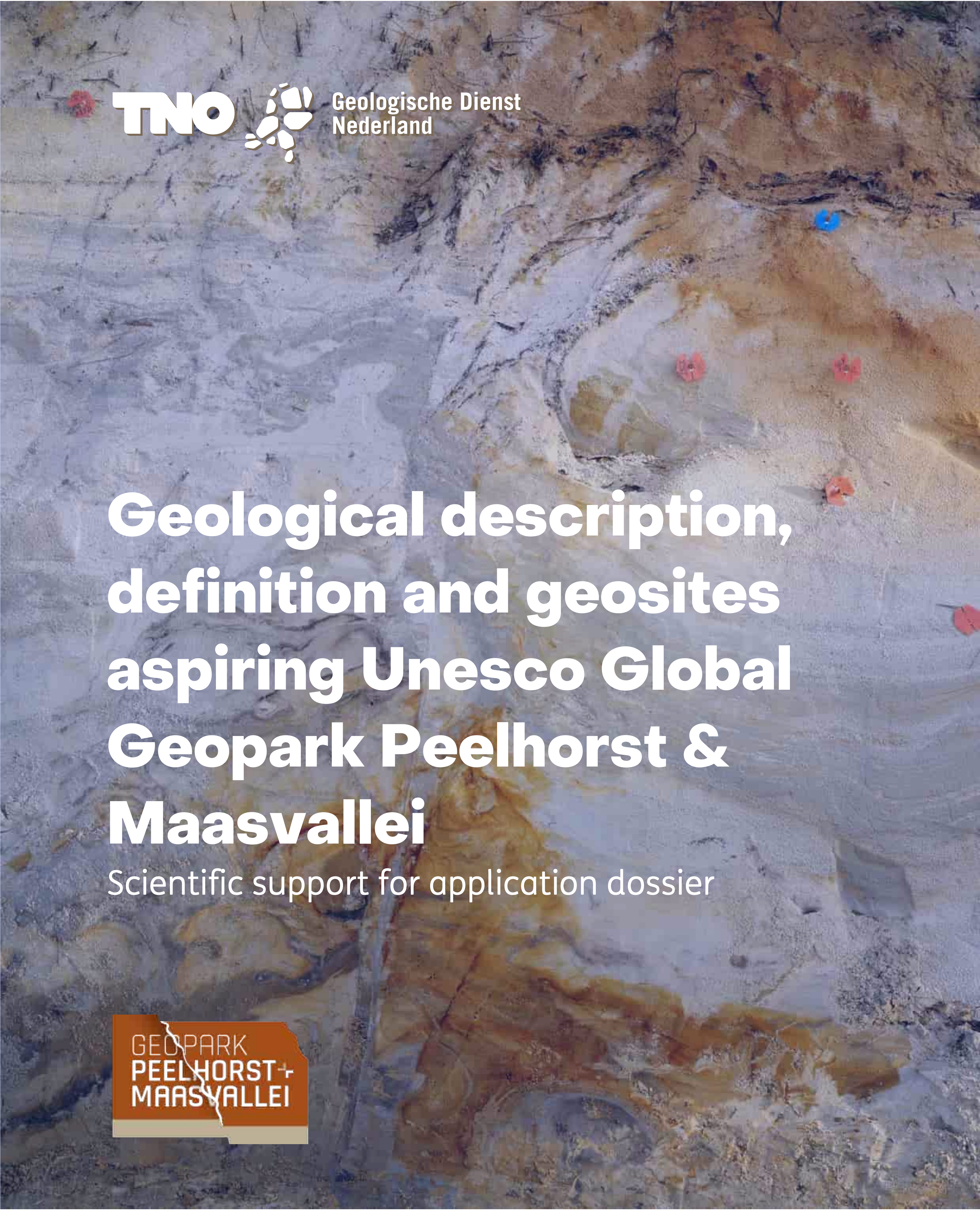

TNO Geologische Dienst Nederland

Geological description, definition and geosites aspiring Unesco Global Geopark Peelhorst & Maasvallei

Scientific support for application dossier

GEOPARK PEELHORST + MAASVALLEI

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Cover: The Peel Boundary Fault with disturbed sediment layers in a research trench near Bakel. (photo: VU – Ronald van Balen)

Contents

Disclaimer

This report includes sections that were originally written in Dutch. This in particular pertains to the Geosite descriptions. For the Dutch-to-English translations the assistance of artificial intelligence (Microsoft Copilot) was used occasionally. While the AI tool was used to enhance efficiency and consistency in translation, all outputs were reviewed by the authors for accuracy and contextual appropriateness. Readers should note that AI-generated translations may not fully capture idiomatic expressions or nuanced meanings inherent in the original Dutch text. The authors bear full responsibility for the final content and interpretations presented.

1 Introduction

In October 2026, the aspiring Geopark Peelhorst and Maasvallei (PHMV) intends to submit an application to obtain the UNESCO Global Geopark status. For this purpose, it is essential that a final boundary for the Geopark area is determined, with at least 40 Geosites included. This must be scientifically substantiated and described. The Steering Committee for PHMV has requested TNO – Geological Survey of the Netherlands (TNO-GDN) to draft both the delineation and description for the Geopark and to characterize 40 selected geosites.
A key requirement is that the scientific description sufficiently underpins the selection of the aspiring UNESCO Global Geopark (aUGGp) area in terms of its international geological significance. This report outlines the choices regarding the boundary, the area's size, and the number of Geosites included within. Furthermore, a comparison is made with Geoparks holding the UNESCO status within a radius of approximately 100 km.

1.1 Reader's Guide

In line with the assignment, this geological description of the Geopark Peelhorst & Maasvallei initially draws upon available scientific literature and reports, such as the Landscape Biography and Field Guide “Breuken in het Land van Peel en Maas”. These sources already describe visible and accessible locations within the Peelhorst & Maasvallei region. The descriptions provided in these sources have been reviewed to ensure they are sufficiently up-to-date and comprehensive, reflecting the latest scientific insights. Where necessary, they have been updated.

For illustrations, existing publications have been used, alongside material available from TNO-GDN (including GIS map data), illustrative material from the provinces of Noord-Brabant and Limburg and local municipalities, as well as freely available sources elsewhere.

The structure of the report partially follows the UNESCO guidelines for preparing the Application Dossier (or bid book, see Figure 1). The first section of the report provides the “General information” (section 2A of the application dossier) and describes the “Name and Identity”, “location and delineation”, the “surface area”, and the “physical and geographical characteristics” of the aUGGP. Key in this description are the geological elements and a plethora of manifestation that, together, shape the storylines of the aUGGp. The second part complies with section 2C (Main geological highlights) and presents a list of the 40 geosites selected. Note that the full description of the geosites is presented as appendix (cf. UNESCO guidelines). The third part of this report will support section 2E of the application dossier (Verification of UGGP criteria) and provides a “General geological description”. Some repetition occurs between this part and the first part on “physical and geographical characteristics”, the context of both descriptions is different, however. The required bibliography (section 3.6) is largely based on a version compiled by the Scientific Board of the aUGGP and supplemented where relevant, but at the moment not yet complete. By following this structure, the report supports the application dossier, but is not meant to be the complete application text as it does not address educational, geo-touristic, and administrative aspects.

With the above in mind, it is important to mention that this report is a data source from which information can be selected for preparation of the application dossier (bid book). In support of that process, the scientific content and terminology presented herein can used directly. It is acknowledged though that language, style, and formulations can subject to adjustments during the various editorial stages of the bid book production.

Some figures in this document are presented as “draft” version. For the time being these should suffice to illustrate the geological description. Later these will be finalized and integrated in the application dossier as part of a follow-up project.

Application Dossier

1. Letter of Intrest
2. Application Dossier (in english).
2.A General information.
2.B Document checklist.
2.C Location of the area.
2.D Main geological highlight and other elements.
2.E Verification of UNESCo Global Geoparks Criteria.
2.F Intrest and Arguments for becoming a UNESCO Global Geopark
3. List of Mandatory Annexes
3.1 Self-evaluation document.
3.2 An additional and separate copy of Section E1.1 "Geological heritage and Conservation".
3.3 An explicit endorsement of any relevant local and regional authorities and a letter of support from the National Commission for UNESCO or the government body in chrge of relations with UNESCO.
3.4 A large scale of map.
3.5 One-page geological and geographic summary.
3.6 Complete bilbliography of the area in Earth Sciecnes highlighting international publications.

Figure 1 – Guidelines for preparation of the AUGGp’s application dossier. The highlighted items are (in part) presented in this report.

2 Name and identity of the aUGGp

Sustainable Harmony: of Faults, Humans, and Rivers

The Geopark Peelhorst and Maasvallei (hereinafter aUGGp) encompasses a unique area that stands out by the intrinsic relationship between faults, waters, rivers, and men, ever since the first inhabitance of the area, several millennia ago. The area connects the provinces of Limburg and North Brabant through a complex fault system that extends from the surface to several kilometres deep. The area considered is within the influence of the Peelrand Fault and the Tegelen Fault and is named after 1) a region uplifted and tilted by fault activity, called the **Peelhorst**, and 2) the **Maasvallei** that crosses the Peelhorst and has been shaped by the continuously changing course of the Meuse river that is closely tied to tectonic movements (Figure 2). Although there have rarely been large and disastrous earthquakes, the aUGGp exhibits many phenomena linked to the presence and activity of faults. These faults, along with the horsts and grabens they delimit, have significantly shaped the landscape.

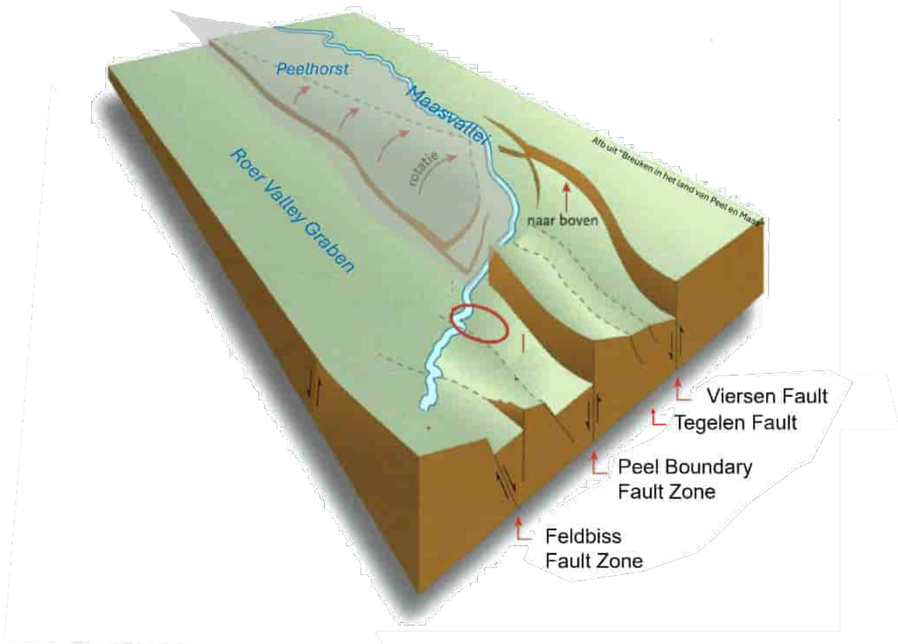

Figure 2 – DRAFT: Artist impression of the geological elements that shape the aUGGP Peelhorst & Maasvallei (shaded area)

The Geopark features several **geological elements** with rare hydrological **phenomena** and significant ecological diversity that are directly associated with faults and fault movements. Often linked to the hydrological situation and the different elevations and soil types are diverse habitats with diverse **flora and fauna**, including special vegetation types and various species of birds, mammals, reptiles, amphibians, and butterflies. This **ecological diversity and the unicity of the ecosystems** sets the Geopark apart from other tectonically elevated areas in the Lower Rhine Graben.

Both geology, (geo)hydrology, peat formation and ecology have led to a unique relationship between humans and nature, which is exemplified by a varied cultural history including a long period of adaptation, a period of landscape exhaust that culminated during the agricultural industrialization and a recent period of sustainable restoration of the landscapes. The

geological elements of the aUGGp contain numerous **geosites** that tell the stories of controlling geological forces and their ever-changing interaction with humans, showcasing the importance of mankind as geological factor in the natural environment as well. The aspiring Geopark should raise visitors' awareness of geology and its relationship with nature and culture and invites them to 'explore and experience" the various **manifestations** related to this relationship. The Geopark Peelhorst and Maasvallei will do so by communicating five inspiring **storylines** that make the geology of the faults, the ensuing unique landscapes and the cultural adaptation and reclamation visible and tangible.

In recent decades, scientific research focused on locating and characterizing the faults and their multivariate influence. Since then, governments and various area partners, residents, businesses, along with researchers, were able to enhance the visibility of the faults. Many hiking and cycling routes have been set out, and information panels have been placed. To make the scientific research accessible, a landscape biography and a practical field guide have been published.

The story of the geopark inspires schools, nature education centers, and organizations such as IVN and local history circles to further disseminate the articulated knowledge. It encourages the tourism sector to offer an interesting stay in Brabant and Limburg, and agricultural entrepreneurs to explore other revenue models and the development of regional products. It will also serve as a solid foundation for the (to be developed) environmental vision and supports the uniqueness of the area. For years, initiatives have been developed by governments, residents, businesses, nature organizations, etc. to further develop the identity of the region as a whole.

Overall, the **Peelhorst & Maasvallei** aspiring geopark has a unique combination of geological, hydrological, ecological, and cultural-historical features that make it outstandingly significant among other tectonically active horst and graben structures in Europe and forms a valuable area for scientific study and conservation. It provides the best way to experience faults by exploring their many spheres of influence. Making the invisible visible, now and in the future.

3 Location and delineation

The aspiring Geopark includes both the Peelhorst and the Maasvallei and is outlined by the Peel Boundary Fault Zone and the River Meuse (Maas) which are intersecting at both the northwestern and southeastern extremities of the aUGGp (Figure 3). The aspiring Geopark is situated in the European Cenozoic Rift System (ECRIS), a large horst and graben system that runs across Western Europe. This Graben system includes the Lower Rhine Graben of which the Roer Valley Rift System (RVRS) in its northwestern reaches is the main tectonic feature. Within the RVRS, the Peelhorst, also known as the Peel Block, is a geologically significant horst located in the southeastern part of the Netherlands, including the eastern part of the provinces of Brabant and the northern part of Limburg. To the west it is bordered by the active Peel Boundary Fault Zone (Peelrand breukzone) that marks the transition to the Roer Valley Graben and is part of the aUGGp as well (Figure 2). The Tegelen Fault delineates the Peelhorst to the east and marks the transition to the Venlo Block (graben). The River Meuse transects the Peelhorst at a right angle and formed the “Maasvallei.” North of where it crosses the Tegelen Fault, the river changes its coarse parallel to the trend of the Venlo Block and gradually shifted northwards. Both the river incision and its northward shift are strongly influenced by tectonic block uplift and -tilting.

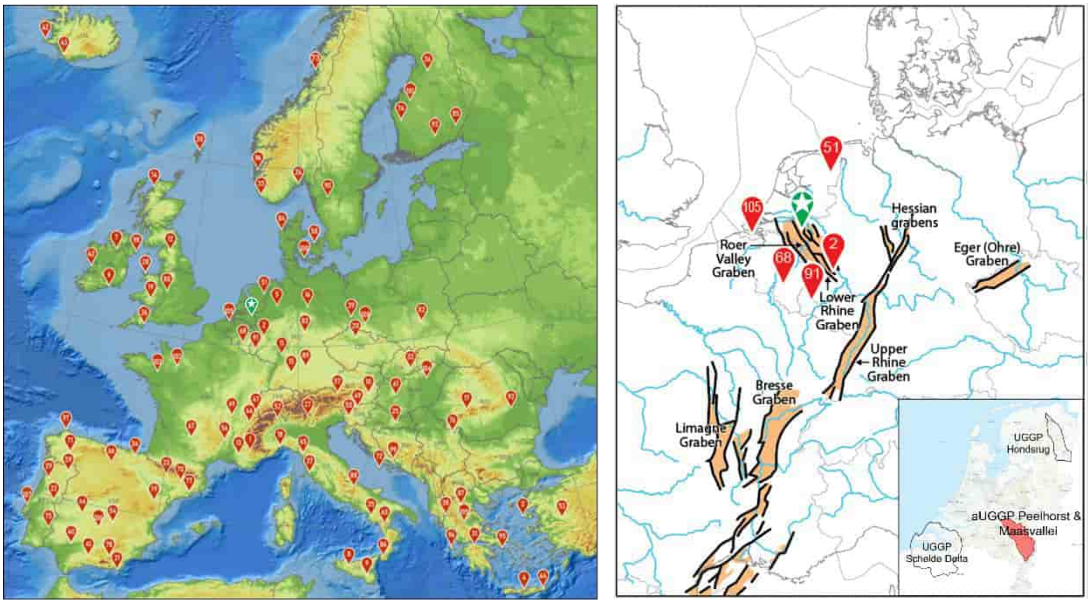

Figure 3 – A) Location of the aUGGP Peelhorst & Maasvallei (green droplet) in relation to other (109) UNESCO Global Geoparks in 28 European countries (source: https://www.europeangeoparks.org). B) Position of the aUGGP within the European Cenozoic Rift System (ECRIS) and relative to nearby Geoparks in the Netherlands, Belgium, and Germany. 2 = Vulkaneifel Geopark; 5 = 51 = De Hondsrug Geopark, 68 = Famenne-Ardenne Geopark (BE), 91 = Geopark Mellerdall; 105 = Schelde Delta Geopark (NL-BE).

3.1 Relationship with surrounding Geoparks

To date, two UNESCO Global Geoparks are present within the Netherlands and one within the bordering country Belgium, i.e. Scheldedelta UGGp, Hondsrug UGGp, and Famenne Ardenne UGGp (Figure 1). The latter, however, is more than 100 km apart

Geopark Scheldedelta in the southwest of the Netherlands is a Netherlands-Belgium cross-border geopark that represents a dynamic estuarine landscape that, over 50 million years, was shaped by subsidence, uplift, sea-level changes, and tidal forces that resulted in sediment-starved lowlands and preserved tidal landscapes. The unicity of the UGGP lies in the more recent interaction between these natural processes, climate change, coastal dynamics, and human impact as a geological force (dikes, waterworks, land reclamation).

Geopark Hondsrug it themed around Ice-age geology and cultural history, with a strong focus on glacial geomorphology and human adaptation. The geopark represents a glacial landscape formed during the Saalian glaciation (~150,000 years ago). It features linear till ridges and ice-age landforms, such as megaflutes, pingo remnants, erratics (boulders from Scandinavia). The UGGp embodies rich archaeological heritage (e.g., hunebeds, prehistoric settlements).

The Famenne-Ardenne Geopark focuses on karst geology, paleoenvironments, and biodiversity, with strong ties to scientific research and tourism. The geopark is characterized by karst landscapes in the Calestienne limestone belt and contains geological formations dating back to the Paleozoic era. The area boasts an exceptional geological heritage, with more karst phenomena (caves, swallow holes, underground rivers) to admire than anywhere else in Europe.

The aUGGp Peelhorst & Maasvallei is themed around tectonic activity, paleoseismology, and fault-induced hydrology. The area is formed by a tectonic fault zone (Peel Boundary Fault Zone) separating the elevated Peelhorst from the subsiding Roer Valley Graben. It is an active fault system with ongoing vertical movement (~5 cm per 1000 years), historical earthquakes (e.g., Roermond 1992) and related tilting of the Peelhorst that significantly influenced the course of the River Meuse. The uniquely manifested geological and hydrological features include “wijstgronden” (iron-rich seepage zones caused by groundwater forced to the surface due to impermeable fault zones), bog iron banks and rust-coloured water streams.

A comparison of the main geological themes and features of the aUGGp’s and surrounding UGGp’s (presented in Table 1) learns that each of them exhibits unique geological features and that the cultural history, related to geology and landscape evolution, consequently is different. The evaluation highlights the Peelhorst & Maasvallei aUGGP as possessing a notably high degree of uniqueness.

Table 1 - Result of a comparison of the aUUGP with surrounding UGGP's

	Peelhorst & Maasvallei aUUGP	Scheldedelta UUGP	Hondsrug UUGP	Famenne-Ardenne UUGP
Geological landscape	• Faults & Rivers	[illegible]	[illegible]	[illegible]
Rivers	• Maas	[illegible]	[illegible]	[illegible]
Faults	• Peelrandbreuk	n.a.	n.a.	[illegible]
Morphology	• Contrast in elevation between uplifted Peelhorst and Roer Valley Graben across the Peel Boundary Faultzone. • River terraces where river Maas transects uplifted Peelhorst	[illegible]		[illegible]
Hydrology	• Wijst (iron-rich seepage)	[illegible]	[illegible]	[illegible]
Biodiversity	• Hoogveen, wijst (wet) • Stuifzand (dry)	[illegible]	[illegible]	[illegible]
Climate control	• Meuse river behavior and course • Drought (present)	[illegible]	[illegible]	[illegible]
Human impact	• Peat extraction and landreclamation affected hydrology significantly. • Former hydrological situation are restored at multiple locations	[illegible]	[illegible]	[illegible]
Human adaptation	• Settlement locations • Agriculture adapted to the reversed hydrology	[illegible]	[illegible]	[illegible]
Land reclamation	• Ditches, canals, and pumping stations used to regulate water levels and reclaim land for peat extraction, drainage, and agricultural development.	[illegible]	[illegible]	[illegible]
Earliest inhabitants	• The edges of the Peelhorst were first inhabited during the late Bronze Age and early Iron Age (1500 BC)	[illegible]	[illegible]	[illegible]
Economics	• Peat extraction • Iron bog • Sand, gravel exploitation	[illegible]	[illegible]	[illegible]
Tourism & Heritage	• Walking and cycling routes with fault and wijst themes • Watermills • Wijst areas • Historical settlements • Old agricultural zones • History of peat extraction • River valley nature parks	[illegible]	[illegible]	[illegible]

[illegible]

[illegible]

4 Surface area

The aUGGp Peelhortst & Maasvallei covers an area of 1.600 km², comprises 14 municipalities and counts more than 500.000 inhabitants. Spread over the area of the aspiring Geopark are 40 identified sites of geological scientific interest (Figure 4).

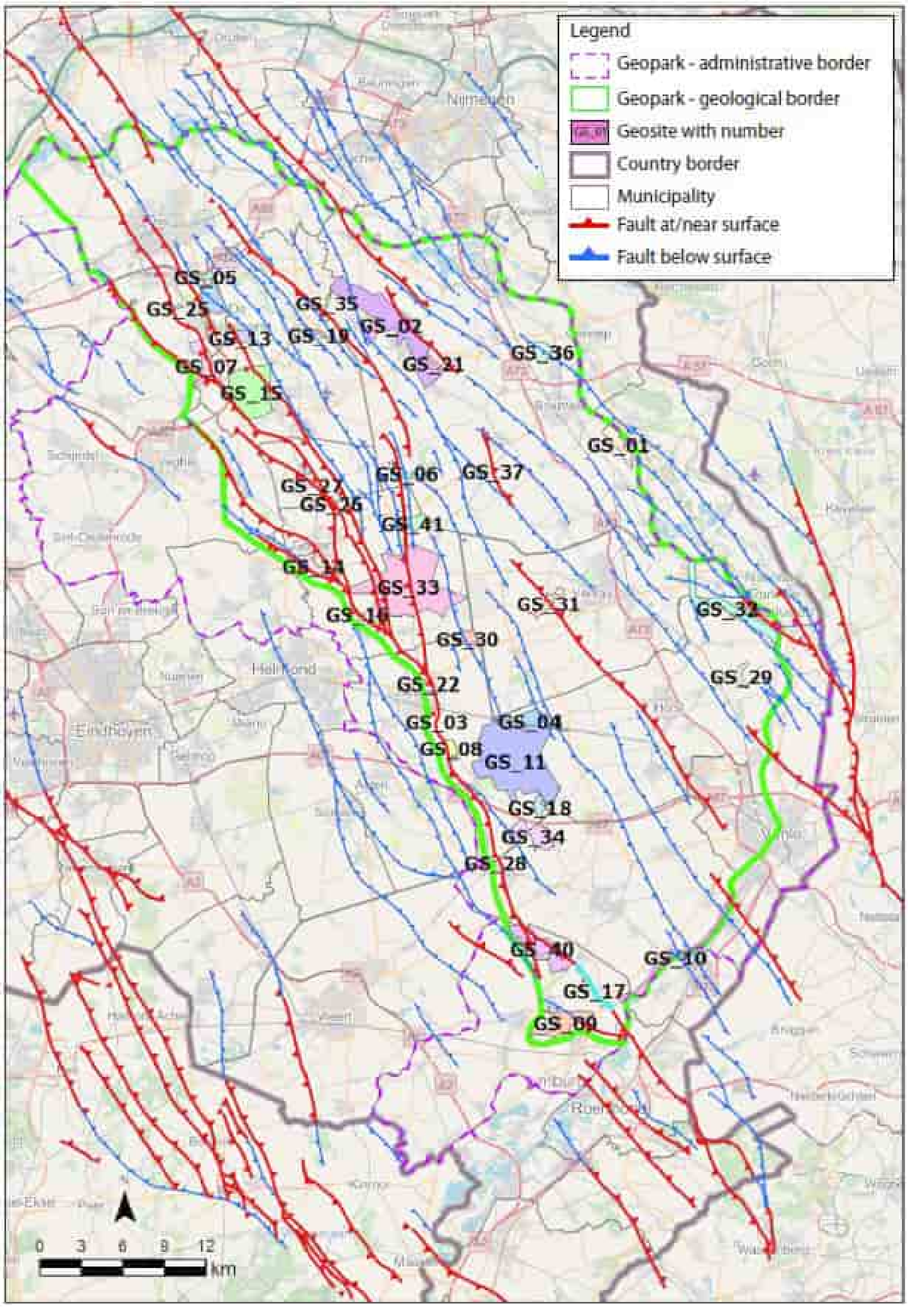

Figure 4 – The delineation of the aUGGP Peelhorst & Maasvallei with its geosites.

5 Physical and geographical characteristics

The **Peelhorst & Maasvallei** encompasses an area with an extensive range of **manifestations**, such as terrain steps, significant differences in hydrology, shifting rivers, and large inaccessible peatlands that all have their bearing on unique flora and fauna and cultural development. For centuries, mankind adapted to this landscape, but the connection of all these phenomena was only poorly understood until 100 years ago. Coal exploration in the Peel during the last century made the subsurface more comprehensible through deep borehole- and later also seismic data. Although the search for coal did not lead to actual exploitation, it made a significant contribution to the geological knowledge of the subsurface. For instance, numerous smaller faults were found in addition to the major faults. Researchers still gratefully use the data collected at that time but also stress that more research is still needed to locate underexplored faults and to elucidate their effect on landscape development as that is not yet fully understood. The main potential of the aUGGp lies in its further utilization as freshwater reservoir during times of climate change, ensuring sufficient water for drinking, agriculture, and nature, making the application of geological knowledge a socially relevant issue for the 21st century and beyond.

5.1 Geological Elements

The Peel Boundary Fault Zone and the Tegelen Fault are the key geological elements of the aUGGp that, through their activity, demonstrate that the geological history of Europe is not limited to large mountain complexes like the Alps, Ardennes, or Eifel. The latter stand out through by presence of all types of hard rocks and prominent tectonics feature that can be observed directly in the field. In the relatively flat Netherlands, the thick pile of unconsolidated sediments (soft rocks) that was deposited over the last ~50 Myr in the delta toward the North Sea, turns out to be fragmented into smaller fault blocks delineated by main faults such as the Peelboundary and the Tegelen Fault zones. These faults, together with the intervening fault blocks and the interactions with the Meuse river, make up the five **geological elements** within the aUGGp, each of which is characterized by a unique combination of geological, hydrological, ecological, and cultural historical phenomena.

5.1.1 Peel Boundary Fault Zone (1)

The Peel Boundary Fault zone is an active fault zone that separates the higher-lying Peelhorst from the sinking Roer Valley Graben. As with many other faults, it is not a single straight line but rather represents a zone with fault segments that at some places merge and at other diverge, leaving an anastomosing fault pattern. Although less visible in the landscape, many of the surficial faults (indicated in red in Figure 18) merge at depths greater than 1 km, resulting in flower-like structures in cross-sectional view. Considering all this, it is difficult to delineate a single Peel Boundary Fault and it is better to refer to it as a zone. The fault branches that are significant as far as manifestation are concerned, are named individually (for example the Milheeze fault), but still belong to the same complex fault zone.

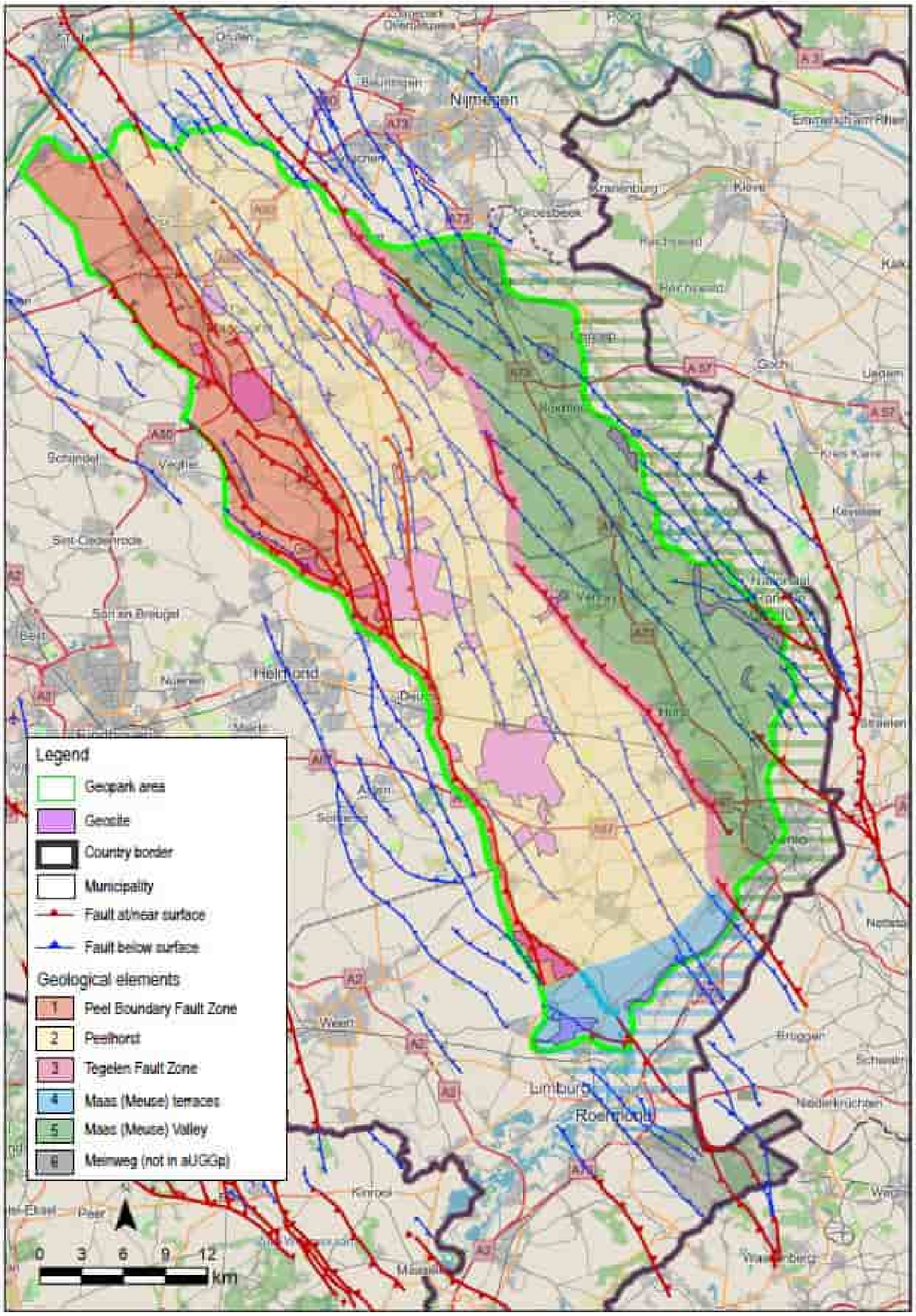

Figure 5 – DRAFT: The five geological element that are the building blocks of the aUGGp. The striped parts of the elements fall outside the aUGGP area. Geological element 6 (Meinweg) is not part of the aUGGP, which is motivated below.

5.1.2 Peelhorst (2)

The Peelhorst is a prominent **geological element** in the aUPPg, characterized by its elevated position relative to the surrounding areas. It is bordered by the Peel Boundary Fault (Peelrandbreuk) and the Tegelen Fault. The faults mark the transition to the subsiding and lower-lying Roer Valley Graben and Venlo Block in the west and east, respectively. The Peelhorst features a unique landscape which is distinct from lower-lying rift grabens and is characterized by a variety of hydrogeologic manifestations and ecological habitats. On the Peelhorst, fine and impermeable, shallow marine, and nearshore sediments from the Miocene (Breda Subgroup) are directly overlain by coarse Maas sediments deposited in a time the river occupied a more westerly position. Because the Peelhorst was continuously uplifted, the Miocene deposist are now close to the surface and form a natural barrier for water to penetrate. Consequently, the Peelhorst turned into a “bathtub” that is typified by poor drainage and high groundwater levels. Conditions that around 4000 BC eventually led to the formation of vast peatlands that used to cover large part of the Peelhorst. The diverse hydrological conditions support a wide range of flora and fauna. The region is home to various species of birds, mammals, reptiles, amphibians, and butterflies, making it an important ecological area. Efforts are ongoing to restore the original peatland ecosystems in the Deurnese & Mariapeel and the Groote Peel. Both are Ramsar international Wetlands and European Natura 2000-regions because of the unique interactions of (geo)hydrological system and the ensuing biosphere.

5.1.3 Tegelen Fault (3)

The Tegelen Fault delimits the Peelhorst to the east. Although terrain steps are not observed along this fault, it is considered to be an active and important fault for several reasons. Foremost, the Tegelen Fault plays a significant role in blocking the transport of water towards the east, i.e. east of the watershed on the Peelhorst. This is exemplified by many spots of iron-rich seepages and numerous streams that run towards the Maas and emerge in the vicinity of the faults. Natural earthquakes have not been prominently associated with the Tegelen Fault. Recent seismic activity linked to this fault was induced by human activities. The felt earthquake of magnitude 1.7 near the Californië geothermal field in 2018 was a result of geothermal operations, specifically the injection of cold water into the fault zone. Additionally, various hiking trails have been established along the Tegelen Fault, such as those offered by the Breukenland Web-App. This app provides an adventurous journey along the Peelrand Fault and Tegelen Fault, where you can listen to fascinating stories about earthquakes, underground waterfalls, and other geological phenomena along the way.

5.1.4 Maas Valley (4)

Whereas the Meuse flows over the Campine Block, the Roer Valley Graben, and the Peelhorst in an orientation more or less perpendicular to the orientation of the tectonic blocks, this changes east of the Tegelen Fault. Here, the Meuse shifts in a north-westerly direction, more or less parallel to the orientation of the Venlo Block, an area that is delineated by the Tegelen fault to the west and the Vierssen Fault to the east.

In this geological element, the river Meuse shows another way of adapting to tectonic influence. Since the last ice age, the Meuse has shifted in a northeasterly direction on the Venlo Block, which is evident in the preferential preservation of river terraces on the western bank of the Meuse. This shift is the result of the tilting of the Venlo Block in a northeasterly direction, a phenomenon that also occurs with the Peelhorst. During the Holocene, there have been an above-average number of shifts in the river channels of the Rhine and Meuse near the Peel Boundary and Tegelen Fault Zones (*Stouthamer and Berendsen, 2001*). Stream valleys developed especially after the Younger Dryas and are representative of the tilt-induced drainage system that sources at the Tegelen Fault and stream into the Maas. The Maas Valley nicely illustrates that faults have great influence on the direction of stream courses. The longer segments of the past and present river courses parallel the main faults, whereas meanders occur as overstep zones from one fault to another.

5.1.5 Maas terraces (5)

Approximately 300,000 years ago, the River Meuse was still located south of the Peel Boundary Fault, in the Roer Valley Graben. Due to lateral displacement towards the northeast, it occupied its current location in the Venlo Slenk for the last 150,000 years. The Maas terraces developed when the River Meuse started its northern course and cut through the uplifting Peelhorst, locally forming up to 15 m high steep cliffs. Consequently, Meuse deposits are found in the subsurface of the entire Geopark. The intersection of the Maas terraces and the Peel Boundary Fault nicely illustrates how faults in soft and unconsolidated sediments have great influence on the direction of streams that, counter intuitively, flow against the northerly current direction of the Meuse. Overall, this reach-to-reach spatial variance in river terrace preservation and morphology can be ascribed to tectonically driven variations in river gradient and subsurface lithology, and to river-driven throughput of sediment supply.

De Meinweg (6) and Eastern Maas terraces - A motivation for exclusion

For the scientific substantiation for the application of UNESCO status, 40 characteristic places (geosites) within the aUGGP must be designated. As this is a relatively limited number, for the selection, a balance is sought between sites of international, national, or regional significance. Furthermore, the uniqueness of a geosite is considered so that the aUGGP has as much variation in manifestations and experience as possible. Both within and outside the aUGGP, there are countless "parels" (gems) that also fall within the theme of the geopark and are well accessible to tourists and recreational visitors and often serve educational purposes. For example, there are about 20 beautiful wijst areas in the Geopark area. Not all these sites are included in the application but are well documented and also included on the gems map (which is a living document).
The aUUGP "Peelhorst & Maasvallei" tells the story of the interaction of faults, rivers, and humans and is delineated and defined by the PBFZ and the Maas. By using these two geologically important boundaries, some valuable areas fall outside the geopark. These are the Meinweg area (municipality of Roerdalen) and the eastern Maas bank (municipalities of Beesel and Swalmen).

<u>Meinweg</u>

National Park De Meinweg lies east of Roermond and is part of the Limburg Maas terraces with a unique terrace landscape. The Meinweg area extends far into Germany (up to Wassenberg), and the border with Germany does not form a geological boundary. The terraces in the area are connected by three steep transitions with a total height difference of 50 meters. These terraces mainly represent high terraces formed by the Rhine, in conjunction with the river Roer and displacement of the PBFZ.

Figure 6 – Landscape form east of the Maas and across the border with Germany.

Perpendicular to these terraces run several brook valleys and rivers. In between are ponds, extensive forests and heathlands, estates, and a varied agricultural landscape. The Limburg Maas terraces not only have rich nature but also a fascinating cultural history. Agriculture has played an important role in this from an early stage. The area has been used communally by surrounding villages for centuries. Today, it is a place where recreation, agriculture, habitation, and nature management go hand in hand.

Nevertheless, the Meinweg area is not included in the aUGGP for the following reasons (listed in decreasing order of relevance):

1. The geological story is more complex than that of Peelhorst and Maasvallei alone.
2. The area extends far into Germany.
3. Many of the manifestations related to geology are not unique compared to the aUGGP.
4. There are currently no national or international participation partners within the Meinweg area.

Eastern Meuse terraces
The part of the eastern Meuse terraces that is part of the municipality of Roermond has a special event in recent history, namely the Roermond earthquake with the epicentre at Herkenbosch. It is worth considering adding this area to the aUGGP because here the direct tectonic influence of the faults on humans was felt and seen. On the other hand, the event is mainly anecdotal, and much stronger earthquakes regularly occur worldwide. Although the earthquake was also felt within the geopark area, the story of the geopark is not so much about earthquakes but rather about faults and their influence on the landscape and how humans deal with them. Adding this area to the base area makes the Geopark story less coherent and also difficult to frame geologically.

The part of the eastern Maas bank that is part of the municipalities of Beesel and Swalmen is characterized by steep terraces and brooks that drain into the Meuse. There are also some fault-related manifestations in this area. At Turfbroek in Asenray (Limburg), the location of the Peel Boundary Fault can be determined quite accurately based on the boundary between green and yellow grass. The presence of the fault also affects the roof structure of a farm there. Despite repeated repairs, the structure continues to crack and subside.

Boukoul is a good example of a castle farm on the PBFZ with a moat fed by seepage water. The Natura-2000 area Swalmdal is located around the Swalm, a meandering brook on the eastern Maas bank that is deeply incised into the Maas terraces landscape. The brook lies at the transition from the plateau between Maas and Rhine to the Maas valley, this transition roughly coincides with the Netherlands-Germany border. At various places at the foot of the terraces, seepage occurs, and springs emerge.

The eastern Maas bank is not included in the aUGGP for the following reasons (listed in decreasing order of relevance):

1. The earthquake story is mainly anecdotal and can also be told/demonstrated within the aUGGP itself.
2. Adding this area makes the Geopark story less coherent and also difficult to frame geologically, as the Peelrand fault extends much further into Germany.
3. There are currently no national or international participation partners from the municipalities of Roermond, Beesel, and Swalmen.

5.2 Storylines

Each of the **geological elements** is characterized by a range of **manifestations** in morphology, soil and/or water conditions, the associated ecology (flora & fauna) and the human interaction that make the long geological history of the area tangible. Six inspiring **storylines** exist at the intersections of the **geological elements** and **manifestations**. The storylines (Figure 7) represent a set of Unique Selling Points compared to UNESCO Global Geoparks worldwide and describe the dynamic, living fault landscape shaped by tectonic activity and its influence on the freshwater system (rivers, streams, groundwater). **Humans** have always played a significant role, either through adaptation or by actively utilizing the opportunities provided by the **geological elements**, thereby also changing them over time. The human impact is visible throughout cultural history and can, at times, be considered a geological factor in its own right.

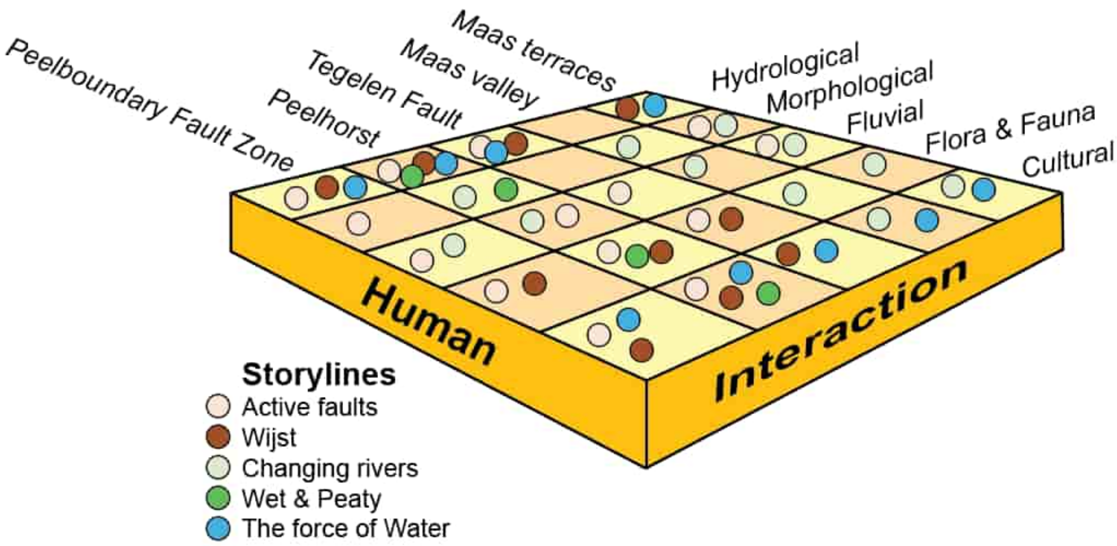

Figure 7 – DRAFT: Storylines of the aspiring Unesco Geopark Peelhorst & Maasvallei

5.2.1 Active faults

The Peelhorst is characterized by significant fault movements along active fault zones that record historic earthquake activity and have geomorphological scarp expressions that remained, despite erosion and human interference. The resulting **terrain steps,** to date, are still visible at many locations and are usually around 1 m in height. Very rarely, fault displacements are accompanied by light to moderate earthquakes. The terrain steps, together with information about the displaced sediment units at the surface (from trench studies) or below the surface (from boreholes and geophysical surveying such as seismic and ground-penetrating radar studies), and hydrological phenomena such as “wijst,” allow to trace the faults through the landscape. The most up-to-date fault pattern is a results of connecting the many “dots” of information, rather than being visible and traceable over lengths of kilometres.

Terrain steps: The total elevation difference at faults grew fairly gradual over the millions years of fault activity. At the fault lines, though, clear terrain steps are visible in several places. The height of these terrain steps varies. In some places, the terrain step is clearly visible. Terrain steps are especially visible where a paved road crosses a fault line. Examples include Scheiweg and Haveltweg (Handel fault), Daalhorst (Gemert-Zuid fault), and Esp (Peelrand fault). If the terrain steps at all the faults are combined, the height difference between the lowest point in the municipality of Gemert-Bakel (12 m above sea level at Esdonk) and the highest point at De Bult in Milheeze (30 m above sea level) is a remarkable 18 m. For reference: the height difference between the North Sea and the municipal boundary is smaller. Terrain steps are most prominent at the 6 active fault lines, but also exist at some inactive fault lines. Due to solifluction phenomena during the ice ages and human interference, many of the original terrain steps may have dissapeared.

Earthquakes: The most famous recent earthquake in the Netherlands is the Roermond earthquake of 1992 (magnitude 5.8), which occurred at a time the Uden earthquake of 1932 (magnitude 5.0) was almost forgotten. The Roermond earthquake remains the strongest earthquake ever recorded in Europe north of the Alps. Therefore, scientists claimed that the Peel Boundary Fault is one of the most important, still active faults in the Lower Rhine region (*Ahorner, 1994*). He also stated that it is an extraordinarily active fault structure by Central European standards, which undoubtedly must be considered a potential earthquake source.
This Roermond earthquake was a significant stimulus for renewed research into fossil earthquakes in the Roer Valley Graben system. Other (historical and prehistoric) earthquakes find their evidence in research trenches over faults that are visible in the landscape as terrain steps.
These trenching studies (e.g. *Van den Berg et al., 2002*; *Van Balen et al., 2019; 2024*) have shown that three to four paleo-earthquakes occurred in the northwestern part of the Peel Boundary Fault Zone. Two of these events took place during the Late Pleniglacial to Late Glacial transition, around 15,000 and 14,000 years ago, with estimated magnitudes of approximately Mw 7. These earthquake were at least 10 times stronger than the Roermond earthquake and involved a fault segment of approximately 35 km. The timing of both events suggest that glacio-isostatic adjustment is the triggering mechanism. A younger earthquake occurred in the Holocene, between approximately 10,000 BP and 800 BP. The recurrence interval of periods with major, surface-rupturing earthquakes is therefore estimated at 10,000 to 15,000 years, depending on location and type of fault activity.
Fluidization of sediment during earthquakes is a well-known phenomenon, caused by ground shaking. This has also been observed in Herkenbosch during the Roermond earthquake of 1992. The presence of fluidized sediment along the fault structure is further evidence that the abrupt fault displacement was the result of an earthquake, rather than a gradual, creeping process.
The most recent recorded earthquake along the Peel Boundary Fault occurred on 9 October 2020 near Sint Odiliënberg, south of Roermond (magnitude 1.2; hypocenter depth 15 km). Just three weeks earlier, two minor quakes (M 1.1 and 2.0) were also recorded in Sint Odiliënberg within the span of an hour (source: https://www.knmi.nl/nederland-nu/seismologie/aardbevingen)

Hydrology: The elevation change across the faults is often accompanied by an abrupt change in the phreatic groundwater levels of up to 1.0 to 2.5 meters due to the impermeability of the fault. This causes iron-rich groundwater seepage at the upthrown side of the fault and the formation of bog iron banks close the fault. The surface water in the surrounding ditches and trenches is often bright orange. Such discoloration is characteristic of wijst, i.e. iron-rich groundwater emerging at fault zones. These hydrological conditions at the fault zones support rare ecological phenomena that are unique in Europe and have been recognized as an internationally significant geological monument.
Due to the seepage and the emergence of numerous streams on the upthrown sides of the fault (the footwall), the downthrown sides of the faultzones (the hanging wall) have been an attractive place for settlement ever since prehistoric times. At present the fault zones are focal points for educational and recreational activities. Various walking and cycling routes, like the

“Breuken Beleven” (Fault Experience) route, allow people to explore and learn about the fault's hydrological and ecological features.

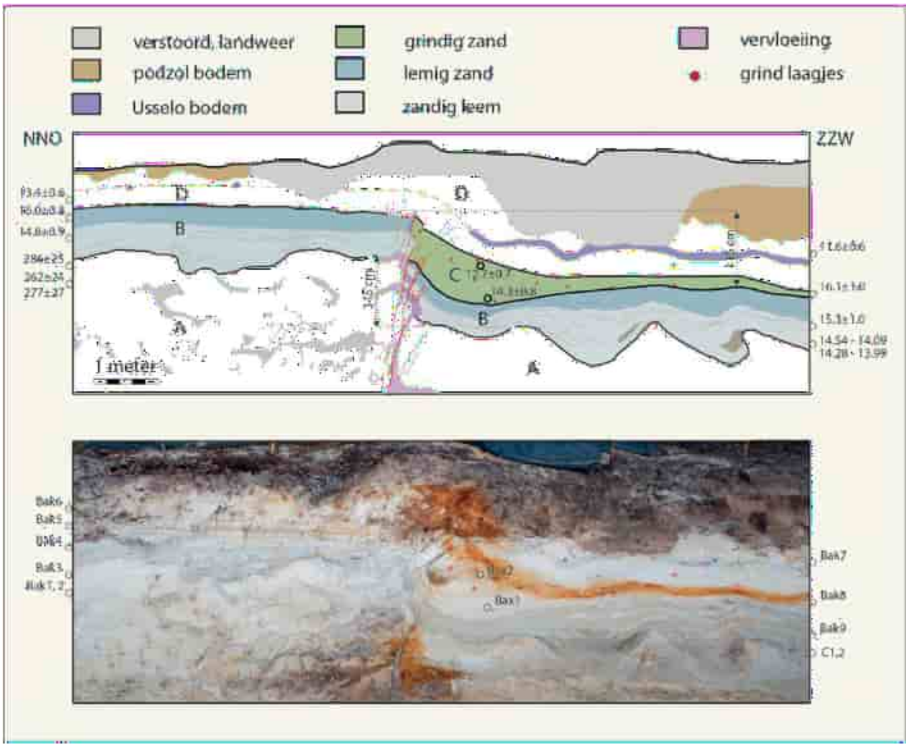

Figure 8 – Photograph and drawing of the east wall of the trench across the Peer Boundary Fault near Bakel, showing the fluidized clayey sediment along the fault plane (modified from Van Balen et al. 2019).

An important observation from the trench studies at Bakel (Van Balen et al., 2019) and Uden, Lapperre et al., 2022) is that clayey sediment is the presence of clayey sediment within the fault structure itself (Figure 8), occurring both along the main fault branch and along several smaller branches. Structures within this sediment indicate that it must have reached its current position from deeper layers while still in a liquid state. This is a significant indication that the abrupt fault displacement is the result of an earthquake and not a gradual, creeping process. Moreover, this clayey sediment in the fault plays a key role in water management, as it enhances horizontal impermeability and thus contributes to the marked groundwater jump around the faults in the southern Netherlands.

5.2.2 Changing Rivers and Streams

Processes in the Earth's crust have had many consequences for the course of rivers in the Geopark area. The Peel Boundary Fault zone has played an exceptional role in this, as relatively large and abrupt shifts have occurred in this narrow fault zone. The Meuse river has had to adapt to these changes in the Earth's crust and landscape. By geological timescale standards, these developments have taken place quite recently. Consequently, research into the Roer Valley Graben System and the Peel Boundary Fault zone has provided much information about the interaction between fault movements, climate change (glaciations) and river dynamics. Much of this interaction is still visible today as elevated Maas terraces, abandoned Maas meanders, and river and stream valleys that flow upstream relative to the main drainage network (Figure 9).

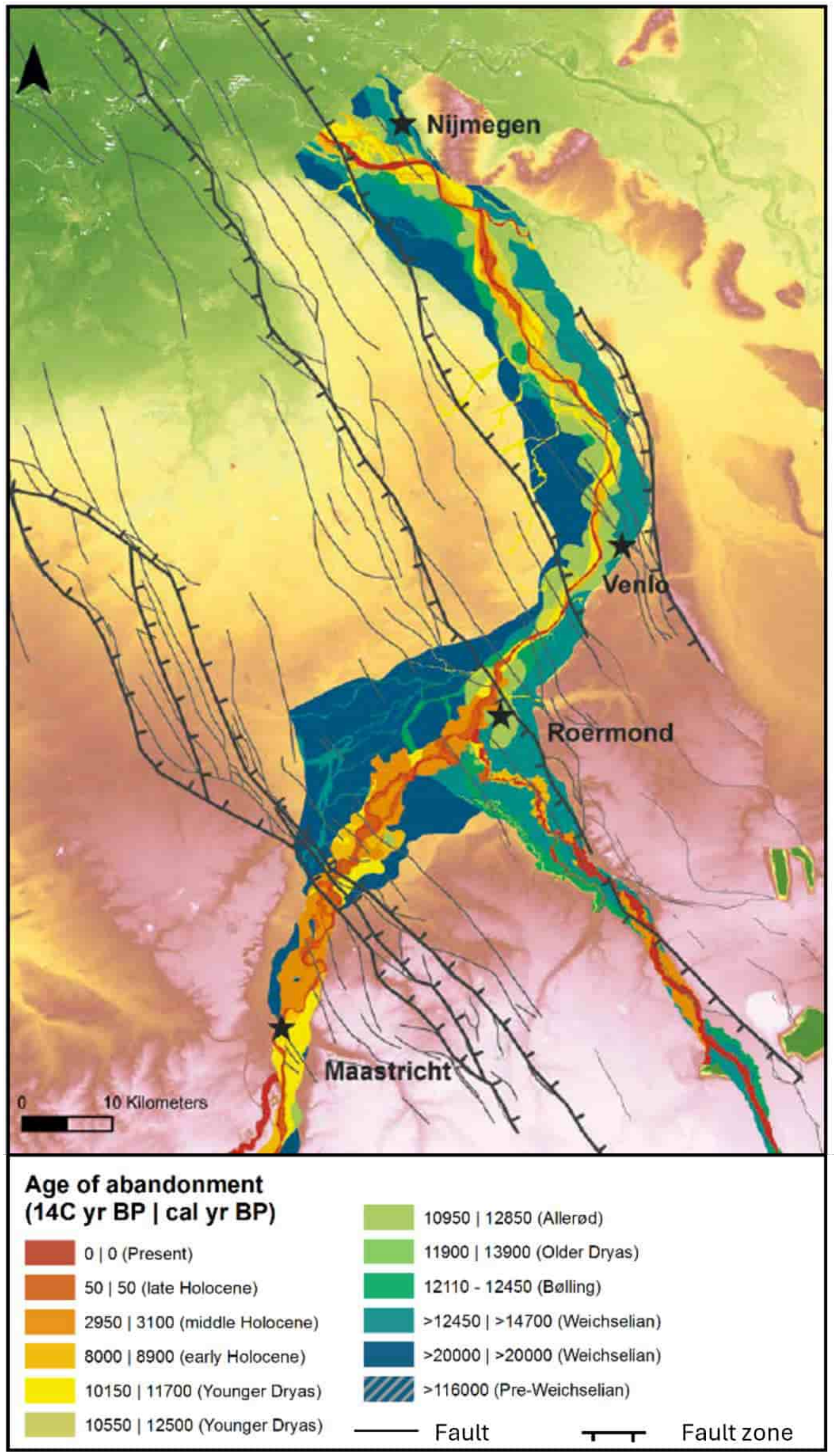

Figure 9 - Map of the Lower Meuse Valley showing the Weichselian and Holocene terraces and stream valleys. The present-day channel of the Meuse is represented by 0 yr BP. Modified from Woolderink et al., 2020 and Woolderink, 2021.

Terraces: As the Ardennes and the Rhenish Massif rose, the river terraces of the Rhine and Maas in Limburg, Belgium, and North Rhine-Westphalia in Germany began to form around 3 million years ago. The terraces were formed as the rivers cut deeper into the landscape, leaving a terrace as a remnant of the old river plain high in the landscape. Due to the continuous subsidence of the Roer Valley Graben system, a substantial sediment package accumulated here, especially in the Roer Valley Graben itself, where the Maas originally flowed. In this graben, and to a lesser extent in the Venlo Graben and on the northern edge of the Kempenhorst, the Rhine and Maas deposited sand and gravel. Around 450,000 years ago, the Rhine shifted to a more northerly position, and the Maas became the main river in the south of the Netherlands. After the Rhine, the Maas also gradually shifted to the northeast over time. This process began with the filling of the Roer Valley Graben, allowing the Maas to shift over the Peelhorst and eventually into the Venlo Graben. The tilting of the Peelhorst towards the northeast caused the Maas to incise into the Peelhorst whereas it lower reaches became gradually shifted eastward, leading to the formation of the northern Maas Valley. By changing the course of the river, the eastward tilt of the Peelhorst influenced local geography and hydrology and became a notable historical feature.
Shifts and tilts due to movements along the Peelrand and Tegelen fault zones have greatly influenced river dynamics. The Maas terraces from the last ice age have been displaced by up to 1.5 meters, and the river course has changed significantly at the fault zones (see Figure 9).

Meanders: The surface movements within the PH&MV area also had a significant impact on the lateral variability of sediment types at or near the subsurface, thereby influencing the course of the Rhine, Meuse, and Roer rivers. Due to the relatively rapid subsidence of the Roer Valley Graben, the Rhine, Meuse, and Roer deposited their coarse, gravelly sediment there for a long time. On the Peelhorst there is a much thinner layer of river sediments; older, fine-grained deposits, such as the Breda Formation, lie near the surface. Thus, sediments of different compositions and ages are found next to each other. This relatively rapid change in the composition of the subsurface around the Peel Boundary Fault has impacted the dynamics of the Meuse at the transition from the Roer Valley Graben to the Peelhorst.
In the Roer Valley Graben, the Meuse meanders through a fairly wide river plain with significant lateral movement. On the Peelhorst, there is a much narrower river plain with an almost straight channel, and the Maas has hardly moved laterally (Figure 9). A key factor in the change in the river's course could be the difference in resistance to erosion. The coarse post Weichselian sediments in the river terraces in the Roer Valley Graben, despite their large grain size, are easier to move due to the lack of cohesion. On the Peelhorst, finer sediments stick together much more, resulting in less material being moved and the river having less opportunity to meander. There is a second reason for the decrease in meandering: As the Peelhorst rises relative to the Roer Valley Graben and the Venlo Graben, the Meuse responds by cutting into the sediment. This leaves less energy for lateral erosion.
The significant impact of faults on river dynamics is also evident from an atypical meander near Roermond, which formed during the beginning of the Allerød (13,900-12,850 years ago). This “abnormal” meander is the result of vertical movements along the Peel Boundary Fault Zone caused by severe earthquakes at the beginning of the Late Glacial (14,700 – 11,700 years ago; Van Balen et al., 2019). As the Peelhorst rose approximately 1 meter relative to the Roer Valley Graben, the bed of the Meuse was displaced by the same amount. Such a sudden displacement of the riverbed has significant consequences for the flow in the river, which affects sedimentation in the river channel and thus also influences the sinuosity of the river. Once this (temporary) obstacle in the Meuse river channel was eroded away, the course of the Meuse could return to its "normal" dynamics.

Streams: A distinctive feature of the Geopark is the vast number of sites where groundwater is pushed to the surface leading to the formation of wet areas and wijst areas. This phenomenon is clearly visible on the Peelhorst in the vicinity of its bounding faults but also at the Maas Terraces. These seepages source the many streams in the area that make use of the terrain steps created by either faults or fluvial incision processes or a combination of the two. Also, the seepage water provides a constant supply of mineral-rich water, contributing to a unique flora and fauna.

5.2.3 Wet & Peaty

The geological structure and history of the Peelhorst have strongly influenced water flow and groundwater levels. During the eastward shift of the Meuse, (relatively) coarse river sediments were deposited on the Peelhorst. Combined with the (relatively) shallow position of marine (poorly permeable) Miocene deposits on the Peelhorst, a unique groundwater system with high groundwater levels established.
In the originally sparsely vegetated landscape of the Peel at the end of the last ice age (Figure 10), the wind created sand dunes that blocked the meltwater valleys, especially at the eastern site of the Peelhorst. As water was unable to penetrate the poorly permeable subsurface, small lakes were formed (e.g. the “Kom van Griendtsveen") that became vegetated as the climate warmed. With this vegetation, peat formation began. Because the soil had been frozen for a long time, few nutrients had been leached out. This led to lush vegetation. The peat that forms in this nutrient-rich environment is called fen peat. Gradually, the vegetation became denser, and forest peat developed. The thickening peat layer made the nutrient-rich groundwater increasingly difficult for plants to access. This eventually ended the formation of fen peat. The high elevation of the Peel also contributed to this process. There seems to be a relationship with the maximum peat distribution and some of the internal faults on the Peelhorst that delineate elongate depressions (minigrabens) that were important for retaining the water and focused the thick accumulaton of peat (see Figure 10Figure 10).

While most fen peat vegetation began to die off during the mid-Holocene (~6000-4000 yrs ago), the environment became suitable for sphagnum moss. Sphagnum thrives in nutrient-poor conditions and retains rainwater well due to its fine branching. Sphagnum mosses secrete acid, which inhibits bacterial growth and thus the decomposition of plant material. With the arrival of sphagnum mosses and acidification, the formation of raised bog peat began. The sphagnum moss areas expanded from the original lakes over the surrounding dry lands. At the peak of peat growth, about 4,000 years ago (Subboreal period, Figure 10), raised bogs with diameters of kilometres formed on the Peelhorst, and the raised bog eventually reached an area of 30,000 hectares. At 1000 BC, the climate became colder and wetter again. These conditions were favourable for renewed expansion of the raised bog, even further than it had during the Subboreal period. This expansion was likely also encouraged by human activity. Since the Iron Age, and especially from the early Middle Ages, many forests were cleared. Numerous villages and hamlets around the Peel owe their names to the felling (“rooijen”) of trees: Castenray, Venray, Tienray, Leveroy, Stramproy, Tungelroy, Wanroy, and Nistelrode all refer to forest clearing (*Joosten, 1991*).

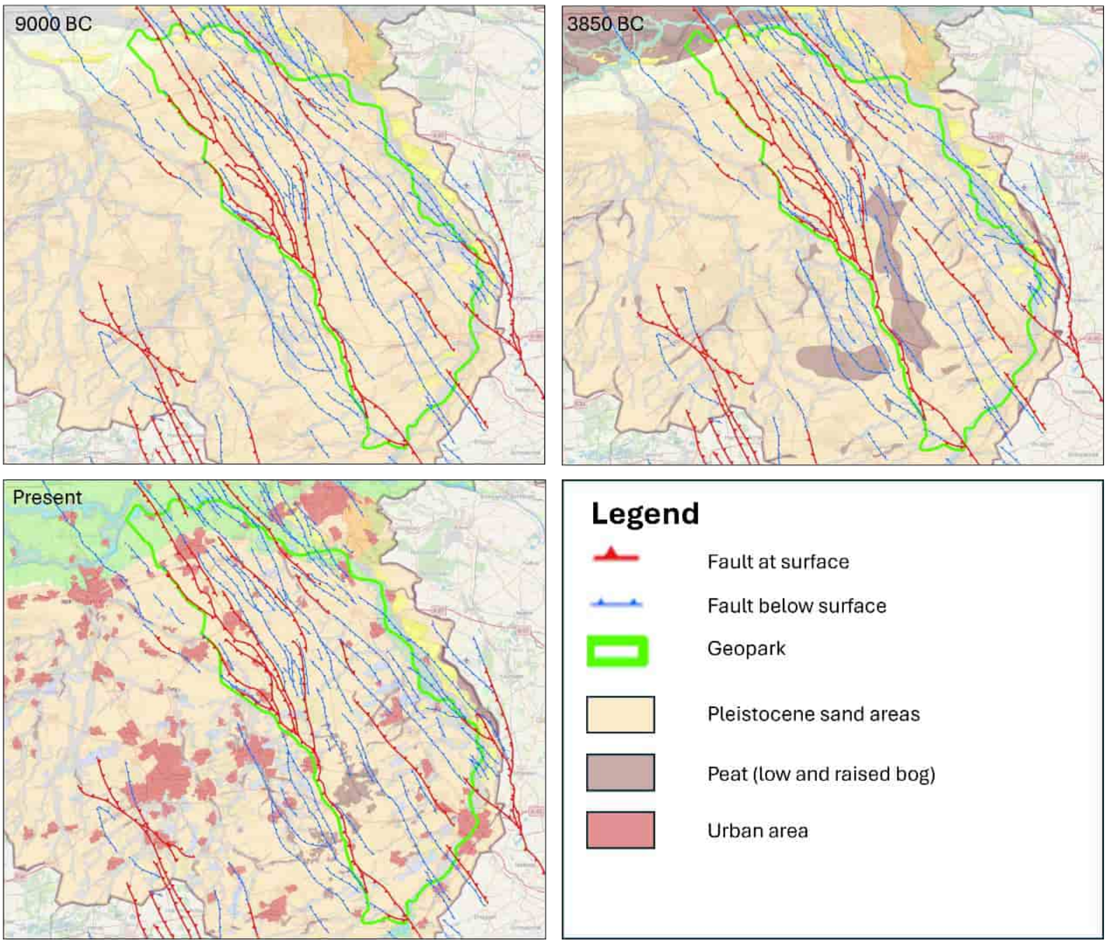

Figure 10 – Peat development in the geopark. At 9000 BC (shortly after the last glacial), no peat had developed; at 3850 the peat had is largest extent; At present, because of the exploitation of bog, only some peat remnants remain. Modified from Vos et al., 2020.

For a long time these wet peat areas were difficult to access but eventually **reclaimed** for the exploitation of bog. Within the aUGGP, the geosite Deurnese Peel and Mariapeel represents an unclaimed area where sphagnum moss remnants are still present. However, sphagnum moss cushions are no longer growing because the Peel has dried out due to intensive drainage and the original extremely nutrient-poor conditions no longer exist. As a result, the decomposition of the peat released nutrients into the groundwater. Additionally, the surrounding livestock farms contribute a lot of nitrogen to the atmosphere and groundwater, making the environment too nutrient-rich for sphagnum moss development.
Restoring wet nature pearls and wijst areas along the main faults along the Peelhorst has received a lot of attention from water boards, provinces, municipalities, and landowners. The past dry summers have shown that it is important to retain water on the high grounds of the Peelhorst. In various places in the large remaining peat areas with a relatively significant thickness, restoration management has successfully led to the development of raised bog vegetation. Dams and weirs are intended to ensure that rainwater remains in the Peel.

To prevent groundwater from seeping away too quickly, the surrounding agricultural businesses and the drinking water companies are allowed to extract limited amounts of groundwater.

Agriculture must also become increasingly sparing with the emission of fertilizers. The measures seem to be having an effect. In the wet peat pits, sphagnum moss is expanding, and the formation of sphagnum peat has begun again. In a few decades, we will know whether the almost disappeared plant communities of the raised bog environment can develop again sustainably.
Through the efforts to restore the original peatland ecosystems in the Deurnsche & Mariapeel and the Groote Peel these areas are now Ramsar international Wetlands and European Natura 2000-regions showcasing the unique interactions of (geo)hydrological system and the ensuing biosphere.

5.2.4 Wijst

On a regional scale, the shallow groundwater and surface water in the geopark generally flows from higher areas such as the Peelhorst to the lower Maas or the Roer Valley Graben. Water also flows from the Limburg river terraces to the Maas. These regional flow directions are intersected by clusters of subsurface faults, such as the Peel Boundary Fault Zone and the Tegelen Fault. These faults have reduced permeability and hinder groundwater flow, affecting surface runoff via ditches, streams, and rivers. This characteristic 'barrier' effect of the underground faults leads to raised water levels at the higher side of the fault, sometimes reaching or even exceeding the ground surface. Across the fault, the water can flow freely again and infiltrate into the predominantly sandy soils of the Roer Valley Graben. This creates an abrupt groundwater jump at faults like the Peel Boundary Fault Zone, comparable to an underground waterfall (Figure 11). An inventory of the jump height has revealed that the groundwater jump is usually 1 to 2.5 meters, although both lower and higher jumps occur as well.
The faults thus form relatively sharp boundaries between a higher side that is often wet and marshy and a lower side that is much drier. This counterintuitive ‘ upside-down world' is a well-known phenomenon of the Brabant and Limburg faults. Those who live high up often suffer from wet feet, while those who live in lower areas remain dry. This is completely different in the rest of the Netherlands, and from a hydrological perspective, the situation along the Peelrand fault is unique.

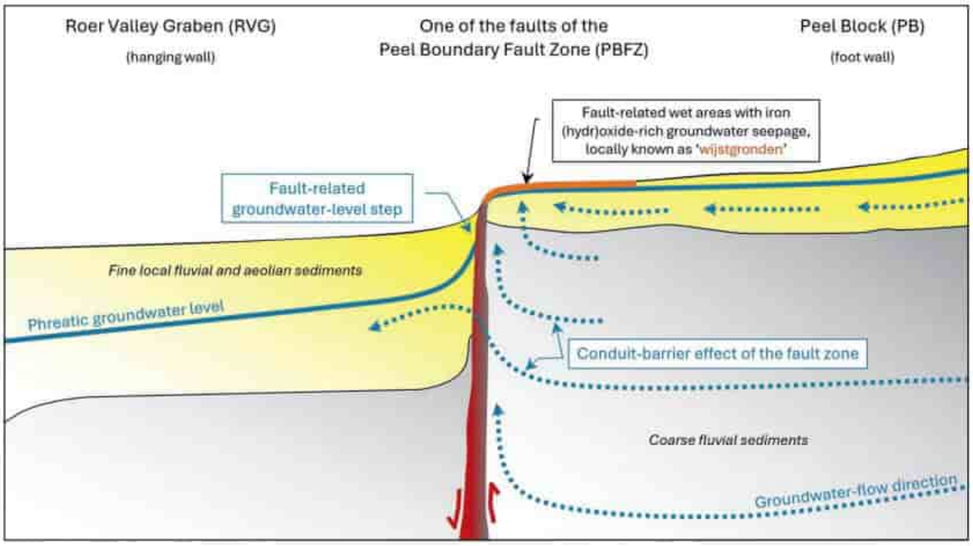

Figure 11 - Schematic representation of the barrier effect of the Peelrand fault zone (in red), its impact on local groundwater flow, and the location of wijst areas fed by iron-rich seepage (modified from *Lapperre, 2025*). Note that similar phenomena occur along faults internal to the Peelhorst and along its eastern boundary (Tegelen Fault) as well.

The water that surfaces at the higher side of the fault contains a lot of dissolved iron derived from glauconite-rich Miocene marine sediments that are relatively close the surface on the elevated Peelhorst. The iron is bound by iron bacteria at the bottom of ditches and in the air through reactions with oxygen, carbon dioxide, and water. The iron compounds give the seepage water a reddish-brown rust color and explain the remarkable coloration of the streams and ditches. The unique relation between of iron-rich seepage and associated faults is referred to as “wijst” and marshy areas as “wijstgronden” and hereafter referred to as wijst areas.
Locally, the iron oxide precipitates in the pore spaces of the coarse sediments close to the fault that, over time, led to cementation of the sediment and formation of **iron ore** banks (bog ore), further reducing permeability. Man has known about the high iron content of the groundwater and surface water in the Peel area for many centuries, and has profited from the bog ore by using it as a building material since Roman times. But the iron ore sometimes hindered the access to suitable drinking water for man and cattle.
The faults that obstruct the groundwater flow are usually difficult to see at the surface. However, if we look closely at specific indicators, the faults reveal themselves through the presence of elongated wijst areas, a jump or slope in the ground surface (a so-called terrain step), watercourses with a strong orange colour, ecological contrasts, and fauna differences in crop growth. The latter occur because plants develop less well in wet and cold soil than in drier and warmer soil. Also, faults and water-related cultural-historical objects are found in more places, such as the iron-containing Wonderbare Bron of Handel and significant references such as the Hooge Wijststraat (in Heesch) and the Roode Beek (Meinweg). When several of these characteristic phenomena occur simultaneously, it provides an additional indication to suspect underground faults. In this way, it is possible to indirectly see what is hidden underground.

Fauna & Flora: Where there is no terrain step, the location of the fault, if undisturbed, can sometimes still be recognized by the presence of seepage flora 'above' the fault, bordered by dry grasslands 'below' the fault. The iron-rich seepage water is typically nutrient-poor to moderately nutrient-rich, soft, and often rich in sulfate. The flora of wijst areas is typically rich in species that thrive in these conditions, such as tufted sedge, marsh ragwort, snakeweed, broad-leaved marsh orchid, and marsh marigold. In the past century, humans have largely drained the wijst areas and used them as grassland. Most of the originally marshy grounds are now characterized by a landscape with ditches, wet hay meadows, alder groves, and small swamp forests. Restoration of wijst, such as at the Sint Annabos area, led to a scenically beautiful alder carr forest on the high side of the fault. On the wet peat under the alders next to ferns and tufted sedges also the water violet grows. The latter is a plant with submerged leaves that occurs in shallow waters in shady areas and is a good indicator of seepage. Also in streams, as well as in pools and fens in the areas surrounding faults, plants typical of seepage areas grow, such as rushes and sedges or species of moist grasslands, such as field sorrel and cuckoo flower. The area around the fault offers birds a wide variety of habitats. Wet and dry, nutrient-rich and nutrient-poor, wooded and open areas lie close together. Among the many different bird species, the rare spotted crake is the most notable.
In most areas on the high side of the fault, the quality of the vegetation has come under pressure due to the increasing nutrient richness due to the rise of artificial fertilizers and intensive farming. Plants like nettle, hogweed, thistle, and reed appeared. This nutrient richness promotes the growth of willows, nettle, hogweed, thistle, and reeds at the expense of alders and tufted sedges. The wijst areas of the Sint Annabos, however, proved that the dissolved iron in the seepage water is able to bind phosphates, retaining the relatively nutrient poor conditions.

5.2.5 The force of Water

The topography caused by fault activity influences the drainage system of streams, rivers, and groundwater. Throughout history, this has sometimes been used beneficially.
Starting from the Middle Ages, water mills and water wells were built in many places (*Bon, 1972*). Their location is often determined by the underground fault system. In places with a fault in the subsurface, the impermeable fault facilitates groundwater seepages that are often the source for streams (brooks) that can be used for the operation of water mills. The strong seepage near the faults provided a more or less constant water supply, while the natural elevation difference in the landscape created additional water-level gradient. The most suitable location for a water mill is on or slightly downstream where a stream crosses a fault. Along the Peelrand fault zone, only one watermill has been preserved: on De Vlier brook in Deurne at Haageind. However, research showed that once there were six more watermills. All known locations are, as expected, situated on the Peel Boundary fault or one of its secondary faults. At the eastern site of the Peelhorst, the water mill in Oploo is situated on the Tegelen fault. The watermill at Neer uses the natural fall of the Neerbeek stream into the Maas
In addition to watermills, the choice of location for castles and terrains surrounded by ditches, often referred to by the English term 'moated site', surprisingly also appears to be related to faults and springs. These castles and moated sites were built in the 13th, 14th, or 15th century as noble residences. Their once existence is partly derived from the presence of a moat. Such a moat was not supposed to dry up in summer and was therefore almost always situated along a brook. In the municipality of Gemert-Bakel, the locations of ten moated sites are known and it turns out that seven of them are located near one of the three existing fault branches of the Peel Boundary Fault Zone. Always on the side of the downthrown block and all within a distance of 100 meters from the fault.
The most intense manifestation of the spring phenomenon was at places that centuries ago were named 'put' (well). These wells were so prominent that everyone knew these places, and for that reason, they were designated as fixed boundary points between villages on the edge of the Peel in the Middle Ages. Just as sources of brooks and rivers often gained religious significance, this was also the case with the so-called Willibrord wells. Saint Willibrord is said to have baptized there. At the border of Deurne and Meijel, we find a Willibrord well, and also at the border of Oss and Heesch. Both wells are associated with a fault. In other places, the spring phenomenon was less intense but still strong enough to be the source of a natural brook. Based on the oldest topographical maps, the natural watercourses can be reconstructed. This has been done for Gemert; ten places have been found where a brook begins. It turns out that all natural watercourses there are sourced from a spring area. In places where a well was present or at the source of a brook, the spring phenomenon was so strong that the water and marshy character dominated, and people were more troubled by the spring than they benefited from it. The advantage of the spring was found in places where the spring was less intense.

5.2.6 The human factor and the landscape

The Peelhorst & Maasvallei aUGGp represents a diverse landscape that is influenced not only by geological forces but also by humans that reclaimed the originally wet and difficult-to-access area. In a country like the Netherlands, where water always shapes the environment, even on the higher sandy grounds, geological history is crucial for our living environment. It serves as a valuable tool in addressing one of this decade's challenges: managing the right amount of water for agriculture, nature, and drinking water
Both faults and rivers have a significant impact on the development of the landscape. This is especially true for the Peelhorst, where the Rhine, Maas, and Peelrand fault contributed to the

formation of the landscape. The Peel, with its extensive, almost impenetrable peatlands for humans, and the Maas to the east and north, formed a border area for hundreds of years. With only a limited number of trade routes over sand ridges, the marshy Peel was well-defensible and an ideal natural border zone. For centuries, territorial boundaries lay here. For the local population, it was an area for peat extraction, and land was reclaimed on a small scale. The mysterious phenomenon of wijst gave rise to stories and legends about miraculous springs. Wijst water was practically used for agriculture, the construction of moats around castles, and the operation of water mills. But sometimes the wijst was so marshy that it simply couldn't be used for agricultural purposes. Especially at the eastern part of the fault zone, the wijst was most intense and disruptive. The unique geology made the area also interesting for the extraction of minerals. In the Peel, iron ore, sand, and gravel were extracted, and even coal was successfully drilled, but never extracted.

Iron ore: The water that surfaces in wijst areas contains a lot of dissolved iron. The iron is bound by iron bacteria at the bottom of ditches and in the air through reactions with oxygen, carbon dioxide, and water. The iron compounds give the wijst water a reddish-brown rust color and the term “rood in de sloot” (red in the ditch) is commonly used to describe the phenomenon. Cementation occurs, and iron ore is formed close to the fault with a variable and complex composition. Either the iron compounds cement the sand on the higher site of the fault as iron-rich wijst water is transported across the fault under influence of the fault-induced slope, or it cements coarse-grained fluvial deposits on the lowerl site of the fault. Both processes occur, explaining the wide distribution of iron ores. In the past, iron ore chunks were extracted for various purposes. The chunks of iron ore were used, among other things, as building material. They are regularly found in the foundations of churches in the region. They were also used for the piers on which the wooden beams of farms were founded. After bricks became affordable, this tradition disappeared. It is notable that iron ore chunks continued to be used in the construction of communal religious structures such as Marian grottos and mounds on which roadside crosses were placed. The ores were also extracted for iron production. Archaeological research has shown that iron production already existed in prehistoric times, based on the findings of charcoal kilns and iron slag (charcoal is produced in charcoal kilns, which is necessary for iron production). The extraction of iron ore remained important in historical times as well. Municipal reports from Deurne and Gemert in the 19th century mention the "export" of iron ore for iron production. The trade in iron ore was more prevalent on the eastern side of the Peelhorst. In the marsh between Wanroy and Rijkevoort, a lot of so-called marsh stone was found, and in 1857 the municipality sold a concession for its extraction. A horse-drawn tram line was constructed to transport the material from this marsh to a depot along the Maas near Beugen, where the iron ore could be shipped.

Peat: Between about 4000-1000 years ago the peat growth reached its greatest extent and from the early Middle Ages (500 – 800 AD) onward the Peelhorst area changed drastically because from then on, peat was extracted on an increasingly large scale. The first historical records of peat extraction in the Peel date from around 1400. The destruction of the last forests around the Peel likely forced people to look for alternative energy sources. Peat extraction was an obvious choice—not only because people in the Netherlands already had experience with it elsewhere, but also because the plaggen agriculture practiced on the sandy soils at the time had already introduced some of the techniques and tools needed for peat cutting (*Joosten, 1995a*). The wild land, where, it was said, wandering lights lured travelers into the swamp, transformed in about a century into an extensive, efficiently organized agricultural area. In the northern part of the Peelhorst, the raised bog had already significantly decreased by the 19th century. In the southern part, large-scale industrial peat extraction began at that time. Until then, the Peel was a large, almost impenetrable, marshy area, resulting in it being not only a natural border but also an administrative and, to some extent, a cultural boundary (*Van den Brand, 1982; Iven and van Gerwen, 1978*). Even in the 1930s, the Peel was so inaccessible that the government considered the area suitable as a natural barrier for the construction of the Peel-Raam Line, a defensive line against a German invasion before WWII. With a canal, casemates, obstacles, and the last remnants of peat, it was hoped in the late thirties to stop or slow down a German invasion close to the border.

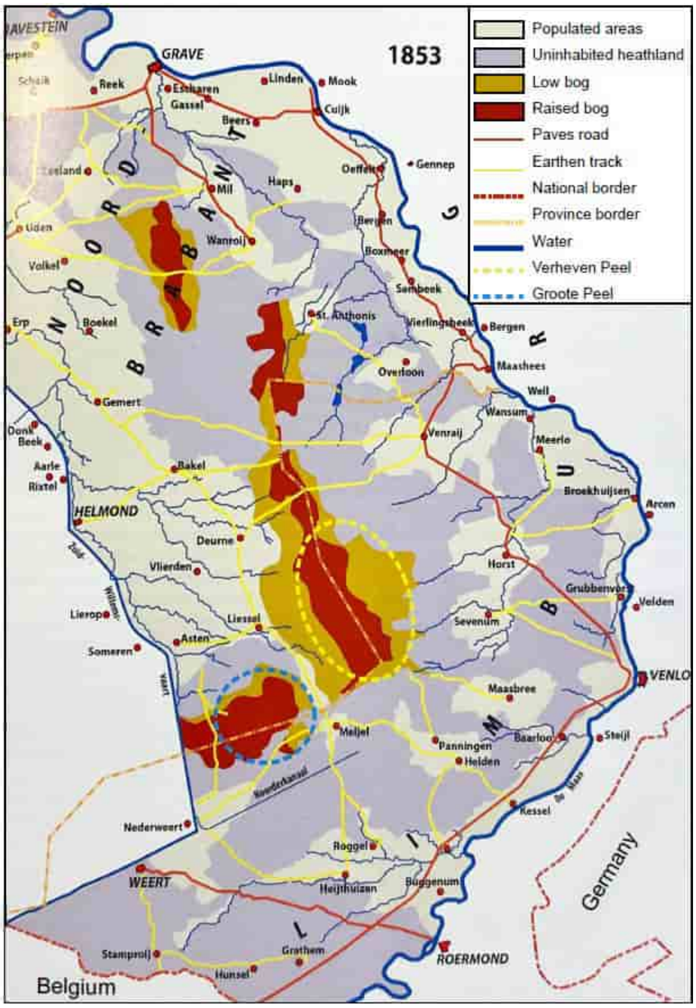

Figure 12 – The situation in 1853, with the old villages around the Peelhorst are indicated. Map originally presented by *Van den Munckhof & Joosten, 1990*

Sand and Gravel

Due to the uplift of the Peel Horst and erosion of younger sediments, Pleistocene, Pliocene, and Miocene sand and gravel formations are relatively close to the surface in this area. In many places on the Peel Horst—such as Milheeze, Zeilberg, Liessel, and Neerkant—extraction has taken place in the past. Most of the sand was and still is extracted from either fluvial deposits of the Beegden and the Kreftenheye Formations which are rich in gravel and coarse sand, or marine deposits of the Breda Subgroup and Kiezeloolite Formation, which are rich in green- and quartz sand, respectively.

The coarse sand is characterized by angular grain shapes. Locally, this sand is referred to as “skèrrep sand” (sharp sand) and is ideal for use as construction material. For road builders, glauconite-bearing sand is a good material; glauconite grains are angular and interlock tightly, a property that makes the green sands particularly suitable for constructing motorway embankments. Sand and gravel extraction has ranged from very small-scale to large-scale commercial operations. The small-scale extraction mainly involved masonry sand and gravel, which was collected in small quantities ‘in the wild’ by farmers, civilians, and contractors at numerous locations. Commercial sand extraction took place in two major concessions on either side of the Peel Horst. At the western side in Hoogdonk near Liessel and on the eastern side at the “De Kuilen” near Langenboom (Figure 13).

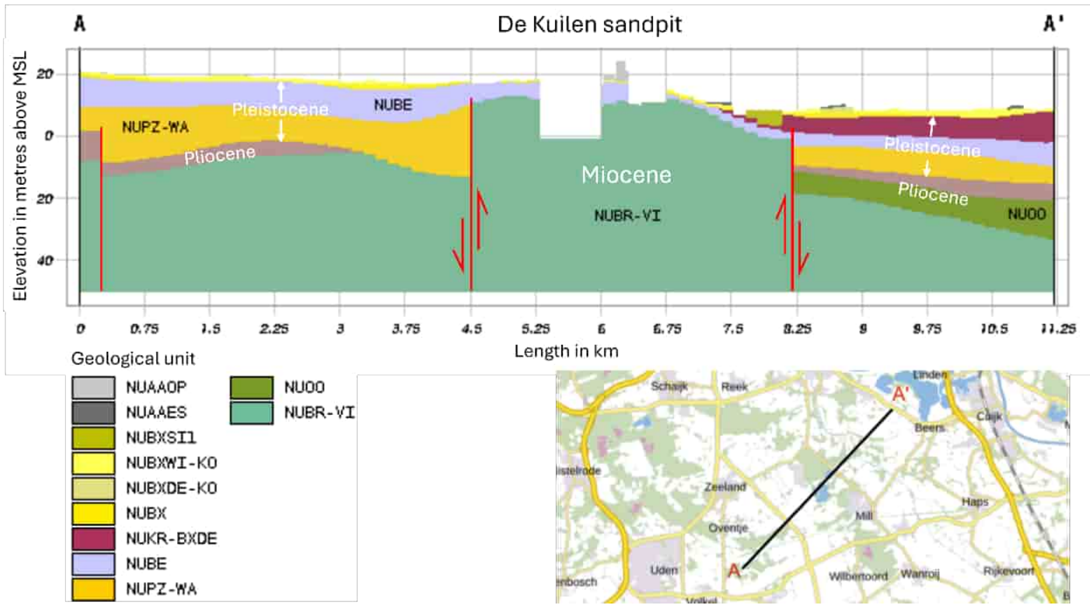

Figure 13 – Southeast-northwest cross section through the subsurface model Geotop (v1.6.1) across De Kuilen sand extraction site situated on an elevated fault block on the Peelhorst where the Miocene is closer to the surface. See inset map for location.

In 1954, the Kalkzandsteen (lime sandstone) factory Hoogdonk was established in Liessel. The Peel Boundary Fault runs directly in front of the factory gates. On the factory grounds, quartz sand of the Kiezeloolite Formation are close to the surface, making it easy to extract. These “silver sands” consists mainly of fine to medium-grained quartz grains that are well sorted. This pure sand is ideal for binding with lime to produce lime sandstone bricks. In addition to silver sand, deeper drillings in Hoogdonk have revealed greenish marine sands from the Groote Heide Formation at depths of 50 to 136 metres. These older sands are not typically used for lime sandstone production but are of geological interest. In 2000, a permit was granted to expand the extraction site, allowing the factory to continue production until around 2030. However, sand extraction was halted in 2022, although Xella Kalkzandsteen resumed sand extraction for lime sandstone products at a different location in 2024. The excavation permit is valid until the end of 2025; further plans remain unknown.

De Kuilen near Langenboom are water bodies formed by the extraction of “green sand.” On the Peel Horst, green sands from Miocene age lie less than 1 meter below the surface, whereas elsewhere in the Netherlands they are found at much greater depths. The sand is extracted using a suction dredger that draws the sand from the bottom of the lake.

Both in Hoogdonk and De Kuilen, sand extraction (down to about 30 metres deep) has led to the discovery of numerous fossils, particularly from the late Pliocene and Miocene. The two sand extraction sites are paleontological mirror images on either side of the Peel Horst and are of exceptional national importance.

In Hoogdonk, fossil finds include shark teeth, whale vertebrae, bird remains, sea urchins, and starfish. Whale remains and many other marine fossils provide evidence that this part of the Netherlands was once a sea (Miocene, Breda Subgroup). Remains of mastodons and other fossils date from a time when the area was land (Pliocene and Pleistocene, respectively Kieseloolite and Beegden formations). Occasionally, large erratics (“vlincken” in Limburg an Noord-Brabant) are found in the Pleistocene river deposits (Beegden Formation) representing

large blocks and stones that were transported by floating ice via the River Meuse.. In Liessel, for example, the “Jaap van de Leijsing” and the “Buntse Kei” are displayed in the town square. Plant seeds and artefacts indicating human presence have also been found, suggesting some archaeological significance.
De Kuilen are known for fossil shells from the Pliocene, which can still occasionally be found on the shores of the lakes, but are especially renowned for the wide variety of fossils excavated there in the past. Langenboom is recognized across Europe as one of the most productive fossil sites from the Miocene and Pliocene—holding the top position for fossil birds. Paleontological finds include the hoofed mammal Chalicotherium, four new auk species, and the short-snouted dolphin (Protophocaena minima). At Langenboom, the extracted sand—including fossils—was sprayed onto land, allowing amateur geologists and paleontologists to easily collect specimens on a large scale.

Settlement: The most important geological feature of the area is, of course, the presence of faults. In the past, people were unaware of their existence but they adapted to and utilized the landscape with all its elements without realizing their interrelationship. The interaction between humans and the landscape is clearly visible on historical maps (see Figure 12). The Peelhorst, the higher area in between the Peelrand and Tegelen fault zones, was originally a wet and empty area where peat formation occurred in marshes. However, the edges of this area were ideal for habitation: here people were always assured of controllable water.
At the northwestern edge of the Peelhorst, south of Oss, the prehistoric inhabitants made use of the existing elevation difference. For those coming from the low-lying clay area in the north, the higher Peelhorst must have been a striking feature. At Vorsel and Zevenbergen, several urn fields and many burial mounds were present on the high edge, including the famous princely graves of Oss. Burial mounds also served as markers of the "property rights" of a local community. They had to be noticeable and were erected in prominent places. Research has shown that the burial mounds around the princely grave of Oss were grazed by sheep at that time. This prevented the growth of shrubs that could obscure the burial mounds from view. As a result, and due to their high location, the mounds were visible from a great distance (*Jansen and Van der Laan, 2011*).
The peatland of the Peel has long been unattractive for habitation. Archaeological finds have mainly been made on sand ridges along the edge. However, tools from hunter-gatherers from the Paleolithic (2.5 Myr – 10.000 BC) and Mesolithic (10.000-8000 BC) have been found in various places. In these early periods, the Peel was not yet covered with peat; it expanded further in later times. Flint axes have been found at Ospel, Venray, and Heibloem. These tools were likely offered at water-rich places. A settlement from the late Stone Age was discovered at Millheeze. Finds at the edge of the Peel near Bakel and Deurne indicate habitation during the Iron Age and Roman Period. On June 15, 1910, the peat cutters Gabriël Smolenaers, Driekske Slaats and Loeves Pier made a spectacular discovery in the Peel marsh. At Helenaveen, they found the personal belongings of a Roman officer: a gilded silver cavalry helmet, a cloak pin, a cavalry spur, bells from a horse harness, and Roman coins. These finds date from the early 4th century. This remarkable find initiated a period in which many more finds were made in the Peel, the oldest dating back to the Mesolithic and Neolithic periods.
After a period of decline, the population in the southern sandy area, and thus in the Peel region, began to increase again from the 6th-7th century. Habitation took place at some distance from the peat. During the Middle Ages, a ring of villages formed around the vast peatland. In Brabant, these included Someren, Asten, Liessel, Deurne, Milheeze, Bakel, Gemert, Handel, Boekel, Volkel, Uden, Zeeland, Nistelrode, and Schaik. To the east are Mill, Wanroij, St.-Anthonis, Oploo, and Overloon. The Limburg part of the ring includes Venray, Horst, Panningen, Helden, Weert, Nederweert, and Heythuysen. Often, the villages lay as an isolated strip of cultivated land amidst the wild grounds of the peat or the extensive marsh

forests and heathlands to the east towards the Maas. In addition to villages, smaller hamlets emerged, originating from a farm or a mill.
Due to the water seepage at the higher sites of faults, streams originated that were utilized for moated sites such as castles, houses and farms that could be perfectly defended thanks to the natural waterline.

Agriculture: The medieval cultural landscape consisted of arable land and grasslands around the old villages. The fields were generally located on the higher, well-drained parts of the valley slopes. There were individual reclaimed fields, surrounded by hedgerows or hedges, and contiguous open field complexes or fields.

However, in the thirteenth century, the population grew rapidly, and farmers from nearby villages began to use the cover sand ridge. They cleared the forests, and on the heathland that replaced them, they grazed their sheep for centuries. In sandy areas, it was difficult to farm without sufficient manure. Therefore, forest and heath sods ("plaggen") were cut, which were mixed with animal manure to increase the fertility of the fields. The nutrients in the manure only partially returned to the heath. At night, the manure was collected in the stable — the potstal — on a bedding of cut heath or grass. The sods were returned to the fields that became increasingly higher. These fields are referred to as “esgronden and these anthropogenic soils classify as Plaggen soils.
The advantage of manure-rich heath sods on the fields lay in the fact that a few weeks of soaking the sods with urine could kill the seeds of potential arable weeds. Because potstal manure was used to fertilise the naturally poor arable land, the already nutrient-poor sandy soil beneath the heath became even more depleted.
After the Middle Ages, as the population continued to grow, the use of the heath intensified. Cutting heath shrubs was no longer sufficient to produce enough fertiliser for the fields. Increasingly, the heath was stripped of its sods. Excessive and deep sod-cutting accelerated the degradation of the heath. The soil became exhausted, and the heath could no longer recover.

Anthropogenic wind deposits:
The severe impoverishment of the heathlands led to one of the earliest large-scale environmental disasters in history. Where vegetation failed to recover in time after cutting or sod removal, the wind took hold of the bare sand. Just as in the Ice Age, the sand began to drift again. People were virtually powerless against this natural force. Large areas of heathland, farmland, and even entire villages were buried under drifting sand.
Parts of the cover sand landscape transformed into sand drift landscapes. These drift dunes can be recognized in the landscape by their much steeper and higher profiles compared to the cover sand ridges and parabolic dunes formed during the Ice Age. The reason for this is that they developed in a landscape where scattered trees, shrubs, and hedgerows were present. These obstacles slowed the wind and trapped the sand, which was then deposited locally in steep dune ridges. The danger of sand drifts was always lurking, as the Bedafse Bergen (Figure 14) show.
To prevent new farmers from settling on the heath, commons were established to regulate the use of the land: everyone's rights and duties were laid down regarding the number of sheep to be grazed, the amount of sod and peat to be cut, and so on. Only in the French period did the common lands come into the possession of the municipalities.

The common heathlands were subsequently sold, new farms were built, and part of the heathlands turned into agricultural land and forest when artificial fertilizer was introduced around 1900.

Figure 14 - The Bedafse Bergen to the west of Uden. In this sand drift landscape, inland dunes have formed that rise up to 15 metres above the original cover sand level. On top of the dunes stands coppiced oak woodland, which was planted to protect the nearby fields from drifting sand and has grown upwards along with the accumulating sand. Photograph presented in *Koomen et al., 2007*.

In the previous century, many of the sand drifts were stabilized by planting pine trees. The steep drift dunes are still clearly visible within the forests today.

Reclamation and consolidation: Ysselsteyn was founded in 1920 as a model reclamation village. The village had a Y-shaped road system (Figure 15). Various facilities, including a school and a church, were located around the junction. The farms were spread out; originally, 15 farms were built, and more followed after 1920. In 1938, 58 farms were established with state support.
After the Second World War, various developments significantly influenced the landscape (Figure 16). These were not specifically regional developments but national issues that had a regional impact. These included the ongoing scaling up in agriculture, including land

consolidations, the growth of villages, the expansion of infrastructure, and the rise of recreation.

Figure 15 – The reclamation village of Ysselsteyn with its typical “Y”-shaped road pattern. Note the geometrical land-consolidation pattern radiating from the village.

In agriculture, the ongoing scaling up led to specialization in dairy farming or poultry and pig farming. Additionally, the average size of farms increased significantly. The narrow, often strip-shaped plots with alder hedges in the stream valleys were replaced by larger block-shaped parcels. The scattered plots of farmers were thus concentrated. New farms were built in places where there had never been farms before. In the region, a total of 40 land consolidations were carried out, covering at least 135,000 hectares (not all of the mentioned projects were entirely within the region). Some started in the 1930s, most took place between 1960 and 1980. Parts were consolidated twice. The parcelling was often changed, and the water management was thoroughly addressed, making arable farming possible even in the lowest parts of the landscape. The low-lying grassland areas became as open as the fields.

Restoration: Due to the reclamations and land consolidations after World War II, the Peel became a modern agricultural landscape. Straight roads and canalized watercourses cut through the fields and meadows. Thanks to the Land Reclamation Service, followed by land consolidation, the Peelhorst became one of the most important intensive agricultural and bio-industry areas of the Netherlands. New villages were founded, and existing settlements grew (Figure 16). In the 1970s, however, there was a shift in thinking about the malleability of the landscape.
Parts of the Peel have been transformed into Natura 2000 areas in recent decades. This happened in some cases as part of land consolidation or reallotment projects. This mainly concerned the non-peat areas, the remaining heathlands, and pieces of forest. Besides the National Park De Groote Peel, this includes the Deurnese Peel-Mariapeel, Boschhuizerbergen, Srasven-De Banen, and the Weerter- and Budelerberg-Ringselven.

There was an increased appreciation for unique elements in the landscape such as the traces of the Peelrand fault, associated wijst and the unusual contrast of high, wet grounds and low, dry grounds. With growing environmental awareness, more attention was paid to the wijst phenomenon. There was also increasing (scientific) interest in the wijst and the faults of the Peel Boundary Fault Zone. As a result, wijst areas were mapped and qualified as “earth science values” (see *Provincie Noord-Brabant, 2004*). In various places, efforts are now being made to restore wijst. Old, more or less existing seepage phenomena are being revived through smaller and larger interventions in the landscape. Overall, there is now quite a bit to see, more

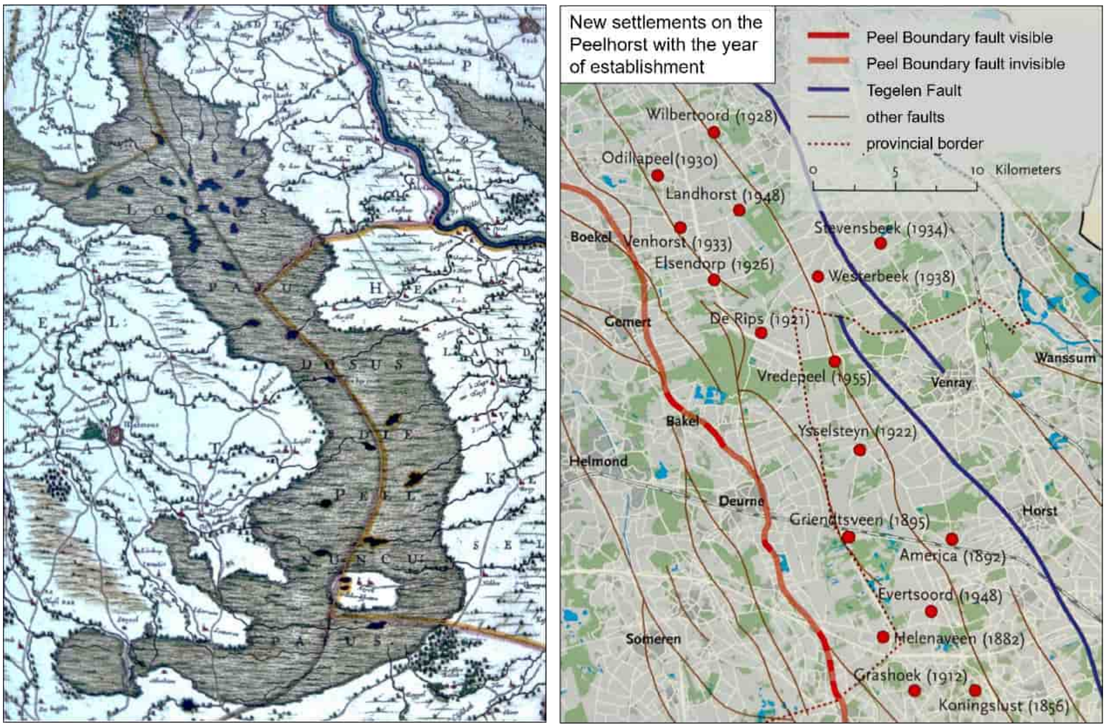

Figure 16 – Until well after the Middle Ages, the Peel was an empty and inaccessible area without any villages (left; the peat areas are marked in grey)). The vast barren lands and small-scale reclamation of the Peel came to an end in the 19th century. From that time onwards, large-scale peat extraction began and new villages were established (right). The peat cutting was also a form of land reclamation: the intention was to use the land exposed by excavation for agriculture and horticulture. The maps cover approximately the same area (modified after *Van Balen et al., 2022*).

than in the heyday of land consolidation when rapid water drainage was necessary to enable the use of heavy agricultural machinery. Meanwhile, due to climate change, priorities have shifted, and water retention is becoming increasingly important. Those who now follow the fault lines through the landscape will encounter not only the geological and cultural-historical traces of the fault but also new wijst restoration projects. Restoring the water retaining function of the fault system, which in many places was destroyed by agricultural activity and ground levelling for urban development, can help combat the drought of recent years and also contribute to water storage during wet periods. Knowledge of the faults and the surrounding subsurface is therefore important for construction projects and sustainable agriculture. In the past, people knew that they did not had to build on the fault and adapted crop choices to the subsurface and specific conditions. Farmers were pleased to own a wijst plot, a refuge in dry times. But local knowledge has disappeared, but thanks to all the recent attention to the fault, people realize (again) that it is time to take the fault into account. The faults are even considered for new developments, such as underground cold-heat systems and the use of geothermal energy that can make use faults.

The Geopark demonstrates how the landscape changed over time: from poor fields to nature reserves, from heathland to forests, and from farmland to recreational opportunities

6 Geosites

This part gives an overview of the selected 40 geosites (for the time being 41 are selected). For the selection of the geosites a geographical and topical balance is sought for. The many different types of manifestations at the geosite are grouped according to “Interests” that, in turn, are grouped in either “Geological”, “Geosite”, or “Other” categories. Internation, National, or Regional significance is indicated for all geosites and a level of Unicity is assigned. Figure 17 summarizes these criteria.

Manifestation	Interest	Cat.
Elevation differences due to faults and/or river terraces	*Geomorphology*	Geological Interest(s)
Seepage, artesian flow, hydraulic head, waterworks (mills, moats, canals)	*Hydrology*	
Ores, minerals, fossils, glacial erratics	*Depo & Foss*	
Abandoned river courses: terraces, streams	*Rivers & Streams*	
Geological age of the manifestation(s)	*Geologic period*	Geosite Interest(s)
Historical structures: castles, farmsteads, military constructions	*Cultural, Hist., Archeo.*	
Vegetation: reeds, alders, oaks, reptiles, birds, butterflies	*Flora & Fauna*	
Land use: bog iron as building material, water bodies for sand and gravel extraction, peat	*Industrial or Economic*	
Has research been conducted on the specific site?	*scientific*	Other interest
Information boards, visitor experience, education	*educational*	
Does the site have visitor appeal?	*(geo)tourist*	
Significance = unique internationally, nationally, or regionally	*I = international* *N = national* *R = regional*	Significance
Unicity within the aUGGp	*A = unique* *B = few other sites equal* *C = many (>5) sites equal*	Unicielt

Figure 17 – Ranking and grouping criteria for the 40 selected geosites

Table 2 - Listing of 41 selected geosites. The yellow highlighted sites represent sites with multiple manifestations combined. Geological Elements: PF = Peel Boundarry Fault Zone, MV = Maasvallei, TF = Tegelen Fault, PH = Peelhorst

	Geositenr	naam potentiele Geosite	Geological interest(s)				Geosite interest(s)				Other interest			Type of p	Significance	Uniciteit
element	Selected gesosites		Geomorphology	Hydrology	Depo & Foss	Rivers & Streams	Geologic period	Cultural, Hist., Archeo.	Flora & Fauna	Industrial or Economic	scientific	educational	(geo)tourist	pm - door TNO nader te benoemen	I = international N = national R = regional	A = unique B = few other sites equal C = many (>5) sites equal
MV	GS_01	Maasheggen	x			x	x	x	x		x	x	x		I	A
TF	GS_02	Steilrand Mill	x		x	x		x	x		x	x	x		I	A
PF	GS_03	Bijzonder Brabant	x	x					x		x	x	x		I	A
PH	GS_04	Griendtsveen - Toon Kortoomspark-		x				x		x		x	x		I	A
PF	GS_05	Vorstengraf	x					x				x	x		I	A
TF	GS_06	Peelraamstelling						x				x	x		I	A
PF	GS_07	Sint Annabos	x	x	x	x		x	x	x	x	x	x		I	B
PF	GS_08	Hoogdonkseweg Liessel	x	x	x	x	x			x	x	x	x		I	B
MT	GS_09	Leudal	x	x	x			x	x	x		x	x		N	A
	GS_10	Maasdoorkruising	x	x		x		x	x		x		x		N	A
PH	GS_11	Maria- en Deurnsche Peel	x						x						I	B
TF	GS_12	Waterzuiverende wijstboerderij Zeeland		x					x			x			N	A
PF	GS_13	Slabroek	x	x	x	x		x	x			x	x		N	B
PF	GS_14	Gemert, Breuken beleven	x	x	x	x		x	x			x	x		N	B
PF	GS_15	Uden - Stadswijst	x	x	x			x	x			x	x		N	B
	GS_16	Geneneind	x	x		x		x	x		x	x	x		N	B
	GS_17	Neer	x	x		x		x	x		x	x	x		N	B
PH	GS_18	Helenaveen		x	x	x		x		x		x	x		N	B
	GS_19	Wijstbos Zeeland		x	x			x	x			x	x		N	B
TF	GS_20	Langenboom/de Kuilen			x		X				x	x	x		I	B
TF	GS_21	Sint Hubert	x						x	x		x	x		N	**B**
PF	GS_22	Kasteel Deurne, Heiakker	x	x				x		x		x			N	B
PF	GS_23	Maashorst		x					x			x	x		R	A
PF	GS_24	De Burgt	x	x				x				x			N	A
PF	GS_25	Donzel		x	x				x						N	C
PF	GS_26	De Specht /Putakker	x	X		X			x		x	x	x		R	**B**
PF	GS_27	De Perekker	x	x		x			x			x	x		R	B
PF	GS_28	Meijel	x	x				x				x	x		R	B
MV	GS_29	Schuitwater Broekhuizen-Lottum	x			x	x		x		x	x			R	B
PH	GS_30	De Bult	x					x	x		x	x	x		R	B
TF	GS_31	Loobeekdal	x						x			x	x		R	B
MV	GS_32	Maaspark Noord Limburg	x			x	x		x		x				R	B
PH	GS_33	Stippelberg Klotterpeel/De Rips	x	x				x	x						R	**B**
PH	GS_34	Zinkske Molentje						x	x			x			R	**B**
TF	GS_35	Hooge Raam		x		x			x						R	B
MV	GS_36	De Vilt				x			x			x			R	B
TF	GS_37	Watermolen Oploo													R	B
PF	GS_38	De Berkt	x	x	x	x		x	x			x	x		R	C
PF	GS_39	Het Loo	x	x	x	x			x				x		R	C
PF	GS_40	Waterbloem	x	x				x	x						R	C
PH	GS_41	De Krim	x						x			x	x		R	C
PH	GS_42	De Elsbeemden		x	x	x		x	x	x	x		x		R	B

7 General geological description

The geological history of the aUGGp dates back to the Carboniferous period, hundreds of millions of years ago. From this distant past, traces have been left in the deeper subsurface. Due to movement of tectonic plates, this particular part of Northwestern Europe travelled all the way from the southern hemisphere to its current position. For example, the coal deposits that lie more than a thousand meters deep under the Peelhorst are remnants from a time in which Northwest Europe was located around the equator and was covered with extensive mangrove forest that developed under a tropical warm climate. However, for the description of the ground directly beneath our feet and the formation of the current landscape, we limit the story to the last 10 million years. The materials from this period are now at the surface or at a depth of at most a few hundred meters. It was mainly a time of sedimentation; a time of deposition of sand, gravel, clay, and sometimes peat. Additionally, erosion occurred where wind, rivers, and the sea carried away previously deposited material. The movements of the earth's crust and the climate, particularly the alternation of cold and warm periods, had a significant influence on the interplay of sedimentation and erosion.

The maps and timelines in this chapter serve as tools for the story of the geological history of the Geopark. The **geological map** (Figure 18), shows the deposits that are now at the surface, while the **cross-section** through the Geopark (Figure 19) provides an impression of the deeper deposits.

The Earth's crust is moving

The 'solid ground' beneath our feet may seem stable and unchanging at first glance. However, earthquakes and fault lines within the Geopark show that the Earth's crust is constantly in motion. The Earth's crust, the outer solid part of the Earth, is about 80 kilometres thick and consists of different plates. These plates move relative to each other across the globe at a rate of a few centimeters per year (this process is called plate tectonics). Where plates move towards each other, collision mountains are formed, and

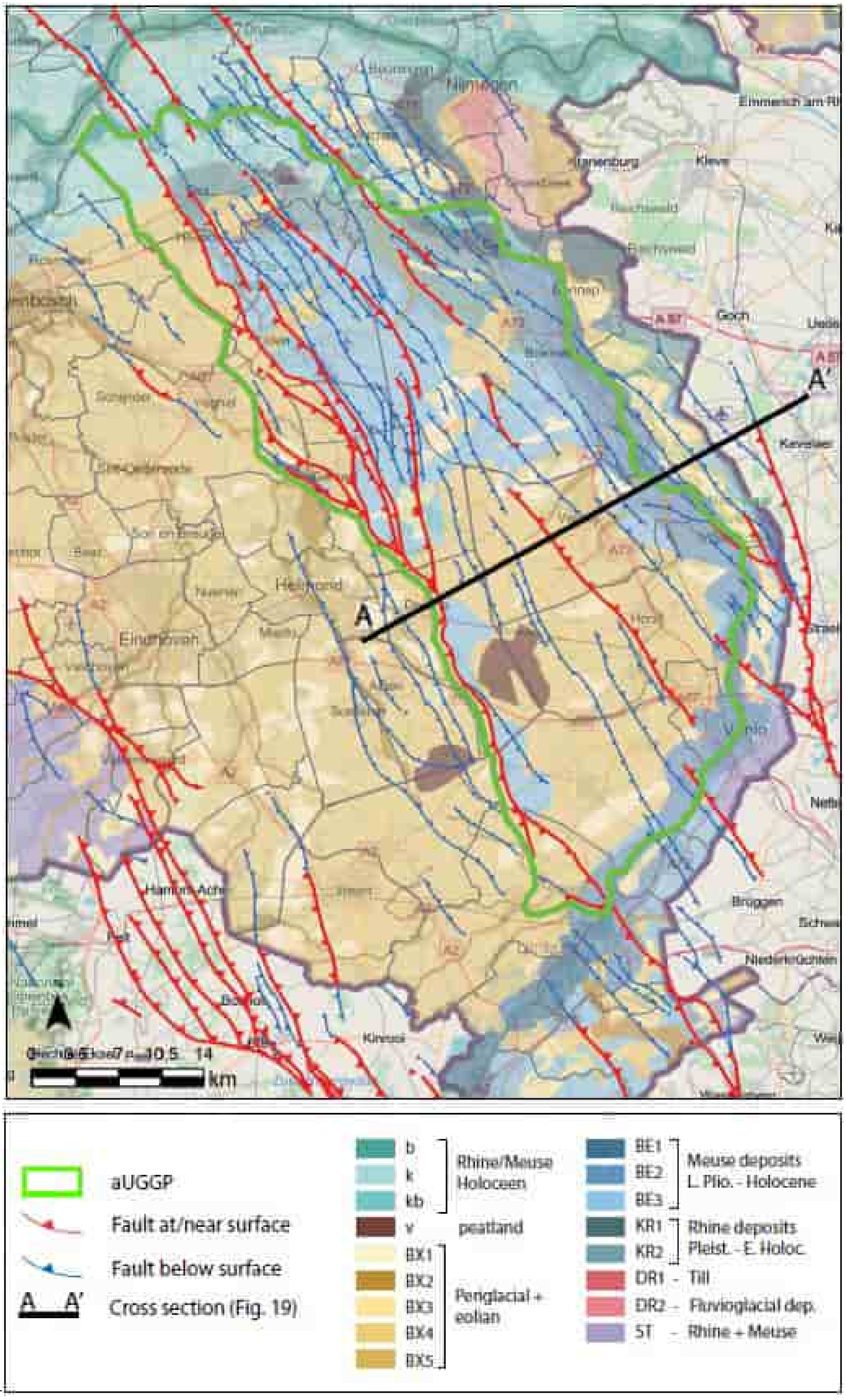

Figure 18 – DRAFT: Geological map of the aUGGP

where they move apart, oceans can form. In the Mediterranean region, the Eurasian Plate and the African Plate collide. This pushed Italy northward and formed the Alps. At the same time, the North American Plate and the Eurasian Plate moved apart along the Mid-Atlantic Ridge, causing the Atlantic Ocean to grow larger. This separation creates pressure in a southeasterly direction. Due to the pressure from two sides, the Dutch part of Europe is being compressed. As a result, parts of the Earth's crust rise and others fall, such as the subsidence area to which the Dutch subsurface belongs. This subsidence area extends across Western Europe, from Spain through eastern France, Germany, to the Dutch Roer Valley Graben system. While mid-mountain ranges such as the Ardennes in Belgium and the Rhenish Massif in Germany are gradually being pushed up, the subsurface of the Netherlands is slowly spreading apart. Therefore, the surface of our country is continuously getting a little larger.

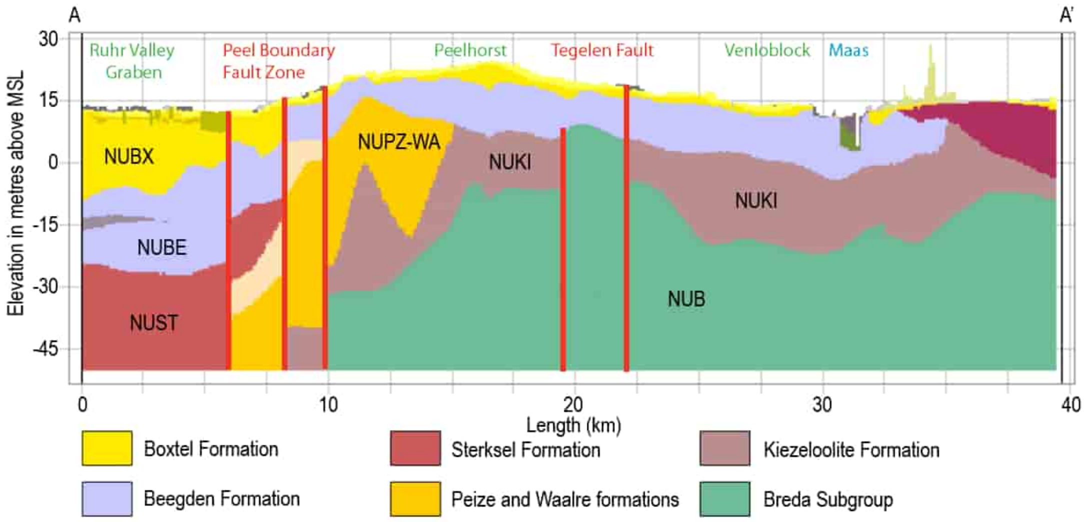

Figure 19 – Geological cross section through the subsurface model GeoTOP v1.6.1 (for location see the geological map in Figure 18)

As a result of these pulling and pushing forces, the Earth's crust comes under tension, and faults are formed. Most of these faults are closely related to structures that formed during the Caledonian and Variscan orogenies. These phases of plate-tectonic movement led to the collision of several micro-continents during the Late Cambium to Early Devonian and Late Devonian to Late Carboniferous periods, respectively. Eventually, the Pangea supercontinent was formed. Most of the structures formed at these phases became reactivated during several later tectonic phases, including the Cenozoic rifting. These faults form systems that branch out and eventually die out. For this reason, it is more accurate to speak of fault zones, the bundling of fault segments that together form a displacement zone. On one side of a fault (zone), the Earth's crust rises or falls faster than on the other side. In this way, a landscape with horsts and grabens can form. A horst is an area bounded by faults that rises relative to its surroundings and is therefore higher; a graben (relatively) sinks and is therefore lower.

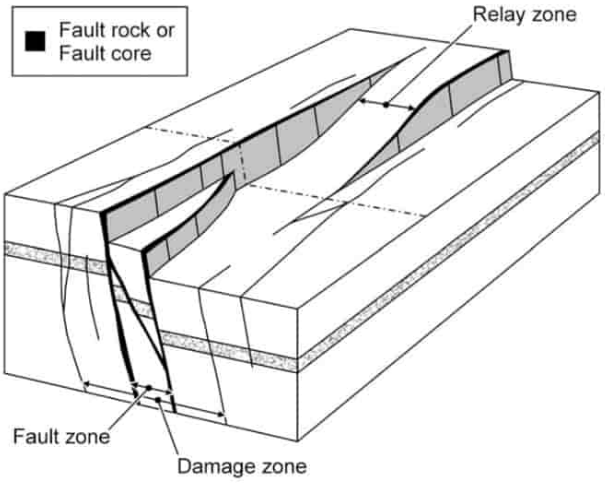

Figure 20 – Typical horst and graben structure with branching fault geometry representative for the Peelhorst and Peel Boundary Fault Zone. Modified from *Childs et al., 2009*

The Peelhorst forms the backbone of the Geopark and is bounded to the south by the Roer Valley Graben and to the north by the Venlo Graben (or Venlo Block). The Roer Valley Graben and the Peelhorst are separated by the relatively narrow Peel Boundary Fault Zone (PBFZ). The Peelhorst and Venlo Graben are separated by the Tegelen Fault Zone.

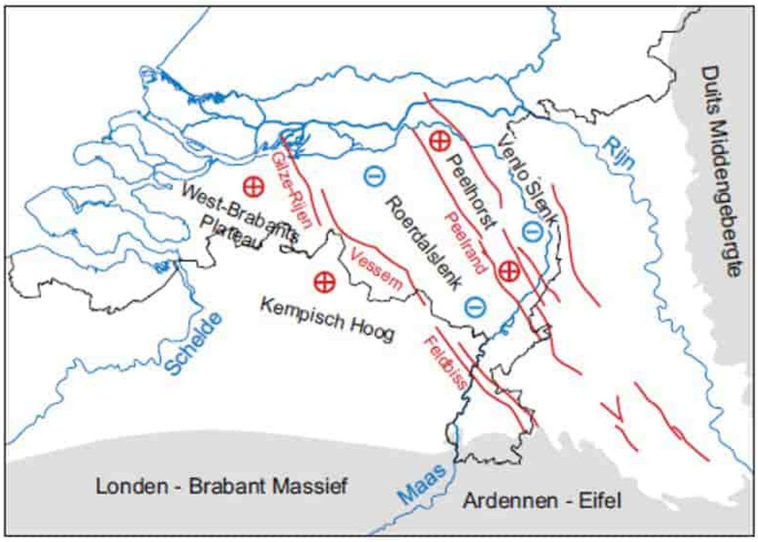

Figure 21 - The major uplift (+) and subsidence (-) areas in the Ruhr Valley Rift System and the main fault lines resulting from the movements of the Earth's crust. Modified from *Koomen et al., 2007*.

The effect of movements along the PBFZ is sometimes strongly felt when earthquakes occurs and the fault itself is sometimes clearly visible as a terrain step. Currently, the subsidence of the Roer Valley Graben relative to the Peelhorst is about one centimeter per century. This may seem small, but in a geologically brief period of one million years, it results in a height difference of one hundred meters! This cumulative effect is very evident in the more than 1 km difference in the depth of the base of the Miocene (30 million years old) on either side of the Peel Boundary Fault. However, due to continuous erosion on the horsts and infilling of the graben, the height differences caused by fault movements are largely - but not completely - compensated. In the landscape of the Geopark, the graben remains visible as an area that is lower relative to the horsts. The faults that are locally visible in the landscape in Brabant and

Limburg can also be traced far to the northwest in the Dutch subsurface. Because rivers and wind have always transported and deposited substantial amounts of sediment (gravel, sand, clay) here, the resulting height difference at the surface is often completely or largely filled. Therefore, the horsts and grabens in the Netherlands are mainly underground.

Fault patterns

As mentioned before, Alpine and Atlantic tectonic forces make that the Roer Valley Rift System is not only slowly spreading apart but that within the rift fault blocks move alongside each other in a right-lateral manner. Such combination of deformation is called "transtension." The fault lines shown in Figure 18 make up a complex pattern of faults and appear to be never straight lines. Faults have limited extent and can converge and diverge resulting in an anastomosing arrangement. Such an arrangement is not typical for the aUUGP, but is a commonly observed feature in faulted transtensional terrains. It is a clear indication that faulting is a dynamic process during which faults segments can start to develop at nuclei, subsequently grow in length and vertical displacement, and may eventually merge with other fault segments. Consequently, fault patterns are not simple and straightforward, something important to consider when trying to locate faults in the field.

Sandbox experiments have tried to mimic the development of faults under transtension and show fault patterns that resemble those seen in the aUGGP and adjacent Roer Valley Graben (Figure 22). Those experiments also show that faults not only branch in the horizontal plane, but also in the vertical plane and may converge into a principal zone of deformation at kilometres depth. Most likely, the fault segments of the Peel Boundary Fault Zone that we observe at the surface nowadays are in fact the most shallow tips of deeper-seated faults. Further geophysical research of the deep subsurface is needed to proof this.

Such deep-seated faults are likely to be inherited from much older deformation phases and probably date back to the Carboniferous period. During subsequent phase of plate-tectonic puulling and pushing, e.g., during the Triassic, Jurassic and Cretaceous periods, these faults were re-used. From the Oligocene onward (~25 Myr) the current phase of deformation started of which the aUGGP forms an area with multiple lines of evidence.

Earthquakes

If movements along faults in the Earth's crust occur in pulses, they are referred to as earthquakes. These are usually light to moderate in the Netherlands. Nevertheless, the Peel Boundary Fault Zone is considered an exceptionally active fault structure by Central European standards. The most powerful earthquake observed at a fault in the Netherlands was the Roermond earthquake in 1992, with a magnitude of 5.8 on the Richter scale (Mw 5.3). Even though there was no surface rupture, the damage in the Netherlands alone amounted to 77 million euros. The last known earthquake before that was the one in Uden in 1932, with a magnitude of 5.0. In the years following the Roermond earthquake, research was conducted in Belgium, Germany, and the Netherlands to gain more insight into the frequency and intensity of earthquakes. More specifically, to answer the question if it is possible that earthquakes from a more distant past were even stronger. In the Netherlands, the Peel Boundary Fault Zone near Neer and the Feldbiss Fault Zone near Born were investigated with trench studies.

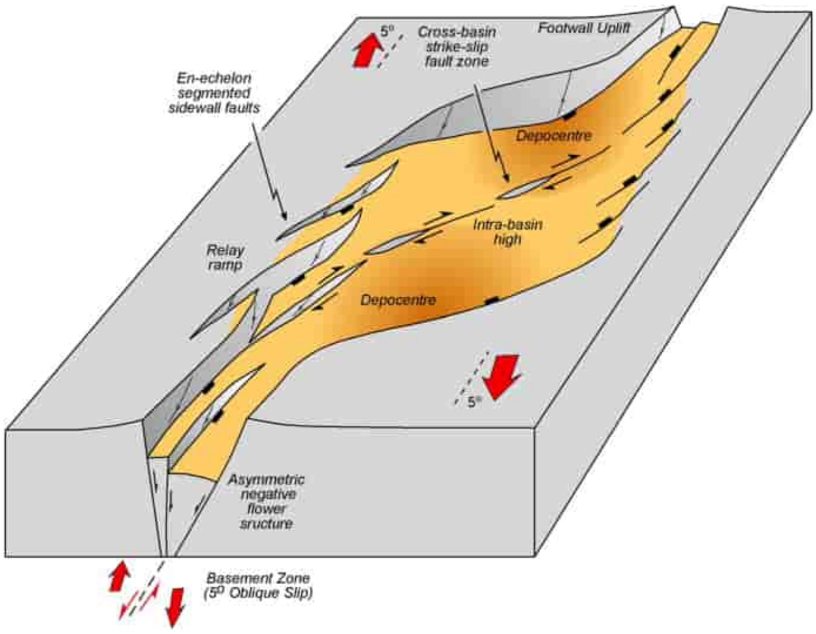

Figure 22 – DRAFT: Three-dimensional geometry of an idealized early stage pull-apart basin developing in 5° transtension based on the results of analogue modelling. From: *Wu et al., 2009* . This geometry is with en-echelon arrangement of branching faults is representative of the Roer Valley Graben (central part of figure) and the Peelhorst (left part of figure).

Results from trenching studies located near Bakel and Neer, in the central and southeastern parts of the PBFZ, respectively, provided evidence for two surface rupturing paleo-earthquakes. The largest earthquake had an estimated magnitude of Mw ~6.8 and a surface rupture length of at least 35 km, approximately 10-20 times stronger than the one in Roermond (*Van Balen et al., 2019).* As it took place around the Late Pleniglacial – Late Glacial transition there is likely a connection between the large-scale surface movements caused by the melting of ice caps in Scandinavia, Great Britain, and the North Sea, and the local, severe earthquakes of that time (*e.g. Houtgast et al., 2005; Van Balen et al., 2019, 2021)*). Results from a new trench situated (*Van Balen et al., 2024*) at the northwestern part of the PBFZ, near Uden, shows evidence for three to four paleo-earthquakes, of which three were surface rupturing. These comprise two normal faulting- and one, younger trans-tensional displacement. The normal faulting events have ~1 m vertical displacements each, which translate into magnitudes of Mw ~7. Like the previous results, they occurred during the Late Pleniglacial-Late Glacial transition, at ~15 ka and ~ 14 ka. The younger transtensional event occurred sometime during the Holocene, pre-dating an unaffected, 13th century man-made paleo-channel on the hangingwall. The potential fourth, non-surface rupturing earthquake is indirectly evidenced by loading deformations of a sand layer and a collapsed brick-wall in the infill of the paleo-channel. Comparison of the trenching results along the PBFZ, show that for one event a correlation is possible and would indicate a surface rupture length of at least 55 km. Combined, all trenching results indicate that the characteristic maximum rupturing displacement is ~1 m, corresponding to Mw ~7 as the maximum magnitude of paleo-earthquakes along the PBFZ. Based on observations, the period between large earthquakes appears to be thousands of years. Thus, it is not ruled out that severe earthquakes can occur today. Moreover, lighter earthquakes occur once every few hundred years and can also cause considerable damage.

Vertical motions and rivers

The movements of the Earth's crust have had a significant impact on the development of the river system in southern Netherlands. For instance, 2 million years ago, the Meuse (Maas) flowed eastward at the height of South Limburg and emptied into the Rhine north of Aachen. Due to the uplift of the Ardennes-Eifel Massif, the Meuse, like the Rhine, had to shift its course westward.

The continuous subsidence of the Roer Valley Graben led to the accumulation of a substantial sediment package, particularly in the Roer Valley Graben. The Roer Valley Graben, and to a lesser extent the Venlo Block and the northern part of the Campine Block, have been filled with relatively fine fluvial sediments from the Late Miocene and Early Pleistocene (Kiezelooöliet, Waalre and Stramproy Formations (*Westerhoff et al., 2008*). These deposits are (mainly in the Roer Valley Graben) overlain by coarse river deposits from the Rhine and Meuse dating to the early part of the Middle Pleistocene (Sterksel Formation). During the later part, the Cromerian (850,000 – 465,000 years ago), the Rhine shifted to a more northerly course, thereby leaving the Roer Valley Graben. As a result, the Meuse became the dominant river in the southern Netherlands. The coarse fluvial sediments of the Meuse in the Roer Valley Graben system belong to the Beegden Formation.

From 400,000 years ago, after filling the Roer Valley Graben, the Meuse also shifted north-eastward, over the now rapidly rising an tilting Peelhorst. The Meuse then descended from this emerging horst and has since flowed into the Venlo Graben located to the east. Due to this shift in the Meuse’s course, and the much lesser subsidence compared to surrounding tectonic blocks, the fine, shallow marine and nearshore sediments from the Miocene (Breda Subgroup) on the Peel Block are directly overlain by the coarse Meuse sediments (Figure 23).

In addition to Meuse deposits, local river and large-scale aeolian sediments were also deposited in the Roer Valley Graben system (Boxtel Formation). Generally, the sediment package belonging to the Boxtel Formation is thicker in the relatively strongly subsiding Roer Valley Graben than on the other blocks of the Roer Valley Graben system.

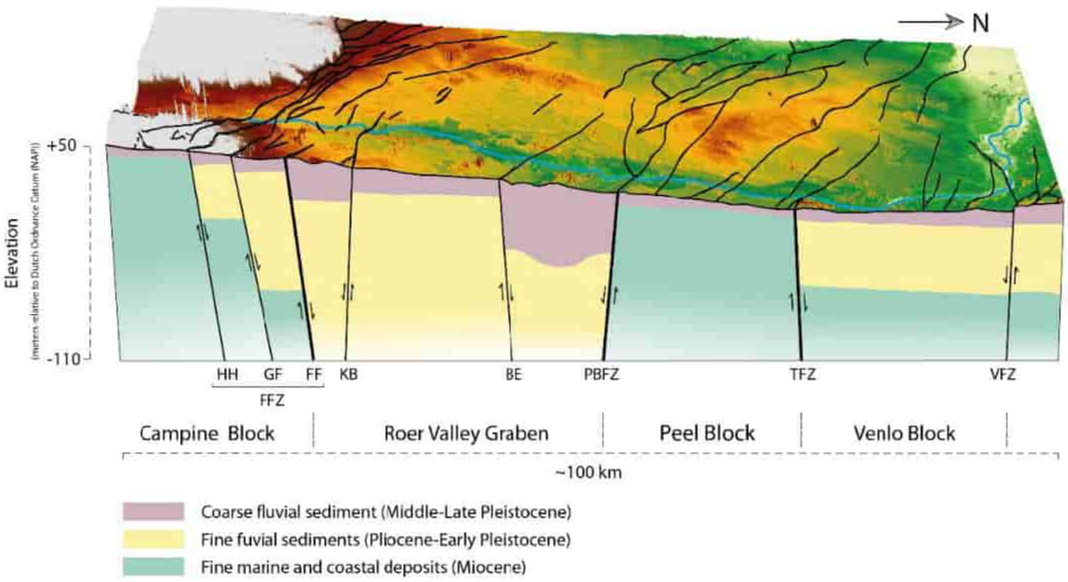

Figure 23 – Blockdigram showing a cross-section throug the Roervalley Graben and adjacent uplifte fault blocks (based on DINOloket), HH = Heerlerheidebreuk, GF = Geleenbreuk, FF = Feldbissbreuk, KB = Koningsbosch breuk, BE = Beegdenbreuk, PBFZ = Peelrandbreukzone. TFZ = Tegelenbreukzone, VFZ = Viersenbreukzone. (modified after *Woolderink, 2021*).

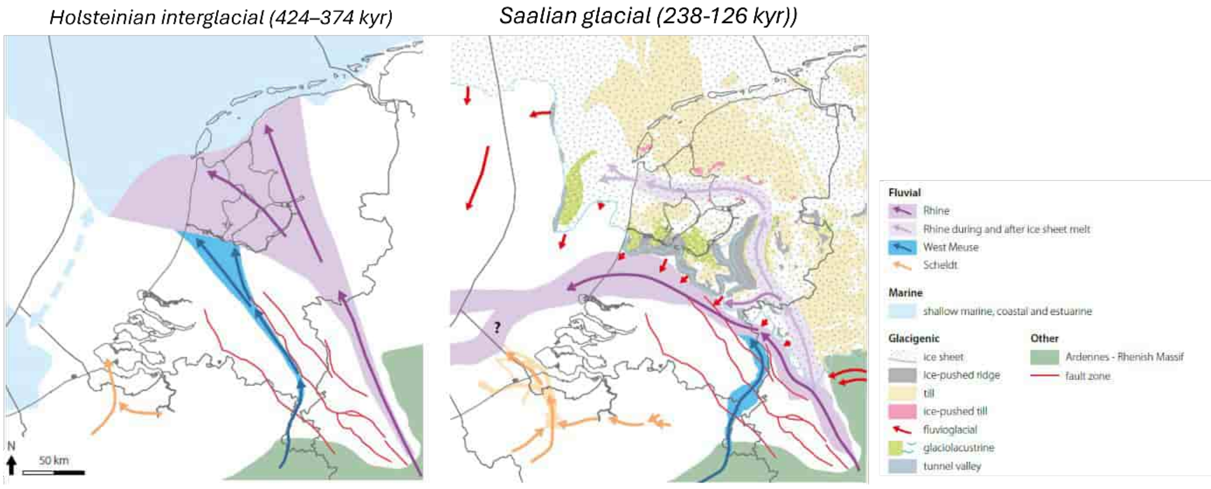

Figure 24 – Due to the movements of the Earth's crust and glaciations, the Rivers Rhine and Meuse were repeatedly forced to change their courses. The maps indicate the locations of the major rivers in southern Netherlands at different points in the past. Modified from *Busschers et al., 2025* and references therein.

High is old, Low is young

The Geopark is located at the transition from uplift to subsidence areas, and through the presence of horsts and grabens, has a great variety in the composition of the subsurface. Old deposits lie close to the surface in the relatively rising areas such as the Peelhorst (Figure 25). Here, river deposition stopped long ago, and as a result of erosion, some of the older deposits have disappeared. In the subsiding areas, the old sediments are buried under thick layers of younger deposits. This occurred in the north and west of the province and in the Roer Valley and Venlo Graben.

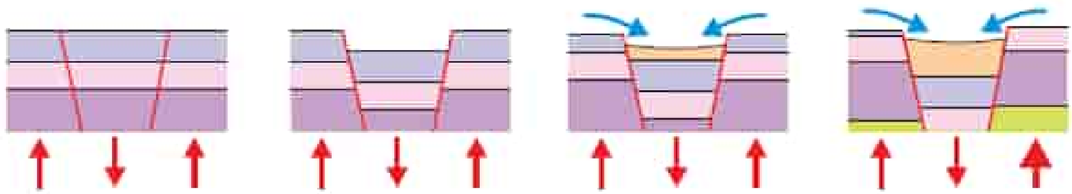

Figure 25 - Schematic representation of landscape development due to uplift of fault blocks (horsts) and subsidence of fault blocks forming grabens. This causes the younger (lilac) geological layers on the horst to be eroded, exposing the older deposits (pink) at the surface. In the subsiding graben, younger river and eolian deposits (salmon pink) are subsequently deposited. Modified from *Koomen et al., 2007*. Consequently, the younger deposits are at a lower elevation and positioned adjacent older deposits at higher elevations (“high is old, low is young”).

Time travel through the Miocene

Subtropical seabed deposits

The oldest deposits found close to the surface in the Geopark date back to the Miocene (Fig. 14). This geological period lasted from 23 million to 2.6 million years ago. During the Neogene, the Netherlands had a temperate warm to subtropical climate, and the Geopark area was covered by a shallow sea. Green to green-black colored loamy sand was deposited on the seabed. The color is due to the mineral glauconite, which forms in warm, calm, shallow seas. Due to subsidence, this 'green sand formation' lies more than 300 meters deep in the Roer

Valley Graben. However, on the Peelhorst, these sediments are found almost at the surface in some places, where they can be easily extracted. From the Pliocene (about 5 to 2.6 million years ago), the sea slowly retreated westward and became shallower. Shell and sand banks were mainly deposited on the seabed. Subsequently, the shallowing continued, and parts of Brabant and Limburg fell dry, allowing rivers coming from the south and east to shift their course to the northwest. The seawater was replaced by fresh water infiltrating into sand layers in the subsurface, these now form an important source for drinking water supply.

The first river deposits
Due to the continuous uplift of the Peelhorst, parts fell dry, and the rivers coming from the south and east extend their course to the northwest. The material brought by these predecessors of the Rhine, Meuse are very rich in quartz; the sand is almost white in color. This is due to the prolonged, intensive weathering of rocks in the source areas under the warm climate conditions during the Neogene. Under these conditions, quartz is more resistant to weathering than other minerals, so after a long time, almost only pale quartz grains remained.

Time travel through the Pleistocene
Ice ages
The Pleistocene epoch, which lasted from 2.58 million to 11,700 years ago, is characterized by an alternation of ice ages and warmer 'interglacial' periods (Figure 26). This highly variable regime of cold and warm times had a significant impact on the geological development of the Dutch subsurface. During ice ages, which typically lasted from several tens of thousands of years to about 100,000 years, the temperature across the entire Earth dropped. The main cause was changes in the Earth's orbit around the sun and the associated major changes in ocean currents. Due to the temperature drop, the snow in the polar regions and high mountains like the Alps no longer melted, resulting in the formation of ice caps several kilometres thick. Under its own weight, the ice in such an ice cap deforms and flows very slowly. Consequently, the ice caps could expand enormously during the coldest periods. During the penultimate ice age, the Saalian (370,000 to 130,000 years ago), the Scandinavian ice cap reached the central Netherlands. The Geopark area was never covered by ice, but it had the climate of a polar desert during the coldest phases. Enormous amounts of water were trapped in the ice caps. As a result, the sea level dropped to more than 100 meters below the current level. Consequently, the North Sea was largely dry land, and the rivers flowed hundreds of kilometres further to the west into the sea. Between the ice ages, the climate was similar to that of our time. The ice caps melted, the sea level rose again, and vegetation returned, initially as tundra and taiga landscapes. These warmer periods lasted about 10,000 to 20,000 years. The current warm period, the Holocene (from about 12,000 years ago to the present), is also a warm interphase between two ice ages. When exactly the next ice age is to be expected has become rather unpredictable due to human interference with climate.

Rivers
On the Peelhorst and Maasvallei are, the currently visible deposits from the Pleistocene largely date back to the Weichselian Stage. Especially during its glacial periods, the rivers transported a lot of material from the hinterland, significantly expanding the delta in the North Sea basin. This delta mainly consists of sandy and gravelly sediments from the predecessors of the Rhine and Meuse. The fact that rivers transport large masses of sand and gravel during ice ages is related to the worsening climate during those periods. The soils were completely or partially frozen, and vegetation significantly declined. Under these conditions, substantial amounts of meltwater are released in a short time during spring or summer, greatly enhancing the runoff of soil material. This led to the formation of so-called 'braided rivers,' that are characterized by a wide floodplain with many channels that are almost dry for much of the year (Figure 27).

During wet periods, the fast-flowing river carries large amounts of water and sediment for a short time. The floodplain is then largely underwater, and the channels shift rapidly, with sand and gravel bars (shoals) being continuously eroded and rebuilt elsewhere. The appearance of the floodplain can thus change significantly in a short time.
In the Roer Valley Graben, the coarse sandy deposits of the braided Rhine and Meuse are about 70 meters thick. They lie here 25 to 50 meters below the surface (see also Figure 23). In the relatively rising areas of the Peelhorst, these river deposits are thinner. The river deposits from the ice ages now form an important source of coarse sand and gravel for use as construction materials and are therefore exploited at various places.

Cover sand
Only in a few parts of Geopark do the Pleistocene river sands lie at the surface. Almost everywhere else, they are covered by a sand layer that was deposited by the wind at the end of the Late Glacial, from about 30,000 to 12,000 years ago. Under extremely cold and dry climate conditions, the wind in the then 'polar desert' took hold of the sparsely vegetated soil, causing it to drift. The sandy valley floors of the braided rivers and streams were particularly susceptible to drifting. Almost the entire landscape became covered with this sand, which is therefore called 'cover sand.' A lot of cover sand ended up in the Roer Valley Graben (Figure 18). Here, on the gravelly deposits of the braided Meuse (Maas) and Rhine, there is a sand layer up to 30 meters thick, consisting of cover sand, interspersed with loamy sand deposited by streams and surface runoff. Only the upper part of these sediments dates from the last ice age; at the bottom are cover sand and stream deposits from previous ice ages. On the Peelhorst, the cover sand is at most a few meters thick and sometimes completely absent.

Time travel through the Holocene

Climate gets warmer
The Holocene is the warm period that began about 12,000 years ago and continues to this day. The improvement in climate brought significant changes to the landscape. Due to the milder climate, vegetation could thicken into a closed forest that covered the entire landscape. The water discharge through rivers and streams became more uniform, and they changed from braided to meandering watercourses. Globally, the ice caps melted, causing the sea level to rise by more than 100 meters. The North Sea area disappeared underwater, and the sea eventually reached as far as the west of the Province of Noord-Brabant.

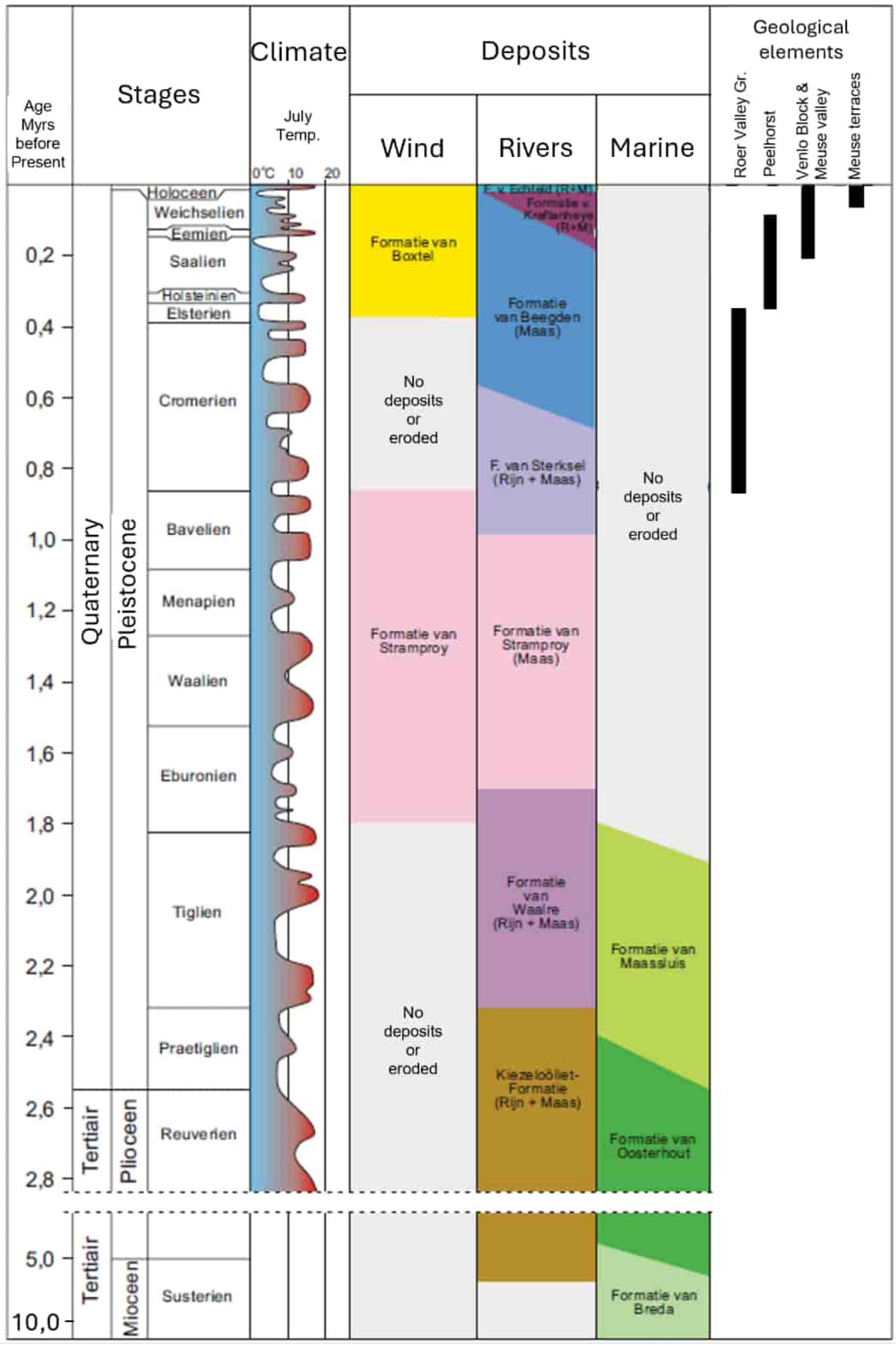

Figure 26 – DRAFT: Geological timeline form the Miocene to Recent, i.e. of the last 10 million years. Just as in archaeology, in geology, names are given to certain time periods and to the depositional layers in the subsurface. On the temperature curve under the heading 'Climate,' the blues represent the ice ages, and the reds represent the warmer interglacial periods. The column 'Geological Elements' shows the approximate ages of the Meuse deposits (Beegden Formation) in the corresponding element. Modified from *Koomen et al., 2007.*

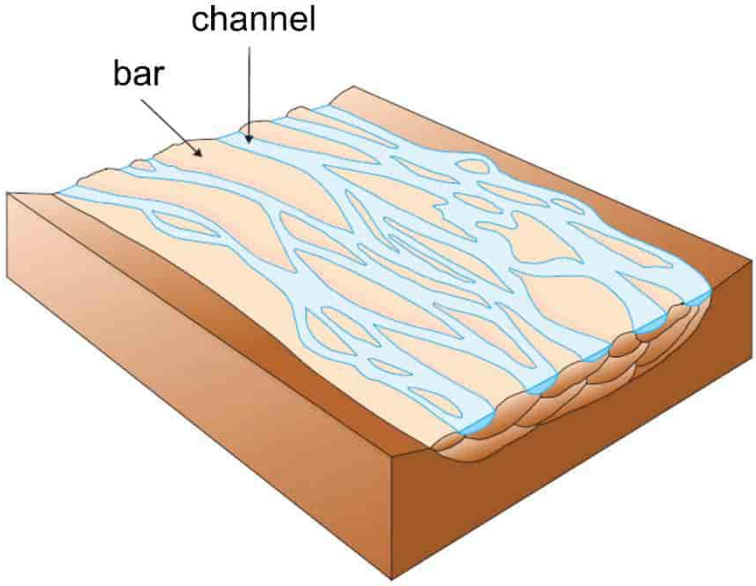

Figure 27 – Diagram of a braided river. Modified from *Koomen et al., 2007*.

Natural levees and floodplains
At the relative warm onset of the Late Glacial (Allerød and Bølling), the Meuse changed from a braided to an exceptionally broad meandering river. Subsequently, during the Younger Dryas glacial, incised braided river valleys formed for a relatively short time (~1200 yr). At the beginning of the Holocene, warmer conditions returned and the Meuse is a meandering river ever since. Although less extensive than during the Allerød and Bølling, the meandering river formed distinct bends, or meanders. In the outer bend, the water flows faster, causing the cut bank to be eroded. In the inner bend, the water flows more slowly, and sand and clay are deposited on the point bar. This process causes the bends to become wider, creating large loops in the river. Eventually, the meander bends meet, and the river cuts off its own meander loop. The cut-off meander loop remains in the landscape as an abandoned river arm (a so-called horseshoe lake). Over time, the abandoned channel becomes completely filled and remains visible only as a slightly lower, wet strip in the landscape. A meandering river also experiences periods of high water discharge, for example, when there is a lot of rain in the hinterland. The river then overflows its banks. Just outside the riverbed, the speed of the inland-flowing water decreases, and mainly fine sand settles. Over the years, this process creates natural levees (ridges) directly next to the riverbed, which are relatively high and can be considered as more or less natural dikes. The old villages, roads, and fields are located on the natural levees of the Meuse, which are several tens to several hundreds of meters wide. In the lower floodplains behind the levee, river clay is deposited. The floodplains have wet, heavy clay soils and are now open grassland areas.

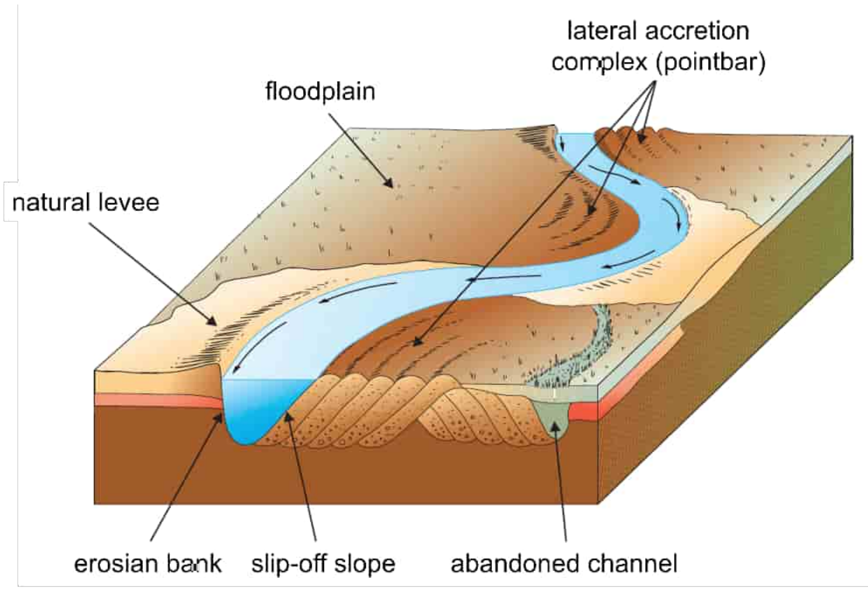

Figure 28 – Diagram of a meandering river. Modified from *Koomen et al., 2007.*

Raised bogs

Most of the Peelhorst, the area known as the Peel, has the shape of an extensive, very flat plateau. This flat terrain is the main reason why extensive marshes could form here because there were no slopes or stream valleys to drain the water. This, however, was not always the case. During the last ice age, there were still meltwater valleys on the horst. At the end of the last ice age, however, these valleys were filled with blown-in cover sand. A plateau with an irregular relief of shallow basins and low cover sand ridges was formed. When it got warmer and more humid after the last ice age, the basins filled with water, creating a landscape with numerous small lakes. After the Last Ice Age, plant growth also returned. The lakes (fens) became overgrown with reeds, sedges, and rushes, and peat began to form (Figure 29). As plant remains in the water do not decompose, the fen slowly filled with peat and became overgrown. This peat, which is nourished by mineral-rich stream or groundwater, is called 'low peat' (laagveen). Low peat can develop into raised bog (hoogveen) if the peat layer becomes thicker and the groundwater is out of reach of the roots of the marsh plants. The plants then only have access to rainwater, which contains few nutrients. Sphagnum moss is one of the plants that can grow under these poor conditions. The dying moss plants are not decomposed in the wet environment and form a good substrate for new moss plants. Sphagnum moss also acts like a sponge. It retains water very well, keeping the marsh soaking wet even as it rises higher. This creates a so-called raised bog cushion that can grow to more than ten meters thick. Raised bog cushions (or domes) can also expand laterally over originally drier areas, such as cover sand ridges. At the peak of peat growth, about 4,000 years ago, raised bogs with diameters of kilometres formed on the Peelhorst, and the raised bog eventually reached an area of 30,000 hectares. Only remnants of the raised bog domes now remain. Medieval people managed to drain the extensive peatlands by digging ditches and canals. Moreover, peat proved to be an excellent fuel. Many peatlands were completely lost due to peat extraction.

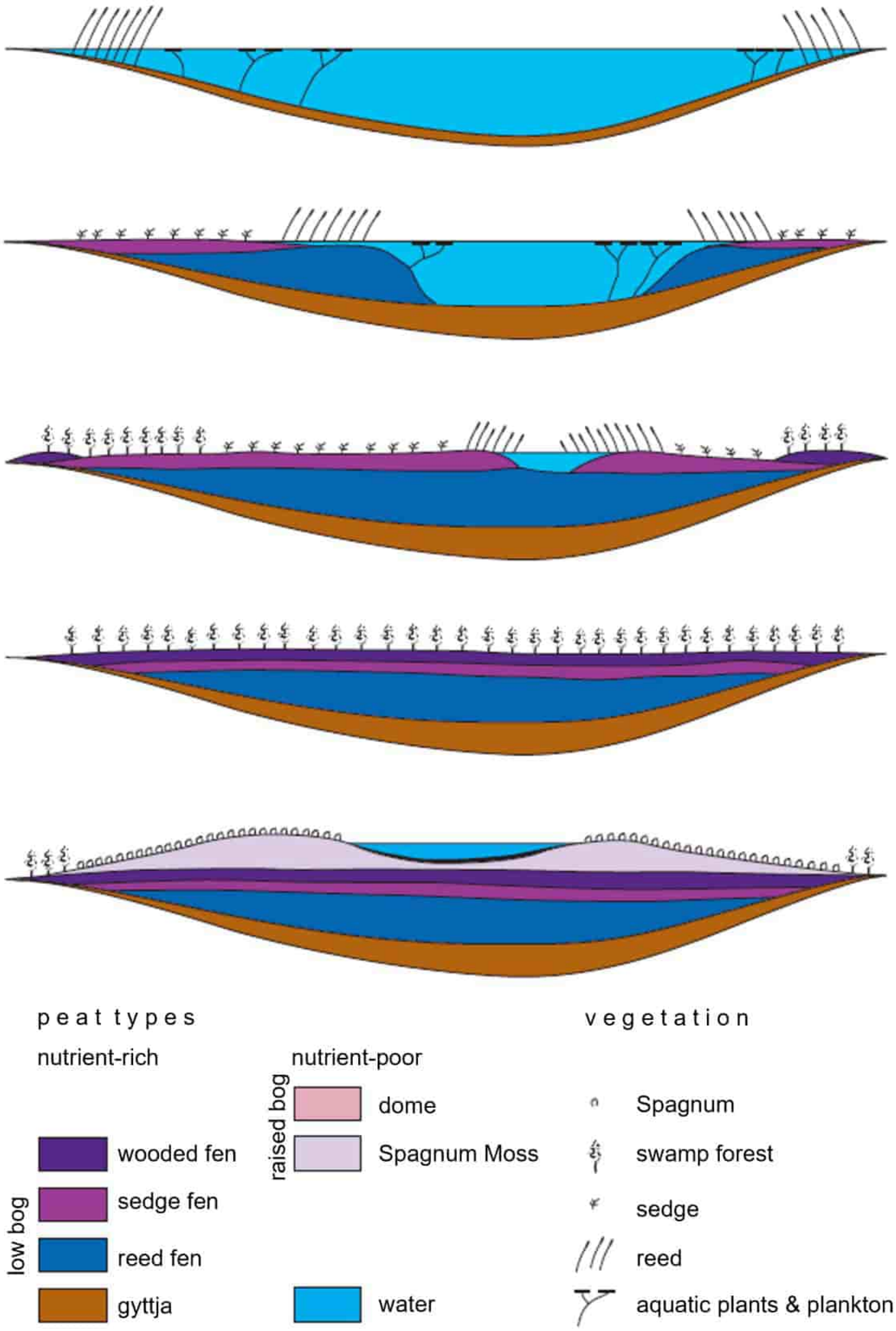

Figure 29 - The formation of low peat and raised bogs. A body of water becomes overgrown and fills with low peat. This nutrient-rich peat develops into an increasingly nutrient-poor type of peat. Eventually, the marsh is fed by rainwater and becomes nutrient-poor enough for sphagnum moss to establish itself and dominate other plant species (Modified from *Koomen et al., 2007*, after *Visscher, 1949* and *Berendsen, 2005*).

The human touch

Early habitants

About 6000 years ago, humans in Northwest Europe began to leave their mark on the development of the landscape. Until then, our prehistoric ancestors lived off what the primeval forest had to offer. They hunted wild animals and gathered fruits and roots. They did not live in fixed places but in hunting camps. These were set up near ponds and streams, where water was available and where the game gathered to drink. Humans gradually began to use the forest more intensively. During the Stone Age (before 4100 years ago), more and more trees were cut down for the production of firewood and construction wood. During the Bronze Age (4100 to 2600 years ago), shifting cultivation became popular, and patches of forest were cleared for the creation of small plots of land. However, fields on the nutrient-poor cover sand soils were exhausted after a few harvests. Farmers had to constantly move to new plots of land. It took about 25 years for the abandoned fields to become sufficiently fertile again for reuse under secondary forest.
In the Iron Age, starting around 2600 years ago, deforestation accelerated. A huge amount of oak wood was needed to produce charcoal for smelting iron. The forests could no longer recover, so by Roman times, large areas of forest had degraded into heathlands. After the Roman period, the forests somewhat recovered as the population decreased. In the Middle Ages, the population increased again, and land use intensified further. Many predecessors of the current villages and towns appeared on the cover sand ridges. For centuries, soil fertility remained the greatest concern of the farmers was how to make productive fields on poor soil? The wet parts, such as stream valleys, marshes, and low sand grounds, would remain almost uninhabited and unused for hundreds of years. Between the tenth and twentieth centuries, these areas were gradually drained and reclaimed

The peat invades

Until about 4,000 years ago, the cover sand ridges in the Peel landscape were habitable. After that, people were driven out of the area as the peat domes completely overgrew the cover sand ridges. In the Middle Ages, the Peel marshes became a gigantic and inaccessible marsh barrier on the border of Brabant and Limburg. Archaeological finds still remind us of life on the 'drowned' cover sand ridges. When habitation was no longer possible, pre-Christian people still came to the marshes to connect with the world of the gods. In 1910, a gilded silver Roman military parade helmet was found near Helenaveen. This so-called 'Helmet of Deurne' is probably an offering to a peat god Figure 30).

Figure 30 – The Golden Helmet of Deurne was discovered in 1910 by Gebbel Smolenaar, Gebbel Smolenaars, Loeves Pier en Driekske Slaats, peat cutters from Meijel. The helmet is currently exposed in the Rijksmuseum of Oudheden in Leiden

Peat extraction by farmers

The peatland only became attractive to humans again when wood as a fuel became scarce. From the Middle Ages, farmers began to dig peat on a small scale at the edges of the marshes. They dried the peat and burned or sold the resulting turf. Over the centuries, large peat marshes were dug away down to the underlying sand. The excavated areas were abandoned, leading to the formation of extensive heathlands. In addition to peat extraction by farmers, there was also systematic peat extraction. For example, from the monastery Padua, founded in 1742, the peatlands around Boekel were systematically excavated. The monks transformed the excavated sandy soils into agricultural land.

Industrial Peat Extraction

Large-scale peat extraction in the Peel began much later than in, for example, West Brabant, where turf was already being extracted on a large scale in the Middle Ages. This was due to the proximity of markets and the better transport options in West Brabant and South Holland. The construction of canals such as the Zuid-Willemsvaart, the Noordervaart, the Helenavaart, and the Deurne Canal was a significant stimulus for peat extraction in the Peel. In 1853, the Van de Griendt brothers bought 610 hectares of peatland from the municipality of Deurne and started the first industrial peat company. Large areas on the edges of the Peel had already been excavated by farmers and monasteries, but the thickest peat layers remained. The industrial method of peat extraction followed a strict pattern, employing hundreds of peat workers. In the peak year of 1893 alone, about 700 peat workers worked for the Griendtsveen company. That year, they excavated 107 hectares of peat marsh, producing 960,000 m³ of turf.

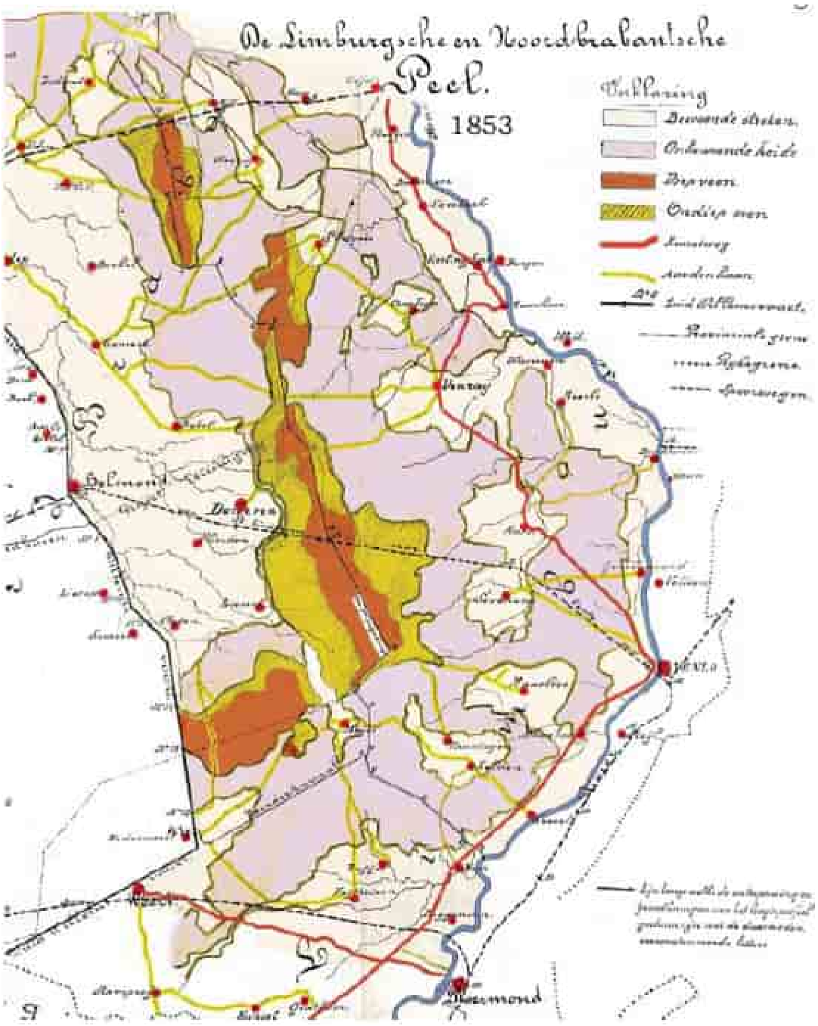

Figure 31 – Map from around 1850 showing the fens on the Peelhorst and the Groote Peel along the watershed between the provinces of Limburg and Noord-Brabant.

Changing agricultural landscapes

Until 1900, a relatively small part of the Brabant landscape consisted of fields. A much larger part consisted of vast heathlands, which initially arose from deforestation and forest degradation. To maintain the fertility of the fields, farmers used manure from sheep that grazed on the heath. In the evenings, the flocks returned to the barns in the village, where the manure was collected on a bed of heather litter. The farmers spread the mixture of litter and manure on the fields. If there was a shortage of manure, the heath was not only mowed but also turfed. The entire sod was then removed and used as litter in sheepfolds. This method succeeded in giving the fields good fertility. However, grazing and turfing made the heath soil increasingly poorer.

Figure 32 - The higher elevation and bulging shape of old fields are usually clearly visible in the landscape, as seen here near Bakel (source: *https://www.landvandepeel.nl*).

The old arable lands are known in the south of the Netherlands as 'es'. In North Brabant, they are often referred to as 'akkers' or 'oude akkers'. The applied manure contained not only humus but also sand grains. By applying sandy manure to the field for centuries, the field layer became increasingly thicker, sometimes even more than a meter. The old fields therefore lie visibly higher than the immediate surroundings and are also called 'bulging fields' (Figure 32). Occasionally, various objects and waste residues were added to the field layer with the manure. Because many remains of old habitation have been preserved under and in the 'enk' covers, they are archaeologically valuable pieces of the soil archive.
Until 1900, the villages with their fields lay like cultural landscape islands in large open heathlands. Most of these heathlands were converted into farmland or forest in the last century. However, some beautiful heathlands still remain.
Nowadays, a large part of the Peelhorst consists of young agricultural landscapes. Sometimes these areas are the result of the planned completion of industrially excavated peatlands. In other cases, heathlands were reclaimed that had sometimes been created centuries earlier from farmer peat extractions. In yet other cases, heathlands were reclaimed that had never been covered by peat.

Figure 33 - The large-scale, geometric parceling pattern of the landscape of the recent reclamations on the Peelhorst is clearly recognizable on the topographic map, as seen here in the Wanroijsche Peel north of the village of Landhorst.

Just like in the cover sand area, the heathlands could be used as agricultural land from 1850 onwards thanks to the introduction of artificial fertiliser. The first agricultural reclamations were carried out by farmers, resulting in a small-scale landscape. From the end of the 19th century, municipalities increasingly involved themselves in the reclamation of heathlands and raised bogs. The so-called 'young reclamations' from this time have large plots and widely scattered farms with names like Annahoeve, Rosinahoeve, and Reginahoeve. These reclamations usually have a rectangular and regular layout of plots and roads (Figure 33). They resemble the young reclamations in the cover sand landscape but are much larger in scale. Unlike in the cover sand landscape, they are not interspersed with old fields or stream valleys. Just like in the Dutch polders of the 19^{th} and 20^{th} centuries, this is a new landscape of tens of thousands of hectares. In the lower-lying areas, where the first peatlands once formed, it can still be wet. Here, there is often a dense network of ditches and trenches to promote drainage.

Peat Remnants

Not all the peat has disappeared. Especially in the southern part of the Peel, remnants have been preserved. These are the most extensive raised bog remnants in the Netherlands, but there are no longer large, growing raised bog cushions. The peat has been too drained and harvested, and precipitation and groundwater have become too rich in nutrients due to bio-industry. Nature management in the Groote Peel, as well as in the Deurnsche- and Mariapeel, aims to restore the raised bog landscape. These nature reserves now give an impression of the former vast wildernesses. The canals and peat pits bear witness to the hard life of the peat workers.

Key references

The references listed here are the ones specifically mentioned in the text and figures of this document and can be considered as key references. Note that a full Bibliography (compiled by the Scientific Board of the Geopark Peelhorst & Maasvallei) is presented as Appendix B.

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