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3D geology in a 2D country: perspectives for geological surveying in the Netherlands

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Abstract

Over the last ten to twenty years, geological surveys all over the world have been entangled in a process of digitisation. Their paper archives, built over many decades, have largely been replaced by electronic databases. The systematic production of geological map sheets is being replaced by 3D subsurface modelling, the results of which are distributed electronically. In the Netherlands, this transition is both being accelerated and concluded by a new law that will govern management and utilisation of subsurface information. Under this law, the Geological Survey of the Netherlands has been commissioned to build a key register for the subsurface: a single national database for subsurface data and information, which Dutch government bodies are obliged to use when making policies or decisions that pertain to, or can be affected by the subsurface. This requires the Survey to rethink and redesign a substantial part of its operation: from data acquisition and interpretation to delivery. It has also helped shape our view on geological surveying in the future.

The key register, which is expected to start becoming operational in 2015, will contain vast quantities of subsurface data, as well as their interpretation into 3D models. The obligatory consultation of the register will raise user expectations of the reliability of all information it contains, and requires a strong focus on confidence issues. Building the necessary systems and meeting quality requirements is our biggest challenge in the upcoming years. The next step change will be towards building 4D models, which represent not only geological conditions in space, but also processes in time such as subsidence, anthropogenic effects, and those associated with global change.

Keywords: Netherlands, applied geoscience, hydrogeology, geological surveying, mapping, geomodelling, geodatabase

Introduction

Scope

Pursuant to a new law that will become effective in 2015, DINO, the national Dutch subsurface database operated by the Geological Survey of the Netherlands, is to become an official government register (a 'key register' / *basisregistratie*). In facing the responsibilities associated with this new status, the Survey is reconsidering and redesigning its operation and in that process a new, or at least sharper picture is emerging of geological surveying in the future.

These developments set the final stages of a process of modernisation that geological survey organisations all over the world are currently entangled in (Allen, 2003; Jackson, 2010). Most surveys are replacing paper archives that were built in the

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course of many decades by electronic databases; many surveys started producing electronically distributed 3D subsurface models in addition to or instead of 2D geological maps that were their primary output since their establishment. For a variety of reasons explained below, the Dutch survey is among the early adapters in both respects.

In this overview paper we present the Geological Survey of the Netherlands as a working example of a geological survey in transition. The overall structure of the paper is based on the following three questions: 1) *Where do we stand?* (as an organisation, then focussing on data management, information technology and subsurface modelling); 2) *What enabled us to get where we are?* (trends and enabling factors); and 3) *Where do we go?* (outlook and perspectives). The overarching question we address is: how can a geological survey exploit modern information technology to its fullest potential, while building on and maintaining consistency with its legacy of (pre-digital) data and information products?

A transition in the delivery of subsurface information

A key register is an officially appointed register containing high-quality data that the government is obliged to use for its public tasks. The objective of a key registry is to enhance efficiency in data management and to avoid error in use, as often encapsulated in the concept of 'capture once, use many times'. Current key registers, linked in one comprehensive information system (*stelsel van basisregistraties*), contain personally identifiable information (PII); identification and ownership of real estate, companies and vehicles; real-estate value; income, employment relations and social-security benefits; addresses and buildings; and base topography.

DINO's upgrade to a key register for the subsurface, further referred to by its Dutch acronym BRO (*basisregistratie ondergrond*), recognises the government's reliance on subsurface data and information for a number important planning and permitting procedures (e.g., for land use planning; exploration and production of hydrocarbons, minerals and geothermal heat; storage of CO_2 and natural gas; and groundwater management). Beyond that, it is expected to help reduce the considerable societal risks and costs associated with adverse ground conditions in public works, especially infrastructure projects. A societal cost-benefit analysis (*maatschappelijke kosten-baten-analyse, MKBA*), an obligatory step in the preparation of certain government policies and investments, showed that the benefits of the BRO are higher than its costs (Terpstra et al., 2011). The BRO will also be instrumental in implementing the European INSPIRE directive for subsurface data in the Netherlands (INSPIRE arranges for an all-encompassing European spatial data infrastructure; Anonymous, 2007).

Future tasks and responsibilities

Once the BRO is established, subsurface data gathered by any Dutch government body will have to be submitted to the Geological Survey, stored in the BRO database, which in its turn has to be consulted by the government when making policies or decisions that pertain to, or can be affected by the subsurface. The BRO will contain the following types of data:

– **Survey data** (*verkenningen*): borehole (including sample analyses), cone penetration testing, well log, seismic, geo-electric.
– **Models** (*modellen*): three of the national geological models ('3D maps') that the geological survey develops and/or maintains, as well as national geomorphological and soil maps of Alterra (part of Wageningen University and Research Centre, WUR).
– **Rights of use** (*gebruiksrechten*), i.e. exploration and production licenses for hydrocarbons, minerals and geothermal heat (Mining Act, outlined below) and groundwater-abstraction permits (Water Act).
– **Constructions** (*constructies*): constructions that serve to extract substances from the subsurface (e.g. hydrocarbon and groundwater wells), store substances in the subsurface, or monitor subsurface processes (e.g. provincial and national monitoring networks for soil quality, groundwater quality and groundwater levels).

The BRO will initially consist of the contents not only of DINO, but also of BIS, the Dutch national soil survey database operated by Alterra. Just as DINO, BIS contains a combination of basic data (borehole descriptions) and their interpretations (soil, geomorphological and groundwater regime maps). The pedological and geomorphological content of the BRO will however not be further discussed in this paper on geological surveying.

The key-register status brings new responsibilities to all parties involved. Up until now, there are only two types of data that are stored in DINO by legal obligation: data from groundwater monitoring networks established under the Water Decree (Anonymous, 2009), and data obtained from exploration and production licensed under the Mining Act (Anonymous 2002). This act applies to minerals and hydrocarbons deeper than 100 m below the surface, storage of substances in the same depth range, and for geothermal energy to targets deeper than 500 m. The BRO extends such obligation to virtually all data and information we manage: the Survey will have to handle and store substantially more data and its user group will not only become larger, but also more diverse. Current users are mostly specialists, who will inevitably be joined by new users who are less familiar with subsurface data, or with the subsurface altogether. At this moment, for example, DINO is used by only a few of the 415 Dutch municipalities that will all have to use the BRO in the near future.

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While the Survey is responsible for quality control, responsibility for data in the BRO rests with the providers ('source owners'; *bronhouders*). In contrast, subsurface models in the BRO are the Survey's proprietary interpretations of subsurface data. We expect that our models, because of their obligatory use, will have to meet higher user expectations. The Survey will be held accountable for its interpretations, possibly up to the point of liability. Issues such as reproducibility and quantifiable reliability now move beyond the academic. This also implies that it is in the Survey's best interest to thoroughly assess the quality of the underlying third-party data, and make sure it is as high as possible.

The Geological Survey of the Netherlands

Operational setting and mission

The Geological Survey of the Netherlands operates in a small northwest European state, with a surface area of 41,500 km^2, about 8,000 of which is inland water (CBS, 2013). Dutch territorial waters encompass about 57,000 km^2 of the North Sea. At an average of more than 400 inhabitants per km^2, the Netherlands is very densely populated and has a high land-use intensity: 85% of its surface area is developed (CBS, 2013). The Netherlands is a predominantly flat country (hence the title). About 60% of the Dutch shallow subsurface consists of fluvial and coastal lowlands of Holocene age (Fig. 1), the latter having surface levels at or below sea level. The remaining part of the country consists almost entirely of Pleistocene terrains: predominantly sandy soils sloping upwards to the south and east, with an average elevation of between 10 and 20 m above Dutch ordnance level (roughly mean sea level) and exceeding 100 m only in the extreme southeast. Ice-pushed ridges are marked morphological features in the central part of the country. We will not discuss Dutch overseas territories in the Caribbean because they will not be covered by the BRO, at least not initially.

Fig. 1. Geological map of the Netherlands showing the location of Figs 7, 9 and 13.

Dutch Earth resources include natural gas, oil, coal (not worked at present), geothermal heat, rock salt, groundwater, aggregates, clay, carbonate rock and silica sand. In addition to that, the subsurface provides space for the storage of substances or for underground constructions. The main hazard associated with the country's geology and physical geography is flooding of its lowlands, at places aggravated by subsidence caused either by water-table lowering (resulting in soil compaction and degradation), or by the extraction of gas or salt. The latter activity may also induce seismicity, with magnitudes ranging up to M_W 3.6, but generally not exceeding 2.0. Not particularly hazardous but significant in terms of costs and financial risks is building on compactable soils, which are especially prevalent in the heterogeneous Holocene coastal and fluvial deposits. The mission of the Geological Survey of the Netherlands is therefore to provide geoscientific data, information and knowledge for:

- Sustainable management of Earth resources and the environment in general.
- The reduction of societal costs and risks associated with geohazards and adverse ground conditions.

Internationally, we set out to assist the public sector with data and information management, enabling them to secure investments in exploration data as well as revenues from the exploitation of earth resources.

Organisational setting and history

The Geological Survey of the Netherlands is part of TNO (Netherlands Organization for Applied Scientific Research), an independent Dutch research and technology organisation active in technical, earth, environmental, life, societal and behavioural sciences, focussing on healthy living, industrial innovation, energy, transport and mobility, built environment, the information society, and defence, safety and security.

The present Survey has its roots in 1) the former State Geological Survey (*Rijks Geologische Dienst*, at the time part of the Ministry of Economic Affairs); and 2) TNO's former Institute for Groundwater and Geo-energy (*Instituut voor Grondwater en Geo-energie*). In 1997, these predecessor organisations merged into a new TNO institute, the Netherlands Institute of Applied Geosciences (*Nederlands Instituut voor Toegepaste Geowetenschappen, NITG*). The current Geological Survey of the

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Netherlands is the result of a number of reorganisations of that institute (which, as such, is no longer an organisational entity of TNO), and the transfer of much of its shallow-subsurface expertise to Deltares, a research institute for delta issues established in 2008. While it previously covered the full range of applied geosciences, the Survey is now almost exclusively focussed on gathering, interpreting and delivering subsurface information, and on providing the Ministry of Economic Affairs (EZ) with advice on geological matters related to the Mining Act[1].

Programme of the Survey

The Survey operates under a strategic mid-term plan, which outlines the foreseen operational context (mission, scope, tasks, funding; Van Daalen et al. 2012). Our survey activities are conducted under a single government-funded programme, the main elements of which are data management (including Geo-ICT) and geomodelling (3D subsurface mapping). Data-management projects deal with main processes in the data-handling workflow, i.e., retrieval, quality assurance and control (QA/QC), storage and delivery. Geomodelling projects are product-oriented: there are separate projects for framework (layer), voxel ('3D pixel') and 4D models, parameterisation and characterisation, and model applications. In addition to that, investments are made in communication, representation and our knowledge base.

This work is subject to yearly planning cycles. The annual survey programme as well as its results are approved by a board with representatives of the Ministry of Economic Affairs and of the Ministry of Infrastructure and the Environment. The research aspects of this programme (supplemented by externally funded research), are approved by a board with representatives of the three geoscience faculties in the Netherlands. The recommendations of both boards are then adopted by a council with high-level representatives from the same ministries, the academia and industry.

In support of our survey task, we develop our understanding of user needs in commissioned projects: how is subsurface information used, for which applications, now and in the future? The aim of every such project is to learn how to improve the products and services developed under our survey programme. Two mechanisms are used to increase the momentum of our R&D efforts: collaboration with sister organisations abroad, mostly in EU-funded projects, and investments in our relationship with the academia (e.g. through the sponsoring of extra-ordinary professorships).

Data management and Geo-ICT

DINO

DINO (***D****ata en* ***I****nformatie van de* ***N****ederlandse* ***O****ndergrond*) is the main asset of the Geological Survey of the Netherlands. It was conceived in 1994, launched for internal use in 1997 (Kiden et al., 1997) and for public use in 2001 (see Lance et al., 2010, for an overview). The DINO database currently contains:

– Data from 6,300 deep exploration and production boreholes licensed under by the Mining Act; mainly for hydrocarbons, but also for salt and geothermal energy. The data includes 28,000 borehole logs, 193,000 sample measurements, production statistics of 1,349 production wells, as well as 136,000 borehole-related documents.
– 456,000 standardised descriptions of shallow boreholes, ranging from a few meters (the majority) to hundreds of meters deep. This number includes 326,000 original survey boreholes, drilled for 1:50,000 geological mapping (see below); the remaining 130,000 were supplied by third parties, and drilled for a variety of purposes, for example groundwater mapping or monitoring.
– Data of 150,000 cone penetration tests.
– 7,000 digital seismic lines (post-stack) with a cumulative length of 360,000 km, and 29,000 km of analogue lines (with digital metadata) spanning 1.5 million km.
– 335 3D seismic surveys (post-stack) covering an area of 146,000 km^2.
– Groundwater level data from 74,000 filters in 49,000 monitoring wells.
– Chemical and physical analyses of more than 195,000 samples, including almost 150,000 groundwater composition analyses.
– 23,000 core sample photographs.
– Data from four subsurface models that the Survey develops and/or maintains in its mapping programme.

The interface of DINO with the user community is DINO*loket*, consisting of a web portal (www.dinoloket.nl) and a service desk. The portal allows users to search the database and download data; the service desk handles non-standard requests. DINO*loket* has about 6,000 registered users, from individual to institutional licensees. Annually, it handles the requests for data from hundreds of thousands of boreholes and cone penetration tests, hundreds of millions of groundwater levels, and thousands to tens of thousands of the other data types mentioned.

1 Our advisory role relates mainly to Dutch home production of hydrocarbons, primarily natural gas. Dutch revenues from State participation in gas production amount to some 14 G€/yr (data for 2012). TNO provides geological evaluations and advise to support decisions towards State participation and to grant exploration and production licences. Our resource assessments and production forecasts are input for policies and measures to regulate future energy supplies and trade. Advisory work is not further discussed in the present paper on geological surveying proper.

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Even though its size and use may seem substantial, DINO as it is today will not be able to meet the requirements of the BRO. Its current intake, management and delivery processes preclude handling the expected data volumes, are unsuitable for the desired physical linkage with government processes, and cannot meet the associated security standards. The BRO will therefore need to be a newly designed system, which will first be fed from DINO, and then largely replace it (Fig. 2).

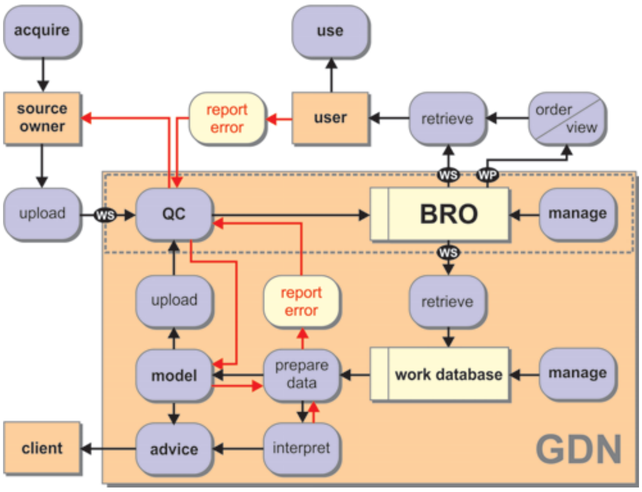

Fig. 2. Data flow diagram showing the BRO in the context of key activities and processes of the Geological Survey of the Netherlands (GDN): data intake, database management, data delivery, modelling and advice (see text for explanation). 'Use' refers to the full range of possible applications of subsurface data and information by government and industry; 'Advice' mainly (but not exclusively) refers to advice on geological matters related to the Mining Act. Red arrows refer to the process of QC and error reporting. GDN = Geological Survey of the Netherlands, WS = web service, WP = web portal.

BRO

Data architecture

The BRO is to become more comprehensive as a system than DINO. A robust data architecture is a prerequisite for its design and to some extent its construction process. The elementary building blocks of key registers are *registration objects*, parcels of information that are defined in terms of the entities they describe, their attributes and the information domains they belong to. Each registration object is given a formal identification and is linked to a specific source owner. Just as with base topography and cadastral data, the BRO is a spatial key register; its objects are linked to a specific location (Anonymous, 2011).

A registration object is not only defined in space but also in time, and this principle needs to be accommodated by the BRO system. The life of a registration object begins when it is registered, as shortly after the production of information as possible. Its lifespan and the extent to which it is active vary from one registration object to the other. For example, a groundwater observation well may yield groundwater level data for decades, and its corresponding registration object needs to be actively maintained in the system. The same principle applies to hydrocarbon production wells and to geological models that are periodically revised: registration objects are the 'avatars' of an object in the real world, just as a parcel is in the cadastral database.

In contrast to such monitoring data, geological and geophysical survey data are to be registered and then remain unchanged unless an error needs to be corrected: its active life ends immediately. In view of the presumption of validity of key register data, it will become even more important than it is today to realise that survey data represent the subsurface at the moment of acquisition; change may have occurred afterwards. For example, most (if not all) cone penetration tests are performed and many boreholes drilled in preparation of building or engineering activities that will modify the subsurface. In such cases the BRO will have registered the subsurface in a (more) pristine state. But also processes such as peat oxidation may render single observations of the subsurface outdated; here the BRO registers an instance of a subsurface process. Dealing with such dynamics and its representation in the BRO is discussed below as a perspective for geomodelling.

A second principle is that interdependency of objects, in terms of logical linkage in the database, should be restricted to the minimum needed to ensure the integrity of the system as a whole, the rationale being that the system has to be modular to guarantee maintainability while growing. The combination of the life-cycle and minimum-interdependency principles implies that understanding information production processes is key to data and system architecture design. These processes are explored in a dialogue with a variety of stakeholders ranging from, e.g., well engineers to policy makers. Analysis of the 20 data types identified has so far resulted in a total of 26 registration objects to be in scope of the BRO.

System architecture

For the design of the BRO we establish how exactly the system should support our users and their processes. The BRO system is designed and built according to rigorous definitions agreed between all stakeholders. Technologically, the BRO needs to be state-of-the-art, but the requested reliability will be accomplished with proven rather than cutting-edge technology: the BRO is a process of technology implementation rather than of technological development.

Data providers and data consumers will only use the BRO when the system is reliable (quality of service) and when the data in the register meet the expectations (quality of data). Quality of service is paramount: the system will have to serve growing numbers of users with large, growing data volumes. According to current estimates, the BRO may receive annually

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up to tens of thousands of borehole descriptions and cone penetration tests: two to three orders of magnitude more than we have been receiving since DINO was launched. In order to be able to support these high and growing demands, the software and hardware architecture of the BRO system needs to scale up (bigger machines) and out (more machines). System health monitoring will be put into place on all levels. On a functional level, the processes of intake, storage and delivery will be monitored, for example: was data received on time? Was it processed and stored in the allocated time period? Is the dissemination of data running as expected? On a system level the software and hardware components are monitored; this process is automated as much as possible, alerting people only when predefined thresholds are crossed.

Access and transactions

In order to accommodate larger data flows and to establish the linkage with government systems, the primary mode of access to the BRO will be through web services. A web service enables machine-to-machine communication over a network, i.e. without human intervention. The principal BRO transactions that will be facilitated in this way are registration, correction, addition, requesting object data (search the register on the basis of object properties) and requesting objects (retrieve data from the register), functionalities that jointly enable the intake, delivery and feedback processes of the BRO system.

Intake is a process that occurs between a data provider and the Survey. Data providers are governmental organisations that produce subsurface data or commission the production of subsurface data. They are legally obliged to submit data to the BRO in the formal role of source owners (Fig. 2), being responsible for the timely delivery of data to the BRO and, most importantly, for the quality of the data. The Survey is responsible for facilitating the intake process and for compliance of all data that enters the register with the standard (standardisation is discussed below). The envisaged level of automation, i.e., the use of web services, brings a very fundamental change to the way we handle and manage data. While all data that enters the Survey literally passes through the hands of survey staff before it is put in the survey database, the BRO will be mainly filled by third parties without human intervention. This obviously challenges QA/QC. Standardisation is a sine qua non for automated intake of data. On the metadata-compliance level, submitted data can be checked automatically, and when such check fails, feedback is provided to the source owner, who then has to submit corrected data. Plausibility will primarily be checked and assessed when the data is actually used.

Feedback: as a mechanism to enhance the quality of data in the BRO (i.e., which has already passed the quality checks during the intake process), a feedback process from data consumers is envisaged (‘*digimelding*’, digital reporting). When a user of the register believes there is an error in the data in the register, this must be reported back to the Survey, which will then investigate together with the source owner and correct the data if necessary. Interpreting data into models, discussed below, presents another approach to data quality assessment. The essence of modelling is to interpret data in a spatial or spatiotemporal context according to a geological concept, which constitutes a very powerful data plausibility check. New data entering the register could also be checked automatically against an existing model, identifying deviations for further inspection. Based on the latter considerations, we would be hesitant to act as a repository for data we do not work with ourselves.

Just as intake of data, **delivery** of data from the BRO will be facilitated by web services. However, in order to serve users that are not able to use web services to access the register directly, and to offer the means to explore, inspect data and models, the BRO will also have a web portal interface (Fig. 2). DINO*loket* will be completely redesigned for that purpose, offering a range of functionalities such as free text search, intuitive and responsive interactive maps, and visualisations of data in the form of graphs and charts.

Standardisation

The BRO will only work if the data are standardised. This bears to consistency of the data and information content and, hence, to its usability, but it is also vital to data quality management. At the given data volumes, quality checking will have to be highly automated, as part of data intake processes, which is only achievable if data are standardised. Standardisation projects are currently carried out for each of the registration objects, delivering a data catalogue (describing the data type and all its attributes) and a data model (which describes data structure), as well as a data exchange format, web services, and an accompanying user manual.

BRO standardisation is a three-staged process. The initial preparatory phase is undertaken by a group of Geological Survey and external experts to deliver drafts of the data catalogue and the data model. The drafts are submitted to a professional group, consisting of representatives from the user community, to assess the usability of the catalogue and model in their daily processes. Based on their recommendations, second versions of these documents are produced and put up for public consultation. The feedback is processed and the final result formally approved by a steering committee with representatives from all stakeholders. The data exchange format and web services are produced as soon as the data catalogue and model converge, typically during the professional-group or public-consultation phase. Some of the data types in the BRO are already standardised to the extent that they may only need to be updated to comply with modern technologies. For other data types this may be a first concerted standardisation effort.

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Wider implications and benefits

The BRO only will not only replace decentralised subsurface databases, it will also capture data that would otherwise not be stored at all. A municipality, for example, may commission ground investigations in preparation of an infrastructure project. The results would typically be provided in a report, which will eventually be shelved rather than registered. In the future, the contractor will need to include evidence that 1) the BRO was checked for existing subsurface data in the area of interest; and 2) that newly acquired data was stored in the BRO for later reuse.

Most importantly, however, even though the BRO will be a governmental register, it will be open to any user free of charge: there is significant potential for new information products and business opportunities by combining and enriching data from the BRO with data from other sources. The Survey will largely refrain from exploiting its data and models for business purposes, in contrast to earlier years, when a lesser extent of disclosure in fact provided a competitive commercial advantage. While at first glance the new situation may be perceived as a bad business model, free flow of our data and information is an essential ingredient of the future Geological Survey of the Netherlands. In fact, our success and legitimacy will partly be judged by the ease and success of others in using our data and information.

Geomodelling

Introduction and definitions

We define digital geological models as predictions of the architecture and properties of the subsurface. In contrast to both point and line observations (e.g. in boreholes and geophysical transects) or to traditional maps, models are continuous representations of the subsurface. They are quantitative and user oriented, i.e. applicable for non-geologists in their own area of expertise. Our models are also stochastic, in the sense that model uncertainty is quantified. At present, we systematically build and maintain two types of nation-wide subsurface models, which will be detailed below: 1) layer-based ones, in which the subsurface is represented by the top and base of geological or hydrogeological units; and 2) voxel models in which subsurface properties are represented in a regular grid of attributed 3D cells (voxels).

Layer-based models include the geological framework models DGM (Digital Geological Model) and DGM-deep, and the hydrogeological model REGIS-II. The distinction made between deep and shallow modelling is based on application and modelling methods. Shallow modelling, having evolved from traditional geological mapping, is primarily based on the correlation of boreholes and covers depths that are relevant to geotechnical and groundwater studies (generally down to about 500 m below the surface). Deep modelling, originally targeted at hydrocarbon resources, primarily uses seismic data down to about 5 km below the surface. Voxel models of the upper tens of meters of the subsurface include GeoTOP, a high resolution model that is in the process of being built, and NL3D, a lower resolution model that already has national coverage. GeoTOP, REGIS-II and DGM are to be included in the BRO.

DGM-deep covers both the on- and offshore domains; the other models are onshore only, because of their intended application (e.g. ground water management) or for lack of data (especially GeoTOP). Developments in marine mapping, which has not yet taken the step to 3D are discussed separately. Model delivery and advanced parameterisation are outlined after a description of the individual model products.

DGM-deep

The deep mapping programme was the first systematic 3D geomodelling effort undertaken by the Geological Survey of the Netherlands. In 1985, we were commissioned to compile a consistent, regional-scale petroleum geological framework. Eleven geological horizons, ranging from Permian to Neogene in age, were mapped, the results of which were first published on paper (depth, isopach and subcrop maps at a scale of 1 : 250,000; compiled at 1 : 1,000,000 in TNO, 2004), and later became the constituents of a stacked grid model now referred to as DGM-deep (Duin et al., 2006; Kombrink et al., 2012; Fig. 3). The model is based on 2D and 3D seismic survey data, combined with a variety of well data, and supported by biostratigraphic, petrophysical and geochemical analyses. Attribution of hydrocarbon and later of geothermal reservoirs relies on well data as well as burial history analysis and basin modelling techniques. The latter approach is used to predict maturation levels of source rocks, as well as reservoir and seal properties (porosity, permeability, geothermal gradients). The general approach and workflow of the deep mapping programme correspond to that of the hydrocarbon exploration and production industry, but on a regional instead of a reservoir scale.

The years between 1985 and 2004 were spent on onshore mapping. The offshore domain was covered between 2004 and 2010. Currently, the onshore area is revisited, with an upgraded, now fully digital workflow, and targeted at new resources and functions of the subsurface, such as unconventional hydrocarbon resources, storage of natural gas and CO_2, and geothermal energy potential. The latter function especially, calls attention to hitherto underexplored areas. The increasing demand for deep subsurface space, with specific properties and utilisation potential, presents potential planning conflicts. Such issues are, amongst others, dealt with in a new policy for underground spatial planning (*structuurvisie ondergrond*; structure vision for the subsurface) which is currently being prepared by the Ministry of Infrastructure and the Environment and the Ministry of Economic Affairs (Schultz van Haegen & Verhagen, 2011). Our subsurface data and models serve as input to this process.

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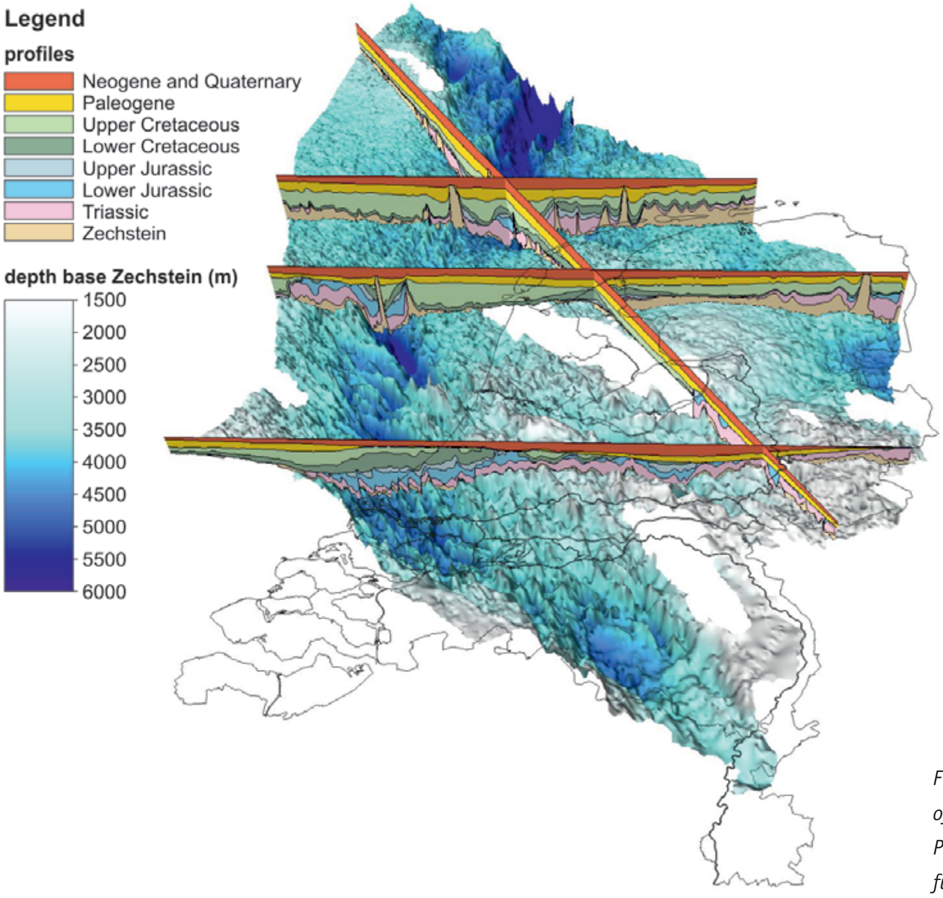

Fig. 3. Example of DGM-deep, onshore and offshore: depth base Zechstein Group (Upper Permian). The Neogene and Quaternary are further detailed in DGM (Fig. 4).

Data confidentiality can be an issue when working in the deep subsurface. Our role as advisor to the Ministry of Economic Affairs involves working with confidential exploration and production data, which cannot be used for public information products unless declassified (5 years after acquisition), or when confidentiality is waivered by the data provider. Combined, data from hydrocarbon exploration, complemented by new data gathered for new underground resources are now being used to derive a more comprehensive 3D model of the deep Dutch subsurface. In the future, possible effects of subsurface activities will have to be evaluated and incorporated, introducing 4D component in such model.

DGM and REGIS II

Digital geological mapping of the shallow Dutch subsurface was conceived in 1998 (Kiden et al., 1998a, 1998b) and launched in 1999 with the development of LKN (*Landelijke Kartering Nederland*, national mapping of the Netherlands; now DGM; Gunnink et al., 2013). Based on a set of some 16,500 high-quality borehole descriptions, DGM is a stacked-grid model, consisting of rasters for the base and top of 31 lithostratigraphical units relative to Dutch ordnance level, and of their thickness.

In most of the country, the lowermost model unit is the Neogene Breda Formation, a marine deposit consisting of glauconite-bearing fine sands and clay that is generally considered to form the geohydrological base. Older units are included at and around places where they crop out and are relevant for application purposes, i.e., Paleogene units in the east and Cretaceous chalk and sandstone deposits in the extreme southeast. The model depth varies, reaching about 1,200 m in the Roer Valley Graben, but generally does not exceed 500 m (Fig. 4). The model units are mostly formations (Westerhoff et al., 2003; Wong et al., 2007), and occasionally combinations of two or more formations. The most important example of the latter case is the Holocene, subdivided into several formations that reflect sharp lithological contrasts, but represented by a single unit for reasons of 'modellability'.

A second important step in shallow geomodelling was made by merging DGM with REGIS, a pre-existing geohydrological information system developed and operated by TNO prior to the merger with the State Geological Survey. Up to the late 1980s, hydrogeological information of the Dutch subsurface was published as paper maps (TNO, 1970-1989). In the early 1990s, a first set of digital subsurface models and maps was developed for groundwater management, under the name of REGIS (**R**egional **G**roundwater **I**nformation **S**ystem). Developed alongside in the newly merged single institute, inconsistencies between both models became apparent and were judged to be unacceptable. A fully revised, integrated mapping concept was developed which resulted in the release in 2005 of REGIS II,

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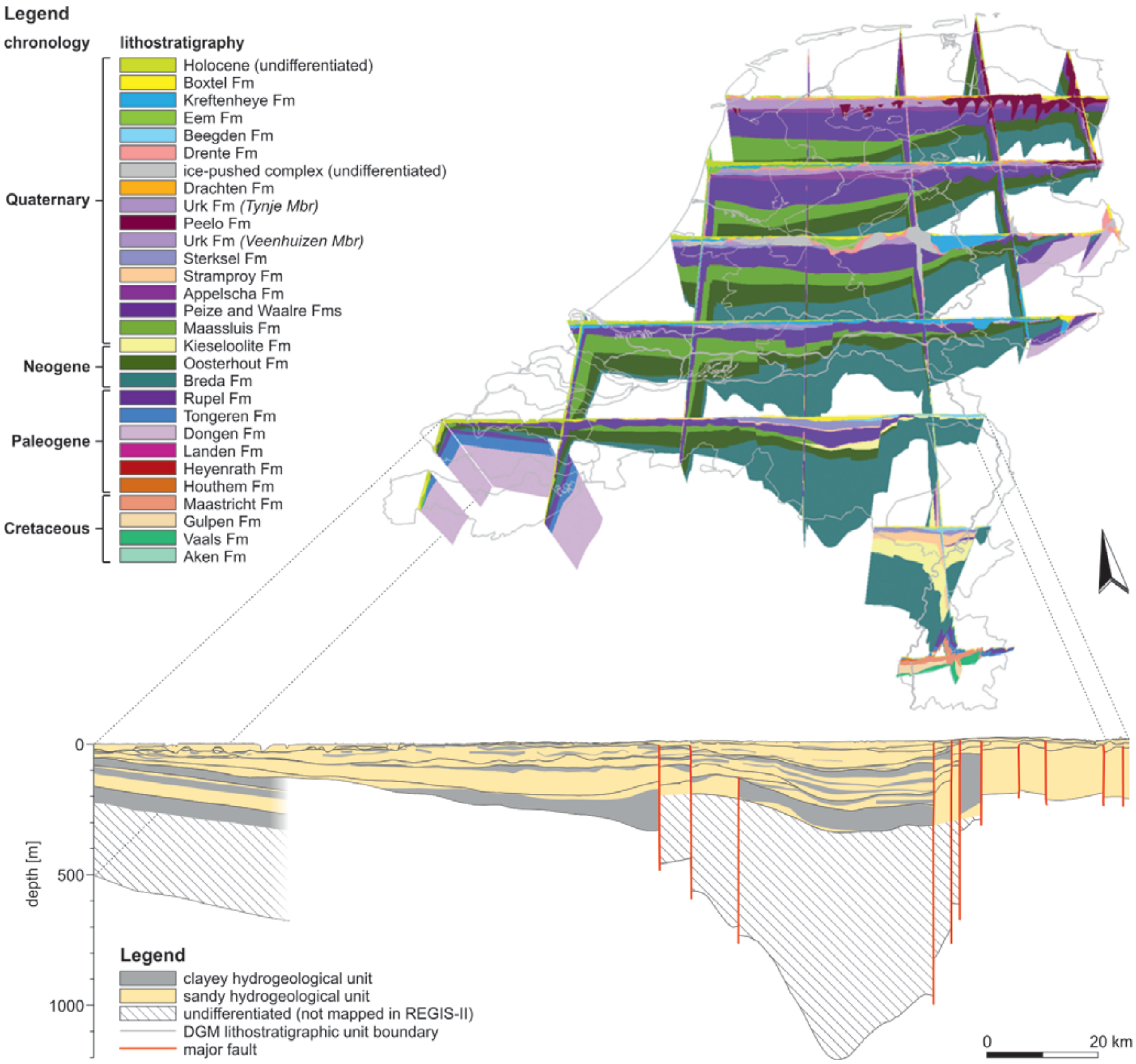

Fig. 4. Fence diagram through DGM. The Roer Valley Graben (mentioned in the text), is clearly expressed in the thickness of the Breda Fm in the 3rd and 4th profiles from the south. The lower panel is the REGIS-II version of one of the west-east DGM profiles.

comprising a 3D hydrogeological schematisation of the Dutch subsurface describing the geometry and hydraulic properties of 133 hydrogeological units (Vernes & Van Doorn, 2005). REGIS II is based on the same set of borehole descriptions as DGM, and both models are currently geometrically consistent.

Other than consistency with geology, a major advantage of this integrated approach was that hydrogeological units could now easily be linked to various parameter ranges and translated into geohydrological models, i.e. schematisations of the subsurface in regional aquifers and aquitards (Fig. 5). From REGIS II, geohydrological models are tailor-made according to user specifications, mostly either for permitting purposes or for groundwater-flow and transport modelling. Depending on purpose and scale, generalised to more detailed geohydrological models can be created for any area, while maintaining consistency with the underlying data. Regional geohydrological schematisations have been created for all provinces. REGIS II is widely used by regional authorities, water supply companies and engineering consultancies for multiple purposes, including permitting and groundwater resources and quality assessments (e.g., Hoogewoud et al., 2010; Emke & Schaeffer, 2011).

GeoTOP and NL3D

GeoTOP is the most recent addition to the model portfolio of the Geological Survey of the Netherlands (Stafleu et al., 2009; 2011). GeoTOP schematises the subsurface in voxels of 100 × 100 × 0.5 m (x, y, z) down to depths of between 30 and 50 meters, covering

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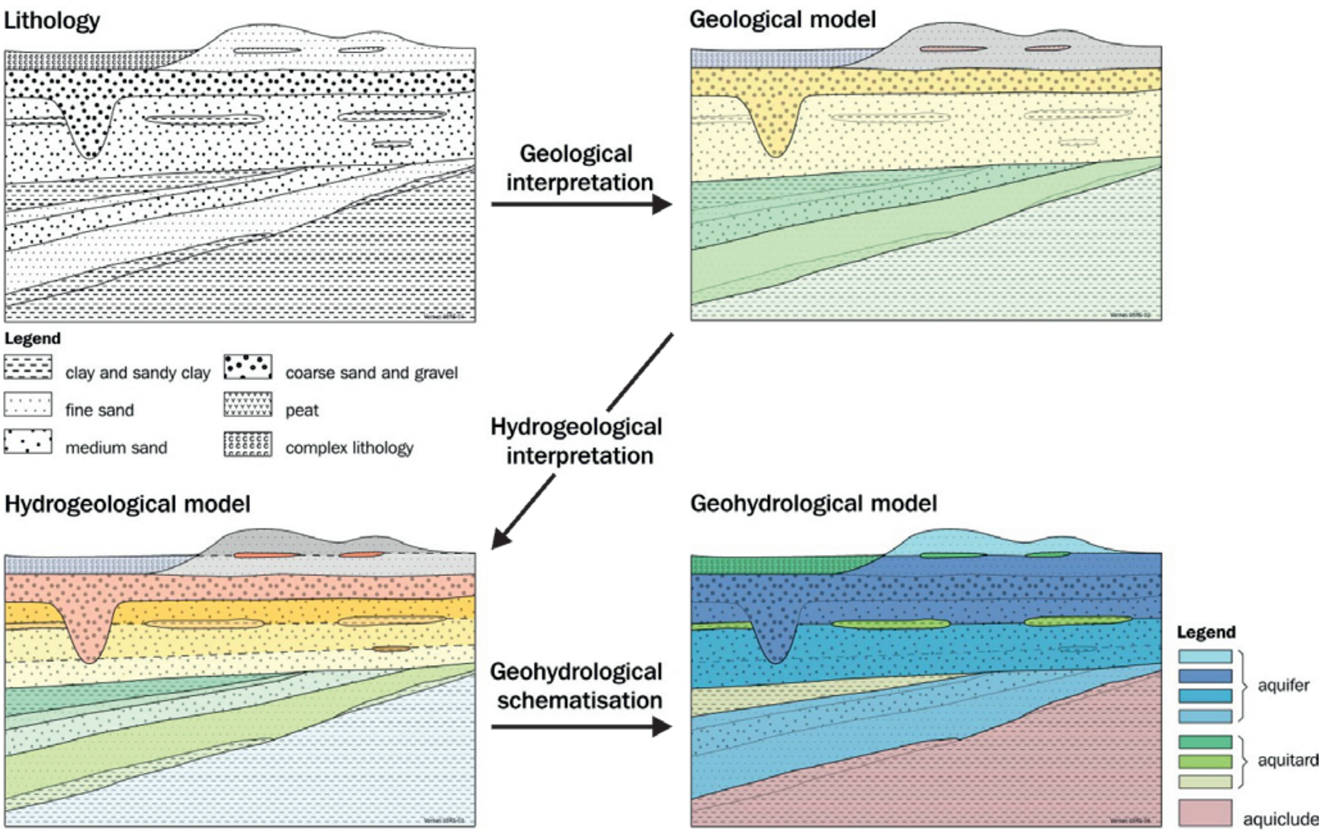

Fig. 5. Schematic visualisation of our geohydrological modelling approach. The upper two panels represent the step of interpreting a geological data set lithostratigraphically. Hydrogeological units, rock bodies with more or less uniform hydraulic properties, the constituents of REGIS II, are then defined according to lithostratigraphy, primary lithology and associated hydraulic properties, and stratigraphic position. Their combination into geohydrological units, as used in flow modelling, is the final step (see text for explanation). In terms of model products, the upper right panel represents DGM, and the lower left panel REGIS II. Maps of the geometry and hydraulic properties are available as grids.

the main zone of human activity. The model currently provides probability estimates of lithostratigraphy and lithological classes (including grain-size classes for sand) per voxel, based on the average of 100 equiprobable model realisations. We are preparing to add physical and chemical parameters such as hydraulic conductivity and chemical element concentrations.

The GeoTOP workflow consists of a layer modelling step, the results of which are lithostratigraphically defined subvolumes in the model space that are then voxelised (Fig. 6). The layer model is more refined than DGM because, it features all Holocene formations that DGM combines, as well as certain Holocene and upper Pleistocene Members and Beds, and it uses in principle all available digital borehole descriptions rather than a subset. Given the large number of boreholes – tens of thousands per region – we developed automated stratigraphical interpretation routines. A region-specific lithostratigraphical concept, featuring superposition, extent, diagnostic properties and approximate depth range, is used to identify and label the units in each

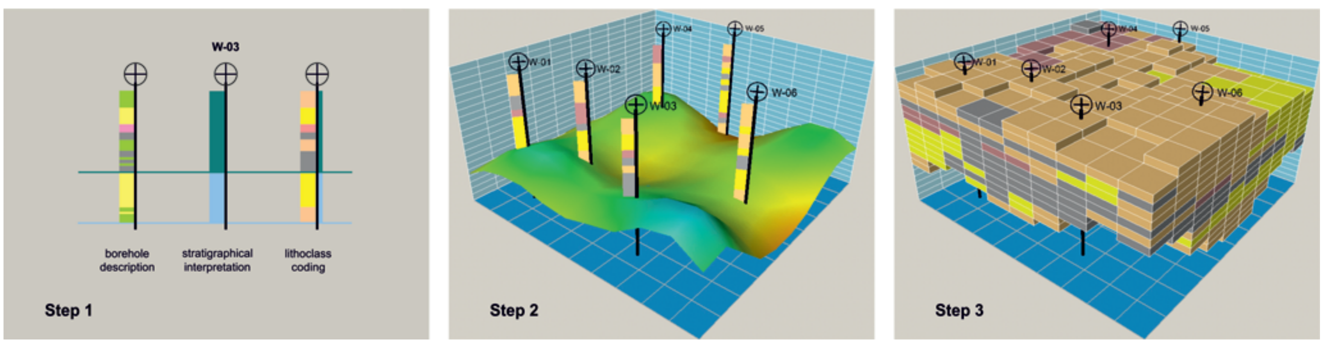

Fig. 6. Voxel modelling workflow. Borehole information is coded lithostratigraphically and as lithological classes (step 1). Lithostratigraphical unit boundaries are obtained just as in DGM, but using more data (step 2). Finally, lithostratigraphical units are voxelated (step 3). Modified from Stafleu et al. (2011).

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borehole. This produces a uniform, consistent and reproducible set of interpretations, the inspection of which is far less time-consuming than manual labelling.

The GeoTOP concept was originally developed because Holocene heterogeneity could not be adequately represented in REGIS II. Such heterogeneity is crucial for the understanding of, e.g., infiltration and seepage, surface-groundwater interaction and contaminants dispersal. Eventually, however, GeoTOP came to be seen as a multipurpose model, designed not only for improved geohydrological assessments, but also for geotechnical applications, resource assessments and environmental geochemical investigations. For these purposes, GeoTOP provides the best regionally available interpretation of lithological variability down to 50 m below the surface.

Specific regional problems may be addressed by incorporating additional data sets from third parties, such as channel belt reconstructions by Utrecht University (Berendsen and Stouthamer, 2001), available geological maps, or AHN (a national high-resolution altimetry grid) in order to identify deposits or structures through their geomorphic expression (e.g. cf. Berendsen & Vollenberg, 2007).

Figure 7 shows the channel belts of the Rhine-Meuse delta from the eastern Netherlands to the North Sea coastline, with lithology and grain-size classes for sand attributed to each voxel. Such a model provides a hitherto unimaginable insight in facies architecture at delta-scale, visualising vertical and lateral trends in lithology and grain size. Figure 8 zooms in on a single channel belt, the Oude Rijn, which was established around 6000 BP and ceased to be active in the early 12th century because of upstream damming. The level of detail captured in GeoTOP is illustrated by plausible array of lithologies and downstream fining (expressed as a downstream increasing share of fine sand). Hence, the geology of areas with GeoTOP coverage is well-resolved by any standard, and the model could also be applied to other uses, e.g., as a reservoir analogue, for scientific purposes or for education.

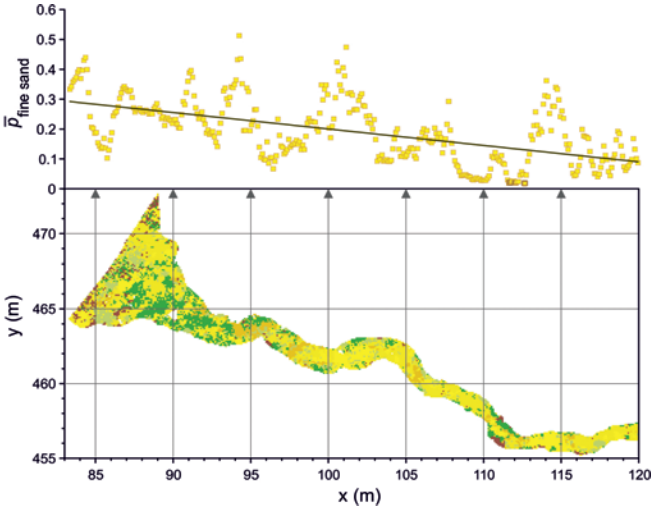

Fig. 8. Downstream (right to left) fining along the Oude Rijn channel belt (see Fig. 7). The upper panel shows the average probability of the occurrence of fine sand in north-south sections through the belt: the probability increases downstream. The lower panel shows the lithology of the upper voxel layer (legend in Fig. 7): clay becomes more prevalent downstream. XY coordinates are in the RD grid, the national geodetic reference frame (De Bruijne et al., 2005).

The general approach of the GeoTOP project is one of learning by doing: while maintaining consistency as much as possible, solutions are added to the modelling workflow when new problems are encountered. For example, a recent improvement is the representation of deformation structures in the ice-pushed ridges indicated in Fig. 1. Ground-penetrating radar data was used to map regional glacio-tectonic structures (Bakker & Van der Meer, 2003). Strike and dip directions were used to 'unfold' the ridges, perform the voxel interpolations horizontally, and

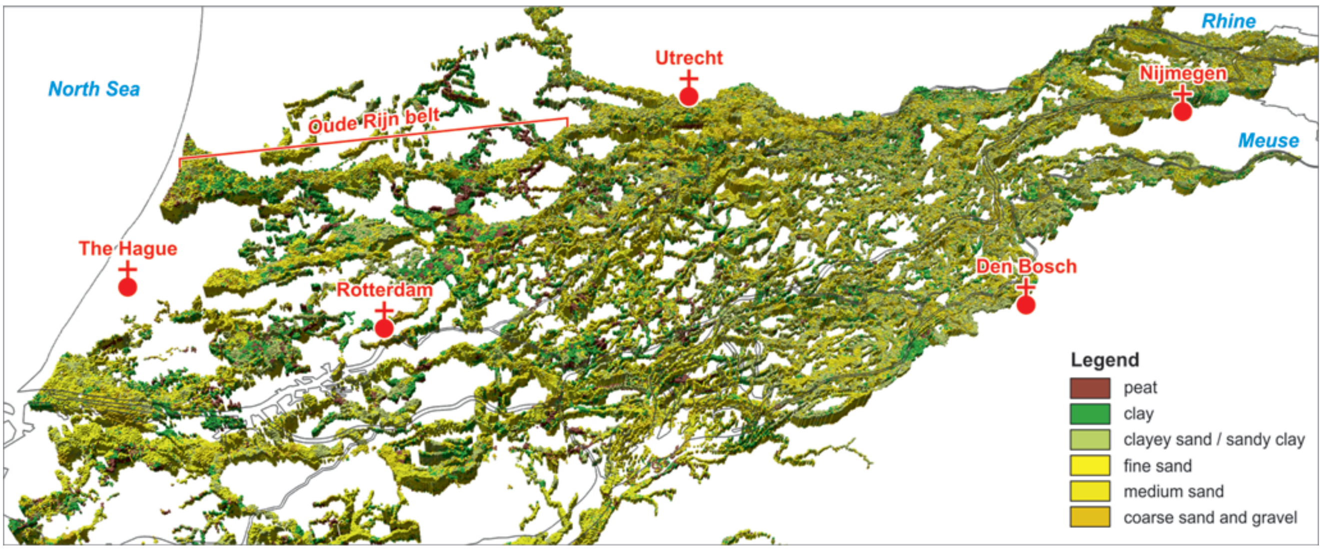

Fig. 7. Holocene channel belts of the Rhine-Meuse Delta in GeoTOP from the German border to the North Sea coast in birds-eye view, looking towards the north-northeast (for topographic reference see Fig. 1; the geodesic distance between Nijmegen and The Hague is about 110 km).

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rotate the grid back to the original orientation (Fig. 9). A second example is the use of soil survey data and information in GeoTOP modelling, creating a higher-resolution top layer (the upper 2 m), in order to account for pedogenic and anthropogenic features that cannot be represented adequately in GeoTOP as it is currently specified. Parameterisation 'beyond' basic lithological characteristics is still largely in the R&D stage, and to be operationalised in the next rounds of model building (see below).

GeoTOP modelling is carried out per region, roughly corresponding to provinces. We have not reached national coverage yet: over the next years the Holocene coastal and fluvial terrains will be covered, followed by the remainder of the country for an estimated completion around 2018. NL3D, a lower-resolution voxel model is already available for the entire country. NL3D models lithology and sand-grain size classes within each of the geological units in DGM, in some 37 million voxels of 250 × 250 × 1 m (x, y, z).

Unlike REGIS, GeoTOP does not yet have a well-established user community. Potential users are involved in the projects in several ways. They are represented in steering committees that are established per mapping area. They are also invited to participate in the programme by funding extensions (higher resolution, additional attributes) or the acceleration of the programme. The first practical model applications (including those of predecessor voxel models) include:

- Assessments of aggregate, clay and silica sand resources (Van der Meulen et al., 2005, 2007a, 2009a, 2009b; based on early voxel models that are now being replaced by GeoTOP).
- Long-term (up to 200 years) forecasts of land subsidence, based on the spatial distribution of clay and peat (e.g., Van der Meulen et al. 2007b, Bruggeman et al., 2011; De Lange et al. 2012; Van der Schans, 2012).
- Parameterisation of the national nutrient emission model STONE, which is used for evaluation of the Dutch Manure act (Anonymous, 1986; Willems & Van Schijndel, 2012) and implementation of the Nitrate Directive (Anonymous, 1991; see also De Klijne et al., 2008).
- Hydraulic shortcut risk maps used in the preparation of dredging the Vecht river (a minor Rhine distributary), based on the architecture and sediment composition of channel belts.
- Assessment of risks and costs associated with the construction of a new metro tunnel in the city of Rotterdam, using a high-resolution local voxel model based on additional, third-party borehole descriptions and cone-penetration-test data (*a posteriori*, as proof of concept; further discussed below).
- Various groundwater studies (water supplies, salt water intrusion risk; De Louw et al., 2011; Faneca Sànchez et al., 2012; Klein et al., 2011; Van Baaren & Harezlak, 2011).
- Maps showing the suitability of the subsurface for municipal sewage infrastructure (TNO, 2013a).

Model delivery

DGM-deep, including the data used, is disseminated through the Netherlands Oil and Gas Portal (www.nlog.nl) as a series of downloadable GIS layers. The other models are delivered through DINO*loket*, as 2D GIS products, as well as with a freely downloadable 3D subsurface viewer based on GSI3D (3D modelling software developed by Insight GmbH (Germany) and the British Geological Survey (Kessler et al., 2009; Sobisch, 2011), allowing users to download and visualise our models on their desktop computers. This 'thick-client' solution is used as a temporary delivery option because current bandwidth does not

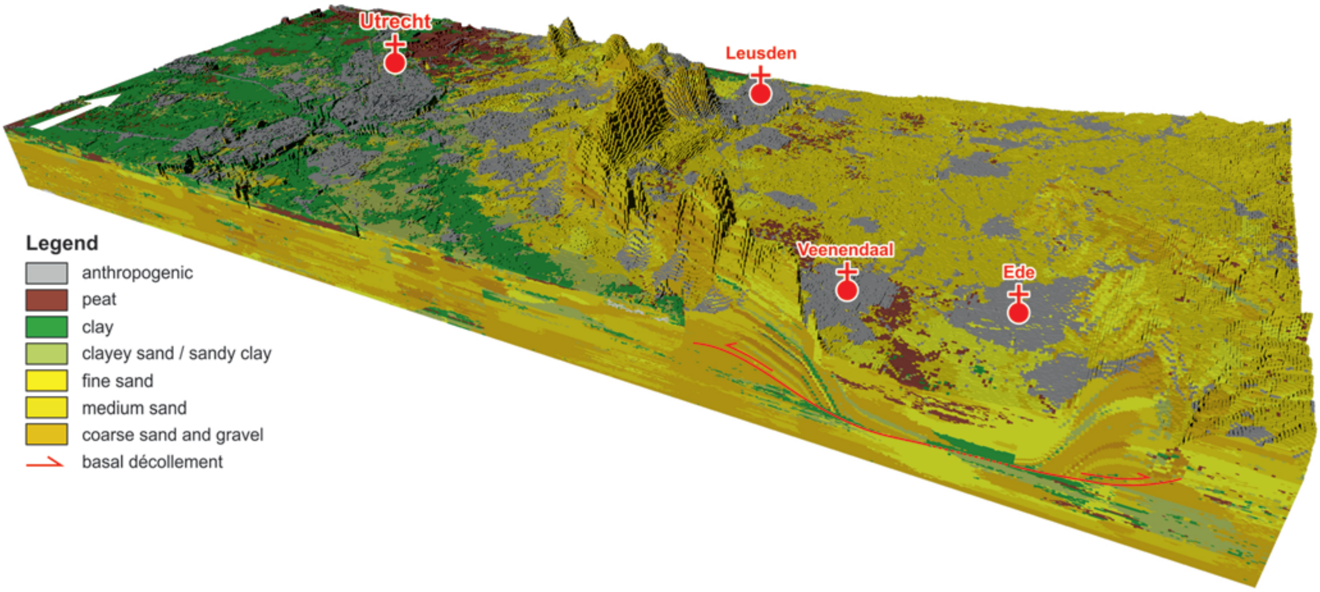

Fig. 9. Block diagram showing the representation of glaciotectonics in GeoTOP (surface area: 62 × 24 km; base is at 50 m below Dutch Ordnance Datum; vertical exaggeration is 75×). Above a predominantly clayey décollement, the internal structure of two back-facing Saalian ice-pushed ridges is modelled according to regional trends in strike and dip. See Fig. 1 for topographic reference.

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allow for a thin-client one (i.e., web access and analysis of a remote data set).

In the future, model data will be delivered through the BRO system (except, for the time being, DGM-deep). The outcome of this exercise cannot easily be predicted. Even though GeoTOP is freely available as a 3D dataset, customers usually request us to use the model to analyse an area or produce derived products for them. A geologically interpreted semi-product is a useful resource for individual projects, which enables us to deliver significantly cheaper and faster than previously. Customers are satisfied with that, but we would prefer to see them using GeoTOP data themselves, because we believe that this better guarantees that the model is used to its fullest potential.

Characterisation and model parameterisation

Most users of subsurface information ultimately require basic physical and chemical parameters such as grain-size distribution, porosity, permeability and reactivity. GeoTOP captures lithology as a first step towards more advanced parameterisation, the possibilities of which are currently explored in a separate programme. In 2006, a drilling campaign was initiated in order to build a new reference data set of physical and geochemical properties of the Dutch subsurface. The objective is to sample all main lithofacies types represented in a total of 27 geologically homologous areas, in order to obtain regional property characteristics (Fig. 10; Vernes et al., 2010). A total of about 325 drillings are planned as a first set of 'golden spikes'. The analyses that are performed on core samples refer to their lithological, hydraulic, geochemical and geotechnical properties, as well as to their correlations.

Fig. 10. The subdivision of the Netherlands into 27 geologically homologous areas (hatched: underwater). See Vernes et al. (2010) for further explanation.

When using such data in the subsurface, we typically have at our disposal the combination of a small set of high-quality, dedicated data and much larger sets of their estimated or semi-quantified equivalents. We currently have, for example, measured grain-size distributions of about 11,000 sand samples, against tens of millions of visually estimated grain-size classes. The question is to what extent the combination of the two, plus sufficiently resolved geological features, produces a predictive parameter model of known, acceptable quality (e.g., Weltje & Roberson, 2012). Without ways to upscale sparse high-quality data, the only way is to straightforwardly derive parameters from grain-size classes or lithoclasses, such as by Van der Meulen et al. (2005, 2007a) for the assessment aggregate and clay resource potential.

Water has always been a primary driver for geological surveying in the Netherlands, especially water quantity management (abstraction permitting, groundwater table management). Groundwater quality management (drinking water protection, groundwater remediation, nature and agriculture policies) requires us to include geochemical data in our information portfolio as well. Systematic geochemical characterisation of sediments is still in its infancy in the Netherlands. We currently include the elemental composition of formations, the association between trace elements and main compounds, and the reaction capacity of sediments as buffer for contamination (Van Gaans et al., 2011; Griffioen et al., 2012). Reaction capacity is considered as a series of geochemical characteristics that control pH, redox condition and sorption capacity. Five primary reaction capacity variables are obtained: pyrite, non-pyrite reactive iron (oxides, siderite and glauconite), clay fraction, solid organic matter, and calcium carbonate. Main reaction capacity variables that are determined by more than one solid compound are also deduced: 1) potential reduction capacity (PRC) by pyrite and organic matter; 2) cation-exchange capacity (CEC) by organic matter and clay content; and 3) carbonate buffering upon pyrite oxidation (CBPO) by carbonate and pyrite. Geochemical attribution is envisaged at multiple scales, from lithostratigraphic units to GeoTOP voxels. In the future, geochemically parameterised models are to become standard products.

The next domain to receive attention is the built environment, including land use planning. This primarily requires geotechnical parameterisation, and the question is which properties can be mapped with data in DINO (and later in the BRO). Cone-penetration-test data, our primary geotechnical data type, will obviously be important: one could think of 3D cone-penetration-test parameters models, from which basic geomechanical properties such as compressibility, shear strength, stiffness and degree of consolidation can be derived or approximated.

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Beyond that, as discussed below, dynamic soil and groundwater properties can be delivered as dynamic models, e.g., of subsidence or groundwater flow.

Developments in marine mapping

Although the Dutch part of the North Sea can be seen as the 13th province of the Netherlands, its mapping and shallow subsurface modelling offers very specific challenges that set it apart from the onshore part of the country. These challenges are related to differences in data types and data densities. Whereas the vast majority of the land data comes from boreholes, our marine waters have been mapped with a balanced combination of boreholes and shallow geophysical surveys. Relatively few North Sea boreholes reach deeper than 10 m. Also, with increasing distance from the shore, the density of boreholes (point data) decreases significantly, forcing us to rely increasingly on 2D and 3D seismics. A second challenge associated with marine mapping is the dynamic nature of this environment. Much more than onshore, sediment is being transported to such an extent that maps of the shallow subsurface may be outdated within as little as a decade.

Seabed sediment maps for the North Sea have been compiled and published since the second half of the 19th century, based on lead-line sounding data, bottom trawls and dedicated surveying (e.g., Delesse, 1872; Olsen, 1883; Jarke, 1956). After the subdivision of the North Sea into exclusive economic zones, countries started focussing on what had become their own sectors (Laban & Meulenkamp, 2011). A Dutch hydrographic campaign in the late 1960s presented the former State Geological Survey with the opportunity to drill into the shallow Dutch North Sea subsurface from the hydrographic survey vessel. This eventually set off systematic marine geological mapping, which took place between the late 1970s and the mid-1990s.

The hunt for hydrocarbons, which were first found in British and Norwegian waters in the mid-1960s and in the Dutch sector in 1968, was the main the main reason to (commercially) explore and map the North Sea subsurface. However, an understanding of the shallower unconsolidated sediments was also required: for platforms foundations, cables and pipelines routes, and later on also for sand resource assessments. To meet the need for marine geological information, a 1 : 250,000 mapping initiative was developed, partly in conjunction with the British Geological Survey. For each sheet of 1° latitude by 2° longitude (about 110 × 130 km), three paper maps were produced: one for seabed sediment and Holocene geology, one for Quaternary sediments, and one for pre-Quaternary consolidated rocks. This effort was instrumental in our understanding of process-response relationships that have governed the evolution of the North Sea Basin (Laban, 1995). It has generated a database that has been used in recent years to provide new end users such as marine-policy makers and habitat mappers with geological information. Surface-sediment parameters such as mud content and median grain size, for example, have proven to be very useful proxies for mapping seabed habitats (Verfaillie et al., 2009).

By the late 1990s, the 1 : 250,000 mapping programme was suspended, and marine geological mapping evolved into updating digital maps, using data and information from commissioned marine survey activities. In line with developments onshore, 2D mapping is starting to be replaced by 3D geological modelling. Optimising data density is at the core of this development, as it determines the scale at which lithostratigraphical and lithological units can be recognised and mapped in light of the limited number of boreholes. In the past, combinations of typically widely spaced seismic lines and boreholes resulted in maps on which only the largest architectural elements (multiple tens of km) were recognisable. Although useful in providing the overall geological setting of sites or transects, they could not provide the detail required by the modern end user. In recent years, dense 2D seismic grids, particularly near the coast, and 3D seismic time slices have allowed us to zoom in to the sub-km scale (Rieu et al., 2005; Fitch et al., 2005; Fig. 11). Currently, lithological horizons are being digitised to form a layer-based model, and initial steps taken to build a voxel model that will allow seamless integration with onshore voxel models.

Geological surveying in the Netherlands: trends and enabling factors

Overall strategy and long-term roadmap

The present information portfolio of the Geological Survey of the Netherlands largely originates from a vision on the delivery of geological information that emerged during the mid and late 1990s, around the time of the aforementioned merger of the State Geological Survey with TNO (Fig. 12). Usability, applicability and updatability became central and a strategic roadmap was drafted, targeted at predicting relevant subsurface properties in 3D (e.g., Weerts et al., 2005). The first steps were to 1) establish DINO; 2) adopt a new lithostratigraphical framework (see below); and 3) create a geological layer model (the DGM programme, which supplemented deep mapping with a shallower 3D counterpart). Next came the aforementioned merger of DGM and REGIS; the GeoTOP programme is the latest step towards property modelling as it was originally envisaged.

From paper to digital data

The late-1990s vision on the future of geological surveying could not have been taken up without the availability of digital geological borehole data. The first digital data that entered the survey were supplied by the oil and gas operators (the results from 3D seismic surveys from the early 1980s onwards, and

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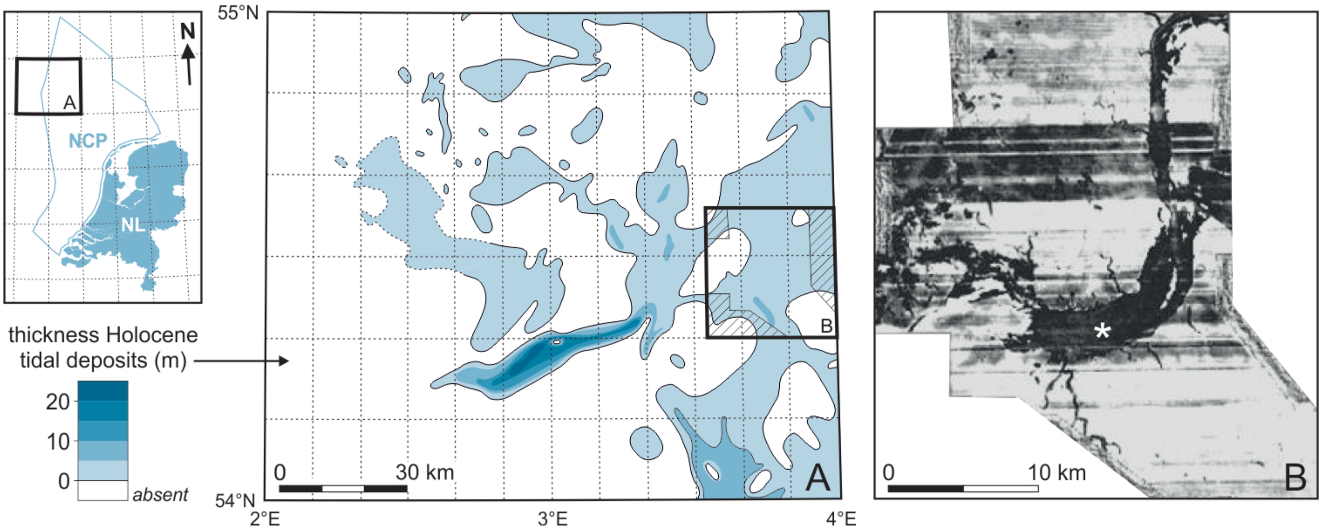

*Fig. 11. Comparison between a traditional 1 : 250,000 map segment showing the distribution of buried fine-grained Holocene tidal deposits (A, modified from Jeffery et al. 1989) and a time slice of 3D seismic data (B, in grey tones). It is impossible to derive from the traditional map all but the coarsest information. In contrast, the time slice shows that the Holocene tidal deposits form a detailed fill pattern (marked with an *) suggesting an estuarine setting. NCP = Dutch exclusive economic zone.*

borehole data from the mid-1980s onwards). In the early 1980s, the State Geological Survey started digitising its own survey borehole description archive (Oele et al., 1983). Entries of such descriptions consisted of a depth range and an associated lithological description in a text string, accompanied by some coded information. In this way, about 326,000 shallow boreholes were digitised, a body of data which still constitutes a significant portion of today's DINO.

When building DINO, the digitised description set was converted into a standardised, coded relational database, fit for automated querying and modelling. A lot of resources have been spent since on checking and improving this conversion. Interestingly, Oele et al. (1983) argued that the fact that the database contained text rather than (only) codes was advantageous, because descriptions could be read by a geologist. Clearly, processing tens of thousands of boreholes at once for 3D mapping purposes was beyond the imagination of our predecessors at that time. Nonetheless, to start digitising was a landmark decision and a sine qua non enabler for all later developments. To date, the Geological Survey of the Netherlands spent between half and two thirds of the survey budget on DINO, amounting to a cumulative investment of between 100 and 150 million euro. This may seem a large sum of money, but it fades against the original acquisition costs of the data, which amount to tens of billions of Euros.

From mapping to modelling

When taking up systematic shallow geomodelling in the late 1990s, 2D mapping was considered a dead end and the national 1 : 50,000 onshore and 1 : 250,000 offshore geological mapping programmes were discontinued. The programmes were too expensive to pursue, their progress too slow, and altogether they were considered not to deliver value for money. Other than for budgetary reasons, mapping was suspended because the application possibilities were considered to be limited; the

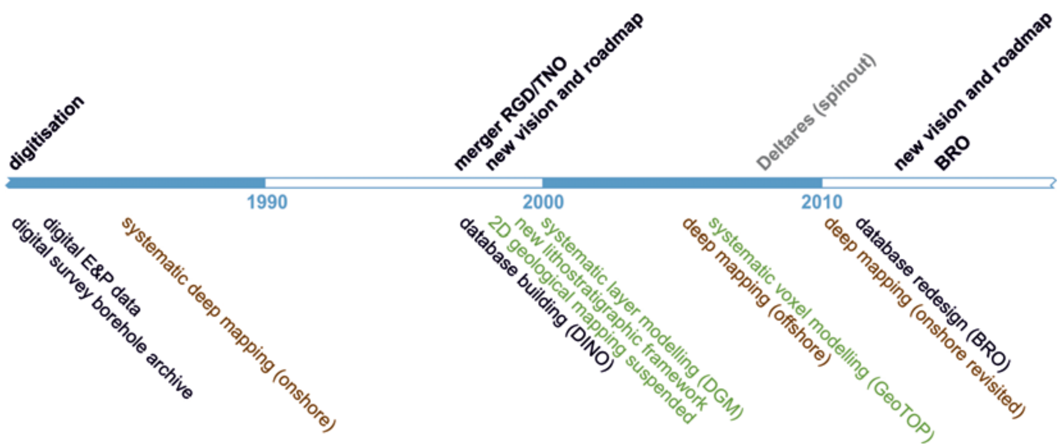

Fig. 12. Timeline showing important steps in the evolution of the Geological Survey of the Netherlands. RGD = State Geological Survey (see text for explanation).

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whole exercise came to be seen to be too much of a self-serving activity. It should be noted, however, that the 1 : 50,000 maps today – where available – turn out to be an invaluable body of information that is used to build GeoTOP. They also relied on massive augering campaigns that yielded the majority of the data that GeoTOP modelling now uses. At the time, many considered replacing systematic mapping by 3D modelling to be a step backwards. DGM did not have the level of geological detail of the prior maps; in fact this level was only recently re-achieved in GeoTOP, but now in full 3D.

The 1 : 50,000 maps we formerly produced already gave some qualitative insight in the third dimension because a profile-type legend was used ('Member X on top of Formation Y'). Map units generally correspond to large-scale facies units such as channel belts and coastal dunes, so the maps have considerable detail and are close to being lithological maps (Fig. 13). Altogether, geomodelling at the Geological Survey of the Netherlands, especially GeoTOP modelling, is the natural progression of its former mapping programme rather than its mere replacement.

Redefinition of the national stratigraphic framework for the Cenozoic

Lithostratigraphical units are the basic constituents of any geological map or model. They are defined on the basis of rock properties and stratigraphic relationships, and need to be mappable, i.e., traceable and representable in a medium of choice at a given scale, traditionally that of regional geological mapping (1 : 25,000 to 1 : 50,000).

Building DGM required a redefinition of the Dutch stratigraphical framework for the Cenozoic. Other than that a mappable unit is not necessarily 'modellable' in 3D, the lithostratigraphical system in use during the 2D mapping era heavily relied on additional biostratigraphical analyses, chronostratigraphical interpretations and mineralogical studies. DGM required the manual interpretation of thousands of boreholes, which could only be achieved with a scheme that is strictly lithostratigraphical: based on robust, mesoscopic lithic properties that are recognisable in the average borehole description. This became even more important for GeoTOP modelling, in which stratigraphic interpretation is automated (cf. Fig. 6).

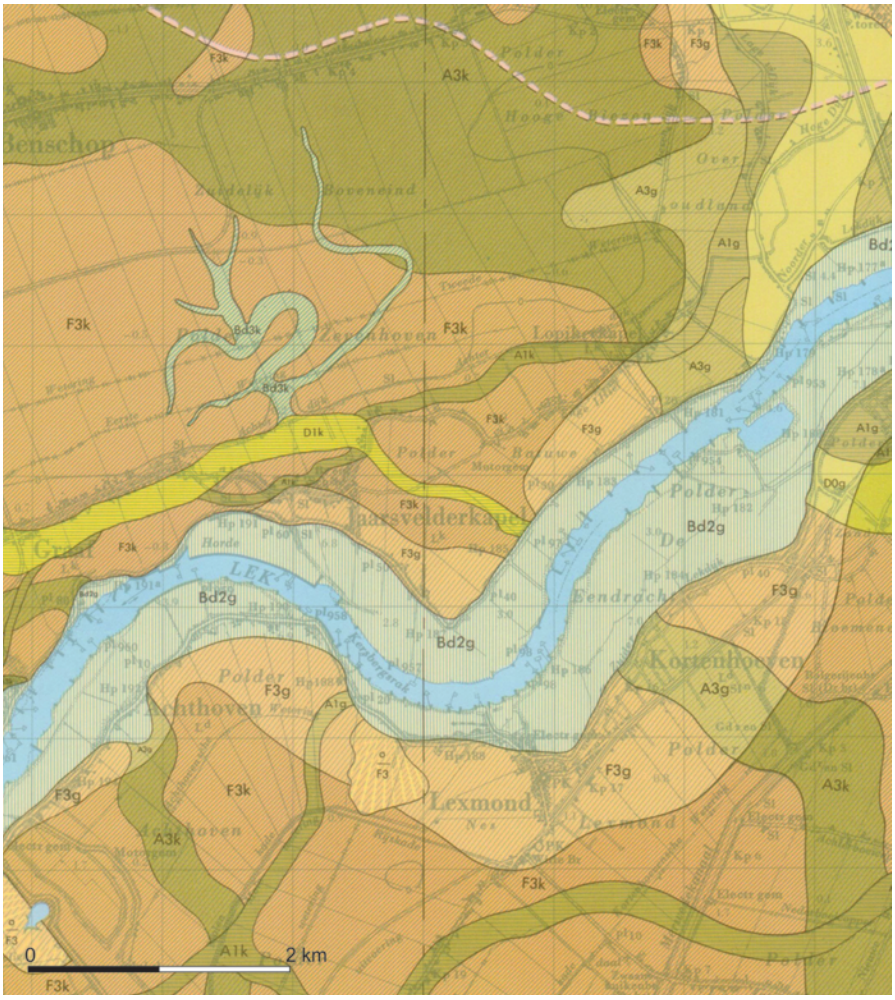

Fig. 13. Detail of a Dutch 1 : 50,000 geological map sheet (Verbraeck, 1970), see Fig. 1 for location. Legend unit F3k is a floodplain profile type; most others are profile types with channel deposits. The superposition of channel units gives a qualitative insight in the 3D dimension.

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The redefined national lithostratigraphical framework was established in 2003 (Weerts et al., 2003; Westerhoff et al., 2003; De Gans, 2007). It currently consists of 32 formations that are partly subdivided in members and beds. Proposals have been made to combine this framework with the seismostratigraphical subdivision that is in use on the Dutch continental shelf (Ebbing et al., 2003; Rijsdijk et al., 2005). To achieve coupling of DGM and DGM-deep, the established stratigraphy for the deeper subsurface (Van Adrichem Boogaert & Kouwe, 1997) and the Cenozoic lithostratigraphy are currently being integrated, finding a common boundary at the Mid-Miocene Unconformity (base of the Breda Formation and of the Upper North Sea Group). Formal definitions of all lithostratigraphical units are publically available through DINO*loket* (TNO, 2013b).

From Moore's law to data density as a delimiting factor

Up until recently, our progress in geomodelling has been delimited mainly by data-handling capacity and computational power ('Moore's law'; Moore, 1965). None of the subsequent modelling approaches (layers, voxels) was new when adopted by the Survey, but they had not been used before at this particular combination of scale (national) and volume of data.

An ever higher level of geological detail, eventually zooming in from formations to facies units, was achieved because a progressively larger part of the available data could be handled. While DGM and REGIS are based on less than 10% of our borehole database, GeoTOP and NL-3D use >90% (rejecting only the lowest-quality logs), not only because of increasing computer performance, but also thanks to the automation of previously manual, time-consuming borehole processing and stratigraphical interpretation steps. In contrast to what its level of automation may suggest, GeoTOP modelling makes better use of 'soft' geological knowledge and of the legacy of prior survey and third-party information (such as geological maps and detailed digital terrain models).

The first Dutch national voxel model, the abovementioned one built for aggregate-resource-assessment purposes (Van der Meulen et al., 2005), had a cell size of 1000 × 1000 × 1 m; higher resolutions would have required an unacceptable amount of computer-processing time. Within 2 years, its successor could be calculated at a 250 × 250 × 1 m resolution, and a clay resource model with narrower depth range at 250 × 250 × 0.2 m (Van der Meulen et al., 2007a). At present, we consider 100 × 100 × 0.5 m to be the resolution limit when working at regional to national scales. While voxel resolution grew by two orders of magnitude, our database grew by 5-10% only. Further detailing will require more (or other) data rather than more powerful computers. The big question is to what extent this will be enabled by the new influx of data under the BRO regime. Local higher-resolution models are already produced by feeding additional data in the existing modelling workflow, which not only shows that this is a technical possibility but also that such workflow is a product in its own right (example in Fig. 14).

From drawing maps to providing numbers

The purpose of interpreting geological data – first into maps, now into models – has shifted from understanding and representing geology to predicting the distribution of certain properties in the subsurface, in accordance with the aforementioned roadmap. On the eve of the BRO, the Survey is producing evermore quantitative information. The general philosophy is that geological models can be populated with properties, as long as these correlate with model units or lithology: bulk attribution in case of layer models, more detailed parameterisation in case of voxel models. Decisions need to be made on which model attributes will be included in the BRO. In case of REGIS: geometries of geohydrological units only, or hydrogeological parameters as well? In case of GeoTOP: lithology only or associated properties as well?

Irrespective of such decisions, increasing volumes of quantitative, freely available data are easier and easier for third parties

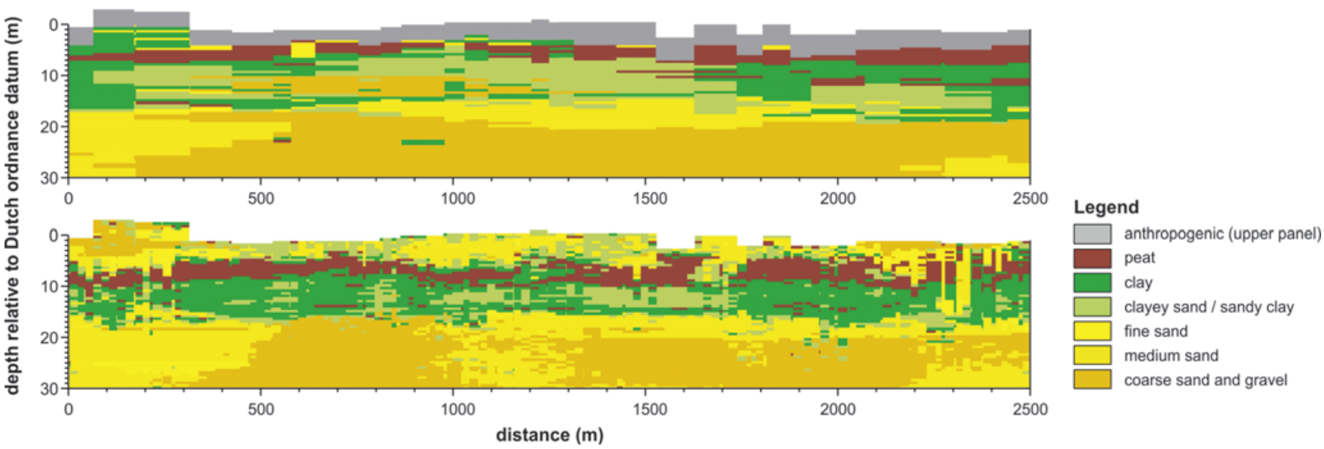

Fig. 14. Two profiles along a tunnel trajectory near the city of Rotterdam (see Fig. 1). The upper panel is standard GeoTOP output, the lower panel was obtained after using more local data in the same workflow, resulting in considerably more detail and a lithologically differentiated anthropogenic layer.

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to use in their own applications. To ease of use, the BRO adds the element of obligation. This combination of technological development and a changing legal framework will raise not only our impact, but also our responsibilities and general accountability. This in its turn calls for increased attention to quality assurance.

Implications for geomodelling quality assurance

At present, we are familiar with two formal quality assurance mechanisms. When publishing results in the scientific literature, a customary peer review is conducted to check whether the research is original, properly positioned with respect to previous work, methodologically sound and reproducible. To a considerable extent, such principles are also implemented internally and applied to reporting in general. A second form of quality assurance is through ISO 9001 certification of our generic quality management systems. This is typically targeted at general and project management: it does obviously bear to work content, but in practice primarily serves financial and legal accountability. The combination of these two mechanisms does however not provide sufficient quality guarantees for the whole array of our outputs, and most particularly it does not fully cover data, geomodels and the information systems they fill.

Our former 1 : 50,000 geological maps and explanatory notes were subjected to a rigorous, scientific-type review procedure, which addressed the consistency and geological plausibility of the interpretation, with particular attention for cartographic representation (Oele et al., 1983). Unfortunately, we cannot develop a geomodelling quality system from this procedure, because it was basically dismantled when 2D mapping was discontinued.

On the one hand, the lost experience presents a disadvantage, but on the other map quality assurance could not simply be transposed to 3D models anyway. An important difference from 2D mapping is the fact that 3D modelling, especially voxel modelling, uses and produces more information than one can wholly oversee by visual inspection or traditional review. In addition, whilst a geological map can relatively easily be corrected if a feature is disputed, a misconceived model may set you back to the start of the whole exercise.

A more fundamental difference is in the overall approach. A map used to be conceived primarily in the mind of a geologist, who could explain how he or she arrived at a certain result. Our current models are the output of an extensive, multi-staged computer process that involves a whole array of data manipulation and geostatistical steps. Geological knowledge is used to design and configure the workflow, prepare the input and assess the output, but the actual model building takes place on a machine. While we are obviously deliberate in designing the modelling process, the exact implementation of selected geostatistical operations in third-party software components is not always clear (e.g., MacCormack & Eyles, 2013). Altogether there is a potential black-box element to geomodelling that presents a liability and needs to be controlled.

In addressing these particular two concerns, designing a quality system for geomodelling could advantageously draw from manufacturing industry quality systems. These concern managing a production chain in order to systematically and efficiently fulfil product requirements. Importantly, such process-oriented systems implement quality control steps at relevant instances along the production chain in order to prevent propagation of errors throughout.

A third important difference between our maps and models is in the fact that the latter are more explicitly conceived to be applied. Hence, model quality should not be assessed on just geological grounds, but also on the extent to which they are fit-for-purpose. When it comes to connecting model specifications to model applications, geomodelling bears resemblance to engineering design. In contrast to manufacturing, where quality systems ultimately optimise replication, quality assurance for engineering concerns applying general quality principles to unique design efforts. It connects design with purpose, addressing use/operability, reliability, safety and maintainability, whether it be constructions, electronics or software. There are two important challenges for geomodelling from such perspective. First, all our models are used for more than one purpose, GeoTOP is explicitly conceived as a multipurpose model. Secondly, as discussed further below, use (and misuse) are intimately linked to scale.

Altogether, while the BRO is designed in accordance with software industry standards and practices, there are no readily applicable concepts for geomodelling. The extent to which our products and quality assurance processes are currently defined puts us, in common Capability Maturity Model terms, at the second and occasionally third out of five levels (i.e., repeatable to defined; Fig. 15; Bush & Dunaway, 2005). However, operating a key register requires at least third to fourth-level maturity, the most important element of which is having a dedicated quality system in place. Such system for geomodelling will need to be conceived and installed before 2015, at which date the BRO will become effective.

From best guess to ensemble prediction

Being explicit about model quality translates not only to compliance with quality standards, but also to providing uncertainty information. Mapping and modelling generally aim to provide or be based on the best possible representation of geological features, given the available data and expert knowledge. Such single result is generally used as the unquestioned reality in further studies or decision making. Fortunately, there is an increasing interest in information on uncertainty and the reliability of the information we deliver. In case of DGM and REGIS we provide probability envelopes

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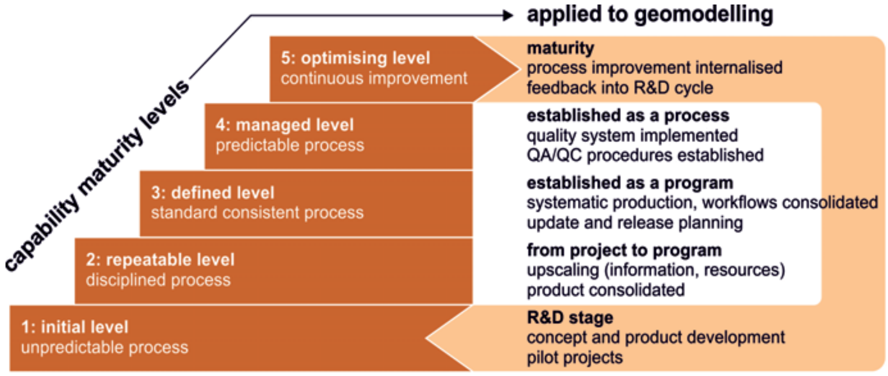

Fig. 15. CMM (capability maturity model, Bush & Dunaway, 2005) applied to geomodelling. The Geological Survey of the Netherlands is at the second to third level; a dedicated quality system is underway (see text for explanation).

around unit boundary surfaces. In case of GeoTOP, the end-product is the average of multiple model realisations that can also be delivered as an ensemble prediction.

For all models, we only provide uncertainty associated with the modelling process, which mainly depends on data density. Ideally one would also want to consider data quality, but the large heterogeneous datasets we use, especially for shallow geomodelling, preclude a case-by-case quality assessment. The aforementioned data selection procedures, aimed to reject bad data, as well as the future effects of standardisation for the BRO should help in this respect, but in lack of straightforward quantification of data reliability, a posteriori plausibility check of modelling results will always be crucial (e.g. Van der Meulen et al., 2007a).

It is obviously in our best interest that the uncertainty information we produce is actually used, instead of single realisations which can only be right or wrong. However, many users are not yet able (or prepared) to handle uncertainty. Appreciation rather than technical causes seem to be the problem, especially where non-technical users are concerned (see Tak et al., 2013, for a discussion).

Outlook and perspective

Introduction

In the recent past, the Dutch geological survey programme was driven by a combination of technological developments (technology push) and an evolving context (demand pull). The effects of both types of drivers are extrapolated in the below overview of our survey strategy in the years to come. The shorter-term consequences of the BRO system will not be repeated: a longer perspective is taken, with as main elements, in no particular order: 1) building with users; 2) from 3D to 4D modelling; 3) focus on the urban environment; 4) from parameters to resource and geohazard potential; 5) European capacity building; and 6) towards scalable (5D) subsurface information.

Building with users

Originally, the Survey mainly relied on its own geological and geophysical data for mapping purposes (Oele et al., 1983), but third-party data sets were acquired and used as well. The obvious next step is to also use third-party knowledge ('crowd sourcing'). The best example of this possibility is presented by REGIS II, a model which is quite often used for local assessments, stretching the possibilities of its regional scaling (as further discussed below). It is comparable to using a road map as a city plan, and criticism on the local predictive value of the model is often technically unjustified. In another perspective, however, such user feedback can potentially be used as a source of information that enables better, and possibly more detailed models.

The most difficult task when the Survey adopts this approach, will be to somehow evaluate the value (credibility, reliability) of user feedback. If it is backed by information that can be inserted into existing workflows (if a comment comes with a new borehole description, for example), this is relatively straightforward. If it is based on other data or information, for instance hydraulic head data from which inferences can be made on the continuity of aquitards, it will be more complicated, especially from the perspective of reproducibility. Common feedback originates from groundwater modellers who may, in the process of calibrating a flow model, come to the conclusion that REGIS II parameters are off, or the geometries are wrong. Initial research investments into incorporating such information have just been made, and are expected to deliver results by 2016.

But not only contributing users need to be engaged with the future Survey. As mentioned above, we expect to be serving a larger group of users who are, on average, less knowledgeable about the subsurface than our current expert user community. This demands adaptation of service and communication alongside improvements to our systems, methods and products.

From 3D to 4D modelling

Geological and human processes modify the subsurface to such an extent and at such a rate, that change can, and should be, represented in our subsurface models.

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For example, in the coastal plains and the western parts of the Rhine-Meuse Delta, compaction of clay and peat and/or peat oxidation result in **subsidence** at rates up to a cm per year. The ages of the boreholes used for modelling typically span several decades and their logs may include peat that has since disappeared, in quantities that are significant against the resolution of a model such as GeoTOP. This is problematic when modelling in 3D, but in a 4D perspective, the same boreholes combined with altimetry data are a record of a process that can be usefully represented. At the current vertical resolution, a 4D GeoTOP model should 'shrink' vertically by about a voxel per 50 years. Similarly, DGM and REGIS II need to be adjusted in the southeast, where coal mining lead to local subsidence up to 5 m, followed by uplift after the shafts became abandoned and filled with water. A similar representation in DGM-deep of subsidence caused by the production of gas or rock salt is not relevant for reasons of resolution (centimetres to decimetres of displacement in a model spanning several kilometres vertically), but deep models are used to predict reservoir compaction and its surface expression.

Human action has a substantial effect on the Dutch subsurface by any measure, especially at shallow depths. For example, between 60 and 70 million m^3 of sand, gravel and clay are extracted annually (Van der Meulen et al., 2007a-b). Filling sand, the largest constituent of this volume, is used as filling and foundation material, basically forming new portions of subsurface where it is laid down. Such volumes are geologically relevant (Van der Meulen et al., 2007c, 2009a): at country scale, man displaces sand at about twice the rate at which the Holocene was deposited. Just as for peat oxidation, this process causes borehole logs to become out of date and in a 4D GeoTOP perspective, it would have to be represented by 'relocating' some 13,000 voxels per year.

Albeit less concentrated geographically, **sediment dynamics** in offshore areas involves comparable volumes of sediment and morphologic change as human action onshore. The superficial geology of areas such as the Wadden Sea, which will soon have GeoTOP coverage, cannot adequately be captured with a static model.

Groundwater dynamics: we provide static hydraulic properties of Dutch aquifers, but a full appraisal of aquifer systems requires a dynamic characterisation of their water content and composition as well. We have hydraulic head and groundwater table time series as well as hydrogeochemical data, which can be interpolated into 4D models, not only for regional syntheses, but also to assess the quality and plausibility of the data in a spatiotemporal context. Proof of concept of a 4D information product as we envisage it has been delivered by Dabekaussen & Van Geer (2013), who built a tool to automatically generate hydraulic head maps for a given area, aquifer and date. Maps are obtained by interpolating the differences between hydraulic head data in DINO and a multiannual average provided by the groundwater flow model NHI (National Hydrological Model; Prinsen, 2013). Their tool will be made available online in the near future.

Focus on the urban environment

Human interaction with the shallow subsurface is arguably greatest beneath cities, where not only the landscape but also the subsurface has been transformed, and underground resources are exploited to their upmost. While cities are traditionally avoided by geological surveys, they are now rapidly evolving into a new focal area. In fact, the release of a smartphone app by the British Geological Survey revealed that their geological maps were most consulted in urban areas (Hughes, 2011). The Netherlands has a very high degree of urbanisation, which has been the result of the agglomeration of many small to medium-sized towns into sizable urban regions, most notably Randstad, a ring of cities including Amsterdam, Rotterdam, The Hague and Utrecht. While not being an administrative entity that is managed as such, it is often referred to as a single metropole with about 7 million inhabitants.

One of the main problems for geological surveys in built-up areas is presented by intense human activity in the shallow subsurface. Made ground is logged in our borehole descriptions quite consistently, and GeoTOP treats it as a lithological class. However, while its extent can be mapped, properties of the anthropogenic layer are unpredictably heterogeneous, not only because of the occurrence of non-natural materials such as granulated construction and demolition waste, but also due to constructions such as underground infrastructure and foundations. Deeper in the subsurface, undermining may cause instability: again a property of the subsurface which is unpredictable when modelling with geological data and concepts alone.

In contrast to the situation at other surveys, urban subsurface data are somewhat underrepresented in our databases. Cities were not surveyed in the days of traditional mapping, as they were simply to be marked as built up. Ensuing systematic modelling efforts for the shallow subsurface were mainly driven by management of groundwater resources and these are generally neither explored, nor exploited in cities. However, most ground investigations in fact take place in cities, so these areas are expected to rapidly catch up when the BRO is effectuated.

The obvious challenge in urban regions is to combine subsurface with above-surface information. This will facilitate a new view of urban planning, which is already evolving into a comprehensive 3D exercise (Tegtmeier et al., 2009). A better understanding of ground conditions will allow to better utilise the city's subsurface and its resources (e.g., groundwater, heat), manage the legacy of previous land use (e.g., anthropogenic deposits and contaminated sites), and facilitate new development. The BRO is designed to at least partly accommodate this by combining subsurface data with rights of use and infrastructure, but it obviously does not yet cover the full range of peculiarities in the urban subsurface. In the next phase of BRO

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development geo-environmental data will probably be added, which is particularly relevant and useful in the urban environment.

From parameterisation to earth resource and geohazard potential

The most important trend in geological surveying is towards better applicability and usability. We have now systemised our modelling efforts up to the prediction of basic properties such as lithology. This allows for the assessment of the potential for a number of designated forms of use of the subsurface, or that of certain geohazards. In the perspective of such applications, our current models are semi-products, and the next step is to start systemising the ensuing assessments and products as well. Examples of the possibilities include aggregates (e.g., www.delfstoffenonline.nl), groundwater, geothermal energy, hydrocarbon and rock salt resource potential, storage potential, subsidence susceptibility, ground source heating suitability and groundwater flooding risk. Except for the latter, we have experience with all such applications, but only in single projects with one-off results. The aim should be to make such information products in a systematic way, building services that are kept up-to-date, both methodologically as in terms of the underlying data, and have national coverage.

European capacity building

The international perspective of the Geological Survey of the Netherlands is primarily a European one, related to the ever-growing cooperation among European geological surveys, and to the increasing interest of the European Commission in geological information. At present there is no single European geological survey, so the Commission has to be served by 28 national organisations. This is facilitated by EuroGeoSurveys, a small organisation in Brussels established for European representation and networking purposes. EuroGeoSurveys has a total of 33 members, including 27 surveys of EU member states (i.e., all but one).

European geological surveys display a great diversity, related to the geology, Earth resources and geohazards of their home countries, and to their national mandate, staff, organisation and funding. Most importantly, when it comes to joint collaboration and services: European geological surveys have been operating alongside for many decades to well over a century, building legacies of data and information according to national specifications and concepts, which cannot easily be combined, let alone aggregated. So, while general trends for individual European surveys are basically similar to those discussed for the Netherlands (digitisation, a transition from mapping to modelling and an increasing focus on usability and applicability), harmonisation and interoperability present major challenges particular to European collaboration.

Harmonisation of spatial data, including earth-scientific data types, is underway under the aforementioned INSPIRE directive (Anonymous, 2007), and tested and implemented in a variety of individual European cooperation projects that cover basic geology (e.g., OneGeology-Europe; www.onegeology-europe.eu/) as well as Earth resources (groundwater, energy, minerals) and geohazards. The main problem of such projects lies in the fact that they are, by definition, finite. While a harmonisation in principle produces a lasting result, the European information portals that such projects typically deliver for demonstration purposes usually do not have full European coverage, and are mostly maintained for just a couple of years.

Irrespective of funding sustainability issues, collaboration among the European geological surveys should be pursued because it fulfils concrete information needs from important European policy domains (environment, enterprise and industry, trade and, now emerging, minerals). Other than for the harmonisation and interoperability of data and information, collaboration could advantageously be developed in the field of research and development. Research is future-oriented, which presents degrees of freedom that allow for easier collaboration than in already well-established, past-rooted national survey tasks and approaches. The main challenge here would be to take the fullest advantage of the European dimension. Building on the best what the European earth-science community as whole has to offer would mean progress with respect to the current, rather fragmented situation, where each survey primarily relies on its own or national resources.

Towards scalable (5D) subsurface information?

Geological information was traditionally presented on hardcopy maps at a certain fixed scale: information content and presentation were in the same medium. Changing the scale of such map, e.g. by stepwise resizing using a photocopy machine, would disturb consistency between information content and presentation, but the mere fact that this also makes a map less readable gave the user a sense of being in some sort of violation. Small-scale and large scale maps used to be truly different products in any aspect but most importantly in their level of detail, with more information content at larger scales and aggregation at smaller scales. As soon as maps became GIS-products, however, representation could be adapted without considering information content, and scale started to become ignored as a concept.

The approximate scales of DGM and REGIS II are 1 : 250,000 and 1 : 100,000, respectively, but for such layer models, scale is even less intuitive than for maps, and users tend to plot and use model components on any scale, with possible dangers of misinterpretation and misuse. GeoTOP is usually characterised by voxel resolution rather than by scale, but it more or less represents the same geological features as the 1 : 50,000

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geological maps. A voxel product makes users scale-conscious at least to some extent, because zooming in too far will eventually reveal individual pixels.

Van Oosterom & Stoter (2010) argue that scale is actually a higher-dimensional geometrical and topological primitive, and consider it the fifth dimension of geo-information products, after the obvious three spatial dimensions and time. Such view encourages improved handling of scale and level of detail, but also presents a possibility of consistent integration of our model products. In a five-dimensional view, for instance, 3D model geometries would represent the same entities at different positions along the scale axis. The challenge is then to construct representations in between, arriving at 5D and hence scalable geo-information

Conclusions

Geology is a cumulative science: geologists build on the work of their predecessors. This applies to earth sciences in general (Philip & Watson, 1987), and particularly to geological survey organisations. Successful geological surveying has come to rely significantly on the level of access to its expanding legacy of data and information. If this works well, investments in a geological survey cumulate rather than just recur, resulting in substantial value enhancement of its databases and services. At the Geological Survey of the Netherlands, such notion led to major investments in data, and in ways to use and reuse geological information and concepts in systematic geomodelling rather than delivering a mere geostatistical exercise.

We have discussed the practice of geological surveying in the Netherlands over the last two to three decades, and identified main trends and drivers. In summary, the major advances in this period were data digitisation, and replacing maps by electronically distributed 3D models, both enabled by ever-growing data handling and computational power. More important, however, is the trend of delivering evermore applicable, useful subsurface information, as envisaged in a roadmap drafted in the late 1990s and expressed in the current Survey's mission.

The BRO is driving most current developments at the Survey, changing the status of our data and information, the relationship with our user community, and demanding a rapid professionalisation. Looking forward, we intend to engage in building 4D information products, and to benefit from further involvement of our users in our work. Following energy and groundwater, the (built) environment is emerging as a new area of attention, which calls us to focus on hitherto ignored urban regions. The longer-term direction of geological surveying in the Netherlands is towards systematically assessing earth resource and geohazard potential, and handling scale in a more rigorous manner. Geology as such may seem to be perceived to fade into the background, but it will obviously remain a vital means to an end.

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