The Maastrichtian type area (Netherlands–Belgium): a synthesis of 250+ years of collecting and ongoing progress in Upper Cretaceous stratigraphy and palaeontology

John W. M. Jagt1*, Leon P. A. M. Claessens2, René H. B. Fraaije3, Elena A. Jagt-Yazykova4, Eric W. A. Mulder5, Anne S. Schulp6,7 and Jonathan J. W. Wallaard3

1Natuurhistorisch Museum Maastricht, De Bosquetplein 6-7, 6211 KJ Maastricht, the Netherlands
2Maastricht Science Programme, Faculty of Science and Engineering, Maastricht University, PO Box 616, 6200 MD Maastricht, the Netherlands
3Oertijdmuseum, Bosscheweg 80, 5283 WB Boxtel, the Netherlands
4Uniwersytet Opolski, Katedra Biosystematyki, ul. Oleska 22, 45-052 Opole, Poland
5Museum Natura Docet, Oldenzaalsestraat 39, 7591 GL Denekamp, the Netherlands
6Naturalis Biodiversity Center, Darwinweg 2, 2333 CR Leiden, the Netherlands
7Utrecht University, Princetonlaan 8A, 3584 CB Utrecht, the Netherlands

*Correspondence: john.jagt@maastricht.nl

Abstract: Cretaceous limestones near Maastricht (SE Netherlands) have been quarried at least since Roman times. In the late eighteenth century, scientific interest developed in their macrofossil content and specimens were illustrated for the first time. Amongst the early discoveries was a partial skull of a large predatory vertebrate that would play an important role in the emergence of modern palaeontology and our understanding of the concept of extinction. After decades of scientific debate, this animal was recognized as a large extinct marine relative of monitor lizards (varanoids) and named *Mosasaurus*. A detailed lithostratigraphy of Upper Cretaceous (Santonian–Maastrichtian) rocks was established in the Maastrichtian type area during the mid-1970s, which resulted in a renewed interest in fossil hunting by professional and amateur palaeontologists alike. During recent decades, both micro- and macrofossils have enabled a refinement of biozonations, correlations within the basin and with sections elsewhere, a greater insight into taphonomic processes and updated taxonomic interpretations. A new age model and chemostratigraphical framework is the most recent addition, permitting the placement of geoheritage in a larger frame and intensifying outreach to the public, including also virtual and augmented reality and hands-on experience to visitors of museum and (disused) quarries alike.

Since the latter half of the eighteenth century, when the first remains of marine reptiles (turtles and mosasaurs) and a range of invertebrates were recognized in the building blocks extracted in subterranean galleries near Maastricht (Fig. 1) and published (Faujas-Saint-Fond 1798–1803), the soft, friable and easily worked limestones in the area have been attracting the attention of scholars and private collectors alike. Taxa illustrated by Faujas-Saint-Fond were given formal Latinized names in the following decades by German, English and French naturalists, including Nathanael Gottfried Leske, Ernst Friedrich von Schlotheim, William Conybeare, August Goldfuss, Gideon Algernon Mantell, Anselme Gaëtan Desmarest and Jean-Baptiste de Lamarck. The coin- ing of the ‘système maestrichtien’ in the summer of 1849 by André Hubert Dumont, the current Maastrichtian Stage, dated between 71.2 and 66.02 Ma, accelerated studies of fossils, which were carried out near-exclusively by local, non-professional pioneers, ‘citizen scientists’ *avant la lettre*, who laid the foundation for later work. When they died, their well-stocked collections, inclusive of type material, were sold off and disappeared abroad. For instance, by auction, the Van Breda Collection, which contained the type femur of the theropod dinosaur, *Betasuchus bredai* (Seeley, 1883), as well as a matrix block with a carapace and plastron of the marine turtle, *Allopleuron hofmanni* (Gray, 1831), in anatomical connection, made its way to the Natural History Museum (London, UK). This ushered in a ‘quiet period’, roughly between 1890 and the early 1960s.

The introduction of a formal lithostratigraphical subdivision for the Upper Cretaceous (Santonian–Maastrichtian) in the mid-1970s (Felder 1975)
brought a new impetus, coupled with extensive collecting by a large group of amateurs at numerous small limestone pits and outcrops that have now all but disappeared or are overgrown. In recent decades, another surge of activity has yielded plenty of new material, including taxa not previously described from the area or new to science. In addition, fossils are being used to ‘paint the larger picture’, backed up by a new age model and chemostratigraphical framework for the type Maastrichtian (Vellekoop et al. 2022) which allow firmer correlations with stratigraphical sections abroad. Museum exhibitions, educational programmes, videos and podcasts can now be better implemented to illustrate the area’s geoheritage. All these offer the public a hands-on experience of a long-gone, warm marine setting teeming with life and cruising mosasaurs at the top of the food chain. Although the Maastrichtian rocks are shallow marine in origin, their fossil record also offers glimpses of the terrestrial environments – isolated dinosaur bones, partial bird skeletons, an odd mammal tooth and washed-in conifer twigs and leaves of other plants. A visit to the historical main Maastrichtian type section quarry, the now inactive ENCI (Eerste Nederlandsche Cement Industrie) open pit, with virtual or augmented reality equipment, provides a powerful additional educational element.

Below, a brief overview of the palaeogeographical–stratigraphical setting will be presented, followed by a summary of recent finds, of both invertebrate and vertebrate biota, plus plants and ichnofossil suites. Added to that is a short list of activities developed at our institutions to illustrate the geoheritage of the Maastrichtian type area, and an outline of future plans.

**Geographical and stratigraphical setting**

The extended type area of the Maastrichtian Stage comprises the area between Maastricht (Netherlands), Liège (Belgium) and Aachen (Germany; Fig. 1), with outliers towards the SE on the Ardennes Plateau (Hautes Fagnes) in NE Belgium (Bless et al. 1991). During the Santonian to Maastrichtian, when this area was situated at a palaeolatitude of approximately 40°N (Voigt et al. 2008; https://www.paleolatitude.org), both siliciclastic and carbonate strata were laid down. Deposition was periodically influenced by local tectonics (Bless et al. 1987; Felder 1996, 2001), which resulted in marked facies changes over short distances of less than 25 km (Felder and Bless 1989; Felder and Jagt 1998). Estimates of palaeowater depth on these generally flat-lying shelves, during the early Campanian to late Maastrichtian, predominantly based on microfaunal assemblages, vary between c. 150 to less than 10 m (Sprechmann 1981; Bless 1991; Jagt 1999a). There is a clear overall tendency for the depositional setting to become shallower upsection, culminating in hardground
development and bryozoan-, scleractinian- and rudist-rich levels within the upper part of the Maastricht Formation (Meerssen Member), except for the highest portion of the Meerssen Member (Vonhof and Smit 1996) which reflects basin subsidence. Spot occurrences in Germany (see e.g. Voigt 1951) prove that this biocalcarenitic, fossil-rich facies formerly had a much wider distribution, being a marginal facies coeval to the white chalk sea of northern Europe.

A formal lithostratigraphical subdivision of strata outcropping in the area, or penetrated in boreholes, was proposed by Felder (1975) and updated twenty-five years later (Felder and Bosch 2000) (Fig. 2). The sedimentology, flint genesis and ichnofossil assemblages of a part of the sequence were analysed by Zijlstra (1994), while biozonations have relied mostly on calcareous nannoplankton, palynomorphs (including dinoflagellates), benthic foraminifera, ostracods, coleoid cephalopods and inoceramid

**Fig. 2.** Local stratigraphy of the Vaals, Gulpen, Maastricht and Houthem formations (Fm), with all members and horizons (Hz) separating the latter. The Aachen Formation, of middle to late Santonian age, as well as the Kunrade Formation, which is the equivalent of the middle Lanaye to basal Emael members, are not shown here. The numerical ages in the right-hand column are taken from Vellekoop et al. (2022). Abbreviations: K/Pg, Cretaceous–Paleogene boundary; Camp/Mstr, Campanian–Maastrichtian boundary.
The discovery of Cretaceous–Paleogene boundary (K/Pg) strata in the underground galleries of the Geulhemmerberg, close to the former Curfs quarry (Fig. 1), has allowed a better constraint of the type section of the Maastrichtian Stage and a more reliable correlation of overlying lower Danian strata in the Geulhemmerberg, close to the former Curfs quarry (Brinkhuis and Smit 1996). In addition, the provenance of building stone (Vonhof and Smit 1996), can also be used in archaeology, for instance to determine the provenance of building stone (‘Maastricht Stone’) used in Roman villas and medieval churches (Lahaye et al. 2022). Active quarrying for the production of Portland cement and fertilizer at numerous limestone pits across southern Limburg (Netherlands) in the 1970–90s, coupled with a growing number of amateur collectors, has resulted in the current availability of large palaeontological and geological collections, both institutional and private.

Recent advances

In recent decades, revisions of existing museum collections have been complemented with records of newly recovered material. A brief overview of biotic groups dealt with in those studies is presented here.

Plants

In addition to pollen and spores (Kedves and Herngreen 1980), sea grass and other marine plants have been recorded, as well as terrestrial taxa of various kinds (van der Ham et al. 2001, 2003, 2007, 2010, 2017). At some stratigraphical levels within the Gronsveld and Emael members (Maastricht Formation; Fig. 2), there are storm-generated accumulations of sea grass stems and leaves that have smothered (endo)benthic life, including bivalves and starfish (Jagt et al. 2019b).

Invertebrates

Amongst molluscs, ammonites have received ample attention (Kennedy 1987; Jagt and Jagt-Yazykova 2019), inspiring discussions of the survival of some groups (e.g. Baculitidae, Scaphitidae) across the Cretaceous–Paleogene (K/Pg) boundary (Landman et al. 2015). The first sepiid (Hewitt and Jagt 1999), bioimmured gastropod egg capsules (Zatoi et al. 2013), a new type of nautiloid jaw element (Mironenko et al. 2022) and the youngest late Maastrichtian trigoniid bivalves (Jagt et al. 2022) have been recorded as well. An analysis of gastropod diversity across the K/Pg boundary (Vellekoop et al. 2020) has illustrated a rapid recovery phase during the earliest Danian in the area.
Amongst crustaceans, new anomuran and brachyuran taxa have been recorded and the stratigraphical ranges of other species documented in more detail (Collins et al. 1995; Fraaije 2003; Jagt et al. 2010, 2014; Van Bakel et al. 2012; Fraaije et al. 2017). In addition, the youngest cycloid crustacean on record to date has been described from the uppermost Maastricht Formation (Fraaije et al. 2003) and there are new records of another important element of crustacean faunas – cirripedes (Jagt and Collins 1999; Gale 2014; Jagt 2020).

An echinoderm Fossil-Lagerstätte, discovered in the mid-1990s, has provided a glimpse of a population of stalked crinoids, ophiuroids, asteroids and echinoids that was smothered by obrution (Jagt et al. 1998). Subsequent records include new species of sea lily, brittle star, starfish and sea urchin of latest Cretaceous and earliest Paleogene age (Jagt 1999b, 2000a, b, c; Blake and Jagt 2005; Gale and Jagt 2021; Jagt et al. 2021), as well as examples of predation, scavenging and attachments of stalked crinoids to secondary hardgrounds (Jagt et al. 2018).

The calcitic tubes of serpulid worms have also been systematically assessed and their stratigraphical ranges been determined in greater detail, from both biotic and abiotic substrates (Jäger 2005). Brachiopod faunas, including micromorphs, have also been revised and a number of new species been added (Simon 2007a, b, 2011).

Fig. 3. Silicified teleost otoliths (NHMM collections) from the lower Maastricht Formation, including newly described cod and bass taxa. Source: copied with permission from Jagt and Schwarzhans (2022); see also Schwarzhans and Jagt (2021).
Ichnofossils

In recent years, ichnofossil suites of a wide range of morphologies, illustrating both bioerosion and burrowing, have received ample attention (Donovan and Jagt 2004, 2013, 2020; Wisshak et al. 2015, 2019; Donovan et al. 2019). For the first ever record of echinoid-produced burrows from the Maastricht Formation, reference is made to Jagt et al. (2018).

Vertebrates

Interesting additions to the bony fish assemblages of the type Maastrichtian comprise new dercetids (Taverne and Goolaerts 2015; Wallaard et al. 2019), as well as silicified otoliths (Fig. 3) of a range of families of which no skeletal material has yet been recognized, thus providing data on an otherwise unknown assemblage (Schwarzhans and Jagt 2021). Recent work on marine turtles includes a revision of the large, paedomorphic (‘superbaby’) Allopleuron hofmanni and an inventory of other marine turtle species (Mulder 2003; Nolis et al. 2018a, b). Isolated teeth and vertebrae of elasmosaurid plesiosaurs (Mulder et al. 2000; Miedema et al. 2019) are the only remains of these reptiles found in the Maastrichtian. The paucity of elasmosaurs (Schulp 2005), comprising isolated vertebrae and scutes and teeth. Possibly, competition is meagre, comprising only dissociated vertebrae, thoracosaurines (Mulder 1997; Mulder et al. 2000; Miedema et al. 2019), and vertebrae of elasmosaurid plesiosaurs (Mulder et al. 2000; Miedema et al. 2019) are the only remains of these reptiles found in the Maastrichtian type area. The paucity of elasmosaurs (Schulp et al. 2017) may reflect an absence of these sauropterygians in the shallow-marine platform setting of the Late Cretaceous Maastricht ecosystem and be linked to incidental floating-in of decomposing carcasses.

The record of neosuchian crocodiles, inclusive of thoracosaurines (Mulder 1997; Mulder et al. 2016), is meagre, comprising only dissociated vertebrae, limb bones, scutes and teeth. Possibly, competition with larger shark and smaller mosasaur species was too fierce for them to become firmly established at the top of the food chain; this is in need of further study.

As apex predators, mosasaurs invariably attract a lot of attention, and every find of associated remains of individuals generates a lot of publicity, not only on a regional, but also on a national level. To commemorate the discovery in August 1998 of the type specimen of Prognathodon saturator, nicknamed ‘Bèr’ (Dortangs et al. 2002; Fig. 4), even a special beer was brewed. In addition to the discovery and reports of new specimens, the fossils recovered have also yielded palaeobiological insights. For instance, palaeopathologies such as the infected quadrate (Schulp et al. 2006) of the ‘Bemelse’ mosasaur, discovered in the mid-1950s, the bitten snout of ‘Carlo’ (Bastiaans et al. 2020) and the rib fracture in ‘Bèr’ (Schulp et al. 2004), have provided good stories to captivate museum visitors. The same can be applied to experiments in feeding ‘the mechanical mosasaur’ (Schulp 2005), or, how did the durophagous species, Carinodens belgicus (Woodward, 1891), grab and process its prey items? Scratch marks on the enamel of teeth of this particular species illustrate its preference for hard-shelled food (Holwerda et al. 2013). Diving and resource partitioning amongst mosasaurs, reflected in tooth enamel isotopes, have also been documented (Schulp et al. 2013), as have differences in oxygen and carbon isotopes in marine vertebrates such as turtles, mosasaurs and sharks (Van Baal et al. 2013). Non-avian dinosaurs are rare (Jagt et al. 2003; Buffetaut 2009; Madzia et al. 2020), considering that the Maastrichtian type section constitutes a fully marine setting. However, they are not entirely absent, with remains likely introduced through post-mortem transport from shorelines, or via rivers. Remains include more than one species of hadrosaur, as well as a carnivorous form, Betasuchus bredai (Fig. 5). Skeletal remains of avian dinosaurs are even rarer and comprise a new, tooth-bearing Ichthyornis-like taxon and the earliest modern bird known to date, Asteriornis maastrichtensis, which is considered to have been a common ancestor of modern chicken- and duck-like birds, or Galleroanerae (Dyke et al. 2002, 2008; Field et al. 2020; Benito et al. 2022).

A single mammal tooth from the type Maastrichtian, the type specimen of Maastrichtidelphys meurismeti, is featured in the exhibit ‘Meeting your true ancestor’ at the Natuurhistorisch Museum Maastricht. This diminutive tooth had far-reaching implications for palaeobiogeography in suggesting the possibility of a land bridge between North America...

Fig. 4. The holotype of the mosasaur Prognathodon saturator Dortangs et al. 2002, residing in a specially designed ‘Mosaleum’ on the inner square of the Natural History Museum of Maastricht. Source: photograph NHMM/Stefan Graatsma.
and NW Europe during the latest Maastrichtian (Martin et al. 2005).

Conclusions and future outlook

Although more than two and a half centuries of research have elapsed, new taxa and novel data are still being extracted from the (few) remaining outcrops, quarries and existing collections alike. Not only do we now have a better idea of which animal and plant taxa are represented, silification of aragonitic molluscs and teleost otoliths offers a previously unnoted glimpse of trophic structures and taphonomic pathways (Hewitt and Jagt 1999; Schwarzhans and Jagt 2021). Correlations with stratigraphical sections elsewhere in Europe (Denmark, northern Germany, Poland, England and France) and North America are also becoming more detailed, both on chemostratigraphical evidence and key index taxa.

Fig. 5. Reconstruction of the skeleton of the sole carnivorous dinosaur known from the Maastrichtian type area, Betasuchus bredai, by Aart Walen. Source: collections of Oertijdsmuseum Boxtel; photograph by Jonathan Wallaard.

Fig. 6. Jubilee exhibitions in 2012, celebrating the 100th anniversary of the Natural History Museum of Maastricht: (a) on the uppermost Maastrichtian in the Geulhem area; (b) on the temporary loan of fossil material collected in the Maastricht area and now held in natural history collections abroad. Source: graphic design NHMM/Arthur Marks, Maastricht.
amongst foraminifera, dinoflagellates and various groups of macrofossils.

It is fortuitous that Maastricht’s geoheritage values are now being considered in earnest by local societies and museums that organize thematic temporary exhibitions (Fig. 6), as well as by universities. Maastricht University, one of the global top universities under 50 years of age, has incorporated earth science and palaeontology research and education in the Maastricht Science Programme of its recently established Faculty of Science and Engineering (Jagt et al. 2019a), providing another limb to the centuries-old scholarly pursuits in the Upper Cretaceous of Maastricht. The Natural History Museum of Maastricht, the Maastricht Science Programme of Maastricht University, and Natuurmonumenten, the Dutch nature conservancy that has taken on the stewardship of the former ENCI quarry, collaborate through a convenant to ensure proper management, continued research and ongoing public education at the original type section of the ‘système maestrichtien’ of Dumont (1849). The type section of the Maastrichtian Stage (Felder and Bosch 1998), underneath the Lichtenberg farmstead and behind the former main office of the ENCI-Heidelberg Cement Group has the status of a geological monument and is protected. Geological and palaeontological field work will remain possible in the adjacent quarry, but prior permission must be sought via Natuurmonumenten. Its staff members, in collaboration with Maastricht University and the Natural History Museum of Maastricht, will decide in such matters.

For now, visitors can use the staircase on the northern quarry face and follow the path parallel to the former cement plant which leads to chalet d’n Observant where refreshments may be purchased. At a later date, the deeper-lying part of the quarry will also become accessible, depending on safety measures and mating and breeding seasons of local fauna.

Fig. 7. Poster of the ‘Rock Fossils on Tour’ exhibition (http://www.rock-fossils.com), which suffered from COVID-19-related measures and was open to the public for several months only, between February 2020 and January 2021.

Fig. 8. The Science Lab at the Natural History Museum of Maastricht, allowing museum visitors to approach preparators and learn more about their activities. Source: photograph NHMM/Johan Strijkers).
In September 2024, the 175th anniversary of the introduction of the Maastrichtian will be celebrated, to be followed by the ‘Mosasaur Meeting’, the first edition of which was staged at Maastricht in 2003.

Thanks to continued public outreach of the Natural History Museum of Maastricht, new target groups come into contact with palaeontology and palaeontologists, including when the ‘Rock Fossils on Tour’ (http://www.rock-fossils.com) (Fig. 7) exhibit was put up in Maastricht (Thuy et al. 2020). Educational programmes (‘mergellessen’, analysing the fossil content of limestones) at the museums cater for local and/or regional schools, preparation sessions by volunteers and museum staff at the Science Lab (Fig. 8). The so-called Museum Jeugd Universiteit (‘Museum Junior University’), for children aged 8–12, allows subject matters to be covered by professionals in the fields of biology and palaeontology. In addition, recently nationally produced, popular Dinosaur Podcasts by Gijs Rademaker and Maarten van Rossum and thematic issues of the programme ‘Vroege Vogels’ on national television (BNNVARA) help highlight the educational value of geoheritage to a wider audience.

There are more chances to bring geology and palaeontology to the public at large, by organizing city ‘stone walks’, covering themes such as sea level, climate change, extinction, geomorphology, the River Maas as landscape architect and builder and recognition of stone types and their use through the ages (Dusar et al. 2011; Lahaye et al. 2022). Added to that, walks at the now abandoned ENCI quarry (Fig. 9), which is currently managed by Natuurmonumenten, a Dutch nature conservancy, enables the public to experience the quarry in person with a knowledgeable guide, or with virtual/augmented reality equipment. Thus, geoheritage in the type area of the Maastrichtian Stage is very much alive and kicking, and the Natural History Museum of Maastricht, Maastricht University, Natuurmonumenten, local societies and many future generations of citizen scientists can be counted on for an ever-growing understanding of the deep geological history of the Maastrichtian of Dumont, the mosasaur, and so much more.

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