

## Silica sand resources in the Netherlands

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### Abstract

Silica sand, (almost) pure quartz sand, is a valuable and scarce mineral resource within the shallow Dutch subsurface. High-grade deposits are exploited in the southeasternmost part of the country, as raw material for the glass, ceramic, chemical and other process industries. Dutch land-use policy requires that scarce mineral resources (including silica sand) are taken into consideration in spatial planning and when preparing for large-scale engineering or construction works. For this purpose, and in order to review the long-term possibilities for home production of silica sand, we determined resource potential nationally.

Our approach was (1) to establish the relevant conditions and processes associated with the deposition of the currently exploited sands, (2) identify lithostratigraphic units that are genetically similar or are otherwise known to contain quartz-rich sands, and (3) query the Dutch geological survey's borehole database for potential silica sand occurrences within those units. As we have to rely on non-dedicated data, the latter step was undertaken using a largely qualitative set of lithological search parameters. Finally, a limited number of available chemical analyses was used for preliminary verification purposes.

Using this approach, we identified three prospective areas: one in the north of the province of Limburg and east of the province of Noord-Brabant (~750 km<sup>2</sup>), one in the central south of Noord-Brabant (~45 km<sup>2</sup>), and one in the east of the Gelderland and Overijssel provinces (~1,200 km<sup>2</sup>). For each area, first-order characteristics of possible silica sand resources are presented (type of deposit, depth, approximate thickness). In the terms of current reporting conventions, we resolved silica sand occurrence to the level of 'reconnaissance mineral resource' or 'exploration result', and our results do not constitute a formal resource declaration. Available chemical data suggest that the resources in the first two areas could be or become economic, although the grades are lower than those of the currently exploited resources. The third area is less promising in that respect, but available data is too limited to reject the area in this stage. Even so, we tentatively conclude that home production of silica sand can probably be maintained after the reserves in Limburg are depleted.

**Keywords:** Netherlands, industrial minerals, silica sand, resource potential.

### Introduction

Silica sand, '*zilverzand*' (silver sand) in Dutch language and also referred to as industrial sand or quartz sand, is natural or processed sand that consists (almost) entirely of quartz grains (SiO<sub>2</sub>). Rather than as aggregate, e.g. for concrete, it is used as a quartz resource for several applications. Dutch consumption amounts to about 1.5 Mt/a (Fig. 1), about 55% of which is used by the glass industry, 20% by the ceramic industry, 15% by the

chemical industry and 10% in foundries (Van der Meulen et al., 2007a). The Netherlands is about 50% self-sufficient. Two companies in Limburg, the southeasternmost province of the country, extract high-grade Miocene silica sand in the vicinity of the town of Heerlen, from resources that rank among the purest in Northwestern Europe (Figs 2, 3). A few smaller operators extract lower-grade silica sand in the same area, for lower-grade applications.

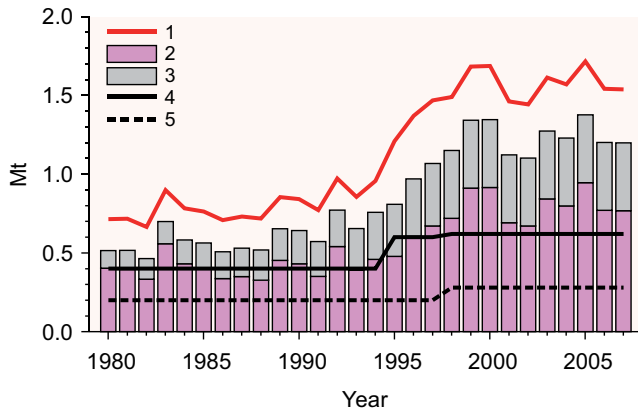


Fig. 1. The demand for silica sand in the Netherlands from 1980 to 2007 (1), and its provision by home production (2), secondary materials (3) and imports (4). Secondary substitution of silica sand is largely achieved by glass-packaging recycling (~80%; cf. Anonymous, 2002). High-grade silica sands are exported to Germany, Belgium and France (5). Sources: National Commission for the Co-ordination of Mineral Planning Policy (LCCO, The Hague) and data at the disposal of the authors. (2) through (5) are estimated figures.

Compared to Dutch resources of, e.g., filling sand and clay, silica sand is scarce and therefore subject to the so-called building materials assessment ('bouwgrondstofftoets'; Anonymous, 2004a; Van der Meulen, 2005a-b). The assessment aims to raise the awareness of mineral resources and interests when planning for large-scale engineering or construction works (hydraulic engineering, infrastructure, urban development, land reconstruction, etc.). Project areas have to be assessed for scarce minerals, in order to avoid their (unintended) sterilisation, and to stimulate their exploitation in conjunction with the work at

hand. The clearest example of this approach is the combination of river widening and gravel extraction along the river Meuse (Silva & Kok, 1996, Van der Meulen et al., 2006). Note that silica sand is explicitly covered by the building materials assessment, even though it is not a building material but an industrial mineral.

Conducting the building materials assessment requires the use of geological information. For this purpose, the Geological Survey of the Netherlands developed 'Delfstoffen Online' (Minerals Online): a nation-wide, web-based information system that provides first-order, regional-scale information on Dutch superficial / shallow mineral occurrences (TNO, 2009a). In a series of papers written in support of this tool, on aggregates in Van der Meulen et al. (2005) and on clay in Van der Meulen et al. (2007b), the present contribution reviews published and unpublished silica-sand resource information.

### Available data and resource inventory methodology

#### Previous work, general approach

The ground work for the present inventory was laid by the Geological Survey in the late 1990s and early 2000s. In 1996-1998, the southern-Limburg occurrences were assessed for mineral-planning purposes (Westerhoff, 1996; Dubelaar & Menkovic, 1998), and in 2002 a reconnaissance study was conducted in the remaining parts of the country, in order to review the long-term possibilities for home production of silica sand (Gruijters & Menkovic, 2002). The latter assessment was to include sands having qualities below the current cut-off grades of Dutch producers, but which would qualify for upgrading in



Fig. 2. Satellite image of Heerlen (©Google 2009), where two operators extract high-grade silica sand (for location see Fig. 3).



Fig. 3. Reference map, showing the geology of the Netherlands and the outlines / locations of other maps and photos.

other countries. For that matter, note that the British Geological Survey defines silica sand as having ‘a high proportion of silica (up to 99% SiO<sub>2</sub>) in the form of quartz’ (BGS, 2006). The top of the range in the United Kingdom appears to equate to the minimum standard for moderately-grade silica sand in the Netherlands, as defined below.

We used the data of all three assessments to arrive at resource information that meets the requirements of the aforementioned online minerals information system. If available and when necessary, we incorporated more recent data and insights. Our general approach was to:

1. identify relevant properties of the known silica-sand resources in southern Limburg (lithological, genetic);
2. establish whether (some of) these properties occur elsewhere in the country;
3. map them, where possible; and
4. verify the results preliminarily with chemical data, if available.

As Van Loon (this issue) discusses the early diagenesis of the southern-Limburg silica sands in considerable detail, we limit our own description of this process to a minimum, and discuss other factors that bear to their formation as a mineral resource. Our primary data sources were (1) DINO, a digital

archive of subsurface data developed and maintained by the Geological Survey of the Netherlands, and (2) DGM, a geological model of the Dutch shallow subsurface that was also developed by the Geological Survey.

### DINO

DINO (TNO, 2009b) currently contains more than 400,000 standardised borehole descriptions, i.e. ~10 per km<sup>2</sup> on average, and it is the single largest dataset of its kind in the country. It contains the Geological Survey’s boreholes, mostly drilled for geological mapping purposes, and a variety of third-party data. However, only a negligible number of boreholes has chemical analyses that are required to establish silica-sand quality. We therefore queried the data for potential rather than proven silica sands, using a predominantly qualitative set of search parameters, i.e. a combination of lithostratigraphic and lithological criteria. The exact criteria vary per area, and are detailed below.

### DGM

DGM (Digital Geological Model) is a national 2.5D, ‘stacked grid-layer model’ of the boundary surfaces of all Neogene and Quaternary formations in the Dutch onshore domain (De Mulder

et al., 2003; TNO, 2009c). The model was constructed by interpolating ~16,500 lithostratigraphically interpreted boreholes, a subset from DINO that was created to arrive at an even distribution of good-quality borehole data over the country. The resolution, i.e. the size of the grid cells, is 100 × 100 meters.

Lithostratigraphic boundary surfaces were interpolated between the corresponding transitions in each borehole. In principle, these transitions were identified in lithologic logs, but where necessary geophysical well-log data was used as well. Additional, non-borehole information was used to guide the interpolation process deterministically, in situations where mere statistics can not be expected to produce a geologically sound result. This information includes the (inferred) distribution of each unit, faults, and sedimentary features such as basins and large-scale channels. Generally, guiding took place by adding 'virtual' points to the interpolation set.

The basal surface of each unit was interpolated using a block-kriging algorithm (Isaaks & Srivastava, 1989; Goovaerts, 1997). The top surfaces, obtained indirectly, are the combined basal surfaces of overlying units.

### Assessing silica sand quality

Table 1 shows the quality requirements for silica sand in its main applications, given as maximum shares of non-silicon constituents. Purity is expressed chemically, i.e. as shares of oxides rather than of minerals, as testing is commonly carried out by chemical analysis (XRF, ICP). Iron ( $\text{Fe}_2\text{O}_3$ ) would typically be related to limonite and goethite grain coatings, and possibly to glauconite. A share of aluminium ( $\text{Al}_2\text{O}_3$ ) is mainly caused by clay minerals (including glauconite; feldspar is less likely in currently exploited Dutch silica sand resources). Titanium ( $\text{TiO}_2$ ) is indicative of rutile or ilmenite. Depending on the application, additional parameters may include grain size distribution, and the contents of chromium ( $\text{Cr}_2\text{O}_3$ ) and heavy minerals. The tabled figures are end-product specifications, which are usually not met by raw, i.e., unprocessed silica sand (Table 2). Clay is removed by washing or wet screening. Grain coatings of iron minerals may be removed by attrition (scrubbing), or acid

leaching (cold or hot). Froth flotation and magnetic or gravity (spiral) separation are used to remove discrete contaminant minerals. The silica sands that are currently exploited in the Netherlands usually only require washing, or the combination of washing and attrition.

## Resource potential indicators inferred from the Limburg deposits

### Stratigraphic occurrence and genetic factors

The silica sands of southern Limburg occur predominantly in the Heksenberg Member and locally in the Vrijherenberg Member, the two uppermost subunits of the Miocene marine Breda Formation (Figs 4, 5; all formations cf. De Mulder et al., 2003). In its outcrop area, the Heksenberg Mbr consists of well-sorted, fine-grained sands that were deposited on the beaches and tidal flats rimming the southern North Sea Basin during the Middle Miocene. The unit has two lignite intercalations, the Morken and Frimmersdorf seams (belonging to the Ville Fm.), both resulting from the progradation of coastal and lacustrine peat swamps from the east (Schäfer et al., 2005; Wong et al., 2007; Figs 5, 6). The seams correlate to the well-known thick lignite deposits that are exploited for fuel 20 - 40 km to the east in Germany, in the Garzweiler, Frimmersdorf and Hambach quarries, operated by Rheinbraun Brennstoff GmbH.

The source material for the Heksenberg Mbr probably originated from the well-weathered and therefore quartz-rich material that was available at the margins of the southern North Sea Basin in Belgium and adjacent areas. The uniform grain-size distribution of the silica sand deposits is consistent with longshore transport and coastal sorting processes. Early diagenetic leaching by humic acids originating from the peat increased silica sand purity by dissolving non-quartz components, i.e. in a process comparable to podzolisation (Kuyl, 1973; Van Loon, this issue). Other than being a normal process associated with organic deposits, leaching can be inferred from the fact that the purest silica sands are indeed associated with the lignite seams. In addition to that, Mörs (2002) argues that

Table 1. Matrix of five categories of silica sand (1 - 5), and their applications in the structural ceramic industry (A), foundries (B), low-grade glass (C), fine ceramics (D), high-grade glass (E), water glass and zeolites (F), and carborundum (SiC) (G). The quality per category is given in terms of minimum quartz ( $\text{SiO}_2$ ) and maximum iron ( $\text{Fe}_2\text{O}_3$ ), aluminium ( $\text{Al}_2\text{O}_3$ ) and titanium ( $\text{TiO}_2$ ) contents, and the maximum loss on ignition (LOI). These are figures for processed silica sand, quality indications for raw sands are given in table 2. Modified from Feenstra & Mulder (2003); reprinted from Van der Meulen et al. (2007a).

Categories	Applications							Chemical characterization					
	A	B	C	D	E	F	G	$\text{SiO}_2$	$\text{Fe}_2\text{O}_3$	$\text{Al}_2\text{O}_3$	$\text{TiO}_2$	LOI	Heavy minerals
1					■	■	■	99.80	0.01	0.05	0.02	0.05	no fusible heavy minerals
2				■	■	■	■	99.70	0.02	0.08	0.03	0.10	no criterion
3				■	■	■		99.50	0.03	0.14	0.04	0.25	no criterion
4		■	■					99.0	0.1	0.2	0.1	0.5	no criterion
5	■	■						97.0	0.5	0.5 - 1.0	0.3	1.0	no criterion

Table 2. Quality indication for wet-screened raw silica sands, based on common practice among Dutch silica-sand producers (Feenstra & Mulder, 2003).

Element	Quality indication			
	Excellent	High	Moderate	Low
SiO <sub>2</sub>	99.75	99.5	99.0	97.0
Fe <sub>2</sub> O <sub>3</sub>	0.01	0.03	0.06 - 0.1	0.5
Al <sub>2</sub> O <sub>3</sub>	0.1	0.2	0.4	1.0
TiO <sub>2</sub>	0.02	0.04	0.1	0.3
LOI	0.1	0.2	0.5	1

the general lack of fossil material in the lignite, formed in a sedimentary environment that was undoubtedly biologically productive, points to dissolution. The intensity of leaching and soil-forming processes has probably been climatologically enhanced: as evidenced by biostratigraphical dating of the Frimmersdorf seam at the Hambach quarry, the Heksenberg Mbr was deposited during the Mid-Miocene climatic optimum, just before the Late Miocene/Pliocene cooling phase (Utescher et al., 2000; Mörs, 2002; Wong et al., 2007).

The Heksenberg Mbr is transgressively overlain by the marine and coastal deposits of the Vrijherenberg Mbr, which consists predominantly of argillaceous and glauconite-bearing sands (marine facies), but locally contains silica sand as well (coastal facies). The conditions were largely comparable to those during Heksenberg deposition, but the favourable coastal sorting and leaching processes shifted to the east, outside of the area of interest (Fig. 4), and deepening came with an autigenic deleterious admixture.

The association of silica sand with peat was not only important because of leaching. In later stages, the lignite seams probably acted as adsorption filters, which reduced the mineral content of percolating groundwater. Apart from that, their impermeability reduced water percolation altogether. In view of the post-depositional geology and geohydrology of the area, this 'conservation capability' of lignite was an important secondary factor that contributed to silica sand quality.

### Post-depositional conditions

Situated at the northern edge of the Ardennes, southern Limburg became uplifted from the Mio-Pliocene transition onwards (Van den Berg & Van Hoof, 2001; Van Balen et al., 2005; Westerhoff et al., 2008). At that time, the area had become a tidal to fluvial sedimentary environment, where an alternation of sand, gravel, clay and lignite was deposited: the Upper Miocene to Pliocene Kieseloolite Fm., which unconformably overlies the Breda Fm. (Fig. 4). Denudation of the well-weathered hinterland, the Rhenish Massif, initially still yielded mature, quartz-rich sediments (Westerhoff, 2009). In fact, the Kieseloolite Fm. contains sands that would qualify as (lower-grade) silica sand, but they are not exploited at present.

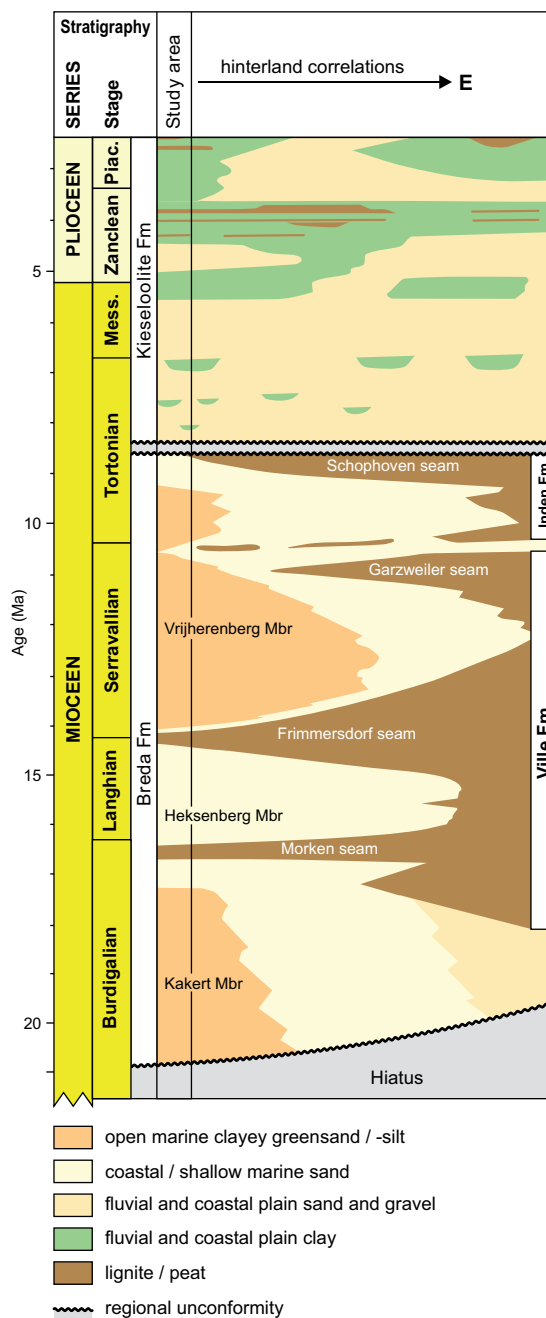


Fig. 4. The Burdigalian to Piacenzian of Southern Limburg and adjacent part of Germany, showing stratigraphic relationships and main lithologies of relevant units discussed in the text. The eastward extension with respect to the study area, which corresponds to some tens of kilometres, is included for better illustration of the overall stratigraphic development ('hinterland correlations'). Modified from Wong et al. (2007).

By the Late Pliocene, deposition of the Kieseloolite Fm. ceased, the area turned into erosional, and the Meuse river system came into existence. Due to tectonic processes, the catchment of the Meuse was larger than that of its predecessor systems, and progressive uplift lead to stronger and deeper erosion. Accordingly, Meuse sediments are coarser and more polymict than those of prior units (Westerhoff, 2009). Up until the Early Pleistocene, a first, eastern course of the Meuse

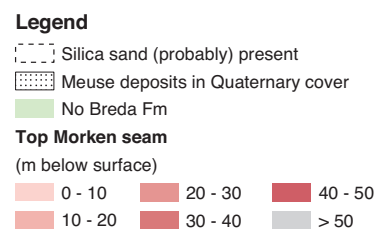
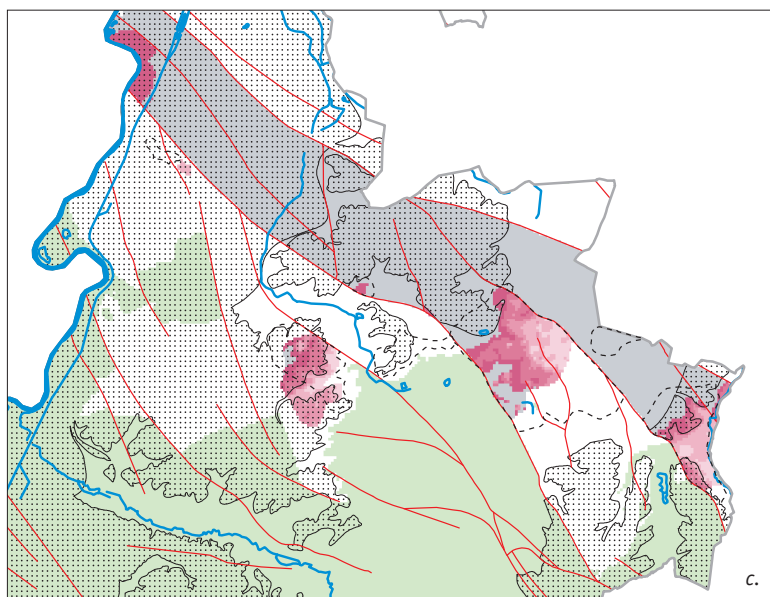
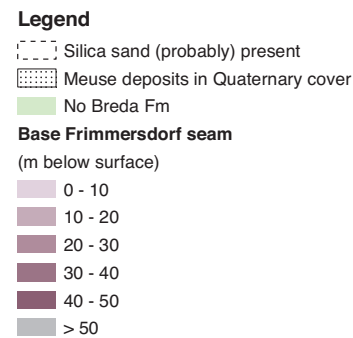
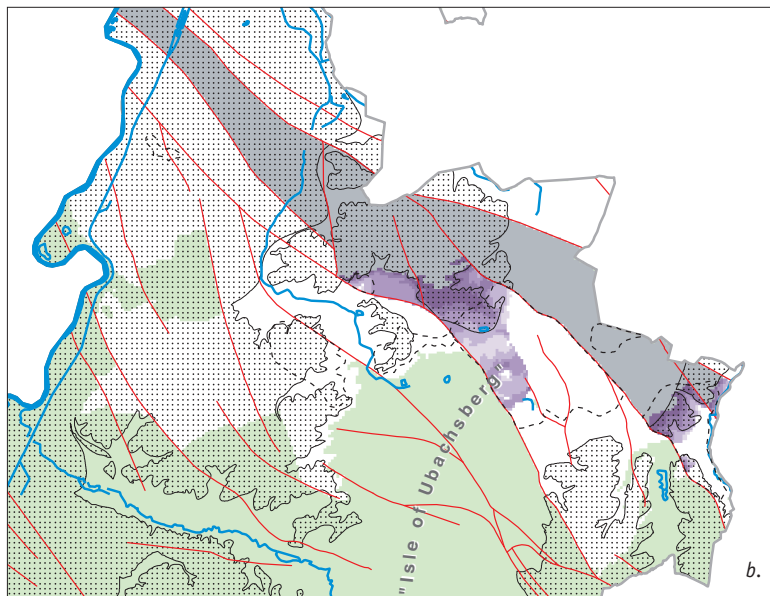
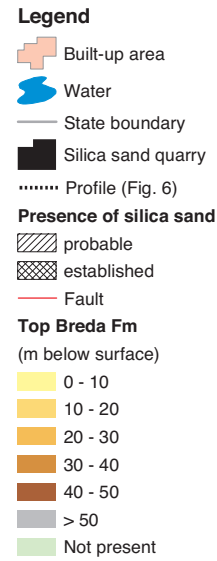
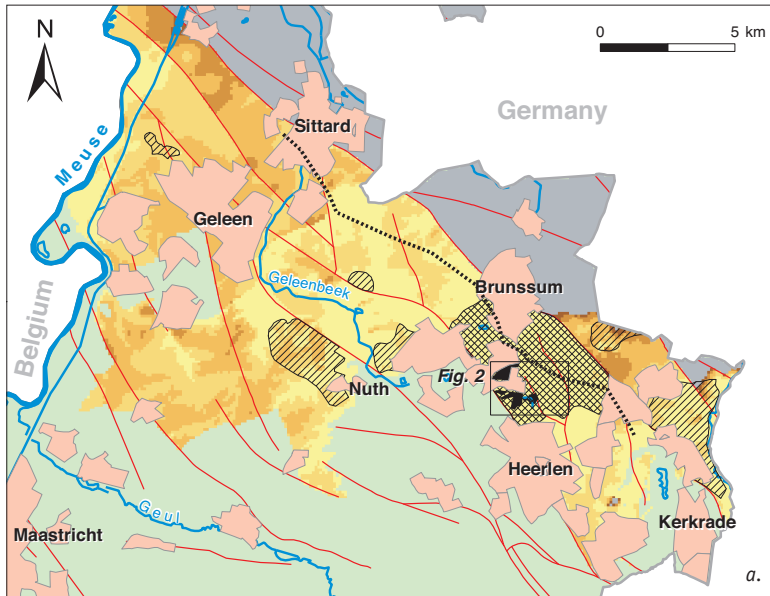


Fig. 5. a. the occurrence of silica sand in southern Limburg (see Fig. 3 for location). The top of the Breda Fm. is shown because most silica sand in the area occurs below this level. b and c show the base of the Frimmersdorf and the top of the Morken lignite seam, respectively: these layers delimit the highest-quality silica sand occurrences of the Heksenberg Mbr (see text). The occurrence of Meuse deposits is shown because of the potential impact of deposition on silica-sand quality. The top-Breda Fm. grid is extracted from DGM (TNO, 2009b, see text), the lignite-seam grids from Regis, a national hydro-geological model of all major aquifers and aquitards (Vernes et al., 2005, 2009). The lignite layers may be discontinuous within their distribution areas.

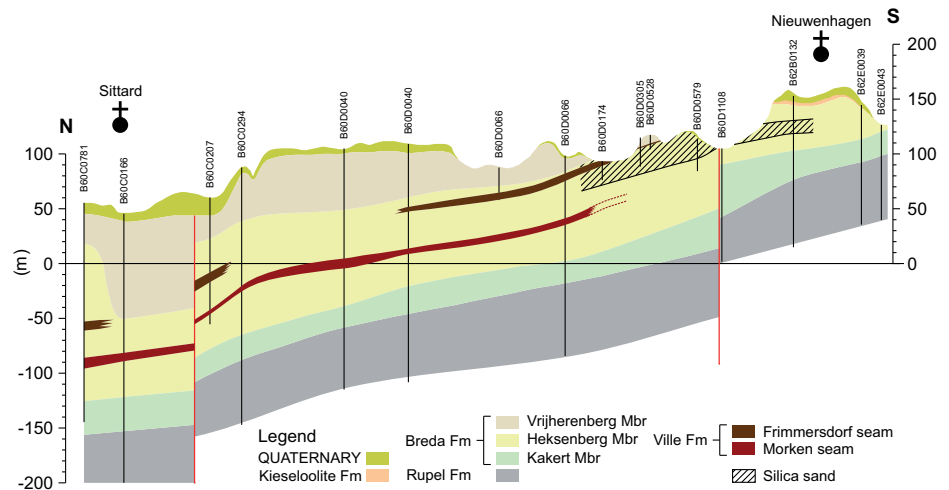


Fig. 6. Profile through southern Limburg (see Fig. 5a for profile line), showing the occurrence of silica sand.

occupied the so-called East-Meuse valley, as a tributary of the Rhine (Juvigné & Renard, 1992; Kuyl, 1980; Westerhoff et al., 2008). Due to tectonic movements around the Early to Middle Pleistocene transition, the Meuse shifted towards the west and formed the valley it still occupies along the Dutch-Belgian border.

Under conditions of ongoing uplift, which accelerated in early Mid Pleistocene times, the sediments of the incising Meuse (Beegden Fm.) have been preserved in terraces that cover the flanks of both river valleys (Van Balen et al., 2005; Westerhoff et al., 2008). To a varying extent, iron-bearing water originating from the highly permeable Meuse sediments, and possibly also from the oxidation of the glauconite in the Vrijherenberg sands, infiltrated the Heksenberg sands, which reduced their quality as a quartz resource. This applies especially at places where the Meuse eroded the lignite seams. The former East-Meuse and present Meuse valleys are separated by an approximately SW-NE trending zone around Heerlen, the so-called 'Isle of Ubachsberg'. The best currently exploited silica sands, never affected directly by the Meuse, are located in this zone (Fig. 5b).

## Resource potential elsewhere in the Netherlands

### Candidate units

In summary, silica sand resources in Limburg are a product of (1) a quartz-rich source area, (2) a specific coastal environment and (3) favourable post-depositional conditions. The highest-quality silica sands are generally found where lignite is present and an iron-bearing / yielding overburden is absent, but high-grade silica sand deposits also occur where the latter two conditions are not met. This set of generic conditions explains the occurrence of the Limburg silica sands in first order only: resource quality is known to vary from the highest to lesser grades even within individual quarries. As all of the aforementioned processes and conditions have a certain degree of spatial and/or temporal variation, this is to be expected.

However, in spite of its importance to silica sand exploration, such heterogeneity cannot be resolved when prospecting on national scale with non-dedicated data. Altogether, this precludes the present study to be more ambitious than an identification of areas of enhanced resource potential.

The exact above combination of (dia)genetic factors is limited to southern Limburg altogether. For the remaining parts of the Netherlands, we searched for potential silica sand deposits on the basis of a lesser number of factors, i.e. in lithostratigraphic units that share general lithological characteristics with the Heksenberg Mbr, have been deposited in comparable depositional environments, or are otherwise known to contain quartz-rich sands. These criteria are met by the aforementioned Kieseloolite Fm., the Lielvelde Mbr of the Upper Miocene to Pliocene shallow marine Oosterhout Fm., the Upper Pliocene to Lower Pleistocene fluviatile Peize Fm., and Pleistocene Stramproy Fm. of mixed continental facies (Table 3).

### Querying for silica sand

Within the candidate units, potential silica sand was searched with median grain sizes between 80 and 320  $\mu\text{m}$  (in case of measured grain size data), or belonging to sand median classes very fine to moderately coarse ( $\geq 105$  and  $< 300$   $\mu\text{m}$ ; classification cf. Anonymous, 1989, 1990). The queried range more or less coincides with the grain sizes preferred by the industry. We used a somewhat higher upper limit, in order to enhance mapping consistency. High quartz contents are assumed when sands are light-coloured, having colour attributes white, greyish-white, yellow-white, etc. This is a relatively safe assumption for Dutch sands, in which non-quartz components are usually darker-coloured. Light-coloured non-quartz sands (e.g. feldspar and calcareous arenites) do not occur.

The data query was limited to 50 m below the surface. As a result of a downward decreasing borehole data coverage, we do not expect to be able to map such narrowly-defined, 'exotic' lithologies successfully below this depth. The range comprises current silica sand exploitation depths.

Table 3. Main characteristics of lithostratigraphic units with an assumed potential for silica sand occurrence.

Formation	Member (stratigraphic delimitation)	Location (topographic delimitation)	Depositional environment	Main characteristics (of member / at location)
Stramproy Fm.	not applicable	Southern Noord-Brabant	fluvial, aeolian, periglacial	fine to medium-grained, quartz-rich sands
Kieseloolite Fm.	not applicable	Eastern Noord-Brabant, southern Limburg	fluvial, tidal	medium to coarse, quartz-rich sand, locally gravel bearing, intercalations of (peaty) clay may occur
Oosterhout Fm.	Lievalde Mbr	Eastern Gelderland and Overijssel	coastal	well sorted, fine, quartz-rich sands, silicified horizons
Breda Fm.	Vrijherenberg Mbr	Southern Limburg	coastal, shallow marine	well sorted fine to medium quartz sands, predominantly glauconite-bearing and argillaceous
	Heksenberg Mbr	Southern Limburg	coastal	Well sorted fine to medium quartz sands

### Query results

The data query yielded occurrences in 534 boreholes, that appeared to be clustered in three prospective areas (A-C). A fourth area in central Limburg (indicated as 'not mapped' in Fig. 3) showed some scattered occurrence of white sands, but the quality of the available data precluded successful elaboration.

**Prospective area A** is located in eastern Noord-Brabant and northern Limburg, and consists of two northwest-southeast trending subzones, separated by a horst-like structure (Fig. 7). The eastern subzone ranges from the town of Cuijk to Venlo, the western one is located just north of the town of Deurne. Sands with the desired characteristics occur in the Kieseloolite Fm., alternating with lignite, clay, or sands that do not meet the search criteria. The formation overlies the Breda Fm., here of a deeper marine facies than in southern Limburg, and it is either overlain by Quaternary Rhine / Meuse deposits (of the Kreftenheye, Waalre and Beegden Fms), or by the predominantly aeolian periglacial deposits of the Boxtel Fm.

Inspection of boreholes in the area reveals that potential silica sand occurs throughout the Kieseloolite Fm., except for in the deepest and thickest part in the west. Presence/absence appears to be associated with facies such as channels, which cannot be captured at the given borehole density. We therefore characterise potential silica sand occurrence in area A with maps of the top and base of the Kieseloolite Fm., with the annotation that not all the sediments contained between these surfaces meet our search criteria.

The depth of the top of the Kieseloolite Fm. varies between 0 and 40 m, averaging at about 16 m; the base varies between 10 and 100 m, averaging at about 30 m. The cumulative thickness of potential silica sands (Fig. 8) ranges between 2 and 20 m, with an average (modal) thickness of about 8 m, this amounts to about 45% of the thickness of the Kieseloolite Fm. Thickness statistics were obtained by interpolating the highest and lowest occurrences of white sands within the Fm. We do not display the interpolation results spatially, because of the aforementioned undersampling.

Chemical analysis on 7 wet-screened samples (Feenstra & Mulder, 2003, Table 4) resulted in quartz percentages ranging from 96.8 to 99.5, meeting the criteria for low to high-grade raw silica sands (Table 2). Earlier analyses on unscreened samples show percentages 97.65 to 98.65 (Gruijters & Menkovic, 2002).

**Prospective area B** is located in the province of Noord-Brabant, near the village of Goirle (Fig. 9). White sands with the queried characteristics occur in the Stramproy Fm., which either crops out or is overlain by a thin cover of the aforementioned Boxtel Fm. The Stramproy Fm. consists predominantly of aeolian sands and the deposits of rivers that drained a composite catchment area stretching from central and northern Belgium towards the northeast. The unit is of Early to Middle Pleistocene age, and deposition took place partly under periglacial conditions. The formation overlies the fluvial deposits of the Waalre Fm., but note that these units may elsewhere have other, more complex relative stratigraphic positions than the superposition observed here.

Within the formation, white sands alternate with silts and clay. We characterised potential silica sand occurrence with the upper and lower formation boundary surfaces, again with the annotation that not all the sediments contained between these surfaces meet our search criteria. Cumulative thickness of potential silica sand averages at about 4 m, which equates to about 40 - 45% of the thickness of the Stramproy Fm. in the area.

Chemical analysis on 2 wet-screened samples (Feenstra & Mulder, 2003, Table 4) resulted in quartz percentages of 99.0 and 99.1, meeting the criteria for moderately-grade raw silica sands (Table 2). Earlier analyses on unscreened samples show peak percentages of 98.10 to 99.14% (Gruijters & Menkovic, 2002).

**Prospective area C** is located in the eastern Gelderland and Overijssel provinces and stretches approximately from the town of Almelo to Doetinchem, in a north-south orientation (Fig. 10). White sands with the desired characteristics occur in the upper part of the Oosterhout Fm. as well as scattered in the



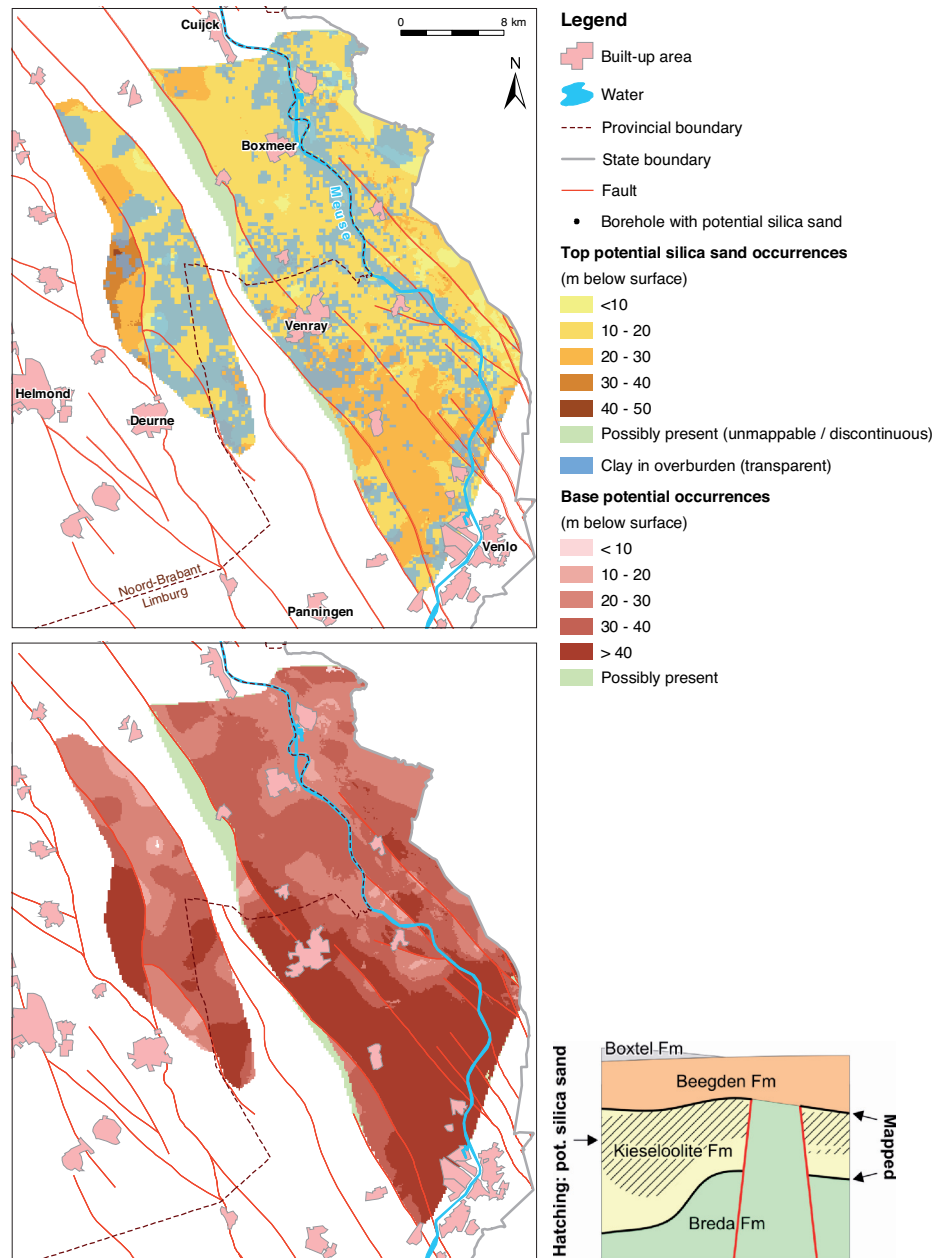


Fig. 7. Prospective area A (see Fig. 3 for location). Resource position is indicated with the top and base of the Kieseloolite Fm. Potential silica sand occurs between these surfaces but, as shown schematically by the inlay, not exclusively (see text for further explanation). 'Clayey overburden' is based on clay resource data presented by Van der Meulen et al. (2007b). The cumulative resources thickness is given in Fig. 8. Borehole data in Gruijters & Menkovic (2002).

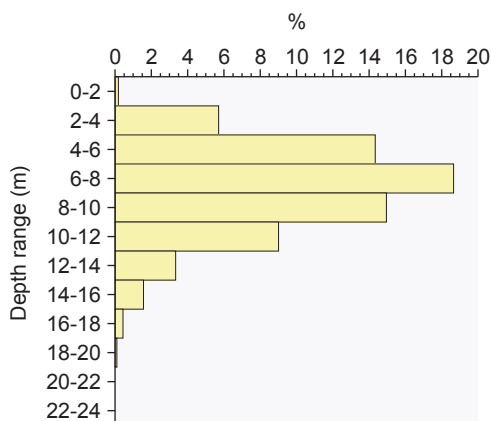


Fig. 8. Histogram of the thickness of potential silica sand deposits in prospective area A (see text for explanation).

overlying Peize Fm. The sedimentary succession of interest is comparable to the Upper Breda – Kieselooliet Fm. succession in southern Limburg, and consists of shallow marine, clayey and glauconite-bearing sands grading, via clayey sands, into well-sorted, quartz-rich, sandy tidal deposits. The latter sediments are stratigraphically distinguished as the Lielvelde Mbr (note that the homonymous unit defined by Van den Berg & Gaemers (1993) included the clayey and glauconite-bearing deposits as well). The Peize Fm. was deposited by east-west flowing rivers of the fossil Eridanos system, which drained the area of the present Baltic sea and surroundings, and built a huge delta into the North Sea Basin (Overeem et al., 2002; De Mulder et al., 2003). Its catchment was generally well-weathered and yielded quartz-rich sands; in that respect the provenance situation of the Lielvelde sands was comparable to that of southern Limburg

Table 4. Chemical analyses for silica sand samples in prospective area A-C (data from Gruijters & Menkovic, 2002).

Area	Borehole	Screened	Method	SiO <sub>2</sub>	Fe <sub>2</sub> O <sub>3</sub>	Al <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>
A	46B0156	yes	ICPAES	99.0	0.06	0.50	0.08
A	46B0156	yes	ICPAES	99.5	0.03	0.22	0.02
A	46G0073	yes	ICPAES	96.8	0.11	1.64	0.10
A	46B0125	yes	ICPAES	98.4	0.08	0.73	0.07
A	46D0139	yes	ICPAES	98.8	0.05	0.60	0.02
A	46D0139	yes	ICPAES	97.5	0.37	1.03	0.19
A	52E0171	yes	ICPAES	98.6	0.12	0.61	0.03
A	46C0124	no	XRF	98.5	0.06	0.83	0.00
A	46C0124	no	XRF	98.3	0.12	0.78	0.03
A	46C0124	no	XRF	98.7	0.05	0.55	0.00
A	46C0124	no	XRF	98.4	0.07	0.72	0.00
B	50G0367	yes	ICPAES	99.0	0.08	0.46	0.06
B	50G0090	yes	ICPAES	99.1	0.06	0.39	0.05
C	28D0213	yes	ICPAES	96.6	0.22	1.66	0.10

during deposition of the Heksenberg sands. With respect to the Breda and Kieseloolite Fms, however, the sediments of the Peize Fm. contain higher percentages of instable heavy minerals, with dominance of garnet. The Oosterhout – Peize suite is unconformably overlain by the fluvatile sands of the Urk Fm., ice-pushed deposits (belonging to various formations) and related (peri)glacial sediments of the Drente Fm., the Kreftenheye Fm., and/or the periglacial deposits of the Boxtel Fm.

The only regionally mappable feature associated with potential silica sand occurrence in area C is the boundary surface between the Oosterhout and Peize Fms. Most potential silica sand occurs immediately or just below this level, only the scattered Peize occurrences lie above. A lower resource delimitation cannot be provided: instead of with some mappable feature, it appears to be associated with facies units, the variation and distribution of which cannot be captured at the given borehole density. We characterise silica resource occurrence in area C with a map of the top of the Oosterhout Fm. only, plus an indication of the cumulative thickness of the underlying potential silica sand deposits. The depth varies between 0 and 50 m (our search limit), averaging at about 16 m. The cumulative thickness of potential silica sand (Fig. 11) ranges between 2 and 22 m, with an average (modal) thickness of about 7 m. Thickness statistics were obtained in the same way as for area A.

Only one wet-screened sample in area C has been analysed for silica sand quality, testing below the demands (Table 2) for low-grade raw silica sand (SiO<sub>2</sub> 96.6%, table 4). The extent to which this material can be upgraded (scrubbing, leaching, etc., see above) has not been determined, and we do not wish to reject area C as prospective on the basis of a single observation. However, also on the basis of provenance and qualitative lithological descriptions, industrial-grade silica sand occurrence is less likely than in areas A and B. The only active sand pit in

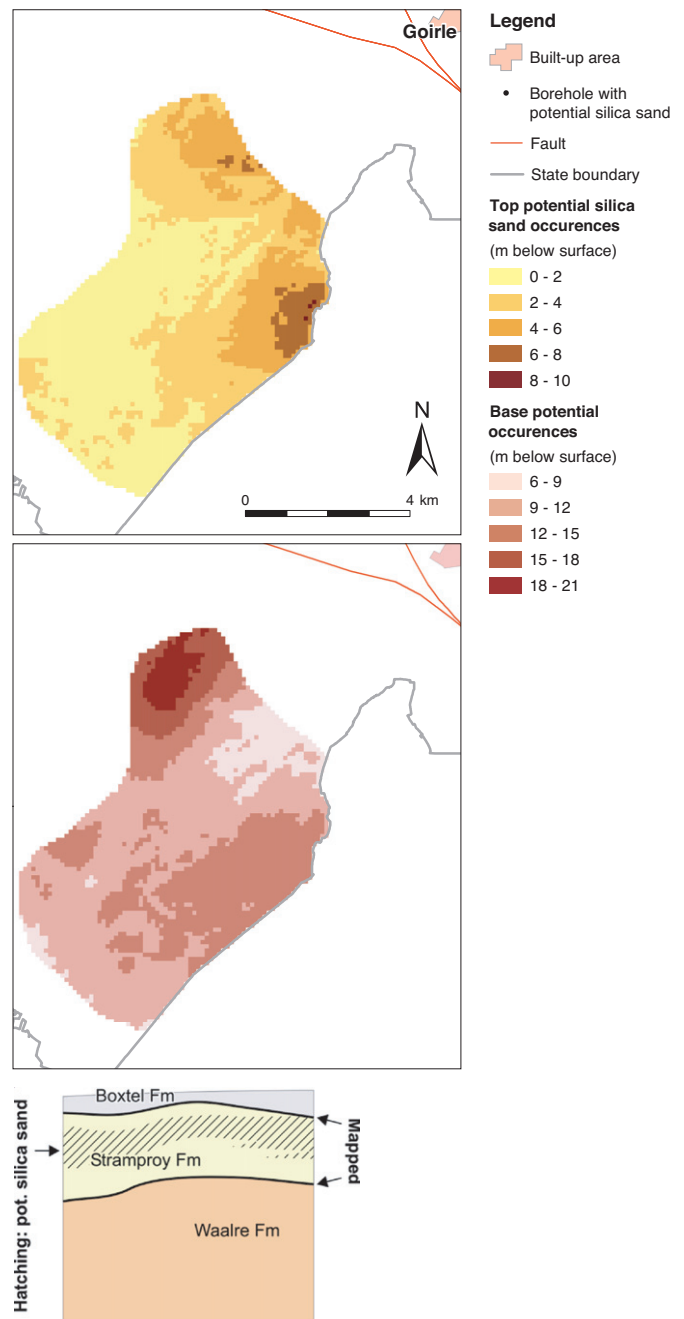


Fig. 9. Prospective area B (see Fig. 3 for location). Resource position is indicated with the top and base of the Stramproy Fm. Potential silica sand occur between these surfaces but, as shown schematically by the inlay, not exclusively (see text for further explanation). 'Clayey overburden' is based on Van der Meulen et al. (2007b). Borehole data in Gruijters & Menkovic (2002).

area C, the Markelo site operated by Dyckerhoff Basal BV, reaches appropriate depths and the product is clearly white (Fig. 12), but it is used as concrete aggregate, not as a quartz resource.

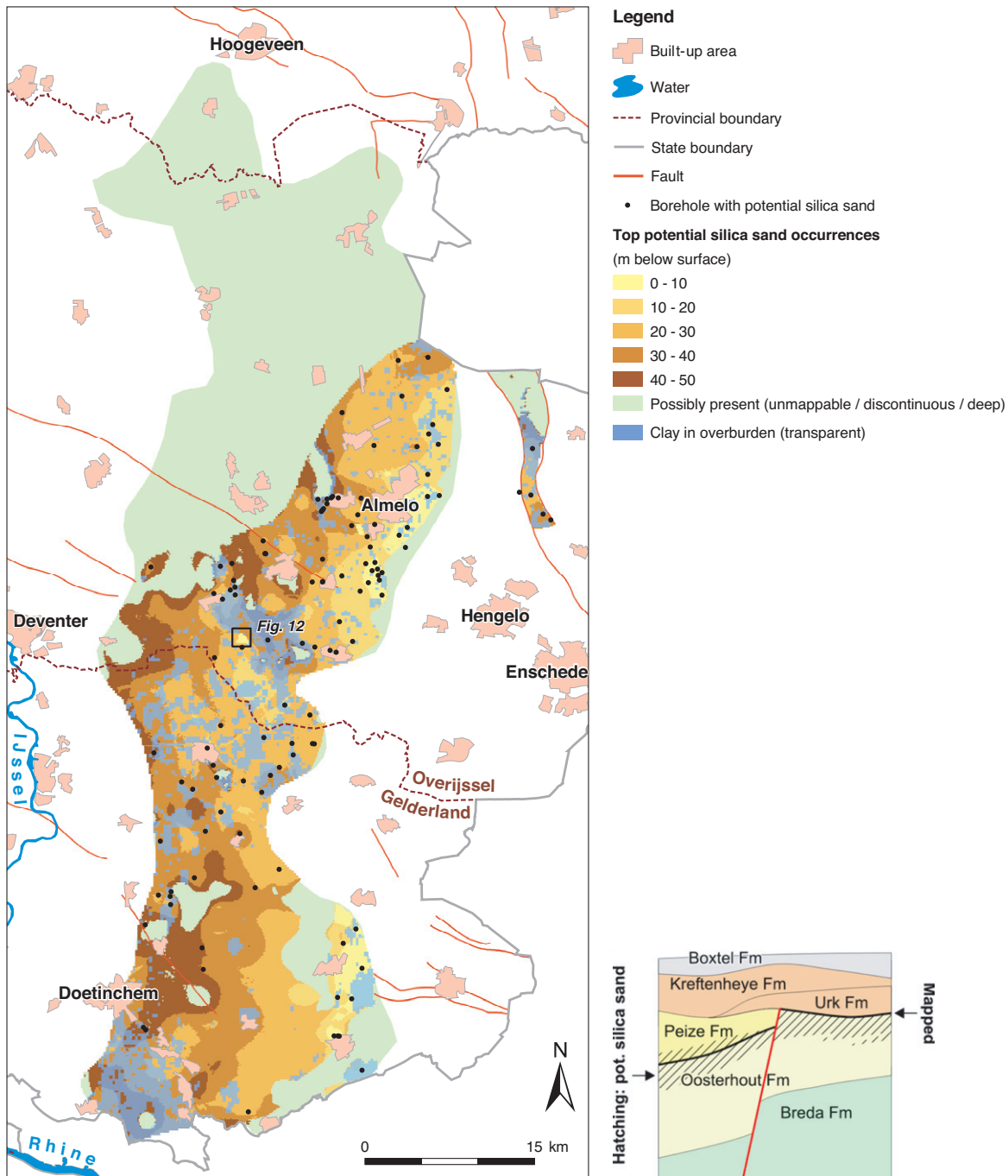


Fig. 10. Prospective area C (see Fig. 3 for location). Resource position is indicated with the top of the Oosterhout Fm.; the inlay shows the schematic relationship between this surface and potential silica sand occurrence (see text for further explanation). 'Clayey overburden' is based on Van der Meulen et al. (2007b). The cumulative resources thickness is given in Fig. 11. Borehole data in Gruijters & Menkovic (2002).

## Discussion and conclusions

We identified three prospective areas for silica sand, in a two-step query of lithostratigraphic and borehole data, searching for combinations of favourable depositional processes and appropriate lithological characteristics. The spatial consistency of the query results suggests that our approach is basically sound. The qualitative lithological search parameters that we used are fairly generic, and would most probably not have been

diagnostic enough for silica sand occurrence without narrowing the query down with stratigraphic and provenance criteria. Our inference that areas A and B are the most prospective two is also spatially consistent in the sense that they are aligned with known silica sand deposits in southern Limburg, northern Belgium and North Rhine-Westphalia (see also Van Loon, this issue). Altogether, conditions at the southern margin of the Mio-Pliocene North Sea Basin appear to have been favourable for silica sand deposition.

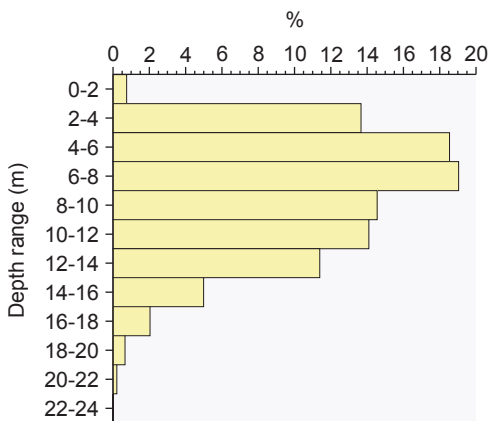


Fig. 11. Histogram of the thickness of potential silica sand deposits in prospective area C (see text for explanation).

We set out to provide silica sand resource information that meets the requirements of the aforementioned building materials assessment. We consider resource potential to be sufficiently resolved for such purpose, especially for the first step, which is to establish whether mineral occurrence can be excluded, or needs to be further explored in conjunction with some spatial planning issue, engineering work, etc. Other than that, our study can be considered a pre-prospecting effort for commercial silica sand exploration. In the terms of the code for reporting of mineral exploration results, mineral resources and mineral reserves (Anonymous, 2001; see also Anonymous, 2004b), the potential silica sand occurrences would classify as ‘reconnaissance mineral resources’. These are ‘based on regional geological studies and mapping, airborne and indirect methods,



Fig. 12. The Markelo sand pit located in prospective area C (see Fig. 10 for location). The product is almost as white as the Heksenberg sands (Fig. 2), but it is used as aggregate, not as silica sand. Satellite imagery ©Google 2009.

preliminary field inspection, as well as geological inference and extrapolation. The aim is to identify areas of enhanced mineral potential worthy of further investigation towards deposit identification. The level of confidence is lower than that applying to an inferred Mineral Resource and is usually not sufficient to quote tonnage and grade figures’. ‘Reconnaissance mineral resources’, reports of which are to be used only for mineral or spatial planning purposes by the government, is no terminology in the more recent PERC reporting code (Anonymous, 2008), because this specifically applies to public reporting by the extractive industry. In the terms of this code, our results classify as ‘exploration results’, and do not constitute a formal resource declaration.

Note that if southern Limburg would be assessed in the same way as the rest of the country, the resulting prospective area would be substantially larger than the extent of the known silica sand resources. This illustrates the difference between determining resource potential and a dedicated resource assessment. Establishing silica sand quality is a specialist undertaking that involves a drilling campaign and chemical analyses. Beyond that, it involves subjecting drilling samples to common silica-sand processing steps, the results of which determine whether or not the deposit is economic.

Notwithstanding the need for further study, available chemical analyses do suggest that there are deposits, at least in area A and B, that could be or become economic, provided that quantities and depths allow for exploitation. Combined with geological considerations, the analyses also suggest that the silica sand qualities and quantities that occur in southern Limburg are not to be expected elsewhere in the Netherlands. Nonetheless, given the low level of consumption (in comparison with regular aggregates), we preliminarily conclude that there are possibilities to maintain home production of silica sand beyond the duration of the operations in southern Limburg, at least to some degree.

The aggregate volume of sand that we identified as potential silica sand, obtained by multiplying the surface areas and modal resource thicknesses for areas A-C, amounts to 6 or 15 km<sup>3</sup> roughly, depending on whether area C is included. We provide this figure, which is a huge overestimation of the actual resources with no practical use, in order to underline the scarceness of silica sand in the Netherlands. Dutch gravel resources are estimated at about 12 km<sup>3</sup>, and about half of that amount is considered technically exploitable (Van der Meulen et al., 2005). At extraction rates in the same order as those of silica sand, Dutch gravel is generally considered a scarce resource. As we expect that a far smaller fraction of the similarly sized potential silica sand volumes will be exploitable, we conclude that Dutch silica sand resources are limited indeed and should be carefully managed.

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Although the authors adhere to its basic principles, this study does not formally comply with the current reporting conventions (Anonymous, 2001, 2008; see also Anonymous 2004b). Our results are not to be used for the purpose of (a) informing investors or potential investors and their advisers or (b) satisfying regulatory requirements.

This paper is dedicated to the memory of Gerrit-Jan Evers († 30 November 2009).

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