

Biostratigraphy, sequence stratigraphy and gamma-ray spectrometry of the Tournaisian-Viséan boundary interval in the Dublin Basin

JIŘÍ KALVODA, ONDŘEJ BÁBEK, FRANÇOIS X. DEVUYST & GEORGE D. SEVASTOPULO



A study of three carbonate and carbonate-siliciclastic sections at the Tournaisian-Viséan (Tn-V) boundary in the Dublin Basin (Ireland), has been carried out using high resolution foraminiferal biostratigraphy and gamma-ray spectrometry. The aim was to identify the Tn-V boundary and trace correlatable log patterns in different environmental settings of the Dublin Basin. The foraminiferal fauna in the heterozoan and mixed heterozoan-photozoan (foramderm and bryonoderm extended) late Tournaisian shallow ramp facies and its calciturbidite products is taxonomically impoverished and resembles the similar impoverished foraminiferal associations of western Canada interpreted as reflecting upwelling zones. The increase of photozoan bioclasts which occurs in the latest Tournaisian is accompanied by the entry of important foraminiferal guides of the Tn-V boundary interval. The combination of biostratigraphic and spectral gamma-ray data proved to be a useful tool for the identification of the sequence boundary just below the Tn-V boundary across the different environmental settings of the Dublin Basin. The recognized sea-level fall is correlatable across the London Brabant Massif from western Ireland through to England, South Wales and Belgium. • Key words: Tournaisian, Viséan, biostratigraphy, sequence stratigraphy, gamma-ray spectrometry.

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The definition of the base of the Viséan that was utilised in the last decades of the 20th century was proposed by Raphael Conil at the 6th International Congress of the Carboniferous System in Sheffield (UK). The proposed level coincided in the Bastion stratotype section in the Dinant basin in Belgium with the first occurrence of the calcareous foraminiferal genus *Eoparastaffella* (Conil *et al.* 1969). However, the choice of the stratotype was not ideal as the entry of stratigraphically significant foraminifers is facially controlled in a peri-Waulsortian context and many taxa regarded by Conil as Viséan guide fossils occur elsewhere significantly earlier (Kalvoda 1982, 1983). Later it was also found that in the Belgian sections some assemblages of foraminifers that were originally considered as Viséan occur below the entry of *Eoparastaffella* (Conil *et al.* 1989, 1991; Hance *et al.* 1994). The use of the first occurrence of the genus *Eoparastaffella* as the criterion for recognition of the Tournaisian/Viséan boundary was also unsatisfactory because the most primitive representatives of the genus

already appear in the late Tournaisian (Hance 1997). Subsequent research resulted in the identification of the Pengchong section (Guangxi, southern China) as a potential candidate for a new stratotype because of the exceptional record of *Eoparastaffella* and continuous sedimentation (Hance 1997, Hance *et al.* 1997, Devuyt *et al.* 2003). The definition of the base of the Viséan at the first appearance of the foraminifer *Eoparastaffella simplex* in the lineage *Eoparastaffella ovalis* Vdovenko–*Eoparastaffella simplex* and the GSSP in the Pengchong section near Liuzhou in Guangxi, southern China have been proposed (Devuyt *et al.* 2003) and recently ratified by the ICS and IUGS (Work 2008).

The definition of the regional stages for Britain and Ireland proposed by George *et al.* (1976) capitalized on the widespread application of foraminiferal biostratigraphy introduced to Western Europe by Raphael Conil (Conil & Lys 1964, Conil *et al.* 1980, Paproth *et al.* 1983). The base of the regional Chadian stage was chosen to be coincident

with the entry of the foraminiferan genus *Eoparastaffella*, supposedly in conformity with the definition of the base of the Viséan in Belgium. However, as is the case in the Bastion section (Belgium), the entry of *Eoparastaffella* in the Chadian type-section occurs in peri-Waulsortian facies with a discontinuous foraminiferal record. In addition, it is now known that *Eoparastaffella* does not appear at the base of the Chadian in the stratotype section but at a significantly higher horizon (Riley 1995).

The task of identifying the base of the Viséan in Ireland is in its infancy. In the past the base has commonly been identified at an horizon substantially older than its true recent position (Sevastopulo & Wyse Jackson 2009). Moreover, the foraminiferal record in the latest Tournaisian–earliest Viséan has been rather poor (Jones & Somerville 1996). Mamet (1969) described Lower Carboniferous foraminiferal associations in the Rush section of the Dublin Basin but did not identify the base of the Viséan. Late Tournaisian–early Viséan foraminiferal associations and *Eoparastaffella simplex* were illustrated in Ireland for the first time by Marchant (1974) and Conil & Lees (1975). Similar associations were then mentioned by Strogon *et al.* (1990) in the Dublin Basin, Somerville *et al.* (1992) in the Limerick syncline and Strogon *et al.* (1995) in the Kingscourt Outlier. Devuyt (2006) outlined the distribution of the main foraminiferal guides, including *E. simplex*, across the Tn–V boundary in the Rush and Lane sections and gave a detailed account of the foraminifers present in the same interval in the Oughterard area, County Galway.

The sequence stratigraphic model of the Lower Carboniferous of the Namur–Dinant Basin (Belgium) was proposed by Hance *et al.* (2001) and correlated with northern France and the British Isles by Hance *et al.* (2002) and Devuyt (2006). The model largely benefited from the advances in foraminiferal biostratigraphy and previous sedimentary models by Ramsbottom (1973) and Conil *et al.* (1977). The boundary between sequences 4 and 5 that falls in the very latest Tournaisian (uppermost part of MFZ 8) is commonly marked by unconformities in shallower sedimentary environments where it thus approximates the Tn–V boundary (Poty *et al.* 2006).

Gamma-ray spectrometry (GRS) has proved a useful tool to supplement biostratigraphy and sequence stratigraphy and improves dramatically the resolution of correlations at the scale of a basin (Doveton 1994; Rider 1999; Thibal *et al.* 1999; Delius *et al.* 2001; Hladil *et al.* 2006).

The present study aims at improving the resolution of the biostratigraphy and sequence stratigraphy of late Tournaisian and early Viséan rocks of the Dublin Basin by combining high-resolution foraminifer biostratigraphy, sedimentology and petrophysical methods (GRS). The Rush and Lane sections were re-sampled in detail and a new section at Bay Lane Quarry was also included.

Geological setting

The Dublin Basin (Fig. 1) is one of several sedimentary basins in Britain and Ireland, which were controlled by Caledonian structures that were reactivated during the Lower Carboniferous (Phillips & Sevastopulo 1986, Nolan 1989, Pickard *et al.* 1994, Strogon *et al.* 1996). The Lower Palaeozoic basement is overlain unconformably by Lower Carboniferous rocks. The lower part of the succession records an overall deepening trend, culminating in the latest Tournaisian with Waulsortian facies carbonate mounds and overlying deep water mudstones of the Tober Colleen Formation. On the Balbriggan platform to the north, the time equivalents are shallow water limestones of the Lane Formation. During the Viséan, relatively deep water sediments, mostly calciturbidites and shales were deposited in the basin, while the Balbriggan platform was covered by shallow water or was emergent and varied skeletal and oolitic carbonates were deposited (Fig. 1) (Somerville *et al.* 1992a, b; Pickard *et al.* 1994; Sevastopulo & Wyse Jackson 2009).

The present study has focussed on three sections, the Lane coastal section representing the shelf facies and the Rush coastal and Bay Lane Quarry sections representing the basinal facies.

The Lane coastal section

The section is located about 1.5 km north of the village of Loughshinny, and about 25 km north-northeast of Dublin, at latitude N-53°33' 23" and longitude W-6°4' 57". Shallow-water shelf sedimentation of the Lane Formation of latest Tournaisian age displays a general coarsening and shallowing-upwards sequence with increasing proportion of sand. A sudden relative sea-level fall resulted in the deposition of a coarse fluvial conglomerate (Smuggler's Cave Formation) with reworked clasts of the Lane Formation at its base. The Smuggler's Cave Formation is overlain by the Arundian Holmpatrick Formation. The Lane section has been the subject of several biostratigraphical and sedimentological studies (Devuyt 2006; Marchant 1974, 1978; Nolan 1986, 1989; these papers contain references to earlier literature). The interval sampled covers the upper part of the Lane Formation (15 m) and the basal Smuggler's Cave Formation.

The Rush coastal section

The section is located south of and in Rush Harbour about 23 km north northeast of Dublin, at latitude 53°31' 21" N and longitude 6°04' 44" W. Its stratigraphy and sedimentology have been studied over a long period (Bábek *et al.*

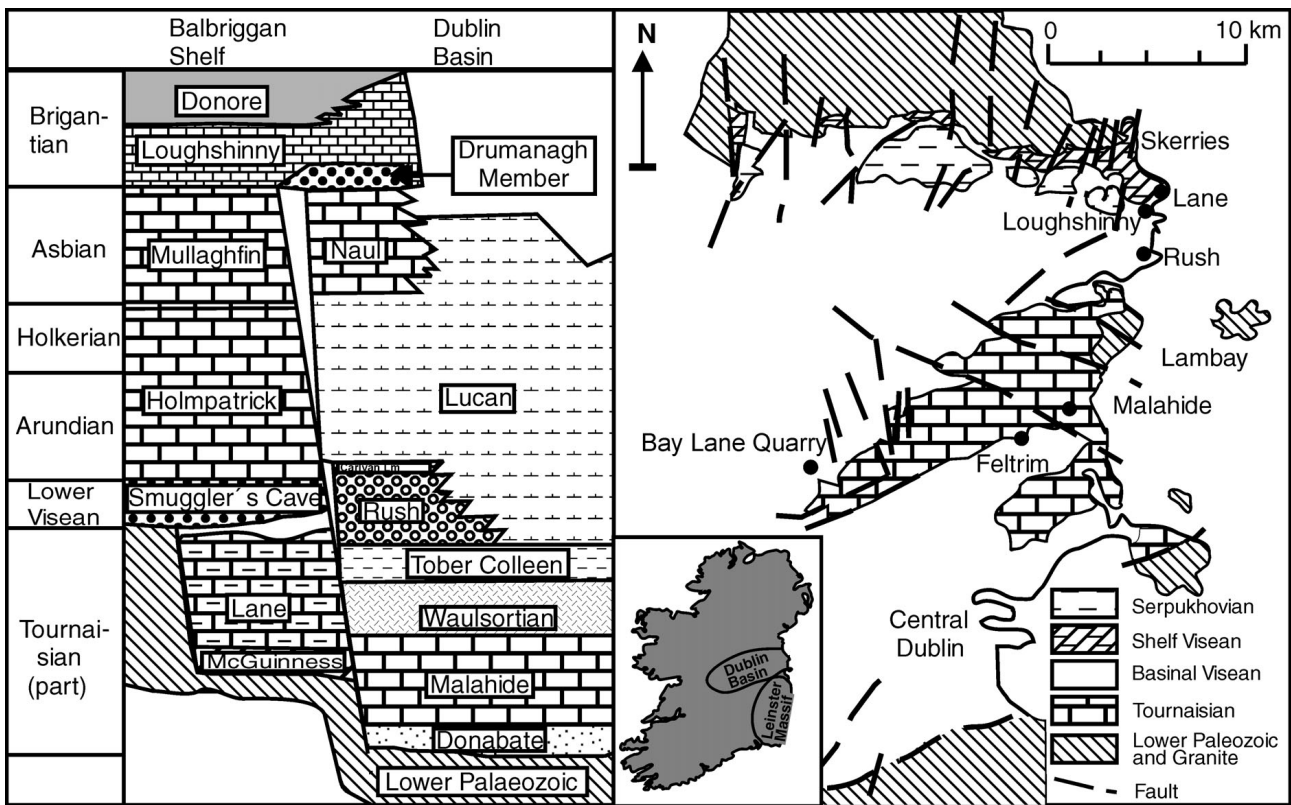


Figure 1. Location and lithostratigraphy of the Dublin Basin. Modified according to Sevastopulo & Wyse-Jackson (2009).

2010; Devuyst 2006; Mamet 1969; Marchant 1978; Nolan 1986, 1989; Smyth 1951; these papers contain references to earlier literature). The Tober Colleen Formation, consisting of basinal calcareous mudrock with rare horizons of limestone, is inferred to overlie Waulsortian mudbank limestones and is overlain in turn by the Rush Formation (siliciclastic turbidites, calciturbidites and sediment flow deposits with appreciable terrigenous input from the east (Fig. 1) (Nolan 1986, 1989; Somerville *et al.* 1992a; Sevastopulo & Wyse Jackson 2009). In this study the upper part of the Tober Colleen Fm. (56 m) and the of the Rush Formation (136 m) were logged lithologically and geophysically, and sampled for foraminiferans.

The Bay Lane Quarry section

Bay Lane Quarry is located 10.75 km northwest of Dublin, at latitude 53° 35' 21" and longitude 6° 21' 00". The succession has not been described before. Jones *et al.* (1988) in their regional map showed the position of the quarry in the outcrop belt of the Tober Colleen Formation; however, the lithologies in the quarry are much more quartz- and limestone-rich than those found in the type section of the Tober Colleen Formation at Rush and the biostratigraphy demonstrates that the Bay Lane succession is the age equi-

valent of the Rush Formation and younger stratigraphical units. The succession in the quarry (over 125 m thick) is dominantly of tabular bedded, dark grey, sandy calcareous siltstone with several horizons of limestone containing conspicuous amounts of quartz sand. The rocks are interpreted here as being dominantly turbidites. There are very few benthic fossils but ammonoids occur at some horizons. Sole structures occur on the bases of many of the beds. The oldest 62 m present in the southeast corner of the quarry were stratigraphically and geophysically logged and sampled for microfossils.

Material and methods

Bed-by-bed logging with field description of bed thickness, bed geometry, grain size and sedimentary structures was performed on the Rush, Lane and Bay Lane Quarry sections.

The sections were also logged for GRS using an RS-230 Super Spec portable spectrometer with a 2 × 2" (103 cm) bismuth-germanate (BGO) crystal detector (Radiation Solutions Inc., Canada). Counts per seconds in selected energy windows were directly converted to concentrations of K (%), U (ppm) and Th (ppm). Depending on the total thickness, the logging interval was 0.5 to 1.0 m

(Rush), 0.5 m (Bay Lane Quarry) and 0.25 m (Lane). One measurement with a 240-s count time was performed at each logging point, perpendicular to the section wall and at full contact with the rock. Detection limits are 0.1% for K and 0.4 ppm for U and Th. The combined error from operating conditions, instrument and repeated measurements was estimated to be less than about $\pm 7.5\%$ for the K, U and Th concentrations. Four hundred and seventy four GRS data points (Rush: 288; Bay Lane: 123; Lane: 63) were measured in total.

Petrographic analysis was performed on a large number of standard size (27 × 46 mm) thin sections (200 from Rush, 100 from the Bay Lane Quarry and more than 120 from the Lane section,) and two existing sets of thin sections from the thesis studies of T. Marchant and F.X. Devuyst. Semi-quantitative percentages of carbonate and non-carbonate constituents were recorded, using the visual comparison charts of Baccelle & Bosellini (1965). Only allochems and detrital siliciclastic grains of the sand and gravel size fractions were considered. Results are presented as percentages of the total volume of the rock.

Foraminifers were studied with a high-magnification binocular microscope (Nikon 80i) in transmitted light at magnifications ranging from 20× to 400×. The best specimens were photographed with a digital camera (Nikon DXM) and a database was created using Nikon NIS Elements software. High-resolution biostratigraphy of late Tournaisian and early Viséan is based on the foraminiferal zonation of Devuyst & Hance (*in Poty et al.* 2006) which was subsequently refined by Devuyst (2006) and Devuyst & Kalvoda (2007).

Results

Facies and grain composition

Lane coastal section

The measured section is ~16.2 m thick (Figs 2, 5). A majority of the section comprises a succession of skeletal calcarenite beds with abundant large skeletal grains (nautiloids, gastropods, corals, brachiopods) alternating with thinner black mudstones (Lane Formation). The calcarenite beds are between ~5 to ~50 cm thick, the mudstones up to ~10 cm thick. Thickness of individual calcarenite beds is commonly very variable, with a tendency for lateral pinch-outs. The calcarenite beds show common soft-sediment deformation, especially at their bases; they incorporate contorted mudstone laminae and lenses with frequent pinch-outs; in some cases they are completely brecciated with the mudstone providing the matrix. Several beds are graded, and some also parallel-laminated. In the lower part of the section (~12.5 to ~14 m below section top), the calcarenites

contain abundant detrital quartz grains and/or layers and lenses of calcirudite rich in quartz pebbles. It is difficult to trace stratal patterns in the uppermost part of the Lane Formation (Fig. 5) and it is possible that this part is deformed by a fault with very limited displacement on the slip face. In the topmost part of the section, the calcarenite succession is overlain by several metres of clast-supported conglomerate (Smugglers Cave Fm.) with angular to subangular clasts of mainly low-grade metamorphic rocks and limestones of the Lane Formation. The basal contact of the conglomerate shows some undulation, which may be suggestive of erosion. This boundary is associated with paleokarst features according to Nolan (1986).

The carbonates can be classified as medium- to very coarse-grained, moderately to poorly sorted wacke-packstones, packstones, grainstones and rarely rudstones. Skeletal allochems (from 7.5 to 47.5% vol.) significantly predominate over non-skeletal ones (from 0 to 8.5% vol.) and detrital grains (from 0 to 31.5% vol.). Skeletal grains include abundant crinoids and other echinoderm fragments, plurilocular foraminifers, dasycladacean algae and bivalves, less abundant ostracods, bryozoans, brachiopods, gastropods, corals, calcispheres and rare spherical microproblematica, cyanophytes (*Girvanella*) and unidentified grains (Fig. 2). There is a weak trend of decreasing abundance of echinoderms and increasing abundance of peloids and dasycladacean algae in the upper part of the carbonate section, at ~6 m below section top. The facies can be characterized as mixed heterozoan-photozoan foraminiferal (foraminiferal echinoderm) (James 1997, Halfar *et al.* 2004). Peloids and intraclasts strongly predominate over rare ooids among non-skeletal allochems. Detrital siliciclastic grains comprise angular to subrounded quartz grains, clasts of siltstones, chert and rare volcanic rocks. Generally, the rocks exhibit diagenetic features such as local dolomitization, rare silicification and micritization of skeletal grains. The stratigraphic distribution of the components is relatively uniform, with the exception of two important incursions of siliciclastic grains, one between ~13 and ~16 m, and the other between ~6 and ~8 m below section top.

Rush coastal section

The basal part of the section (Fig. 6, 192 to 133 m below section top) comprises monotonous, dark-grey to black shales alternating with micritic argillaceous limestones with infrequent gastropods and nautiloids (Tober Colleen Formation; Nolan 1986, 1989). The overlying part (133 to 0 m, Rush Formation) is composed of carbonate and siliciclastic-carbonate arenites alternating with shales, siltstones and siliciclastic-carbonate conglomerates and breccias (Bábek *et al.* 2010). The arenite beds are medium- to coarse-grained, typically 1 cm to ~1 m thick, normally

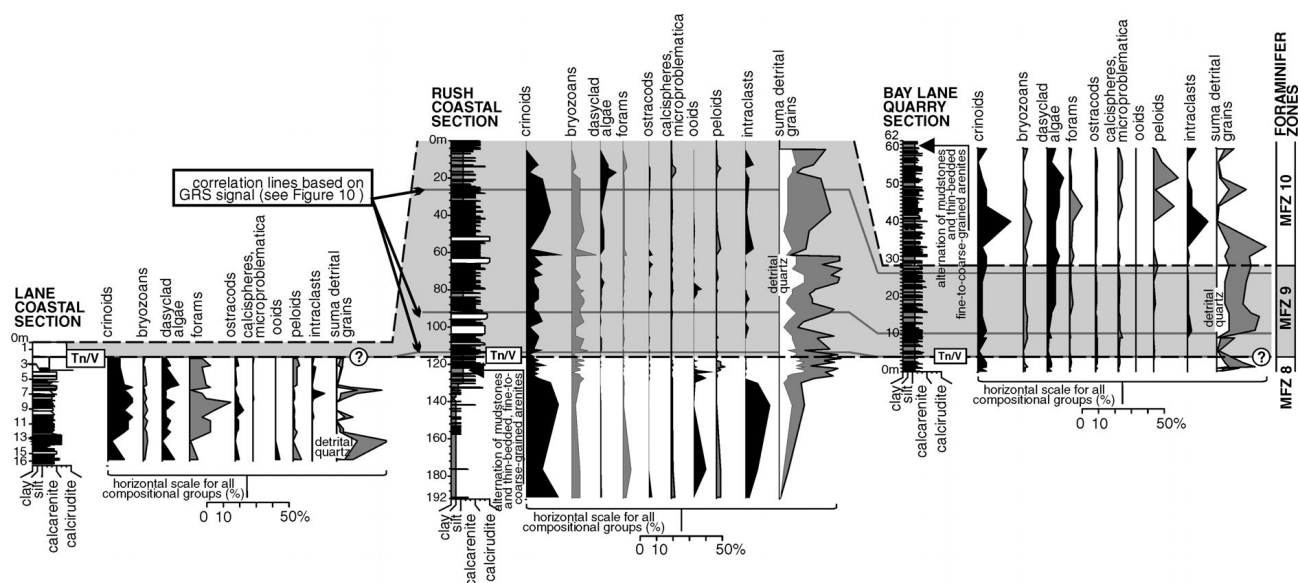


Figure 2. Stratigraphic trends in selected compositional groups (percentages from total rock volume) based on visual estimates, using comparative charts and correlation of the Lane (left), Rush (centre) and Bay Lane Quarry (right) sections based on Mississippian foraminiferal zones of Devuyt & Hance (*in* Poty *et al.* 2006) (MFZ). The correlation is supported by correlation lines based on GRS logs, see text and Fig. 10.

graded, with sharp bases, parallel and wavy lamination, basal scours and shale lithoclasts. The conglomerates and breccias are up to ~4 m thick, graded to non-graded, with outsized clasts, sometimes projecting above the bed tops, and are commonly associated with soft-sediment deformation beneath their bases. This succession is interpreted as carbonate and siliciclastic-carbonate turbidites and sandy debris-flow beds with the background sedimentation of hemipelagic clay-rich and silty sediments (*cf.* Sevastopulo & Wyse Jackson 2009). The Rush Formation starts with a thickening- and coarsening-upward (CU) succession (133 to 104 m) of turbidites and sandy debris-flow beds, which is capped by two thick debris-flow breccias separated by coarse-grained and fine-grained turbidites (Fig. 6 – 104 to 92 m). These debris-flow beds are ~3.5 m to ~5 m thick, inversely and/or normally graded and capped with graded, coarse-grained calcarenites (turbidite cap). In the overlying succession (92 to 52 m), shales and siltstones cyclically alternate with turbidites and debris-flow breccias with an overall 45 to 30 net-to-gross ratio. The top part of the section measured (52 to 5 m), comprising a fining- and thinning-upward succession of turbidites with upward-increasing proportion of shales (75 to 50 net-to-gross ratio at the top of this succession), is capped by thick-bedded turbidites and sandy debris-flow deposits (5 to 0 m; Bábek *et al.* 2010).

Under the microscope, the carbonates can be mostly classified as fine- to very coarse-grained, moderately sorted grainstones and packstone-grainstones with significant admixture of detrital, siliciclastic grains. Limestones of the Tober Colleen Formation are dominated by hetero-

zoan carbonate skeletal allochems, in particular abundant crinoids, other echinoderm fragments and fenestrate bryozoans, less abundant foraminifers, sparse dasycladacean algae, ostracods, coral, brachiopod and bivalve fragments and rare sponge spicules, trilobites and conodonts (Fig. 2). Non-skeletal allochems, in particular intraclasts and rare ooids and peloids are less abundant (up to 17.5%) than skeletal grains. Detrital siliciclastic grains are moderately abundant (up to 15%). A marked compositional change can be traced near the base of the Rush Formation at ~129 m. The lower part of the Rush Formation, between ~129 and ~60 m, has significantly increased percentages of detrital siliciclastic grains (between 11 and 38 %), which include mono- and polycrystalline quartz grains, cherts, clasts of shales, siltstones, acid-intermediate volcanics and rare acid-intermediate plutonic rocks. Allochems are represented by similar groups as in the Tober Colleen Formation, but in lower percentages due to the dilution by detrital grains. The heterozoan-photozoan association of bioclasts is similar to the bryonoderm extended facies (Beauchamp 1994, Halfar *et al.* 2004, Kabanov 2009). The upper parts of the section, between ~60 and 0 m, is characterized by slightly decreased percentages of detrital grains (between 6 and 31%), slightly increased percentages of skeletal grains (mainly crinoids and bryozoans) and relatively high percentages of dasycladacean algae (more than 20% of bioclasts – photozoan association of Halfar *et al.* 2004) together with peloids and intraclasts. Generally, the rocks exhibit common diagenetic alteration such as silicification, authigenesis (opaque minerals), endolithic borings and micritisation and sparse pressure dissolution.

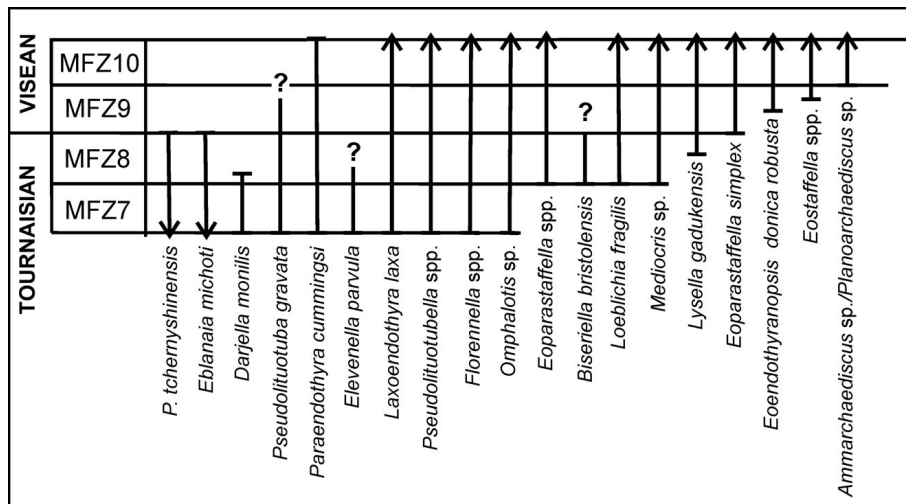


Figure 3. Foraminiferal zones of latest Tournaisian–earliest Viséan and ranges of important taxa. Modified according to Devuyst & Hance (in Poty *et al.* 2006).

Bay Lane Quarry section

The measured section is 61.8 m thick and comprises a relatively monotonous succession of black mudstones alternating with beds of fine-to-coarse-grained, mixed carbonate-siliciclastic arenites (Figs 2, 7). The arenite beds are commonly graded, parallel-laminated, cross-laminated and/or ripple-cross-laminated and contain abundant erosive bases. Majority of the arenite beds can be interpreted as mixed carbonate-siliciclastic turbidites. Their thickness vary from < 0.5 cm to ~60 cm. Convolute bedding, soft-sediment deformation of the mudstones and arenite beds and load casts are present at some levels. Some beds are strongly calcareous and some contain calcareous nodules as large as 30 cm. The basal part (0 to 1 m) and top parts of the section (55 to 62 m) are predominantly fine-grained. The intermediate strata are generally coarser-grained and thicker, but they fail to show clearly visible trends in bed thickness and/or grain size. Higher abundances of thicker and more coarse-grained beds are located between 1 and 3.5 m, 5 and 11 m, 23 and 27 m, and 31 and 35 m. Several levels at the section show tendency to high CaCO₃ contents, indicated by frequent calcareous nodules and presence of strongly calcareous arenite beds, in particular between 5 and 12 m, 23 and 26 m, and 39 and 48 m.

The mainly calciturbiditic carbonates can be mostly classified as fine- to medium-grained, moderately sorted wackestones and wacke-packstones, rarely grainstones, with significant admixture of detrital siliciclastic grains. Skeletal allochems (from 17.5 to 58% vol.) are most abundant, in particular crinoids and other echinoderm fragments, foraminifers, green algae (dasycladaceae), ostracods, calcispheres and spherical microproblematica, coral-, brachiopod-, fenestrate bryozoan-, trilobite- and bivalve fragments, sponge spicules and conodonts (Fig. 2). The association corresponds to the transitional heterozoan-photozoan association (Halfar *et al.* 2004). Radiolar-

ians are abundant in several fine-grained wackestone beds. Non-skeletal allochems including intraclasts and peloids are much less abundant (up to 15%) than skeletal grains; ooids are absent. Detrital siliciclastic grains are moderately abundant (up to 30%) comprising mainly angular to sub-rounded quartz grains and clasts of siltstones, cherts and rare mudstones, and not very abundant K-feldspars, plagioclase feldspars, white micas and opaque grains.

Several not particularly distinct compositional trends can be traced up-section. The lower parts, between 0 and ~15 m, are predominantly fine-grained, with low percentages of allochems and detrital grains and, in places, high percentages of pelagic radiolarians (up to 15%). Between ~15 m and ~40 m there is a strong siliciclastic admixture in the rocks (between 15 and 30%) and the allochem composition is dominated by crinoids, bryozoans and increasing percentages of foraminifers and especially of dasycladacean algae. The facies corresponds to the photozoan association (James 1997, Halfar 2004). Between ~40 m and the top of the measured section, the abundance of detrital grains is markedly reduced (~1 to ~17.5%) and there is a marked increase in peloids, calcispheres and spherical microproblematica, foraminifers and dasycladacean algae up-section, while the percentages of crinoids and bryozoans decrease. Generally, the rocks exhibit common diagenetic alteration such as silicification, authigenesis (opaque minerals) and rarely endolithic borings and micritisation.

Biostratigraphy

Foraminiferal zonation

The search for a new Tn-V boundary stratotype in Eurasia in the last decade has contributed to a substantial improvement in resolution of the biostratigraphical tools for identi-

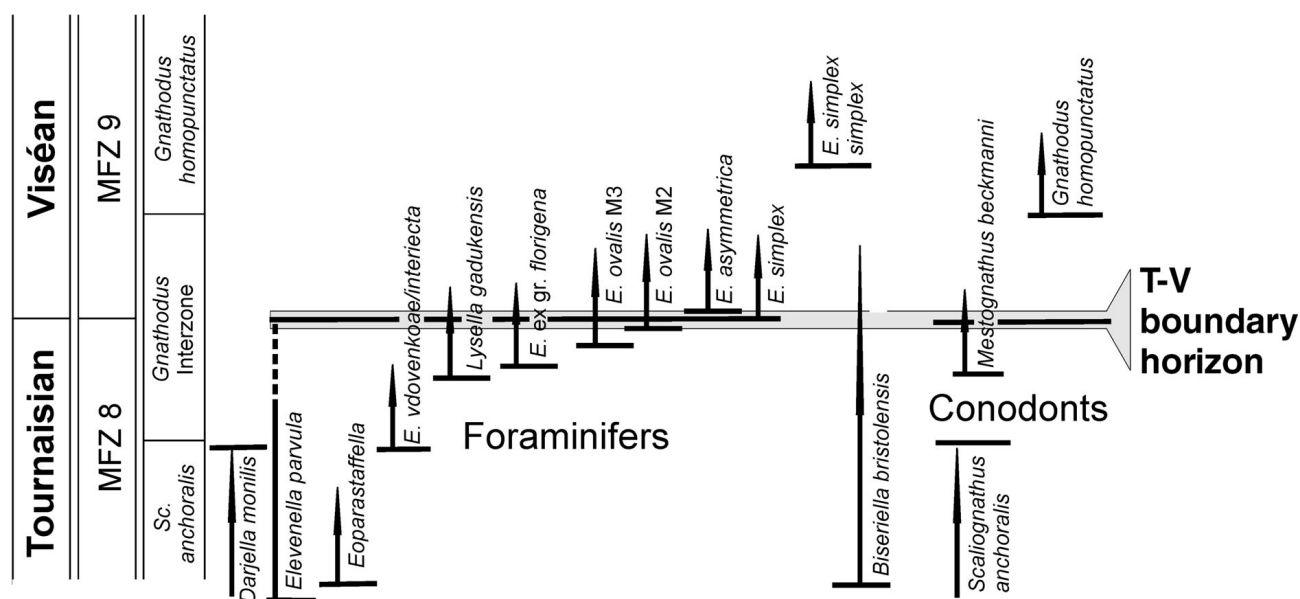


Figure 4. High resolution biostratigraphy of the Tournaisian/Viséan boundary interval. Based on Devuyt (2006).

fication of the Tournaisian–Viséan boundary interval. An example of this is the foraminiferal zonation of Devuyt & Hance (*in Poty et al.* 2006) (Fig. 3), refined subsequently by Devuyt (2006) and Devuyt & Kalvoda (2007). In this zonation, the Tn–V boundary can be identified using the boundary between MFZ 8 and 9. The base of MFZ 8 is characterized by the FADs of *Eoparastaffella* and *Biseriella bristolensis* (Reichel) and the base of MFZ 9 by the FAD of *Eoparastaffella simplex* Vdovenko. The entry of *Eoparastaffella simplex* is preceded by the successive FADs of *Eoparastaffella vdoenkoae* Devuyt & Kalvoda, *Lysella gadukensis* Bozorgnia, *Eoparastaffella ex gr. florigena* (Pronina), *Eoparastaffella ovalis* Vdovenko M3, and *Eoparastaffella ovalis* M2, the latter just below the boundary. *Eoparastaffella asymmetrica* Vdovenko appears at or just above the boundary (Devuyt 2006) (Fig. 4). The entry of *Eoparastaffella ovalis* M2 is very close to the entry of *E. simplex* and because in many sections *E. ovalis* M2 is more common than *E. simplex*, it can be used as an alternative criterion to identify the Tournaisian–Viséan boundary (Devuyt 2006, Kalvoda *et al.* 2010). It should also be mentioned that the LADs of *Eievenella parvula* (Bozorgnia) and *Darjella monilis* Malakhova in the upper part of MFZ 8 represent other important bioevents (Fig. 4) (Poty *et al.* 2006, Devuyt & Kalvoda 2007, Kalvoda *et al.* 2010). Brenckle *et al.* (2009) recently showed that the range of *Biseriella bristolensis* extends well into the Viséan in contrast to what is indicated in the zonation of Devuyt & Hance (*in Poty et al.* 2006). This does not diminish the importance of its FAD for the base of MFZ 8.

Typical foraminifera from the Lane, Rush and Bay Lane Quarry section are illustrated in Figs 11–13.

Lane

The richest foraminiferal associations in this study have been encountered in the shallow water carbonate facies in the Lane section. This is consistent with the observation of Vdovenko (1980) that during the Carboniferous, calcareous foraminifera thrived mostly in shallow water infralittoral facies. However, the taxonomic diversity of the faunas at Lane is quite low. Revision of Marchant's (1974, 1978) samples and new sampling show that the upper part of the Lane Formation sampled in this study corresponds to the latest Tournaisian MFZ 8 of Devuyt & Hance (*in Poty et al.* 2006) (Fig. 5). The presence of *Darjella monilis* (Malakhova) in the lower part of the section is typical of a late Tournaisian age (MFZ 7–8). The presence of *Biseriella cf. bristolensis* and the record of *B. bristolensis* below the part of the section sampled in this study (Devuyt 2006) indicates MFZ 8 even in the lower part of the section. *Eoparastaffella*, the other guide for MFZ 8 is absent or rare which may reflect unfavourable facies.

The entry of *Eoparastaffella ex gr. florigena* and *Eoparastaffella ovalis* M3 in the very top of the section indicates the upper part of MFZ 8 and thus the proximity of the Tn–V boundary. This is in accordance with Marchant (1974) who illustrated *Eoparastaffella ex gr. florigena*, which he identified as *E. simplex*, from a clast in the overlying Smuggler's Cave Conglomerate.

The presence of the late Tournaisian guide *Eievenella parvula* (Bozorgnia) and the absence of *Eoparastaffella simplex* support a latest Tournaisian age despite the presence of species generally regarded as Viséan guides, such as *Forschia parvula* (Rauzer-Chernousova), *Forschia*

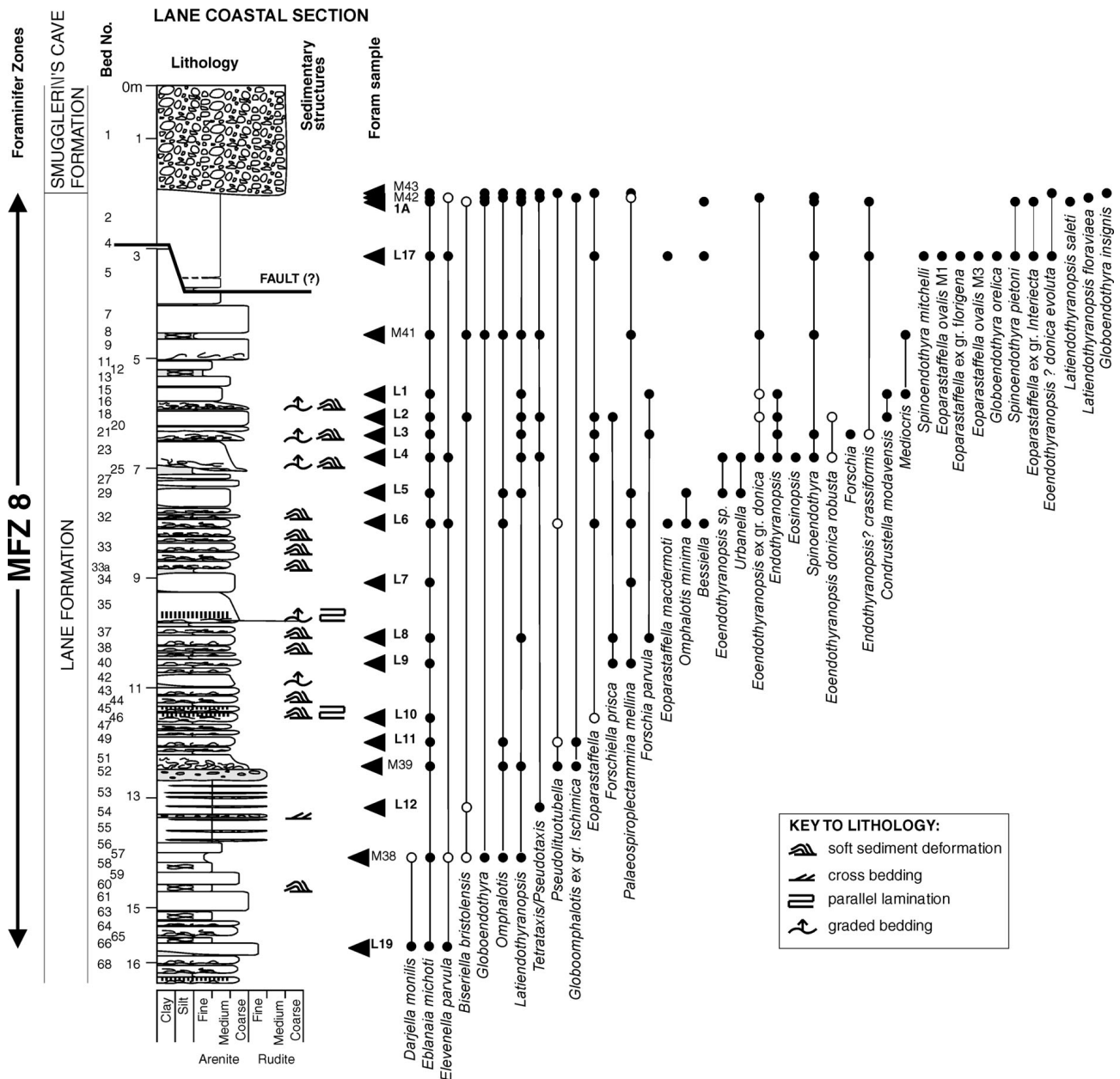


Figure 5. Distribution of most important foraminifers in the Lane coastal section. Foraminiferal zones according to Devuyst & Hance in Poty *et al.* (2006). White circles mean *cf.* identifications. L – new samples, M – samples of Marchant (1978).

mikhailovi (Dain), *Forschiella prisca* (Mikhailov), *Eoendothyranopsis? cf. donica robusta* Conil and *Eoendothyranopsis? donica evoluta* Brazhnikova & Rostovtseva (Brazhnikova & Rostovtseva 1967; Vdovenko 1980; Devuyst & Hance in Poty *et al.* 2006). It is noteworthy that the brachiopod *Levitusia humerosus* (Sowerby), now known to be restricted to the late Tournaisian in Belgium (Devuyst 2006), was recorded from the Lane Formation by Smyth (1949).

Most of the foraminiferal associations are dominated by *Eblanaia* spp. and other Tournayellidae (mostly

Endochernella and *Spinochernella*); more diversified associations occur only close to the top of the studied section. The impoverishment of the foraminiferal associations is most evident in the absence, or very rare occurrence of loeblichiiids (absence of *Dainella*, *Lysella*, *Florenella*, rare occurrence of *Spinoendothyra*, *Urbanella* and *Bessiella*) and absence, or rare occurrence of *Endospiroplectamina*, *Laxoendothyra laxa* (Conil & Lys), *Brunsia*, *Mediocris* and *Plectogyranopsis* which are all common taxa of the Late Tournaisian. *Eblanaia* is represented mostly by *E. michoti* (Conil & Lys); however, as already stressed by

Conil (1976), *Eblanaia* is characterized by considerable variability, both in terms of coiling and basal deposits and transitional forms to *Globoendothyra* occur. High equatorial and high oblique sections of *Eblanaia* are difficult to distinguish from *Globoendothyra* (Mamet et al. 1986). The Endothyranopsinae represent the second most common group and is represented mostly by *Latiendothyranopsis* spp. and less common *Endothyranopsis* and *Globoendothyra* spp. *Globoendothyra* spp. are not very common and are represented by specimens with a poorly differentiated wall (*G. orelica* Vdovenko) and specimens transitional between *Globoendothyra* and *Omphalotis*, which were included in the subgenus *Globoomphalotis* by Bogush (1987). *Globoendothyra orelica* with a poorly differentiated wall enters at Lane in the latest Tournaisian close to the Tn-V boundary. These forms are common in the early Viséan of Ukraine (Brazhnikova & Vdovenko 1973) and the Urals (Postoyalko 1975, Postoyalko & Cherepanova 1990, Ivanova 2008, Stepanova et al. 2008) and in the early Viséan of the Namur Basin, Belgium (Conil et al. 1980). In eastern Europe the same is true for *Globoendothyra insignis* Postoyalko (Postoyalko 1975, Lyadova & Pogorelov 1990). *Globoomphalotis ishimica* (Rauser) was originally described from the middle Viséan of Kazakhstan (Rauser 1948) but is more widely reported from younger parts of the Viséan (Visssarionova 1948, Brazhnikova & Vdovenko 1973) of eastern Europe. However, specimens of *G. ishimica* characterized by a weakly differentiated wall similar to *Eogloboendothyra* have also been reported in the late Tournaisian–early Viséan interval in the Urals, Precaspian depression and Taymir (Malakhova 1975, Postoyalko 1975, Bogush 1987, Kulagina et al. 2003).

Eoendothyranopsis is quite rare and occurs only in the upper part of the section. In addition to *Eoendothyranopsis? donica* (Brazhnikova & Rostovtseva) the entries of *Eoendothyranopsis? donica evoluta* and *Eoendothyranopsis? cf. donica robusta* are important. The first species is a guide of the foraminiferal zone *Eoendothyranopsis donica-Omphalotis chariessa* recognized in the early Viséan of eastern Europe (Vdovenko 1980) and the second and third species have been regarded as indicators of the Viséan (Vdovenko 1980; Devuyst & Hance in Poty et al. 2006). However, the range of the species is not well established because *Eoendothyranopsis? donica* was recorded also below the Tn-V boundary in Pengchong (Devuyst 2006).

Rush

Prior to the establishment of the GSSP for the base of the Viséan, the Tober Colleen Formation was regarded as being of early Viséan age, principally because the highest beds contain an ammonoid fauna that Smyth (1951) compared with faunas from supposedly Viséan levels in Germany. Mamet (1969) recorded faunas with archaeadiscids from the

Rush Formation, implying an Arundian age, but Marchant (1978) was unable to confirm these and identified the base of the Arundian in the uppermost part of the formation formerly referred to the Carlyan Limestone.

The upper part of the Tober Colleen Formation is characterized by intercalations of biotrital limestone beds with foraminifers within a background mudstone facies devoid of foraminifers. The foraminiferal associations of these limestone beds, as in the Lane Limestone Formation, are rich in the number of specimens but of low diversity. *Eblanaia* is the dominant genus accompanied by *Globochernella*, *Spinochernella*, *Latiendothyranopsis*, *Globoomphalotis* (*G. ischimica*) and *Globoendothyra* (*G. insignis*, *G. ukrainica* Vdovenko) and many of the late Tournaisian guides are missing (Fig. 6). This *Eblanaia* facies is also quite common in the pebbles and slumped beds of the Viséan Rush Formation. The facies control evidently also applies to the entry of *Eoparastaffella*. The first rare occurrences are recorded only in the uppermost part of the Tober Colleen Formation. However, the presence of advanced *E. vdoventoae* in the lowest beds of the Rush Formation indicates already the upper part of MFZ 8 (Fig. 4) and suggests that the base of MFZ 8 is substantially lower than the entry of *Eoparastaffella* in bed R 88 (Fig. 6). This is consistent with the entry of *Eoendothyranopsis? ex gr. donica* in bed R 88 which indicates the proximity of the Tn-V boundary.

Occurrences of foraminifers in the mixed carbonate-siliclastic sediments of the Rush Formation are rare due to the dilution by detrital grains and the specimens are commonly poorly preserved. Nevertheless, the associations are generally more diverse than in the Tober Colleen Formation. As already mentioned, the entry of *E. vdoventoae* near the base of the formation indicates the upper part of MFZ 8. It is followed in close succession at Rush by the first *E. ex gr. florigena*, *Eoendothyranopsis? donica evoluta* Brazhnikova and Rostovtseva, and *Lysella gadukensis* indicating already the proximity of the Tn-V boundary (Fig. 4). The presence of the MFZ 8 guide *Elevenella parvula* in the lower part of the Rush Formation, however, suggests still a Tournaisian age (Figs 3, 4). The next bioevent is the FAD of *E. ovalis* M2 which is regarded here as an indicator of the base of the Viséan (MFZ 9). The precise level of the entry of *Eoparastaffella simplex* is difficult to locate because of the rare occurrences and poor preservation of foraminifers. The first unambiguous *Eoparastaffella simplex* specimen represents already an advanced morphotype (Devuyst 2006). It is followed by *E. asymmetrica* Vdovenko & Zavyalova, *E. cf. restricta laciniosa* Postoyalko, reported from the upper part of the lower Viséan in the Urals (Druzhinin Horizon; Postoyalko 1975), represents another indicator of a younger MFZ 9 association. The foraminiferal associations at the top of the studied section are poor containing typical representatives of MFZ 9 (*Eoparastaffella simplex*,

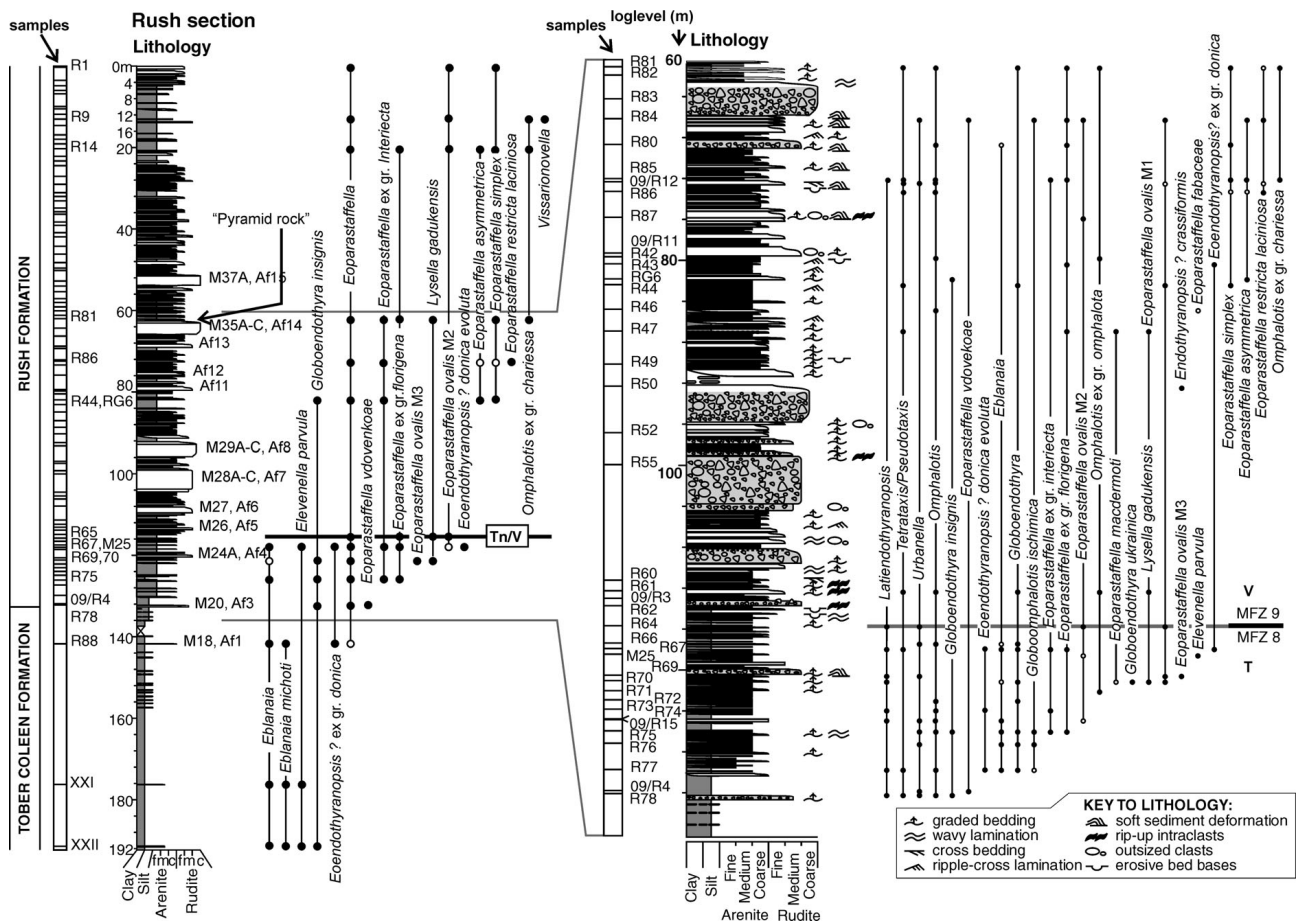


Figure 6. Distribution of most important foraminifers in the Rush section. Foraminiferal zones according to Devuyt & Hance in Poty *et al.* (2006). White circles mean *cf.* identifications. R – new samples, M – samples of Marchant (1978), Af – beds of Afshar (1965).

Eoparastaffella ovalis M2, *Vissarionovella* sp. and lacking the archaeidiscid guides of MFZ 10 (Fig. 6). Archaeidiscids first occur in the highest part of the formation formerly referred to as the Carlyan Limestone (Fig. 1) separated from the studied section by the harbour.

Bay Lane Quarry

In the lower part of the studied section, the predominant facies consists of spiculitic limestones without or with rare foraminifers. In addition common diagenetic alteration makes taxonomic determinations difficult. The lowermost foraminiferal association (sample Q3) contains *Eoparastaffella* sp., *Eoparastaffella* ex gr. *florigena* and *Lysella gadukensis* indicating either uppermost MFZ 8 or MFZ 9 (Fig. 8). The second sample with a richer foraminiferal association occurs about 10 m higher (Q10) and contains in addition *Eoendothyranopsis?* cf. *donica robusta*. The first *Eoparastaffella ovalis* M2 occurs in sample Q13 and is followed by a more diverse association in Q14 with the first *Eoparastaffella simplex*, *Eoparastaffella* cf. *restricta laciniosa*, *Omphalotis* ex gr. *chariesia* (Conil & Lys), and *For-*

schiaella prisca. This association resembles the association in sample R 86 at Rush and represents a level high in MFZ 9. The following interval with only an impoverished foraminiferal fauna is followed by a richer association in sample Q 17 with the first archaeidiscid (*Glomodiscus* sp., *Uralodiscus* sp.) which indicate a level above the base of MFZ 10 (see Fig. 2) (Devuyt & Hance in Poty *et al.* 2006). Archaeidiscids occur only in one thin section and are absent above Q 17 up to the top of the measured section. The presence of *Vissarionovella* sp., *Mediocris mediocris*, *Paralysella* ex gr. *schubertelloides* (Bozorgnia), *Nevillea* sp., *Lapparentidiscus bokanensis* Vachard and transitional specimens between *Eoparastaffella* and *Eostaffella* characterizes the uppermost part of the measured section. Most probably the association still correspond to MFZ 10.

Gamma-ray spectrometry

Bivariate plots of K, U and Th from all sections are shown in Fig. 8. The correlation between the total gamma-ray value (dose rate, nGy . kg⁻¹) and K, Th and U concentrations

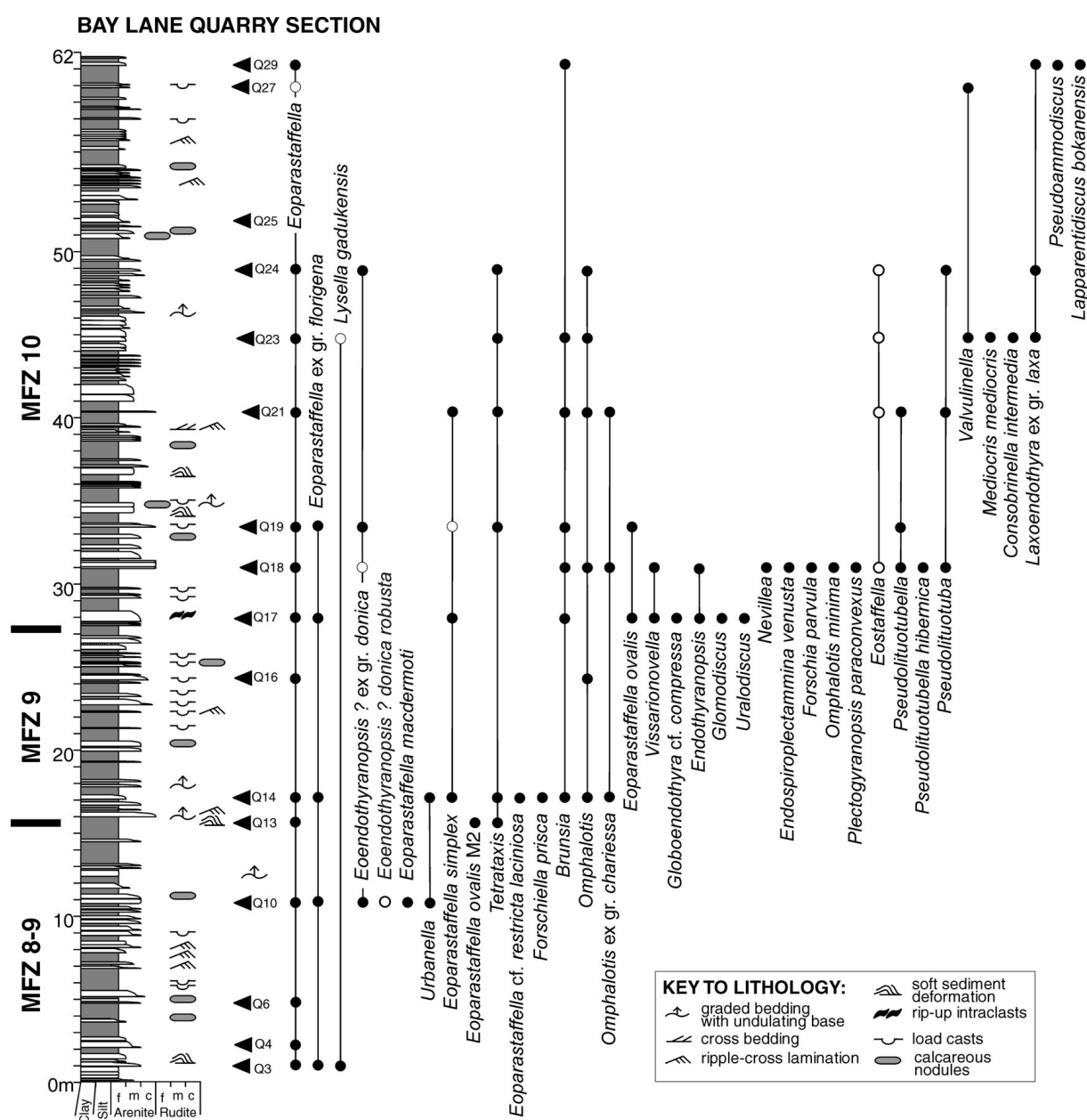


Figure 7. Distribution of most important foraminifers in the Bay Lane Quarry. Foraminiferal zones according to Devuyt & Hance in Poty et al. (2006). White circles mean cf. identifications.

respectively, indicate that a major contribution to the total gamma-ray signal comes from K (linear regression coefficient; $R^2 = 0.57$ for Lane, 0.92 for Rush, 0.79 for Bay Lane Quarry), followed by Th ($R^2 = 0.51$ for Lane, 0.51 for Rush, 0.82 for Bay Lane Quarry) and then U ($R^2 = 0.34$ for Lane, 0.36 for Rush and 0.66 for Bay Lane Quarry). The K and Th concentrations show good correlation in Bay Lane Quarry and Rush (Fig. 8) and almost perfect correlation ($R^2 = 0.96$) in Lane. This indicates that the K and Th variation is driven by the dilution of K- and Th-bearing fine-grained siliciclastic components (illite and other clay

minerals, micas, K-feldspars) in non-radioactive carbonate (Rider 1999, Doveton 1994, Fiet & Gorin 2000, Ehrenberg & Svana 2001, Fabricius et al. 2003, Bábek et al. 2007). This holds true, in particular, in the carbonate-dominated Lane section. In the Rush and Bay Lane Quarry sections, with high concentrations of siliciclastic detrital grains, the correlation is lower indicating that the GRS signal is influenced by additional variables such as the changing mineralogy of the detrital fraction (heavy minerals, micas, feldspars, etc.).

The GRS signal, in particular the K and Th concentrations, are strongly dependent on facies (Fig. 9) in all

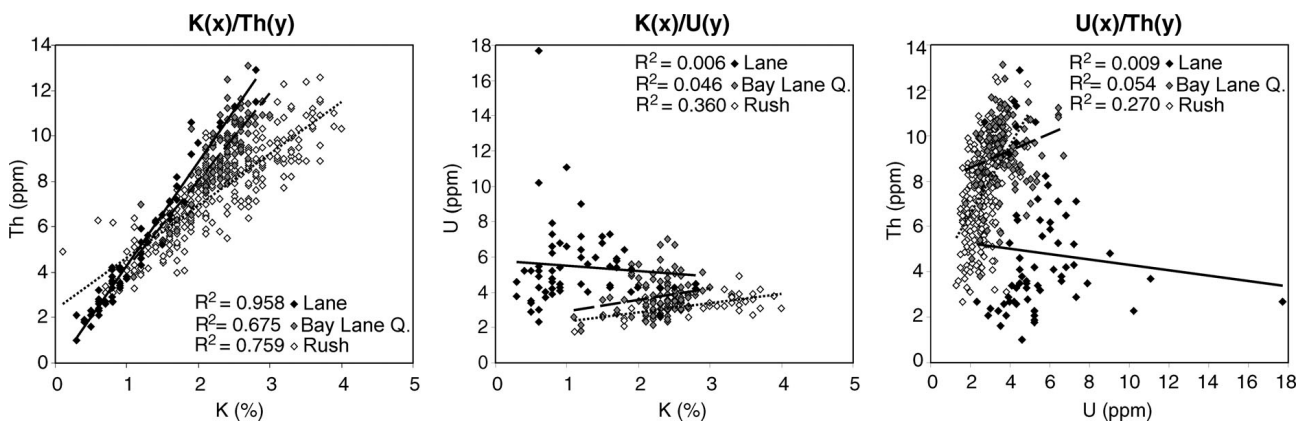


Figure 8. Bivariate plots and linear regression coefficients for K, Th and U concentrations at the Rush, Bay Lane Quarry and Lane sections. High linear regression coefficients in K : Th plots indicate the dilution effect of non-radioactive components (mainly carbonate) in radioactive components (mainly clay minerals).

sections. Relatively pure carbonates in the Lane section and thick carbonate breccias in Rush have low concentrations of K (~0.6 to ~1.7 %) and Th (~2 to ~7 ppm). Carbonates with siliciclastic admixture in the lower part of the Lane section have higher K (~1 to ~2 %) and Th (~5 to ~10 ppm) concentrations. Mixed carbonate-siliciclastic turbidites of the Bay Lane Quarry and Rush section have even higher K and Th concentrations (K: ~1.5 to ~3.2%; Th: ~7.5 to ~12 ppm), which are strongly proportional to decreasing grain size. The highest K and Th concentrations (K: ~2.5 to 3.8%; Th: ~8 to ~12 ppm) are attained in shales and fine-grained turbidites of the Rush and Bay Lane Quarry sections. Individual data points (layers) at the Bay Lane Quarry section have extremely high values of K and Th; these layers might represent tuff horizons (Fig. 9). Uranium has distribution, which is strongly dissimilar to Th and K and does not show the facies dependence. The U concentrations are relatively uniform in Rush and Bay Lane Quarry but there are strong peaks in the Lane section.

The GRS logs in the Lane section (Fig. 9) show a vertical organization, which is consistent with the lithology and component analysis. There is an increasing trend in concentrations of K and Th in the lower part of the section, between ~16.5 and ~12.5 m, which corresponds to the high contents of detrital grains (Fig. 9). Coinciding with low U/Th ratios, the high K and Th concentrations suggest an increased influx of siliciclastics due to the proximity of land. A sudden drop of the K and Th contents at ~12.5 m, associated with the transition from mixed carbonate-siliciclastic deposits to pure carbonates, may therefore indicate a marine flooding surface. The overlying interval of relatively low concentrations of K and Th between ~12.5 and ~5 m corresponds mainly to pure carbonate beds with shale interbeds, which indicate fully marine facies. Higher up in the carbonate succession, between ~5 and ~2 m, the K and Th contents tend to increase again. High uranium con-

centrations in the shale interbeds between ~6 and ~5 m coincide with moderate K and Th concentrations in a generally fine-grained carbonates facies with low detrital sandy admixture (Fig. 9). In contrast to thorium, which indicates terrestrial influence, uranium is usually assumed to indicate increased marine influence due to the presence of organic carbon and phosphate minerals (see below). The high U/Th ratios in this interval may therefore indicate conditions of maximum flooding (*cf.* Lüning *et al.* 2003, Dove-ton & Merriam 2004, Halgedahl *et al.* 2009), which is supported by the relatively distal, fine-grained carbonate facies in the corresponding interval. The passage to the conglomerates of the Smuggler's Cave Formation at ~2 m is associated with a sudden increase in K and Th concentrations and decrease in U concentrations and U/Th ratios. This is assumed to reflect a sudden influx of terrigenous sedimentation (sea level lowstand conditions) as supported by the clast composition of the conglomerate. As suggested by the foraminiferal biostratigraphy, the base of the conglomerate may represent a boundary between the underlying, late Tournaisian marine carbonate sedimentation and the overlying, Viséan terrigenous sedimentation. However, the facies contrast and the K, U and Th logs suggest the Tn/V boundary might be associated with a hiatus.

In the Rush section (Fig. 9) the shales and limestones of the Tober Colleen Formation are characterized by moderately high concentrations of K and Th, which show a cyclic arrangement and overall increase towards ~156 m depth. The K and Th concentrations remain high up to the base of the Rush Formation at ~133 m depth. Associated mainly with shales and distal, fine-grained turbidites, this peak GRS signal is suggestive of a maximum coastal shift of facies. The base of the Rush Formation is represented by a decreasing trend in the GRS signal ending up in a particularly low concentration of K and Th in the coarse-grained turbidites and carbonate debris-flow breccias between ~92 and ~115 m. The base of this interval (~116 to ~115 m)

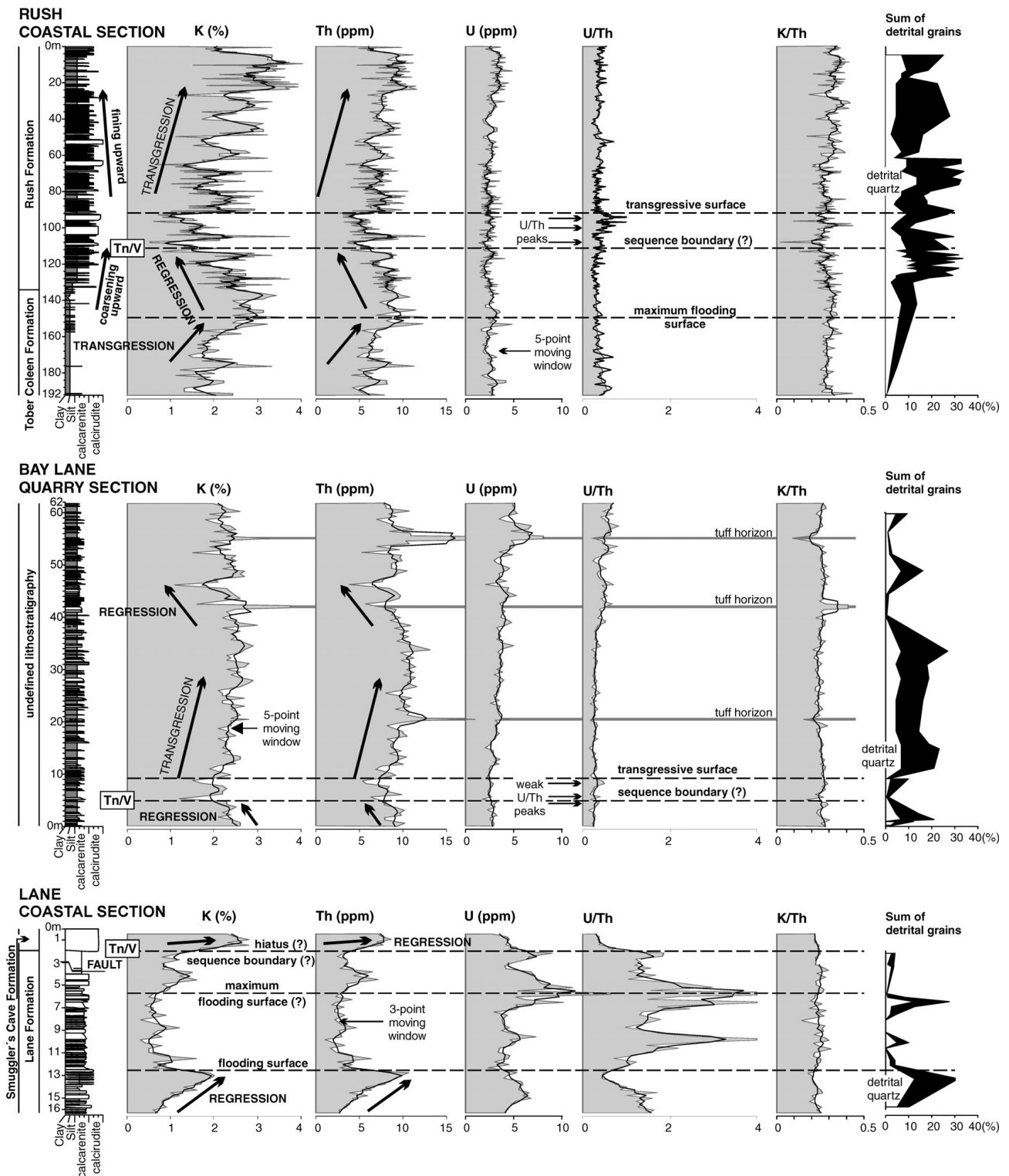


Figure 9. Lithology and spectral gamma-ray logs of the Rush (top), Bay Lane Quarry (centre) and Lane (bottom) sections with interpretation of important genetic surfaces and trends (arrows).

coincides with the first occurrence datums of the Viséan foraminifers (see section Rush above). These K and Th trends coincide with the CU trend in turbidite facies indi-

cating overall progradation (regression?) of the turbidite system during a sea-level lowstand. An abrupt increase in K and Th concentrations at 92 m depth, associated with a

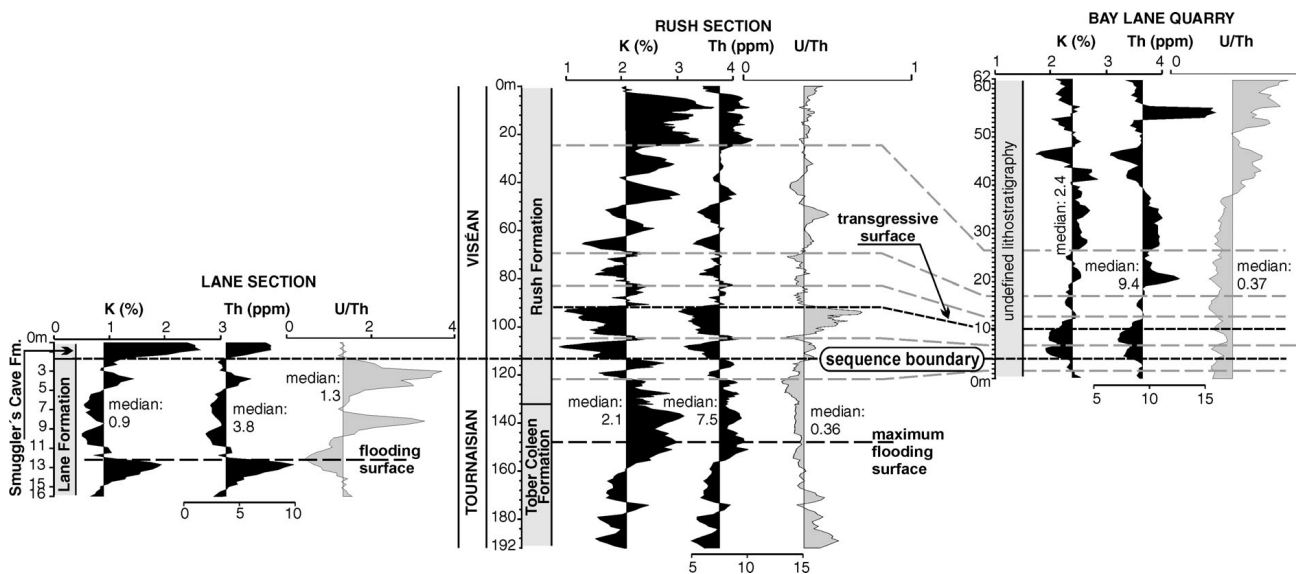


Figure 10. Geophysical correlation panel (K, Th and U/Th logs smoothed by 5-point moving window) of the Lane, Rush and Bay Lane Quarry sections with interpretation of important sequence-stratigraphic surfaces.

facies shift to a shale-rich interval, is suggestive of a transgressive surface (Fig. 9). This surface separates the K and Th logs into a lower, generally regressive section and an upper, generally transgressive section. The surface is followed by two K and Th cycles, which coincide with two CU facies trends ending up in debris-flow breccias, between 92 and 63 m and between 63 and 51 m. Slightly higher U/Th ratios in the shaly interval at ~81 m depth are suggestive of a local condensed horizon. Between 51 m and 24 m depth, the K and Th logs show increasing values, which are followed by maximum K and Th concentrations between 24 m and 4 m. Since they are associated with a fining-upward facies trend, these log trends are suggestive of a major transgression followed by sea-level highstand conditions. In this interval, however, the Th and K logs reveal a hierarchic pattern with minor cycles superimposed on the major trends. Another major drop in K and Th concentrations occurs at ~4 m depth indicating a regressive surface. The U/Th ratio is low (0.25 to 0.45) throughout the Rush formation, apart from several minor peaks coinciding with low K and Th concentrations and carbonate-rich breccias where the U/Th ratio varies between 0.5 and 1. In such examples, the higher U/Th ratios are assumed to indicate a carbonate-rich lithology rather than condensation.

The GRS logs in the Bay Lane Quarry (Fig. 9) show a certain degree of vertical organization. The most significant features include the low concentrations of K and Th at ~5 and ~11 m, which coincide with a local positive peak on the U/Th log and a set of relatively thick, strongly calcareous turbidite layers. This level is situated between foraminifer sample Q3, which may indicate the uppermost Tournaisian or the lowermost Viséan, and the Viséan foraminifer sample Q10 (see section Bay Lane Quarry

above). Consequently, we tentatively correlate these GRS log patterns with similar log patterns in the Rush section located between ~92 and ~115 m, close to the Tn/V boundary (Figs 9, 10). Up-section, the concentrations of K and Th as well as the total GR signal increase reaching maxima between ~26 and ~37 m and then decrease again to reach distinct minima in the strongly calcareous turbidites between ~42 and ~47 m. The increasing trend can be correlated with the log patterns between ~92 and ~4 m in Rush and it is interpreted as a transgressive succession. There is another increase of K and Th concentrations in the upper part of the Bay Lane Quarry section, between ~47 and 61.8 m, which may represent another transgressive-regressive cycle, or a part of it, in the higher part of MFZ 10. Uranium concentrations show dissimilar vertical distribution. There is a net increase in U concentrations throughout the section. Three outliers (Fig. 9) showing extremely high concentrations of Th (18.2 ppm at 20.5 m above the section base), K (4.9% at 41.9 m) and U and Th (10.5 and 36.8 ppm, respectively, at 54.9 m) can be interpreted as volcanoclastic layers with variable geochemical composition. Such layers can be extremely thin and overlooked during facies logging.

Discussion

Biostratigraphy and microfacies

Among the three studied sections, the Tn-V boundary is best documented in Rush, where it falls in the lower part of the Rush Formation, as already suggested by Devuyst (2006). Ammonoids in Rush reported by Smyth (1951) correspond to *Ammonellites-Fascipericyclus* zone

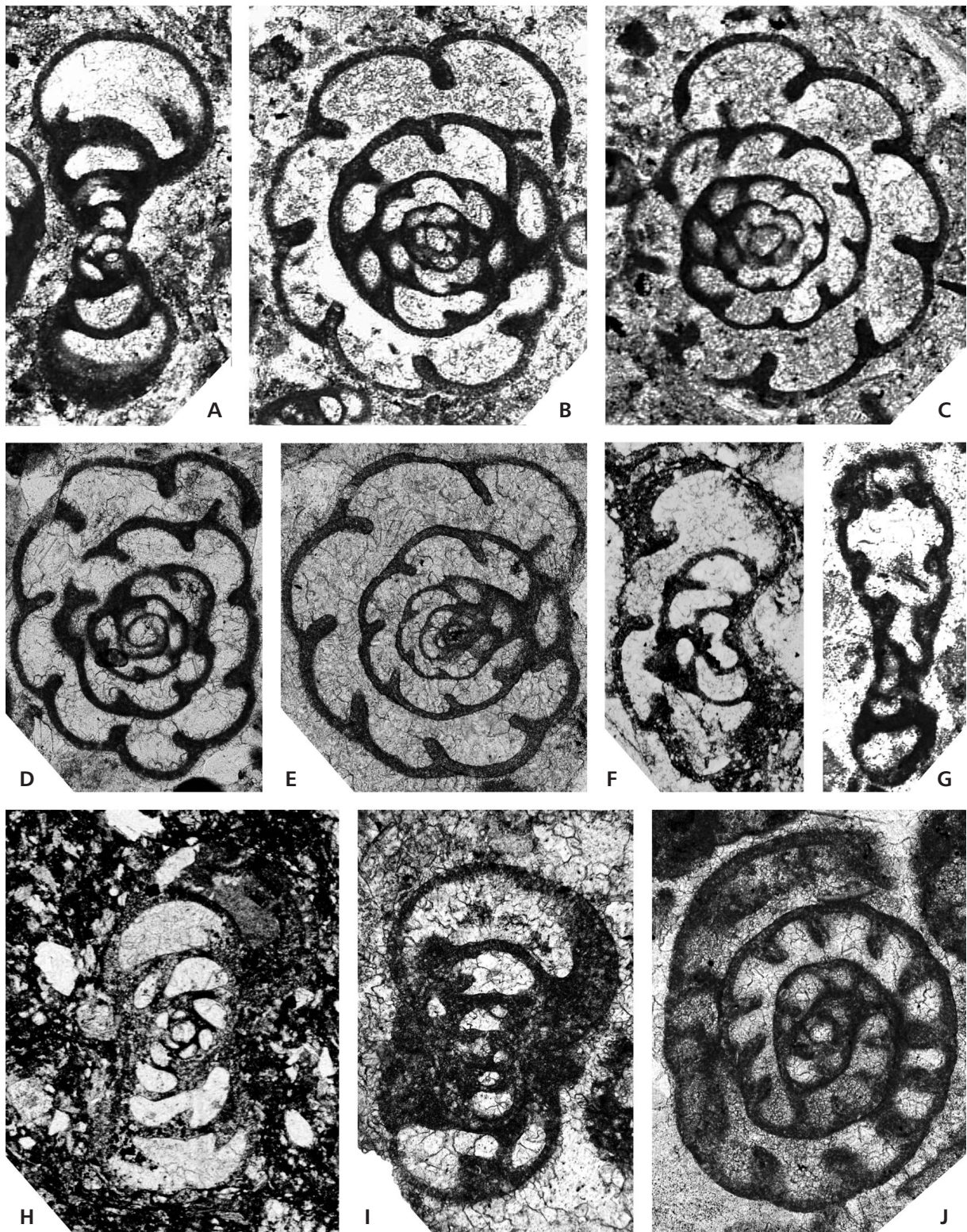


Figure 11. Typical foraminifera from Lane, Rush and Bay Lane Quarry sections. Foraminiferal zones MFZ according to Devuyst & Hance (*in Poty et al. 2006*). • A–F – *Eblanaia michoti* (Conil & Lys), A – Lane L6, t.s. 1, MFZ 8, 50×, B – Lane L6, t.s. 2, MFZ 8, 50×, C – Lane L2, t.s. 2, MFZ 8, 50×, D – Lane L19, t.s. 1, MFZ 8, 50×, E – Lane L10, t.s.2, MFZ 8, 50×, F – Rush R88, t.s. 1, MFZ 8, 50×. • G – *Forschiella prisca* Mikhailov, Lane L9, t.s. 1, 50×; MFZ 8. • H – *Eoendothyranopsis?* ex gr. *donica* Brazhnikova & Rostovtseva, Bay Lane Quarry Q10, t.s. 3, MFZ 8–9, 50×. • I, J – *Eosinopsis* sp., I – Lane, T43, MFZ 8, 75×; J – Lane L4, t.s. 3, MFZ 8, 50×.

which in the British Isles correlates with the early and late Chadian, *i.e.* both with the latest Tournaisian and earliest Viséan (Tilsey & Korn 2009). The FAD of *Eoparastaffella vdoenkoae* at the very base of the Rush Fm. and the FAD of *Lysella gadukensis* and LAD of *Elevenella parvula* a bit higher suggests that the boundary between the Tober Colleen and Rush Formations is in the latest Tournaisian (upper part of MFZ 8 – see Fig. 4) and may correlate with the boundary between the Waterfall and Owenriff Members of the Oughterard Formation in western Ireland where *Lysella gadukensis* starts at the base of the Owenriff Member (Devuyst 2006). Both levels are characterized by an increase in moravaminids which may be connected with the reorganization from a ramp into platform – rimmed basin (Somerville *et al.* 1992, Pickard *et al.* 1994, Strogon *et al.* 1996). In the Lane section, the Lane Formation corresponds to the latest Tournaisian MFZ 8 foraminifer zone and the top of the section correlates with the latest part of MFZ 8, as already stressed by Devuyst (2006).

In the Bay Lane Quarry section the oldest foraminiferal association in sample Q3 (Fig. 7) is not adequate for a conclusive date (MFZ 8–9), but both GRS logging and microfacies study suggest that the Tn-V boundary is present in the lowermost part of the section above this sample. In the middle of the measured section, Arundian strata was detected (Fig. 7). The entry of the first archaedisks in the Bay Lane Quarry indicates a level above the base of MFZ 10 (Fig. 2). A similar fauna was obtained from the Carlyan Limestone above the studied part of the Rush section (Marchant 1978). The base of the Arundian in the British Isles may be difficult to identify (Simpson & Kalvoda 1987, Strogon *et al.* 1990) and additional criteria may be required. Similar problems with the entry of archaedisks above the probable base of the Arundian have been encountered in Belgium (Hance 1988) and in the Pengchong Tn-V boundary stratotype in southern China (Devuyst *et al.* 2003, Devuyst 2006). Up-section the increasing representation of dasycladaceans is apparent. The bioclast association in the calciturbidites corresponds to the heterozoan-photozoan facies in the lowermost part and to the photozoan facies in most of the section. This change in the upper part of MFZ 9 approximately 15 m from the base of the section may correlate with the similar change to photozoan associations in the higher part of MFZ 9 approximately 60 m below the top of the section in Rush and may

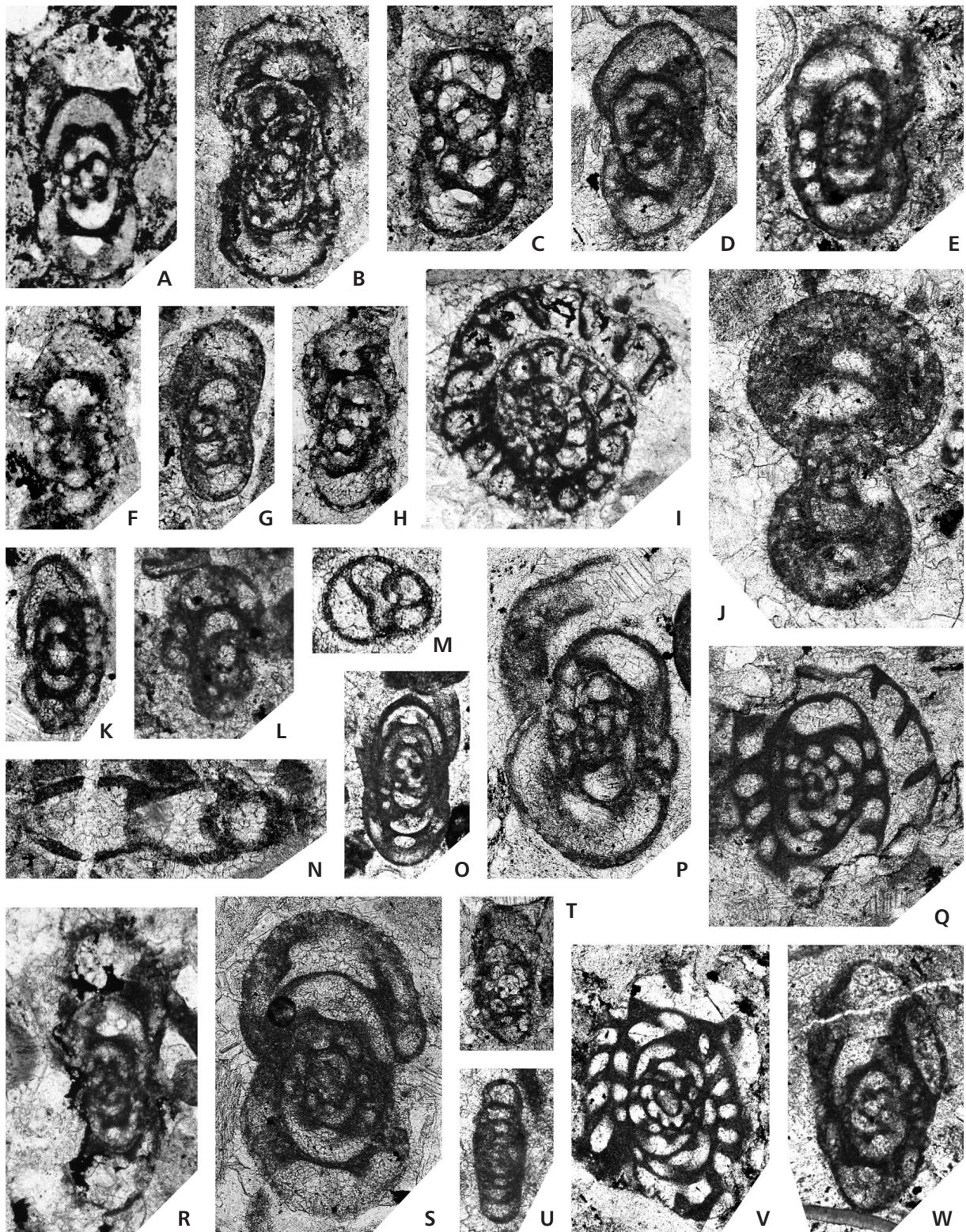
be connected with the growth of the carbonate platform (Somerville *et al.* 1992a, Pickard *et al.* 1994, Strogon *et al.* 1996).

The late Tournaisian *Eblanaia* facies in Lane and Rush is associated with heterozoan-photozoan facies and closely resembles similar associations described by Devuyst (2006) in the Oughterard Formation in western Ireland. The impoverishment of the foraminiferal associations is most evident in the absence or very rare occurrence of loeblichids and *Eoparastaffella*. The occurrence of the stratigraphical guides for the latest Tournaisian represented by species of *Eoparastaffella*, *Lysella gadukensis*, *Elevenella parvula* and *Darjella monilis* (Devuyst & Kalvoda 2007) is facially controlled. The Lane section is a good example of a succession where the whole sequence corresponds to the MFZ 8 biozone but the most important guide of the zone, *Eoparastaffella*, is absent in the lower part of the section. A similar late entry of the first *Eoparastaffella* has been reported also in the Oughterard Formation in western Ireland (Devuyst 2006). Both in Lane and Rush, and in Oughterard the entry of *Eoparastaffella* is connected with the transition from heterozoan carbonates to more diversified heterozoan-photozoan facies.

On the other hand the study of the Irish sections shows that some species that have generally been regarded as Viséan guides in eastern Europe, such as *Forschia parvula*, *Forschia mikhailovi*, *Forschiella prisca*, and *Euendothyranopsis? donica evoluta*, *Euendothyranopsis? donica donica* (Vdovenko 1980, Postoyalko 1975) first occurred in the Tournaisian. A possible explanation for this may be the absence of detailed bed-by-bed studies in Russia and Ukraine.

Further progress in high resolution foraminifer biostratigraphy of the Early Carboniferous will have to take into account the ecology of foraminifers (especially depth stratification and interplay between nutrients and oxygen levels) and the depositional features of limestones (especially granulometric sorting). Although this is beyond the scope of the present paper, it is worth mentioning that the low diversity foraminiferal fauna lacking some foraminiferal guides and containing abundant and morphologically diverse *Eblanaia* and other Tournayellidae that characterize the latest Tournaisian occurs in Lane in shallow water heterozoan-photozoan (foramderm) carbonates of the Lane Formation (Strogon *et al.* 1996). A similar association (bryonoderm extended) (Beauchamp 1994, James

Figure 12. Typical foraminifers from Lane, Rush and Bay Lane Quarry sections. Foraminiferal zones MFZ according to Devuyst & Hance (*in Poty et al.* 2006). • A – *Eoparastaffella* aff. *restricta laciniosa* Postoyalko, Bay Lane Quarry, Q14, t.s. 2, MFZ 9, 75x. • B – *Eoparastaffella macdermoti* Devuyst & Kalvoda, Rush R86, t.s. 1, MFZ 9, 75x. • C – *Eoparastaffella* cf. *macdermoti* Devuyst & Kalvoda, Lane L17, t.s. 2, MFZ 8, 75x. • D – *Eoparastaffella* sp., Rush R14, t.s. 4, MFZ 9, 75x. • E, I, P, S – *Eoparastaffella* ex gr. *florigena* (Pronina), E – Lane L17, t.s. 4, MFZ 8, 75x, I – Rush RG6a, MFZ 9, 75x, P – Rush R14, t.s. 4, MFZ 9, 75x, S – Rush R14, t.s. 3, MFZ 9, 75x. • F – *Eoparastaffella* ex. gr. *asymmetrica* Vdovenko & Zavyalova, Rush RG6b, MFZ 9, 75x. • G, H – *Eoparastaffella macdermoti* Devuyst & Kalvoda, juvenile or *E. ovalis* Vdovenko M1, G – Lane L17, t.s. 1, MFZ 8, 75x, H – Rush R47, t.s. 3, MFZ 9, 75x. • J – *Euendothyranopsis? donica evoluta* Brazhnikova & Rostovtseva, Lane 41, TCD 18331, MFZ 8, 75x. • K – *Eoparastaffella simplex* Vdovenko, Rush R85, t.s. 2, MFZ 9, 75x. • L – *Eoparastaffella* cf. *vdoenkoae* Devuyst & Kalvoda, juvenile, Lane L17, t.s. 3, MFZ 8, 75x.



• M – *Biseriella bristolensis* (Reichel), Lane 31, TCD 12382, MFZ 8, 100×. • N – *Elevenella parvula* (Bozorgnia), Rush R89, t.s. 3, MFZ 8, 75×.
 • O – *Paralysella schubertelloides* (Bozorgnia), Bay Lane Quarry Q23, t.s. 4, MFZ 10, 75×. • Q, V – *Vissarionovella* sp., Q – Rush R9, t.s. 1, MFZ 9, 75×,
 V – Bay Lane Quarry Q18, t.s. 4, MFZ 10, 75×. • R – *Eoparastaffella* cf. *restricta* Postojalko & Garan, Rush RG9a, MFZ 9, 75×. • T – *Eoparastaffella*
ovalis Vdovenko, M2, Rush Marchant's sample 25, MFZ 9, 75×. • U – *Lapparentidiscus bokanensis* Vachard, Bay Lane Quarry Q29, t.s. 5, MFZ 10,
 100×. • W – *Eoparastaffella simplex* Vdovenko (transitional to *Eostaffella*), Bay Lane Quarry, Q21, t.s. 1, MFZ 10, 75×.

1997) was encountered in calciturbidites of the Tober Colleen Formation at Rush. Heterozoan-photozoan associations in shallow water tropical belts commonly indicate cold water upwelling (Carannante *et al.* 1988, Schlager 2003, Westphal *et al.* 2010). Similar associations in shallow water tropical carbonates were described by Brandley & Krause (1997) from the early Carboniferous formations of the Rundle Group (especially the Turner Valley Formation) in western Canada which are also dominated by *Eblanaia* and other tournayellids (Beauchamp & Mamet 1985, Mamet *et al.*, 1986). Generally *Eblanaia* is common in late Tournaisian and earliest Viséan in the North American Cordillera where also the widespread species *Septabrunsiina parakrainica* Skipp (Sando *et al.* 1969, Beauchamp & Mamet 1985) can be included in the genus (Conil & Lys 1977, Brenckle 1997).

Upwelling and high nutrient levels strongly influenced Early Carboniferous low-latitude shallow seas of Laurussia (Wright 1994) and a wide belt of oceanic upwelling has been postulated to have been active along the southern margin of western Laurussia (Wright & Faulkner 1990; Wright, 1991, 1994; Bridges *et al.* 1995; Pickard 1996; Stanton 2006). The dominance of *Eblanaia* and other tournayellids in the North American Cordillera can be attributed to this upwelling and compared with buliminid dominance in foraminiferal associations in the Cretaceous or Paleocene upwelling belt of southern Tethys (Guasti *et al.* 2005, Aschkenazi *et al.* 2010). It remains to be clarified whether similar foraminiferal associations in Ireland can be attributed also to the upwelling hypothesized in the early Carboniferous of the British Isles (Wright 1991) or to an alternative explanations of higher trophic levels. The may be linked also to the increased humidity in the late Tournaisian of the British Isles followed by the change to semi-arid conditions close to the T-V boundary (Wright 1990). Whatever the reason may be, an important role played the transition from ramp sedimentation with high rates of heterotroph sediment production in mid-ramp settings in late Tournaisian to platform sedimentation in Viséan when the narrow belt of the photozoan carbonate factory with fusulinids widened (Somerville *et al.* 1992, Pedley 1998, Schlager 2003, Wright & Burgess 2005).

Gamma-ray log correlation and sequence stratigraphic interpretation

Our analysis of the GRS signal and correlation with the facies logs suggest that the K and Th concentrations may serve as a proxy for overall landward / basinward facies shifts and as a proxy of CaCO₃ contents in mixed carbonate-siliciclastic facies. Both can be linked to relative sea-level changes. The geophysical response of carbonate systems to transgressions and normal/forced regressions

may vary significantly depending on platform morphology and position on platform-to-basin transect. Regressions in updip areas of carbonate systems result in decelerated/ceased carbonate production and increased aeolian/fluviol influx of siliciclastic material, which causes positive excursions on gamma-ray logs (*cf.* Hladil *et al.* 2006). In downdip areas of carbonate ramps, a regression implies basinward shift of the carbonate factory (Wright 1986), which is associated with increased carbonate supply into the basin and negative excursions on gamma-ray logs (Koptíková *et al.* 2010). Transgressions and marine flooding imply opposite trends on geophysical logs. In extreme situations, minimum carbonate production in downdip areas of carbonate ramps and mixed carbonate-siliciclastic systems is attained during maximum flooding, which is associated with maximum gamma-ray values (Halgedahl *et al.* 2009). The response may differ significantly on slopes of rimmed carbonate shelves and flat-topped carbonate platforms, such as the Cainozoic Bahamas, which have tendency to maximum supply of carbonate into the basin during highstands (highstand shedding; Droxler & Schlager 1985, Westphal *et al.* 2010). Concentrations of uranium in GRS logs are usually interpreted as relating to the presence of organic carbon and calcium phosphates, which may indicate dysoxic/anoxic conditions and low carbonate productivity (Rider 1999, Ehrenberg *et al.* 2008). Intervals with high U/Th ratios are therefore in some cases interpreted as maximum flooding surfaces (*cf.* Lüning *et al.* 2003, Doveton & Merriam 2004, Halgedahl *et al.* 2009).

The three sections studied show correlatable patterns on the GRS logs, which are in line with the scenarios on mixed carbonate-siliciclastic systems. The K and Th concentrations and U/Th and K/Th ratios close to the biostratigraphic Tn/V boundary are correlatable between Rush and Bay Lane Quarry sections (Fig. 10). There is a distinct drop in the K and Th concentrations, accompanied with a slight increase in the U/Th ratios near the FAD of the basal Viséan index foraminifer taxa (112 to 96 m in Rush; 5 to 11 m in Bay Lane Quarry). This interval coincides with the carbonate intraclast-rich, mass-flow breccias at the Rush section and carbonate-rich turbidites in the Bay Lane Quarry. The mass wasting associated with basinward shift of facies inferred from negative K and Th excursions can be interpreted as a result of destruction of the carbonate platform slope during relative sea-level fall (forced regression; *cf.* Sarg 1988, Coe 2003). This interpretation is supported by the regionally recognised forced regression / sea-level fall, which is associated with very rapid shallowing, exposure features and karstic surfaces in shallow-water Tn/V boundary sections around the London-Brabant Massif (Faulkner *et al.* 1990, Hance *et al.* 2001, Devuyt 2006).

Below the Tn/V boundary interval, the K and Th concentrations tend to decrease (152 to 112 m in Rush; 0 to 5 m

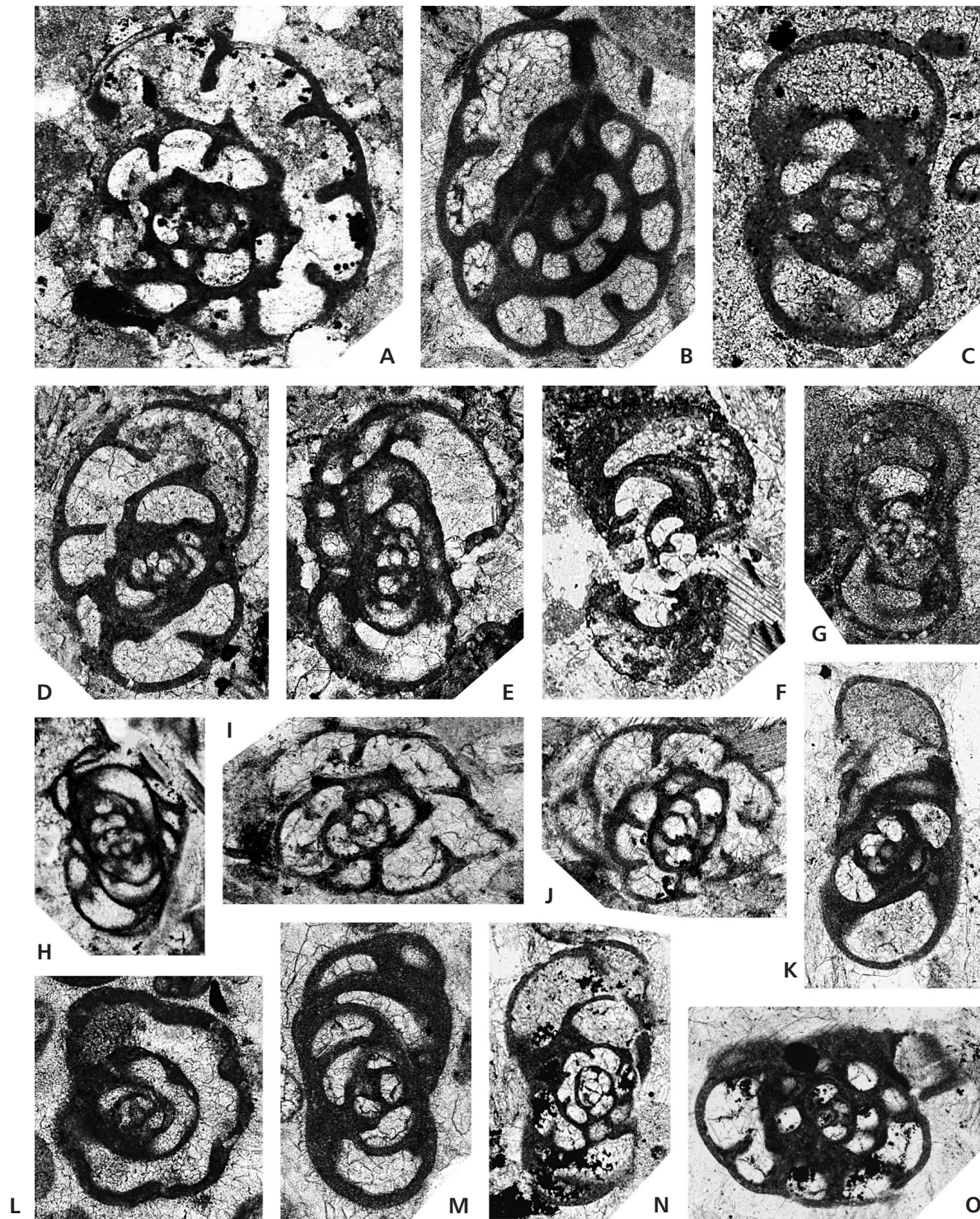


Figure 13. Typical foraminifera from Lane, Rush and Bay Lane Quarry sections. Foraminiferal zones MFZ according to Devuyst & Hance (in Poty *et al.* 2006). • A, K – *Omphalotis* ex gr. *chariessa* (Conil & Lys), A – Bay Lane Quarry, Q 18, MFZ 10, t.s. 1, 75×, K – Rush, R75, t.s. 2, MFZ8, 75×. • B – *Omphalotis omphalota* (Rauzer-Chernousova & Reitlinger), Rush R14, t.s. 5, MFZ9, 75×. • C – *Latiendothyranopsis* sp., Lane L1A, t.s. 4, MFZ 8, 75×. • D – *Globoomphalotis* sp., Bay Lane Quarry, Q 21, t.s. 6, MFZ 10, 75×. • E – *Eoendothyranopsis?* cf. *robusta* (Conil & Lys), Lane L4, t.s. 2, MFZ 8, 50×. • F – *Eoendothyranopsis?* ex gr. *donica* Brazhnikova & Rostovtseva, Rush R77, t.s. 6, MFZ 8, 50×. • G – *Eoendothyranopsis?* *donica evoluta* (Brazhnikova & Rostovtseva), Rush, 09/R13, t.s. 6, MFZ 9, 75×. • H – *Lysella gadukensis* Bozorgnia, Rush, R81, t.s. 3, MFZ 9, 75×. • I, J – *Spirochermella brenecklei* Conil & Lys, Rush, R89B, t.s. 3, MFZ 8, 75×. • L – *Bogushella* sp., Lane L1, t.s. 4, MFZ 8, 75×. • M – *Globoomphalotis ischimica* (Rauzer), Lane, M39, MFZ 8, 75×. • N – *Globoendothyra* cf. *insignis* Postoyalko, Rush, R73, t.s. 2, MFZ 8, 75×. • O – *Omphalotis* ex gr. *omphalota* (Rauzer-Chernousova & Reitlinger), Rush R71, t.s. 4, MFZ 8, 75×.

in Bay Lane Quarry) while above it they tend to increase (96 to 6 m in Rush; 11 to 35 m in Bay Lane Quarry) indicating increasing and decreasing CaCO_3 contents, respectively (Figs 9, 10). The upper Tournaisian K and Th trends correlate with the coarsening-upward succession in Rush, which indicates normal regression during late sea-level highstand or, more probably, forced regression (falling-stage systems tract), which is supported by the sudden influx of detrital grains slightly before the biostratigraphic Tn/V boundary. At the Bay Lane section only the uppermost part of the decreasing K and Th trends is exposed.

The lower Viséan increasing K and Th concentrations coincide with fining-upward successions, mainly in Rush but partly also in Bay Lane Quarry section, indicating deepening of the depositional setting (transgression). This is consistent with the early Viséan deepening-upward trend in shallow-marine carbonates at the Oughterard section, western Ireland (although this part of the Oughterard section may be affected by local synsedimentary tectonics) (Devuyst 2006). These deepening-upward trends are also correlatable with time-equivalent deep-water carbonate sections in other areas around the London-Brabant Massif (Brown End Quarry, Staffordshire, England and Sovet and Salet sections, Dinant synclinorium, Belgium; Bábek *et al.* 2010). The transgressive patterns immediately above the Tn/V boundary suggest that the Viséan parts of the logged sections correlate with the lower parts of depositional sequence 5 of Hance *et al.* (2001).

The carbonate-dominated, turbidite-free succession in Lane was deposited in a much shallower depositional setting than the Rush and Bay Lane sections (Nolan, 1989) and the log response is consistent with the updip response of a carbonate system to regression (see above). Two regressive intervals can be seen in the section. The lower one, showing increasing trends in K and Th concentrations and siliciclastic admixture in carbonates (13 to 16 m; Fig. 9, uppermost Tournaisian MFZ 8) is followed by the latest Tournaisian (MFZ 8) marine flooding, which is indicated by a distinct shift towards low K and Th concentrations at the base of pure bioclastic limestones (transgressive systems tract, which may pass upwards into highstand systems tract). The late Tournaisian maximum flooding surface might be indicated by extremely high U/Th ratios at ~6.5 m depth. The upper regressive event corresponds to the base of the Smuggler's Cave Conglomerate (2 m, Fig. 9), which is Viséan in age and is associated with subaerial erosion (Marchant 1974, 1978; Nolan 1986). This interval in the Lane section is assumed to represent the shelf equivalent of the Tn/V forced regression, which can be correlated with the situation in Rush and Bay Lane Quarry (Fig. 10) and with the boundary between depositional sequences 4 and 5 (Hance *et al.* 2001, 2002; Devuyst 2006).

Conclusions

The late Tournaisian in the Dublin Basin is characterized by a widespread occurrence of heterozoan and heterozoan-photozoan facies (Tober Colleen Formation, Lane Formation) with impoverished foraminiferal faunas indicating environments with higher nutrient levels which are typical of upwelling zones or regions with increased humidity. Both the facies and foraminiferal associations resemble those described in the Rundle Group in western Canada. The transition to heterozoan-photozoan facies with higher representation of dasycladaceans is typical for the base of Viséan and probably coincided with the change from a ramp into platform – rimmed basin (Somerville *et al.* 1992, Pickard *et al.* 1994, Strogon *et al.* 1996). The further development of carbonate platforms is recorded in the transition to photozoan facies higher in the Viséan MFZ 9.

The biostratigraphic study supported by GRS logging, demonstrates a good applicability of the foraminiferal zonation of Devuyst & Hance in Poty *et al.* (2006) even in the difficult setting of heterozoan facies with a taxonomically impoverished fauna. These facies have a negative impact on the entry of the MFZ 8 guide *Eoparastaffella* which is thus facially controlled and diachronous. In the absence of *Eoparastaffella*, *Biseriella bristolensis* can serve as another guide of MFZ 8; however, the species is not very common. Some problems are also connected with the entry of the MFZ 9 and Viséan guide *Eoparastaffella simplex*. First occurrences, both in Irish and other European sections, may be quite rare and often only more advanced evolutionary younger morphotypes are encountered (Devuyst 2006, Kalvoda *et al.* 2010). In its absence, the entry of *Eoparastaffella ovalis* M 2 following the latest Tournaisian entries of *Lysella gadukensis*, *Eoparastaffella ovalis* M3 and *Eoparastaffella ex gr. florigena* and preceding the FAD of *Eoparastaffella asymmetrica* enable high resolution biostratigraphy of the Tn-V boundary interval (Devuyst 2006, Kalvoda *et al.* 2010). The foraminiferal data from Bay Lane Quarry demonstrates that also the entry of the first archaedisks may be quite diachronous and thus the base of the Arundian stage may be difficult to identify.

The gamma-ray logs offer important added information to biostratigraphic correlation. They proved to be very useful tools for correlating the boundaries between depositional sequences 4 and 5 of Hance *et al.* (2001) just below the Tn-V boundary not only across the variable depositional settings of the Dublin Basin but also in other sections around the London-Brabant Massif (Bábek *et al.* 2010).

The good correlation of the sequences around the London-Brabant Massif may indicate a global glacioeustatic signal (Kalvoda 2002, Isaacson *et al.* 2008, Bábek *et al.* 2010). However, similar sequence boundaries have not yet been traced in Laurussia outside the London-Brabant Massif (Devuyst 2006). If glacioeustatic sea level changes

did occur around the Tn/V boundary, the glacioeustatic signal may have been locally overprinted by tectonic processes connected with the transition to synorogenic flysch sedimentation (Moravia, Czech Republic; Kalvoda *et al.* 2010). Alternatively, the sea-level fluctuations may have been regionally restricted, reflecting extensional tectonics around the London-Brabant Massif (Leeder 1987, Nolan 1989, Gawthorpe *et al.* 1989).

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