

Faculté des sciences

Unraveling the characteristics of the Early and Middle Pleistocene Meuse River : study of the Zutendaal Gravels on the Campine Plateau

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1 Introduction

During the Early and Middle Pleistocene, deposition in low land Europe was mainly fluvial. Climate consisted of an alternation of glacial and interglacial periods, evolving towards colder conditions with the Middle Pleistocene climatic transition (Gibbard and Lewin 2016). Deposition in North-East Belgium was dominated by the Meuse and Rhine rivers, whose course changed several times during the Early and Middle Pleistocene (Westerhoff et al. 2008; Beerten et al. 2018).

The Campine Plateau, located in the North-East of Belgium, is a triangular-shaped geomorphic unit rising above its surrounding (Dreesen 2011; Beerten et al. 2018) (Figure 1.1). Its altitude varies between about 100 m a.s.l. (TAW: Tweede Algemene Waterpassing) in the south and about 30 m in the north. The Plateau results from a relief inversion due to differential erosion, fluvial erosion, uplift and fault activity (Beerten et al. 2018). The shape of the plateau and the gradual downstream fining of the Zutendaal Gravels towards the north (Beerten 2003; Beerten et al. 2018) lead to the common view that the gravels were deposited as an alluvial fan. The Zutendaal Gravels are badly sorted, coarse fluvial gravel from the Vosges and Ardennes including large boulders (Gullentops et al. 2001; Dreesen et al. 2005; De Brue et al. 2015). The gravel sheet is up to 15 m thick in the south and 8 m in the north (Dreesen et al. 2005). The Zutendaal Gravels were deposited by the Meuse between 0.5 and 1 Ma ago (Beerten et al. 2018), but age control and knowledge on the timing of deposition of the gravels remain poor.

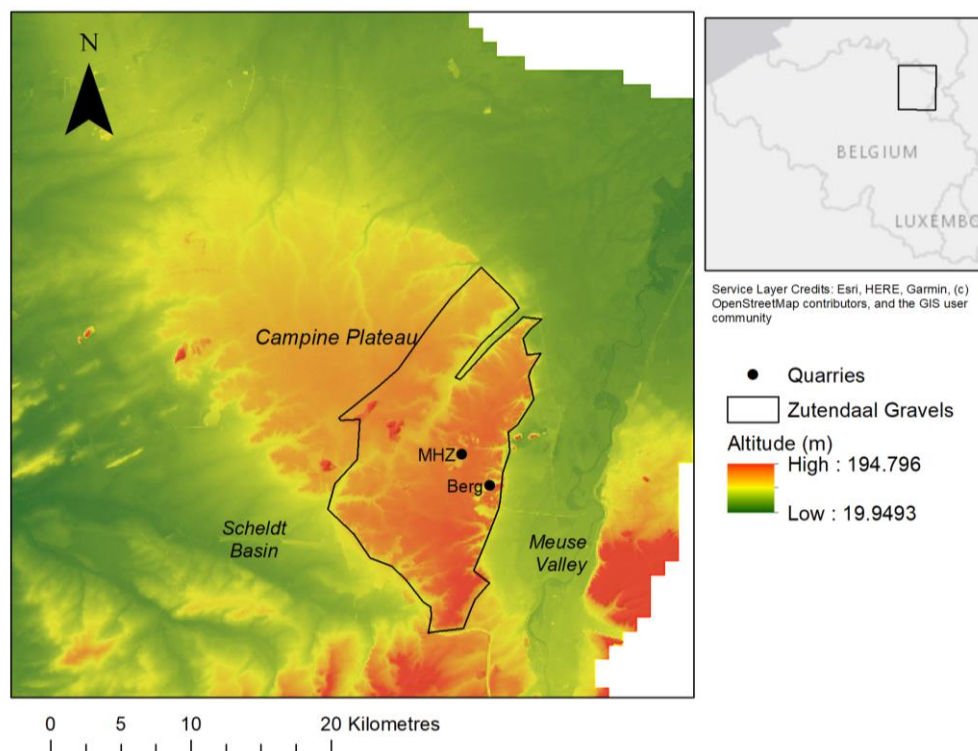


Figure 1.1 Zutendaal Gravels extent and location of the visited quarries (Digitaal Hoogtemodel Vlaanderen II, 100 m resolution, Informatie Vlaanderen 2015).

At the time of deposition, the Meuse was a braided river (Gullentops et al. 1981). Braided rivers consist of multiple intertwined channels between bars and ephemeral islands (Ashmore 2003; Miall 2014). It is a dynamic environment with shifting channels and bar development (Ashmore 2003; Miall 2014). Miall (1996) reviewed and classified river styles, including braided rivers. Miall (1996) identified 18 clastic lithofacies based on the grain size and sedimentary structure. The facies classification includes a corresponding deposits interpretation scheme. Based on facies association and geometry, 10 architectural elements can be recognised. Finally, Miall (1996) classified braided rivers into 6 categories based on constituent architectural elements. Although it is generally accepted that the Zutendaal Gravels were deposited by a braided river, the characteristics of the Meuse and its type of braided river has not yet been studied.

Therefore, this MSc thesis focuses on the following question: What was the depositional environment of the River Meuse during the Pleistocene? What were the palaeoenvironmental conditions of this region?

Three outcrops of the Zutendaal Gravels were studied in two active quarries (Figure 1.1). An overview of units within the sediment sequence was obtained using UAV images and the application of a supervised classification. Samples were also collected to study the grain size distribution.

2 Literature review

2.1 Braided river systems

2.1.1 Characteristics of braided river

The braided pattern is one of the four traditionally described river patterns. The transition between straight, meandering, braided and anastomosing patterns is gradual (van den Berg 1995). Channel style results from the combination of various parameters. The first parameter is the discharge, its variability (Miall 2014), and the channel-forming discharge of the river (Bridge and Demicco 2008). The channel-forming discharge is the discharge assumed to be representative of flood discharges responsible for the steady-state geometry of channels (Bridge and Demicco 2008). The slope, width, depth, velocity, bed roughness and vegetation also influence the planform (Bridge and Demicco 2008; Miall 2014). Finally, the amount and granulometry of the sediment load determine the river pattern as well (Bridge and Demicco 2008; Miall 2014).

The four river patterns can be identified using Rust's classification (1978), which is based on the sinuosity and the braiding parameter (Miall 1996; Bridge and Demicco 2008). The latter is defined as the number of bars or islands per meander wavelength (Bertoldi 2015). Channel patterns are classified as single-channel if their braiding parameter is lower than 1. Those single-channel rivers are then classified into straight if the sinuosity is lower than 1.5 and meandering for higher values of sinuosity. On the other hand, multichannel rivers (braiding parameter >1) are classified as braided if they show a low sinuosity (<1.5) and anastomosing if they show a high sinuosity (>1.5). Rust's classification is widely used, however, Miall (1996) argued that the classification needed revision, especially to include the wandering type. This type is an intermediate style between braiding and meandering. Wandering rivers have a single and relatively stable channel of medium sinuosity but show short braided reaches. Miall (1996) suggested that wandering should be defined as belonging to an intermediate range of 1-3 for the braiding parameter and 1.2-1.5 for sinuosity. Furthermore, the patterns are not mutually exclusive as Rust's classification seems to indicate (Bridge and Demicco 2008; Miall 2014). Each fluvial style corresponds to different conditions and processes. For instance, some braiding and some meandering processes can take place simultaneously in a river, and thus both terms can be used in the description of the river (Miall 2014).

A river is described as braided when its pattern is characterised by multiple, intertwined channels separated by ephemeral bars and islands (Ashmore 2003; Miall 2014). The planform of such rivers is dynamic and complex, with rapidly migrating channels and the development of bars. In braided rivers, channels remain divided at high flow even if some bars may be submerged (Ashmore 2003).

Although anastomosing has been considered synonymous with the braided pattern for a long time (Bridge and Demicco 2008; Miall 2014), the two patterns are now distinguished based on the river planform stability and sinuosity. Anastomosing is rather used for rivers with low- to high-sinuosity, a

network of stable channels and vegetated islands (Miall 1996; Bridge and Demicco 2008; Miall 2014). Nevertheless, the two terms are not mutually exclusive as many rivers can be qualified as braided and anastomosed (Bridge and Demicco 2008). The anastomosing pattern occurs in rivers with low slopes, small stream power, cohesive banks and net aggradation (Miall 2014). Braiding is more likely to develop in laterally unconstrained rivers flowing over a cohesionless bed (Murray and Paola, 1994 cited in Bertoldi 2015).

2.1.2 Development of braided river systems

- Controls on the braided pattern

First, discharge variability is one of the variables that contribute to braiding. A high discharge variability was previously regarded as a major parameter influencing the channel pattern (Miall 1996; Bridge and Demicco 2008; Miall 2014). However, many rivers vary along-stream in channel patterns, and laboratory experiments showed that all patterns could be formed at constant discharge (Bridge 2003 cited in Miall 2014; Bridge and Demicco 2008).

Secondly, stream power is considered to be an important factor for braiding (van den Berg 1995; Ashmore 2003; Bertoldi 2015). It also controls the development of large width-depth ratios, which in turn enhances braiding (Ashmore 2003). The stream power, Ω , is defined as (Bagnold 1966; Bridge and Demicco 2008):

$$\Omega = \rho g Q S \text{ (Equation 2.1)}$$

with ρ : water density [$1000 \text{ kg} \cdot \text{m}^{-3}$], g : gravitational acceleration [$9.8 \text{ m} \cdot \text{s}^{-2}$],

Q : water discharge [$\text{m}^3 \cdot \text{s}^{-1}$], S : channel slope [m/m]

The specific stream or unit stream power is the stream power divided by the flow width (Bagnold 1966). van den Berg (1995) described the ranges of specific stream power that are commonly observed for each river pattern. Straight rivers typically have a unit stream power under 10 Wm^{-2} , then meandering rivers have stream power up to 60 Wm^{-2} . Braided patterns are observed in rivers with a specific stream power between 50 and 300 Wm^{-2} , and wandering gravel rivers between 300 and 600 Wm^{-2} . Empirical data show that the upper and lower boundaries for the different classes vary widely, and threshold values of specific stream power increase with grain size (van den Berg 1995). Therefore, braiding may be observed at lower stream power values in finer sediments (van den Berg 1995; Ashmore 2003; Bridge and Demicco 2008; Miall 2014).

Thirdly, the channel slope, S , influences the fluvimorphology via its influence on the stream power. For a given sediment size, the width-depth ratio and degree of braiding increase with valley slope (Bridge and Demicco 2008). And for a given discharge, braiding occurs on steeper slopes than meandering (Miall 2014).

Fourthly, the characteristics of the sediment and sediment load also influence the channel pattern. Braiding develops spontaneously for unconfined flow over non-cohesive and mobile sediment

(Ashmore 2003). A high load of coarse-grained sediment on the river bed is, according to Miall (1996) and Bertoldi (2015), one of the primary factors for braiding. However, early studies from which those conclusions were drawn were not representative of the global diversity of braided rivers as many braided rivers actually transport a large amount of suspended load relative to the bedload (Bridge and Demicco 2008). Heterogeneous sediment load contributes to braiding in transport-limited systems as sediment bars develop by deposition of material that the river cannot transport. Deposition occurs without braiding in supply-limited systems (Leopold and Wolman 1957 cited in Miall 2014).

Finally, erodible river banks are a primary condition for braiding (van den Berg 1995; Bertoldi 2015). Confined rivers with erosion-resistant banks typically have a lower width-depth ratio, hence a higher transport capacity and lower likelihood for deposition of bedload (Miall 2014). If the banks are more resistant than the bars, the latter are removed as flow increases (Miall 2014). The banks must, therefore, also be erodible enough for lateral migration of the river and the development of a braided pattern. Vegetation can influence braiding directly via stabilisation of the river banks by dense root networks or indirectly via its impact on discharge characteristics and sediment load (Miall 1996).

Although the five above-mentioned controls on braiding are commonly reported, there is no consensus on their relative importance. van den Berg (1995) suggests that bedload transport and erodibility of river banks are the two necessary conditions for braiding and considers that discharge variability is less important. Instead, Miall (2014) points to the importance of discharge variability and adds the channel slope gradient to the set of criteria that need to be fulfilled for the development of braiding.

- **Climate and river pattern**

Based on the study of river terraces in the Meuse valley, Ruegg (1993) suggested that there is a direct link between the river pattern and the climate conditions, whereby a braided pattern is characteristic of cold conditions and a meandering pattern of warm conditions (Vandenberghe 1995). Vandenberghe (1995, 2008) revised this linear model, and he developed a non-linear model of fluvial development during cold-warm cycles in lowland regions. Vandenberghe (1995) argues that although river processes are conditioned by a complex combination of physical parameters, most of them are determined by vegetation. The evolution of river patterns is, therefore, a function of climate but modulated by vegetation.

When all other factors are constant, the transition from a warm to a colder climate is expected to enhance braiding (Vandenberghe 1995, 2008). First, the drop in temperature lowers evapotranspiration and thus increases the water yield. For a certain time, the vegetation adapts to colder conditions, and it protects the soils from erosion. Consequently, the discharge to sediment yield ratio rises which facilitates river incision. This is expected to result in a shallow incision over the entire channel width, producing width-depth ratios that are characteristic of braided and wandering rivers. The persistence of cold conditions gradually decreases the protective vegetation cover, and the exposed hillslopes supply more sediment to the river causing transport-limited conditions and rapid

channel aggradation. After this short phase of incision and aggradation, a longer period of stability is predicted to follow with the formation of a laterally shifting floodplain. This stable period is characterised by the development of wide laterally migrating channels and bars. Those deposits would be shallower than the channel fills that were rapidly formed towards the end of the unstable phase.

Conversely, a meandering or anastomosing pattern can appear following a cold to warm transition (Vandenberghe 1995, 2008). As the climate warms again, the vegetation on the hillslopes needs time to recover, leading to a first instability phase. At the start of the warm period, the evapotranspiration is low, and the discharges are characteristically high. With time, the system comes back to equilibrium. As vegetation and soils develop, the sediment supply from the hillslopes to the rivers decreases, resulting in a deep fluvial incision and adoption of a meandering or anastomosing pattern. Rivers then typically have a small width-depth ration and a constrained and stable floodplain (Vandenberghe 2008).

According to the nonlinear model, there should be twice as many incision-aggradation cycles (and terrace levels) as climatic cycles. However, there are fewer incision phases than climatic transitions observed in the sediment record (Vandenberghe 2008) which can be explained by the preservation potential of the sedimentary bodies. Braided rivers tend to remove sediments of previous meandering systems because of their large lateral extent and potentially high energy. Meandering systems have only a limited lateral extent, and thus a large part of the previous floodplain is preserved. The cold-warm erosion features are typically deep but narrow, therefore, those features are less likely to be preserved than the warm-cold transition features. Similarly, the floodplains from the warm period are rarely observed because meandering rivers form constrained floodplains and are laterally much smaller.

2.1.3 Examples of Early and Middle Pleistocene braided rivers in lowland Europe

During the Early and Middle Pleistocene, the Thames and the Bytham river, which were braided rivers, deposited sediments in East Anglia (Rose et al. 1999; Rose 2009). Their deposits respectively make up the Kesgrave Sands and Gravels and the Bytham Sands and Gravels. The Kesgrave Sands and Gravels were deposited between 1.7 Ma and 0.45 Ma (Rose et al. 1999). Rose et al. (1999) studied the deposits' organic matter content that is indicative of tundra vegetation and a corresponding periglacial environment. The majority of the sediments of the Kesgrave Sands and Gravels were deposited under those conditions by a braided river Thames. However, there are also signs of temperate fauna and flora in some of the organic deposits. The sediments of those temperate periods have a limited extent and were deposited in a single channel, probably from a meandering river. Several palaeosols have been identified in the Thames deposits and constitute another evidence of the climatic variations that took place during the deposition of the gravel pack (Rose et al. 1999). Similar to the Kesgrave Sands and Gravels, the Bytham Gravels and Sands also show evidence of alternation between cold and temperate climates and comprise palaeosols (Rose 2009). The majority of the gravel pack is made up of coarse sediment deposited by a braided river system. Fine sediment is not rare and represents

overbank sediments from a single channel river or channel infill in the floodplain. Palaeobotanical proxies show that those fine sediments were deposited under temperate to Mediterranean climates (Rose 2009).

Gibbard and Lewin (2002) summarised the observations of fluvial sedimentation patterns for lowland Britain for the Middle to Late Pleistocene. They identified 6 fluvial phases during glacial-interglacial cycles and their typical channel forms, sediments, depositional systems and vegetation (Table 2.1).

Table 2.1 Interglacial and glacial fluvial sedimentation pattern during the Middle to Late Pleistocene, summary for lowland Britain (Gibbard and Lewin 2002).

Fluvial phase	Channels	sediment	Depositional system	Vegetation
Full and late-glacial	Braided	Gravel and sand Inorganic	laterally shifting floodplain deposition	Herb-dominated Discontinuous cover
Phase 1	Multiple	Marl, tufa, organic mud, silt Increasingly organic, fossil-rich	Infill of channels and depressions	Interglacial forest
Phase 2	Few to multiple, anastomosing	Clay, silt, peat Organic, fossil-rich	Infill of channels and depressions, as sheets in the floodplain	Interglacial, dense, deciduous forest
Phase 3	Meandering, anastomosing	Clay, silt, peat Organic, fossil-rich	Infill of the remaining floodplain depressions	Interglacial, dense, deciduous forest
Phase 4	Single or multiple	Silt, clays Increasingly inorganic, plant and animal remains	Floodplain planar surface	Mixed deciduous-coniferous forest
Early glacial	(?)	Sand, silts and clay drapes, Inorganic	Enlarging channels, lateral accretion, floodplain splays	Forest to shrub and then herb-dominated
Early full-glacial	Single (?)	Increasingly coarse (?), inorganic	Incision and gullyng	Herb-dominated discontinuous

2.2 Braided river deposits

2.2.1 Facies and architectural elements classifications

Miall (1996) developed a classification of rivers based on lithofacies and architectural element analysis.

- Braided river facies

Lithofacies described by Miall (1996) are primarily classified based on texture, grain size, bedding and sedimentary structures. Their names refer to the dominant grain size and characteristic texture or structure.

The main controlling factor for gravel transport and gravel facies deposition is the river flow and sediment concentration. Two types of processes can be differentiated. First, turbulent flows with low sediment concentrations commonly result in clasts imbrication, i.e. orientation of each clast along the plane formed by the long and intermediate axis dipping upstream (planar-cross-bedded gravel and trough-cross-bedded gravel) (Table 2.2). The variation of flow and transport rates leads to gravel deposition in pulses. The second type is sediment-gravity flow, i.e. flow with higher sediment concentration and less turbulent flow. When the sediment concentration is moderate, it leads to crude lamination and imbrication of clast. In hyperconcentrated flow (>40% sediment concentration),

inverse grading and isolated large clasts are common. At even higher sediment concentration occurs debris flow where there is little sorting but there can be a crude clast grading. As the clay content decreases deposits evolve from matrix-supported gravel (when low clast content), clast-supported massive gravel (intermediate clast content) and clast-supported inverse-graded gravel (high clast content) to matrix-supported massive gravel (Table 2.2).

Table 2.2 Gravel facies classification (Miall 1996).

Facies	Sediment structure and texture	Geometry	Interpretation
Trough-Cross-Bedded gravel (Gt)	Trough cross-beds	Erosional base, shallow scoop-shaped (typically < 3 m deep and 1-12 m wide).	Minor channel fills
Planar-Cross-Bedded Gravel (Gp)	Planar cross-beds, textural variation	Typically < 1 m	Transverse bedforms
Matrix-supported Massive Gravel (Gmm)	Weak grading, poorly sorted clast, poorly sorted matrix of sand silt and mud	Sharp non-erosional boundary with underlying beds Convex-up margin	High-strength debris flow
Matrix-supported Gravel (Gmg)	Inverse to normal grading, poorly sorted clast, poorly sorted matrix of sand silt and mud	Sharp non-erosional boundary with underlying beds Convex-up margin	Low-strength debris flow
Clast-supported, inverse-graded gravel (Gci)	Inverse grading	-	Clast-rich high-strength debris flow or low-strength debris flow
Clast-supported, massive gravel (Gcm)	-	-	Low-strength debris flow
Clast-supported, horizontally Stratified gravel (Gh)	Horizontal bedding, imbrication, clast framework and sand matrix	Typically a few centimetres thick individually, several metres thick multistorey units.	Longitudinal bedforms, lag deposits, sieve deposits

Sand can be transported as bedload and by intermittent suspension. Grain size, flow velocity and flow depth are the three main parameters determining sand bedform morphology. Ripples form at low flow velocities and median sediment sizes. Dunes occur at higher median sizes and flow velocities. For a given grain size, 2D dunes form at lower flow speeds than 3D dunes. Antidunes occur at very high flow velocities. Upper plan bed configuration results from high flow velocities and small sediment size. The sand lithofacies are classified by Miall (1996) based on the structures, which results from the bedform morphology, but the grain size is not used as a key criterion (Table 2.3).

Table 2.3 Sand facies classification (Miall 1996).

Facies	Sediment structure and texture	Geometry	Interpretation
Trough-Cross-Bedded Sand (St)	Solitary or grouped trough cross-beds Fine to very coarse sand, may be pebbly	Erosional base, set are usually <1 m thick	Migration of 3D dunes
Planar-Cross-Bedded Sand (Sp)	Solitary or grouped planar cross-beds Fine to very coarse sand, may be pebbly	Flat upper and lower boundaries	Migrating 2D dunes
Ripple Cross-Laminated Sand (Sr)	Ripple cross-lamination Very fine to coarse sand	Ripples are <5 cm high	Ripples migration
Horizontally Bedded Sand (Sh)	Horizontal lamination parting lineation Very fine to coarse sand, may be pebbly	-	Plane-bed flow
Low-Angle Cross-Bedded Sand (Sl)	Low angle cross-beds Very fine to coarse sand, may be pebbly	-	Plane beds deposited on dipping surfaces, humpback or washed-out dunes, antidunes
Scour-Fill Sand (Ss)	Broad to shallow scours Fine to very coarse sand, may be pebbly	Irregularly shaped base	Rapid deposition of coarse and poorly sorted bedload
Massive Sand (Sm)	Massive or faint lamination Fine to coarse sand	-	Sediment-gravity flow deposits

Fine-grained sediment deposition, transported in suspension, does not take place in active channels but rather in floodplain areas, abandoned channels and abandoned areas of an active channel. Deposits range from proximal floodplain deposits, which are relatively coarse, to finer distal deposits (laminated sand, silt and mud, siltstone and claystone, and massive mud, silt) (Table 2.4).

Table 2.4 Fine-grained clastic facies (Miall 1996).

Facies	Sediment structure and texture	Geometry	Interpretation
Laminated Sand, Silt and Mud (Fl)	Fine lamination, small ripples Mud, silt and very fine sand interlamination. Possible sand bed (Sr) intercalation.	A few centimetres to several metres	Overbank areas
Siltstone, Claystone (Fsm)	Massive Absence of sand	-	Distal floodplain deposit
Massive Mud, Silt (Fm)	Massive with desiccation cracks Mud drape	Typically a few millimetres to a few centimetres	Deposition in pools during low-stage, channel abandonment or most distal floodplain deposits
Root Bed (Fr)	Massive with bioturbation and roots	-	Soil development in humid climate

- Braided rivers architectural elements

Then, Miall (1996) classified architectural elements. An architectural element is defined as a unit of a depositional system with a specific assemblage of facies, an internal geometry, and typical bedform. The definition of elements is therefore based on texture, dimensions (thickness and extent), the bounding surfaces, the external geometry (sheet, lens, u-shaped fill, etc.) and sedimentary structure.

Channels (CH). Channel elements are not characterised by a specific facies' assemblage. However, in fluvial systems, channels are the units where the coarsest deposits are found. Channel elements have a concave-up erosional base, while their size and shape are variable. Internal concave-up erosion

surfaces are common between multistorey fills. Fining-upward, i.e. gradual grain size decrease towards the top, is common in channel fills resulting from simple vertical aggradation.

Gravel bars and bedforms (GB). Gravel bars and bedforms are primarily constituted of clast-supported crudely bedded gravel (Gh) and stratified gravels (Gp and Gt). Those elements tend to form tabular bodies such as lenses and blankets and are often interbedded with lenses or sheets of sandy bedforms. Sediment gravity-flow deposits may also be interbedded with GB elements. Multistorey sheets of GB element typically are tens to hundreds of metres thick.

Sandy bedforms (SB). Sandy bedforms are composed of any assemblage of sand facies. They form lenses, sheets, blankets or wedges. They occur as channel fills, crevasse splays (sediments surrounding channels that broke through its levees (Aslan 2013)) or minor bars. A typical example of SB elements is a shallow channel-fill upward-coarsening assemblage dominated by planar-cross-bedded sand deposits. Other examples include channel floor deposits with 3D dunes, bar-top assemblages with ripple cross-laminated sand, crevasse splay and channel deposits and distal floodplain sand sheet with fining-upward cycles.

Downstream-accretion macroform (DA). The downstream-accretion macroforms can be made up of any of the sand facies. Those architectural elements appear as lenses overlaying a flat or channelled base with convex-up internal erosion surfaces. In sand-bed rivers, those architectural elements are the result of accretion within sediment bar complexes. DA element may laterally grade to LA architecture.

Lateral-accretion macroform (LA). Lateral-accretion macroforms are composed of any assemblage of the sand facies, with sometimes matrix-supported gravel (Gm), and stratified gravel (Gt and Gp). Those macroforms are wedge, sheet or lobe-shaped and display lateral-accretion surfaces. Lateral-accretion macroforms are indicative of mid-channel bars in multiple-channel rivers or point bars.

Laminated sand sheet (LS). Laminated sand sheets resulting from flash floods are made of Sh and Sl facies with some Sp, St or Sr elements. LS units have a flat or lightly scoured erosive base and are between 0.4 and 2.5 m thick.

Scour hollow (HO). This architectural element is scoop-shaped (unlike channels that are cylindrical) and bounded by a concave-up surface at the bottom. It can be up to 20m deep and 250m wide and is present in gravel-braided and sand-braided rivers. Scour hollows are principally composed of an assemblage of clast-supported crudely bedded (Gh) to stratified gravel and sand facies (Gt, St, Sl). The fill is typically asymmetric.

Sediment gravity flows (SG). The principal facies assemblage of sediment gravity flows is a matrix-supported gravel (Gmm and Gmg) and clast supported gravel (Gci and Gcm). It forms lobes or sheets and is commonly interbedded with GB or SB. SG elements have irregular, non-erosive bases, and individual beds are usually between 0.5 and 3 m thick.

Overbank fines (OF). OF elements, composed of FI and Fm facies, form blankets. They are often interbedded with SB elements and may fill abandoned channels. Overbank architectural elements can be further categorised into levees, crevasse channels, crevasse splays, floodplain fines and abandoned channels. However, such overbank deposits do not make up an important part of braided river deposits.

2.2.2 Braided rivers classification

Based on the facies and architectural elements, Miall (1996) suggest fluvial styles models as a framework for the description and analyses of braided systems.

- **Gravel-bed braided rivers**

Gravel-bed braided river with sediment-gravity-flow deposits. This type of braided river is common in alluvial fans. It is characterised by sediment gravity flows, which typically have a tabular shape, convex-up margins and non-erosional bases. For this type of braided river, thin layers of sand and overbank sediments can be observed. The latter correspond to low-water and overbank deposition. Gravel bars and bedforms with a channelised or irregular erosional base can also be observed.

Shallow, gravel-bed braided river (Scott-type). Shallow, gravel-bed braided river deposits are primarily made of gravel bars and bedforms elements (GB). Deposition in low-water areas and overbank deposition can result in thin units of sand and overbank sediments (SB and OF). Sediment gravity flows deposits are rare to absent. Channel depth is usually about 1 m and channel margins are rarely visible. This type of braided channel is also typical in alluvial fans.

Deep, gravel-bed braided river (Donjek-type). Sedimentation is dominated by element GB, but there may be some element LA and DA. Several topographic levels may be identified. The lower level of the channel is similar to the shallow, gravel-bed braided river, and the higher levels, active during flood stages, are characterised by element SB.

- **Sand-bed braided rivers**

Shallow, perennial, sand-bed braided river (Platte-type). Element SB is dominant in shallow, perennial, sand-bed braided rivers. This class of river is characterised by fields of low-flow dunes (either Sp or St). Those rivers are not braided at high stage because water submerges the dunes. The resulting deposits are tabular sandstone sheets.

Deep, perennial, sand-bed braided river. Deep, perennial, sand-bed braided rivers are characterised by internal accretionary geometries and compound bars. The latter typically show fining-up succession and can be classified as LA or DA. Element SB is also present. Overall, the channel topography should be identifiable with the channel floor, bars and bar-tops.

High-energy, sand-bed braided river. The distinctive characteristic of high-energy, sand-bed braided river is the scoop-shaped architectural element HO. Horizontal lamination (Sh) and low angle cross-

bed (SI) are also common. In this type of river, sedimentation occurs during high-energy discharge events.

- Intermediate styles

There is an intermediate class between the low-sinuosity rivers with multiple channels and the ones with a single channel with high-sinuosity. The gravel-bed wandering river is similar to the deep, gravel-bed braided type regarding the facies assemblage. Element LA is predominant, and elements LA and GB are also present. Then the intermediate type for sand-bed rivers is the low sinuosity river with alternate bars. This type of river has only one active low-sinuosity channel. Midchannel and bank-attached bars may be present.

2.3 Lowland Europe during Neogene

The underlying Paleogene deposits in the North Sea basin are mainly marine (Gibbard and Lewin 2016). The Miocene was characterised by progradation in the northwest of the North Sea Basin with the development of the Baltic River or Eridanos delta system (Gibbard and Lewin 2016) (Figure 2.1). In the Roer Valley Rift System (RVRS), the direction of maximum horizontal stress changed to NE-SW and subsidence rates increased (van Balen et al. 2005).

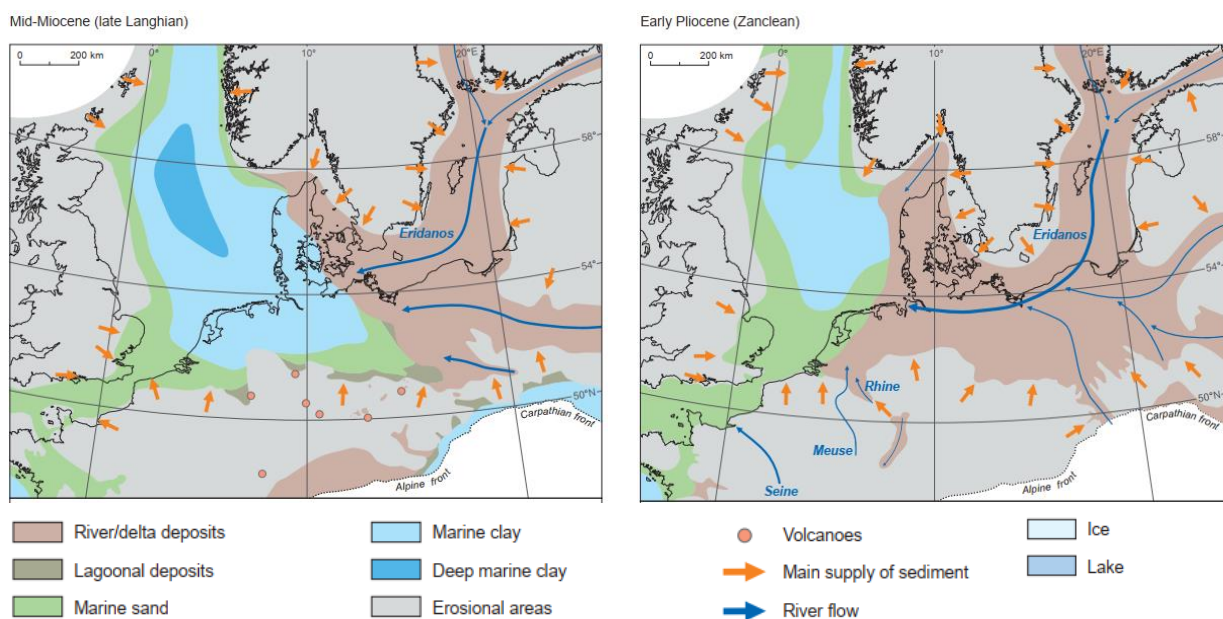


Figure 2.1 Evolution of sedimentation in the North Sea Basin during the Neogene (Gibbard and Lewin 2016).

Deposition on the Campine Block was first continental with the Bolderberg Formation during the Lower Miocene, then marine during the Upper Miocene with the Diest (glauconite-bearing sands) and Kasterlee Formations (glauconitic sands and clays) (Vandenberghe et al. 2020) (Figure 2.2). During the end of the Miocene, in the eastern part of the RVRS, fluvial sediments were deposited (Van Balen et al. 2000; Westerhoff et al. 2008) by a pre-Rhine drainage system which was gradually progressing toward the west (Westerhoff et al. 2008).

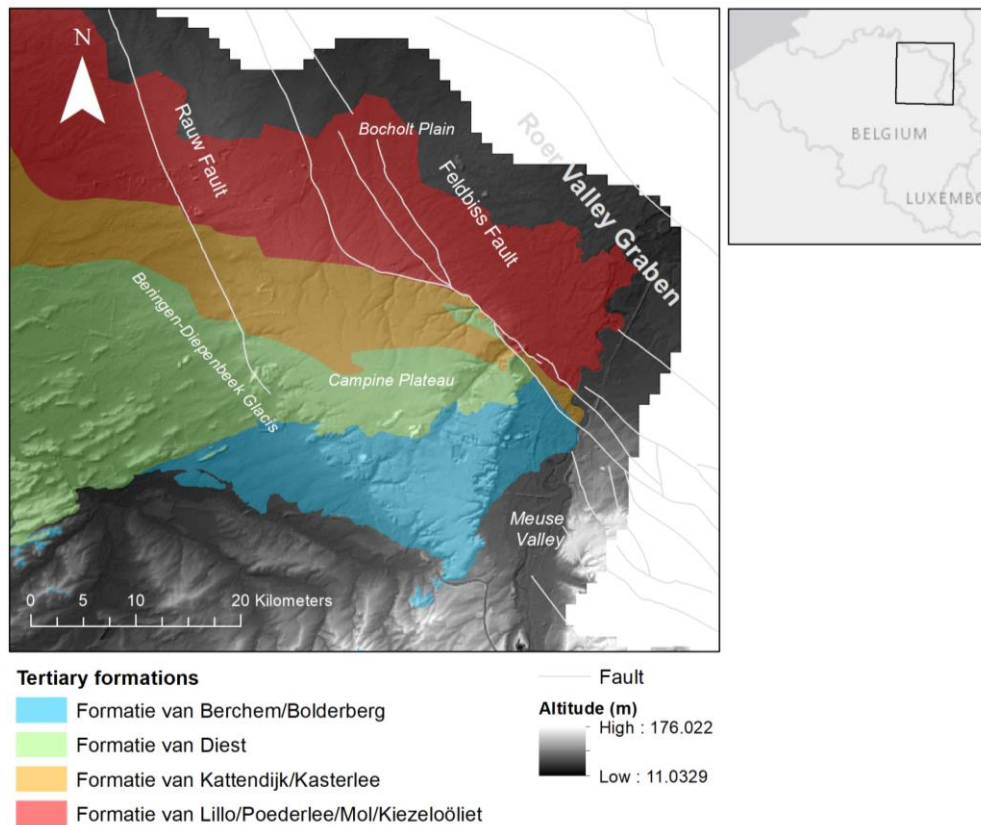


Figure 2.2 Tertiary geological formations in the Campine Plateau area (Geologisch voorkomingsgebied van de Tertiaire formaties van Vlaanderen, Vlaamse overheid, Vlaams Planbureau voor Omgeving 2009), relief (Informatie Vlaanderen 2015), tectonic framework (Verbeeck et al. 2017) and geomorphological units.

During the Pliocene, the Eridanos system continued to extend further towards the west (Gibbard and Lewin 2016) (Figure 2.1). Eridanos dominated the sedimentation in the increasingly subsiding North Sea Basin (Gibbard and Lewin 2016). During the Pliocene, the Meuse system was established in the Ardennes, and only minor changes took place during the Quaternary (Van Balen et al. 2000). By the end of the Pliocene, the Meuse and Rhine confluence was located in the southern part of the Roer Valley Grabben (RVG). The other smaller rivers flowing in the centre and north of Belgium were draining the Campine area towards the north-east, bringing only limited sediment supply to the RVG (Westerhoff et al. 2008). Pliocene deposits in the Campine area consist of estuarine and fluvial sediments (Beerten et al. 2018; Louwye et al. 2020). The former are rich in quartz and called the Mol Formation (Louwye et al. 2020). The latter, the Kieseloolite Formation, was deposited by the Paleo Rhine and is made of quartz-rich white gravel-bearing sands derived from the Rhenish Massif (Westerhoff et al. 2008; Kemna 2008).

2.3.1 Quaternary

- Early Pleistocene

The Early Pleistocene was marked by an alternation of glacial and interglacial periods and a transition towards predominantly cold-periglacial climates (Gibbard and Lewin 2016). The RVRS subsidence continued, first relatively rapidly and then at a lower rate (van Balen et al. 2005). The Eridanos River (Figure 2.3) continued to expand towards the north and the northwest (Gibbard and Lewin 2016). At

that time, the Rhine changed its course gradually towards the east, abandoning the RVG before the end of the Tiglian (1.8 Ma) (Figure A.1 in appendix) (Westerhoff et al. 2008). The Meuse had an eastern course through the palaeo-valley of the East Meuse (Meuse course 1 in Figure 2.4) and deposited sediments in the RVG (Westerhoff et al. 2008).

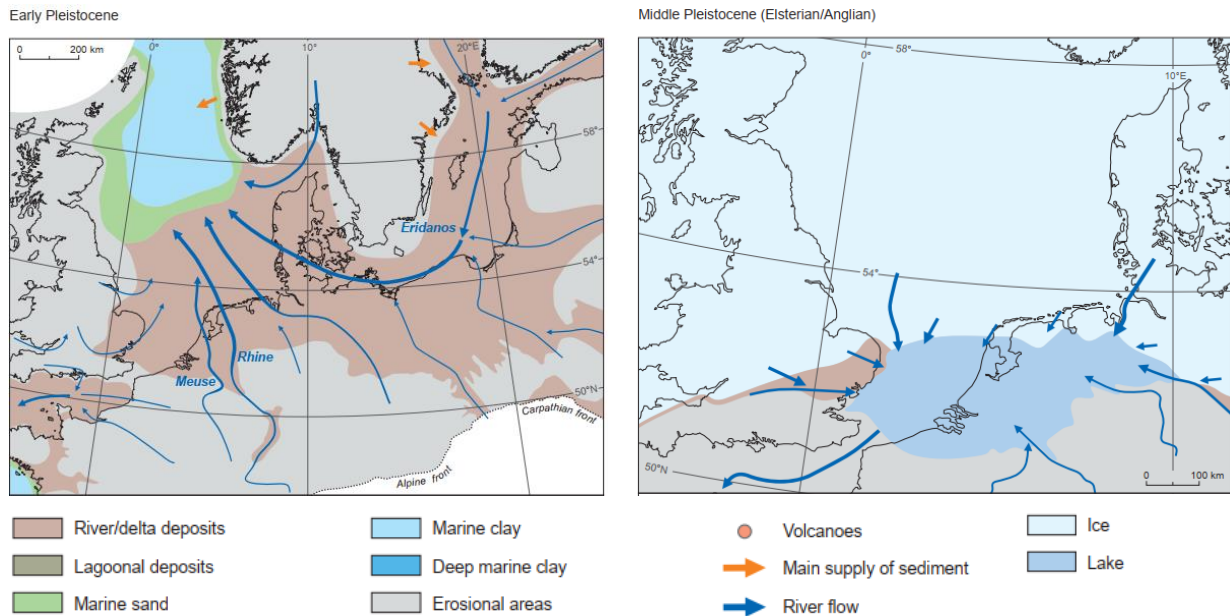


Figure 2.3 Evolution of sedimentation in the North Sea Basin during the Pleistocene (Gibbard and Lewin 2016).

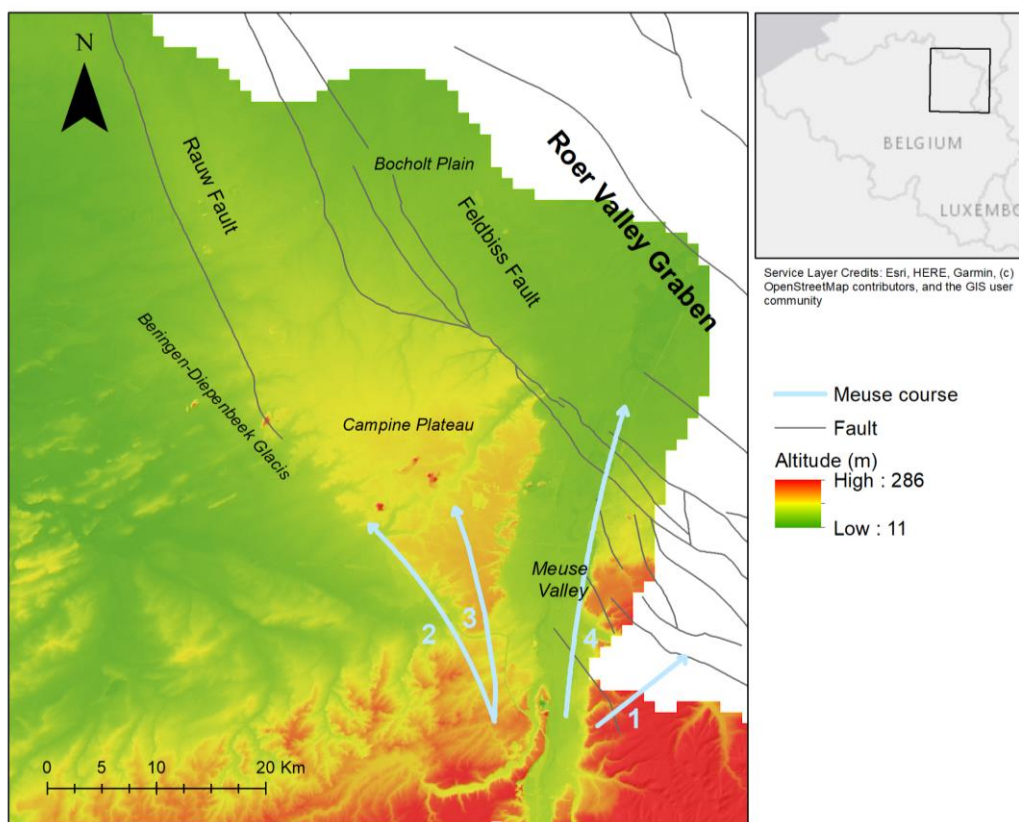


Figure 2.4 Overview of the Campine Plateau with the relief (Informatie Vlaanderen 2015), its tectonic framework (Verbeeck et al. 2017) and geomorphological units. The numbers on the map refer to the past Meuse courses (Beerten et al. 2018), with 4 being its current position.

The Early Pleistocene deposits in the North Sea Basin were primarily fluvial, especially in the shallowest parts of the Basin (Figure 2.3). In the RVRS, the Rhine, Meuse and the other Belgian rivers deposited sediments with a gradually lower quartz content over time (Van Balen et al. 2000). On the Campine Block, deposits from local Belgian rivers are described as the Stramproy Formation (Westerhoff et al. 2008). The Stramproy Formation was deposited from the Tiglian and for most of the Early Pleistocene (Westerhoff et al. 2008), and it consists of quartz-rich fine to coarse-grained sand (Westerhoff 2009).

During the Early-Middle Pleistocene transition, the river network changed on the Campine Block (Beerten et al. 2018). By 1 Ma at the earliest, the Meuse shifted its course (course 2 in Figure 2.4) from the palaeo-valley of the East Meuse to a new western course over the Eastern Campine Block following tectonic movements along the Feldbiss and Rauw Faults, uplift of the Ardennes-Eifel massif and the blockage of the area where the Meuse was flowing in the RVG by sediments (Beerten et al. 2018). During the end of the Early Pleistocene, the Meuse deposited the Winterslag Sands (Gullentops et al. 2001). Around the same time, the course of the Rhine also moved and flowed over the north of the Eastern Campine Block, where it deposited the Sterksel Formation. The Sterksel Formation consists of coarse, gravelly fluvial sands from the Rhine (Gullentops et al. 2001). However, there is some discussion on the definition and chronology of its two members: the Lommel and Bocholt Sands. According to Gullentops et al. (2001), the two members have a different mineralogy. Although they both date from the end of the Early Pleistocene, the Bocholt Sands are considered to be older than the Lommel Sands (Gullentops et al. 2001). An alternative definition of the two members is based on location and suggests the opposite chronology whereby the older Lommel Sands were deposited on the Campine Plateau, and the Bocholt Sands in the north, west of the Feldbiss fault in the RVG (Wouters and Vandenberghe 1994; Beerten et al. 2018). The Lommel-Bocholt Sands ages are not well known. While some authors suggested that they are slightly younger than 1 Ma (Beerten et al. 2018), others suggested that the Lommel Sands are much younger (Middle Pleistocene ca. 0.8-0.6 Ma) (Wouters and Vandenberghe 1994).

- **Middle and Late Pleistocene**

The Middle Pleistocene climatic transition, which took place from 1.2 to 0.8 Ma (Gibbard and Lewin 2016), led to an increase in the severity of glacial minima and more extensive glaciations (Cohen et al. 2014; Gibbard and Lewin 2016). Large ice sheets developed in the Alps, Scandinavia, Wales and Scotland (Gibbard and Lewin 2016). During the Anglian or Elsterian Stage (ca. 450 ka ago), those extensive ice sheets blocked the drainage system in the North Sea Basin and a large lake formed as the Weald-Artois anticline was forming a topographic barrier for outflow to the south (Figure 2.1).

The Middle Pleistocene was marked by an increase of tectonic activity (Wouters and Vandenberghe 1994) with the accelerated uplift of the Campine Block and Ardennes Massif ca. 750 ka ago (Van Balen et al. 2000; van Balen et al. 2005). After 250 ka, the uplift rate of the Ardennes decreased (Van Balen et al. 2000).

During the Middle Pleistocene (by 0.5 Ma at the latest), the Rhine and Meuse had again both shifted their course (Beerten et al. 2018). The Meuse flowed on the eastern part of the now Campine Plateau, and the Rhine shifted towards the north (Beerten et al. 2018) (course 3 on Figure 2.4). The Meuse deposited the Zutendaal Gravels on the Campine Plateau. The Winterslag Sands and Zutendaal Gravels are the two members of the Zutendaal Formation. The Meuse then gradually shifted its course towards the east (Beerten et al. 2018) and deposited the Lanaken Formation during the Upper Cromerian to Early Saalian (Figure A.1 in appendix). Then it deposited fine gravel with sand lenses, the Lanklaar Formation, between the Upper Saalian and the Late Weichselian (Gullentops et al. 2001). The western Vosges Mountains, part of the Meuse river basin, was captured by the Moselle during the Saalien (ca. 0.25 Ma) (Bosch 1992; De Brue et al. 2015). It reduced the Meuse Basin by about 3400 km².

During the Middle to Late Pleistocene, spillover of the large proglacial lake led to the opening of the Strait of Dover (Gibbard and Lewin 2016; Gupta et al. 2017). The opening took place over two major erosion episodes (Anglian glaciation and Wolstonian or Saalian glaciation) (Gibbard and Lewin 2016; Gupta et al. 2017). The event caused the diversion of the Belgian rivers towards the Channel River (Gibbard and Lewin 2016).

- **Holocene**

Nowadays, the Meuse begins on the Plateau of Langres (Bosch 1992) in the Haute Marne Departement, France and has a catchment area of about 33 000km² (e.g., Bosch 1992; De Brue et al. 2015). The Meuse Basin can be divided into 3 sections with characteristic geologies (e.g., Bosch 1992, Van Balen et al. 2000). First, the Lotharingian Meuse section extends from the source to Charleville-Mézières along the eastern edge of the Paris Basin, this section is mostly underlain by Jurassic limestone (Bosch 1992). Then, the Ardennes-Meuse section flows through Cambrian, Devonian and Carboniferous rocks until Liège or Visée (Bosch 1992; De Brue et al. 2015). Finally, the last section, called the Lower-Meuse, flows until its mouth through unconsolidated sediments from the Cenozoic (De Brue et al. 2015).

2.4 Campine Plateau

2.4.1 Location and tectonic framework

The Campine Plateau forms a subregion in the east of the Campine area, which extends over the northeast of Belgium and the south of the Netherlands (Beerten et al. 2018). The plateau is a triangular or fan-shaped geomorphologic unit raising above its surroundings (Dreesen 2011; De Brue et al. 2015; Beerten et al. 2018). This large alluvial structure of more than 7.5 km³ was deposited by the Meuse. The western edge of the plateau is bordered by the Beringen-Diepenbeek Glacis, and the eastern edge by the Bocholt Plain and the Meuse Valley (Beerten et al. 2018) (Figure 2.4).

Geologically speaking, the Campine Plateau is situated at the border between the Campine Basin and the Roer Valley Graben. The Campine Basin is the southernmost part of the North Sea Basin (Beerten et al. 2018). The Campine Basin is bordered in the north by the West Netherlands Basin (Figure 2.5)

(Deckers and Matthijs 2014). In the north-east of the Campine Basin, the Feldbiss fault system marks the border between the Eastern Campine Block and the Roer Valley Graben (Deckers and Matthijs 2014; Beerten et al. 2018). The Eastern Campine Block can be seen as a structural unit in the east of the Campine Basin that is bordered by the Feldbiss fault in the east and the Rauw-Beringen fault in the west. In the south, the Campine Basin is bordered by the London-Brabant Massif (Deckers and Matthijs 2014; Beerten et al. 2018). The main direction of fault systems in the Campine Basin is NW-SE, and it corresponds to the NW-SE maximum horizontal stress direction in place since the Middle to Late Miocene (van Balen et al. 2005).

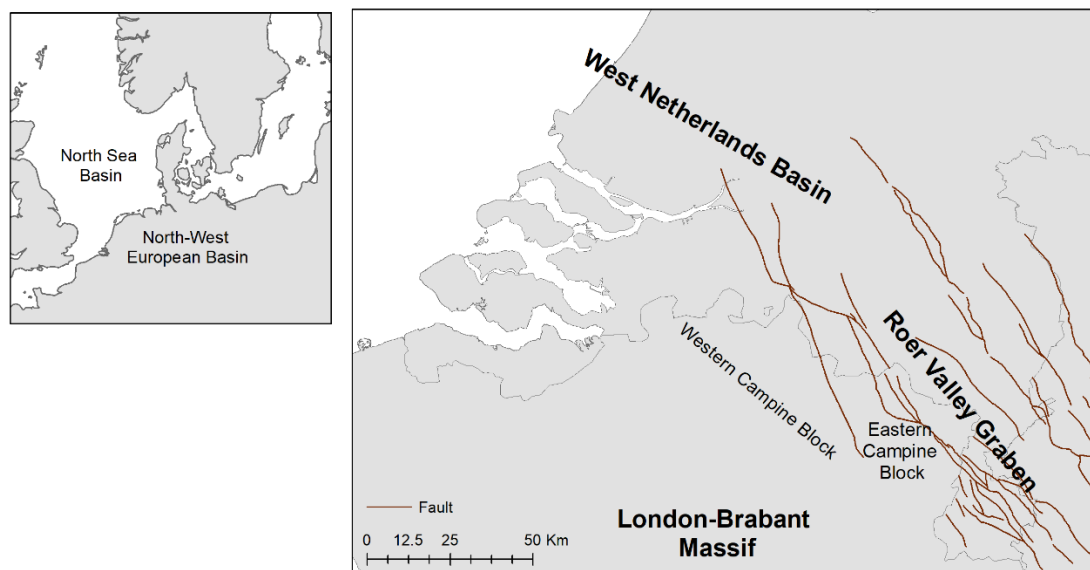


Figure 2.5 Geological framework (Deckers and Matthijs 2014; Gibbard and Lewin 2016; Verbeeck et al. 2017; Beerten et al. 2018)

2.4.2 Geology of the Neogene and Quaternary deposits on the Plateau

- Bolderberg formation

The Bolderberg Sands are yellow to white in colour and have homogenous grain size distribution (with an average of 200 μm) (Dreesen et al. 2005; Beerten et al. 2018). The sands were deposited in a shallow North Sea bay environment under the influence of tidal currents (Dreesen et al. 2005; Beerten et al. 2018) during the Middle Miocene (Dreesen et al. 2005) or Lower Miocene (Beerten et al. 2018). The Bolderberg Sands are up to 40 m thick in Limburg on the edge of the graben (Dreesen et al. 2005; Beerten et al. 2018) and in the south-east of the Campine Plateau they underlay the Zutendaal Gravels (Beerten et al. 2018).

The formation is divided into two members (Louwye et al. 2020), the oldest member is the Houthalen Member. It was deposited in a shallow marine environment and is made of fine to medium glauconitic clayey sand (Houthuys 2017; Louwye et al. 2020). The second member of the formation is called the Genk Member and is divided into several units according to the interruption of the sand deposition during a continental phase and the occurrence of gravel layers (Dreesen et al. 2005; Beerten et al. 2018; Louwye et al. 2020). Within the Genk Member, there are the Maasmechelen sands which are also called glass-sands or “silversands”, economically valuable for their purity (Dreesen et al. 2005;

Beerten et al. 2018). The Maasmechelen silver sand is white because its ferruginous compounds were removed by chemical leaching. Humic acids from the degradation of vegetal residues in the overlying lignite layer bleached the underlying sands. The impervious lignite layer also protected the sand from iron oxide staining caused by infiltration from the upper layers (Dreesen et al. 2005). The lignite layer, called the Kikbeek lignite, was formed during a short marine regression with the development of extensive coastal swamps (Dreesen et al. 2005; Beerten et al. 2018). Over the white sands with lignite layers lays a gravel layer, the Opgrimbie Gravels. The gravels are well-rounded pebbles of dark flint (Houthuys 2017; Louwye et al. 2020). Then, this is overlain by white pure quartz sand (6 to 7 m) with abundant bioturbation decreasing upward, and another gravel layer, the Meulenberg Gravel (Louwye et al. 2020). A sand layer caps the Meulenberg Gravels. It is white to pale grey with orange staining in the bottom (Louwye et al. 2020).

- **Winterslag Sands**

The Zutendaal Formation is composed of two members, the Winterslag Sands and the Zutendaal Gravels. The Winterslag Sands were deposited by the Meuse (Robaszynski and Dupuis 1983) around 1 Ma (Beerten et al. 2018). The contact with the underlying Miocene sands is undulating due to fluvial erosion of the underlying Neogene sands (Gullentops et al. 1981). The Winterslag sands, filling those erosional channels, consists of clay and fine sands followed by gravelly sands (Robaszynski and Dupuis 1983).

- **Zutendaal Gravels**

The conical shape of the deposits and the gradual downstream fining of the sediments with coarse gravels in the south to gravels and coarse sands in the north lead to the common view that the Zutendaal Gravels were deposited in an alluvial fan (Beerten 2003; Dreesen et al. 2005; De Brue et al. 2015; Beerten et al. 2018). However, there is no other evidence that this is effectively the case. The conical shape of the Campine Plateau could be a coincidence resulting from erosional and tectonic processes (Beerten et al. 2018). The gravels are part of the oldest Meuse Terrace, also called Main Terrace (Dreesen et al. 2005; De Brue et al. 2015; Beerten et al. 2018). The gravels are interpreted to be braided river deposits under periglacial conditions (Gullentops et al. 2001; Beerten et al. 2018). The sediments mainly come from the Vosges and the Ardennes (Van Straaten 1946 and Felder 1989 cited by De Brue et al. 2015). The coarse fraction was transported during peak discharges due to snowmelt in early summer (Dreesen et al. 2005; Beerten et al. 2018), and sediment was produced by frost shattering during cold periods and supplied to the river systems by solifluction (Beerten et al. 2018). The gravel unit is up to 15 meters thick in the south of the Plateau and 8 meters in the north (Dreesen et al. 2005). The age control on the Zutendaal Gravels is poor. The depositional age is bracketed between 1 and 0.5 Ma based on the lateral migration of the Meuse River during the Early to Middle Pleistocene: The Meuse left the East Meuse valley, and its course shifted west, on the Campine Plateau, 1 Ma ago at the earliest (Westerhoff et al. 2008), and it left the Campine Plateau shifting north-eastwards between 800 and 500 ka (Schokker et al. 2005). Several hypotheses exist on the time

window of deposition: during the Cromerian (Gullentops et al. 2001), about 0.7 Ma ago (Van Balen et al. 2000) and between 0.6 and 0.8 Ma (Beerten et al. 2018).

The Zutendaal Gravels are primarily made up of resistant rocks (physically and/or chemically) (Dreesen et al. 2005; Dreesen 2011; Beerten et al. 2018). Precambrian and Cambrian quartzites and vein-quartz are predominant (Dreesen 2011). Then Lower-Middle Devonian sandstones and conglomerates, Upper Cretaceous silicified calcarenites, and Upper Cretaceous flints are frequent (Dreesen 2011). Finally, there is rare Devonian microgranitic dyke material, Lower Carboniferous limestones, Tertiary quartz-arenitic sandstones or silcrete and Devonian granites (Dreesen 2011). The gravel unit has a red to brown matrix with a colour that intensifies upward and is due to weathering after deposition during interglacial periods (Dreesen et al. 2005). The colour results from the oxidation of the iron compounds. The iron oxides then percolated down with groundwater and stained the entire unit (Dreesen et al. 2005). The Zutendaal Gravels are badly sorted (Dreesen et al. 2005; De Brue et al. 2015) and subangular to well-rounded (Dreesen 2011; De Brue et al. 2015). The majority of the gravel has a diameter between 2 and 8 cm (Dreesen et al. 2005). The gravels are supported by a sand, loam and clay matrix (Dreesen et al. 2005). The presence of abundant fine sediments throughout the entire layer can be indicative of a high suspended sediment concentration (De Brue et al. 2015).

The gravel unit is made up of several sedimentation and aggradation cycles characterised by a basal coarser channel-lag deposit fining upward to a fine gravel layer, a sand layer, or a clay lens. (Gullentops et al. 1981; Paulissen 1983 cited by De Brue et al. 2015 ; Dreesen et al. 2005 ; Beerten et al. 2018). Each cycle corresponds to deposition in a broad and shallow channel (Gullentops et al. 1981; Beerten et al. 2018). The presence of coarse and finer material can be caused by the alternation of peak-flow events and periods of low competence (De Brue et al. 2015). At the base of the gravel unit, there are channel lag deposits made of cobbles and boulders (Gullentops et al. 1981).

The Zutendaal Gravels include large boulders with an intermediate axis up to 2 m (De Brue et al. 2015). More than 80% of the boulders are dark-coloured quartzites from the Palaeozoic massifs in the Ardennes (De Brue et al. 2015), the rest comes from the Vosges (Dreesen et al. 2005). In the Maasmechelen gravel quarries, the boulder deposition density is ca. 1 per 14 000 m³ of gravel for 1 m boulders and 1 per 3000 m³ for 0.80 m boulders (D. Musiek, SBS nv Maasmechelen, pers. comm., 2010 cited by De Brue et al. 2015). The general assumption is that those boulders were transported by ice-rafting processes (De Brue et al. 2015), i.e. transport by floating ice either on an ice raft or included within the ice (Dowdeswell 2009). Ice-enclosed boulders would reach the surface and then be transported on its ice raft before being deposited as the latter melt (Dreesen et al. 2005). De Brue et al. (2015) studied the mechanisms of ice transport. Their results showed that hydraulic transport of small boulders could have been possible in the palaeo-Amblève (the Amblève is a tributary of the Ourthe, itself a tributary of the Meuse), but it could not explain the boulders' transport on the lower palaeo-Meuse. They also concluded that the minimal ice volumes needed to transport boulders by ice rafting were realistic. However, they suggest that other processes might have played a part: ice jams

and ice dam failure can induce flood surges, slush flows due to snow accumulation melt in the river valley, and flood waves from an outburst of an ice or moraine-dammed lakes.

Apart from the large boulders that are observed in the lower part of the gravel deposits, traces of cold climate conditions are rare in the Zutendaal formation (Gullentops et al. 1981). Gullentops et al. (1981) documented isolated perturbations at the contact between layers with different textures in Opgrimbie quarry and observed angular Miocene sand blocks in the Zutendaal Gravels that are assumed to be eroded and transported in a frozen state. Despite being scattered, these features constitute one of the clues that lead Gullentops et al. (1981) to interpret the Zutendaal Gravels as being periglacial deposits. The abrupt change in the Meuse bedload from locally reworked sand (Winterslag Sand) to allochthonous gravel (Zutendaal Gravel) is another observation that supports the increase in mechanical weathering in the upstream basin as a result of e.g. a transition to colder conditions (Gullentops et al. 1981).

- Post-depositional processes

After the deposition of the Zutendaal Gravels, relief inversion took place. The inversion resulted from differential erosion, fluvial erosion, uplift and fault activity on the edges of the Plateau. The western edge of the Campine Plateau developed after regressive erosion of the Nete River, and the topographic step is a result of the difference in erodibility between the Quaternary coarse-grained deposits and the finer less resistant Neogene Sands (Beerten et al. 2018). The southern edge was formed by incision of the Meuse River in response to the ca. 50 m uplift of the southern part of the plateau over the last 0.7 Ma (Beerten et al. 2018). The eastern edge of the Plateau was caused by erosion by the Meuse as it shifted east (Beerten et al. 2018). Finally, the north-eastern edge is associated with the Feldebiss Fault and the vertical displacement of about 25 to 40 m since the deposition of the gravels (Beerten et al. 2018).

The glacial-interglacial cycles that followed the deposition of the Zutendaal Formation induced soil development and periglacial deformations. The As soil, a red-brown interglacial palaeo-soil, formed in the Zutendaal Gravels (Beerten et al. 2018). Its development required intense weathering of the gravels, containing Fe-bearing minerals, sufficient precipitation to facilitate water percolation, chemical weathering and mobilisation of dissolved elements to the groundwater table. The soil is well-developed and preserved in the eastern part of the Plateau but is not present in the western and north-western parts because it has not been preserved or did not develop (Beerten et al. 2018). The glacial cycles also caused cryoturbation in the upper part of the Zutendaal Gravels (Dreesen 2011; Beerten et al. 2018). The cryoturbation is due to intense frost and thaw cycles in the active layer of the permafrost during glacial periods (Dreesen et al. 2005; Beerten et al. 2018). The resulting involutions, vertical tongues or flame-looking features, are 2 to 3 meters in length (Dreesen et al. 2005; Beerten et al. 2018). During the Weichselian, the Zutendaal Gravels were overlain by fine and homogeneous windblown sands, which were remobilised as a result of anthropogenic perturbations during the Holocene (Dreesen 2011; Beerten et al. 2018).

2.5 Working hypotheses

Based on the hereinabove literature review, this study focuses on two working hypotheses:

- (i) Miall (1996) established a classification for braided river deposits to facilitate the interpretation of the depositional environments. We hypothesise that this classification can be transposed to the study of the Zutendaal Gravels, and we will test if the corresponding schemes can be used to gain insight into the depositional environment of the Early to Middle Pleistocene River Meuse.
- (ii) Besides the depositional environment, the timing of deposition of the Zutendaal Gravels is not well known. Based on the literature of Vandenberghe (1995, 2008) and observations in East Anglia of Early and Middle Pleistocene fluvial deposits (Rose et al. 1999; Rose 2009), we hypothesise that we can link the variations in grain size and geometry to glacial and interglacial cycle, and infer the timing and duration of deposition.

3 Materials and methods

3.1 Study area

The study area is located in the south of the Campine Plateau, where the Zutendaal Gravels are best preserved from erosion (Figure 3.1). In this work, observations were made in two active quarries (i.e. MHZ and Berg quarry) and were briefly compared with previous observations by Dreesen et al. (2005) in the Opgrimbie quarry further to the south. In the MHZ ('Mechelse Heide Zuid') and Berg quarries, pure quartz sand from the Bolderberg formation is extracted by Sibelco. Gravel, lying on top of the industry sand, was previously extracted by other companies. Extraction in the Opgrimbie quarry, also called Kikbeekbron groeve, ceased in 2004. The area is now preserved for its scientific and educational value and was converted into a nature reserve (Dreesen et al. 2005).

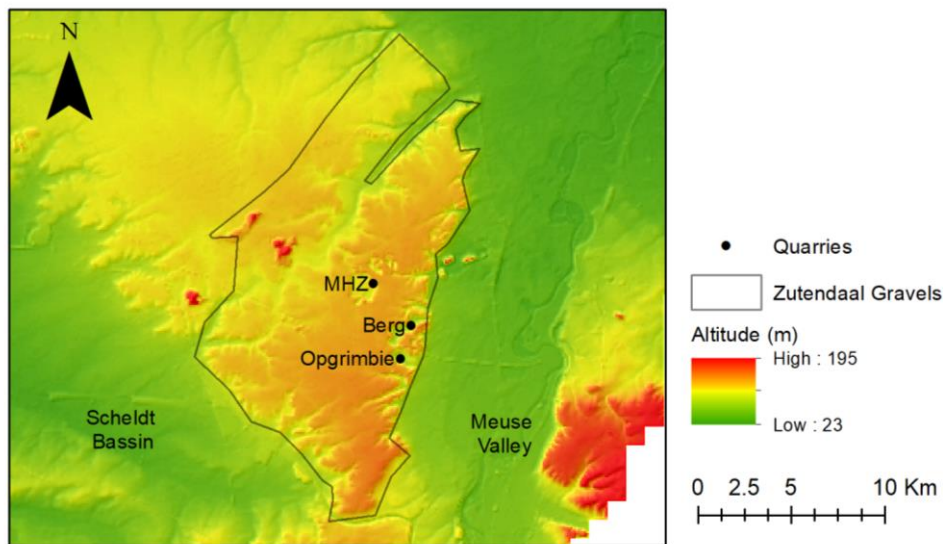


Figure 3.1 Quarries in the South of the Campine Plateau (Informatie Vlaanderen 2015).

The MHZ study site was chosen because two walls partly in gravel deposits were recently exposed during extraction (2020). As a result, the sediments are clearly observable and not masked by colluvium and/or vegetation. Wall 1 is NW facing, and wall 2 is SSW facing (Figure 3.2). This setting gave an insight into the 3-D structure of the deposits. Wall 1 is 16 m tall, and wall 2 is 6 m tall.

The studied section in Berg quarry was chosen for its large extent, which allows for the study of the constitutive units of the Zutendaal Gravels. The studied wall at Berg is NW facing (Figure 3.3) and is about 15 m tall along the studied section. In the quarry, it was also the section with the least vegetation cover. The two quarries, Berg and MHZ, were visited several times over the course of 6 days. The first two days took place in quarry Berg and MHZ in September 2020 (7 and 8/09/2020), further fieldwork was conducted in MHZ in November (20/11/2020), December (8/12/2020) and April (6/04/2021). Quarry Berg was visited again on 16/03/2021. Information on sedimentary structures and pictures from a previous field campaign, in August 2019, collected by Koen Beerten, Veerle Vanacker and Nathan Vandermaelen, was also used.

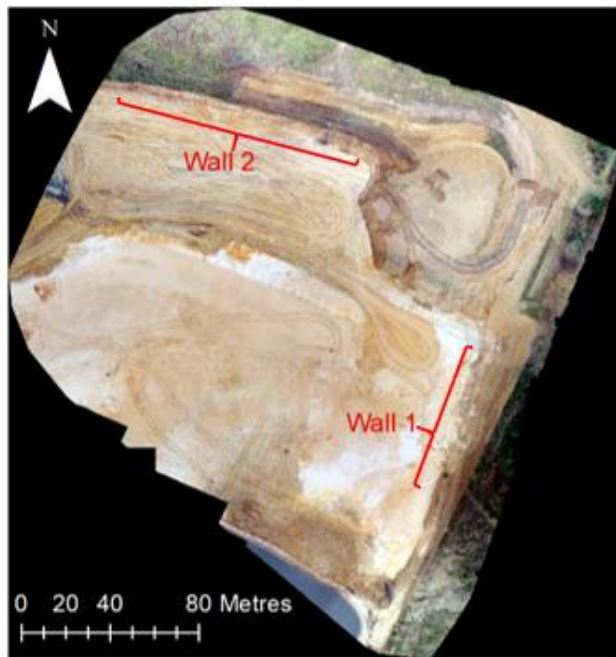


Figure 3.2 Orthomosaic of the studied area in MHZ quarry (December 2020).



Figure 3.3 Aerial photograph of quarry Berg with the GPS points (two red dots) measured on the studied section (16/03/2021) (Layer credits: Orthofotomosaïek, middenschalgig, winteropnamen, kleur, 2020, Vlaanderen – Agentschap Informatie Vlaanderen, Geopunt.be)

3.1 UAV images and classification

The objectives of the UAV image acquisition and classification are (1) to identify large units and (2) to have more observations for the top of the walls, which are not easily observable from the ground.

3.1.1 Data acquisition

Aerial photographs were taken with a Phantom 4 unmanned aerial vehicle (UAV) in MHZ quarry with a frontal and lateral overlap of 80 and 70% (Table 3.1). The objective of the aerial images was to (1) have an overview image of the study area, (2) create a Digital Surface Model, and (3) obtain a 3D reconstruction of the walls. The overview flight was done with a 90° angle at a 40 m altitude. The flight that aimed at collecting images for 3-D reconstructions of wall 1 was carried out with a 65° at a 30 m altitude. The UAV flew at an altitude of 20 m and with an 80° angle over wall 2.

Table 3.1 Drone, camera and flights settings.

Drone model	Phantom 4 advanced
Lens model	FOV 84° 8.8 mm/24 mm (35 mm format equivalent) f/2.8 - f/11 auto focus at 1 m - ∞
Image size	5472 x 3648
Approximate sensor size	2,5cm
Shutter interval	2 s
ISO Range	100-3200
f number range	2.8-11
Frontal and lateral overlap	80%, 70%
Images geotags CRS	WGS 84

- **Georeferencing**

About 13 Ground Control Points (GCPs) were distributed over the study area. The position of each point was calculated as the average of about 120 position measurements. The position was measured with a Trimble R1 GNSS receiver in Belgian Lambert 72, and the data was collected with the Penmap app. FLEPOS, the Flemish Positioning Service, was used for RTK measurements. It provides the correction signals from satellites and allows for accurate geolocation in Flanders. The accuracy of the positioning was further evaluated by measuring the position of a 3-D geodetic reference point from the Belgian National Geographic Institute (National Geographic Institute n.d.) in Houthalen. Logging of the signal was done until 120 measurements were taken (Figure 3.4). The signal from about 20 satellites was received during the measurements. Based on this external accuracy assessment, we evaluated the horizontal accuracy of the Trimble GNSS receiver to be 91 cm, and the vertical accuracy is 33 cm.

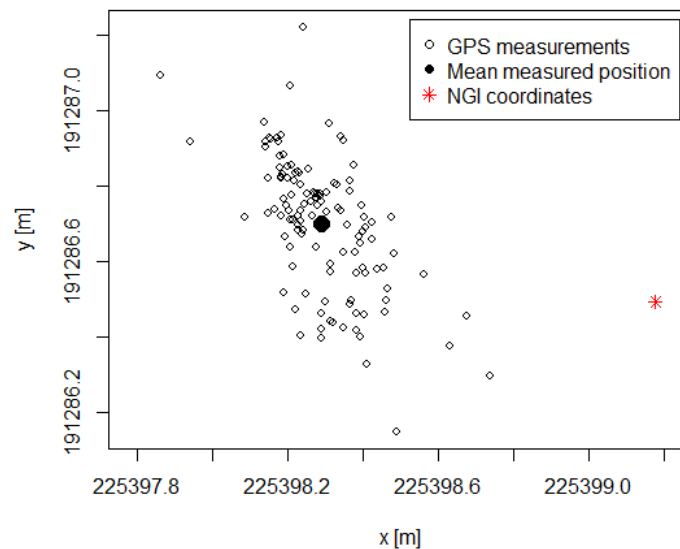


Figure 3.4 Geodesic reference point coordinates from the NGI compared to measurements with the Trimble. The horizontal accuracy (i.e. 91cm) is the difference between the NGI coordinates (red star) and the mean measured position (black dot).

3.1.2 UAV image processing

Structure-from-Motion (SfM) allows to generate a 3-D reconstruction from 2-D images. The technique is based on the identification and matching of key points on pictures taken under several viewing

angles. The reconstructions were computed in Pix4D Mapper. Before loading the UAV images in Pix4D, they were reviewed, and only the images centred on the zone of interest were kept as flight plans covered an area larger than the actual area of interest. The output coordinate system was set to Belgian Lambert 72 (EPSG 31370). The first step of the workflow in Pix4D detects and matches key features in the pictures, creates the tie points and optimises the camera parameters (Pix4D Documentation n.d.). The resulting point cloud is georeferenced with relative coordinates only. The GCPs were then added and identified on several images for absolute georeferencing. After the addition of the GCP, the point cloud was re-optimised. In the second step, the point cloud is densified, and a 3D textured mesh is created. Finally, step 3 computes the DSM and an orthomosaic.

Orthofacades or orthoplanes are ortho-rectified 2-D images of a vertical façade obtained from a 3-D point cloud (Pix4D Documentation 2017). The orthofacade was inserted parallel to the object to avoid distortion and blurry patches on the resulting image. The generated orthofacades in Pix4D are not georeferenced. Orthofacades were created for each wall and used for the classification.

3.1.3 Classification

- Pre-processing

The orthofacades of the quarry were pre-processed before classification to mask the anthropogenic influence and focus the study on in-situ material. The masking of anthropogenic sediments was based on information from Sibelco and field observations. First, there is an old deciduous tree on the top of wall 1 in MHZ. It confirms that the high section on the left of the outcrop is in situ material. The top part of the left section displays unsorted homogenous deposits that clearly differ from the visible layers underneath the old tree. Secondly, on wall 2, the upper part of the wall is also visibly unsorted and homogenous. This top part sits on an organic-rich layer, which when followed toward the left of the outcrop, meets with the grassed surface where the wall becomes smaller. Old aerial photographs from Geopunt.be (1989, 2003, 2007, 2009, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019) (Informatie Vlaanderen n.d.) and Cartesius (2005) (National Geographic Institute 2005b, 2005a) confirm those first assumptions. The uppermost material in the wall 2 area was removed, and then some refill material was deposited towards the east (2003 Figure A.2 in appendix). Some material was also moved along wall 1 south of the deciduous tree, with a step-like structure towards the south (2009 Figure A.2 in appendix). By 2011 it looks like those areas were refilled or smoothened out.

- Supervised classification

The use of supervised classification on the orthofacade allows for a first identification of the main sedimentary units based on the orthofacades' RGB bands. The classification was conducted in ArcMap 10.6.1. The supervised classification method classifies each pixel of an image into categories chosen a priori by the user based on a set of training samples. The maximum likelihood method, available in ArcMap, is the most used supervised classification method (Richards 2013b). The classification was applied to the RGB orthofacades on material that is in-situ. Training samples were created for a priori determined classes representing textures (clay, sand, gravel). The classification output includes the

classified raster and an output confidence raster. The latter gives a confidence index of the category attribution between 1 (very high confidence) and 14 (very low). After a first attempt, a few additional training samples were added to improve the classification in areas of high uncertainty and clarify the difference between categories.

- **Unsupervised classification**

Unlike supervised classification, unsupervised classification does not require calibration. However, one needs to specify the number of classes. There are various clustering methods for unsupervised classification. Iso Clustering is one of the commonly used for remote sensing applications (Richards 2013a) and is available in ArcMap. The Iso Cluster method is a modified version of the iterative k-means (or migrating means) method (Richards 2013a; ArcGIS Desktop n.d.). At each iteration, the observations are assigned to the closest cluster centres, and a new mean is calculated for the cluster. The distance is computed using the Euclidean distance as the similarity metric. In the next iteration, those new means are the new cluster centres. The process is repeated until the clusters become stable and the error sum of squares decreases. The method includes automatic verification of the number of pixels and shapes of the clusters (Richards 2013a).

The aim of the unsupervised classification is to compare its classes with the a priori defined classes used for the supervised classification and highlight potential factors besides the combination of texture and colour influencing the pixel reflectance.

3.2 Field sampling and grain size analysis

3.2.1 Field observations

Before sampling, the walls were characterised with an overall description of the constitutive units, their geometry, and sedimentary structures. The units were identified on sketches. Dimensions of the units were estimated on the field, and some exact measurements were taken with a Leica laser distance metre for reference. Detailed pictures and panorama are taken with a Canon EOS 550D camera. Panorama pictures were stitched together with Hugin. This method was used when UAV surveying was not possible and to get a higher resolution panorama along a profile. Pictures were taken with a 50 mm lens. Hugin is an Open-Source panorama photo stitcher software based on common control detection and horizontal and vertical line detection. In Hugin, the pictures are first aligned, then parameters such as output projection and extent can be adjusted. If needed, additional manual control points and horizontal and vertical lines can also be added.

3.2.2 Samples

- **Sampling strategy**

Samples were taken both in quarry MHZ and Berg. In total, 54 samples were selected for further analysis. The majority of samples (42) was taken in wall 1 of quarry MHZ (Figure 3.5). For the former, the sampling strategy was to collect samples from the different sediment units. The samples were

taken in a selected number of vertical profiles along the exposed wall to represent lateral variability if there were to be any. Along those profiles, samples were taken as high as it was possible to reach. Sampling the lower section of the wall was important for the determination of the lower boundary of the Zutendaal formation. One additional sample was taken at the bottom of wall 2 for comparison. In quarry Berg, 11 samples were taken along the exposed wall to verify for correspondence with the samples from MHZ. They were taken in the lower section of the outcrop because of accessibility. One sample was taken per unit except the highest one, and two extra samples were taken in a unit that displayed lateral and vertical variation in grain size. Once collected, the samples were dried in an oven at 60°C for over 24 hours.

Figure 3.5 Sample locations for wall 1 in MHZ quarry.

Besides the position measures taken for the UAV images, a few additional points were measured in order to georeference the profiles. Depending on the availability of the instruments, some measures were taken with the Trimble GNSS system and others with the EMLID Reach RS+ GNSS receiver. The measurements with the Trimble were taken just like the GCPs positions as explained in section 3.1.1. The positioning with the EMLID used during the March and April fieldwork required PPK correction as the GNSS measurements showed inconsistencies in the RTK correction during the first field visits. The PPK correction workflow was adopted for the later field visits. PPK stands for Post-Processed Kinematic, and the correction was applied using RTKLIB 2.3.4. The used workflow is described on the EMLID website (EMLID Docs n.d.), with the rover being the EMLID receiver used on the field and the EUREFF Eijsden Station used as the base. The EUREF Permanent GNSS Network is a network of reference stations providing daily positioning data (Bruyninx et al. 2019; Royal Observatory of Belgium. n.d.). Amongst the network's stations, Eijsden ('Eijsden, Netherlands (the) (EIJ00NLD) - EUREF Permanent GNSS Network' n.d.), is the closest one to the study area (ca. 23 km). First, the raw logs from the rover were converted to RINEX files using RTKLIB RTKCONV (format: u-blox, other fields: default value). The second step in RTKPost requires as input the newly converted .obs and .nav files for the rover and the base station RINEX file (V3.04 from the EUREF ftp server). In the options, the

positioning mode was set to Kinematic. Then, in the Position tab, the Base Station was set to X/Y/Z-ECEF m, and the resulting fields were filled according to the position values indicated on the EUREF page for the Eijsden station. The other parameters were set to the default values from the EMLID tutorial. The output from this second step is a .pos file. Finally, the corrections were applied to the surveyed points .csv file using Posprocessor (Ješkins 2019), a free software, which allows to quickly extract the points from a .pos file with a .csv. The accuracy of the EMLID measurements is missing because no measurement of a reference geodetic point was taken.

3.2.3 Grain size analysis

- Dry-sieving

The dry sieving methodology was chosen for its simple implementation and the range of particle grain size it is optimal for. Dry-sieving is useful for coarse samples (López 2017), and many of the samples had a significant gravel and sand fraction. The sieve stack had the following apertures: 71 mm, 50 mm, 25 mm, 12.5 mm, 2 mm, 1.25 mm, 1 mm, 500 μm , 250 μm , 125 μm , and 63 μm . The larger clasts were passed through the largest sieves (71 and 50mm) manually. The rest was sieved using sieves on a Retsch AS 200 basic vibratory sieve shaker.

The results of sieving are influenced by the sieving time. At first, the particles with a major axis smaller than the aperture quickly pass through the sieve (Syvitski 1991; Merkus 2009). Then, the slightly larger grains, which can pass through the sieve only if oriented in a certain way, require a longer sieving time (Syvitski 1991). The duration after which there are no more particles that could pass through the sieve can only be reached asymptotically, and it depends on many characteristics of the sample material, including the grains' shape (Merkus 2009). However, experiments showed that the amount of material passing through the sieve decrease sharply after 20 minutes (Syvitski 1991), and dry-sieving time is typically between 5 and 30 minutes (Merkus 2009). The samples were first sieved for 20 minutes at 50% amplitude (i.e. 1.5 mm) and then for an extra 20 minutes at 30% amplitude (i.e. 1 mm) using the Retsch vibratory sieve shaker. The two amplitudes were used because sieving with too little movement does not let many chances for all particles to pass through, but an amplitude too large limits the passage of particles that are close in size to the sieve aperture (Merkus 2009).

The resulting fractions were subsequently weighted. The main drawback of using dry-sieving in this study is its lower reliability for cohesive material (López 2017). Some samples were clayey and thus formed aggregates when dried. Therefore, those samples were first gently crushed in a mortar bowl before sieving to limit the impact of the aggregates on the final results.

- Grain-size analysis

In the literature, 4 types of grain size distribution parameters are reported: those relating to (1) the mean size, (2) the sorting, i.e. standard deviation, (3) the symmetry of the distribution on each side of the average, i.e. the skewness and the kurtosis, and (4) the cumulative percentile values (Blott and Pye 2001). The latter indicates the particle size for which the specified percentage of the sample is coarser. We used GRADISTAT to process the results of the grain size analysis. GRADISTAT is a grain size analysis

program developed by Blott and Pye (2001), integrated into an Excel spreadsheet. The user enters the weight of the measured grain size fractions, and the program calculates sample statistics: mean, mode, standard deviation, skewness, kurtosis and some cumulative percentile values. GRADISTAT includes two methods to calculate those statistics, the method of moments and the Folk and Ward method (Blott and Pye 2001).

Reliable calculation of the grain size indexes requires that the size distribution is well defined both at the coarse and fine end. At the coarse end, it is necessary to have measures on one particle size class that is larger than the maximum size (Blott and Pye 2001). The calculation accuracy decreases with the increase of the proportion of the sample that is finer than the finest sieve (Blott and Pye 2001). The method of moments is especially prone to this loss of accuracy. The Folk and Ward method is less prone to it, and parameter calculations are reliable if the fraction remaining in the pan is smaller than 5 percent. The latter is also more robust for the calculation of skewness and kurtosis, and it was thus chosen over the method of moments for the grain-size analysis (Table A.2 in appendix). The Folk and Ward method can be applied geometrically or logarithmically (Blott and Pye 2001). The geometrical method and the logarithmic method are both based on a log-normal distribution. The former uses metric particles sizes and the later phi size values. The phi values are based on $\varphi = -\log_2(d)$, where d is the grain diameter [mm] (Blott and Pye 2001). We used boxplots and histograms to characterise the grain-size distribution in each unit and to compare them between units. The terminology used in this work follows the one used in GRADISTAT (Table A.1 in appendix) except for the fraction $<63 \mu\text{m}$ that is just referred to as clay.

- **Laser diffractometer**

The grain-size distribution obtained with the dry-sieving method was incomplete for samples with an important $<63 \mu\text{m}$ fraction. As dry-sieving also has limited precision and resolution for finer sediments (López 2017), the $<63 \mu\text{m}$ fraction of 10 samples were analysed with a Laser Diffraction Particle Size Analyser (LS13320 from Beckman Coulter) by L. Fondu (Geo-Instituut, KULeuven). The laser diffraction method is based on the measurement of the scattering pattern of laser light by particles (Merkus 2009). The analyser converts the signal into a volume-based grain size distribution. The particles are assumed to be spherical, and when they are not, it results in a distribution of equivalent spherical diameter, which depends on particle orientation (Merkus 2009). The laser diffractometer was used to measure the grain size distribution between 63 and $0.04 \mu\text{m}$.

4 Results

This chapter first describes the results obtained in the MHZ quarry, starting with the overview orthomosaic and digital surface model. The orthofacades and the results of the classification allow the first identification of units on the walls. Those first results determined where to sample to have data from as many units as possible. Then, the delineation and description of the units are improved using the grain size data combined with detailed field observations. Less data is available for quarry Berg which is described in the second section of this chapter. For quarry Berg, the delineation and description of the sedimentary units rely on field observations, photo-stitching and grain size analysis. Finally, the last section of this chapter attempts to link the results of the two quarries.

4.1 MHZ quarry

4.1.1 Structure from motion & orthofacades

Observations in the MHZ quarry were made along two roughly perpendicular walls. First, the overview reconstruction gives us a map and a surface model (Figure 4.1). The studied area in MHZ has several levels. Its highest point is 93.3 m, and its lowest point, near the lake, is 67.2 m. Wall 2 (south-west facing) stands at about an altitude of 76 m and wall 1 (north-west facing) at about 72 m. None of the walls has a constant height, wall 1 gets smaller southwards, and wall 2 becomes smaller westward.

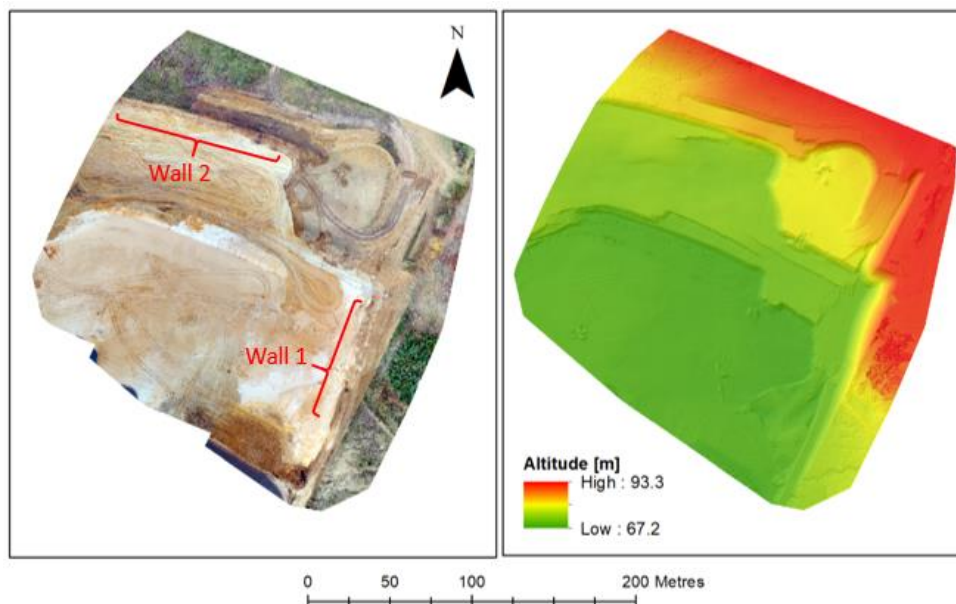


Figure 4.1 MHZ quarry orthomosaic and DSM obtained from SfM.

4.1.2 Classification

- Supervised classification: wall 1

The supervised classification neatly identified several units of each a priori defined class of clay, sand and gravel. The classified image (Figure 4.2) clearly highlights the difference between the lower half

and the upper half of the wall. The lower part consists of a few thick layers, and most of them are laterally extensive. First, there is homogenous sand with a clay layer at the bottom. Then the boundary with the overlaying gravel is neat. However, the base of the next unit, the clay layer, seems gradual as the classification indicates some sand in between. The clay layer includes some thin sand intercalations. In the upper half of the wall (Figure 4.2), the layers are thinner, and there is more lateral variability as the layers are interrupted by sandy patches. The classification shows 4 sets of alternating gravel and clay (a to d on Figure 4.2). Finally, there is one sand layer and then some clay under the bioturbated soil at the very top of the outcrop. Overall, the confidence index for the wall is good (Figure 4.2). The two areas with a lower confidence index are the darker layer at the bottom and the bioturbated uppermost part of the wall.

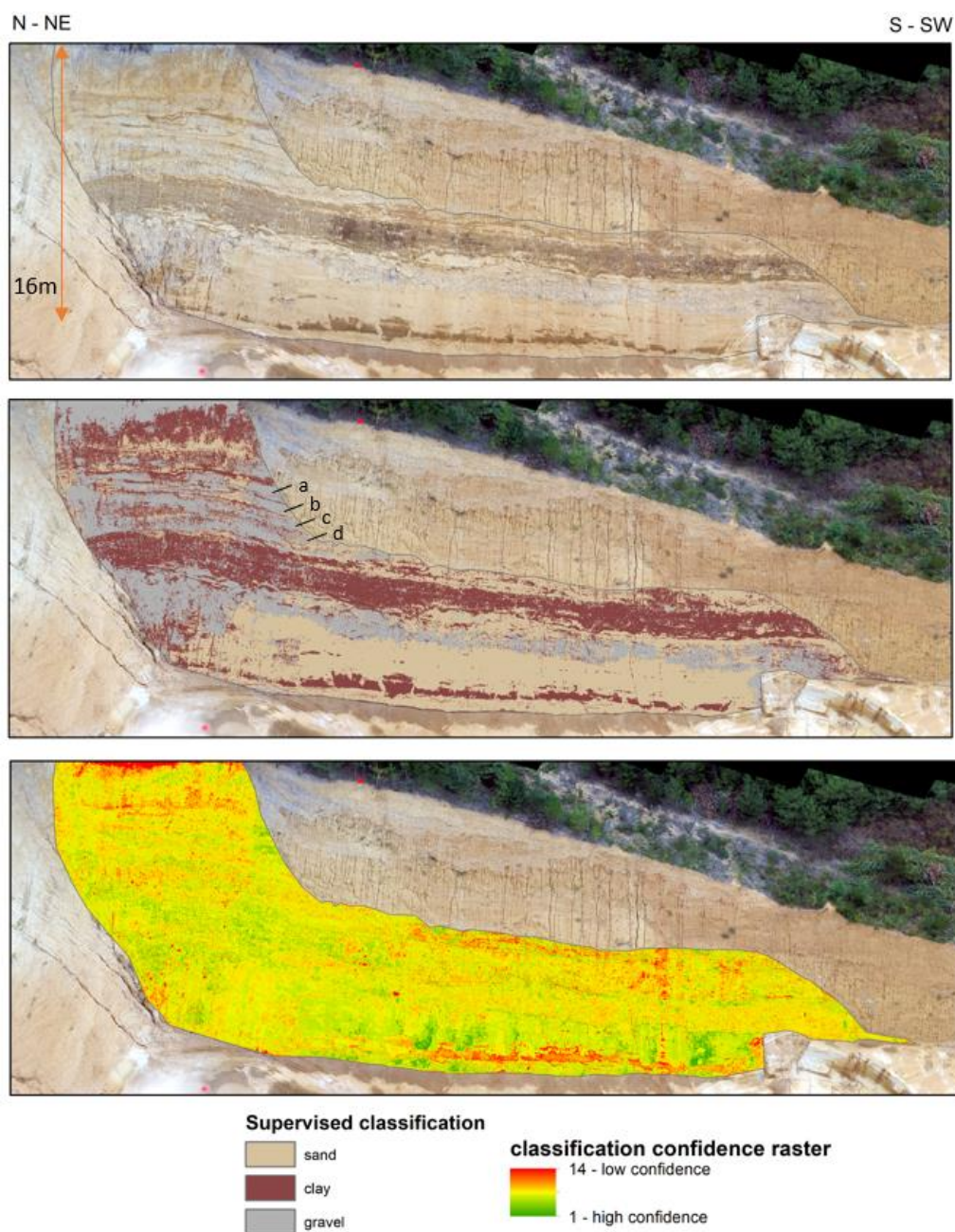


Figure 4.2 Quarry MHZ, wall 1, orthofacade, supervised classification and confidence raster. The letters a to d indicate the four sets of alternating gravels and clay.

- Supervised classification: wall 2

Unlike wall 1, there are few sand-classified pixels on wall 2 (Figure 4.3). According to the classified raster, this outcrop is mostly made of gravel deposits with thin clay layers interbedded. At the top of the wall, the classification highlights an extensive clay unit. The black material category was added to set apart the black stains that come from non in situ material laying on the track located on the top of the outcrop. The confidence raster for wall 2 includes more pixels classified with low confidence. The sand at the bottom is notably classified as such with little confidence. It could be explained by the limited sand exposure and, therefore, the limited number of training samples for that category, as well as the two colours of stained and non-stained sand present.

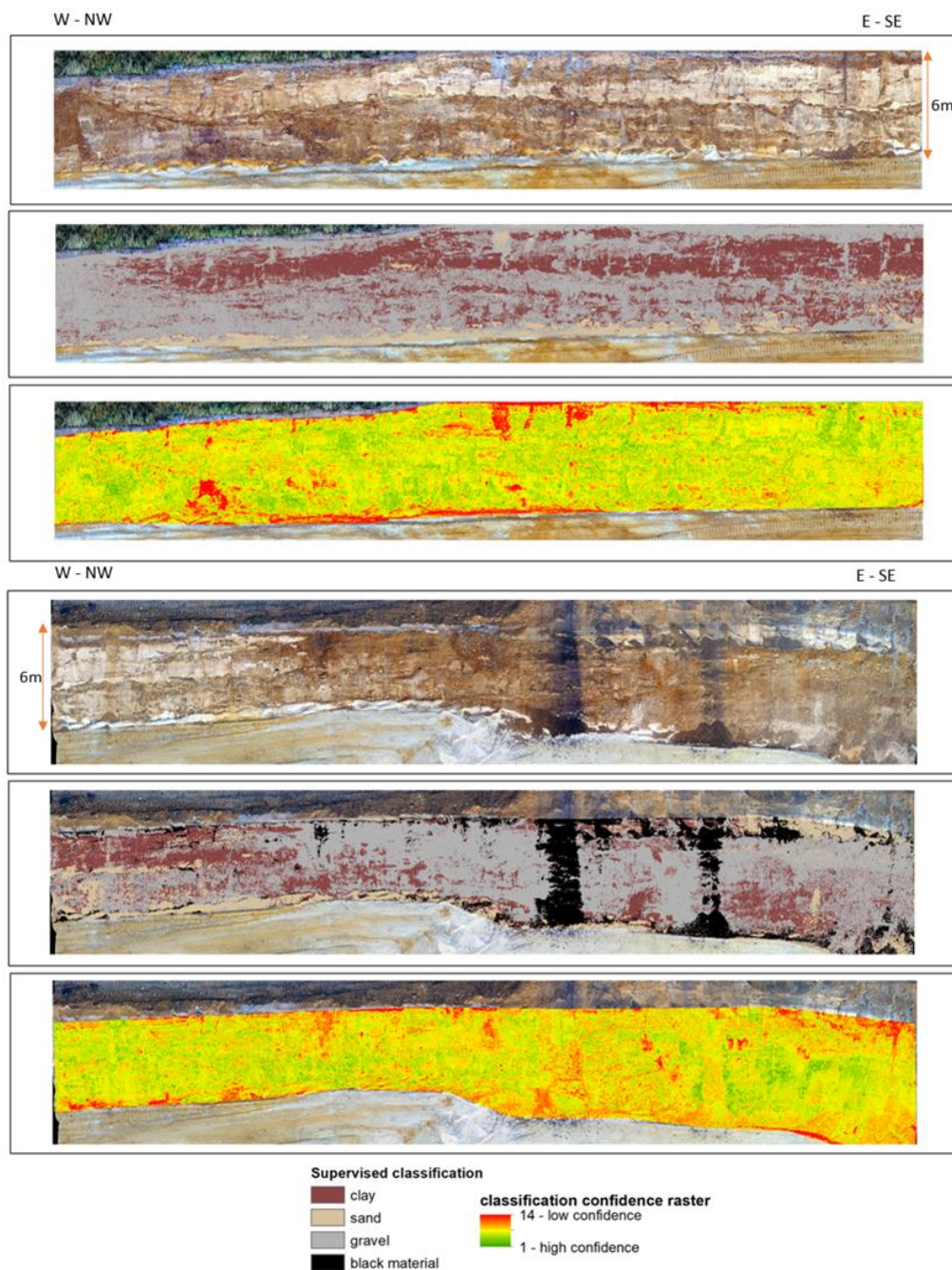


Figure 4.3 Quarry MHZ, wall 2 left half (top) and right half (bottom), orthofacades, supervised classification and confidence raster.

- Unsupervised classification

The unsupervised classification for wall 1 highlights the general structure of the outcrop (Figure A.3 in appendix). The main middle clay layer is clearly visible on the classified raster. The first class could be interpreted as the clay class. The second class also seems to represent clay but also the top sandier bioturbated section. The third class corresponds to sand. No class representing gravels unit was identified in the unsupervised classification. The gravels units identified with the supervised classification on the outcrop are a mix of 3 and 2 pixels according to the unsupervised classification.

As for wall 1, the unsupervised classification brings out the clay layers well on wall 2 for both sections (Figure A.4 in appendix). The rest of the orthofacade is assigned as a mix between the other classes. None of those classes can clearly be assigned to a corresponding texture class. The dark material on the right half has been clearly identified, but its extent is larger than according to the supervised classification.

The unsupervised classification results show that without explicit input from the user on the three texture classes (clay, sand and gravel), the latter are not clearly identified by the classification algorithm.

4.1.3 MHZ wall 1

- Units identification

The classifications gave an insight into the overall structure of the outcrops. Based on these, sampling and further observations were done (Figure 4.4, Table 4.1, and Figure A.5 and Table A.3 in appendix). The latter allow to characterise in more detail the units identified with the classification and highlight additional smaller variations in the sediment and units.

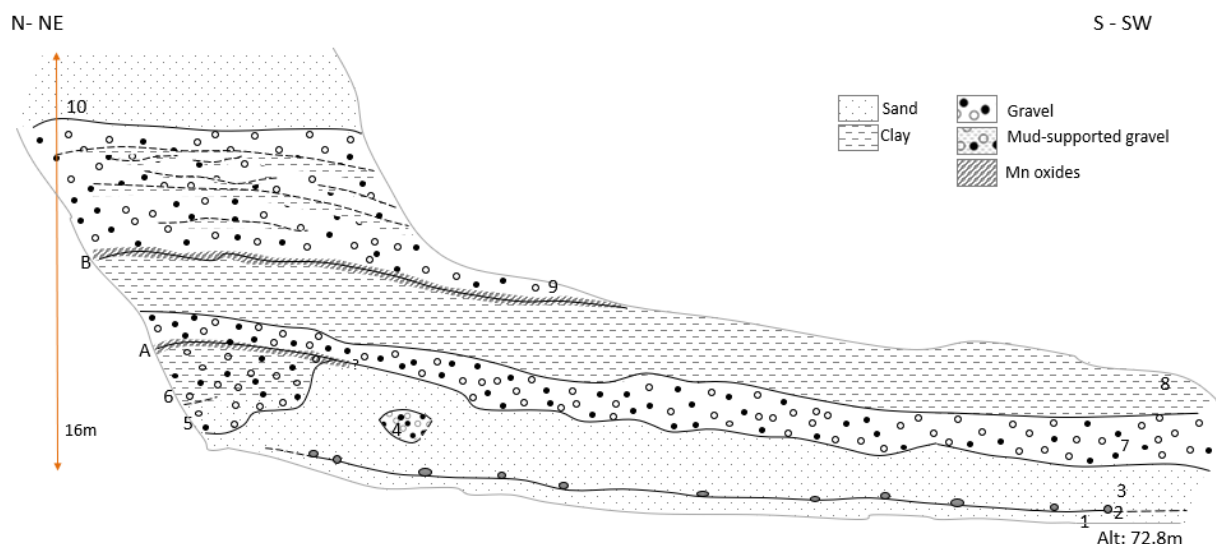


Figure 4.4 Sketch of MHZ wall 1: Bolderberg Formation (units 1-3, with the Meulenberg Gravel 2), and Zutendaal Gravels (unit 4-10).

Table 4.1 Mean of the grainsize analysis indexes for each unit on MHZ wall 1. The mean, sorting, skewness and kurtosis are calculated using the geometric Folk and Ward method. The number in bracket indicates how many samples in the unit have a large (>5%) <63 μm fraction. Raw data in appendix (Table A.3).

Unit	mean (μm)	sorting	skewness	kurtosis	D10 (μm)	D50 (μm)	D90 (μm)	Number of samples
1	268	1.56	-0.1975	0.8175	143	284	451	4
2	741	5.295	0.46	3.345	153	341	20341	2
3	177	1.597059	0.004706	1.247059	98	176	329	18
4	1897	9.01	0.25	0.72	152	1189	38020	1
6	8447	5.49	-0.8	0.45	444	17332	66283	1
7	5498	4.285714	-0.15286	1.161429	761	6788	24452	7 (1)
8	502	5.178889	-0.01111	0.884444	73	516	4354	9 (4)

At the very bottom of the wall (Figure 4.4), unit 1 is made of pure white sand with bioturbation that becomes more abundant towards the south-south-west. It corresponds to the pure quartz sand with some bioturbation from the Genk Member of the Bolderberg formation (Houthuys 2017; Louwye et al. 2020). The bottom unit of the Genk member, characterised by more abundant bioturbation from Ophiomorpha as described by Houthuys (2017), is visible deep in the quarry MHZ close to the lake level. Samples from unit 1 consist of medium and fine sand and have an average mean grain size of 268 μm (SD= 10 μm). The unit is poorly sorted (Table 4.1).

A thin layer of medium to coarse pebbles, unit 2, caps unit 1 (Figure 4.4). The pebbles are aligned, well-rounded and light to dark grey. Because of a difference in humidity, this area of the wall appeared darker and was wrongly identified as clay in the classification. This pebble layer corresponds to the Meulenberg Gravel (Matthijs 1999 cited by Louwye et al. 2020).

The main pale-grey to pale-yellow sand unit with orange staining, unit 3, corresponds to the uppermost unit of the Genk Member described by Houthuys (2017) and Louwye et al. (2020). The average mean grain size of the samples is 177 μm (SD= 20 μm), and the sediment is poorly sorted (Table 4.1). The unit is homogeneous vertically (profile 7) and laterally (profiles 3,4,5,7).

Unit 4 is extremely poorly sorted, bimodal, and it consists of medium to coarse gravel with a medium sand matrix (Figure 4.5) (Table 4.1). It is the first unit belonging to the Zutendaal Gravels. The Winterslag Sands cannot be observed in this part of the MHZ quarry.

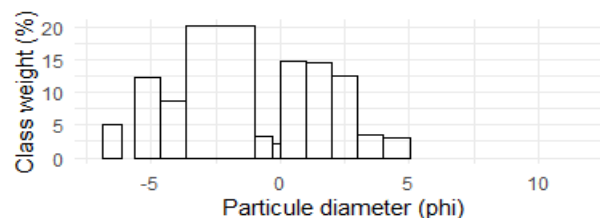


Figure 4.5 Grain size distribution sample Mhz1_g1 (unit 4) (on the phi scale, 10 corresponds to 1 μm , 5 to 31 μm , 0 to 1 mm and -5 to 32 mm).

Unit 5 has an erosive boundary with unit 3. The limit between units 5 and 6 is unclear. Unit 5 is made of very coarse sand with sparse gravel. Unit 6 is made of mud-supported gravels. The gravels are

medium (mean grain size: 8.4 mm) and extremely poorly sorted. At the contact of units 6 and 7, there is black staining from manganese oxides (A on Figure 4.4)

A laterally extensive coarse gravel layer, unit 7, caps units 6 and 3. Its lower and upper boundaries are irregular, with some sandier patches at the contacts. The average mean grain size in unit 7 is 5.5 mm (Table 4.1). The unit is heterogeneous, and there is some variation between the 7 samples for the mean (SD=3.3 mm), D10 (SD = 682 μ m), D50 (SD= 4330 μ m), D90 (SD=10951 μ m) and sorting. Most samples have a large coarse gravel fraction and a small finer fraction due to a coarse to medium sand matrix. However, 2 samples are overall finer (Mhz1_7K and Mhz1_g3d), with a smaller or finer gravel fraction and a more important sand fraction (Figure 4.6).

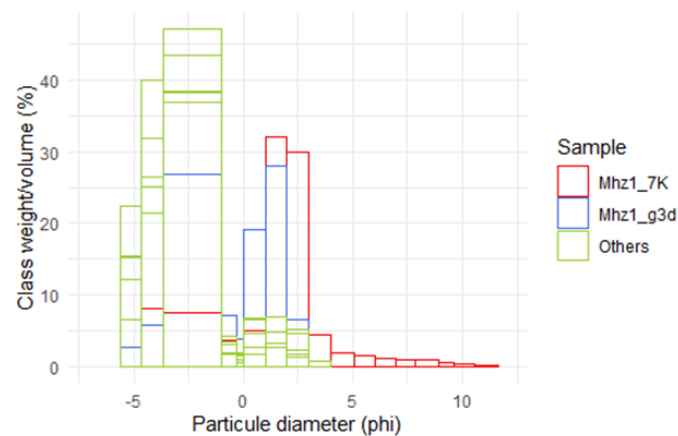


Figure 4.6 Grain size distribution for unit 7 (on the phi scale, 10 corresponds to 1 μ m, 5 to 31 μ m, 0 to 1 mm and -5 to 32 mm).

Unit 8 is a layer of massive clay. However, some samples have a significant sand or even fine gravel fraction (Figure 4.7). The clay layer is not homogenous and includes sand and finer gravel intercalations. There is some black staining in the top due to manganese oxides (B on Figure 4.4).

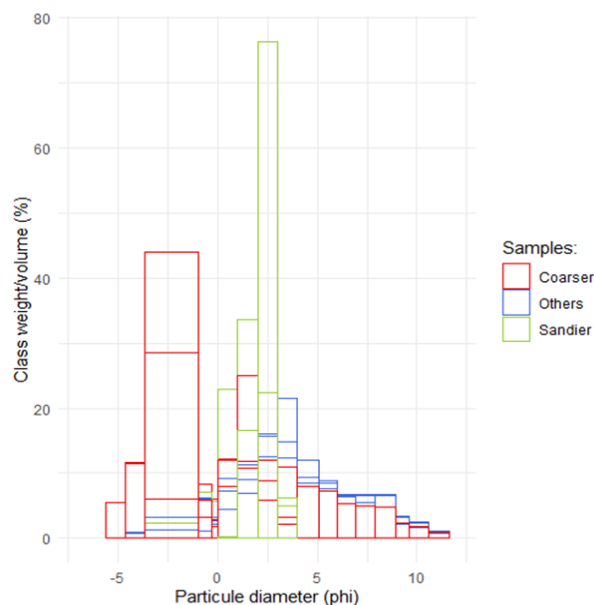


Figure 4.7 Grain size distribution for the samples of unit 8 (on the phi scale, 10 corresponds to 1 μ m, 5 to 31 μ m, 0 to 1 mm and -5 to 32 mm).

In the upper half of the outcrop, unit 9 is made of an alternation of thin gravel-clay duplets. Finally, before the soil and the bioturbated sediments, there is a sandier unit, unit 10. These units were inaccessible and thus not sampled.

- Units comparison

The sand units from the Bolderberg formation (units 1 and 3) are finer than the units belonging to the Zutendaal Gravels (units 4, 6 and 7) (Figure 4.8) except for the clayey unit 8. The units from the Bolderberg formation are also better sorted than the units from the Zutendaal Gravels (Figure 4.9).

Unit 4 is made of finer material than unit 7 and is more poorly sorted than unit 7 (Figure 4.8, Figure 4.9). The gravel fraction of unit 4 is also not as coarse as in unit 6 (Figure 4.8). However, unit 4 is similar to the gravel and sand unit 5. Despite unit 4's shape, which points towards a gravel pocket deposited at the same time as unit 3, unit 4 could be a remnant of a channel that eroded unit 3. The observed pocket shape is due to the orientation of the wall and its slope.

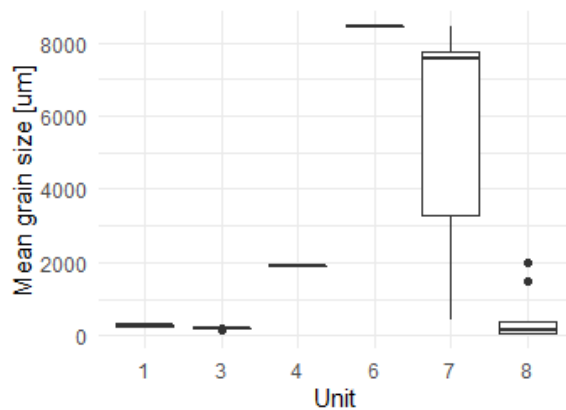


Figure 4.8 Boxplot of MHZ samples mean grain size for unit 1 (4 samples), 3 (18 samples), 4 (1 sample), 6 (1 sample), 7 (7 samples) and 8 (9 samples).

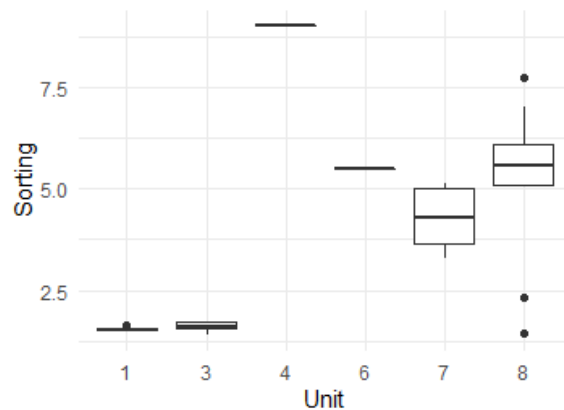


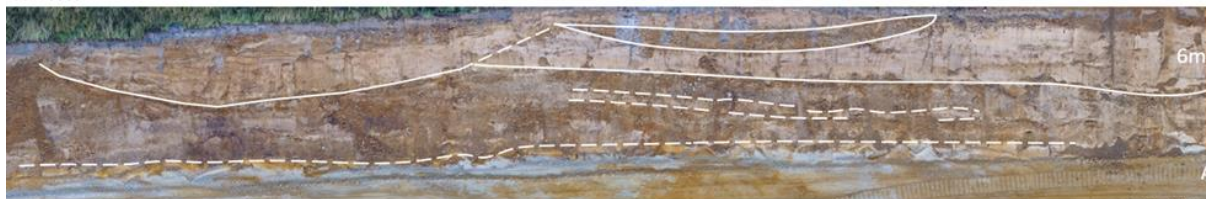
Figure 4.9 Boxplot of MHZ samples sorting for unit 1 (4 samples), 3 (18 samples), 4 (1 sample), 6 (1 sample), 7 (7 samples) and 8 (9 samples).

The boundary between units 6 and 7 is highlighted by the manganese oxide staining. The two units can also be differentiated based on their grain size. Unit 6 is overall coarser and less well sorted (Figure 4.8, Figure 4.9). Unit 6's fine fraction is also, in comparison to its coarse fraction, more important than unit 7's fine fraction.

4.1.4 MHZ wall 2

Detailed observations were made along one profile (Figure 4.10, yellow marker EPSG 31370 coordinates: 237541.60 m 187664.26 m), where erosion of the wall caused several units to crop out clearly. The lowest unit visible on wall 2 (unit 1 Figure 4.11) corresponds to the uppermost unit of the Genk Member in the Bolderberg formation described by Houthuys (2017) and Louwye et al. (2020) having orange staining.

W - NW



E - SE



Figure 4.10 Visible units on wall 2 in MHZ quarry mostly large clay plug except one small gravel layer (top). Dashed lines indicate uncertain unit's limits. The yellow marker indicates the position of the profile described in Figure 4.11. Left half of the outcrop is on top, the right side at the bottom.

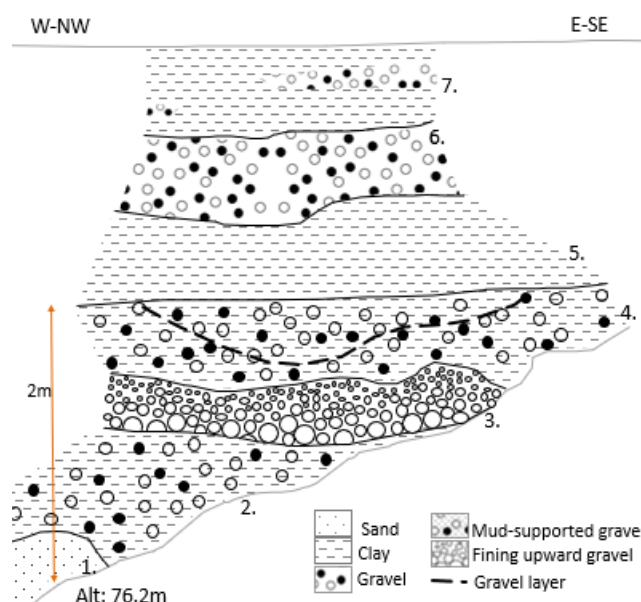


Figure 4.11 Picture and sketch profile on wall 2 in MHZ.

The second unit is made of debris-flow deposits, i.e. mud-supported boulders (Figure 4.12). The largest visible boulder in unit 2 had a 20 cm long axis. Unit 3 consists of very coarse gravel at its base, and it fines upward to very fine gravel and very coarse sand (Figure 4.13). Then, there is another debris-flow deposit unit, unit 4 (Figure 4.11). The largest visible boulder is ca. 19 cm. The debris-flow deposits are interrupted by a concave-up washed-gravel layer. Unit 5 is made of massive clay with some gravel, and the amount of gravel decreases towards the top, where it is almost pure clay. It is capped by a poorly sorted gravel layer, unit 6. Finally, in unit 7, massive clay and gravel lenses alternate.



Figure 4.12 MHZ quarry wall 2: Debris-flow deposits of unit 2, the largest boulder is about 20 cm long.



Figure 4.13 MHZ quarry wall 2: fining upward sequence from very coarse gravel to very fine gravel and very coarse sand in unit 3.

4.1.5 MHZ quarry: summary

Overall on wall 2, the lowest unit is the orange-stained sand from the Bolderberg formation (Figure 4.10). Then there are units of poorly sorted gravels, units of mud-supported gravels, gravel units fining upward, thin layers of very coarse gravels and some massive clay units. Those units are not all laterally extensive, and not all of them are present in every location along the wall. The order of the alternation between those units varies along the outcrop. Some of the massive clay units form large channel plugs. The latter are clearly visible on the orthofacade (Figure 4.10).

There is about a 4 m elevation difference between the bottom of wall 1 (72.2 m) and wall 2 (76.3 m). On wall 1, the contact between the Zutendaal Gravels and the Bolderberg is usually at 74 – 75 m on the right and lower on the left of the outcrop (with unit 5). The contact (ca. 76 m) is slightly higher along wall 2. The lowest gravels with a sand matrix, associated with channels, are only visible on wall 1. Debris-flow deposits are then visible on both walls. The debris-flow deposits of wall 2 are located higher (ca. 76 m) than the one observed on wall 1 (ca. 73m). Overall, those oldest deposits of the Zutendaal Gravels are only locally present. Then, there is a laterally extensive gravel layer which displays a large grain size variability between sampling spots.

The main clay layer of wall 1 (unit 8) seems to correspond to the clay units 5 and 7 on wall 2, which are interrupted by the gravelly unit 6. The lower boundary of the massive clay layer on wall 1 is between 76 and 77 m high. It is at about 78 m on wall 2. Unit 8 on wall 1 is relatively heterogeneous, as indicated by the supervised classification and the grain size analysis. The supervised classification on wall 1 classified the unit as clay and highlighted that there were gravel and sand patches. On wall 2, in cross-section, several broad channels are visible. On a longitudinal section such as on wall 1, it looks like one large tabular unit.

Wall 2 is 81.5 m high, and the highest section of wall 1 is 88.1 m tall. The highest section, only visible on wall 1, is made up of thin layers of clay and gravel.

4.2 Quarry Berg

The studied section in quarry Berg was 33 m long and 15.7 m high (Figure 4.14). The wall is NE-SW oriented and located in the east of the quarry (Table 4.2). Nine units were identified based on texture, colour, staining, sorting and sedimentary structure. Samples were taken for each unit identified on the field, except for the gravel of unit 9 (Table 4.3).

Table 4.2 Coordinates (EPSG 31370) of both ends of the studied section in quarry Berg.

X [m]	Y [m]	Altitude [m]
239025.2	184735.9	74.3
239048.2	184758.8	75.7

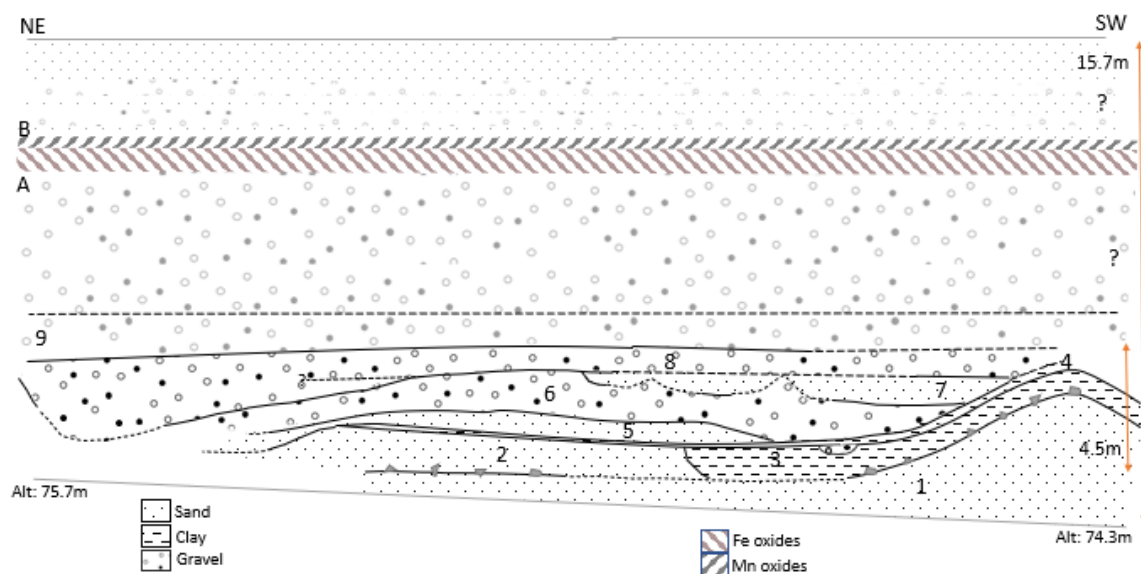


Figure 4.14 Quarry Berg: panorama and corresponding sketch of a 33m long section between the 2 GPS points.

The first unit, made of white, fine sand (Figure 4.14), is the Bolderberg sand. The contact between the Bolderberg and the Winterslag Sands is undulating. And there is a lag deposit made of heterogeneous coarse and fine gravels, which was also sampled and named B10. The lag deposit has a mean grain size of 39 mm (Table 4.3) between the Bolderberg sand and unit 2 and 3. This kind of gravel accumulation

can form in a fluvial context when there is a stable surface (Mackay and MacKay 1977; Hansom 2005). The contacts between units 1 and 2, and 1 and 3 are erosional.

Table 4.3 Grainsize analysis indexes for the quarry Berg samples. The mean, sorting, skewness and kurtosis are calculated using the geometric Folk and Ward method. The samples in light grey italic have a large (>5%) <63µm fraction.

sample	mean (µm)	sorting	skewness	kurtosis	D10 (µm)	D50 (µm)	D90 (µm)	<63µm
B1	215	1.72	-0.01	0.93	99	208	419	
B2	269	1.58	-0.25	0.84	139	290	454	
B3	183	7.90	-0.02	0.99	11	187	1944	26.4%
B4	73	3.52	-0.30	1.26	10	94	291	28.8%
B5	208	1.82	-0.07	1.58	119	197	396	5.9%
B5b	207	1.55	0.15	1.12	130	196	386	
B5c	212	4.67	-0.16	1.24	19	230	1199	17.9%
B6	3466	5.16	0.00	0.76	414	3405	29637	
B7	338	1.50	-0.06	1.46	180	340	491	
B8	4424	3.77	-0.24	1.36	589	4824	17881	
B10	39485	1.47	-0.08	0.95	25271	39245	62640	

Unit 2 (Figure 4.14) is made of medium to coarse heterolithic sand with an average grain size of 269 µm. It is moderately well sorted (Table 4.3), and there is some orange to yellow staining. Unit 3 is a massive clay layer containing a small gravel pocket. Unit 3 is mostly made of clay, with a coarser fraction of medium to fine sand (B3 on Figure 4.15). Similarly, unit 4, which caps both units 2 and 3, is made of clay with some fine sand (B4 Figure 4.15). The clay layer of unit 4 is 15 to 20 cm thick at its middle section and becomes thinner and sandier towards the left. Unit 4 seems to have aggregational upper and lower boundaries. Unit 5 (Figure 4.14) is made of coarse heterolithic sand, and the top-right part is more clayey (Figure 4.16). The sand is reddish towards the right, where it rests on top of unit 3. The colour results from the precipitation of iron oxides. Units 2 to 5 belong to the Winterslag Sands, and they correspond to the lowest part of the member, which consists of clay and fine sand.

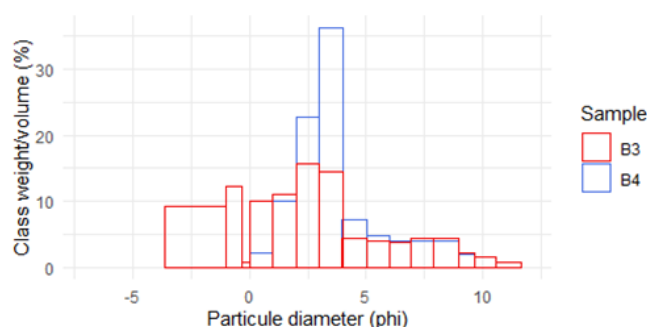


Figure 4.15 Grain size distribution for unit 3 (B3) and 4 (B4) in quarry Berg (on the phi scale, 10 corresponds to 1 µm, 5 to 31 µm, 0 to 1 mm and -5 to 32 mm).

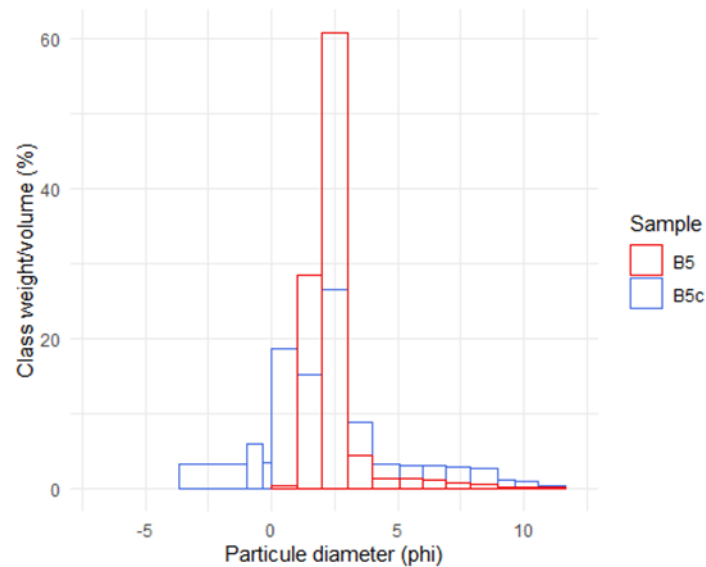


Figure 4.16 Quarry Berg, samples in unit 5. B5 was taken in the middle and B5c in the upper part of unit 5 (on the phi scale, 10 corresponds to 1 μ m, 5 to 31 μ m, 0 to 1 mm and -5 to 32 mm).

There are some manganese and iron stains at the contact between units 5 and 6. Unit 6 is composed of quartz-rich very fine gravels (mean grain size: 3.5 mm) with coarse sand and some coarse gravels in places. Overall, the unit is very poorly sorted (Table 4.3). Then, units 7 and 8 have erosive lower boundaries. However, the geometry of the lower boundary of unit 7 is unclear. Unit 7 is a medium sand layer (mean grain size: 338 μ m) which is only locally present and seems to form small channels eroded in unit 6. Unit 8 is coarser and made of poorly sorted fine to medium gravel, with a sand and clay matrix (mean grain size: 4.4 mm) (Table 4.3). Unit 8 includes manganese oxide and iron oxide concretions. A coarse gravel sheet, unit 9, with boulder size gravels caps unit 8. Unit 9 is laterally extensive. It is visible along the entire wall and can potentially be used as a marker horizon (K. Beerten, personal communication, 16/03/2021).

The higher part of the sequence looks gravelly, but there is a lot of recent colluvium and vegetation that prevent detailed observations except for a net red iron oxide-rich horizon, unit A (Figure 4.14), and an overlying manganese horizon, unit B. The manganese oxide horizon is clearly visible all over the quarry. In another location in the north of the quarry, the manganese and iron horizons are more accessible. There, the black horizon was observed to be made of black gravels, and the red horizon to be sandy with some gravels.

4.3 Quarry Berg and MHZ: comparison

The outcrop in Berg has similar dimensions and elevation to wall 1 in MHZ (Table 4.4). Unlike in MHZ, the first units in Berg belong to the Winterslag Sands (Figure 4.17). Unit 6 from Berg has a similar grain size distribution as unit 4 on wall 1 in MHZ. However, no debris-flow deposits were observed in Berg. The marker horizon gravel layer in Berg (unit 9) can be related to the extensive gravel layer visible on wall 1 in MHZ (unit 7) (Figure 4.17). The base of this layer is at about 75 m in MHZ and 75.7 m in Berg (Table 4.4). No clay plug was clearly observed on the studied section in Berg. However, clay plugs were

observed further north on the same wall in 2019 underneath the extensive gravel layer (Figure 4.18). Finally, observations from the 2019 field campaign also indicate thin clay layers in the higher section of the outcrop, which are similar to the one observed in MHZ (gravel-clay duplets of unit 10 in MHZ). Two black manganese oxide horizons were observed in MHZ (Table 4.4). In quarry Berg, only one extensive manganese horizon was observed. The latter was underlain by a red iron oxide layer. The second manganese horizon in MHZ is at a similar altitude to the manganese and iron oxides horizon in Berg. Unlike in the nearby Opgrimbie quarry, no intra-formational indications of cold climate were observed in MHZ or Berg quarries.

Table 4.4 Elevation of the walls, contacts and marker horizon. () altitude of the oxide layer for another location in the south in Berg, data from a previous field campaign.*

	Bottom outcrop [m]	Bolderberg - Zutendaal Formation contact [m]	Gravel marker horizon [m]	MnOx horizon [m]	Aeolian sand [m]	Top outcrop [m]
MHZ	72.2 (wall 1) 76.3 (wall 2)	~72.5 to 76	75	~76.5 (A) ~79.5 (B)	~85 (wall 1)	88.1 (wall 1) 81.5 (wall 2)
Berg	71.2 to 72.6	~71.5 to 75.5	~75.7	~80m* (top of the thick Mn and Fe horizon)	(?)	86.9

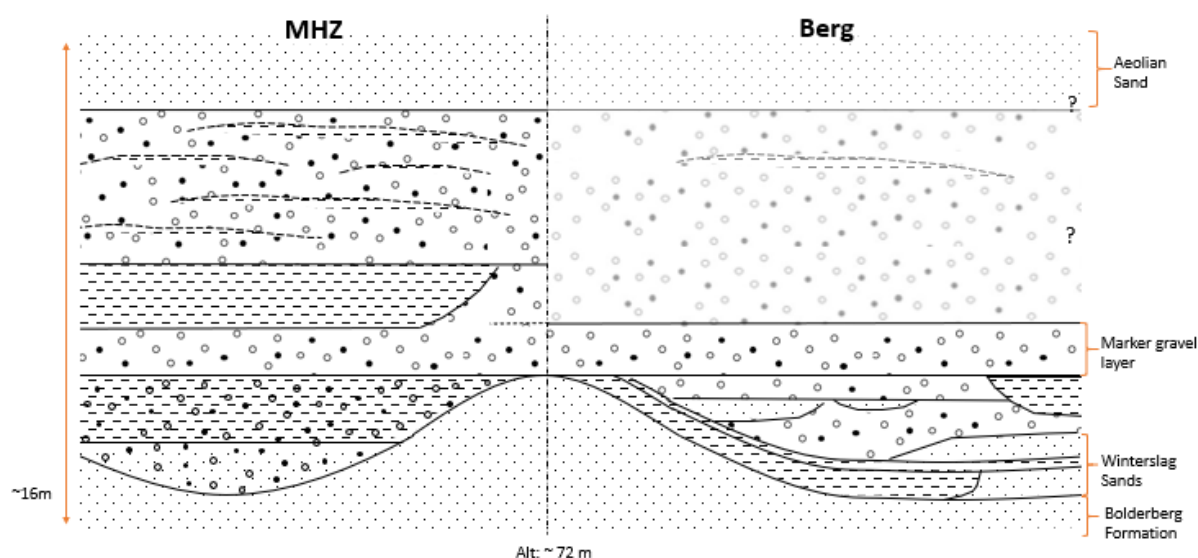


Figure 4.17 Composite summary sketch of the outcrops in MHZ (left) and Berg (right) quarries.



Figure 4.18 Clay plug in Berg quarry (21/08/2019).

5 Discussion

5.1 Pertinence of using aerial photographs

The main limitation of the application of a supervised classification to the Zutendaal Gravels is that the a priori set texture-based classes are not clearly spectrally distinct. The reflectance variance within each class is large, and there is overlap between the classes of each of the RGB bands (Figure 5.1). Without the training sample input, the algorithm does not differentiate clay, gravel and sand as the unsupervised classification showed. The unsupervised classification also highlighted the sensitivity of classification to exposition and moisture conditions. For instance, there is a darker spot in unit 8 of wall 1 in MHZ. The unsupervised classification showed that this area of darker clay is spectrally more different from the rest of the outcrop than the areas of gravel are. Representative training samples can account for this variation (Figure 5.2). However, the brown patches in the sand at the bottom of the wall were wrongly classified as clay in both unsupervised and supervised classification (Figure 5.2). The results show that reflectance is related to grain size but also humidity and exposition.

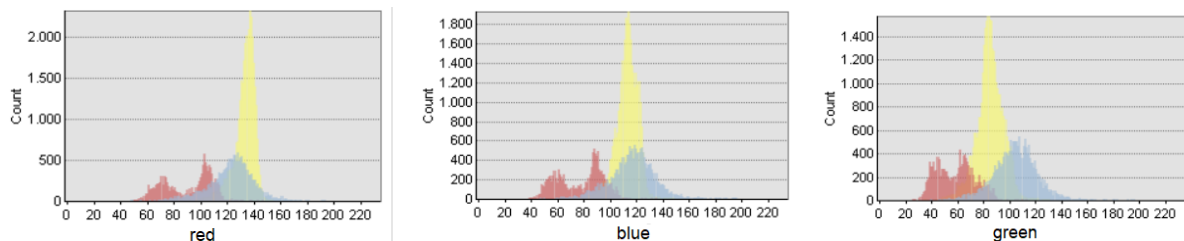


Figure 5.1 Spectral signature of the 3 texture-based classes (sand in yellow, gravel in blue and clay in brown) for each RGB band for wall 1 in MHZ. 'Count' is the number of pixels in the class with the corresponding reflectance value.

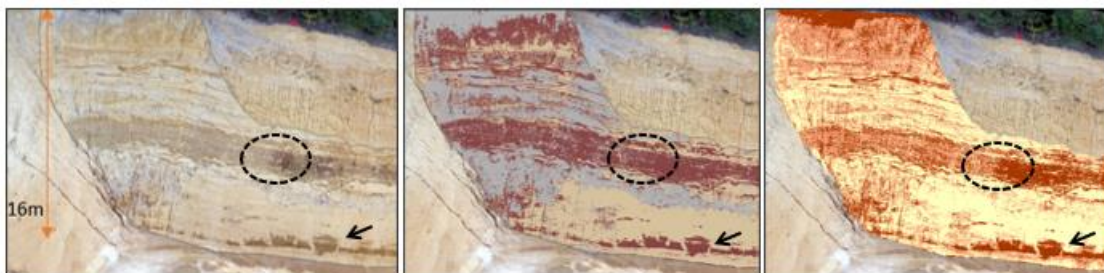


Figure 5.2 Orthofacade, supervised classification and unsupervised classification for wall 1 in MHZ quarry. Exposition and humidity variations, corrected with the appropriate training samples (circle), and not corrigible with training samples (arrow).

The classification method is a helpful tool to identify large structures and to study the high sections of the outcrop. However, classification reflects other variables (humidity and exposition) and has thus to be interpreted with caution. Classification and sampling or detailed observations along a profile are complementary methods. They give information at two different scales. The classification gives an overview and allows to make first hypotheses about sedimentary units. The latter can be refined by sampling or detailed observations. In MHZ quarry, their combination allowed us to get a better understanding of the wall than in Berg, especially because observations in the higher section was not possible.

5.2 Miall's classification

The following section attempts to link observations with the lithofacies described by Miall (1996). The latter are based on grain size and sedimentary structure. No clear sedimentary structure was observed in our study area, which indicates that the structures are not clear. Then, based on facies assemblage and geometry, the section attempts to link observation with architectural elements and river styles Miall (1996).

- **Berg quarry**

The first Zutendaal Gravels unit in Berg quarry is unit 6 (Figure 4.14). Unit 2 to 5, the Winterslag Sands, fill the erosional channel in the underlying Bolderberg Sands (Figure 5.3). These units observed in the Berg quarry belong to the lowest part of the Winterslang Sands. No gravelly sand, which is characteristic of the upper part of the member, was observed in the studied section. The latter might have been eroded before the deposition of the Zutendaal Gravels.

Unit 6 is matrix-supported, poorly sorted, and does not show grading, and can thus be classified as matrix-supported massive gravel (Gmm) facies which Miall interprets as high-strength debris flow deposits. The sand lithofacies described by Miall are distinguished based on sedimentary structures. No clear sedimentary structure was observed for unit 7. It, therefore likely, corresponds to the massive or faint lamination sand facies. According to Miall's such deposits can be interpreted as sediment-gravity flow deposits. Clast's size increases upward with units 8 and 9. Unit 8 has a sand and clay matrix, it is poorly sorted and is not graded. It can thus be considered as a Gmm facies. Unit 9, the marker coarse to very coarse gravel layer, is coarser than unit 8 but is also matrix supported.

Based on geometry and facies assemblage, the most likely category of architectural element for the units 6 to 8 observed in Berg is a channel element (CH) (Figure 5.3). First, there are several concave-up erosional bases. Then, there are sand and gravel facies. Architectural elements are often characterised by a specific facies' assemblage, but channels are not. Unit 9 forms a tabular body and is, therefore, more likely to be a 'Gravel Bars and Bedforms' element (GB).

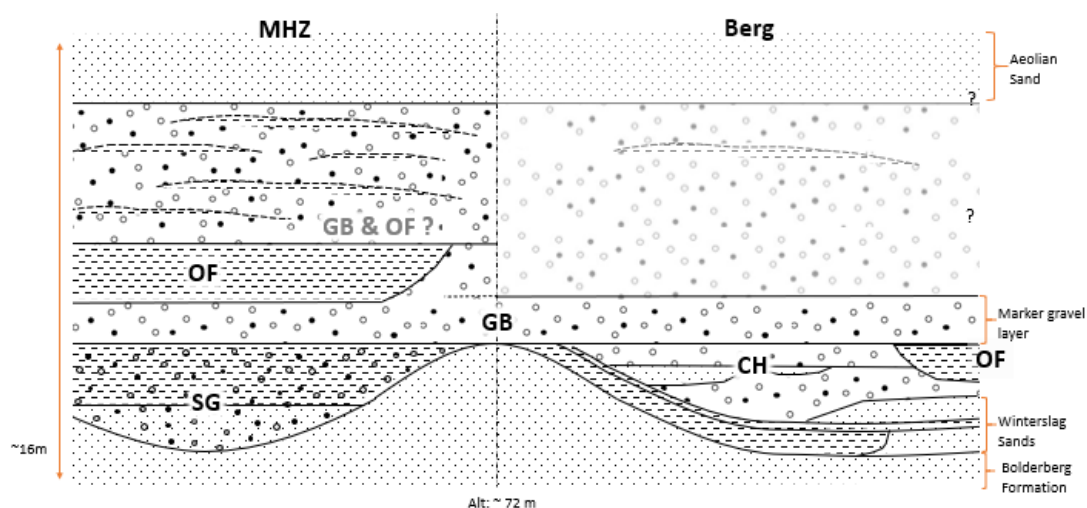


Figure 5.3 Summary composite sketch with architectural elements. SG: Sediment gravity flow, CH: channels, OF: overbank fines, GB: gravel bars and bedforms.

- MHZ quarry

Most of the lower units in the MHZ quarry are made of gravel with a sand or clay matrix, they are poorly sorted and show a sharp non-erosional lower boundary (Figure 4.4 and Figure 4.11). They can thus be classified as Gmm. Unit 3 on wall 2 is different, it is fining upward, and therefore it could be identified as matrix-supported gravel (Gmg) facies. Those two facies are interpreted by Miall as high and low-strength debris flow. The more likely corresponding architectural element for this low section is 'Sediment Gravity Flow' (SG) (Figure 5.3) which characteristic facies assemblage is Gmm, Gmg and clast supported gravels. The lower section in MHZ also includes some massive clay, which according to Miall's scheme, can be interpreted as deposition during low-stage. Then comes the marker gravel layer, which has also been identified in Berg as an element GB (Figure 5.3).

The large clay plugs are not bioturbated and include some sandier material. According to Miall's facies classification, it is either laminated sand, silt and mud (Fl) or massive mud, silt (Fm). Fl facies are typically up to a few metres, but Fm are usually only a few centimetres. It is, therefore, more likely that the units observed in MHZ belong to the Fl class and represent overbank areas. Both Fl and Fm facies correspond to 'Overbank Fines' (OF) architectural elements. Miall indicates that OF elements can fill abandoned channels, which corresponds to the channel geometry observed on wall 2.

Finally, observations in the upper section are limited. The gravel sub-units do not have a sharp lower boundary or inverse grading and are not scoop-shaped, so the Gp, Gmm, Gci and Gt classes are unlikely. Possible classes left are planar-cross-bedded gravel, clast-supported massive gravel and clast-supported horizontally stratified gravel. These facies are respectively interpreted as transverse bedforms, low-strength debris flow, and longitudinal bedforms. The clay sub-units could be Fl or Fm facies. The Fl facies can be interpreted as overbank deposits and Fm as low-stage deposition in pools or distal floodplain deposits. No architectural element described by Miall include gravel and fine-grained facies as observed in MHZ, but it could be an alternation of GB and OF elements.

- River type

Miall described 6 types of braided rivers: three are gravel-bed, three are sand-bed. Very little sand was observed in the Zutendaal Gravel, and the three sand types are therefore unlikely. Among the three gravel styles, the 'Deep, gravel-bed braided river' is the less likely. Deep, gravel-bed braided river displays topographic levels. The lower levels are dominated by GB elements and the higher levels by sandy bedforms. No such topographic levels were observed. The lower section of the Zutendaal Gravels includes SG elements. The latter is a distinctive feature of 'Gravel-bed braided river with sediment-gravity flow deposits' according to Miall's classification (Figure 5.4). Thin fine overbank sediments can be observed for this type of river. This style is common in alluvial fans. Trollheim fan, in California, is considered as the type example of this type.

The several metres thick clay plugs observed in the middle section of the Zutendaal do not match with any braided river styles. Fine-grained units of those dimensions are not described in any of Miall's

braided river styles because overbank fines elements are not common for braided rivers as channels typically occupy most of the floodplain (Miall 1996).

No SG elements were observed in the higher section of the outcrops. The latter resemble more to the last gravel-bed braided type: ‘Shallow, gravel-bed braider river’ or Scott-type (Figure 5.4). This is the other type of river common in alluvial fan and is characterised by deposits mainly as GB and some thin sand of OF units. This type seems more likely for the highest part where gravel-clay duplets are found. The typical channel depth for this type of river is about 1 m. The thickness of OF sediments is usually limited, however, some examples show thicker fine deposits resulting from high deposition rates and preservation of overbank deposits (Miall 1996).

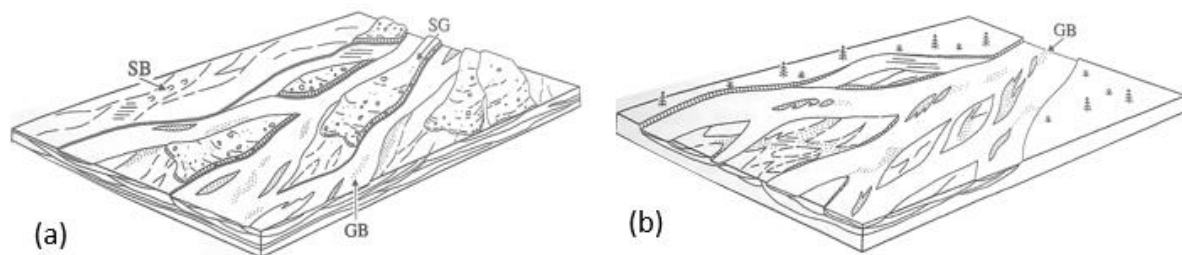


Figure 5.4 River styles (Miall 1996). (a) Gravel-bed braided river with sediment-gravity-flow deposits, (b) Shallow, gravel-bed braided river

- **Applicability**

The main difference between our observations and Miall’s classification is the presence of thick clay channel fill. None of the gravel braided river styles described by Miall includes such units. Braided rivers usually occupy most of the river floodplain and leave little space for overbank fine deposits.

The classification is based on selected examples (Scott, Platte, Donjek, Trolheim fan). However, the relevance of the type example can be discussed. For instance, Trolheim fan might not include the range of facies typical for Gravel-bed braided river with sediment-gravity flow deposits’ (Miall 1996). The type example for ‘Shallow, Gravel-Bed Braided River’, the Scott River is not characterised by thick fine deposits. Nevertheless, Miall (1996) gives an example of a ‘Shallow, Gravel-Bed Braided River’ in France, where thick overbank deposits were preserved. Vertical profiles are of limited reliability to diagnose the fluvial style, and its interpretation should include several potential scenarios (Miall 2014). The geological record depends on the preservation and can display fragmentary deposits from several fluvial styles and depends on the pattern of preservation (Miall 2014).

5.3 Climate and timing of deposition

- **Undulating base**

Both in quarry Berg and carry MHZ, the boundary between the Bolderberg and the Winterslag Sands or Zutendaal Gravels is undulating. The channels of about 5 m eroded in the Bolderberg Sands have also been observed in Opgrimbie quarry (Gullentops et al. 1981). Incision occurs at warm-cold and cold-warm transitions and is followed by aggradation during the following stable phase (Vandenberghe

1995, 2008). Incision during warm-cold transition is typically wide and shallow. The deep gullies at the base of the Zutendaal Formation are remnants of the end of an incision phase, which took place at the beginning of a cold phase.

- **Fine deposits**

Accounting for climate and its influence on river style could explain the presence of the large clay plugs within the coarse braided-river deposits. Climate and river pattern change is an explanation that is often found in the literature for river sequences in low land Europe during the Quaternary (Vandenberghe 1995; Rose et al. 1999; Gibbard and Lewin 2002; Vandenberghe 2008; Rose 2009). According to the model of Vandenberghe (1995, 2008), river style changes at warm-cold and cold-warm transitions. The lower section of the Zutendaal could have been deposited under periglacial conditions. Its coarse sediments and wide extent are characteristic of cold periods (Vandenberghe 2008). The top section of the Zutendaal Gravels, which resemble the shallow, gravel-bed braider river described by Miall (1996), also correspond to cold period deposits from Vandenberghe (2008). However, the thick clay channel fill in the middle section of the sequence does not correspond to the description of braided cold period deposits in the model of Vandenberghe (1995, 2008).

Meandering river deposits have a low preservation potential, unlike braided river deposits and are, therefore, rarely visible in the sediment record (Vandenberghe 2008). Warm period fine sediments are thus rarely preserved (Vandenberghe 2008), but sediments from the early interglacial are not uncommon (Gibbard and Lewin 2002). As the channels gradually fill and the floodplain surface becomes planar, the channel form gradually changes from braided to anastomosing or meandering (Gibbard and Lewin 2002). Early interglacial deposits are fine and typically include high organic content (plant, animal, fossils and peat). Rose et al. (1999) and Rose (2009) observed finer deposits between coarse gravel packs for the Thames and the Bytham rivers. Those fine sediments were deposited in a single channel, attributed to channel infill in the warm conditions' floodplain. Palaeobotanical proxies indicated deposition under temperate to Mediterranean conditions. Regarding the grain size and geometry, the observed clay channel fills in the Zutendaal Gravels resemble early interglacial deposits. However, no organic content was observed in MHZ and Berg's clay channel fills.

Fine sediment can also be observed at warm-cold transition. Gibbard and Lewin (2002) highlighted fine inorganic sediments deposition during the early glacial substage in lowland British river sequences. Those deposits consist of sand sheets, silts and clay drapes. Those inorganic channel fills from the end of an unstable period at a warm-cold transition resemble the clay plugs observed on the field. The classification and the result from the grain size analysis of the clay plug sampled in MHZ indicate that there are intercalations of coarse material.

- **Channel abandonment**

However, the geometry and the grain size alone do not give enough information to allow the identification of aggradation cycles linked with climate and channel patterns. Although overbank fine deposits are not typical of braided rivers (Miall 1996; Mol et al. 2000), the broad clay channel fills could

also result from channel abandonment and therefore be part of the braided river deposits sequence. The trigger of channel abandonment is rarely identifiable in the ancient record, and many studies thus relied on external factors explanations (Gibling et al. 2010). Gibling et al. (2010) managed to identify log jams and build-up of flood sediment as the cause of channel abandonment. No trace of similar processes was observed in the Zutendaal Gravel. Nonetheless, one could hypothesise that the debris flows observed in the sequence could have resulted in reduced flow, channel abandonment and fine-grained sediments accumulation.

- **Manganese and iron oxides horizons**

Oxides horizons can result from pre or post-depositional processes. Oxidation due to pre-depositional processes indicates a different provenance; oxidation before deposition or oxidation due to contrasting mineralogy. For post-depositional oxidations, the presence of the manganese and iron oxides horizons indicates intense alteration after deposition of the underlying unit or fluctuation of the water table level (Cornu et al. 2009; Retallack 2019). In a scenario of slow deposition of the Zutendaal Gravels with hiatuses, the oxide horizons may be an indication of a period of stability and soil development in the floodplain linked with a meandering river pattern. Each aggradation block would thus have an individual weathering history. In a scenario of rapid deposition of the Zutendaal Gravel, the oxides horizons would have been formed later as the water table level decreased with incision of the Meuse.

- **Limitations**

Organic matter analysis data allowed Vandenberghe (1995), Rose et al. (1999) and Mol et al. (2000) to have a better insight into the palaeoenvironmental characteristics of their cases studies. They analysed the organic matter content to reconstruct the fauna and flora present at the time of deposition. Vegetation is an important parameter for river style evolution and is an indication of climate (Vandenberghe 1995; Mol et al. 2000). However, no organic matter remanent was observed in the deposits because of the intense weathering of the Zutendaal Gravels. The absence of organic matter in the Zutendaal Gravels limits the study of their depositional environment.

A better insight into the palaeoenvironmental characteristics of the Campine Plateau at the time of deposition of the Zutendaal Gravels could be gained by combining our results with additional dating. Mol et al. (2000) and Rose (2009) also used dating to relate the sediments deposits with glacial and interglacial cycles. Mol et al. (2000), working on sequences from the Weichselian, used radiocarbon and OSL dating as well as the correlation of their sequence to another dated sequence. For his Early and Middle Pleistocene deposits, Rose (2009) used cosmogenic radionuclide dating, electron spin resonance dating and luminescence dating (for the Middle Pleistocene, however, the resolution is low), U-series dating (for the Middle Pleistocene). For the Zutendaal Gravels, post-IR IRSL (i.e. a feldspar infrared stimulated luminescence method (Buylaert et al. 2012)) and cosmogenic radionuclide (^{10}Be depth profile) could be used.

Vandermaelen et al. (submitted) studied the aggradation phases in the high section of the Zutendaal Gravels on an outcrop in As combining granulometry, geochemistry and ^{10}Be depth profile. They highlighted 2 to 4 potential aggradation blocks. Those findings support the deposition phases and hiatus scenario and a near-surface weathering origin of the oxides horizon. Post-IR IRSL dating indicated that the studied sequence in As was deposited between ca. 500 ka and 460 ka. The Winterslag Sands, present in Berg quarry, was also dated and are estimated to be ca. 700 ka old (Vandermaelen et al. in prep.). Further similar analyses over the whole sequence as accessible in MHZ and Berg would allow to better constrain the timing and duration of deposition of the Zutendaal Gravels.

6 Conclusion

Previous studies of the Zutendaal Gravels have interpreted them as periglacial braided river deposits. This thesis attempted to go further and studied the palaeoenvironmental characteristics of the Campine and the characteristics of the depositional environment of the River Meuse when it deposited the Zutendaal Gravels. The study was based on observations and data from two quarries in the south of the Campine Plateau (Berg and MHZ quarries). Besides typical field observations, measurements and sampling, we also used UAV images and applied a supervised classification to the resulting orthofacades. The orthofacades of the outcrops were extracted from the 3D point cloud of the study areas obtained by SfM. The orthofacades and classified images allowed a first identification of the large sedimentary units. This was particularly useful for the higher sections, which are difficult to sample and observe from the ground. We observed that classification results have to be interpreted with caution as the classification, besides texture, can reflect humidity and exposition. Classification gives a first overview which can be refined with detailed observation and samples' analysis.

The first working hypothesis was related to the applicability of Miall (1996)'s classification of rivers and corresponding interpretation. First, each unit identified on the outcrops was matched to a lithofacies class from Miall's classification. Then based on the facies assemblage and geometry, architectural elements were identified. In particular, sediment gravity flow elements were observed in the lower section of the Zutendaal Gravels. The latter are characteristic for one of the braided river types described by Miall: gravel-bed braided river with sediment-gravity flow deposits. The middle section of the Zutendaal Gravels consists of thick and broad clay channel fills. Such thick fine deposits are not represented in any of Miall's braided river types. The high section of the Zutendaal Gravels resembles more the shallow, gravel-bed braided river or Scott-type. Miall's classification is based on selected examples, and the relevance of each can be discussed.

The second working hypothesis, based on the literature and case studies (Vandenberghe 1995; Rose et al. 1999; Vandenberghe 2008; Rose 2009) concerned the link between grain size, fluviomorphology and climate. The undulating base of the Zutendaal Formation (i.e. Winterslag Sands and Zutendaal Gravels) is a remnant of an incision phase at the beginning of a cold phase. Fine sediments present in a gravel sequence are often associated with deposition during a warm period and a meandering or anastomosed river-style (Rose et al. 1999; Mol et al. 2000; Gibbard and Lewin 2002; Rose 2009). However, the geometry and the grain size only do not allow us to interpret the thick clay plugs observed in our study area as an indication of a climatic transition. Although overbank fine deposits are not common in braided rivers, the observed clay plugs may also result from channel abandonment.

Combining the information from this study on grain size and fluvial geometry with geochemical analyses and geochronology, such as undertaken in As (Vandermaelen et al. submitted; Vandermaelen et al. in prep.), can allow to obtain new insights in the timing and duration of the entire Zutendaal Gravels sequence.

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Appendix

Appendix for chapter 2

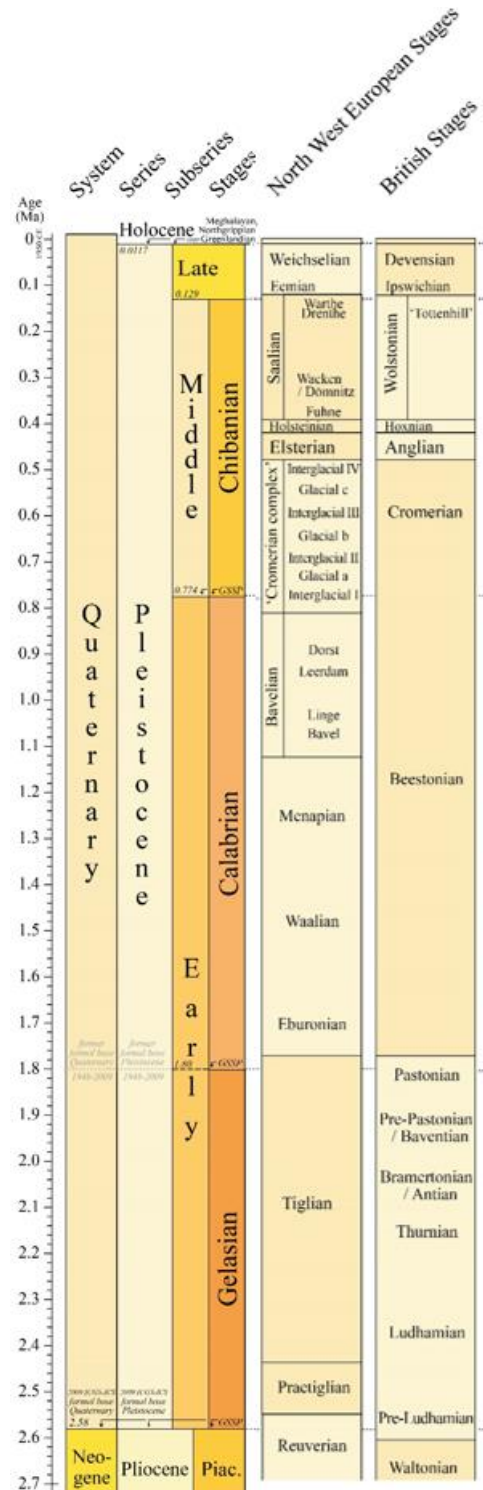


Figure A.1 Global chronostratigraphical correlation table for the last 2.7 million years (v.2020b), Major division and Regional stage divisions (International Commission on Stratigraphy 2020).

Appendix for chapter 3

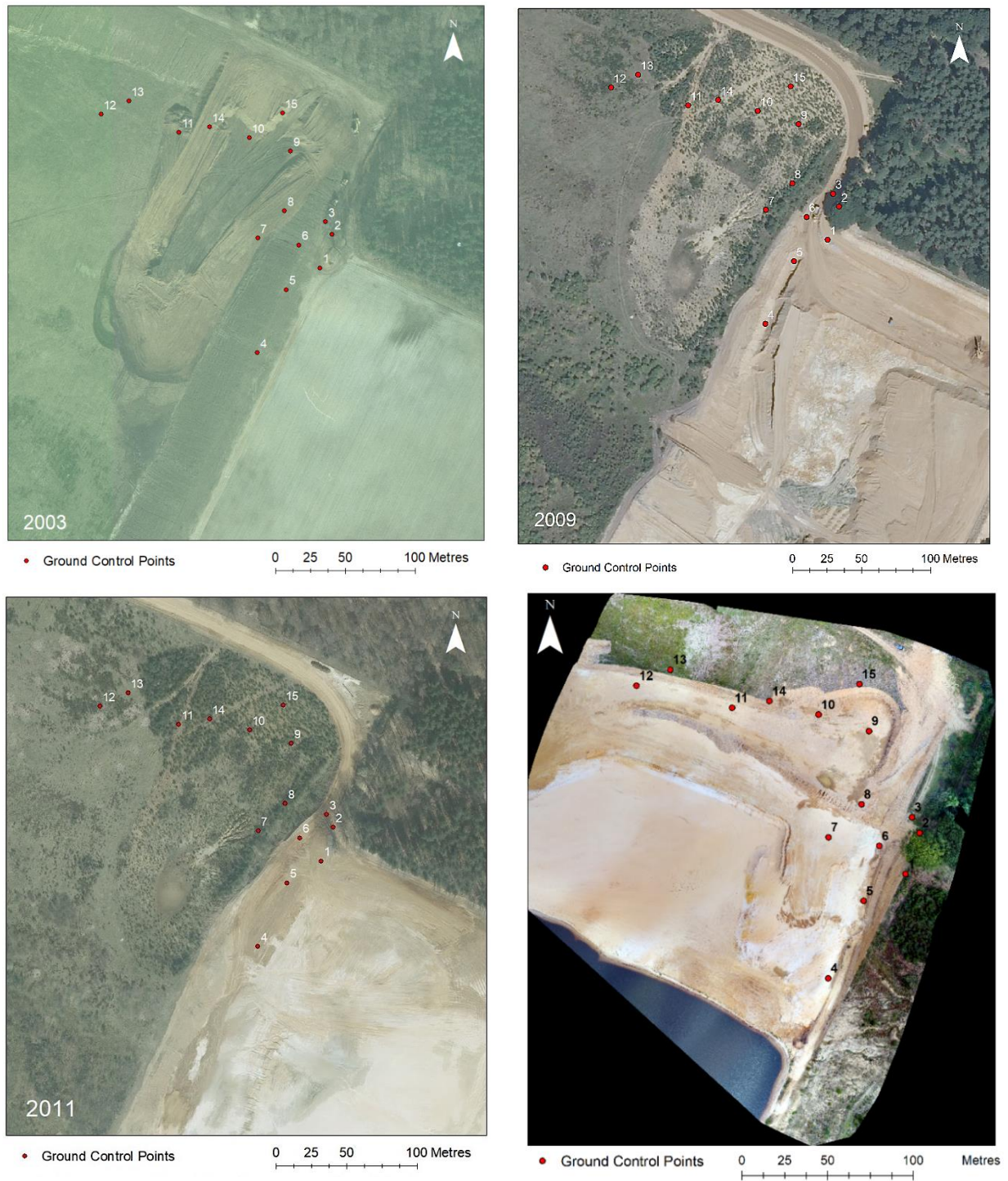


Figure A.2 Aerial photographs of the studied area in MHZ quarry (orthofotomozaïek, middenschalgig 2003, 2009 and 2011), and orthomosaic of the area in September 2020 (Aerial photographs credits: Agentschap Informatie Vlaanderen – Geopunt.be)

Table A.1 Grain size terminology used in GRADISTAT (Blott and Pye 2001).

Grain size			
phi	mm/ μ m	GRADISTAT program	
-11	2048 mm	Very large	Boulders
-10	1024	Large	
-9	512	Medium	
-8	256	Small	
-7	128	Very small	
-6	64		
-5	32	Very coarse	Gravel
-4	16	Coarse	
-3	8	Medium	
-2	4	Fine	
-1	2	Very fine	
0	1	Very coarse	Sand
1	500 μ m	Coarse	
2	250	Medium	
3	125	Fine	
4	63	Very fine	
5	31	Very coarse	Silt
6	16	Coarse	
7	8	Medium	
8	4	Fine	
9	2	Very fine	
		Clay	

Table A.2 Folk and Ward grain size statistics (Blott and Pye 2001).

A. Logarithmic Folk and Ward graphical measures.

Mean	Standard deviation		Skewness	Kurtosis	
$M_z = \frac{\phi_{16} + \phi_{50} + \phi_{84}}{3}$	$\sigma_I = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_5}{6.6}$		$Sk_I = \frac{\phi_{16} + \phi_{84} - 2\phi_{50}}{2(\phi_{84} - \phi_{16})} + \frac{\phi_5 + \phi_{95} - 2\phi_{50}}{2(\phi_{95} - \phi_5)}$	$K_G = \frac{\phi_{95} - \phi_5}{2.44(\phi_{75} - \phi_{25})}$	
Sorting (σ_1)	Skewness (Sk_1)			Kurtosis (K_G)	
Very well sorted	<0.35	Very fine skewed	+0.3 to +1.0	Very platykurtic	<0.67
Well sorted	0.35–0.50	Fine skewed	+0.1 to +0.3	Platykurtic	0.67–0.90
Moderately well sorted	0.50–0.70	Symmetrical	+0.1 to -0.1	Mesokurtic	0.90–1.11
Moderately sorted	0.70–1.00	Coarse skewed	-0.1 to -0.3	Leptokurtic	1.11–1.50
Poorly sorted	1.00–2.00	Very coarse skewed	-0.3 to -1.0	Very leptokurtic	1.50–3.00
Very poorly sorted	2.00–4.00			Extremely leptokurtic	>3.00
Extremely poorly sorted	>4.00				

B. Geometric Folk and Ward graphical measures.

Mean	Standard deviation				
$M_G = \exp \frac{\ln P_{16} + \ln P_{50} + \ln P_{84}}{3}$	$\sigma_G = \exp \left(\frac{\ln P_{16} - \ln P_{84}}{4} + \frac{\ln P_5 - \ln P_{95}}{6.6} \right)$				
Skewness	Kurtosis				
$Sk_G = \frac{\ln P_{16} + \ln P_{84} - 2(\ln P_{50})}{2(\ln P_{84} - \ln P_{16})} + \frac{\ln P_5 + \ln P_{95} - 2(\ln P_{50})}{2(\ln P_{25} - \ln P_5)}$	$K_G = \frac{\ln P_5 - \ln P_{95}}{2.44(\ln P_{25} - \ln P_{75})}$				
Sorting (σ_G)	Skewness (Sk_G)	Kurtosis (K_G)			
Very well sorted	<1.27	Very fine skewed	-0.3 to -1.0	Very platykurtic	<0.67
Well sorted	1.27-1.41	Fine skewed	-0.1 to -0.3	Platykurtic	0.67-0.90
Moderately well sorted	1.41-1.62	Symmetrical	-0.1 to +0.1	Mesokurtic	0.90-1.11
Moderately sorted	1.62-2.00	Coarse skewed	+0.1 to +0.3	Leptokurtic	1.11-1.50
Poorly sorted	2.00-4.00	Very coarse skewed	+0.3 to +1.0	Very leptokurtic	1.50-3.00
Very poorly sorted	4.00-16.00			Extremely leptokurtic	>3.00
Extremely poorly sorted	>16.00				

Appendix for chapter 4

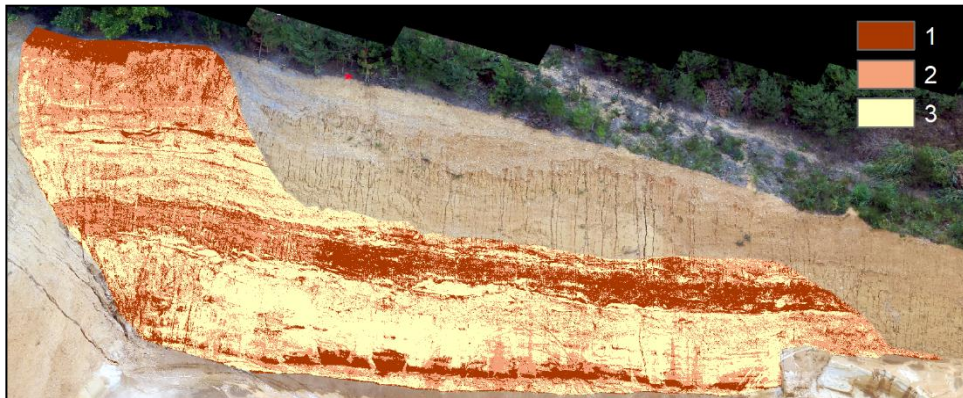


Figure A.3 MHZ quarry, wall 1 unsupervised classification.

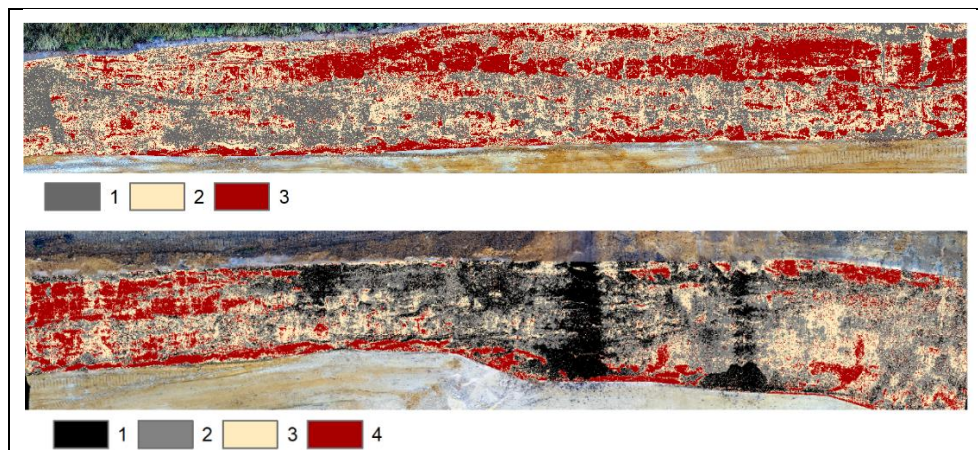


Figure A.4 MHZ quarry, unsupervised classification for wall 2 left half (top) and right half (bottom).

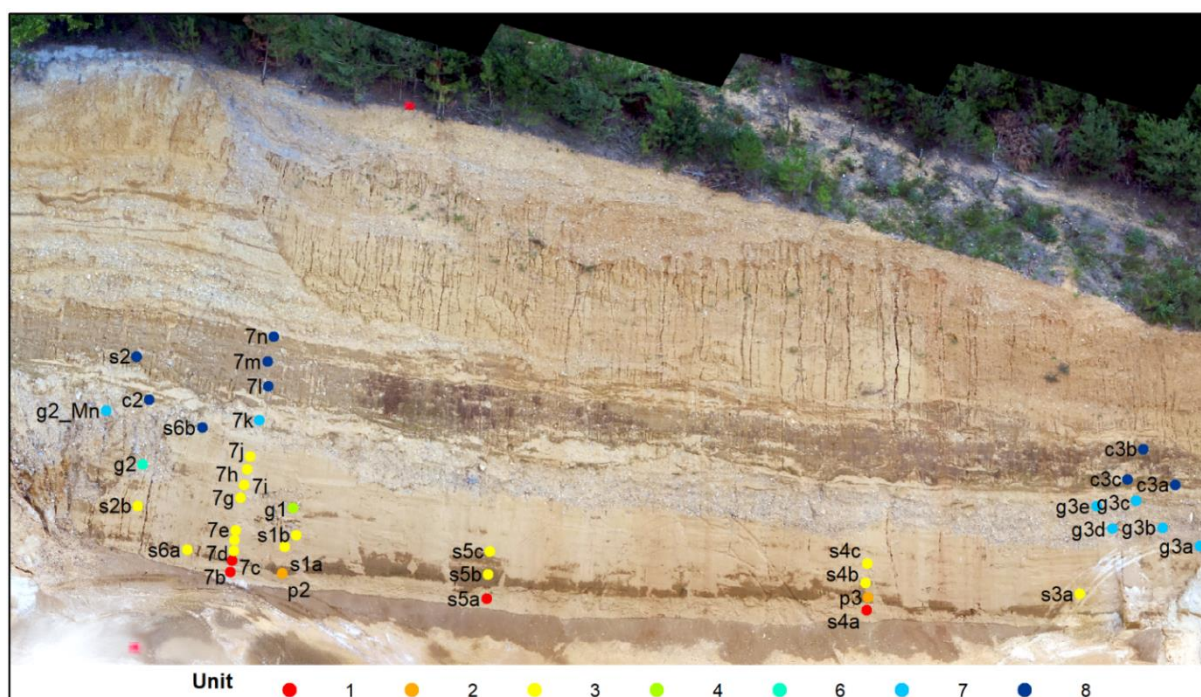


Figure A.5 Samples' localisation in MHZ for the first wall and their corresponding unit.

Table A.3 Grainsize analysis indexes for the MHZ quarry samples. The mean, sorting, skewness and kurtosis are calculated using the geometric Folk and Ward method. The sample in light grey italic have a large (>5%) <63µm fraction.

sample	fw_mean (µm)	fw_sorting	fw_skew	fw_kurto	D10 (µm)	D50 (µm)	D90 (µm)	<63µm
Mhz2_1	181	1.59	0.01	1.47	93	179	344	
Mhz1_g1	1897	9.01	0.25	0.72	152	1189	38020	
Mhz1_p3	301	2.82	0.22	3.1	147	322	8958	
Mhz1_s1b	148	1.71	-0.06	1.06	75	157	303	
Mhz1_c2	64	5.08	-0.1	0.87	7	75	462	
Mhz1_g2	8447	5.49	-0.8	0.45	444	17332	66283	
Mhz1_g2_Mn	7554	4.28	-0.27	0.91	764	9235	36652	
Mhz1_s2	1498	6.11	0.23	0.69	170	1059	18983	
Mhz1_s2b	149	1.7	-0.07	1.05	75	158	304	
<i>Mhz1_c3a</i>	<i>69</i>	<i>5.56</i>	<i>-0.05</i>	<i>0.98</i>	<i>8</i>	<i>80</i>	<i>810</i>	<i>42.50%</i>
<i>Mhz1_c3b</i>	<i>91</i>	<i>7.02</i>	<i>0.04</i>	<i>0.83</i>	<i>7</i>	<i>88</i>	<i>1265</i>	<i>42.85%</i>
<i>Mhz1_c3c</i>	<i>72</i>	<i>5.77</i>	<i>-0.05</i>	<i>0.8</i>	<i>7</i>	<i>79</i>	<i>713</i>	<i>45.88%</i>
Mhz1_g3a	5332	5.06	-0.34	0.96	429	7778	31855	
Mhz1_g3b	8433	3.28	-0.3	1.08	2092	9896	28144	
Mhz1_g3c	7765	3.76	-0.5	1.16	506	10601	23513	
Mhz1_g3d	1270	4.96	0.25	0.94	272	871	11246	
Mhz1_g3e	7705	3.53	-0.23	0.95	1168	8839	31817	
Mhz1_p2	1181	7.77	0.7	3.59	160	360	31724	
Mhz1_s3a	145	1.72	-0.03	1.01	73	153	302	
Mhz1_s1a	147	1.59	-0.17	1.03	77	157	242	
Mhz1_s4a	275	1.53	-0.21	0.81	148	292	452	
Mhz1_s4b	173	1.55	-0.02	1.41	92	174	309	
Mhz1_s4c	179	1.51	-0.01	1.42	109	179	317	
Mhz1_s5a	254	1.54	-0.06	0.74	142	259	440	
Mhz1_s5b	185	1.66	0.03	1.35	89	180	367	
Mhz1_s5c	195	1.54	0.1	1.31	126	187	361	
Mhz1_S6B	186	1.45	0.09	1.25	129	185	332	
Mhz1_S6A	190	1.57	0.05	1.4	115	184	352	
Mhz1_7A	275	1.53	-0.23	0.82	148	294	450	
Mhz1_7B	268	1.64	-0.29	0.9	134	290	461	
Mhz1_7C	191	1.71	0.02	1.18	89	186	387	
Mhz1_7D	184	1.68	0.03	1.29	89	180	373	
Mhz1_7E	181	1.57	0.02	1.38	96	179	340	
Mhz1_7F	225	1.6	0.13	0.85	131	213	428	
Mhz1_7G	184	1.55	0.05	1.34	102	181	344	
Mhz1_7H	218	1.71	0.1	1.01	115	203	443	
Mhz1_7I	176	1.38	-0.01	1.22	127	176	245	
Mhz1_7J	179	1.41	0.04	1.27	128	179	265	
<i>Mhz1_7K</i>	<i>428</i>	<i>5.13</i>	<i>0.32</i>	<i>2.13</i>	<i>95</i>	<i>299</i>	<i>7937</i>	<i>7.40%</i>
<i>Mhz1_7L</i>	<i>136</i>	<i>7.75</i>	<i>-0.09</i>	<i>0.75</i>	<i>8</i>	<i>160</i>	<i>1592</i>	<i>35.83%</i>
Mhz1_7M	402	2.33	0.06	0.93	142	391	1221	
Mhz1_7N	1998	5.54	-0.23	0.86	175	2527	13811	

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