	1.73	0.24
Tc$_2$ Woltwiesche	21.4	34.9	5.17	20.4	4.00	0.69	3.52	0.53	3.06	0.63	1.70	0.23	1.43	0.21
Tc Woltwiesche	21.5	36.8	5.44	21.8	4.23	0.68	3.57	0.56	3.04	0.65	1.66	n.d.	1.35	0.20

Major element data are expressed as oxide wt %, trace element data as _g g^{-1}