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Spatial prediction of the variability of Early Pleistocene subsurface sediments in the Netherlands – Part 1: Heavy minerals

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Abstract

We investigated the spatial variability of the heavy-mineral composition in the Early Pleistocene fluviatile Kedichem Formation in the Netherlands in order to meet the demand for more information about subsurface sediment composition. We first determined the spatial extension and thickness of the sediment body, then used Fuzzy clustering techniques on a database containing approx. 2000 heavy-mineral counts from the Kedichem Formation to map the spatial extension of the various sediment provenances within the formation. Three clusters could be discerned, one representing a combined Meuse-Scheldt source, the other two representing a mixed Rhine-Baltic source. We made slice maps at several depths through the formation, and plotted the cluster memberships.

The maps show an overall dominance of the Meuse-Scheldt source in the south of the Netherlands, whereas the Rhine-Baltic source occurs mainly in the central Netherlands. The methods employed show that it is possible to map and study the 3-D variation in heavy-mineral composition and hence sediment provenance in the Dutch subsurface with the use of simple statistical and visualization techniques.

Keywords: heavy minerals, mapping, provenance, sediment, subsurface

Introduction

Analysis of the heavy-mineral composition of sandy sediments was explored since the 1930's to distinguish sediments from different sources. In the Netherlands, early studies have been carried out by particularly Edelman (1933). Since the 1950's, heavy-mineral analysis was used systematically for geological research and mapping by the then Geological Survey of the Netherlands (currently TNO-NITG) (see, among others, Zagwijn & Van Staalduinen, 1975). An extensive database was thus built up containing numerous heavy-mineral counts from boreholes in the Dutch subsurface. An important distinction made in heavy minerals in the Netherlands is the difference between stable and unstable heavy minerals. Typical unstable heavy minerals include garnet, epidote, saussurite, alterite and hornblende, whereas typical stable minerals are zircon, rutile, staurolite and tourmaline. Until now, Dutch heavy-mineral data have been applied only for research in single boreholes and cross-sections.

As sediment provenance is one of the factors that determine the detrital geochemical sediment composition (cf. Huisman & Kiden, 1998; Huisman et al., 2000b), 3-D spatial analysis of heavy- mineral data may help to predict the geochemical composition of subsurface sediments. In the present study, we investigate the variation in heavy-mineral composition in one specific formation in the Dutch subsurface, the Kedichem Formation. This formation was chosen for its large variation in lithology and sediment provenance, and for the availability of good-quality cores. We investigate the 3-D variability in the mineralogy using simple statistical, mapping and visualization tools. The results are used as a geological framework for the geochemical characterization of the formation (Huisman et al., 2000a).

Geological setting

The Kedichem Formation consists, according to the stratigraphy of Zagwijn & Van Staalduinen (1975), of a series of Early Pleistocene fluviatile fine sands and clays with localized peat layers in the central and southern Netherlands (Fig.1). Several Meuse terrace deposits that are incorporated in the Kedichem Formation have not been considered in the present study. Sediments were supplied by the Rhine in the central Netherlands and by the Meuse and Scheldt river systems in the south. Rhine-derived sediments are generally mica-rich, and their heavy fraction is dominated by unstable minerals such as garnet, epidote, saussurite, alterite and hornblende. Early Pleistocene Meuse- and Scheldt-derived sediments are characterized by low mica contents and a stable heavy-mineral composition (including zircon, rutile, staurolite and tourmaline).

The Kedichem Formation overlies the Early Pleistocene Tegelen and Harderwijk Formations, which have a Rhine and a Baltic provenance, respectively. It is overlain by Middle to Late Pleistocene, coarse-grained Rhine deposits that belong to the Sterksel, Urk and Kreftenheye Formations. To the north, it is lateral equivalent to, and interfingers with, the Baltic-derived coarser grained Enschede Formation (see Zagwijn & Van Staalduinen, 1975).

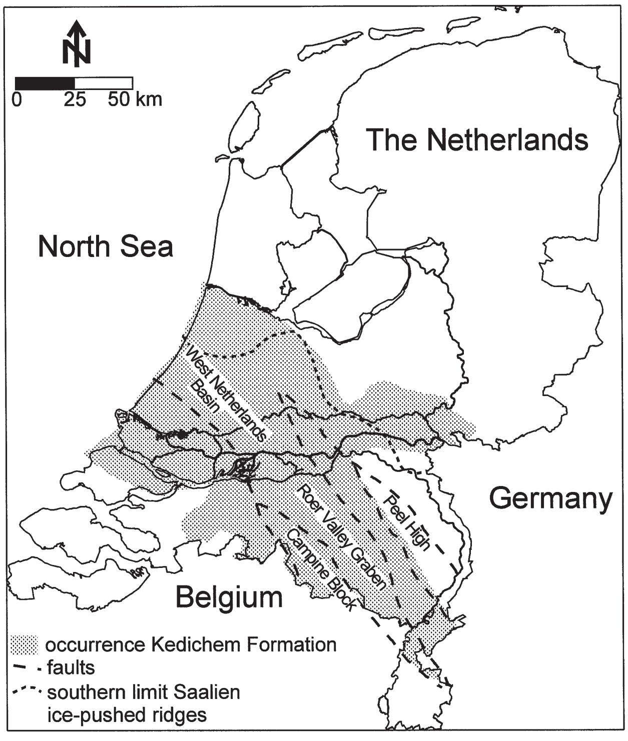

Fig. 1. Occurrence of the Kedichem Formation in the southern Netherlands, with fault pattern used in the present study (from Van den Berg, 1996, and pers. comm.) and the maximum extent of the Saalian ice sheet (Zagwijn & Van Staalduinen, 1975).

In the province of Zuid-Holland, both the Kedichem and the underlying Tegelen Formations have a Rhine provenance; they are therefore rich in mica and have a heavy-mineral fraction that is dominated by unstable minerals. Furthermore, they both consist of fine sands and clays deposited in a perimarine fluviatile facies, so that it is difficult to distinguish the formations macroscopically (Van Staalduinen, 1979). The Tiglian and the Late Pliocene Reuver deposits in the southern part of the Roer Valley Graben (to the south of Eindhoven) have a Scheldt/Meuse provenance, which makes them locally hard to distinguish from the Kedichem Formation. In this region, a large number of TNO-NITG boreholes show a sudden increase in the thickness of the Kedichem Formation from 20 to 80 m, which is caused by the incorporation of Tiglian and Reuverian deposits into the Kedichem Formation. This is contrary to the definition by Zagwijn & Van Staalduinen (1975), who state that the Kedichem Formation was deposited after the Tegelen Formation, but this is a reflection of the similarity in the sediment composition.

Materials and methods

Data sources

Lithological and stratigraphical data

Lithological and stratigraphical data were obtained from the REGIS database. This is a collection of core descriptions from the main TNO-NITG borehole database, that were selected for their nation-wide coverage and good quality to serve as a basis for the TNO-NITG aquifer model, REGIS (Broers et al., 1992). The core descriptions were checked for errors for the purpose and, when needed, a new stratigraphic classification was added (Weijers, 1995).

The REGIS database contains X and Y co-ordinates, relative height above sea level (NAP = Dutch Ordnance Level), lithological data, date of borehole, and depth reached as well as a quality label for each borehole. The upper and lower depth, the lithological description and – where present and applicable – estimations of clay content, median grain size and carbonate content are also included for each lithological unit. Lithological descriptions distinguish the main lithological classes sand, clay, gravel, peat and loam.

Additional properties include the content of humus or plant remains, micas, shells, clay lumps, etc. Note that these descriptions are based on macroscopically visible properties, and that they are meant to describe good-quality cores as well as bad-quality flush samples.

Additionally, a stratigraphic classification is given for each borehole, with the upper and lower boundaries of each formation within the borehole. As the province of Limburg in the southeast of the Netherlands was not incorporated in the REGIS database, additional stratigraphical data from this province were obtained from the mapping program (Van den Berg, pers. comm.).

Heavy-mineral data

The heavy-mineral data were extracted from the TNO-NITG heavy-mineral database. This database contains all heavy-mineral counts that were performed by TNO-NITG (and its predecessors) on samples from the Netherlands and surrounding areas since the 1950's. These heavy-mineral counts were obtained by optical determination of the transparent grains of the 63-500 μm sand fraction with a density >2.87 g/cm^3, after treatment with HCl and HNO_3 to remove carbonates, Fe (hydr)oxides and humus. Unfortunately, some relevant data like the contribution of the heavy fraction to the total sediment and the amount of opaque minerals have not been archived.

The database contains in total approx. 40,000 analyses, 25,000 of which are from boreholes in the Netherlands. Other analyses are from quarries or from foreign boreholes. The heavy-mineral database was extended with 120 heavy-mineral counts by Kasse (1988).

Data treatment

Lithological units that had been classified as belonging to the Kedichem Formation – including uncertain classifications (such as 'Kedichem or Harderwijk Formation') – have been selected from the REGIS database. We filtered out incomplete records and wrong classifications interactively. These unused data include a series of boreholes where the Kedichem Formation has a thickness of 0-50 cm, boreholes outside the Kedichem area (e.g., on the Peel high), Kedichem sections in ice-pushed ridges, and sections that – because of the lack of correlation with the surrounding boreholes – had clearly erroneously been classified as Kedichem Formation. About 10% of the boreholes was thus discarded.

Because of the problems regarding the distinction of the Kedichem Formation from the underlying Tegelen Formation, the lower boundary of the Kedichem Formation in the REGIS cores shows a large variation in parts of the province of Zuid-Holland. As in those areas the top of the Tegelen Formation was not encountered above 75 m depth, we decided to consider the maximum depth of the Kedichem Formation as being located at 75 m below NAP in this area; sections below 75 m are regarded as representing the Tegelen Formation.

In order to determine the upper and lower boundaries of the formation, we used the moving average module of the ILWIS package without linear prediction, with a limiting distance of 10 km and weight method of $(1/d^2)-1$, and with the data stratified according to the tectonic units. The position of the faults for this stratification, as presented in Figure 1, is based on Van den Berg (1996) and on personal comments by this researcher.

We selected the samples from the Kedichem Formation from the heavy-mineral database either by directly selecting the Kedichem sections from the boreholes that were also incorporated in the REGIS database, or – if no stratigraphic data were available – by interpolating the upper and lower boundaries of the Kedichem Formation from neighbouring boreholes. As heavy-mineral samples from boreholes are often mixed over a considerable core length, a sample was regarded as belonging to the Kedichem Formation when even a small part of this sample range fell into a Kedichem section. Samples that were composites of over 7.50 m were discarded. This means that samples over a length of several metres of depth are still included. In view of the thickness of the various deposits in the Dutch subsurface (Zagwijn & Van Staalduinen, 1975), we assume that, in most cases, these samples are from sediment bodies that have a more or less homogeneous provenance. If this were not the case, one might question whether such samples provide meaningfull analysis results. Still, we think that such samples do not significantly disturb the overall picture.

Apart from this, a series of samples were discarded that had clearly been classified incorrectly, as they should be attributed to Middle to Late Pleistocene formations according to their high content of volcanic minerals. About 2000 heavy-mineral analyses remained for our analysis.

Heavy-mineral counts are conventionally used for stratigraphic research, in which they are a semi-quantitative aid in determining lithostratigraphic boundaries in (a series of) cores. In this respect, the datasets are small, usually only some dozens of analyses at the most for one core, and the results can be interpreted in great detail. Such an approach is not suitable for our purpose, however, because the large size of the dataset would make this amount of detail unworkable. For our purpose, it appeared necessary to search for homogeneous groups in this complex dataset, and to investigate whether they could provide useful information to support stratigraphical, mineralogical and geochemical studies. One way to do this is by applying cluster analysis, a multivariate statistical technique used for classification of numerical data by grouping into clusters the observations that are most alike. From the many clustering techniques that exist (see Davis, 1986, for an overview), we chose the fuzzy C-means cluster analysis for an objective classification of the heavy-mineral suites. Standard (non-fuzzy) C-means clustering simply assigns observations to a certain cluster. Fuzzy clustering, however, describes the likeliness of a sample to a cluster in a membership function that varies between 0 (not alike to the cluster) to 1 (almost identical to the cluster). It is therefore most appropriate to use fuzzy clustering in datasets where one can expect large compositional overlaps (cf. Frapporti et al., 1993). This is the case in our dataset because of the possible mixing of sediments from different sources. The FUZZY program of S.P. Vriend (Utrecht University) was used; technical and theoretical information can be found in Vriend et al. (1988). As the heavy-mineral composition in the Kedichem Formation is determined by the relative contribution of three sediment sources (Rhine, Baltic, Scheldt/Meuse), we started clustering towards three clusters. Increasing the number of clusters did not provide a better interpretable subdivision.

Visualization

We made visualizations of the spatial distribution of the heavy-mineral clusters. As a 2-D approach to the 3-D spatial variation, we made maps that each represent a 'slice' of 5 m thickness of the Kedichem Formation. If insufficient data were available, thicker slices were used. The maps of the heavy-mineral clusters give, for each sample that falls (entirely or partially) within the slice, the membership with each of the three clusters.

Results and discussion

Spatial characteristics of the Kedichem Formation

Figure 2 shows the interpolated maps of the upper and lower boundaries of the Kedichem Formation, and its thickness. The shape of the Kedichem body appears to be determined primarily by tectonic processes; this accounts for its deep position in the fastest subsiding part of the Ruhr Valley Graben, its limited thickness in the western part of the province of Noord-Brabant, where it lies on the rift shoulders of the Brabant Massif, and in the province of Gelderland, where it lies close to the northern edge of the Peel High, and its absence on the Peel High, where it was either never deposited, or was eroded later.

The map of the formation thickness is dominated for a large part, however, by the large thickness in the southern Ruhr Valley Graben, which represents the incorporation of Tegelen and Reuver sediments into the formation because of definition problems (see above). The increased thickness of the formation between the present Rhine and Meuse river courses may represent a northwestern extension of the graben, but could also be the result of incorporating some of the underlying Tegelen sediments. Moreover, it is unclear to what extent the observations in the Arnhem-Nijmegen area refer to ice-pushed ridges, and thus give a distorted stratigraphical position.

Heavy minerals

Figure 3 presents the composition of each of the three heavy-mineral clusters. The first cluster consists of stable heavy minerals (tourmaline and the metamorphic and rest groups), and is similar to the heavy-mineral suites usually found in sediments derived from the Scheldt drainage area and in Pliocene Rhine sediments (cf. Kasse, 1988). The other two clusters show an unstable heavy-mineral association of garnet, epidote, alterite, saussurite and hornblende. The main difference between these two is that cluster 2 has higher alterite contents, whereas cluster 3 shows higher contents of epidote and hornblende. They probably represent two types of Rhine- and Baltic-derived sediments (cf. Zagwijn & Van Staalduinen, 1975).

The map of the memberships for cluster 1 (stable minerals) shows that this cluster is mainly restricted to the south of the area (Fig. 4). It can therefore be identified as Scheldt-derived material. The occurrence of samples with high memberships for the stable cluster in the present-day reaches of the Rhine and Meuse at a depth of 50-55 m indicates that sand bodies that are mainly derived from the south occur locally in this area. This suggests that the Scheldt system at times reached that far north. The occurrence of samples with high memberships for the stable cluster in the deeper parts of the southern Ruhr Valley Graben may also reflect the incorporation of the Pliocene Reuver sediments into the Kedichem Formation (see above).

The two clusters of unstable heavy minerals occur

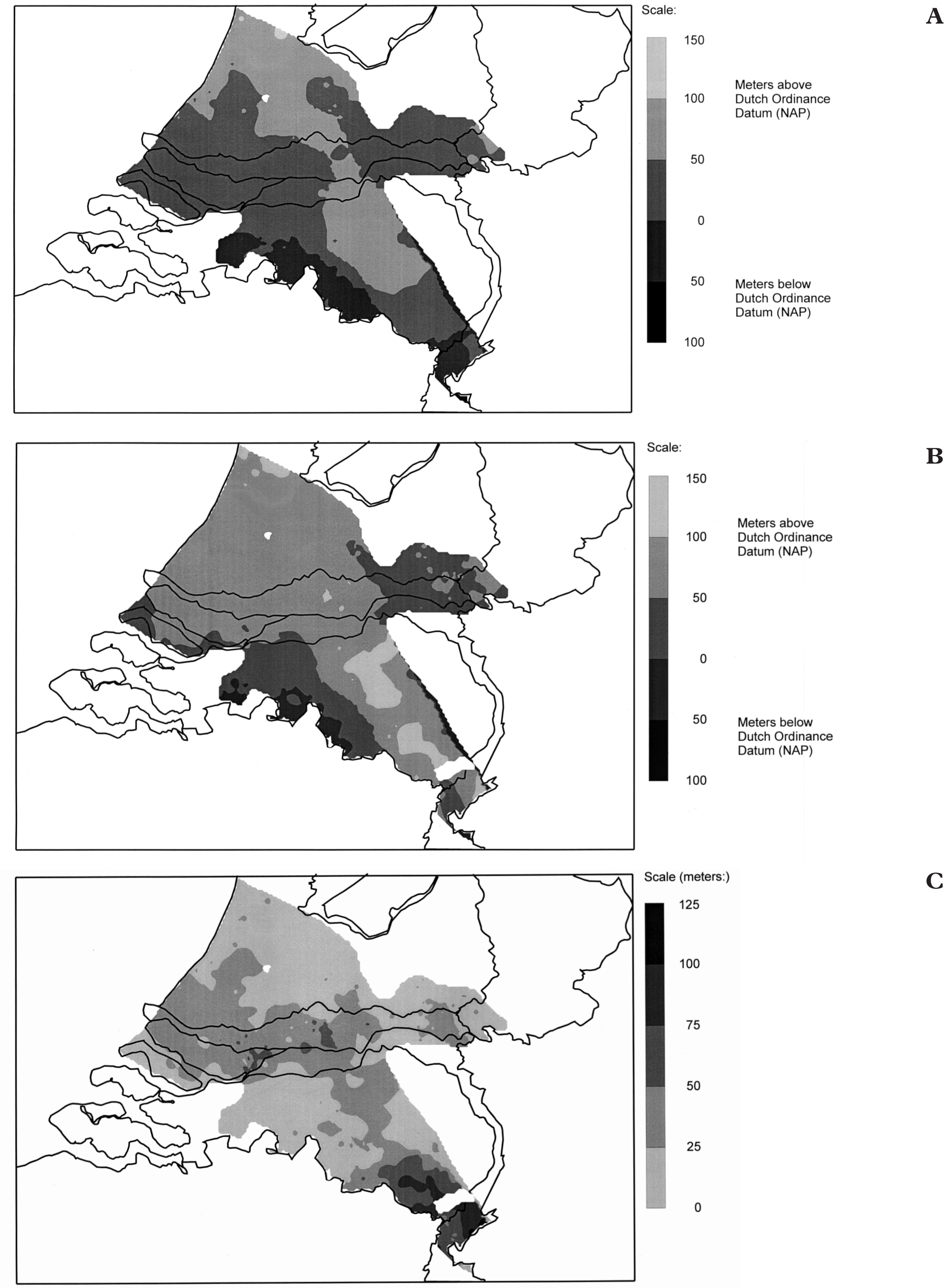

Fig. 2. Boundaries and thickness of the Kedichem Formation.
A: upper boundary. B: lower boundary. C: thickness.

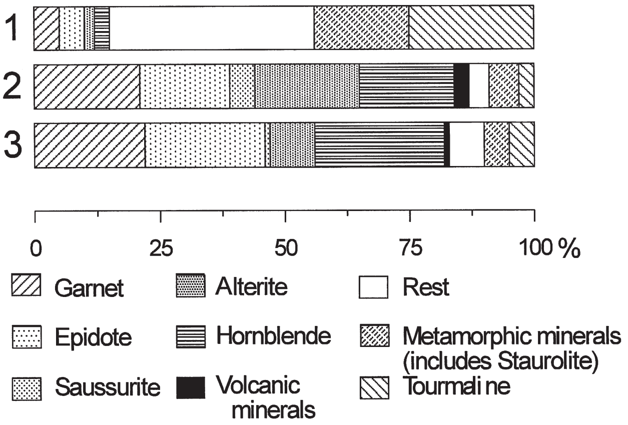

Fig. 3. Heavy-mineral clusters as determined by fuzzy clustering. Cluster 1 consists of stable heavy minerals, whereas clusters 2 and 3 show an association of unstable heavy minerals. The main difference between the two is that cluster 2 has higher alterite contents, whereas cluster 3 shows higher contents of epidote and hornblende.

mainly in the north of the area, and do not show a large difference in their spatial distributions (Figs. 5 and 6). Both clusters probably represent a mixture of Rhine and Baltic sediments, with the main difference based on the contents of hornblende. The distribution indicates that the methods we used to discern provenance are unable to distinguish between sediments of Baltic and Rhine provenance. This may be caused by a limited Baltic influence in our dataset, but it is more likely that the differences in the concentrations of the heavy minerals from the two sources are too small to be detected with these methods.

Some of the limitations of the use of heavy-mineral analysis must be stressed: the method can be used only in sandy sediments, which makes it unsuited for establishing the provenance of clay layers. Moreover, the overall grain size of the sand may have a major effect on the heavy-mineral composition, as a result of which sands from the same source may show considerable variation in their composition. The stable cluster, as an example, shows a large variation in the contents of zircon and tourmaline. This variation can be attributed entirely to the grain size of the sand, with high percentages of tourmaline in coarse sand, and high contents of zircon in fine material. The variation caused by these grain-size effects can easily hide the relatively subtle provenance-related differences. Applying more elaborate statistical techniques on larger datasets (i.e., including more formations) may help in better discerning sediment sources by filtering out grain-size effects. Moreover, datasets that incorporate more formations and that include sediments from more different sources would probably show larger differences between the sources, and clearer patterns in the spatial variability.

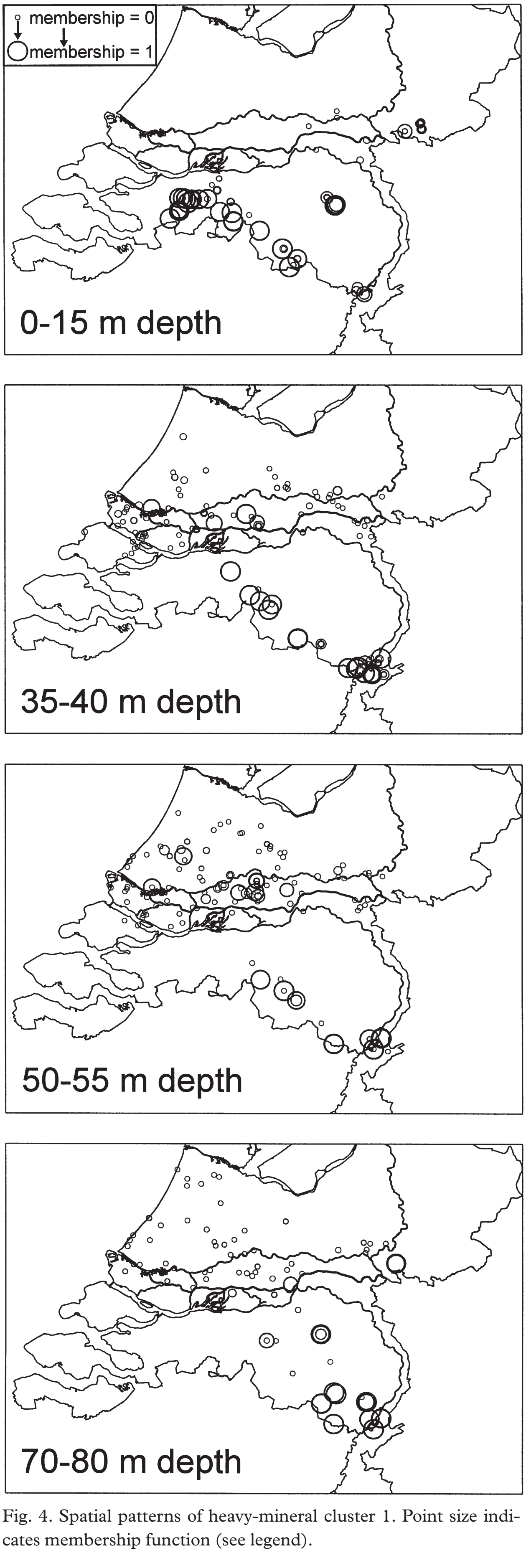

Fig. 4. Spatial patterns of heavy-mineral cluster 1. Point size indicates membership function (see legend).

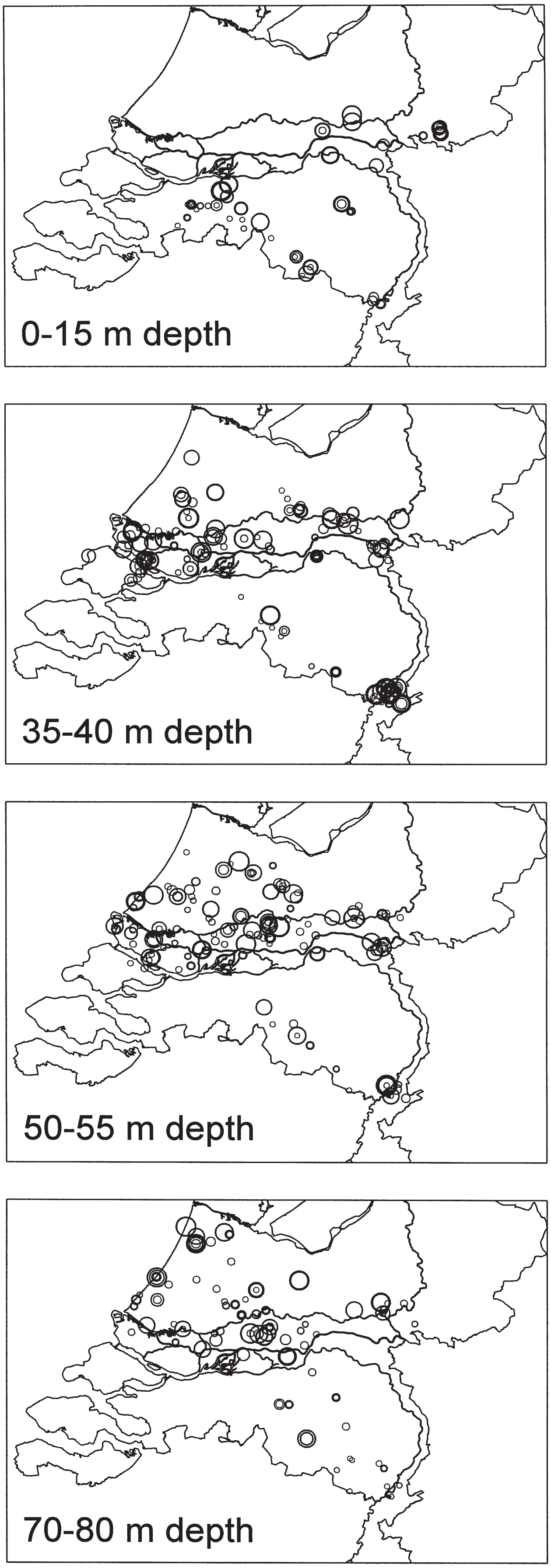

Fig. 5. Spatial patterns of heavy-mineral cluster 2. Point size indicates membership function (see legend with Fig. 4).

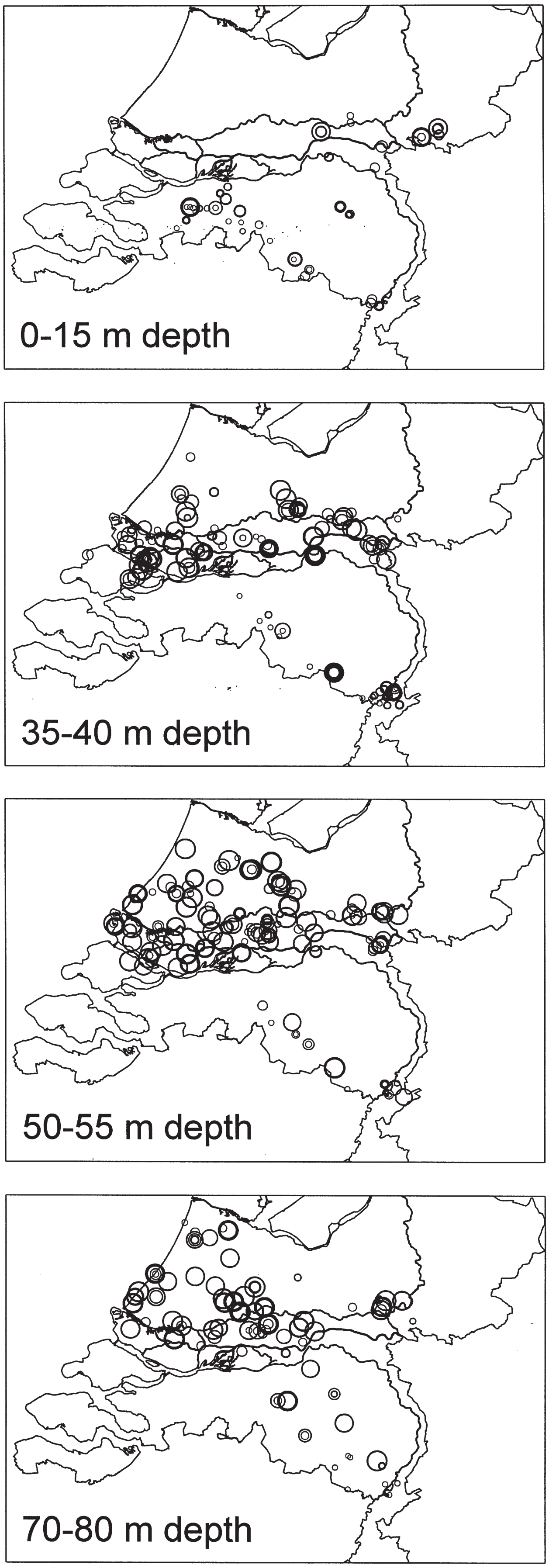

Fig. 6. Spatial patterns of heavy-mineral cluster 3. Point size indicates membership function (see legend with Fig. 4).

Conclusions

The present study demonstrates that there are important – as yet virtually unexplored – possibilities for using multivariate statistical methods like (fuzzy) cluster analysis, and relatively simple visualization techniques on heavy-mineral data to establish the spatial distribution of sediment sources in the subsurface of the Netherlands. By such methods, 3-D sediment-body geometry can be deduced from the heavy-mineral data. This information is not only interesting from a stratigraphical and a sedimentological point of view, but may also contribute to hydrogeological modelling of the subsurface, as well as in predicting geochemical parameters of the sediments.

Possible future research includes multivariate statistical and spatial analysis of the complete heavy-mineral dataset, in order to map nation-wide the heavy-mineral variation in the subsurface. Moreover, the methods employed can be improved by using more elaborate statistical analyses, and by using a true 3-D GIS instead of the 2-D approach used here.

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