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TNO report

TNO 2023 R10118

The results of the palynological analysis of selected samples from the Neurath Sand, Garzweiler quarry, Lower Rhine Basin (W-Germany)

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Number of pages	28 (incl. appendices)
Number of appendices	2
Sponsor	TNO-GSN, GeoModeling
Project name	Cross border Miocene correlation
Project number	060.51859/01.10

Contents

1 Introduction

After the Neogene Symposium in Brussels organized by the Belgian Stratigraphical Commission on May 19th 2022, a field trip to the Garzweiler open-cast mine in Germany was planned by TNO-GSN, VU-A'dam, GD-NRW and VITO. The main aim was to discuss the cross-border correlation of mid-Miocene successions. The field trip was organized by Alexandra Siebels (PhD, VU-A'dam), Linda Prinz (GD-NRW, Krefeld) and Peter Lokay (RWE) and took place on November 4th, 2022. Linda Prinz guided the trip.
The participants were Alexandra Siebels, Johan ten Veen, Ronald van Balen, Jef Deckers, Stijn Everaert, Freek Busschers & Dirk Munsterman.

Figure 1: Location map

The Garzweiler open-cast mine is located at the northwestern end of the mining region extending along the western margin of the Köln Block and adjacent southeastern Venlo Block, as part of the Lower Rhine Basin (Figure 1 and 4). During this field trip samples were collected for palynological analysis of the Frimmersdorf (Figures 5 and 6) and Neurath Sands (Figures 7-9). As expected, the white Frimmersdorf Sand samples did not yield any palynomorphs (were barren). Post depositional processes, linked to groundwater leaching with humic acids from the overlying coals, led to the dissolution of all organic material, leaving only quarts grains.

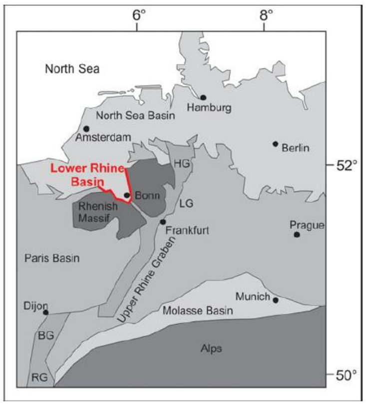

Figure 2: A structural map of the NW European Cenozoic Rift System, emphasizing the position of the Lower Rhine Basin (sensu Prinz et al., 2017).

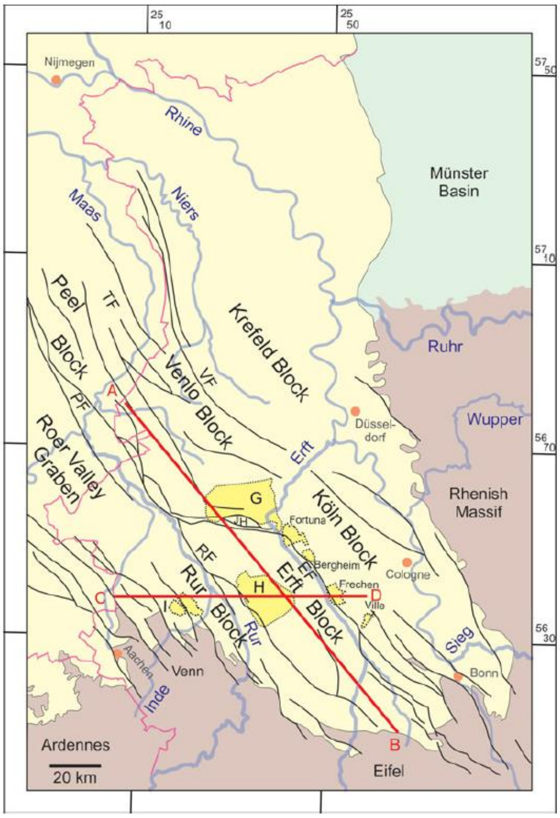

Figure 3: Structural map of the Lower Rhine Basin (Garzweiler open-cast mine – G in dark yellow colour; sensu Prinz et al., 2017). The six main tectonic blocks (Rur, Erft and Köln blocks in the SE; Peel, Venlo and Krefeld blocks in the NW) are bounded by the Rur (RF), Erft (EF), Peel Boundary (PF), Tegelen (TF) and Viersen faults (VF), as well as the fault system bounding the Jackerath Horst (JH). The Rur Block extends into the Roer Valley Graben in the NW. G = Garzweiler open-cast mine; H = Hambach open-cast mine; I = Inden opencast mine; pink line: Germany–Netherlands–Belgium border. The two red lines mark the position of two cross sections (A–B and C–D), which are shown in Figure 4. Modified after Geluk et al.(1994), Schäfer et al. (1996), Klett et al. (2002) and Schäfer & Utescher (2014).

Figure 4: Photo 1: Northern part of the Garzweiler pitt (Google Earth)

Figure 5: Photo 2: Frimmersdorf Sand and Frimmersdorf Seam on top

Figure 6: Photo 3: Discussion on the Frimmersdorf Sand

Hence, this palynological analysis and report focuses on the outcrop samples of the younger Neurath Sand. The main aim of the palynological analysis will be age assessment, in particular identification of biozones sensu Munsterman et al., 2019, in order to facilitate correlation to the Dutch successions (e.g. well Groote Heide a.o. (see Figure 1). In addition, attention is paid to sequences and palynofacies.

The results of the analysis are described in chapter 3. Correlations between the Neurath Sands (Garzweiler quarry) and the Vrijherenberg Member (Venlo Block) are described in chapter 4. Focus is in particular on the type-section well Groote Heide. Discussion and conclusions are presented in chapter 5. The references are listed in chapter 6.

2 Material and methods

2.1 Abbreviations

Standard abbreviations in use by TNO-GSN are listed in Table 1.

Table 1: Used abbreviations in this report.

CO	Core sample
SC	Sidewall core sample
OC	Outcrop
CU	Cuttings sample
m	Meter
ft	Feet
LOD	Last Occurrence Datum
LCOD	Last Common Occurrence Datum
FOD	First Occurrence Datum
FCOD	First Common Occurrence Datum

2.2 Samples

Four OC samples are collected from the Neurath Sand in the Garzweiler quarry. Three of these OC samples (codes NS3, NS4 and NS5; Figure 7) are selected near the base of the Neurath Sand. The fourth OC sample (code NS6) is taken higher in the succession in the lowest of three dark colored organic rich (planar-laminated) sandy 1 cm intervals (1.5 m below an angular-shaped gravel succession).

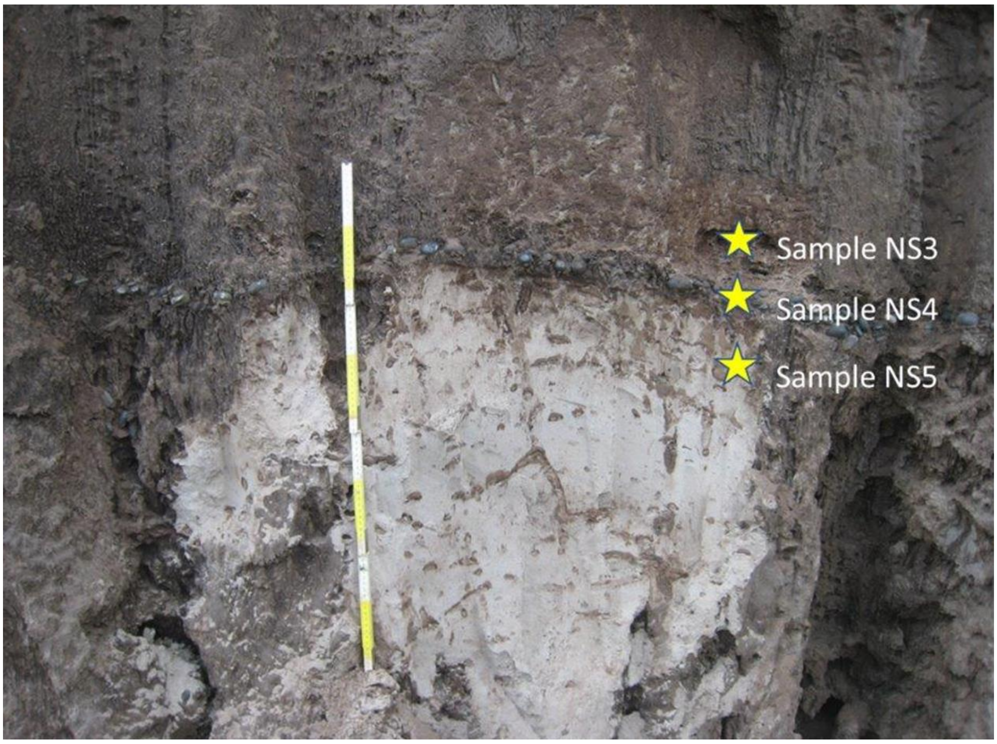

Figure 7: Photo 4: Position of 3 selected samples in the Neurath Sands, approximately 2 m (pers. comment LP) above the Frimmersdorf Seam; sample NS4 is taken from the chert-pebble lag.

Figure 8: Photo 5: Sampling the chert-pebble bed (Photo: Stijn Everaert)

Figure 9: Photo 6: Details of the chert-pebble bed.

Table 2: Samples (cf. Section 1 in Fig. 8; Prinz et al., 2017).

Code	**Position (m)***	**Lithological description**
NS3	c. 2.05	Dark grey-colored, fine- to medium-grained sands with up to 15% mud which contain clasts of mud, wood and lignite (Photo 4)
NS4	c. 2	Chert-pebble bed (Photo 4)
NS5	c. 1.85	Bioturbated fine-grained sands incl. *Ophiomorpha* ichnosp. (Photo 4)
NS6	c. ?48**	Dark colored organic rich planar-laminated fine-grained sand; the lowest of 3 dark colored 1 cm beds (c. 1.5 m below gravel succession)

*Relative to the top of the Frimmersdorf Seam below
**estimated, but uncertain, most likely associated with c. 9.5 m level in Section 3 (cf. Fig. 8; Prinz et al., 2017) where an evident hiatus is shown 1.5 m above this level (personal comment Linda Prinz: “ in the open-cast mine the thickness of the Neurath Sand change over very short distances, but I think your estimated position can be correct”).

2.3 Sample processing

The samples were processed at the TNO-GSN laboratory by Nico Janssen using the standard sample processing procedures, which involves HCl and HF treatment, and sieving over a 18 µm mesh sieve.

2.4 Palynological analysis

The microscopy analysis was done according to standard procedures. The associations on the microscope slides are counted until a total of ca 200 sporomorphs and dinoflagellate cysts (palynomorphs) is reached. The miscellaneous categories (Botryococcus, inner chambers of foraminifers, Tasmanaceae, etc.) are also calculated, but kept outside the total sum of palynomorphs. The remainder of the slide is thereafter scanned for any (rare) dinocyst species which are simply noted as “present” (+ symbol on the distribution chart).
Diagnostic species are discussed in the report, a complete distribution chart including all species found is given as appendix.

2.5 Taxonomy

For the dinoflagellate cyst taxonomy the so-called “Lentin and Williams” index is followed (Fensome et al., 2019).

2.6 Age-interpretation

The age interpretation is based on the LOD’s and FOD’s of dinoflagellate cysts.

Palynological interpretation is based on key-references concerning the palynostratigraphy of Paleogene to Neogene from the North Sea region such as: Bujak & Mudge (1994), De Schepper and Head (2009), De Schepper et al. (2015), Dybkjaer & Piasecki (2010), Heilmann-Clausen (1985), Köthe (2003), Kuhlmann et al. (2006), Louwye (2005), Louwye et al. (2010), Munsterman & Brinkhuis (2004; Figure 10), Munsterman et al. (2019), Powell (1992) and Van Simaeys, Munsterman & Brinkhuis (2005). For the Miocene the dinocyst zonation scheme of Munsterman and Brinkhuis (2004), is used, recalibrated to Geological Time Scale (GTS) 2016 of Ogg et al. (2016) in Munsterman et al. (2019).

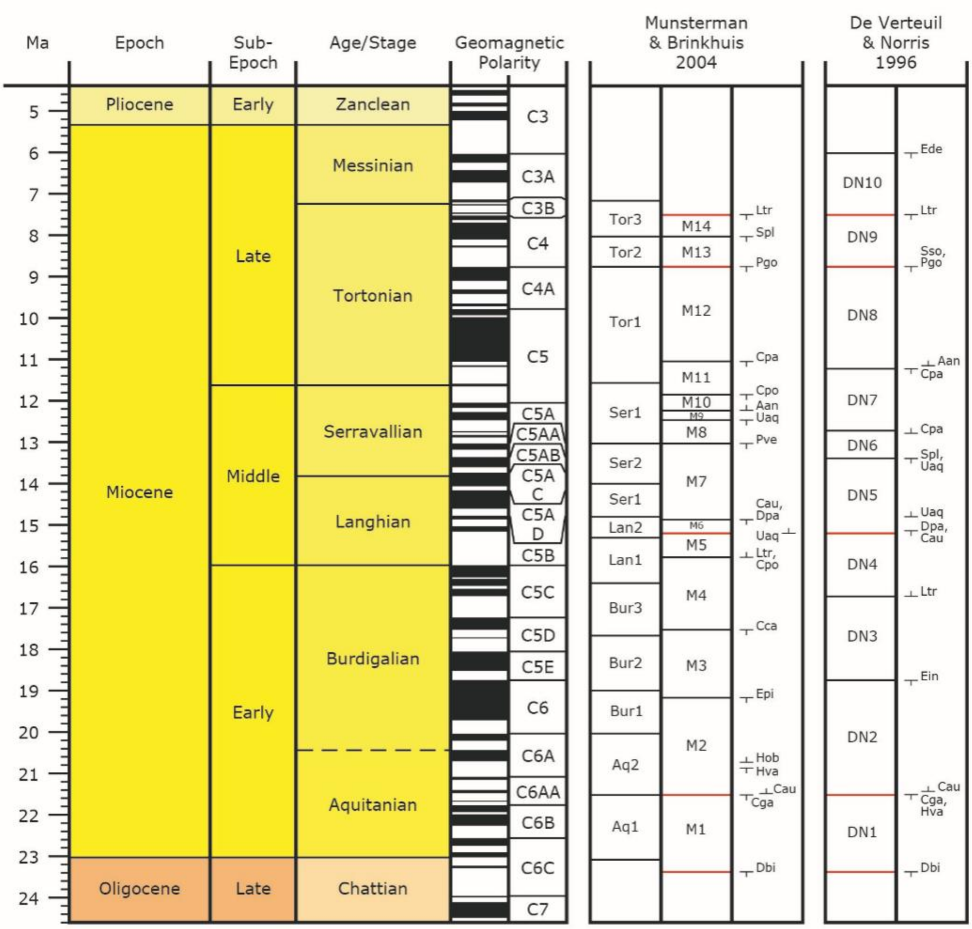

Figure 10: Miocene dinozonation sensu Munsterman & Brinkhuis (2004), recalibrated to the GTS sensu Ogg et al. (2016) in Munsterman et al. (2019).

2.7 Stratigraphic correlation of wells Groote Heide, Broekhuizenvorst en Heumensoord in the Venlo Graben (Munsterman, 2001)

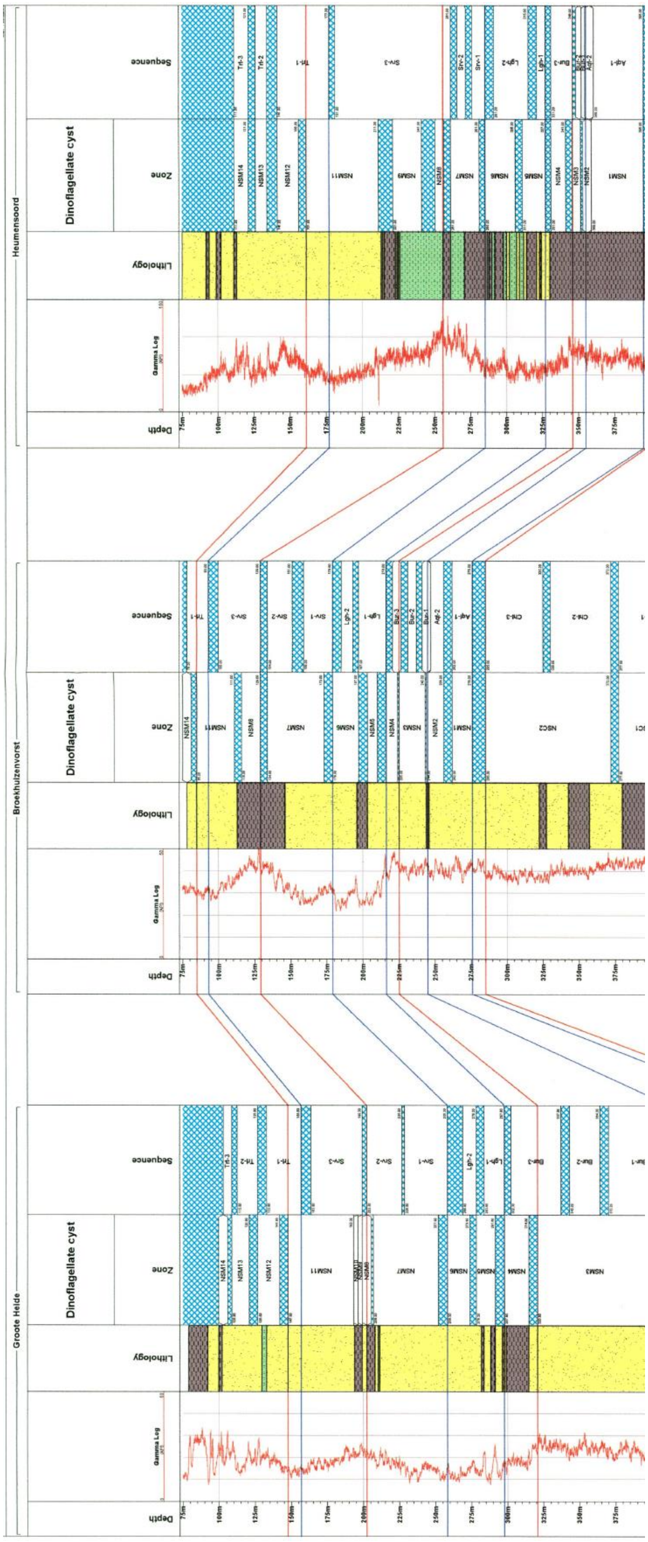

Figure 11: Correlation of wells in the Venlo Graben, based on biostratigraphy, gamma-ray logs, lithology and sequences (Munsterman, 2001).

3 Results

All samples from the Neurath Sands are rich in palynomorphs. The associations are all dominated by bisaccate pollen (gymnosperms). The percentages of the bisaccate pollen vary from 54-81 % of the total sum palynomorphs (spores, pollen and dinoflagellate cysts). These pollen represent an upland vegetation ecogroup. Bisaccate pollen have a high buoyancy in both air and water and may transported over (very) long distances (the pollen are even recorded in the open ocean). The spores, however, are present in relatively low numbers (3-9 % of the total sum palynomorphs). The marine component is the highest in the chert-pebble bed (sample NS4 comprises 43 % dinoflagellate cysts of the total sum palynomorphs; just above this bed in sample NS3: 33 % dinocysts; below the chert-pebble bed in sample NS5: 21 % dinocysts). The coastal algae *Paralecaniella* is very well represented. The freshwater alg Pediastrum is very rare in the assemblages. The lower 2 samples include low percentages (1,5 %) of reworking from Lower Cretaceous origin (e.g. *Classopollis* tetrad, *Trilobosporites* sp., *Gonyaulacysta* and *Chlamydophorella nyei*)
The microflora of highest sample NS6 shows a lower variety of marine dinocysts compared to the associations of samples at the base of the Neurath Sands. The relative number of dinocysts is 20 % of the total sum palynomorphs. Very remarkable is an increase of brackish water algae *Botryococcus* (38 % of the marine component).

3.1 Sample NS5 (10-15 cm below chert-pebble bed): middle Miocene, late Langhian-early Serravallian, Zone SNSM7

The dating is based on:
- LOD *Palaeocystodinium ventricosum*
- LOD *Apteodinium tectatum*
- FOD *Habibacysta tectata*

Remarks: the presence of *Cerebrocysta poulsenii* and *Labyrinthodinium truncatum* confirm the age assessment. Older dinocyst markers like e.g. *Cousteaudinium aubryae* and *Distatodinium paradoxum* are absent.

Facies: shallow marine

Marine dinocysts: 21 % of the total sum palynomorphs
Species variety: good
Spiniferites spp. : 58 % of the sum dinocysts
Hystrichokolpoma spp.: 9 % of the sum dinocysts
Systematophora placacantha: 13 % of the sum dinocysts

Paralecaniella: 35 % marine component
Botryococcus: 1 % marine component

3.2 Sample NS4 (chert-pebble bed): middle Miocene, late Langhian-early Serravallian, Zone SNSM7

The dating is based on:
- LOD *Palaeocystodinium ventricosum*
- FOD *Unipontidinium aquaeductus*
- Superposition

Remarks: see remarks sample NS5

Facies: shallow marine

Marine dinocysts: 43 % of the total sum palynomorphs
Species variety: good
Spiniferites spp.: 37 % of the sum dinocysts
Hystrichokolpoma spp.: 8 % of the sum dinocysts
Systematophora placacantha: 28 % of the sum dinocysts

Paralecaniella: 19 % marine component
Botryococcus: absent

3.3 Sample NS3 (5 cm above chert-pebble bed): middle Miocene, mid Serravallian, Zone SNSM8

The dating is based on:
- LOD *Unipontidinium aquaeductus*

Remarks: *Palaeocystodinium ventricosum* is absent. Present is *Cerebrocysta poulsenii.*

Facies: shallow marine

Marine dinocysts: 33 % of the total sum palynomorphs
Species variety: good
Spiniferites spp.: 45 % of the sum dinocysts
Hystrichokolpoma spp.: 13 % of the sum dinocysts
Systematophora placacantha: 8 % of the sum dinocysts

Paralecaniella: 11 % marine component
Botryococcus: 2 % marine component

3.4 Sample NS6 (lowest of 3 dark organic rich 1 cm beds, estimated at c. 48 m in Section 1 and correlated to c. 9.5 m in Section 3 cf. Figure 8 in Prince et al., 2017): middle-late Miocene, latest Serravallian-early Tortonian, zones SNSM10-SNSM12

The dating is based on:
- LOD *Sumatradinium druggii*
- FOD *Achomosphaera andalousiense*

Remarks: present are also *Bitectatodinium tepikiense, Labyrinthodinium truncatum* and *Systematophora placacantha.* The latter taxon is relatively good represented (8% of the total dinocyst sum), indicating that a latest Serravallian age (zones SNSM 10-11), pre-MMU position is most likely.

Facies: estuarine

Marine dinocysts: 20 % of the total sum palynomorphs
Species variety: moderate to good
Spiniferites: 68% of the sum dinocysts
Hystrichokolpoma: 3 % of the sum dinocysts
Systematophora placacantha: 8 % of the sum dinocysts

Lingulodinium machaerophorum: 11 % of the sum dinocysts

Paralecaniella: 10 % marine component
Botryococcus: 38 % marine component

4 Correlation of the Neurath Sand Member to the Vrijherenberg Member (Groote Heide Formation) in well Groote Heide (Venlo Block)

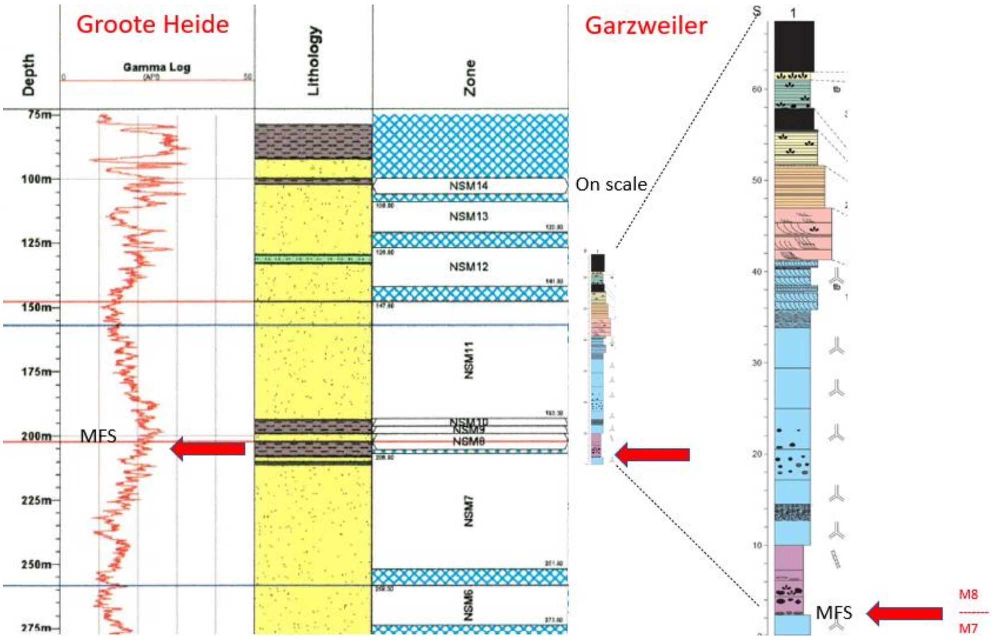

Figure 12: Correlation of successions in well Groote Heide (Munsterman, 2001) and the Neurath Sand in the Garzweiler quarry (Prinz et al., 2017) supplemented with data from this study

Earlier correlations (Munsterman, 2001; see Figure 11) between air-lifted wells Groote Heide, Broekhuizenvorst and Heumensoord in the Venlo Block (NL) led to the establishment of a dinoflagellate zonation for the Miocene in NL (Munsterman & Brinkhuis, 2004 and updated to the Gradstein et al., 2016 time scale in Munsterman et al., 2019). The gamma-ray logs (max. values) of these wells show a MFS, confirmed by the facies interpretation of the dinoflagellate cysts (Deckers & Munsterman, 2019), positioned very closely to the dinocyst Zone boundary SNSM7/SNSM8. The increasing upward gamma-ray values at the end of Zone SNSM7 corresponds to a fining upward sequence (FS) from sands to clays.

In the Neurath Sand Member of the Garzweiler quarry Prinz et al. (2017) recorded an evident lithological boundary at approximately 2 m (Figure 12). Here, the lithology changes from fine-grained sands to muddy sands, with a chert-pebble bed at the base and is interpreted as the FA1/FA2 facies transition (Prinz et al., 2017). Dinoflagellate cyst interpretation (this study) indicates a shift in zones from SNSM7 to SNSM8 at the chert-pebble bed. In addition the palynofacies of the chert-pebble bed sample shows a maximum marine percentage of the total sum palynomorphs, compared to facies of the samples below and above this bed. Number and species diversity of the dinocysts are the highest in the chert-pebble bed.

The trend in the dinocyst association, the unique chert-pebble bed and the sudden increase in the muddy content of the lithology in concert with the biozone change make it tempting to correlate this event with the MFS recorded in the Roer Valley Graben (NL).

5 Discussion and Conclusion

The palynostratigraphic results of the Neurath Sand Member are tabulated below:

Table 3: Overview age-assessments of the Neurath Sand Member (Garzweiler). *Depths are relative to the top of the Frimmersdorf Seam. It is estimated and assumed here that the distance from the top of the Frimmersdorf Seam to the chert-pebble bed is 2 m.

Depth (m)*	Age, Zone
1.85-2	middle Miocene, late Langhian-early Serravallian, Zone SNSM7
2.05	middle Miocene, mid Serravallian, Zone SNSM8
?48	middle-late Miocene, latest Serravallian-early Tortonian, zones SNSM10-SNSM12

The zonal M7/M8 transition (Munsterman et al., 2019) is evidently presented in the Neurath Sand Member at the chert-pebble bed. Based on the interpretation of the lithological transition, dinocyst facies trend, and correlation to the Venlo Block boreholes, including gamma-ray logs, the chert-pebble bed is closely associated with a MFS.

This MFS level seems to be widely preserved in the North Sea Basin (De Bruin et al., 2015). Above this level a hiatus occurs (the MMU), which canbe seen as the culmination of the shallowing upward trend (perceptible as a coarsening upward in lithology, and decreasing values on the gamma-ray log) above the MFS. Sediments in between the MMU and a maximum regressive surface is reached at the end of Zone NSM11 are (partly) missing in many parts of the North Sea Basin. Subsequently, sedimentation resumes during the Tortonian flooding (Zone NSM12).

Sediments associated with the “MMU phase” are however preserved in the Lower Rhine Basin (Garzweiler quarry) and in the Venlo Block (Groote Heide). One of the processes that might explain the preservation here is the increased subsidence of this part of the North Sea Basin due to lithospheric downfolding under Alpine compression (Deckers & Louwye, 2020). Like in the Venlo Block, it seems that the mid to late Serravallian succession is apparently semi-continuously preserved, while this interval elsewhere is largely missing and represented by the MMU unconformity. The measured profile of Prinz et al. (2017; Figure 13) evidently shows the shallowing upward marine facies trend. This shallowing trend is confirmed by the interpreted brackish facies, higher up in the dark colored organic rich planar-laminated fine-grained sand (sample NS6) that is dated as latest Serravallian-early Tortonian (zones SNSM10-SNSM12). Estuarine conditions prevail here in sample NS6.

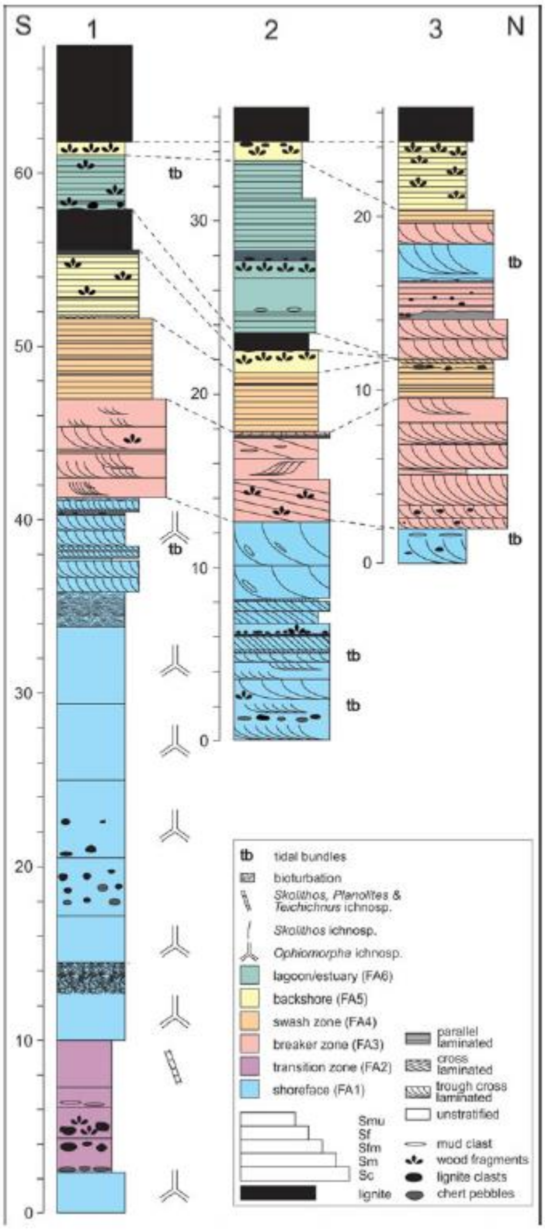

Figure 13: The measured profile through the Neurath Sand, Garzweiler open cast mine. The three sections 1, 2 and 3 are separated at 200 m from each other along a N–S axis (sensu Figure 8 in Prinz et al., 2017).

It is recommended to increase the number of palynological analyses above sample NS6 at c. 9.5 m, estimated c. 1.5 m below the unconformity recorded in Section 3 (Figure 13). The current unconformity could perhaps be correlated to the unconformity of well Groote Heide at the top of Zone SNSM11 (depth 156.8-159.8 m) where the palynofacies changes abruptly (Figure 14). This change is expressed by, an decrease in *Paralecaniella* from over 60% to 5% of the total marine component and the absence of foraminifer Zone FC2B2 (Van Leeuwen, 2002).

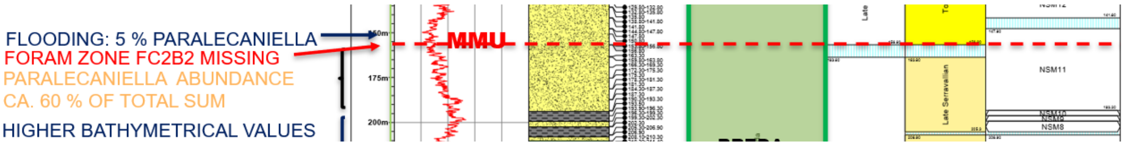

Figure 14: Section of borehole Groote Heide (Venlo Block), emphasizing the MMU at the end of the coarsening upward sequence at the Serravallian-Tortonian boundary (top Zone SNSM11)

The variable regional observations of the MMU interval as described in Munsterman et al. (2019) relate to the proximal-distal position in the basin and indicate that the MMU is a local expression of coinciding tectonic and/or climatic events in between a MFS (Zone SNSM 7/8; roughly mid-Serravallian in age) and a MRS (top Zone SNSM 11; roughly at the Serravallian/Tortonian boundary).

6 References

Dale, B., 1996.
Dinoflagellate cyst ecology: modeling and geological applications, In: Jansonius, J. and McGregor, D.C. (eds), Palynology: principles and applications; *Am. Ass. Strat. Palynol. Found. (3): 1249 – 1275.*

De Bruin, G., Geel, K., Houben, A., Munsterman, D.K., Verweij, H., Smit, J., Janssen, N., Kerstholt-Boegehold, S.J., and Vandeweijer, V., 2015.
MMU. Unraveling the stratigraphy and structural development of the strata found underneath and above the Mid-Miocene Unconformity. *TNO report 2015 R10425.*

De Schepper, S., Beck, K.M., Mangerud, G., 2017.
Late Neogene dinoflagellate cyst and acritarch biostratigraphy for Ocean Drilling Program Hole 642B, Norwegian Sea. Rev. *Palaeobot. Palynol.236, 12–32. https://doi .org /10 .1016 /j .revpalbo .2016 .08 .005.*

Deckers, J., Vandenberghe, N., Lanckacker, T., De Koninck, R., 2016.
The Pyrenean inversion phase in northern Belgium: a relaxation inversion phase? *International Journal of Earth Sciences, 105, 583-593.* http://link.springer.com/article/10.1007%2Fs00531-015-1189-8.

Deckers, J. and Louwye, S., 2020.
Late Miocene increase in sediment accommodation rates in the southern North Sea Basin. *Geological Journal 55.1: 728-736.*

Deckers, J. and Munsterman, D.K., 2020.
Middle Miocene depositional evolution of the central Roer Valley Rift System. Geological Journal 55(9): 6188-6197. https://doi.org/10.1002/gj.3799.

Dèzes, P., Schmid, S. M., & Ziegler, P. A., 2004.
Evolution of the European Cenozoic Rift System: interaction of the Alpine and Pyrenean orogens with their foreland lithosphere. *Tectonophysics, 389(1-2): 1-33.*

Donders, T.H., Weijers, J.W.H., Munsterman, D.K. Kloosterboer-van Hoeve, M.L. Buckles, L. Pancost, R.D. Sinninghe Damsté, J.S., Brinkhuis, H., 2009
Strong climate coupling of terrestrial and marine environments in the Miocene of northwest Europe. *Earth and Planetary Science Letters 281 (2009): 215-225*

Dybkjaer, K., Piasecki, S. (2010).
Neogene dinocyst zonation for the eastern North Sea Basin, Denmark. *Review of Palaeobotany and Palynology* 161, 1-29.

Dybkjaer, K., Rasmussen, Śliwińska, K.K., Esbensen, K.H., Matthiessen, A., 2018.
A palynofacies study of past fluvio-deltaic and shelf environments, the Oligocene-Miocene succession, North Sea Basin: A reference dataset for similar Cenozoic systems. *Marine and Petroleum Geology, 100: 111-147.*

Fensome, R.A., Williams, G.L., and MacRae, R.A., 2019.
The Lentin and Williams Index of fossil dinoflagellate cysts. *AASP Contribution Series, 50: 1173 pp.*

Geluk, M.C., 1990.
The Cenozoic Roer Valley Graben, southern Netherlands. Mededelingen Rijks Geologische Dienst 44(4): 63-72.

Geluk, M. C., Duin, E. T., Dusar, M., Rijkers, R. H. B., van den Berg, M. W., & van Rooijen, P., 1994.
Stratigraphy and tectonics of the Roer Valley Graben-Geo. *Geologie en Mijnbouw, 73: 129.*

Hager, H. 1966.
Das Braunkohlenvorkommen. Geologische und bergbauliche Übersicht des rheinischen Braunkohlenreviers. *Broschüre Tagung der deutschen Geologisches Gesellschaft in Köln. Krefeld: 11-13.*

Hager, H., 1968.
Zur Gleichstellung und Genese der Flöze im rheinischer Braunkohlenrevier. *Fortschritte in der Geologie von Rheinland und Westfalen, 16: 73-84.*

Huhn, B. , Utescher, T., Ashraf, A.R., Mosbrugger, V., 1997.
The peat-forming vegetation in the Middle Miocene Lower Rhine Embayment, an analysis based on palynological data. *Mededelingen Nederlands Instituut voor Toegepaste Geowetenschappen TNO 58: 211–218.*

Janssen, N. en Dammers, G. , 2008.
Sample processing for pre-Quaternary palynology. *Internal TNO report, May 2008.*

Klett, M., Eichhorst, F. & Schäfer, A., 2002.
Facies interpretation from well logs applied to the Tertiary Lower Rhine Basin fill. In: Schäfer, A. & Siehl, A. (eds): Rift tectonics and syngenetic sedimentation – the Cenozoic Lower Rhine Graben and related structures. Netherlands Journal of Geosciences 81(2): 167– 76.

Knox, R.W.O'B., Bosch, J.H.A., Rasmussen, E.S., Heilmann-Clausen, C., Hiss, M., De Lugt, I.R., Kasińksi, J., King, C., Köthe, A., Słodkowska, B., Standke, G. & Vandenberghe, N., 2010.
Cenozoic. *In Doornenbal, J.C. & Stevenson, A.G. (eds), Petroleum geological atlas of the Southern Permian Basin area. EAGE Publications B.V.: 211-223.*

Köthe, A., 2003.
Dinozysten-Zonierung im Tertiär Norddeutschlands, *Revue Paleobiologie, 22(2): 895-923.*

Köthe, A., 2007.
Cenozoic biostratigraphy from the German North Sea sector (G-11-1 borehole, dinoflagellate cysts, calcareous nannoplankton). *Z.dt.Ges.Geowiss., 158/2:287-327*.

Kuhlmann, G., Langereis, C.G., Munsterman, D.K., Van Leeuwen, R.-J., Verreussel, R., Meulenkamp, J.E. and Wong, Th.E., 2006.
Chronostratigraphy of Late Neogene sediments in the southern North Sea Basin and paleoenvironmental interpretations. *Palaeogeography, Paleoclimatology, Palaeoecology* 239: 426-455.

Larsson, L.M., Dybkjaer, K., Rasmussen E.S., Piasecki, S., Utescher, T., and Vajda, V. S., 2011.
Miocene climate evolution of northern Europe: A palynological investigation from Denmark. *Palaeogeography, Paleoclimatology, Palaeoecology 309*: 161-175.

Louwye, S., 2002.
Dinoflagellate cyst biostratigraphy of the Upper Miocene Deurne Sands (Diest Formation) of northern Belgium, southern North Sea Basin. *Geol. J. 37: 55-67.*

Louwye, S., 2005.
The Early and Middle Miocene transgression at the southern border of the North Sea Basin (northern Belgium). *Geological Journal, 40: 441-456.*

Louwye, S. and Laga, P., 2008.
Dinoflagellate cyst stratigraphy and palaeoenvironment of the marginal marine Middle and Upper Miocene of the eastern Campine area , northern Belgium (southern North Sea Basin). *Geological Journal 43, 75–94.*

Louwye, S. and De Schepper, S., 2010.
The Miocene–Pliocene hiatus in the southern North Sea Basin (northern Belgium) revealed by dinoflagellate cysts. *Geological Magazine, 147, 760–776.*

Louwye, S., Marquet, R., Bosselaers, M. & Lambert, O., 2010.
Stratigraphy of an Early-Middle Miocene sequence near Antwerp in northern Belgium (southern North Sea Basin). *Geologica Belgica 13: 269-284.*

Louwye, S., Deckers, J., Verhaegen, J., Adriaens, J. & Vandenberghe, N., 2020.
A review of the lower and middle Miocene of northern Belgium. *Geologica Belgica 23/3-4: 137-156*. Https://doi.org/10.20341/gb.2020.010.

Mosbrugger, V., Gee, C.T., Belz, G., Ashraf, A.R., 2022.
Three-dimensional reconstruction of an in-situ Miocene peat forest from the Lower Rhine Embayment, northwestern Germany—new methods in palaeovegetation analysis. *Palaeogeography, Palaeoclimatology, Palaeoecology, 110 (3–4): 295-317.*

Mosbrugger, V., Utescher, T., & Dilcher, D. L., 2005.
Cenozoic continental climatic evolution of Central Europe. Proceedings of the National Academy of Sciences, 102(42): 14964-14969.

Munsterman, 2001.
Borehole Groote Heide (58F0064): the lectostratotype section for the Breda (Groote Heide) Formation. *TNO report*

Munsterman, D.K. & Brinkhuis, H., 2004.
A southern North Sea Miocene dinoflagellate cyst zonation. *Netherlands Journ. Geosc. 83 (4): 267-285.*

Munsterman, D.K., Ten Veen, J.H., Menkovic, A., Deckers, J., Witmans, N., Verhaegen, J., Kerstholt-Boegehold, S.J., Van de Ven, T. and Busschers, F., 2019.
An updated and revised stratigraphic framework for the Miocene and earliest Pliocene strata of the Roer Valley Graben and adjacent blocks. *Netherlands Journal of Geosciences, Volume 98, e8. Https://doi.org/10.1017/njg.2019.10.*

Munsterman, D.K., and Deckers, J., 2020.
The Oligocene/Miocene boundary in the ON-Mol-1 and Weelde boreholes along the southern margin of the North Sea Basin, Belgium. *Geologica Belgica.*

Ogg, J.G., Ogg, G., Gradstein, F.M., 2016.
A Concise Geologic Time Scale, pp. 240.

Powell, A.J., 1992.
Dinoflagellate cysts of the Tertiary System, In: *Powell, A.J., A stratigraphic index of dinoflagellate cysts: 155 – 272.*

Prinz, L., Schäfer, A., McCann T., Utescher T., Lokay P., & Asmus, S., 2017.
Facies analysis and depositional model of the Serravallian-age Neurath Sand, Lower Rhine Basin (W Germany). Netherlands Journal of Geosciences, *Geologie en Mijnbouw, 96 – 3: 211–231.*

Quaijtaal, W., Donders, T.H., Persicoc, D., Louwye, S., 2014.
Characterising the middle Miocene Mi-events in the Eastern North Atlantic realm: A first high-resolution marine palynological record from the Porcupine Basin, *Palaeogeography, Palaeoclimatology, Palaeoecology*, 399: 140-159.

Rasmussen, E. S., 2004.
The interplay between true eustatic sealevel changes, tectonics, and climatical changes: What is the dominating factor in sequence formation of the upper Oligocene–Miocene succession in the eastern North Sea Basin, Denmark? *Global and Planetary Change, 41, 15–30.*

Rasmussen, E.S., Dybkjær, K. and Piasecki, S., 2010.
Lithostratigraphy of the Upper Oligocene – Miocene Succession of Denmark, *Geological Survey of Denmark and Greenland Bulletin 22: pp 92*.

Schäfer, A., Hilger, D., Gross, G. & von der Hocht, F., 1996.
Cyclic sedimentation in Tertiary Lower-Rhine Basin (Germany) – the ‘Liegendrücken’ of the browncoal open-cast Fortuna mine. Sedimentary Geology 103: 229–247.

Schäfer, A., Utescher, T., Mörs, T. 2004.
Stratigraphy of the Cenozoic Lower Rhine Basin, northwestern Germany. *Newsletters in Stratigraphy, 40 (1/2): 73-110.*

Schäfer, A. & Utescher, T., 2014.
Origin, sediment fill, and sequence stratigraphy of the Cenozoic Lower Rhine Basin (Germany) interpreted from well logs. *German Journal of Geoscience, 165: 287-314.* https://doi.org/10.1127/1860-1804/2014/0062.

Schäfer, A., Utescher, T., Klett, M. & Valdivia-Manchego, M., 2005.
The Cenozoic Lower Rhine Basin – rifting, sediment input, and cyclic stratigraphy. *International Journal of Earth Sciences (Geologische Rundschau), 94: 621–639.* Https://doi.org/10.1007/s00531-005-0499-7.

Utescher, T., Mosbrugger, V., and Ashraf, A.R., 2000.
Terrestrial climate evolution in Northwest Germany over the last 25 million years. *Palaios, 15 (2000): 430-449.*

Utescher, T., Bondarenko, O. V., & Mosbrugger, V., 2015.
The Cenozoic Cooling—Continental signals from the Atlantic and Pacific side of Eurasia. *Earth and Planetary Science Letters, 415: 121–133.*

Utescher, T., Bruch, A.A., Micheels, V., Mosbrugger, V. and Popova, S., 2011.
Cenozoic climate gradients in Eurasia — a palaeo-perspective on future climate change? *Palaeogeography, Palaeoclimatology, Palaeoecology, 304: 351–358.*

Utescher, T., Erdei, B., Hably, L., & Mosbrugger, V., 2017.
Late Miocene vegetation of the Pannonian Basin. *Palaeogeography, Palaeoclimatology, Palaeoecology, 467: 131–148.*

Utescher, T., Ashraf, A.R., Kern, A.K., & Mosbrugger, V., 2021.
Diversity patterns in microfloras recovered from Miocene brown coals of the lower Rhine Basin reveal distinct coupling of the structure of the peat-forming vegetation and continental climate variability. *Geological Journal 56: 768-785. DOI: 10.1002/gj.*

Van Leeuwen, R,J., 2000.
De stratigrafie van het Oligoceen en Mioceen op het Venlo Blok: kalkige microfossielen, logs en sequenties. Rapport TNO-NITG 00-16-B.

Wijnker, E., Bor, T. J., Wesselingh, F. P., Munsterman, D. K., Brinkhuis, H., Burger, A. W., & Taverne, N., 2008.
Neogene stratigraphy of the Langenboom locality (Noord-Brabant, the Netherlands). *Netherlands Journal of Geosciences, 87(2): 165-180.*

7 Signature

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on 2023-01-30 12:14:12

Drs. D. Maljers
Research manager

Garzweiler

Samples | Chronostratigraphy | Age | Barren

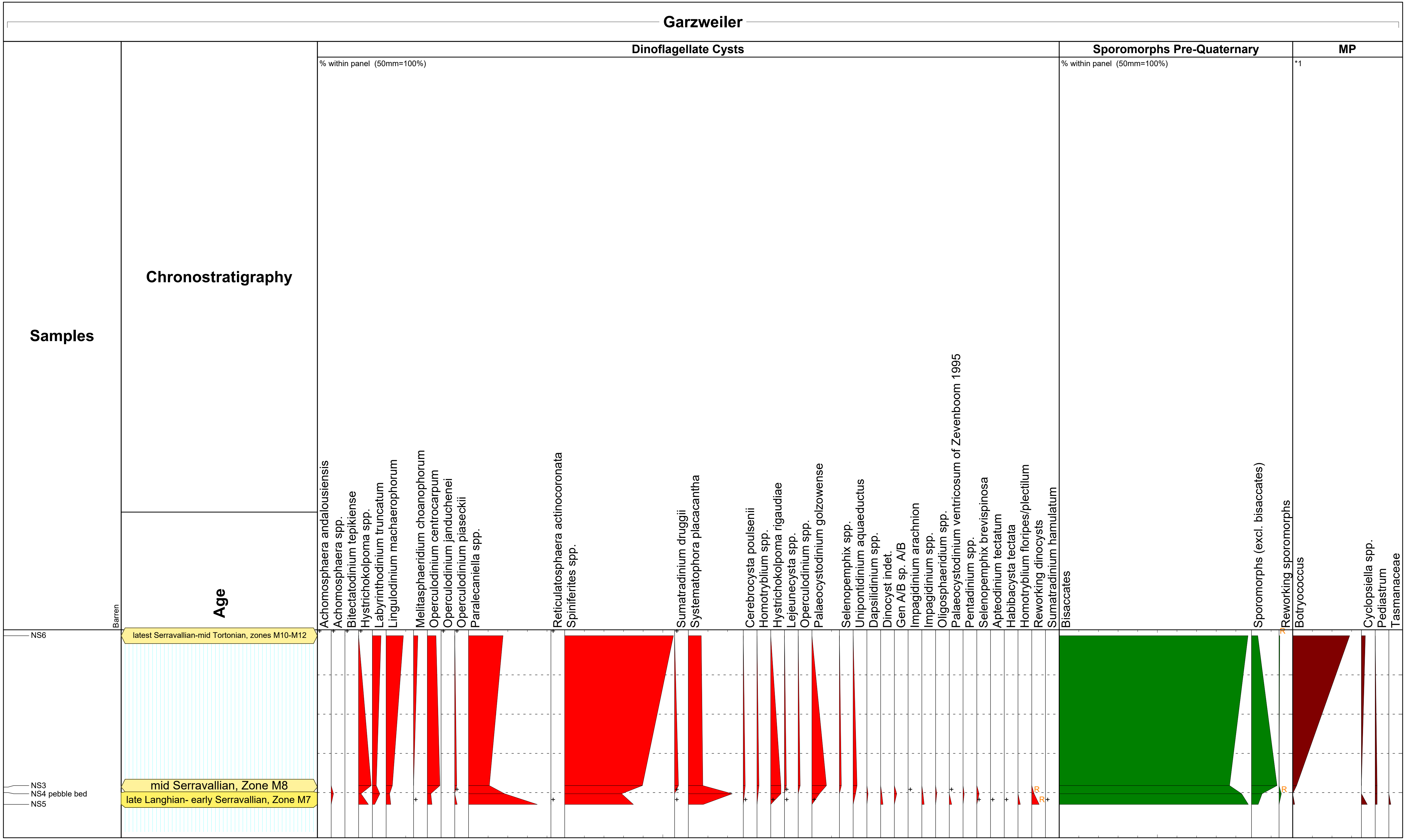
Dinoflagellate Cysts — Absolute abundance

Samples	Age	Achomosphaera andalousiensis	Achomosphaera spp.	Bitectatodinium tepikiense	Hystrichokolpoma spp.	Labyrinthodinium truncatum	Lingulodinium machaerophorum	Melitasphaeridium choanophorum	Operculodinium centrocarpum	Operculodinium janduchenei	Operculodinium piaseckii	Paralecaniella spp.	Reticulatosphaera actinocoronata
NS6	latest Serravallian-mid Tortonian, zones M10-M12	+	+	+	+	2	4	1	2	+	+	8	+
NS3	mid Serravallian, Zone M8				6	2	3		6		1	10	
NS4 pebble bed			2		2	6	3		3		+	28	
NS5	late Langhian- early Serravallian, Zone M7				4	1	2	+	2		1	27	+

Samples	Spiniferites spp.	Sumatradinium druggii	Systematophora placacantha	Cerebrocysta poulsenii	Homotryblium spp.	Hystrichokolpoma rigaudiae	Lejeunecysta spp.	Operculodinium spp.	Palaeocystodinium golzowense	Selenopemphix spp.	Unipontidinium aquaeductus	Dapsilidinium spp.	Dinocyst indet.
NS6	25	+	3										
NS3	37	2	7	1	1	5	1	1	7	1	2		
NS4 pebble bed	44	+	34	1	1	8	+		6		2	1	1
NS5	27	+	6	+		+	+		+				1

Samples	Gen A/B sp. A/B	Impagidinium arachnion	Impagidinium spp.	Oligosphaeridium spp.	Palaeocystodinium ventricosum of Zevenboom 1995	Pentadinium spp.	Selenopemphix brevispinosa	Apteodinium tectatum	Habibacysta tectata	Homotryblium floripes/plectilum	Reworking dinocysts	Sumatradinium hamulatum
NS6												
NS3												
NS4 pebble bed	2	+	1	1	+	1	2				2R	
NS5			1		1		+	+	+	1	3R	+

Samples	SP *1: Bisaccates	SP: Sporomorphs (excl. bisaccates)	SP: Reworking sporomorphs	MP *1: Botryococcus	MP: Cyclopsiella spp.	MP: Pediastrum	MP: Tasmanaceae
NS6	180	6	1R	29	2		
NS3	147	22		2		1	
NS4 pebble bed	150	9	2R			1	
NS5	168	6		1	3	1	1



Garzweiler
Samples
Chronostratigraphy
Age
Barren
Dinoflagellate Cysts
% within panel (50mm=100%)
Sporomorphs Pre-Quaternary
% within panel (50mm=100%)
MP
*1
Achomosphaera andalousiensis
Achomosphaera spp.
Bitectatodinium tepikiense
Hystrichokolpoma spp.
Labyrinthodinium truncatum
Lingulodinium machaerophorum
Melitasphaeridium choanophorum
Operculodinium centrocarpum
Operculodinium janduchenei
Operculodinium piaseckii
Paralecaniella spp.
Reticulatosphaera actinocoronata
Spiniferites spp.
Sumatradinium druggii
Systematophora placacantha
Cerebrocysta poulsenii
Homotryblium spp.
Hystrichokolpoma rigaudiae
Lejeunecysta spp.
Operculodinium spp.
Palaeocystodinium golzowense
Selenopemphix spp.
Unipontidinium aquaeductus
Dapsilidinium spp.
Dinocyst indet.
Gen A/B sp. A/B
Impagidinium arachnion
Impagidinium spp.
Oligosphaeridium spp.
Palaeocystodinium ventricosum of Zevenboom 1995
Pentadinium spp.
Selenopemphix brevispinosa
Apteodinium tectatum
Habibacysta tectata
Homotryblium floripes/plectilum
Reworking dinocysts
Sumatradinium hamulatum
Bisaccates
Sporomorphs (excl. bisaccates)
Reworking sporomorphs
Botryococcus
Cyclopsiella spp.
Pediastrum
Tasmanaceae
NS6
NS3
NS4 pebble bed
NS5
latest Serravallian-mid Tortonian, zones M10-M12
mid Serravallian, Zone M8
late Langhian- early Serravallian, Zone M7