
# Research Evaluation

## Self-Assessment Report 2008-2014

**Geo-Cluster**
Department of Geoscience & Engineering
Department of Geoscience & Remote Sensing

TUDelft

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TU Delft

## Colophon



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# Introduction to the Geo-Cluster

# 1 Introduction

In the Netherlands, research in the earth sciences is performed at Utrecht University (UU), Delft University of Technology (TU Delft), VU University Amsterdam, Wageningen University, Twente University, and Groningen University, with the programme at Utrecht University being by far the largest. By and large, UU and TU Delft have a complementary perspective, where 'Utrecht' aims for the understanding and explanation of natural phenomena, while 'Delft' adds a strong 'observation/prediction', and 'influencing/control' emphasis to this mix. TU Delft's earth sciences portfolio was significantly strengthened in 2010, when it was decided to cluster the activities in the field of earth science, engineering and remote sensing, aiming for scientific focus and increasing the critical mass. All related disciplines were formally organised in the Faculty of Civil Engineering and Geosciences from January 1, 2013 onwards.

## 1.1 Units to be assessed

This self-assessment involves the Department of Geoscience & Engineering (GSE) and the Department of Geoscience & Remote Sensing (GRS), which together form the Geo-Cluster within the Faculty of Civil Engineering and Geosciences (CEG) of Delft University of Technology. The research units that are being presented in this evaluation are listed in Figure 1.

Department of Geoscience & Engineering (head: Prof. Jansen)

- **Geology**
  Unit leader: Prof. Bertotti
  Involved groups: Section of Applied Geology
- **Geophysics**
  Unit leader: Prof. Wapenaar
  Involved groups: Section of Applied Geophysics & Petrophysics
- **Geo-Engineering**
  Unit leader: Prof. Hicks
  Involved groups: Section of Geo-Engineering
- **Geo-Resources**
  Unit leader: Prof. Rossen
  Involved groups: Section of Petroleum Engineering and Section of Resource Engineering

Department of Geoscience & Remote Sensing (head: Prof. Hanssen)

- **Geodesy**
  Unit leader: Prof. Hanssen
  Involved groups: Mathematical Geodesy & Positioning, Physical & Space Geodesy, and Optical & Laser Remote Sensing
- **Atmosphere**
  Unit leader: Prof. Russchenberg
  Involved groups: Atmospheric Physics and Atmospheric Remote Sensing

**Figure 1** Research units that are being presented in this evaluation and their composition.

During the evaluation period, some changes took place within the two departments. In the Department of GSE, a section dealing with Resource Engineering was re-established (here included in the unit Geo-Resources). The Department of GRS was officially established in January 2013, with the aim to merge research groups studying our system Earth. Therefore, the Department of Remote Sensing (Faculty of Aerospace Engineering), the section Remote Sensing of the Environment (Faculty of Electrical Engineering, Mathematics and Computer Science), and the group working in the field of Clouds, Climate and Air Quality within the Department Multi-Scale Physics (Faculty of Applied Sciences) formed a new department within the Faculty of Civil Engineering and Geosciences.

The review period comprises the years 2008-2014 for GSE and 2007-2014 for GRS. This is due to the fact that the last evaluation of the Geodesy unit of GRS took place until 2006 and the unit prefers a concatenated record. Parts of the unit Atmosphere were evaluated more recently.

## 1.2 TU Delft and its Faculty of Civil Engineering and Geosciences

### TU Delft

TU Delft was founded in 1842 as the *Royal Academy for the education of civilian engineers* and has grown into a university with eight faculties, 20,0000 students and 3,000 scientific staff members. TU Delft's mission is "to make a significant contribution towards a sustainable society for the twenty-first century by conducting groundbreaking scientific and technological research which is acknowledged as world-class, by training scientists and engineers with a genuine commitment to society and by helping to translate knowledge into technological innovations and activity with both economic and social value".

**Faculty of Civil Engineering and Geosciences**

Next to the two geosciences' departments, the Faculty consists of four departments in the civil engineering domain, namely Structural Engineering, Hydraulic Engineering, Transport & Planning, and Water Management. These departments are evaluated within their own discipline.

The mission of the Faculty is to excel in research into delta technology, urban water, civil infrastructure, transport and applied geosciences. The faculty provides students and staff from the Netherlands and abroad with an inspirational learning and working environment by means of state-of-the-art research and support facilities and research-driven education programmes. The Faculty works with its alliance partners to achieve innovative solutions for society.

The Faculty is led by the dean (Prof. Geerken), who has overall responsibility for research, education and management of the Faculty. The dean, the heads of the six departments, and the faculty director of education together form the management team (MT) of the Faculty, which has a leading role in all decision-making processes at strategic and policy levels, such as discussions on major research directions and major developments in educational, research and valorisation processes, including budgetary issues. The Faculty Secretary, and its HR and Finance Managers participate in the MT meetings.

**HR strategy of TU Delft and the Faculty CEG**

The TU Delft HR policy is aimed at "organisational, personal and professional development, talent management and leadership". TU Delft sees four factors as being critical to success: excellence, personal leadership, coaching leadership and a flexible, learning organisation (see TU Delft HR Strategy "Freedom to excel").

Annual staff appraisals are held about the results achieved in the previous year, the targets for the upcoming period and wishes for development. The transition from tenure-track to tenure and promotion from assistant to associate professor is based on recommendations made by the Faculty's Permanent Career Committee (VLC). The members of this VLC include professors from all departments. This enables to properly assess the academic level of the candidates and places it in a broader context. The term scientific staff comprises all professor-levels, including assistant professors in tenure-track positions (also in the fte-tables).

## 1.3 Application-inspired, fundamental research

To explain the nature of research carried out at TU Delft, we use a classification in two dimensions as shown in Figure 2. The first dimension concerns the motivation of the research activities which may range from curiosity-driven to application-inspired, as indicated on the horizontal axis. The second dimension concerns the nature of the research activities which may range from fundamental to pragmatic as indicated on the vertical axis.

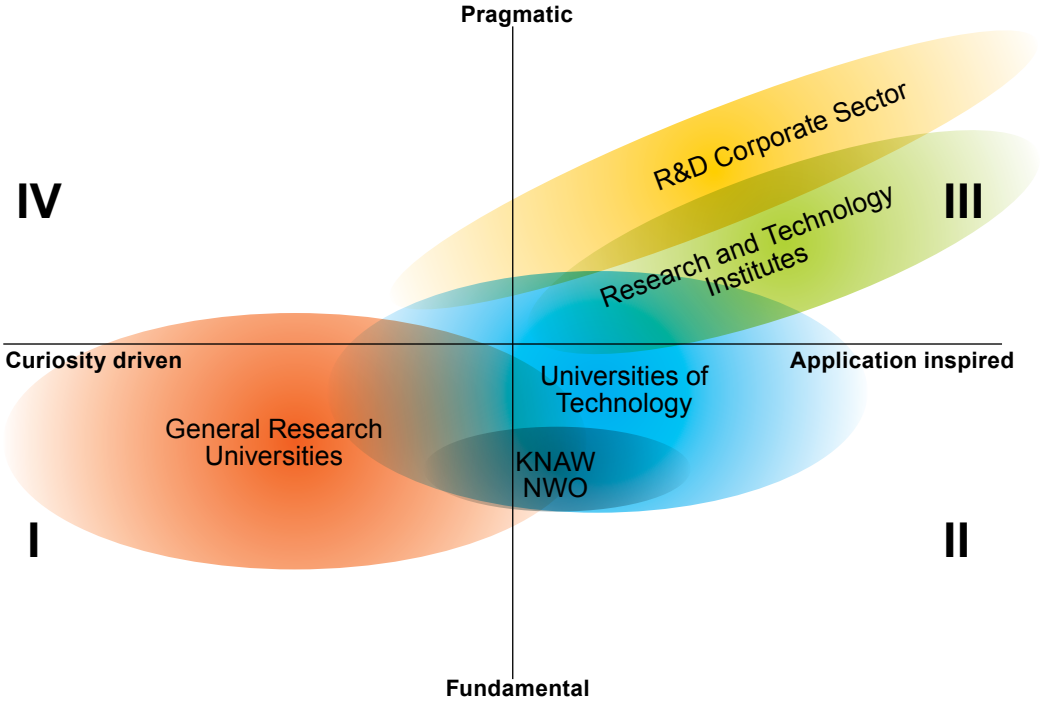



**Figure 2** Two-dimensional field describing the nature of research (from the TU Delft Roadmap 2020)

Both general research universities and universities of technology are primarily concerned with fundamental research. The difference between these two types of university lies in the motivation for their research, namely curiosity-driven or application-inspired. Universities of technology share the application-inspired motivation with large research and technology institutes (GTIs; like TNO, Deltares or KNMI) or R&D departments of the corporate sector. Their research differs, however, in the nature of the respective research activities. Whereas universities of technology carry out (application-inspired) fundamental research, technological institutes and industry mainly are engaged in more pragmatic research. The common motivation, inspired by application, forms the basis for our cooperation with industry and the difference in the nature of research is reflected in the structure of many of our collaborative research contracts: Fundamental research questions are addressed in PhD and post-doc research projects, whereas the more pragmatic research questions and the implementation aspects are addressed by research staff from our partners at GTIs or the industry.

## 1.4 Funding schemes

In the Netherlands, research funding schemes are divided into three pillars. Note that in spoken Dutch, these types of funding are often referred to as ‘first’, ‘second’ and ‘third’ ‘money stream’.

1. **Direct funding**: Internal funding received by the faculties/departments from the Executive Board of the university, originating from the Dutch Government.
2. N**ational governmental funding**: External funding received in competition, from the Netherlands Organisation for Scientific Research (NWO) and related organisations (STW for engineering, FOM for physics). In the Standard Evaluation Protocol (SEP), this category is called Research grants; we use this slightly different term to indicate the similarity with EU funds in terms of funding level and governmental source.
3. I**ndustrial/EU funding**: External funding from industry, mostly received in competition; if partly matched by the government, the governmental funds are included here as well; EU projects, including personal ERC Grants and Marie Curie Fellowships. In the SEP, this category is called Contract research, a term which - to our opinion - might be misinterpreted as commercial orders; therefore we use this slightly different term.

Due to reduced **direct funding**, post-docs' and PhD students' salaries are not paid by university funds anymore and Dutch research more and more depends on national governmental funding and industrial/ EU funding. **National governmental funds** are valued because they contribute to the international academic reputation. This is especially true for personal research grants, e.g. the NWO Innovational Research Incentives Scheme (often referred to with its three levels, Veni-Vidi-Vici). Unfortunately, these grants do not cover the integral costs. **EU funding** normally covers more, but still not fully the integral costs. Therefore, there is an overall need for matching of these funds. Consequently, **industrial funding**, which mostly covers all integral costs, is increasingly important for a healthy budget. Within this domain, we aim to concentrate on projects that are scientifically attractive and offer potential for publication in refereed journals. A specific industrial funding scheme that is of increasing importance in the Dutch research landscape, is formed by the policy of Top Sectors implemented by the Dutch Ministry of Economic Affairs in 2011. Nine excelling branches of the Dutch economy have been chosen to boost innovation through joint research programmes between universities and industry, financed by both the industry and the government.

Due to the relevant differences in the funding, we decided to present the category of industrial/EU funding in three separate subcategories in the chapters of funding strategy, namely (a) European funds (that are actually more like the National governmental funds), (b) Public-private funds (e.g., the Top Sectors; the public funds included in them actually don't show up in the financial sheets), and (c) pure industry funds.

## 1.5 Strategic cooperation in research

Scientific cooperation takes place between the research programmes of the Faculty (intra- and interdepartmental), as well as between the Faculty's research programmes and the programmes of other faculties, other universities (national and international), GTIs and the industry. The decision on whether or not to collaborate in a joint research programme is mainly taken at department level.

Strategic cooperation with other parties is gaining more importance. The GRS and GSE strategic cooperation include (see also Tab.1):

- BioGeoCivil programme on bio-based geo & civil engineering
- BE Basic programme on industrial bio-based products
- CATO programme on $CO_2$ storage
- CESAR Observatory in Cabauw
- Delft Aardwarmte Project (DAP) on geothermal energy
- Delft research-based Initiative on Energy (DEI)
- Delphi consortium on exploration geophysics
- Intergovernmental Panel on Climate Change (IPCC)
- ISAPP and Recovery Factory (RF) programmes on smart fields
- ISES programme on integrated solid earth sciences
- LOFAR programme on seismic monitoring
- TKI Gas consortium on shale gas (as part of top sector Energy)
- Topsector Water consortium on Delta and water technology
- TU Delft Climate Institute
- TU Delft Space Institute

The formation of the Geo-Cluster, in 2013, offers opportunities for cooperation between the two geo-departments of the Faculty. Until now, already a few projects where we bundle our expertise, have been started:

- Dike monitoring (Geo-Engineering and Geodesy)
- Subsidence (Geo-Engineering and Geodesy)
- Deltas (Geology and Geodesy)
- Shallow sub-surface processes, volcano monitoring, and seismic imaging (Geodesy, Geophysics and Geo-Engineering)

- Infrasonic monitoring of (sources in) the atmosphere (Geophysics, Atmosphere and Geodesy)
- Exploring combinations of seismic and satellite radar interferometry (Geodesy, Geophysics)

For the future, these individual projects are intended to grow into larger cooperation programmes, e.g. by joint EU proposals. Also cooperation with the Water management department is ongoing and being strengthened.

**Table 1** Cooperation in which the six units participate.

| | Geology | Geophysics | Geodesy | Geo-Engineering | Geo-Resources | Atmosphere |
|---|---|---|---|---|---|---|
| BioGeoCivil | | | | x | | |
| BE Basic | | | x | | | |
| CATO | x | x | x | | x | |
| CESAR | | | x | | | x |
| DAP | x | x | | x | x | |
| DEI | | | | | x | |
| Delphi | x | x | x | | x | |
| IPCC | | | x | | | x |
| ISAPP/RF | x | x | x | | x | |
| ISES | x | x | x | | | |
| LOFAR | | x | | | | |
| TKI Gas | x | x | | | x | |
| Topsector Water | | | | x | | |
| TU Climate | | | x | | | x |
| TU Space | | | x | | | x |

# 2 Performance indicators

From the various performance indicators, we gathered the ones that are in line with our mission and the profile of our research. In general, all units report on these indicators in their self-assessment. Some units may have additional indicators or do not report on all indicators mentioned. Several of the indicators are quantitative data that are given in figures in the Unit's chapters and tables in the Appendix (e.g., number of publications, invited talks, editorships, H-index, and funding).

Our choice for indicators of research quality (Tab. 2) is motivated as follows:

- Journals papers are most valued as a means to make our findings known to our academic peers. The number of **peer-reviewed articles** is a clear indicator for the quality of our research and the productivity of our tenured and non-tenured staff. **Citation records** of articles and **H-indices** of individual staff members give additional evidence for the recognition of our work.
- We find it likewise important to present our research at conferences, and hence publish **full-length (>3 p.) conference papers**. At conferences, intermediate results can be discussed easily with international peers and participation in conferences is a perfect way to introduce our junior scientists to their supervisor's network, to gain presentation skills and to get acquainted with the publication procedure (in case of peer-reviewed proceedings, which many of them are). A well-recognised effect of presentations at conferences of international associations like SPE, SEG, IEE, EAGE, AAPG, IAG is the fact that also R&D staff of GTIs and industry attend these meetings, which enables us to disseminate our findings into both universities, GTIs and industry. Depending

on the conference, a paper in a conference proceeding can be an indicator of academic quality and/or a product for the wider (R&D) community. In our publication list, no distinction was made because in most cases both aspects are relevant.

- PhD students, and post-docs alike, are performing a large part of our research activities. Therefore, the number of **dissertations** is also indicative for our productivity. Graduated PhD's who leave TU Delft will contribute in making our expertise known to their new work environment, be it in academia or outside. Although we strongly stimulate that theses are written as a compilation of papers, dissertations are still valuable to us as a publication, because they offer the possibility to include more details, e.g. in case of experimental or numerical work. These details can often not be treated in journal papers but are certainly crucial for people working on the same subject. Our PhD theses are published open access in the Repository of TU Delft.
- The high quality of our research is also proven by **Awards, Prizes and personal grants**, both for senior and junior staff. Some of our senior researchers are extremely well-known experts in their field and are, therefore, also engaged in **training activities** for peers and junior staff. Besides giving courses in our own Research School (CTG), they are invited to lecture at continuing education programmes, international summer schools or organise summer schools themselves. We do appreciate this engagement very much. The discussions with junior staff from all over the world inspire us and every now and then it results in further cooperation.
- Taking up **editorships** is an essential form of community service in an academic environment and adds to the reputation of the individual editor and the group.
- Substantial income from both **national governmental/EU and industrial funding** indicates our academic standing. In addition, the mix of both sources ensures a healthy budget (see Chapter 1.4).

Indicators for **Relevance to Society** are also given in Table 2. The reasoning behind the choice is explicitly explained in the various unit chapters and therefore needs no further explanation here. The overall notion of all the activities towards society and industry is that we are convinced that science at a university of technology is not meant to stay only within academia but should reach R&D staff in GTIs and industry as well as the general public.

| Research Quality | | Relevance to Society | |
|---|---|---|---|
| **Research products for academic peers** | | **Research products for public and private entities** | |
| Number of Articles in peer-reviewed journals | U 2, A Ux.3 | Contributions to public debate, incl. public lectures and media appearance | U 4, A Ux.3 |
| Number of full-length (>3 p.) Conference papers (depending on conference) | U 2, A Ux.3 | Number of full-length (>3 p.) Conference papers (depending on conference) | U 2, A Ux.3 |
| Number of Dissertations | U 2, A Ux.3 | | |
| **Use of research products by academic peers** | | **Use of research products by public and private entities** | |
| Hirsch indices | U 3, A Ux.4 | Projects/Consortia and strategic cooperation with societal groups/companies | U 4 |
| Training for peers (courses, summer schools etc.) | U 3, A Ux.4 | Staff with part-time position/secondment in company or societal group | U 2, U 4 |
| Citations of individual articles | U 3 | | |
| **Marks of recognition from academic peers** | | **Marks of recognition for public and private entities** | |
| Scientific Awards / Scholarly Prizes / Prestigious personal grants (e.g., Veni-Vidi-Vici) | U 3, A Ux.4 | (Co-)financing of chairs/research appointments | U 2, U 4 |
| Academic reputation of staff (keynote/invited lectures, memberships in programme committees) | U 3, A Ux.4 | Representatives of companies or (semi) governmental institutions in user committees | U 4 |
| Chief/full/associate editorships of scientific journal/book/conf. proc. | U 2, A Ux.3 | Industrial funding | U 2, U 4 A Ux.2 |
| National governmental/EU funding and parts of industrial funding | U 2, A Ux.2 | | |

# 3 Laboratory Infrastructure

The two departments use a multitude of lab facilities. The GSE Laboratory offers many facilities housed within the department, whereas GRS mainly uses external experimental facilities. Both departments have laboratory support for both research and education purposes.
Financially, the laboratories are part of the respective departments. If there is an added value for the Department's research, it is allowed for technicians and staff to carry out small commercial laboratory R&D projects. For example, the CT-scanners are regularly used for third parties like other faculties, musea, or companies, and gravity measurements are done for the Dutch Metrology Institute (VSL).

## 3.1 GSE Laboratory Infrastructure

The GSE laboratory is outfitted with equipment and experimental set-ups to perform research under simulated in-situ conditions to study the physical, (bio)chemical, and (thermo-) mechanical conditions in the shallow and deep sub-surface. With these often highly specialised facilities, it is one of the leading geosciences laboratories in Europe engaged in experimental geomechanics, geophysics / petrophysics, and reservoir geology. In addition, the lab also supports (the development of) facilities and set-ups to be used during field work.

Laboratory facilities and staff are managed at a departmental level and the researchers are responsible for the research programme carried out in the lab. All lab activities are monitored and strategic decisions are taken by its Management Team, that is composed by two technicians and the director, Dr Wolf.

Most of the laboratory activities are organised within expertise groups that are built around specific infrastructures:

- Acoustics and Petrophysical methods
- Hydraulics, Pneumatics and Applied Chemistry
- Optics, (X-ray) imaging and Image Quantification
- Data-acquisition and IT

The GSE lab technicians are highly skilled and trained to design, develop, operate, maintain and improve the instrumentation in different fields of expertise. New equipment and experimental set-ups are developed in close cooperation between technicians, the responsible researchers and project leaders. Thanks to their experience, the technicians are able to run the laboratory in a rather autonomous way, in self-steering teams of the expertise groups and project teams, which are based on activities and strongly interact with each other. By thus organising the technician time more efficiently, we were able to compensate for the loss in work force (from 15 fte in 2008 to 10.5 fte in 2014). Recently, two young technicians were hired. Through strong interaction of technicians within and beyond the expertise groups, we continuously improve our equipment and the quality of experiments.

Next to the laboratory, GSE owns the following facilities:

- computer cluster for, e.g., advanced simulations,
- a plot with shed and field-infrastructure for (preparation of) field work,
- acquisition infrastructure for seismic monitoring at the Lofar site (in cooperation with TNO and KNMI),
- a professional drone equipped with ArcGIS.

## 3.2 GRS Laboratory Infrastructure

The main laboratory infrastructure of GRS can be divided in several facilities:

- Observatories
- Measurement equipment
- Computer equipment with data storage facilities

GRS manages several **observatories**, among them the Fundamental station Westerbork. There we have a specifically designed bunker for gravity observations. Other designed observatories are the GNSS lab in Delft (on top of the VSL building), our part of the Dutch Permanent GNSS Array (DPGA) observatories, and our share in the Cabauw Experimental Site for Atmospheric Research (CESAR). The world-class CESAR Observatory in Cabauw (PI Prof. Russchenberg) is widely recognised as one of the most advanced sites for atmospheric studies. TU Delft owns and operates the high-resolution atmospheric radar systems IDRA and TARA. CESAR consists of a large set of instruments to study the atmosphere and its interaction with the land surface. It also serves as a permanent bridge between the participating universities (TU Delft, WUR, TU/e) and research institutes (KNMI, RIVM, TNO, ESA, ECN). Many of the available atmospheric remote sensing instruments located at Cabauw offer unique possibilities for sensor synergy.

**Measurement equipment** is either permanently located at an observatory site for continuous monitoring (e.g., at WAGO), or used for long-lasting campaigns (several months or years), or shorter campaigns (days to weeks). The laboratory provides state-of-the-art GPS equipment, theodolites, levelling, and laser distance measurement devices. Terrestrial acquisition is also carried out using digital cameras and a Laser Scanner. The equipment includes GNSS receivers, several relative gravimeters, an FG-5 absolute gravimeter, a 3D laser scanner, a rainfall radar and various other surveying attributes.

The GRS laboratory possesses some powerful **computer equipment with data storage facilities**. We also use the Sara super computing facilities and Oak Ridge Leadership Computing Facility (OLCF). GRS has access to a local cluster, mainly used for traditional HPC applications and a low-latency grid-network for special GPU and visualisation applications.

# 4 PhD programme

## 4.1 TU Delft Graduate School

In the Netherlands, PhD students are usually employed by the university for a period of four years. In line with national developments, a Graduate School (GS) was established at TU Delft; it officially started in January 2012. All PhD students are enrolled in the GS, whether they are employees or come to Delft with a fellowship.

The GS has been established in order to offer excellent **skills training, supervision and mentoring** to the PhD candidates, in order to ensure high quality dissertations. The overall aim is to provide valuable skills for the future career, either in academia or elsewhere. The GS supports a structured and transparent PhD process, facilitated by a monitoring system that keeps track of the students' progress. A personal 'Educational and Development Plan' is made with the PhD student at the start of the project and a Go/NoGo assessment is held after one year. Thereafter, progress is monitored during yearly appraisal meetings.

The Doctoral Regulations of TU Delft require that all PhD candidates complete a tailored **Doctoral Education programme** before the PhD defence. This programme consists of three pillars:

A. Discipline-related skills
B. General scientific research skills
C. Personal development (transferable skills)

Whereas the GS offers training courses in pillar C, the Faculty Graduate School is responsible for pillars A and B. Discipline-related courses are often organised by research schools (see below).
For all newly starting PhD students, the **PhD Start Up programme** is obligatory. This three-day event secures that the new arrivals get acquainted with TU Delft and their new situation as PhD student. An introduction to Dutch culture is included which is important for many foreign students who are, for example, not used to open and frank discussions with supervisors.

For the **supervision**, a Code of Good Practice has been developed for both supervisors and doctoral candidates. The Code is a practical guideline which helps to optimise the (sometimes delicate) relationship between supervisor and candidate. It is discussed with the PhD candidates during the PhD Start Up and with the supervisors during small-scale workshops with the Rector.

**Mentoring** is organised by the Faculty GS, in first instance in groups (quarterly cohorts), and personal meetings are arranged on request of the PhD candidates. In addition to the GS activities, the HR department has developed guidelines to support a successful **recruitment** process. The improved recruitment procedure and the monitoring shall help reduce dropout rates and realise timely finishing of the PhD project.

## 4.2 Departmental recruitment strategy

It is the Departments' policy to have a good mix of PhD students educated in our own MSc programmes and students from other universities. Recruitment is, thus, done by advertising internationally, using the staff members' network, and by giving attention to the students graduating from the TU Delft MSc programmes, like Applied Earth Sciences and Civil Engineering. About two third of our PhD students are internationals. Graduation projects of our MSc students are often carried out as part of a research project. Thus, we actively involve our MSc students in research, which gives them the opportunity to gauge their affinity for a future career in research.

## 4.3 Doctoral Education and publication policy

The research school Centre for Technical Geoscience (CTG) is coordinated by the Department of Geosciences & Engineering and meant for PhD students of the two geo-departments of our Faculty and the Hydrology department of Utrecht University. CTG offers a large variety of courses in the field of geoscience, focused on the specific topics that are relevant for TU Delft, at introductory and advanced level. The courses are given by own staff, a few hired lecturers, and occasionally by visiting professors. Courses usually comprise about 32 hours of lectures/assignments and the average number of participants is about 10 to 20 PhD students. Several of our PhD students related to the Smart Fields programme are also a member of the research school Dutch Institute for Systems and Control.

General scientific research skills are obtained by learning-on-the-job. All PhD students are encouraged to present their research findings at international meetings. They are introduced to the networks of senior staff and start building their international position and their own network, both in academia and industry. To further prepare them for their future careers, they are involved in teaching activities and supervising BSc and MSc students during their graduation phase.

In order to train the PhD students in writing scientific papers and to increase the number of results published in the international arena, we encourage PhD students to publish in international peer-reviewed journal papers. We generally expect two to four publications in international peer-reviewed journals during a PhD project. To further stimulate publication of scientific papers, a Best PhD paper Award is given to two PhD students who wrote the best journal papers. This prize is awarded yearly during the Research Day, along with the Best MSc thesis Award and the Best Poster Award. Thanks to full sponsorship by Shell since 2010, the total amount of money rewarded is 5500 €. Since 2011, the Research Day, a tradition of the Department of Geoscience & Engineering, is held together by both geo-departments.

In addition, many MSc students write their thesis in the form of scientific papers (with supplementary material in appendices, as required), which frequently leads to additional conference or journal publications.

## 4.4 Graduation rates

The average graduation rates for both departments are largely comparable with TU Delft and Dutch averages (Fig. 3). Finishing within four years is very rare, partly because of the obligatory period of at least 11 weeks between the final draft of the thesis and the actual defence. As the Graduate School has been established in 2012, we expect to see first results of its effect on the success rate by 2016.

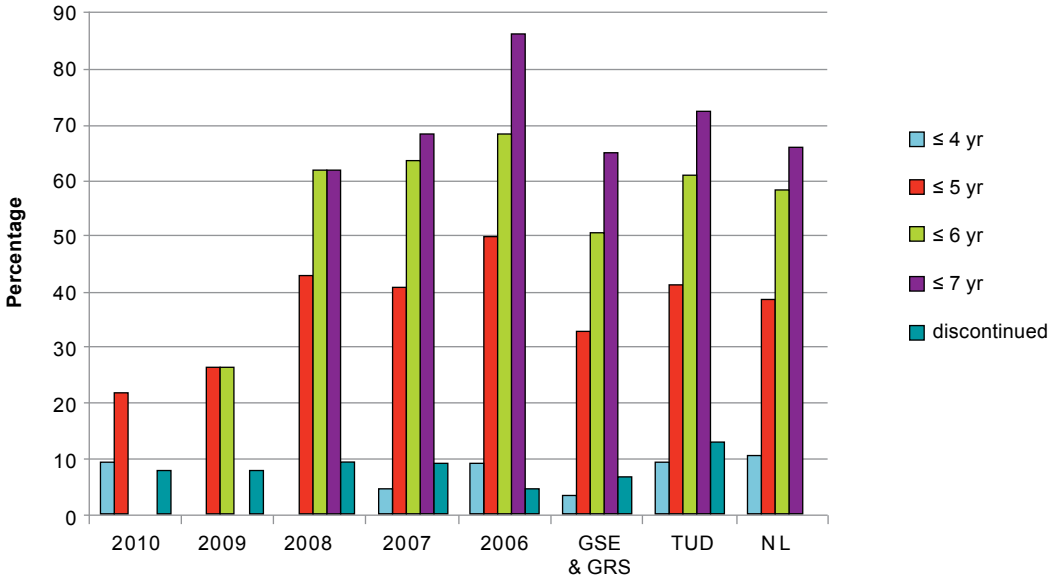



**Figure 3** Cohort study of graduation rates of PhD students of the Departments GSE and GRS for the years 2006-2010 and comparison with GSE&GRS average over all cohorts, TU Delft and Dutch averages (NL numbers do not report discontinued). Percentages of graduation rates are cumulative within one cohort. Numbers and additional information about percentages of female PhD students are available in the Appendix. Note that in this calculation only full-time PhD students are taken into account (≥0.8 fte), because only those are expected to finish their thesis in 4 to 5 years. Consequently, the population is smaller than in our fte-lists.

## 4.5 Guidance to the labour market and career destinations

Throughout their study, PhD candidates are introduced to the networks of senior staff and start building their international position and their own network, both in academia and industry. To further prepare them for their future careers, they are involved in teaching activities and supervising MSc students during their graduation phase, which trains them in skills that are not only valuable in the academic environment. In addition, the GS provides courses on general research and transferable skills and it is mandatory to take one career development course. An increasing number of PhD students becomes active in the Student Association MV and in the Student Society Snellius and student chapters of the SPE, SEG, and AAPG, through which they participate in company visits, recruitment days, etc.

All graduated PhD students find jobs in industry, research institutes, and universities. About 50 to 70% of the graduates leave academia to work with (multinational) companies, sometimes after a short post-doc period. PhD graduates are often heading for an international career and examples of employers are Shell, Fugro, Statoil, NAM, Total, Schlumberger, BP, Booking.com, and TomTom. The remaining 30 to 50% has its (first) employer in academia or (semi)governmental institutions (Geological Surveys, Deltares). We are not aware of any medium term unemployment, on the contrary, usually, our graduates have several offers before graduation.

# 5 Research Integrity

## 5.1 Integrity policy of TU Delft

Scientists can be faced with dilemmas regarding integrity on a number of topics, e.g., joint research with commercial partners, ancillary activities, fraud, and plagiarism. Research integrity and ethics are therefore important topics of discussion at TU Delft. TU Delft's 'Code of Ethics' formulates the aspirations, responsibilities and rights that ought to inspire and guide all those working and studying at TU Delft. The 'Code of Ethics' is a living document (published in October 2012) and discussions on this topic are held frequently, e.g., at faculty meetings hosted by the Rector Magnificus, dilemma sessions and meetings/courses for new employees and (PhD) students. Since March 2013, all letters of appointment refer to the 'Code of Ethics'. We strive to be an open academic community where employees, students, and guests communicate with each other openly.

TU Delft has an infrastructure to support employees and students with regard to integrity and ethics that is laid down in the 'Roadmap for Matters of Integrity' (Fig. 4). Rules and regulations are provided on different topics such as ancillary activities, reimbursements and academic integrity. These topics are also covered by a formal university committee and confidential advisors at the faculty level, to which employees and students can apply for matters on research integrity, administrative integrity, conflicts of interest, and undesirable behaviour.

One very hands-on result of the ethics policy is that all PhD theses are standard checked for plagiarism by the TU Delft Library. It is also written down in the Doctoral Regulations that the chairperson of the PhD defence ceremony "will explicitly draw the attention of the Doctor to the scientific integrity associated with obtaining a doctorate".


**Figure 4** Roadmap for Matters of Integrity (click to download the detailed map).

## 5.2 Integrity at the Geo-Cluster

The research groups of the Geo-Cluster adhere to the rules set by the university. Senior researchers train and supervise their junior staff, including PhD students, mostly individually and case-based. Discussions mostly take place while writing papers, e.g. on choosing examples from larger data sets or the way of presenting data. Incidentally, when a question is more of a general nature, it is also discussed in small working groups. PhD students can also discuss issues of integrity with their mentor. We strive to bring potential dilemmas of integrity across as a natural part of doing science, and not just as a matter of obeying the rules.

We have posted a link to TU Delft's Ethics policy on our website and new staff members are made aware of the Ethics policy during their introduction meeting.

## 5.3 Data management within the Geo-Cluster

Accessible and durable storage of data, for future consultation by TU staff and external parties, is a major issue of research integrity within the Geo-Cluster. Data that are essential to prove the integrity and ownership of our research results should be retained in a durable and appropriately referenced form for at least 5 years from the last publication. The procedure has been developed in late 2014/early 2015 by a small working group and brought into a pilot stage in 2015.

The procedure concerns various data types, i.e. measured, collected and/or numerical computed data, as well as source code. Its implementation is carried out in close cooperation with the TU Delft Library, which takes part in the 3TU Datacentre. Whenever possible, the data are uploaded in the Repository of the 3TU Datacentre. This specialised organisation ensures

- long-term (15 years) accessibility and data maintenance despite changing software and technologies over time,
- full data protection, e.g. against corruption,
- restoration of data after loss or damage by accident, breach of security, or natural disaster.

Items that are carefully looked at prior to uploading the data are: the file format (some file formats are preferred and will automatically be upgraded when new releases are available) and the description of the meta data (e.g., ownership, persons involved, associated publications, methodology, software, programming language/platform). As regular data upload is limited to 4 gigabyte, tailor made solutions are found for larger or complex data sets.

In general, data stored at the 3TU Datacentre are open access, but (temporary) restrictions are possible (e.g., in case of running patent applications or data sets of which TU Delft is not the owner). In addition to these practical aspects, the TU Delft Library supports us by giving courses on working with and storage of (large) data sets and on the up-front integration of this item in H2020 proposals.
With the set-up and implementation of our data management procedure in cooperation with the TU Delft Library, we are leading at TU Delft (see the show cases of Ngan-Tillard and Russchenberg).

# 6 Benchmarking

## 6.1 Benchmarking of GSE with Imperial College

We decided to benchmark ourselves against Imperial College London for three main reasons: (a) Imperial has a comparable set of disciplines working together in one faculty, with the majority of disciplines in one department, (b) Imperial has a common strategy of working at the boundary of geosciences and engineering, and (c) Imperial is a world class university ranking consistently higher than TU Delft. The Faculty of Engineering at Imperial College contains the Department of Earth Sciences and Engineering (ESE) which fulfils all criteria but lacks the subject of geo-engineering. Therefore, we added the Department of Civil and Environmental Engineering (CE), from the same faculty, that includes geotechnics.

### Department and Faculty organisation

The departments at Imperial have no sections, but have a few research lines and dynamic research groups that evolve over time, allowing for flexibility to adapt to upcoming themes. In contrary, GSE has discipline-based sections, each with its own MSc track. This system has historically grown from the fact that the sections are oriented towards different industrial sectors. In recent years, more and more interdisciplinary research has been carried out, without being hampered by the section system.
At Imperial, being head of a department is a full time position. In contrary, TU Delft has chosen for professional managers on dean's level but to keep the leading of a department to active scientists, who take the job on a rotating basis and in part-time (2-3 days a week, 4 year term).

ESE has a Strategy Committee with external advisers and a Research Committee that, among others, assesses proposals for scholarships and maintains the ties with the national Research Council. The Faculty Research Committee, for example, identifies staff to apply for ERC grants, holds mock interviews and makes a pre-selection of proposals to be submitted. At TU Delft, these functions are covered on various levels, the section, the department, the faculty, and the TU-Valorisation Centre. In line with the different organisational structures, the finances are dealt with at a different level. The heads of department at Imperial fully control the scientific as well as the financial affairs of their departments, whereas at GSE, the power is shared between the faculty, the department and the sections.

### HR strategy

Imperial's HR policy is targeted towards the "brightest minds", therefore, the individual capacity of the prospective candidate is set above the specific research interest (just the general subject needs to fit). The way to secure a permanent position in the UK is rather similar to the NL-system: Important criteria are the publication record, as well as the proven ability to acquire research grants. Imperial offers a start-up package with a PhD student and 10 kGBP, whereas at GSE, the start-up consists only of the overhead costs for hiring one PhD student who comes with their own fellowship.

### Publication policy

At Imperial, the publication policy is very much tuned to the UK-Research Evaluation protocol that assesses 4 top papers per staff member per period of 5 years. In a less stringent way, TU Delft also heads towards an increased emphasis on publication quality over quantity.

### PhD programme

In the UK, a PhD study is mostly started after a 4-year first degree programme and takes in principle 3 years. At Imperial, a PhD is finished within 3+1 years in almost all cases, whereas at GSE only 42% finish their PhD in 4+1 years. The higher success rate in the UK is probably mostly due to a severe selection and supervision regime and the fact that not finishing in 4 years is considered a failure (also of the supervisor). Like Imperial, we consider a stricter selection and a firm regime in supervision and monitoring as crucial to achieve higher success rates. In the UK system, PhD students go to (international) conferences typically only once during the PhD trajectory and they do not necessarily publish journal articles. Also, PhD students are not required to teach; they may just give occasionally a lecture within a series. In contrary, in the Dutch environment, the experience of presentations to an international audience, writing papers, and teaching is seen as a crucial part of the training for the future scientific career.

### Funding

Both in the UK and the Netherlands, the Research Council grants do not cover all costs and the deficit is compensated by industry funding. The ratio of governmental funding over sponsored research is about equal for all (ESE, CE, GSE) departments in 2012. It was much higher for Imperial's ESE and CE in the preceding years, though, which is due to increasing financial support from multinational companies. External funding per academic staff member is increasing at ESE over the last years, too, whereas it is rather constant for CE and GSE. ESE reports income per staff of 1.5 times as high as GSE, the latter being 1.5 times as high as CE. At Imperial, project overheads go to the department, but researchers get an individual budget of up to 10 kGBP per year. At TU Delft, the financial surplus of our projects is transferred to the section/department.

### Laboratory

Imperial's technicians are involved in developing new set-ups and training of (PhD) students but they don't do experiments themselves, which is sometimes the case at GSE. Although the labs are run on a PI-level, Imperial's technicians are paid by the department, with the understanding that part of their salary is raised via grant proposals. New set-ups are only built for research with a long-term perspective, as short-term "exploratory research" is only internally funded and therefore has a lower budget. It is seen as a policy of efficiency, to only spend higher amounts of money when you are almost sure that it will deliver results. GSE does not prohibit set-up development for single projects because PI's generate funds for this (including technician time) and a new apparatus might be needed even to test a hypothesis.

### Societal relevance

At Imperial, the research is very much application-driven and transfer of academic knowledge to businesses is largely done via “programme research”, i.e. large and long-term industry-sponsored consortia and centres, comparable with GSE programmes like ISAPP, Recovery Factory and CATO. In addition, Imperial sees consultancy as building a relationship with a company that may result in more intense collaboration and, therefore, encourages staff to do consultancy in work time and be paid for it personally. In the Netherlands, public perception of ties between industry and academic research seems to be discussed much more critically and, consequently, Dutch universities often find themselves in a delicate situation trying to compromise between societal relevance and (perceived) dependence on industry. Consequently, regulations on auxiliary activities have recently been tightened at TU Delft, e.g. the GSE policy is that payment to a personal account is only allowed when the activity is carried out in personal time.

### Conclusions and Follow-Up

We are very grateful to ESE-department head Prof. Cilliers who provided us with important numbers and enabled a site visit with open discussions with several staff members. We will take the observations made during our benchmark visit as a starting point for internal discussion on several aspects. The findings we found most interesting to consider further are:

- Dynamic research groups as compared to discipline-based sections,
- Explicit division of research into exploratory, developmental and programme research levels, with consequences for financial and laboratory support,
- Implementation of a (Faculty) Research Committee, and/or Strategy Committee,
- Increased emphasis on publication quality (instead of quantity).

A longer version of our observations can be found in the Appendix.

## 6.2 Benchmarking of GRS with MIT

As there are no departments in the world that specifically combine geodesy and atmospheric research, GRS chose its benchmark partner to be challenged and inspired on how to organise a research program, rather than on discipline resemblance. The Department of Earth, Atmospheric, and Planetary Sciences (EAPS) of the Massachusetts Institute of Technology (MIT) in Cambridge, Massachusetts, headed by Prof. Van der Hilst, satisfied these criteria by its overall focus on the earth sciences, and its high reputation and standards. Even though the US academic system, and the fact that MIT is a private research university, are incomparable to the Dutch situation, we set out to learn from the sometimes radically different attitude towards the organisation of scientific research.

### Department and Institute organisation

EAPS is a department within the *School of Science*, one of the five schools within MIT. The overarching mission of the EAPS department is to pursue strategic research in areas of strong societal interest that will ultimately lead to beneficial applications in the private and public sectors. Its research portfolio encompasses elements of geology, geochemistry, geophysics, geobiology, atmospheric science, oceanography, astronomy, and planetary science. The research is divided in four research programs: (i) Atmospheres, Oceans, and Climate, (ii) Geology, Geochemistry, and Geobiology, (iii) Geophysics, and (iv) Planetary Sciences. Next to these *research programs*, there are *research centers*, which could be intra- or interdepartmental, and consist of formal groupings of faculty that perform interdisciplinary work. Yet, individual scientists have a strong autonomy in choosing their research interests, and there are no other hierarchical levels except that of the department chair and that of the faculty. EAPS has about 38 faculty members.

The GRS department is a department within the Faculty (School) of Civil Engineering and Geosciences, with 15 full-time faculty members (and a limited number of part-time faculty), which is less than half the size of EAPS. Starting from a historically developed structure in 5 sections, we have organised our research in two themes (units): geodesy and atmosphere. This is somewhat similar to the ‘research programs’ of EAPS. There is an extra hierarchical level between the department head and the faculty,

formed by the full professors ('section heads', full-time), who officially act as formal managers of the assistant and associate professors. Interdepartmental research programs are carried out, e.g., by institutes such as the Delft Climate Institute, or the Delft Space Institute. Within the units, we have defined 'themes', which are common denominators to cluster research activities.

### HR strategy, talent selection and tenure

MIT-EAPS careers can be either defined in a faculty track or in a *research track*. The faculty track consists of assistant, associate and full professors ('hard money', directly from the Institute level), and follows a tenure track system, while the research track includes vcs, research scientists, principal research scientists, and senior research scientists, all on 'soft money', based on external grants. At TU Delft, we also have faculty (scientific staff), dominantly on hard money, directly from the University, but our research positions (non-faculty) can be based on hard money as well. The Dutch legal system does not allow for continued temporary positions after a fixed number (3) of temporary contracts, or a minimum time. While this is considered an asset in the Dutch social system, it limits the degrees of freedom for hiring (or keeping) talent, as the financial risks are high.

MIT (EAPS) hires only at the assistant-professor level, based on the idea that the main innovation will come from young scientists. Job-adds are formulated vaguely (only the field is identified), acknowledging that only the quality of the candidate and the potential impact of his/her research is of real importance. At TU Delft, we generally hire either at the assistant/associate professor level, or at the full professor level, where the procedure for the latter is involved, including a quite specific description of the field the candidate should be expert in. This implies that the match between (a) the candidate and (b) the prior specific definition of the research field is subject to more boundary conditions in Delft.

MIT/EAPS has a rather active scouting attitude to find new faculty candidates. After the first selection a shortlist is made, followed by requests to external referees to send evaluation reports. The opinion of the referees on the candidate's quality is considered more important than the H-index or citation analyses. Potential candidates are then invited for a job interview and a seminar. Candidate selection in Delft also involves reference letters, but their weight is generally less dominant in the selection process.

The MIT tenure track system takes a period of 7 years. After about 4-5 years there is an intermediate evaluation and when passed a promotion to (non-tenured) associate professor. If the tenure-track period is evaluated positively, a promotion to full professor within a short period after the tenure is rather standard procedure. Both the promotion to associate professor, as well as the tenure-decision, rely heavily on the judgment of a large number of external peers. The main criterion used in this evaluation is whether the candidate is a world leader in a relevant scientific field.

### Publication policy

At MIT, publications are aimed at peer-reviewed journals, and the policy for PhD students is clearly to write papers and not a stand-alone PhD thesis. The PhD thesis may contain already published material. Sometimes PhD students get, after finishing the PhD, limited funding as postdoc (sometimes via MIT funds for teaching assistants) to write a couple of papers to get the maximum out of the PhD research.

The publication policy at TU Delft is similar to that of MIT, although it can differ per group leader. Some group leaders recommend not to publish in conference proceedings at all, to encourage submitting peer-reviewed articles. For others, this division is less strict, and conference proceeding papers are regarded as first versions of journal papers to be published later. The same difference in vision holds for PhD theses, which were traditionally published as a book, while some professors recommend a thesis based on bundled articles. TU Delft also stimulates keeping just graduated PhD's a bit longer, if funding permits, to write additional articles based on their research.

### PhD programme

About 20-30 PhD students enter the department per year, while a similar number comes from Woods Hole, who also get a degree at MIT, hereby increasing the PhD thesis output. Many PhD's have an undergraduate from a different field (e.g. mathematics or physics), so the first two years they mainly take classes: a set of core classes for each program which is recommend to be taken. The decision

about the courses is made by the PhD student and the junior advisor. There are no compulsory courses. At the end of this 2-year period they either do two independent research projects or one project and write essays on specific assignments within a tight 5 day time limit. On average most advisors meet their students once per week for 30-60 min, but there are significant differences. After two years and finishing the general exam, the candidate has to submit a PhD thesis proposal within 6 months (literature study, research objectives) and meet with the PhD committee (supervisor, 1 external professor and 2 professors from the department). Every year this PhD committee assesses the progress and decides on continuation.

At Delft, the amount of PhD students depends mostly on the funding possibilities. For starting tenure-track staff, it is difficult to start directly with PhD students, as it takes time to get proposals accepted. New PhD students are enrolled in the TU Delft graduate school. After one year, there is a go/no-go decision on the project, based on the progress made in this first year.

### Scientific and social atmosphere

Internal collaboration and communication is organised through a large number of seminars, separately for faculty staff and researchers/PhD students. High attendance is guaranteed, as the seminars are seen as the main mechanism to organise collaboration and to develop ideas for joint research projects and fund raising. Several aspects of the scientific culture at MIT are appealing and we have already started implementing these in the department, such as the GRS faculty lunches including staff, as well as the GRS weekly seminars.

### Funding

Funding at MIT/EAPS for PhD research is mostly arranged by writing and submitting research proposals, e.g. to NSF. However, for faculty positions, including start-up packages, MIT has significantly more resources to compete for high quality staff. In Delft, budgets are rather tight for scientific staff positions, making generous start-up packages very difficult. For PhD research, the situation is similar as at MIT, where research proposals need to be submitted to funding organisations such as NWO, EU, or industry.

### Conclusions and Follow-Up

We are very grateful to Rob van der Hilst, EAPS' department head, who provided us with a good overview of MIT's methods and procedures to ensure and maintain quality in research. We also thank the delegation of MIT scientists we had the pleasure to discuss with: Tom Herring, Hilke Schlichting, Brad Hager, Andy Miller, Maria Zuber, and Noa Bechor. The benchmarking inspired us to change the way we search for talented tenure-track scientists, to use different ways to stimulate further interaction within the department, and to maintain focused on high-quality publications.

A longer version of our observations can be found in the Appendix.

Department
of Geoscience
& Engineering

# 1

# Geology

# 1 Mission

The use of the shallow and deep subsurface is becoming increasingly intensive as worldwide growing welfare presses for more and better natural resources. Subsurface layers are characterised by multi-scale sedimentological and structural heterogeneities. Detailed predictions of their geometry, physical properties and mechanic and flow behaviour of are key for an effective and responsible resource exploration and exploitation.

Focussing on subsurface sedimentary bodies that host natural resources such as hydrocarbons, groundwater and geothermal energy, but that also represent potential $CO_2$ storage sites, the mission of the Geology unit is to

*develop knowledge and tools to quantify and predict the multi-scale architecture, the physical properties of sedimentary bodies in the subsurface - including their uncertainties - and their flow and geomechanical behaviour*

Driven by the ambition of scientific excellence and aware of present and future societal challenges, the unit builds on its embedding in the Faculty of Geoscience and Engineering and aims at developing a unique combination of geological and engineering sciences. Such a combination is uncommon in the landscape of research organisations. In this endeavour, linking curiosity-driven science with application-driven engineering methods is a core value of the unit.

# 2 Strategy

Key in the overall strategy of the unit is a powerful combination of observation, mostly of recent and outcropping fossil sediments, and process-based modelling. Outcrops provide invaluable information on the end-result of natural sedimentological and structural processes. Process-based models allow for the phenomenological understanding of how these end-products have been obtained and, thereby, allow extrapolation in uncovered spatial and temporal domains.

As the architecture and properties of subsurface bodies depend on how they formed and how they were deformed, the unit chooses to develop both sedimentological and structural approaches. This choice guides the scientific, personnel and financial strategy of the unit. Sedimentology and Structural geology pursue specific research initiatives and are linked in the overarching domain of source-to-sink studies and in the investigation of the subsurface of the Netherlands. A balance between discipline-specific and overarching, holistic projects is key to the success of the unit.

To pursue its ambition of combining fundamental Geology and Engineering research, the units strengthens it geological visibility in the Dutch and European landscape and stimulates projects in common with other units such as Geophysics and Geo-Resources, for instance in the domains of siliciclastic reservoirs, fractured reservoirs and geothermal energy.

## 2.1. Research strategy

The Geology unit organises its research around the four themes shown in Figure 1 with strong links and synergies. At the discipline level, the unit focuses on siliciclastic systems and on fractured reservoirs (Themes 2 and 3). These two pillars are supported by joint development of innovative cross-disciplinary hardware and software for the characterisation of outcrops and for process-based numerical models (Theme 1).

Sedimentary and structural research converge in the overarching topic of source-to-sink systems and in studies on relevant aspects of the Netherland subsurface (Theme 4).

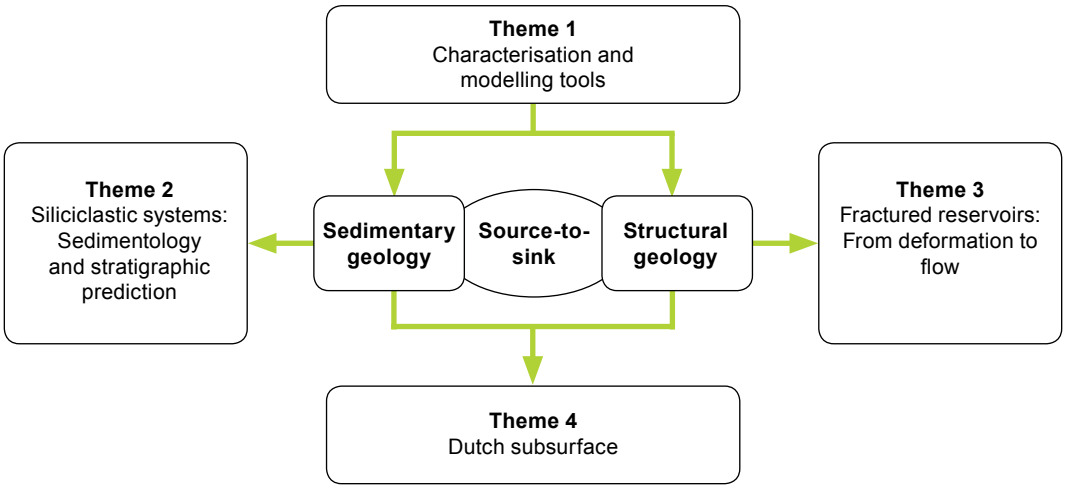



**Figure 1** Themes of the unit Geology and their interrelationship.

## 2.2 Theme 1: Characterisation and modelling tools

This theme comprises Rock Characterisation and Process-based and statistic numerical models. The characterisation of recent sediments and ancient sedimentary rocks is a strategic step to constrain the main processes controlling the formation and deformation of strata. It provides the data necessary for the construction of realistic and robust 3D geological subsurface models. Advanced process- and statistics-based numerical models are a crucial element in the unit's strategy to simulate sedimentary and structural processes. These not only help understanding the dynamics of such systems, but - if validated properly in controlled environments - allow to construct more robust and detailed 2D and 3D models of the subsurface.

### Review period

**Rock Characterisation.** The strategy of the unit has been to focus on hardware and software tools that improve the quantitative characterisation of outcrops and subsurface rocks. Specifically, digital image photogrammetry, state-of-the-art logging tools and advanced automatic core scanning tools have been successfully developed and applied. The Netherlands Top Research School ISES facilitated the acquisition of a professional drone (Figure 2) with which the architecture of outcropping geological bodies can be quantified in georeferenced platforms and then visualised with GoCAD-like tools. The


**Figure 2** The TU Delft-ISES drone Geobee flying towards the steepened carbonates of the Kef Eddour Formation (Tunisia) on its way to acquire fracture data.

earlier acquired palaeomagnetic logging and parametric echosounder tools have been applied in a variety of research projects, as well as the ground-penetrating radar of the Geophysics unit. All of these tools have provided significant contribution to 2D and 3D models of the subsurface.

**Process-based and statistic numerical models**. The powerful Delft3D modelling software has been successfully applied to sedimentary systems in fluvial and marginal marine settings at a scale commensurate with heterogeneities at a reservoir scale (Figure 3). Delft3D is an open-source benchmark model that simulates hydrodynamics and coupled sediment transport in fluvial and marine settings and is increasingly recognised as an extremely powerful tool for sedimentary geology. Proprietary in-house codes have been developed at larger temporal and spatial scales to simulate stratigraphic sequences in fluvial, deltaic and deep-marine environments. Numeric codes were used in an innovative combination with sand-box experiments - in collaboration with the Tectonic Modelling Laboratory TecLab (VU Amsterdam and later UU) - to model turbidites on complex margin topographies such as relay ramps, mud diapirs and mini-basins.

On the static modelling side, a geologically-guided elastic non-linear full-waveform inversion scheme has been developed that uses sequence stratigraphic and rock physics principles. This effort, sponsored by the Delphi consortium and developed together with the Geophysics unit, starts forming a very useful link to the reservoir characterisation community.

Since the appointment of Prof. Bertotti in 2010 and the subsequent opening of the structural geology research line, the first strategic steps have been made to use finite-element modelling tools (ABAQUS and others) to accurately predict structural deformation patterns of heterogeneous subsurface sedimentary bodies.

## Coming period (2015-2020)

**Rock Characterisation**. The strategy for the coming period is to further develop our characterisation tools with the goal of producing efficiently 3D models of multiscale geological bodies which can be checked and ground-truthed at the outcrop shortly after acquisition. With further code development we will be able to use the 3D model as backdrop in tablets to extract, visualise and quantify relevant sedimentological and structural architectures. In-house developed tools such as DigiFract will be used to quantify topological relations, for instance, between fractures and sedimentological boundaries. Eventually, these tools will enable us to make digital models of the sedimentological and structural architecture of geological bodies at scales ranging from $10^0$ to $10^3$ m which can then form the basis for numerical simulations.

**Process-based and statistic numerical models**. In the sedimentological domain, the focus will be on forward and inverse numerical models that address the relationships between palaeoclimate change, basin geometry and stratigraphic response. In a joint effort with Statoil and Deltares we will develop Delft3D into a fully open-source web-based software specific for reservoir geology applications in the shallow-marine domain (Delft3D-GeoTool). An online and open database structure will also be developed to store and analyse previous runs. In addition, specific open-source post-processing tools will be developed to analyse the raw simulated data into higher order geometric and kinematic data products. For the deep-marine environment we embark on coupling viscous (non-Newtonian) flows with turbidity currents, a combination thus far not achieved anywhere and here done with both numerical as well as laboratory experiments in the Eurotank facility at the Utrecht University. At the basin-scale, we will make increasing use of existing numerical codes such as Dionisos to couple the tectonic history of the catchment area to a set of sedimentary basin infill data; this approach will allow us to better understand and predict controls on passive continental margins sedimentary systems such as NW Africa.

In the static modelling efforts, we will fully exploit the information intrinsic in full-waveform seismic signals by expanding our work on non-linear inversion to time-lapse and real field data (Figure 4) and to investigate the impact of fracture networks on the seismic signal. The goal is to achieve a subsurface quantification of relevant reservoir parameters such as porosity and fluid saturations that can be used by the reservoir specialists.

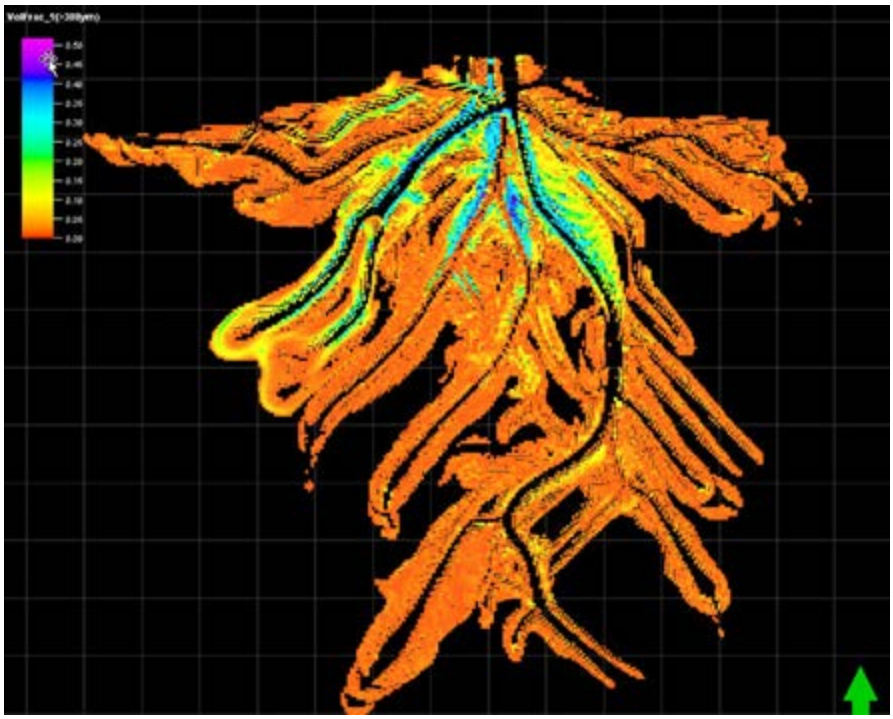


**Figure 3** Delft3D simulation of a tidally influenced wave-dominated river delta. The area is 12 by 15 km. The delta apex is in the north and the flow is towards the reader. The colours represent the volume fraction of sand. Within the channelized network, two trends can be observed were the overall sand fraction decreases i) from the apex to the basin, and ii) from the channel to the adjacent interdistributary areas. Simulation by PhD student Van der Vegt.

In the structural domain, numerical tools will acquire a central role in our effort to predict the impact of fracture networks on fluid flow in heterogeneous sedimentary sequences. We will improve our ability to predict reservoir-scale patterns of stress and strain during subsidence and folding when local stress fields interact with regional ones. Together with Geo-Resources, efficient ways will be sought to i) populate the different reservoir domains with fracture networks extracted from rock mechanical experiments and outcrop studies and, ii) to predict apertures in the different fracture sets. In collaboration with Geo-Resources and top international groups (e.g. Heriot-Watts University), advanced academic simulators (CSMP++) will then be incorporated in our work-flow to investigate the interaction between geomechanics and flow behaviour.

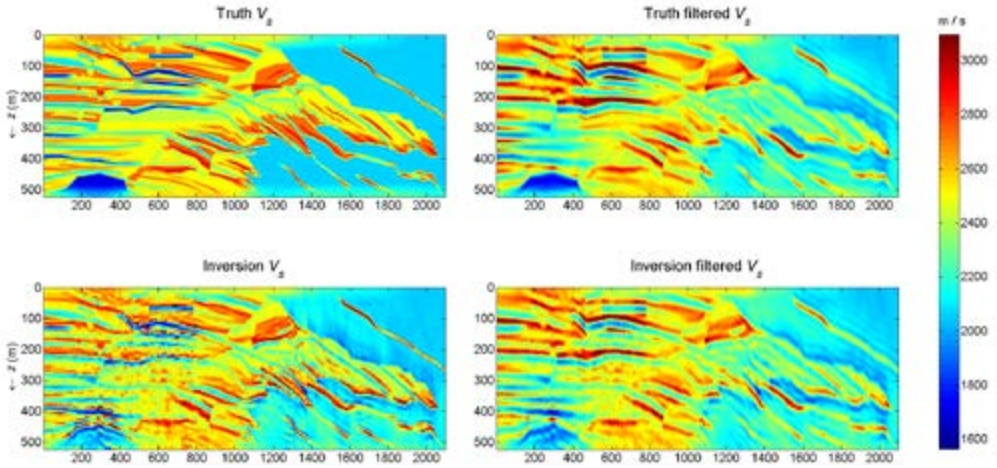



**Figure 4** A geological model developed by post-doc student Tetyukhina of the fluvio-deltaic Book Cliff outcops (Utah, USA) was refined by PhD student Feng into a high-resolution petrophysical and rock-physical model. It was then inverted using our proprietary full waveform elastic inversion software. These figures show in the left column the shear velocity of the actual model (top) and its inversion (bottom), and in the right column the seismic bandpass filtered version of the model (top) and its inversion (bottom). The fluvial floodplain is to the left, the delta in the center, and the offshore area to the right.

## 2.3 Theme 2: Siliciclastic systems

Siliciclastic systems form major hydrocarbon and groundwater reservoirs worldwide. Combining modelling and studies on outcrop and modern-day sedimentary systems and covering a broad range of scales ($10^3$-$10^6$ years and $10^0$-$10^4$ meters), the unit adopts a holistic approach considering the entire system from the source area to the final resting places in the deep oceans.

### Review period

The strategy in this period has been to study a large number of exceptionally well-exposed ancient and modern-day settings from glacial tunnel valleys (North Africa and North America) to braided river plains (Greenland and Jordan), endorheic basins (Altiplano, Bolivia, Caspian Sea, Russia, Iran), deltas (Mahakam delta, Borneo; Volga Delta, Russia; Golo, Corsica) and deep-marine turbidites (Tanqua-Karoo, South Africa). The approaches involved fieldwork, often with digital-geology tools, geophysical methods such as echosounding, ground-penetrating radar or shallow seismics (Figure 5), and sometimes the drilling of research boreholes including logging with state-of-the-art tools. These studies were nearly always accompanied with numerical modelling studies.

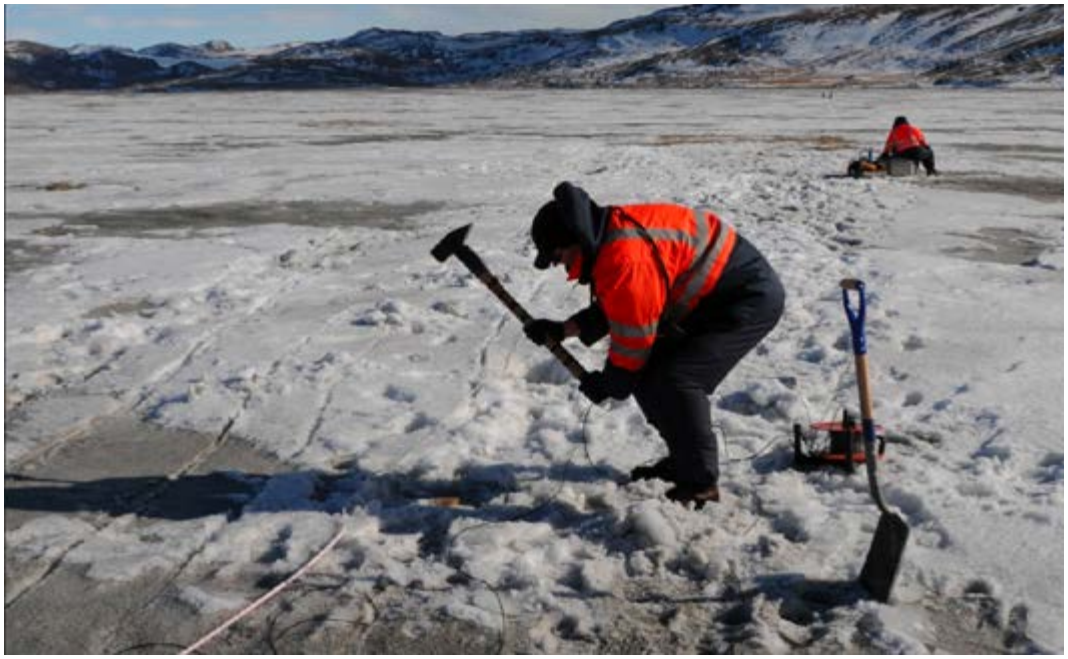


**Figure 5** Acquisition of shallow seismic data on a braided river plain in Kangerlussuaq, western Greenland.

### Coming period (2015-2020)

Studying outcrops of ancient sedimentary systems and their modern-day counterparts will continue to be a crucial part of the unit's efforts. Our main challenge is to improve fundamental understanding of ancient and modern sedimentary systems, supported by new modelling, data acquisition and data analyses techniques. At the small scale, the main objective is to improve heterogeneity quantification and prediction. At a larger spatial scale we aim to better quantify coupled sedimentary systems, specifically the delta-to-shore face and delta-to-deep marine interactions; these settings are understudied with respect to the influence of auto- and allogenic controls and downstream signal propagation. The Golo sedimentary system (Corsica), the Morocco continental margin and, possibly, its conjugates on the Atlantic margin in Canada and in Brazil will be the main study areas.

## 2.4 Theme 3: Fractured reservoirs

Since 2011, the unit has started a research theme on fractured reservoirs based on a combination of tools and scales. Predicting patterns of fracturing and associated fluid flow provides an excellent platform for synergy and collaboration with other units in the Department.

## Review period (since 2011)

The initial focus has been on improving tools to acquire and process data from outcrops (see Theme 1). Studies have been performed on km-scale outcrops of weakly deformed rocks such as Cambrian sandstones in Jordan, Permian sandstones in South Africa, and Cretaceous carbonates in NE Brazil, all analogs to hydrocarbon reservoirs. In the latter outcrops we have cooperated with the sedimentology group of VU University Amsterdam, to constrain flow conditions using isotopic compositions of vein cements.

Studies that address fracture intensities and patterns in geological bodies with strong sedimentological and structural heterogeneities include the Latemar atoll-like carbonate platform in the Italian Dolomites where sedimentologically very different domains (interior, margin and reef) are juxtaposed. Changes in fracture intensities and patterns related to folding have been studied in beautifully exposed anticlines at the southern front of the Atlas belt in central Tunisia.

Characterisation of fracture patterns at the scale of m-sized outcrops has also been an important priority for quantifying the fracture-related anisotropy of rocks prior to deformations by induced stress changes such as hydraulic fracturing. Incorporating these anisotropies is of key importance and very challenging because it requires an effective medium approach to be incorporated into numerical simulations.

In the laboratory we used real rocks to develop a quantitative way of determining fracture apertures from electrical borehole imaging tools, in collaboration with Schlumberger. This approach will allow determining fracture apertures as thin as several tens of microns in industry and research boreholes.

## Coming period (2015-2020)

To achieve a deeper comprehension of fracturing in natural rocks, we i) will expand the spatial scales of our analysis, ii) further diversify the types of rocks and settings analysed and iii) tackle the challenging issue of fracture aperture.

At the $10^{-3}$-$10^{0}$m scale, we will study fracture networks in samples deformed in the laboratory and small outcrops to investigate how fractures are generated, propagate, and interact with other discontinuities. At the reservoir scale ($10^{0}$-$10^{3}$m), modelling and outcrop studies will focus on the impact of sedimentological and structural heterogeneities on the geometry and distribution of fractures and on geomechanical and flow properties. Field work will be performed in rocks and settings not addressed previously, such as the pre-Cambrian carbonates of central Brazil.

We will address the issue of fracture apertures, the most important single parameter controlling flow. Making full use of the unique knowledge of natural fracture networks we have acquired in different geological settings and using the physical description of the different fractures, we will perform flow simulations (Figure 6) on real-world networks with physically consistent aperture distributions.

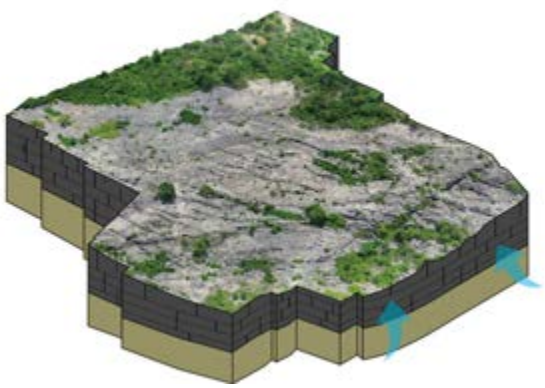


**Figure 6** Schematic representations of a model used for flow simulations: the fracture pattern obtained from the photogrammetry processing of images acquired by the drone is superimposed on a geological model composed of a carbonate layer overlaying a porous sandstone.

## 2.5 Theme 4: Dutch subsurface

The Dutch subsurface has been investigated in a number of smaller projects in the past decade, and will become a key target for the unit in the coming years, especially in light of important societal issues such as geothermal energy, shale gas and $CO_2$ sequestration. The unit considers the Dutch subsurface an excellent natural laboratory for integrating and applying its sedimentological and structural knowledge and for performing predictive studies relevant for society.

### Review Period

The unit has participated in large programmes on $CO_2$ sequestration (CATO) and geothermal energy (DAP). The focus has been on elaborating the geological complexities of potential targets, especially the Lower Cretaceous siliciclastic units. The task has been aided by significant industry data acquired in the past by E&P companies that was made available for these studies.
Building on this know-how, projects were started to address the geothermal potential in the southwest of the country, and to study tight gas sandstones and shales of the Dutch subsurface. Both take place within the Top Sector Energy (TKI Gas) and in collaboration with Geo-Resources and Geophysics.

A proposal to drill two research boreholes to obtain a complete Cenozoic record in the Dutch subsurface (CONOSC) has obtained the initial support of the International Continental Scientific Drilling Program (ICDP) in the form of a workshop. Our unit has been crucial in this effort and provides one of the three Principal Investigators (Prof. Luthi).

### Coming Period (2015-2020)

One of the main targets of the coming period is to integrate sedimentary and geomechanic knowledge to provide full predictions of reservoir behaviour. In the framework of the industry sponsored Fluid Flow in tight Sand and Shales (2F2S) programme running under the umbrella of TKI Gas, we will use the P6 block (Dutch offshore) as a natural laboratory to predict stress and strain conditions and how these change when rocks are stimulated. In the frame of DAP, a similar approach will be used for areas of interest for geothermal energy such as West Netherland Basin.

A full drilling proposal for the CONOSC project will be submitted to ICDP in early 2016. If approved, funding will be sought from potential sponsors such as the Dutch science foundations (NWO, STW) and international as well as industry partners. After Prof. Luthi's retirement, the newly hired assistant professor Dr Abels shall take over as PI. If successful, this project will eventually employ a significant number of PhD students and post-docs.

## 2.6 Personnel strategy

### Review period

A strategic decision was taken during this period by appointing Prof. Bertotti as successor to Prof. Kroonenberg in 2010 and thereby developing a research line in structural geology. This research line was strengthened in 2011 with the hiring of Dr Hardebol as post-doc. Bertotti kept a 0.4 fte appointment at VU University Amsterdam with the mission of fostering the collaboration between the two institutions. At the same time, Luthi handed over the department chairmanship after nine years in office to Prof. Jansen and took over as head of Geology. Based on his remarkable performance in strengthening the sedimentological research, Dr Storms was promoted to associate professor in 2012.
Three staff members (Dr Moscariello, Dr Weijermars and Dr Weltje) left the unit in the past years to accept full professorship positions at prestigious foreign universities (Geneva, Texas A&M and Leuven, respectively). The temporary contracts of Prof. Petersen and Prof. Reijmer were not extended due to them having other commitments. Figure 7 depicts the development in personnel during the review period. While the scientific staff has been decreasing, the number of PhD students shows an increasing trend. The number of Post-docs has been constant in the last few years.

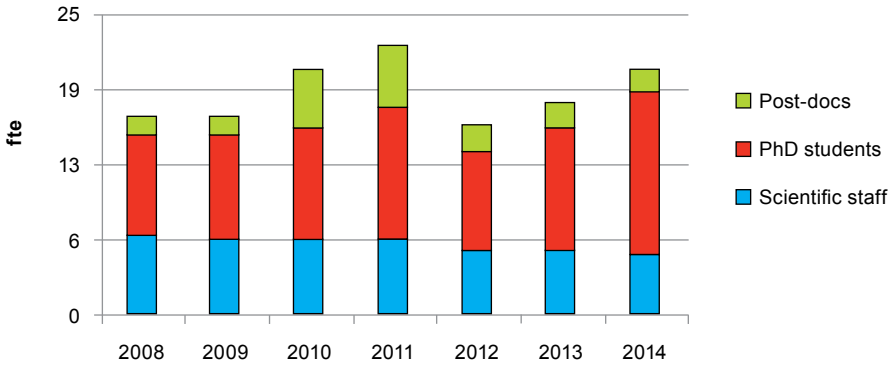



**Figure 7** Personnel during the review period (for numbers see Appendix U1.1).

### Coming period (2015-2020)

With the overarching goal of strengthening the sedimentological and structural geology research lines, the Geology unit, supported by the Department, has reacted swiftly to the changes described above. A sedimentology position has been advertised beginning 2015 and - among a strong field of candidates - the position has been offered to Dr Abels, a highly promising sedimentologist. The academic record of Dr Abels will be an important component of our strategy of increasing the visibility of TU Delft geological research in the Netherlands and abroad. To strengthen the research themes in structural geology, the appointment of Bertotti has been increased to 1 fte as to April 1st, 2015.

The unit will face more changes in the coming years due to the retirement of Prof. Luthi at the end of 2015, and of Dr Donselaar in 2017. To preserve the strong links with industry developed during the tenure by Luthi, the procedure for opening a 0.4 fte position in Petroleum Geology has been started. The ideal candidate will be an industry professional with substantial experience and academic credentials. The task of unit head will be transferred to Bertotti per September 2015. In 2017, a replacement for Donselaar will be sought, ideally with a structural-tectonic expertise.

After these changes, the Geology unit will have a homogeneous and streamlined research personnel profile with sedimentological and structural activities characterised by a strong degree of synergy. Most of the unit members have a record of joint projects with industry and other units of the Department thereby contributing to our ambition of bridging Geological and Engineering sciences. A major effort will be done to increase the number of post-docs who can form an efficient link between (Associate) Professors and PhD students.

## 2.7 Funding strategy

### Review period

The unit maintained a strategy in which a balanced source of funding is obtained, from national governmental funds, from public-private partnerships, and from industry. Although variable throughout the years, the percentages of these three sources of income have been on average roughly equally spread (Figure 8).

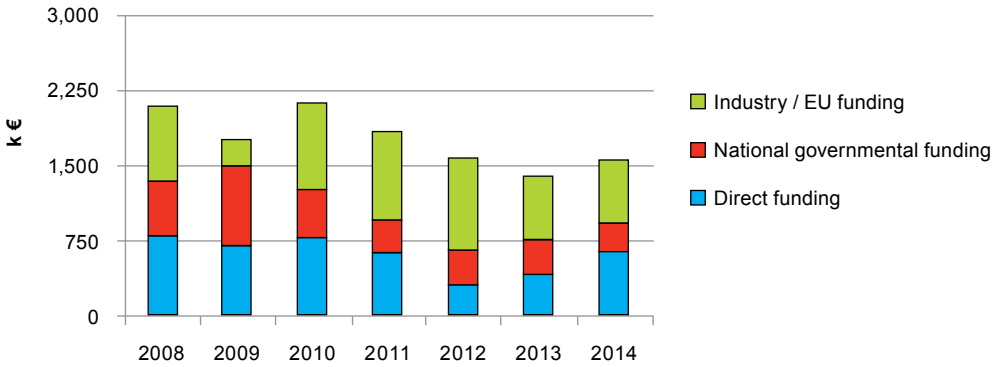



**Figure 8** Research funding during the review period (for numbers see Appendix U1.2).

**National Governmental Funding**
The unit has been very successful in acquiring prestigious funding from NWO with the projects "Simulating the Mahakam Delta" (Kroonenberg), "Sediment supply to the Arctic zone" (Storms, Overeem), and the Vidi project "Untangling the sediment flux" obtained by Storms. Seven research projects were awarded from the top research school ISES (Luthi and Bertotti). ISES also financed the acquisition of the professional drone used by the unit.

**Public-Private Funding**
In the public-private domain, the unit has also been very successful in acquiring funding from the Tight Gas Initiative of the Top Sector Energy (as part of TKI Gas). During the three years of the programme since 2012, two projects by Bertotti and Donselaar have been consistently highly ranked and financially supported. Motivated by the excellent quality of the projects, participating industry sponsors have in both cases decided to expand their funding to generate full PhD and post-doc positions. The project awarded to Bertotti is part of the larger 2F2S initiative ("Fracture networks and Fluid-rock interaction in tight Sands and Shales"), which groups the universities of Delft (lead PI), Utrecht and Eindhoven together with EBN, GdF-Suez, Wintershall and BakerHughes. Demonstrating the strong collaborative links with other research groups, the Geology unit has been an important component of the CATO project through a one-year support of three post-graduate students.

**Industrial Funding**
The unit has been successful in developing strategic partnerships with industry to perform research in areas considered strategic priorities. Projects have been awarded from the geophysical consortium Delphi (2 PhD student and 1 post-doc), from the closed-loop monitoring programme ISAPP (2 PhD students), from the industry consortium GRASP on glacial tunnel valleys (1 PhD student) and from the geothermal programme DAP (1 PhD student). In 2014, the unit joined the industry-sponsored North Africa Research Group (NARG) which facilitates interdisciplinary petroleum-related research in the North Africa region. Support from individual companies has been obtained from Deltares (co-funding of 2 PhD students), Wintershall (1 PhD student), TOTAL E&P (1 PhD student), Shell (full and co-funding of 2 PhD students), Statoil (full and co-funding of 2 PhD student), Petrobras (1 PhD student) and Schlumberger (1 PhD student, 1 PD). Schlumberger, in addition, effectively also sponsored 50% of Prof. Luthi's chair. The strategic importance of the collaboration with Petrobras is also documented by the funding it provided (via UFRN-Natal) for three campaigns of field work on fractured reservoirs. The wide span of this sponsoring illustrates the broad international recognition of our research programme.

## Coming period (2015-2020)
The goal of the unit is to preserve a balanced funding stream from the three main sources mentioned above such that both curiosity-driven as well as application-driven research in sedimentology and structural geology can continue and expand along the lines described in Chapter 2.1.

**National Governmental Funding**
To fulfill its ambition of being at the forefront of academic research, members of the Geology unit will apply for a number of Dutch Science Foundation (NWO and STW) programmes. Building on the successful Vidi project which is nearing completion, Storms will submit a NWO-Vici proposal in 2016, proposing to study the interrelation and feedback mechanisms of coupled sedimentary systems. Abels, the recently appointed assistant professor, intends to submit a Vidi proposal focusing on the impact of astronomical cycles on fluvial sediments, which are notoriously more challenging than their marine counterparts. Pursuing his work on arsenic contamination in fluvial deposits and following the approval of the pre-proposal, Donselaar will submit a full proposal to NWO. A related proposal to H2020 is also being considered. If awarded, it will be continued by Storms and Abels after Donselaar's retirement.

In structural geology, Dr Hardebol will submit an STW proposal on the impact of subsurface fracturing on seismic and mechanical anisotropies as well as an ERC starting grant on the development of multiscale fracture networks in analog and numerical experiments and in outcrops.

**Private-Public Funding**
A major initiative in the coming years is the CONOSC project which is now, following the successful

pre-proposal and workshop, in the final phase of preparation and will be submitted to ICDP in January 2016. Significant support from NWO, EBN, COVRA has already been secured and more institutions and companies will be contacted once ICDP has approved the project. If successful, we expect to be able to hire PhD and/or postdoc.

Members of the unit (sedimentology and structural geology) are involved in a number of initiatives related to the induced earthquakes in the Groningen region. At the moment of writing, the state of these proposals is still fluid but it is expected that within a few months the main lines of these programs will become established. This will be of great importance in strengthening the geomechanic expertise of the unit.

The unit will also continue its efforts to obtain PhD students through the “Science without Borders” Programme of the Brazilian government on the tectono-sedimentary evolution of the NE Brazilian passive continental margin.

### Industry Funding

The unit aims to form a new consortium of industry partners to maintain a constant funding stream in order to improve and further develop the open-source Delft3D-GeoTool. First exploratory discussions with industry have taken place and we expect the consortium to be operational in 2016.

The first phase of the successful collaboration with Petrobras on fractured carbonate reservoirs has just ended. In collaboration with the Federal University of Rio Grande do Norte and other academic institutions, a large proposal has been submitted to Petrobras and, despite current financial difficulties the company is experiencing, a preliminary approval has been given, with the final decision expected in 2016.

The unit is also developing plans for a new phase in the collaboration with TOTAL. This will build on the strong ties developed during the last years with Heriot-Watt University (Edinburgh) and will focus on the impact of natural fracture networks on mechanic and fluid flow behaviour of carbonate reservoirs.

A new collaboration is being developed with ENI in the domain of geomechanics and fractured reservoirs. Following a first general green light, detailed plans are being drafted and decided upon in the beginning of 2016.

Furthermore, a proposal to study economic marginally fields searching for synergies between enhanced recovery and production of geothermal energy has been approved by the Dutch petroleum company EBN and will start in 2016.

## 2.8 Publication strategy

The Geology unit has always followed a strategy of publishing all its results in international peer-reviewed journals (Figure 9). Fundamental sedimentological results are published in *Sedimentology*, the *Journal of Sedimentary Research, Sedimentary Geology, and Quaternary Science Reviews*. More hydrocarbon-related contributions are typically published in the *Bulletin of the American Association of Petroleum Geologists, Basin Research or Marine and Petroleum Geology*. For structural and geomechanic studies, journals such as *Tectonophysics* are considered. In the coming years, we want to expand our visibility to journals such as *Journal of Geophysical Research* and journals in hydrogeology for the results of studies on flow in fractured media. Results of studies from our modelling work are published in specialised journals such as *Computer & Geosciences* and *Mathematical Geology*. In addition, we are increasingly using open access and repositories to share publications and store and make large data sets available to the scientific community. This is in line with recommendations of European and Dutch policies.

Members of the unit participate actively in main international congresses in many different functions (see personal websites of staff). They are also active in scientific journals as Chief and/or Associate Editors (see output list). Dr Weltje has been chief Editor of *Sedimentology* until 2014, Prof. Bertotti Associate Editor of *Tectonics* until 2014 and is presently Associate Editor of *Petroleum Geoscience*.

Dr Donselaar is Editor of the *Netherlands Journal of Geoscience*, and Dr. Storms is a member of the editorial board of *Sedimentary Geology*.

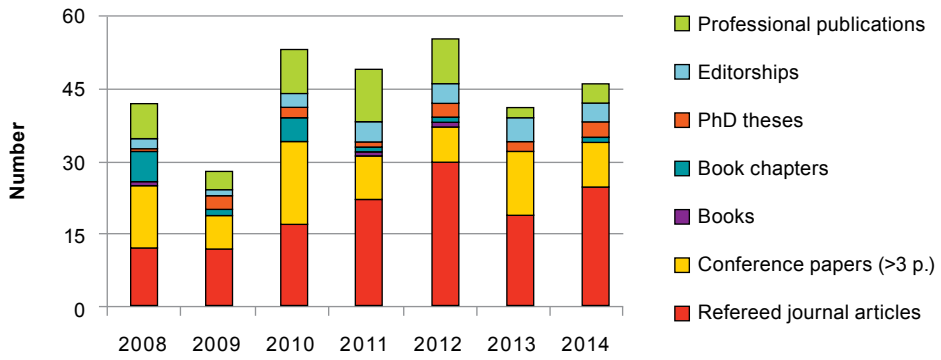



**Figure 9** Research output during the review period (for numbers see Appendix U1.3).

# 3 Research results and plans

## 3.1 Research theme 1: Characterisation and modelling tools

*Scientific staff: Prof Bertotti (0.2 fte since 2010), Prof. Luthi (0.2 fte), Dr Storms (0.4 fte), Dr Weltje (0.5 fte)*

One of the most important result obtained in the domain of rock characterisation is the development of a very efficient workflow covering the entire path from imaging to processing of outcropping successions. Images acquired by a hand-held or air-borne camera are assembled and processed using photogrammetry tools and resulting in a 3D model of the outcrop within a few hours. The 3D model is used to trace geological objects such as fractures and layers which are checked immediately in the field. The geological information is eventually processed by the DigiFract platform to extract relevant spatial and topological information. Because of its high efficiency and the effective links between the various components, the work-flow is unique world-wide and has enabled us to produce a unique data set of natural fracture networks. This has created the basis for new collaborations with Geo-Resources and with international groups in academia and industry (publications by Bertotti, Hardebol, Bisdom). DigiFract, in particular, started as a simple software tool to calculate changes in fracture densities in outcrops and has now become a very advanced tool for the 2D and 3D quantitative interpretation of structural and sedimentological features. The software is shared with and used by the scientific community.

Significant improvements have been obtained with tools to quantitatively characterise grain-size and other properties from cores and samples. Using automated XRF scanning followed by an in-house generated post-processing scheme, we are able to unravel aspects related to provenance and grain-size properties as a function of the distance along their source-to-sink path (publications by Weltje and Bloemsma).

In process-based modelling, we have developed the FanBuilder software that simulates turbidity currents and their deposits, and we have applied it successfully to settings such as the Tanqua-Karoo basin (South Africa), the Vøring Basin (North Sea) and conceptual bathymetries generated using sandbox models. This has led to publications on the algorithmic part (Groenenberg and Weltje) as well as on the applications (Athmer and Groenenberg). The software is now requested by Petrobras and Shell for applications in their deepwater oil fields. Similarly, PacMod, a lumped catchment model to simulate sediment yield to a basin based on palaeoclimate trends, SimClast, a fluvio-deltaic model at the basin scale, and 2DstratSim, a 2D coupled delta/shoreface stratigraphic model have led to a significant number of publications (key publication by Forzoni et al., 2014; papers by Storms, Forzoni, Dalman, Karamitopoulos, Roberts and Weltje). These models also generated strong interest from industry, in particular from Statoil for funding, and a broad request to build a larger industry consortium.

## 3.2 Research theme 2: Silicilastic systems

*Scientific staff: Prof. Luthi (0.5 fte), Dr Storms (0.6 fte), Dr Donselaar (0.8 fte), Dr Weltje (0.3 fte), Prof. Kroonenberg (1.0 fte until 2009), Dr Moscariello (0.3 fte until 2011)*

In this theme, we follow an integrated approach where case studies, either from outcrops or modern-day sedimentary systems, model development and applications are combined to address fundamental and application-driven research questions. In most cases, either the in-house developed or modified Delft3D software has been used, as well as geophysical tools (Figure 10).

**Figure 10** Application of ground-penetrating radar in Corsica (left), on Greenland (right).

Studies devoted to the reconstruction and modelling of climate-induced dynamics in the Northern Adriatic system (Italy) revealed a highly non-linear interaction between sediment supply and sea level changes that has led to a new understanding of Adriatic shelf flooding since the last glacial maximum (key publication by Weltje and Brommer, 2011; papers by Storms). Work on marginal marine settings predominantly addressed high-resolution studies of outcrops (Book Cliffs, Utah), Holocene as well as modern systems (Aceh, Indonesia, and Adriatic Sea) in combination with modelling (publications by Storms, Weltje, Luthi). River and fluvio-deltaic dynamics have been addressed with both modern-day and outcrop data often in combination with numerical modelling (publications by Storms, Weltje, Donselaar). Specifically, avulsion processes at the terminus of low-gradient semi-arid fluvial systems were studied in the endorheic Altiplano Basin, Bolivia (key publication by Donselaar et al., 2013; publications by J. Li). This research has deepened our understanding of the river dynamics in this type of basins and it also serves as outcrop analogue for the project on Permian and Triassic tough gas reservoirs. Behind-outcrop drilling in the Miocene fluvial succession of the Huesca fluvial fan yielded a series of borehole image log facies which were directly linked with the fluvial facies associations in outcrops (publication by Donselaar).

The combined research on fluvio-deltaic architectures has helped to understand the fundamental behaviour of these systems as well as the distribution of grain-size properties related to variable forcing parameters. The unit has been successful in reproducing some main delta morphodynamics (bifurcations, avulsions, mouth bar growth, channel infill, crevasse splays, lobe switching) that directly affect deltaic stratigraphy for a range of bedload and suspended load-driven fluvial systems under fluvial, wave and tide dominated forcings. Work on subsidence processes in the recent Mississippi delta revealed that the present-day subsidence is primarily driven by peat compaction. The autogenic behaviour of the Holocene Mahakam delta, a textbook example of a tide-dominated delta, has been studied in the framework of a NWO-supported project. The distribution of tidally-induced heterolithics, distributary and tidal channels was quantified, together with their local deposition rates, and the influence of human-induced agricultural changes in the hinterland was demonstrated (publications by Kroonenberg). Modern Caspian deltas and barrier coast have been studied offshore and onshore as analogues for Pliocene hydrocarbon reservoirs in the endorheic South Caspian Basin. As Caspian Sea Level until recently rose at a rate 100 times the eustatic rate, the response of its coastal sedimentary systems also was used to validate numerical simulations of the coastal effects of present-day global sea-level rise (publications by Kroonenberg, Storms, Kakroodi).

The research performed on the formation and infill characteristics of glacial tunnel valleys and fjords was funded by the industry consortium GRASP, and by NWO in the frame of the International Polar Year. Field work in Greenland as well as extensive data mining of borehole data has shown that these systems are extremely complex with a large range of different lithofacies, but that there are some commonalities such as a sudden transition from braided fluvial to turbiditic deposition (publications by Moscariello, Janszen, Storms, De Winter).

An important field site where the unit has been involved for the last 15 years is the Tanqua-Karoo basin (South Africa) with its world-class outcrops of Permian basin-floor fans (Figure 11). Earlier work sponsored by the EU included drilling and analysing research boreholes, and in the current period the focus was on modelling the fans and their lobes numerically (publications by Groenenberg). These studies provided some very good matches with reality. Based these results, new research directions have been opened. For instance, higher-density flows will be needed than those below the Boussinesq approximation adopted in the Fanbuilder software, an issue now being addressed by two PhD students (Empinotti and Hermidas (started 2015)). It also became evident that more complex bathymetries may have to be considered, and this was addressed by two PhD projects (publications by Athmer, Luthi).

**Figure 11** View of basin-floor fan 2 of the Permian Skorsteenberg Formation in the Tanqua-Karoo basin of South Africa. The geology group was for many years active in this area in the framework of a EU project.

New results have been obtained in the interpretation of the sedimentary record from boreholes using our innovative palaeomagnetic logging tool. These studies were carried out in the Vienna Basin together with high-resolution electrical borehole images in wells being drilled by industry onto which we could piggy-back with our tools. By combining the high-resolution magnetostratigraphic, biostratigraphic and sedimentological records, it was possible not only to document the variable influences of the standard orbital cycles, but also much shorter cycles that so far have mostly been reported from ice cores (key publication by Paulissen and Luthi, 2011; papers by Paulissen and Luthi).

Geological constraints have been successfully to full-waveform inversion schemes of seismic data. The key findings were the use of clinoform geometries and well data to guide the inversion (publications by Tethyukhina, Luthi). A refinement of this method is being worked out in the projects sponsored by the Delphi consortium (collaboration with Geophysics). Similarly, geological guidance has been used in two projects within the ISAPP programme with the goals to optimise history matching of individual wells and entire oil fields (publications by Farshbaf Zinati and De Jager).

## 3.3 Research theme 3: Fractured reservoirs

*Scientific staff: Prof Bertotti (0.4 fte since 2010), Prof. Luthi (0.2 fte), Dr Weijermars (0.2 fte)*

This research theme started only a few years ago and has already produced significant results. Characteristic for this research has been the multi-scale and multidisciplinary approach.

Modelling work at the borehole scale has shown the importance of local stress fields in controlling the propagation of new fractures resulting from pressure changes in boreholes and in salt-induced structures (publications by Weijermars). At the $10^{-1}$-$10^{0}$m scale, we have quantified fracture networks in small outcrops and used them to derive hierarchical relationships and efficient ways to analyse their impact on fluid flow patterns (publications by Hardebol and Bertotti). This type of study is crucial to quantify the structural anisotropy of sedimentary bodies and to predict how this impacts the development of new fracture networks during (induced) stress changes.

At the larger scale of $10^{1}$-$10^{2}$m, comparable to that of a reservoir simulator grid cell, we have first fully quantified fracture networks exposed in a carbonate quarry to estimate the natural variability of fracture spacing and densities and to assess uncertainties and errors associated with standard industry work flows. It was found that even data considered as “hard”, such as fracture densities from one (synthetic) well, was unable to represent the reality correctly (key publication by Bisdom et al., 2014; publications by Bertotti).

To address fracture patterns at the reservoir scale, we have used the work-flow previously described to produce maps of natural fracture networks which, to our knowledge, are unique world-wide. These maps have typical dimensions of $10^{4}m^{2}$, contain thousands of fractures all stored as digital objects and depict networks developed in different types of rocks in different tectonic settings. We have investigated fractures in weakly deformed fluvial siliciclastic successions (Jordan) and carbonate ramps (Brazil), both with extensive and well organised fracture networks. We could demonstrate that a substantial portion of these fractures developed during subsidence and that, therefore, they are likely to be present in buried reservoirs even in the absence of folds and faults (publications by Strijker, Bertotti, Bisdom).

Work on reservoir-scale outcrops with significant sedimentological heterogeneities in the Tanqua-Karoo turbidite basin and the Latemar carbonate platform documented for the first time the changes in height and density that fracture systems exhibit from one sedimentological domain to the other and, consequently, how the permeability changes in parallel with it (publications by Bertotti, PhD thesis by Taal-van Koppen, Hardebol). The interactions between regional and fold-related stress fields and their impact on fracture patterns have been analysed in the beautifully exposed Alima anticline in Tunisia (publications by Bisdom and Bertotti). Preliminary conclusions suggest that the folding creates less fractures than normally expected and that most of the deformation is accommodated by features developed during subsidence.

We have used numerical tools, mainly finite element methods, to understand the fracture networks we have documented in outcrop studies. Possibly the most interesting result is that commonly observed facture patterns have no obvious mechanic explanation. This is the case for the sub-orthogonal fracture sets (PhD thesis by Taal-van Koppen and publications by Bertotti, Strijker, Luthi) and the type and distribution of fold-related fracturing (publications by Bertotti and Bisdom (Figure 12)). In line with the ambitions to explore the impact of fracture networks on reservoir-scale fluid flow, we have developed a permeability model for sedimentologically complex systems such as atoll-like carbonate platforms based on the fracture patterns observed in the different domains. This has shown how permeabilities can vary up to 50% from one domain to the other and that the fracture networks impose an important anisotropy in the horizontal dimension (publications by Bertotti).

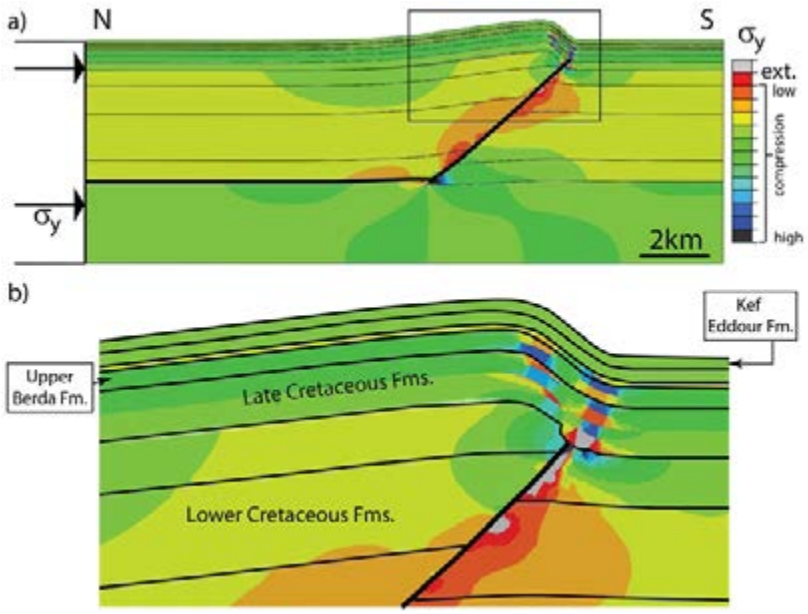



**Figure 12** Finite element simulations predicting stress and strain fields in folds.

In collaboration with colleagues of the Geo-Resources unit, we have developed a workflow allowing the physically consistent prediction of fracture apertures - a crucial parameter in reservoirs - depending on their orientation with respect to the maximum compressional stress, the fracture length and different mechanical parameters (publications by Bisdom and Bertotti). Their impact on flow has also been modelled using advanced flow simulators (Figure 13).

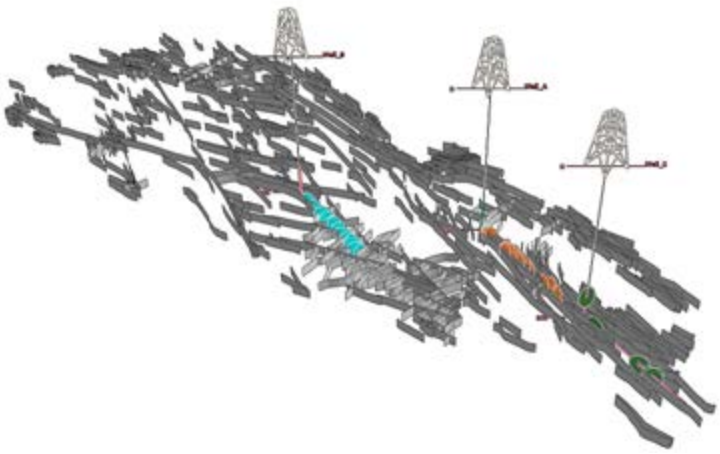


**Figure 13** The fracture network acquired from outcropping pavements is extruded to create a 3D model for a fractured reservoir. Adopting the aperture derived from mechanic studies, synthetic borehole are placed in different localities of the model to investigate permeability and flow behaviour.

## 3.4 Research Theme 4: Dutch subsurface

*Scientific staff: Dr Weijermars (0.3 fte), Dr Donselaar (0.2 fte), Dr Weltje (0.2 fte), Prof. Luthi (0.1 fte)*

Although the Dutch subsurface was always of interest for the unit, research was mostly done in the context of MSc theses. Since 2010, the unit has embarked on a more rigorous and long-term approach aimed at a quantitative characterisation of the geometry as well as sedimentological and mechanical properties of relevant portions of the Dutch subsurface. This subject is also of relevance for ongoing debate on earthquakes associated with gas production in the North of the Netherlands and potential shale gas, shale oil and geothermal resources. The unit was successful in obtaining funding for projects

on geothermal energy (PhD student Willems), on marginal thin-bedded fluvial reservoirs (PhD student Van Toorenenburg), and on the storage of $CO_2$ (MSc projects). At the time of writing, these projects are still underway with preliminary results.

**Bisdom, K**, Gauthier, B, **Bertotti, G** & **Hardebol, N** (2014). Calibrating discrete fracture-network models with a carbonate three dimensional outcrop fracture network: Implications for naturally fractured reservoir modeling. *AAPG Bulletin*, 98/7, 1351-1376.

**Donselaar, ME**, Cuevas Gozalo, MC & Moyano, S (2013). Avulsion processes at the terminus of semi-arid fluvial systems: Lessons from the Río Colorado, Altiplano endorheic basin, Bolivia. *Sedimentary Geology*, 283, 1–14.

**Forzoni, A, Storms, JEA,** Whittaker, C & **De Jager, G** (2014). Delayed delivery from the sediment factory: modeling the impact of catchment response time to tectonics on sediment flux and fluvio-deltaic stratigraphy. *Earth Surface Processes and Landforms* 39, 689–704.

**Paulissen, WE, & Luthi, SM (2011)**. High-frequency cyclicity in a Miocene sequence of the Vienna Basin established from high-resolution logs and robust chronostratigraphic tuning. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 307, 313-323.

**Weltje, GJ, & Brommer, MB** (2011). Sediment-budget modelling of multi-sourced basin fills: application to recent deposits of the western Adriatic mud wedge (Italy). *Basin Research*, 23/3, 292-308.

**Figure 14** Key publications.

## 3.5 Summary of research quality

### Research products

The number of peer-reviewed articles has doubled during the review period. In 2012, it even reached almost three times as many papers as in 2008, but due to staff leaving the number has gone down in 2013, showing an increase again towards 2014 (Figure 9).

The development of characterisation and modelling tools (Theme 1) has produced important results. Software packages such as FanBuilder, BarSim, 2DStratSim, DigiFract and the scripts associated with Delta3D are now fully functional and used in variety of projects. Most of these packagaes are shared with other researchers on a collaborative basis.

### Use of research products

The papers we publish are very well read in the community. Hirsch indices are therefore rather high, usually above 10, with Bertotti having an H-index of 28 (ISI). Certainly, the high H-indices of Weijermars and Weltje have also resulted in their excellent positions as full professors at renowned universities (Chapter 2.2).

The three most cited publications produced by members of the unit during the evaluation period are

- **Weltje, GJ**, Tjallingii, R (2008). Calibration of XRF core scanners for quantitative geochemical logging of sediment cores: Theory and application. Earth and Planetary Science Letters 274, 423-438. (97 citations (Scopus))
- **Storms, JEA, Weltje, GJ**, Terra, GJ, Cattaneo, A, Trincardi, F (2008). Coastal dynamics under conditions of rapid sea-level rise: Late Pleistocene to Early Holocene evolution of barrier-lagoon systems on the northern Adriatic shelf (Italy). Quaternary Science Reviews 27, 1107-1123. (50 citations (Scopus))
- **Geleynse, N, Storms, JEA**, Walstra, DJR, Jagers, HRA, Wang, ZB, Stive, MJF (2011). Controls on river delta formation; insights from numerical modelling. Earth and Planetary Science Letters 302, 217-226. (26 citations (Scopus))

### Marks of recognition from academic peers

Our staff members are very well embedded in the academic community, nationally as well as internationally. Besides being invited to hold (co)editorship positions in renowned journals (see

Chapter 2.4) the staff of the Geology unit regularly acts as members of numerous scientific committees, such as Weltje in the NWO-ALW-Vidi committee, Storms in the NWO-ALW-Veni committee, Bertotti in the NWO-Vici committee and Luthi as chairman of an Open Call Committee of NWO-ALW. Similarly, members of the unit are asked by Science Foundations of different countries to provide reviews of scientific proposals and to participate to PhD opposition committees. Kroonenberg has been appointed Honorary Professor at Moscow State University (2008) and received the Van Waterschoot van der Gracht Medal of the Royal Dutch Geological and Mining Society KNGMG (2010).

The Geology unit has played a crucial leading role in applying for and obtaining Dutch membership in the International Continental Scientific Drilling Program (ICDP). Luthi was the main initiator in 2010 and formed a group of scientists that applied to NWO for funding this membership for a period of 5 years. He is now member of the Executive Board of the ICDP and head of the board of the Dutch Branch ICDP-NL.

Luthi has also been a member and co-chairman of a workgroup of a white paper called "Aardwetenschap Agenda 2020", commissioned by the KNAW and submitted to the ministries in which a vision of the future of Earth Sciences in the Netherlands is outlined. Bertotti is the TU Delft representative in the working group in charge of preparing an implementation plan for this Agenda.

# 4 Relevance to society

Following its mission of combining and integrating fundamental and application-driven research for a better understanding of the Earth's subsurface, the Geology unit has established a substantial number of collaborations and activities with industry and in public-private joint research programmes. The results of these studies have had a significant impact on industry as well as society at large. Outreach continues to be an important priority of the unit, with members of the unit participating very actively in the debate on relevant Earth Science issues in the Netherlands and elsewhere. This focus on the wider energy and resource debate, and specifically on issues such as shale gas, induced earthquake occurrence and soil subsidence, is where we are often asked to contribute in the form of interviews and talks to the public in a variety of settings. We strive to maintain academic independence even though these issues are often highly controversial.

## 4.1 Collaboration with industry

Collaboration with industry has remained strong during the last years (Figure 8) and the unit aims at further strengthening this trend. In a variety of cases, the knowledge generated in these projects has been considered as very valuable by industry which in turn has stimulated continuation of these research activities. Four examples demonstrate this:

1. Statoil and Shell have shown strong interest in the process-based models developed by Storms and centred around the open-source Delft3D and auxiliary software packages developed in-house. These companies financially and scientifically support the development of process-based modelling to build realistic reservoir models because they recognise the need for innovative approaches that complement the more conventional statistics-based methods, and some of them are users of our software. At the time of writing, a new phase in this development has dawned where Delft3D will be further developed from a hydrodynamic tool into a reservoir geological tool in collaboration with Deltares (an independent institute for applied research in the field of water and subsurface). Associated to this development Storms is developing new initiatives to further strengthening the geological application of Delft3D and, thereby, let it become fully integrated in the work flow of these and other companies.

2. Research supervised by Prof. Luthi (supported for 50% by Schlumberger) in the framework of the Delphi consortium and in close collaboration with the Geophysics unit has provided tangible

results in geologically conditioned full-waveform inversion. This provides a crucial link between geophysicists and specialists in reservoir characterisation, as the results are not elastic parameters but actual reservoir properties such as porosities, saturations and - in the long run - permeabilities. The Delphi sponsors consider this one of the key developments in this consortium.

3. Similar positive impact of our work for industry has been achieved by two projects in the structural domain. The choice of focusing on outcropping analogs using advanced imaging and processing tools has been valued by various companies. TOTAL, as one of them, has been sponsoring further developments in DigiFract which has now able to handle 3D outcrop data and extra relevant spatial information. DigiFract is now linked with goFRAC, one of the standard tools used by TOTAL for fracture-related permeability predictions.

4. Industry has greatly appreciated our work on the sedimentary architecture of (potential) reservoirs in the NL subsurface has also been greatly valued by the hydrocarbon industry and by companies related to geothermal energy generating a significant line of funding.

## 4.2 Public-Private projects

Collaborations involving a mix of public and private (industrial) partners invariably focus on issues of public interest and relevance. Participation in and successful development of projects mentioned in previous chapters put us in the position of having a significant impact on a variety of public-private projects. Because of the sedimentological knowledge developed in the unit during the last years and, more particularly, because of its activities in the shallow subsurface, Dr Storms has been acting as a consultant to quality-check the shallow parts of the geological models generated by NAM and used for predicting the consequences of earthquake activity in the Groningen region (NISP and other initiatives). Building on the recognised impact of our Top Sector projects (tough-gas domain) we are participating in formulation of the Roadmap Upstream Gas Consortium 2016-2019 which can become a guideline for the government and related institutions for the coming five years. Similarly, the Geology unit is a major player in the Delft Geothermal Program (DAP) which envisions, among others, drilling a doublet of wells on the campus for heating some of the major buildings of TU Delft.

## 4.3 Outreach activities

Prof. Kroonenberg continues to be publicly very active with frequent appearances on TV programmes and with the publication of his popular scientific books on climate change and other geology-related issues (key societal output by Kroonenberg, 2008).

Members of the Geology unit have been very active in ongoing discussions on Earth Science issues of societal relevance, with which it is hoped that the perceived or real gap between academia and the public on these issues can be narrowed. Dr Weijermars has been invited numerous times to express his ideas about shale gas and he has published a great number of papers on the topic as well as on energy issues in general (e.g., key societal output Weijermars & Luthi, 2011). Prof. Luthi has also contributed to the shale gas discussion giving interviews to newspapers and talks to industry and public organisations such as the Royal Netherlands Academy of Science (KNAW). His lectures on this topic at the Chongqing University of Science and Technology (China) resulted in him being awarded the title of Visiting Professor. He was also repeatedly interviewed by radio and newspapers on the highly controversial Macondo oil spill by BP in the Gulf of Mexico. Furthermore, he was asked to author a report to the Ministry of Economic Affaires on the safety of nuclear sources left behind in boreholes in the Dutch subsurface.

Dr Storms initiated the project Spiegelzee "Spiegelzee" which was carried out in collaboration with TNO and cosponsors to communicate the effects of the Holocene sea level rise on the Dutch coast (Figure 15). A large temporary pavilion was built at the beach near Katwijk which was visited by over 30,000 people in a three months period. Storms also worked an article on delta formation in the Dutch weekly *De Groene Amsterdammer* (key societal output).

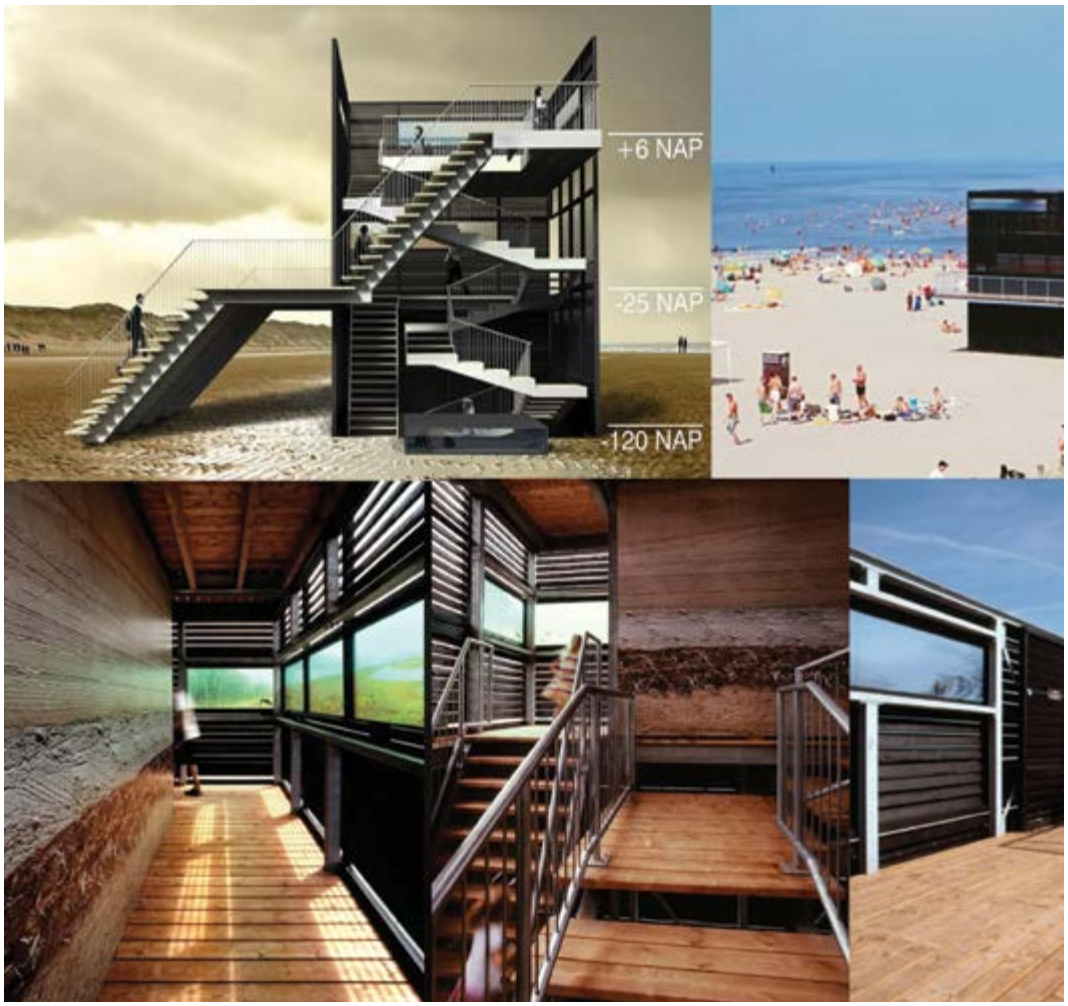



**Figure 15** The Spiegelzee pavilion at the beach near Katwijk. Images and Photo by ZUS and Dennis Guzzo. More images at http://www.denisguzzo.com/projects/spiegelzee/.

The ICDP programme has a significant public outreach programme that involves making documentaries of their activities, publishing their main results in mainstream journals and giving speeches at schools to raise interest among young students. The unit is dedicated to contribute to this in the future through the CONOSC project.

Prof. Luthi developed a Teaching Set on Production Geology that was published at AAPG in 2008 (key societal output).

## University links

Similarly to other units and departments in the Faculty of Civil Engineering and Geosciences, the unit is engaged in capacity building projects, namely in Brazil, Tanzania and Mozambique. These countries have made major hydrocarbon discoveries in the last decades (Brazil) or years (Tanzania and Mozambique) and are faced with a shortage in skilled technical personnel. The engagement of the unit in these initiatives responds not only to the general value of cooperation between Universities from different parts of the world but is also seen as an investment in research. Capacity building activities of the unit are exclusively at the level of Master and PhD and, therefore, are centred around research projects defined with companies active in the corresponding regions.

Activities in Brazil are supported by the Science without Border programme and Prof. Bertotti has been recently awarded the status of Special Researcher at the Federal University of Rio Grande do Norte. In Tanzania, our efforts in collaboration with UU and UTwente have been supported by the Dutch government and have been instrumental in launching the first Master in Hydrocarbon Geology in the country. At the moment of writing, research projects are being defined in cooperation with two of the main companies working in Tanzania, namely BG Group and Statoil.

Kroonenberg has supported the EAFIT University in Medellin, Colombia in a survey of the geology and petroleum potential of the Colombian Amazones (2011). Since 2011 he is involved in joint Suriname-Brazilian geological mapping projects with the University of Suriname, Geological Survey of Brazil CPRM and the University of São Paulo. He also supported the University of Suriname through thesis supervision of MSc and BSc students in Mineral resources. He was a member of the Peer Review Committee Earth Science Education at Tallinn University of Technology, Estonia (2009), chairman of the International Peer Review Committee Earth Science Educational Programmes in Flanders, Belgium (University of Ghent and Leuven) (VLIR)(2009-2010), chairman of the NVAO Accreditation committee of the newly established MSc Petroleum geology course in Suriname (2011) and a member of the Accreditation Committee BSc Future Planet Studies University of Amsterdam (2012).

Research on arsenic in India was presented at an international conference on this topic (key societal output Donselaar 2014).

**Weijermars, R & Luthi, SM (2011)**. Dutch Natural Gas Strategy: Historic Perspective and Challenges Ahead. *Netherlands Journal of Geosciences*, 90/1, 3-14.

**Luthi, SM** (2008). Production Geology. Chapter in Leetaru, H (Ed.): *AAPG Teaching Sets in Petroleum Geology*. American Association of Petroleum Geologists, Data Pages and Miscellaneous Publications, ISBN 978-1-58861-337-0, download

**Kroonenberg, SB** (2008). *De menselijke maat – de aarde over tienduizend jaar*. Olympus, 256 p., 12th edition. Also translated into German, English, Turkish and Chinese. link

**Storms, JEA** (2012). Hoe ontstaan delta's? *De Groene Amsterdammer*, May 2012, 1-1. link

**Donselaar, ME** (2014). Dissolution and entrapment of arsenic in fluvial point bars - Case Study of the Ganges River, Bihar, India. In: Litter, MI, Nicolli, HB, Meichtry, JM, Quici, N, Bundschuh, J, Bhattacharya, P & Naidu, R (Eds.): One Century of the Discovery of Arsenicosis in Latin America (1914-2014). *Proceedings of the 5th International Congress on arsenic in the environment*, Buenos Aires, Argentina, 11-16 May 2014. CRC Press/Balkema, Leiden, the Netherlands, 26-28. ISBN: 978-1-138-00141-1.

**Figure 16** Key societal output.

# 5 Viability

## 5.1 Benchmarking with Imperial College

The Departments of Earth Science and Engineering at Imperial College London (IC) and of Geoscience and Engineering (TU Delft) are quite different in size and organisational structure. Imperial has significantly more geologists than GSE in Delft and are spread over different units, reflecting the merely informal role units have at IC. The Geology unit in Delft has a more compact form essentially including all geologists active in the Department. This fosters collaboration and facilitates synergies between the different disciplines (sedimentology and structural geology in our case). Based on the strong record of common projects, this does not prevent us from intensive collaboration with other units of the Faculty. The limited size, however, does pose the challenge of guaranteeing the continuity of geological research.

At present, geological research at Imperial College is spread over a very wide range of topics with a strong sedimentological focus, both siliciclastic and carbonate rocks. In these fields, they profit form the presence of very well-known sedimentologists and from very large contracts (carbonate). Research in structural geology at IC has a strong tradition but, in our view, is at present weaker than it used to be and less innovative than what done at TU Delft. Collaboration between Imperial College scientists and engineers is less developed than in Delft. The Geology unit at TU Delft makes clear choices in the disciplines it wants to address and actively pursues projects at the interface with engineering sciences.

The groups at IC have proportionally more PhD students and significantly more post-docs, which results in a more efficient distribution of teaching and supervision loads in their department. This is partly due to the costs of PhD and post-docs in the Netherlands which are 2 to 3 times higher than at Imperial and

in most other universities worldwide. Increasing the number of PhD students and post-docs is a priority of the Geology unit, but it should also be noticed that a significant number of PhD students in London is attributed at the department level, depending on the strategic choices made and not only on the basis of individual projects. The aim of the Geology unit of increasing the number of PhD project and post-docs is strengthened by the comparison with Imperial College.

IC has strong links with industry manifested in the sponsoring of professorial chairs and scholarships for PhD students and, maybe more importantly, for Master's students. Industry links are essentially managed at the Department level with industry providing funding for MSc thesis projects and being directly involved in the selection and hiring of outstanding students. We believe that such a policy would be also of advantage in Delft where relations are more built at the individual level.

## 5.2 SWOT analysis

**Strength**
The Geology unit has a strong record of obtaining research funding from the Dutch national science foundations (NWO and STW) and from other state-funded initiatives (Top research school ISES; Top Sectors). The unit has also been able to keep a substantial funding from industry, and also opening collaborations with new companies. These two records document the ability of the unit to perform high level research bridging the fundamental and pragmatic domains which has been identified as one of the ambitions of the unit.

Following the personnel changes which have taken place in the last few years, the unit has worked towards a homogeneous and well streamlined structure which makes it possible to optimally exploit the synergies among projects and successfully address the future challenges.

Last but not least, a fundamental strength of the unit lies in its strong embedding within the Department. Through a number of common projects, for instance on the inversion of seismic data together with Geophysics and on flow in reservoirs with Geo-Resources, the units of the Department have developed a common language and a remarkable degree of joint research.

**Weaknesses**
The Geology unit is relatively limited in size compared to geology units in the benchmark institution. Furthermore, the unit has a smaller number of PhD students and post-docs per staff member than other units. Taking into account also the considerable number of courses provided by the unit, this translates in a high working load. It is crucial, therefore, that enough funding is available to fill the vacancies of the recent past and the immediate future be filled with dedicated and excellent new staff members. The unit's goal is to publish 3-4 papers per PhD project and in some cases this objective has not been reached.

**Opportunities**
There is little doubt that the increasing pressure societies are exerting on their subsurface will require in the future a high number of highly skilled professionals, able to develop knowledge at the interface between geology and engineering. Our field will therefore even be more important in the next decades. In the Netherlands, the Geology unit is the only group with the explicit and realistic ambition of connecting Earth Sciences with Engineering. The two focus points of the unit, siliciclastic systems and fractured reservoirs, are not covered in a similar manner by other Dutch universities. In Europe, only few universities have a valuable Geology unit well embedded in an engineering department.

In the field of fossil energy, increasing need to explore and exploit difficult hydrocarbon fields calls also for the approach integrating geologic (sedimentology and structural) and engineering, pursued by the Geology unit. Similarly, the Geology unit can play an important role in transferring knowledge from the highly developed hydrocarbon industry to the domain of geothermal energy and of water. The benchmarking with Imperial College has confirmed that the Geology unit has already established strong steps in the envisioned integration process.

The international visibility of the Geology unit has increased thanks to our English-taught BSc and MSc programmes, as well as the opening (in February 2015) of the first Massive Open Online Course in general Geology for Hydrocarbon and Water related studies. With this increased visibility, we expect an increase in the number of highly qualified students which will translate in high-quality MSc-level research projects and a consequent rise of our research portfolio.

**Threats**

Given continued limited government resources provided to universities, the unit sees as the main threat that some of the vacancies in the near future will not be replaced. This might make it very difficult to fulfil the ambitions of developing excellent geological research at the interface between Earth Sciences and Engineering.

The low prices of hydrocarbons and the associated budget cuts that companies are implementing in their research programmes is an important threat to the Geology unit. A fundamental component in this threat is the high costs per PhD project in the Netherlands, which are twice to three times higher than PhDs in other countries. This seriously undermines our international competitiveness.

Department
of Geoscience
& Engineering

# 2

# Geophysics

# 1 Mission

Applied Geophysics is dedicated to the development and application of geophysical methods to address societal problems. In our unit Geophysics, we deal with a part of this rather wide definition. Here, *applied geophysics* is understood to cover exploration geophysics, addressing seismic and electromagnetic (EM) imaging and monitoring of hydrocarbon reservoirs, and shallow subsurface geophysics, dedicated to environmental and engineering problems. In relation to this, we define *petrophysics* as the study of physical rock properties and their interaction with fluids in porous and/or fractured materials, from micro scale up to reservoir scale.

*The mission of the unit Geophysics is to execute fundamental geophysical (seismic & EM) and petrophysical research, directed towards developing cutting–edge acquisition, imaging, characterisation and monitoring methodologies for resource-exploration, environmental and engineering applications.*

# 2 Strategy

## 2.1 Research strategy

### Review period

The research of our unit is inspired by the societal need for natural resources (hydrocarbons, groundwater, etc.), the use of subsurface space (storage of heat or waste products, engineering constructions), and the mitigation of hazards (e.g. induced seismicity). To address these societal needs, we divide our research in three main themes, which correspond to the different scales covered by the various applications (Fig. 1a). These themes are:

- Theme 1: Exploration Geophysics (maximum depth of 5 km),
- Theme 2: Environmental and Engineering Geophysics (maximum depth of 50 m),
- Theme 3: Petrophysics (pore- and fracture scale, 1 μm to 10 cm).

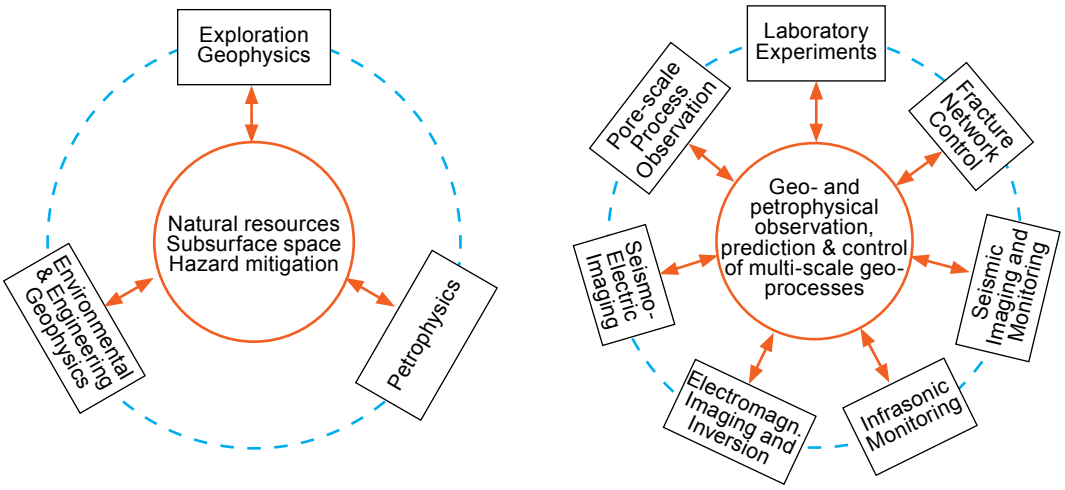



**Figure 1a** (left) **& 1b** (right). Societal applications and themes (a) and scientific challenges and disciplines (b) of the unit Geophysics.

Theme 1, Exploration Geophysics, comprises primarily seismic and electromagnetic methods, dedicated to the search for hydrocarbons and the monitoring of hydrocarbon production and storage of waste products, down to a depth of 5 km. Theme 2, Environmental and Engineering Geophysics, covers the monitoring of processes to a depth of 50 m, such as ground water flow, pollution, tunnel boring, and the inference of properties (like the in-situ stress-state), relevant for subsurface engineering. Much of the methodology developed for theme 1 can be used for theme 2 and vice versa. Theme 3, Petrophysics, covers physical processes at the pore- and fracture scale, from 1 μm to 10 cm. On

the one hand this supports the monitoring methodology of themes 1 and 2, for example to translate time-lapse imaged reflectivity into changes of saturation and stress in a reservoir or aquifer. On the other hand, it also supports the understanding, prediction and control of the pore- and fracture-scale processes such as rock-fluid-gas interaction, $CO_2$ storage and fracturing. On this aspect, there is much cooperation between this theme and the unit Geo-Resources.

Derived from the societal needs, the scientific challenges of our research programme encompass the geophysical and petrophysical observation, prediction and control of multi-scale geo-processes. To this end, our research concentrates on a number of interrelated disciplines, such as seismic and electromagnetic acquisition, imaging, characterisation and monitoring methodology (active and passive), seismoelectric imaging, pore-scale process observation, fracture network control, etc. All these expertises are supported by laboratory experiments (Fig. 1b). Our laboratory includes facilities for acoustic and petrophysical measurements, optical and X-ray imaging and image quantification, data acquisition, and hydraulic and pneumatic infrastructure, see also the introductory chapter.

For a proper understanding of the multi-scale subsurface processes, the disciplines covered by our unit Geophysics are necessary but not sufficient. Therefore, the unit cooperates with other units in the Geo-Cluster. For example, our reservoir characterisation is constrained by geological models developed in the unit Geology, whereas reservoir monitoring benefits from fluid flow models developed by the unit Geo-Resources. With the arrival of the units Geodesy and Atmosphere to our Faculty in 2013, we have added infrasonic monitoring as a new geophysical discipline and initiated cooperation with these units. Collaboration with the units Geodesy and Geo-engineering has been initiated on shallow sub-surface processes, volcano monitoring, and seismic imaging.

### Coming period (2015-2020)

During the transition from energy supply by hydrocarbons to sustainable energy supply, the research themes (Fig. 1a) will remain as relevant as they were in the past period. In addition, more emphasis will need to be put on the effects of production of hydrocarbons in the subsurface as well as on the development of sustainable geo-resources. Hence, monitoring and prediction of induced seismicity, storage of waste products (such as $CO_2$), fracturing of reservoirs, production of geothermal energy etc., are all issues which will be part of our research programme in the coming period. Together with the other units in the Geo-Cluster and external partners we will set up thematic programmes to address these issues.

These thematic issues will put higher demands to our geophysical and petrophysical disciplines (Fig. 1b). Some of the scientific challenges are (i) imaging with higher resolution and repeatability, (ii) more reliably linking the characterisation and monitoring of reservoirs and aquifers to fluid flow and geomechanical changes in and around the reservoir, and (iii) better understanding of fracture growth and connectivity in fracture networks. This requires a continuing research effort to further improve our disciplines. For example, for our imaging research we will put much emphasis on seismic/electromagnetic interferometry “and beyond”, whereas an important issue for our petrophysics research will be the monitoring of fracture network connectivity and the changes in seismic signature during fracturing.

Our ultimate goal is to develop geophysical and petrophysical methodology, integrated with geological, geomechanical and fluid-flow modelling, for accurate and reliable observation, prediction and control of multi-scale geo-processes.

## 2.2 Personnel strategy

### Review period

We strive to have the three research themes covered by scientific staff members who either are tenured scientists with a proven excellent academic record, or tenure-track assistant professors with a high scientific potential. Moreover, we aim to have a pool of part-time professors with strong research positions in industry or institutes, to strengthen the link between the fundamental research and its applications.

In the review period the following actions were taken, in line with this strategy:

- In 2010, Prof. Fokkema ended his term as Rector Magnificus of the university and decided not to return to the unit Geophysics. This implied that geophysical electromagnetic (EM) methods were no longer covered by a full professor. Given the importance of EM methods for all three research themes, we decided to establish a chair Geophysical EM methods and started a search for a new full professor. After interviewing several excellent (inter)national candidates, including Dr Slob, the board of the university decided to promote Dr Slob to full Professor of Geophysical EM methods in October 2011. With his strong publication record (83 journal papers until 2011) and his proven record as supervisor and fundraiser, Prof. Slob easily fulfils the excellence criterion.
- The petrophysics programme has come under significant strain by the departure of Dr De Pater and Dr Smeulders. Due to the difficult financial situation of the department, the two positions have been replaced by one new position, which has been filled by Dr Barnhoorn as of July 2011. With his PhD of ETH Zürich (2004), his six years post-doc experience, including a Veni position at Utrecht University (2007-2010), and his strong publication record (19 journal papers until 2010), Dr Barnhoorn fulfils the criterion of high potential scientist without doubt.
- To strengthen the link between geophysics in the earth and atmosphere within the Geo-Cluster, we appointed Dr Evers from the Royal Netherlands Meteorological Institute (KNMI) as part-time associate professor in September 2012 (0.2 fte). Despite his non-academic career, Dr Evers had a list of 17 journal papers until 2012 and continued to prove his high scientific profile by publishing another 8 journal papers in 2013/2014, which includes co-authorship of two papers in Nature and Science.

The fte of scientific staff decreased from 8 to 7 over the review period. The number of PhD students per staff member remained approximately constant at 2.5, whereas the number of postdocs increased (Fig. 2). Where the post-doc:PhD student ratio was 1:3 in 2008, it is 1:2 at present.

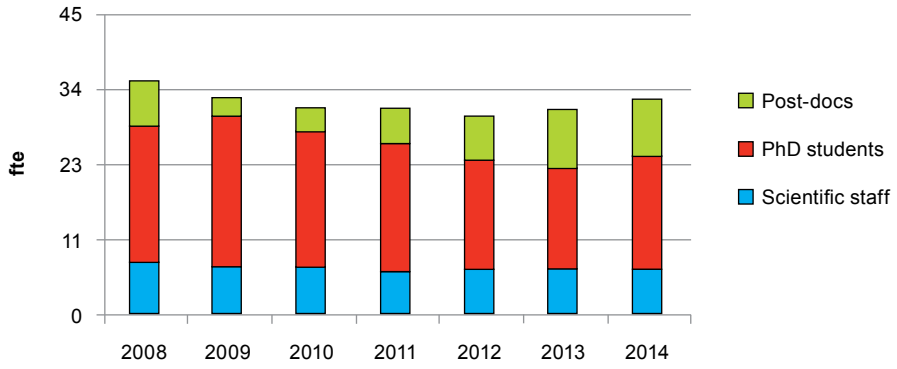



**Figure 2** Personnel during the review period (for numbers see Appendix U2.1).

## Coming period (2015-2020)

In the next period, the personnel strategy will be continued, for which the following actions will be taken:

- To give our research on passive seismic methods a more permanent basis, Dr Draganov has been appointed as tenure-track assistant professor in December 2014. Draganov's track record includes a Veni grant (2007-2010), a Vidi grant (2012-2017), SEG's J. Clarence Karcher Award for young scientists (2010), a publication record of 32 journal papers, and an H-index of 14 (Scopus).
- To continue our cooperation with the geophysical industry, we have received approval from the university board to extend the part-time position of Prof. Mulder for another five years (0.2 fte). Prof. Mulder published 65 journal papers and has an H-index of 19 (Scopus).
- We intend to increase the junior staff gradually to 24-30 PhD students and 8-12 post-docs. Quality remains the main criterion for appointments. In selecting new post-docs, we consider their capacity for being a potential Veni recipient as a crucial criterion.

## 2.3 Funding strategy

Our funding strategy serves our mission to execute fundamental geophysical and petrophysical research with societal applications. In order to deal with the multi-disciplinary aspects of our programme, we strive to cooperate with earth scientists from various disciplines in the Netherlands and Europe. By keeping a balance between governmental and private funding, we do not only ensure a healthy budget but also strengthen partnership with academia and industry. Furthermore, we stimulate post-docs and staff members to apply for personal grants.

Figure 3 depicts the funding of our unit during the review period. National governmental funding seems to be decreasing, but this is partly because reserves of acquired long-term funding are not visible and partly a matter of fluctuations: per December 1, 2015, the unit will employ 2.2 Postdocs (+ 2 vacancies), 1 tenure tracker and 10 PhD students (+ 2 vacancies) funded by NWO, STW, FOM and ISES (this comes to approximately 1.0 mEuro/yr national governmental funding for personnel costs alone). Moreover, long-term national governmental funding is expected to undergo a further significant increase in the coming period due to our planned research on induced seismicity (discussed below). Industry/EU funding is constantly on a high level (50-60%).

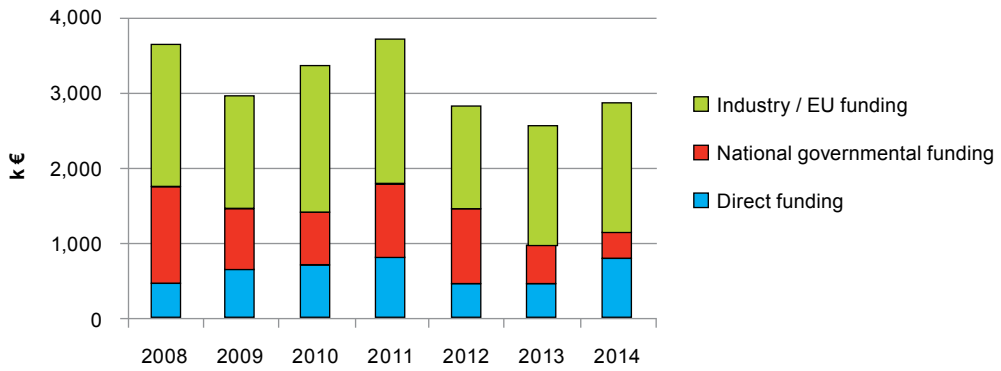



**Figure 3** Research funding during the review period (for numbers see Appendix U2.2).

### Review period

Our main funding sources have been:

**National Governmental Funding**

- **ISES**(Integrated Solid Earth Science) was established in 1999 as one of six National Top Research Schools in the Netherlands, to bring together the top researchers in the field of solid earth science in the Netherlands. In Delft, approximately 70% of the ISES-funded research is carried out in our unit Geophysics. The ISES activities in Delft are coordinated by Prof. Wapenaar. The second phase of ISES ended in 2009. An international committee evaluated the six National Top Research Schools and rated ISES as excellent. This led to the funding of the third phase of ISES (2010 to 2013, 889 kEuro per year for the units Geophysics and Geology).
- **Veni-Vidi-Vici** Post-docs and staff members of the unit Geophysics are actively stimulated to apply for one of these prestigious NWO grants. During the review period, two post-docs received Veni funding (Draganov and Van der Neut) and one acquired a Vidi grant as well (Draganov). One PhD student (Ruigrok) was funded via the **Toptalent** programme of NWO.
- **FOM and STW** Through the years, the unit Geophysics has been very successful in acquiring funds from FOM and STW (9 PhD students in the review period).
- **Lofar** is a national infrastructure programme, which facilitates astronomical and geophysical measurements. The geophysical activities in Lofar are carried out by the unit Geophysics, in cooperation with TNO and KNMI and are coordinated by Dr Drijkoningen. Until the end of 2008, the unit Geophysics received 1.46 mEuro (over a period of six years in total) for Lofar activities from the Dutch government and the Northern Provinces of the Netherlands.

**European Funding**

- **EU FP7** The unit Geophysics participated in four FP7 programmes (2 post-docs, 3 PhD students).

**Public-Private Funding**

- **CATO programme** Throughout the review period, the Department was heavily involved in the national CATO programme on $CO_2$ capture, transport and storage. The programme started in 2003, and went into its second phase in 2009 (with ca. 1.3 mEuro per year for our Department over 5 years). CATO is a public-private partnership involving universities, research institutes, industry and government. In the review period, five post-docs/PhD students (divided over all units of the Department) have been working on a combination of geophysical, petrophysical, reservoir-engineering and geological aspects of $CO_2$ storage and $CO_2$-enhanced oil recovery. CATO activities in Delft are coordinated by Dr Wolf.
- Top Sector Energy (TKI Gas). The unit Geophysics participates with one post-doc.

**Industrial Funding**

- The unit Geophysics received funding via ISAPP (two PhD students) and many **individual industry-sponsored projects** (NAM, Shell, Maersk, Saudi Aramco, Statoil, BP, Schlumberger, TNO, Total, Galp, Deltares).
- **Delphi** is a consortium project, sponsored by 35 companies from the oil and gas industry, dedicated to geophysical exploration research for the industry, managed by the Faculty of Applied Sciences. During the review period, the unit Geophysics received funding for the part-time position of Dr Blacquière and for five PhD students.

## Coming period (2015-2020)

We will continue to fund our research via large programmes and individual projects:

**National Governmental Funding**

- Although much of the ISES-funded research will continue for a number of years, we will investigate possibilities for a new ISES-like programme, together with partners in the Netherlands. One possibility is to apply for a prestigious **NWO Gravitation grant**.
- We will continue to actively stimulate post-docs and staff members to apply for **Veni-Vidi-Vici** grants. One Vidi application has already been granted in May 2015 (Dr Evers).
- **NWO/FOM** will set up a National Knowledge Centre for the Deep Subsurface to stimulate research on induced seismicity, its causes, effects and mitigation. The total budget will be 30 mEuro for the first five years, with a possible extension for another five years. Our unit has been selected as one of three groups in the Netherlands that will form the nucleus of this Knowledge Center.
- We intend to continue applying for **FOM** and **STW** grants. Two STW-funded PhD students have already been granted in February 2015.

**European Funding**

- We increase our efforts to apply for grants from the EU, in particular the **EU H2020** programme. As of 2015, we participate in an EU-funded International Training Network (ITN) (2 PhD students).
- Several of our staff members will apply for prestigious personal grants from the European Research Council (**ERC** starting, consolidator and advanced grants).

**Public-Private Funding**

- We participate in setting up a cooperation programme between TU Delft and KNMI. Within this cooperation, our unit will work on the characterisation and monitoring of remote sources in the oceans and atmosphere.
- Negotiations on funding for a third phase of CATO are currently ongoing.
- We furthermore anticipate to increase the programme on fracturing in shales and tight sandstone (Top Sector Gas), together with partners at Utrecht and Eindhoven Universities, by e.g. STW grants and further industry involvement.

**Industrial Funding**

- We will continue our efforts to apply for further industrial funding. For example, together with the units Geo-Resources and Geology, we are negotiating with an Iranian Geotechnical Research Institute for the Petroleum Industry to start a programme on improved hydrocarbon recovery and related rock physical and geological issues. Intended budget 3 mEuro for three years.
- It is our intention to increase the cooperation with the Delphi consortium. As of 2016, Delphi will be merged with two programmes dealing with smart fields and EOR, run by the Geo-Resources unit (ISAPP and RF). With the petroleum and geophysics aspects combined, this consortium will thus have a stronger basis in our Geo-Cluster.

## 2.4 Publication strategy

### Review period

The research of the unit Geophysics is primarily published in international peer-reviewed journals, conference proceedings and PhD theses (Fig. 4). Although fluctuating over the years, we see an increase in journal articles by roughly 50%. This is remarkable as the number of staff slightly decreased over time. The unit stimulates PhD students to compile their theses, as far as possible, from journal papers. Apart from the typical applied geophysics and petrophysics journals (Geophysics, Geophysical Prospecting, Journal of Applied Geophysics, Near-Surface Geophysics, Transport in Porous Media), the unit strives to publish a good number of the papers (roughly 40%) outside this domain, to reach a wider scientific community. On the one hand, this concerns physics-oriented journals for the more fundamental research, such as Physical Review Letters (key publication Wapenaar et al. 2013), Journal of the Acoustical Society of America, IEEE Transactions on Antennas and Propagation. On the other hand, we publish in broader geoscience-oriented journals, such as Journal of Geophysical Research (Solid Earth; Atmospheres), Geophysical Journal International, Geophysical Research Letters (key publication Van Dalen et al. 2010), IEEE Transactions on Geoscience and Remote Sensing, International Journal of Greenhouse Gas Control, International Journal of Coal Geology (key publication Mazumder & Wolf, 2008). Occasionally, we contribute to papers in Nature and Science. Scientific visibility is further enhanced by editorships of major journals: Wapenaar was Editor-in-Chief of Geophysics from 2007 until 2009 and Slob is Editor-in-Chief of Geophysics from 2013 until 2015 (this position is combined with membership of the SEG Board of Directors); for all editorships, see the Output list (Appendix U2.3).

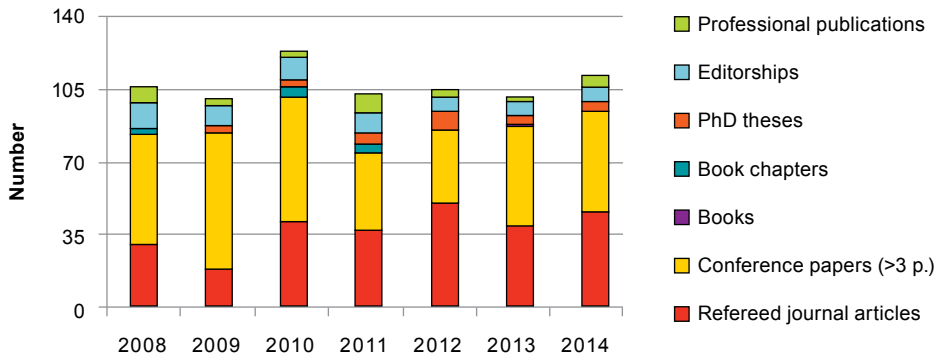



**Figure 4** Research output during the review period (for numbers see Appendix U2.3).

### Coming period (2015-2020)

To maintain the scientific visibility of the unit, we will continue to publish in the major geoscience and physics journals. We strive to keep the publication rate on the high level that has been reached during the evaluation period, i.e. 0.75 journal papers per PhD student per year, 2 papers per post-doc per year, and 1.5 papers per staff member per year (numbers refer to first-author journal papers). With the intended growth of junior staff this comes to a total of 45 to 55 peer-reviewed journal papers per year. We continue to stimulate editorships of major journals, organisation of international workshops and special sections, participation in research committees, etc.

# 3 Research results and quality

## 3.1 Theme 1: Exploration Geophysics

*Scientific staff: Prof. Wapenaar (0.8 fte), Prof. Slob (0.5 fte), Prof. Mulder (0.4 fte until 2010, 0.2 fte since 2011), Prof. Arts (0.4 fte until 2010), Prof. Petersen (0.1 fte, 2010-2012), Dr Drijkoningen (0.5 fte), Dr Ghose (0.2 fte), Dr Blacquière (0.2 fte until 2010, 0.4 fte since 2011), Dr Draganov (1.0 fte since December 2014).*

**Introduction**. Using fundamental aspects of wave propagation and scattering in inhomogeneous media, we develop novel seismic and electromagnetic imaging and monitoring methodologies, accounting for the complex propagation and scattering phenomena of the inhomogeneous subsurface. This methodology development aims to contribute to the next generation of geophysical exploration methods employed by the oil and gas industry. Moreover, our imaging and monitoring methodology finds applications in regional and global geophysics and in non-destructive imaging of materials.

**Seismic interferometry** encompasses the creation of virtual sources at positions where there are only receivers. The responses to these virtual sources are constructed from field measurements at receivers, without the need to know the medium parameters and the positions and properties of the physical sources. The applications range from subsurface imaging using ambient noise to high-resolution reservoir imaging and monitoring using controlled-source data. The main developments during the review period concern the introduction of interferometry by multidimensional deconvolution to compensate for irregular illumination, and the application of the methodology to many case studies at a wide range of scales (Fig. 5). During the review period we published 64 journal papers on seismic interferometry and three PhD students finalised their thesis (Hunziker (2012), Ruigrok (2012), Van der Neut (2012, cum laude)). See our website and the key publication by Draganov et al. (2009) for more information.

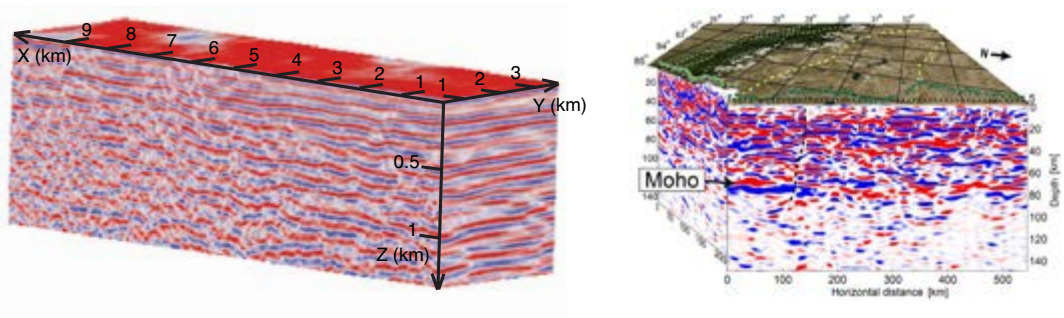


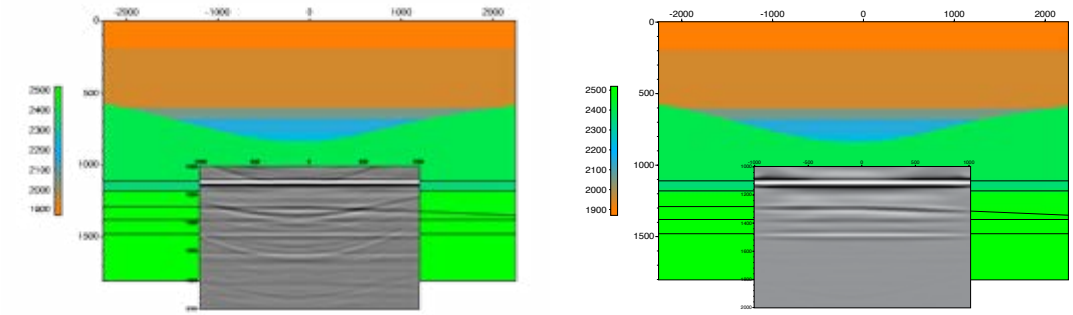

**Figure 5** Two case studies of seismic interferometry at different scales. **Left**: Geology beneath the Libyan desert, obtained from ambient noise. **Right**: Tectonic blocks below the Tibetan Plateau, obtained from teleseismic data.

The unit Geophysics is recognised as one of the pioneering groups in this field and received several distinguished prizes (see Chapter 3.4).

In the coming period we will continue our research in this field, with an emphasis on developing new practical applications. Cooperation in this field with many universities and companies around the world will continue. Dr Draganov will play a prominent role in co-leading this research. Together with colleagues of the unit Geodesy, we explore combinations of seismic interferometry and satellite radar interferometry.

**Marchenko imaging** is a new imaging methodology, pioneered by the unit Geophysics since 2011, in cooperation with Colorado School of Mines. It represents the next step beyond seismic interferometry, in the sense that no physical receivers are needed at the positions where virtual sources are created. This opens a fundamentally new line in seismic imaging and inversion. One of its promises is to deal

with internal multiple scattering in a data-driven way, i.e., without the need to derive a model which explains the multiple scattering (Fig. 6). Since 2012, we published 11 journal papers on Marchenko imaging. For more information, see our website and the key publication by Wapenaar et al. (2013). Marks of recognition of our work in this still very new field are a Physics spotlight article, a Geophysics Bright Spots column in The Leading Edge (highlighting three of our Geophysics papers in 2014), invitations for workshop presentations (AGU, SEG, EAGE, DGG, CNRS, EuCAP), two nominations as Top-30 presentations (SEG, 2013, 2014) and an EAGE-E-lecture. Moreover, inspired by our preliminary results, other groups have started similar research (ETH Zürich, Edinburg University, Schlumberger, Shell, etc.).




False images from internal multiples

Marchenko imaging

**Figure 6** Standard seismic imaging is hampered by false images from internal multiples (left), whereas Marchenko imaging properly deals with internal multiples (right).

For the coming period, we plan to spend much effort on this emerging field. Van der Neut obtained a Veni grant (2013) for research related to Marchenko imaging and we recently acquired an STW grant for 2 PhD students. We will continue our cooperation with Colorado School of Mines and extend cooperation in this area with other universities and companies.

**Reservoir characterisation and monitoring**. Part of our work on reservoir characterisation is carried out in close cooperation with the unit Geology. We developed methods that invert seismic data at high resolution by constraining the inversion process with geological knowledge (4 papers by Toxopeus, Tetyukhina and Hjelle, 2 PhD theses by Tetyukhina (2010) and Hjelle (2014)). Moreover, we investigated the characterisation of fractured reservoirs from their frequency-dependent response. Significant progress has been made in using linear slip theory for imaging and characterisation of the individual large-to-intermediate-scale fractures, which primarily control the permeability of a fractured reservoir (3 papers by Minato).

To monitor time-lapse changes in a reservoir during production, we combined time-lapse seismic monitoring with geomechanical modelling and investigated the interaction between oil production and changes in the overburden (PhD thesis Angelov, 2009). We investigated the use of time-lapse seismic monitoring combined with data-assimilation techniques to improve production of oil reservoirs (paper plus PhD thesis (2012) by Trani). Furthermore, we developed a monitoring tool, which consists of borehole radar coupled with subsurface fluid-flow modelling to optimise hydrocarbon production (2 papers plus PhD thesis (2012) by Miorali).

Controlled-source electromagnetic method (CSEM) has become an established derisking tool for hydrocarbon exploration. Since 2007, several forward and inverse modelling and monitoring studies have been performed (7 papers plus 2 PhD theses (2012) by Tehrani and Wirianto). Moreover, we developed CSEM interferometry by deconvolution (8 papers plus PhD thesis (2012) by Hunziker). This has led to new insights in fast modelling, using synthetic aperture processing, and exploring acquisition geometries for monitoring, see also Chapter 4.3.

There is an increasing interest for monitoring and controlling of subsurface processes, not only in hydrocarbon reservoirs, but also in environmental and engineering applications. In the coming period we will increase our efforts in further developing geophysical time-lapse methodology, which will

be coupled with multiscale modelling of subsurface processes as well as with laboratory research on fractures, fracture networks and signatures of fractures. This will require a concerted effort of researchers in the three themes of our unit, as well as a strengthening of our cooperation with the unit Geo-Resources. This cooperation will be facilitated by the intended merger between Delphi, ISAPP and RF.

**Acquisition infrastructure and methodology**. In cooperation with TNO and KNMI, an acquisition infrastructure for seismic monitoring has been built in the northern part of the Netherlands (Lofar, Fig. 7). It has created the possibility to validate our interferometric methods (paper by Almagro Vidal, 2014), and it is used for validating active-seismic monitoring methods. On the technological side, it has generated new concepts of how to set up such large-scale networks, and this continues to be used in projects from TNO nowadays. In the coming period, the Lofar network will amongst others be used for the programme on induced seismicity (see next item), to monitor gas-induced earthquakes occurring in that region.

**Figure 7** Installing the LOFAR geophone & hydrophone (right) at depth at Annerveen.

A new trend in the seismic exploration community is simultaneous-source acquisition, also known as blended acquisition. Seismic sources are ignited with relatively small intervals one after the other, to reduce the total acquisition time or to improve the image quality. As a result, the seismic response can be seen as a superposition of time-delayed seismic shot records. Using standard shot-record oriented processing and imaging, “crosstalk” between the sources causes the images to be noisy. We investigated the reduction of the crosstalk (“deblending”) by prediction and subtraction (3 papers plus PhD theses by Mahdad (2012) and Doulgeris (2013)), and by inverting the “blending operator” via seismic interferometry by multidimensional deconvolution. Ongoing PhD research (Kumar) concerns blended acquisition design for fluid front monitoring in the northern part of the Netherlands.

**Figure 8** New type of vibrator based on Linear Synchronous Motors: the lower the frequency, the better it works.

Research on velocity estimation (7 papers plus 2 PhD theses (2010) by Hak and Van Leeuwen) reveals that low seismic frequencies, which are usually absent in seismic exploration data, are important to get a more reliable estimate of the background velocity model. Generating those low frequencies (typically down to 1.5 or 2 Hz) cannot be done by standard seismic vibrators and therefore a new technology has been used to make a vibrator that can generate them, using so-called Linear Synchronous Motors (ongoing PhD research by Noorlandt, Fig. 8). This new vibrator is not only being used for velocity estimation, imaging and monitoring, but also for characterizing structure stabilities under earthquakes, such as occurring in the northern part of the Netherlands.

**Intended programme on induced seismicity**. Gas production in the northern part of the Netherlands has recently led to an increase in number and strength of induced earthquakes. NWO and FOM are in the process of setting up a National Knowledge Centre for the Deep Subsurface to create the fundamental basis of understanding the geomechanical processes of induced seismicity and to develop an improved basis for hazard estimation and mitigation. Our unit will be one of the key players in this programme. We will investigate the mechanisms of gas-induced earthquakes via experiments in the laboratory, and seismic methods to detect, image and characterise such earthquakes via new approaches in acquisition and processing.

## 3.2 Theme 2: Environmental and Engineering Geophysics

*Scientific staff: Prof. Slob (0.3 fte), Prof. Wapenaar (0.2 fte), Dr Drijkoningen (0.5 fte), Dr Evers (0.2 fte since 2012), Dr Ghose (0.8 fte).*

**Introduction**. With the increasing infrastructural loads and the demand for use of the underground space, as well as the effects of human activities, climate change and natural disasters on the shallow subsurface and the environment, the importance of environmental and engineering geophysics is growing rapidly. We develop novel concepts and efficient methodologies to address this demand.

**Hydrogeophysics** faces the challenge of providing the necessary information for understanding the presently unknown impact and consequences of anthropogenic activities on the shallow subsurface and associated ecosystems. Improving the information delivery is investigated by the ground-penetrating-radar method (key publication by Slob et al., 2010), combined with full waveform inversion (4 papers plus PhD thesis (2013) by Patriarca). Moreover, we investigate the practical application of interferometry applied to electromagnetic noise at ground-penetrating radar frequencies (PhD research Feld). Close collaboration with the Université Catholique de Louvain has led to an integrated approach for coupling subsurface hydrodynamic flow models and geophysical inverse models (see 14 papers and 5 book chapters of Slob and Patriarca published together with Prof. Lambot). A new approach to seismo-electric imaging aims to retrieve the coupling coefficient between elastic wave motion and electric field disturbances. This parameter can provide information on the bulk hydraulic permeability. PhD student Grobbe received recognition from SEG for his presentation on this subject at the 2014 SEG conference (runner-up as best student presentation). We work on the implementation of correlation imaging using seismo-electromagnetic wavefields (2 papers by Grobbe).

The shallow subsoil is generally more porous than the deeper, compacted earth formations. It has been found recently that poroelastic wave propagation in the shallow subsoil layers can be practically utilised to obtain reliable, in-situ values of properties like hydraulic conductivity and porosity of the shallow soil layers (2 papers plus PhD thesis (2014) by Zhubayev). Inversion schemes, which take advantage of the underlying physics of seismic wave propagation in fluid-filled porous media have been developed and successfully tested in the field. This has opened up a new direction of research in this field. We will continue developing further this promising approach for reliable quantification of the transport properties, not only in the near-surface unconsolidated formations, but also in porous reservoirs containing water or hydrocarbons.

Novel near-surface geophysical approaches, incorporating high-resolution seismic methods (using ultra-shallow body wave reflections and surface wave dispersion), electrical methods, and innovative use of interferometric retrieval of shallow seismic wavefield, are being developed for reliable imaging and characterisation of municipal solid waste landfills, in cooperation with the unit Geo-Engineering (paper by Konstantaki). The recent results show improved capability to locate shallow buried objects and define the leachate pathways in a highly heterogeneous environment (Fig. 9). Further research will supplement data-driven chemical modelling in order to provide a robust technology for reduction of emission potential of solid-waste landfills.

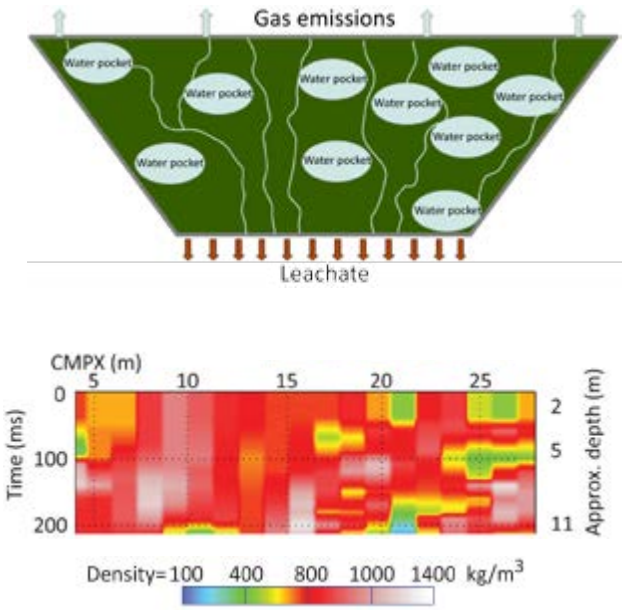



**Figure 9a** (Top) The distribution of heterogeneities control the leachate flowpaths in a landfill (schematic).
**Figure 9b** (bottom) Density distribution in the body of a landfill determined from high-frequency shear-wave reflection data.

**Engineering Geophysics.** Novel approaches are being developed for quantitative integration of multiple field measurements based on the underlying physics, in order to predict and monitor the subsurface properties. Quantitative integration of seismic and geotechnical field measurements and high-frequency seismic and electromagnetic (GPR) wavefield measurements has established new possibilities. Innovative concepts for data-driven and model-based integration of shear-wave seismic reflection data and cone-penetration-test (CPT) data have been proposed and successfully tested on field data (2 papers by Ghose, 2012). We have also developed new field hardware to facilitate these new applications. With further research on these innovations we strive to accomplish breakthroughs in in situ quantitative characterisation of the near-surface soil layers.

We perform research in the field of high-resolution imaging and characterisation of the near-surface soils using shear-wave reflections (paper by Ghose, 2013). For this purpose, a novel high-frequency electromagnetic vibrator system and its application are being continuously improved. Besides enhanced imaging capability, the combination with modelling is considered crucial in this research. The results are valuable to geotechnical and civil engineers, and to those engaged in disaster mitigation works. We will continue these developments and seek for new and effective applications.

It has been found that seismic shear waves can be used to monitor changes in the stress state in the unconsolidated formations at shallow depths. New conceptual developments, design of novel field hardware, and laboratory tests constitute key components of this research. In-situ monitoring of the stress state in the shallow subsoil is very difficult, yet remains crucial in many projects (book chapter by Ghose, 2010). Research is now under progress to illuminate the effect of stress on the grain contacts and toward inversion of in-situ stress state using the related physics.

Acquiring seismic data for retrieving the shear-wave properties of the subsurface is quite cumbersome in a marine environment, and therefore new acquisition and processing methods have been and are being developed. Our research showed that the so-called P*S wave is a type of wave that can be generated in the water and converts to a conventional shear wave at the sea floor (2 papers plus PhD thesis (2011) by El Allouche). This requires adapted acquisition and processing strategies to obtain shear-wave images of the shallow subsurface. Such methods find their applications in the offshore industry, e.g., constructions on the sea floor or finding sand for building purposes.

When a Tunnel-Boring Machine (TBM) bores in soft soil, it does this nearly always “blindly”, i.e., no system is then available to sense the ground in front of the TBM. Using the expertise of our unit on shear waves in shallow environments, a full-waveform-inversion approach has been developed to image in front of a TBM (PhD research Pisupati). This includes the development (with partners) of a new type of seismic vibrator and an automatic processing sequence. This is part of the EU-sponsored project NeTTUN.

**Monitoring the atmosphere and oceans with infrasound**. Low frequency acoustic waves travel over enormous ranges through the atmosphere and oceans, since the energy is hardly attenuated. Measurements of infrasound can be used to monitor the properties of the atmosphere and ocean, or to identify infrasound sources, such as volcanoes, meteors, earthquakes, calving ice, explosions and military activity. Sudden Stratospheric Warmings drastically change the upper atmospheric wind and temperature and have been studied with ambient infrasonic noise (2 papers by Smets). Our results show that more details can be retrieved than global atmospheric models can resolve. Interferometry applied to infrasonic recordings also showed its merits for monitoring changes in the atmosphere (2 papers by Fricke, Fig. 10).

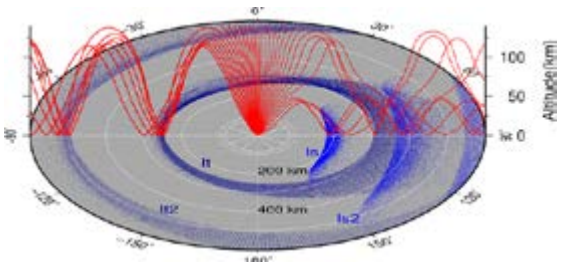



**Figure 10** Infrasound propagation through the dynamic atmosphere. The footprint on the earth’s surface is continuously changing as a function of time and geographical location and thus contains information on the upper atmospheric wind and temperature structure.

Source-specific studies on underwater volcanoes and disintegrating icebergs (2 papers by Evers, 2013) were realised by using seismic, hydro-acoustic and infrasonic recordings of the International Monitoring System (IMS) for the verification of the Comprehensive Nuclear-Test-Ban Treaty (CTBT). The IMS consists of seismic, hydro-acoustic and infrasonic stations. The added value of an integrated analysis was also shown in a study on evanescent wave coupling, where infrasound was discovered in the atmosphere from an underwater earthquake (paper by Evers, 2014). A huge meteoroid exploded over Siberia on 2013, February 15, and the associated infrasound was globally detected. The explosive energy was estimated at 500 kT TNT equivalent and specifics on the source were published in Nature and Science, with Evers as co-author.

For the coming period, we plan to extend our work on integrated seismo-acoustic monitoring, using deterministic transient signals and interferometry with random noise. Data from local, regional and global seismo-acoustic networks will form the input for these studies. These projects entail a close collaboration with the KNMI and the units Geodesy and Atmosphere and funding is requested from NWO/STW (this includes Evers’ Vidi project, 2015), the Dutch Ministry of Foreign Affairs, the EU and the CTBT Organisation.

## 3.3 Theme 3: Petrophysics

*Scientific staff: Prof. Slob (0.2 fte), Dr Wolf (1.0 fte), Dr De Pater (0.8 fte until 2009), Dr Smeulders (1.0 fte until 2010), Dr Barnhoorn (0.9 fte since 2011).*

**Introduction**. Using the physics of porous and fractured media, we investigate the effects of porosity, saturation, permeability, fracture density and fracture connectivity on fluid flow, we study

rock mechanics and rock structure, and we study seismic, electromagnetic and coupled seismo-electromagnetic wave propagation, both with computer models and laboratory experiments. The acquired knowledge supports themes 1 and 2. It leads to improved geophysical characterisation methodology for porous and fractured media, with applications in environmental and engineering geophysics, in exploration geophysics, as well as in reservoir engineering.

**Seismic and electromagnetic fields in porous media**. For the characterisation of fluids in rocks, understanding wave propagation in poroelastic media is essential, and research was carried out on different aspects. It has been discovered that mesoscopic heterogeneities in the frame and the fluid are needed to explain wave attenuation in fluid-saturated porous media (paper plus PhD thesis (2009) by Vogelaar). Our research also showed that using the full waveform in predictions of poroelastic wave propagation sometimes characterises the medium properties much better than travel time and attenuation attributes alone (6 papers plus PhD thesis (2011) by Van Dalen, including the key publication Van Dalen et al., 2010). For his PhD work, Van Dalen received the Springer thesis award, and his thesis has appeared in the Springer Thesis series.

Using complex resistivity measurements we study the electric response of heterogeneous porous media to electromagnetic disturbances. This provides fundamental understanding of the electric properties of porous media that is used in electromagnetic inversion (6 papers plus 2 PhD theses by Kavian (2011) and Ponziani (2012, co-supervised with unit Geo-Engineering)). Through physical experiments on porous soil and rock samples, we study the coupled electromagnetic and seismic response of porous media. This confirms the validity of the existing theoretical model for these coupled wavefields (5 papers plus 2 PhD theses (2011) by Schoemaker and Schakel (cum laude)).

**Fracture control, networks, fluids and seismic signatures**. Fractures, either naturally present or man-made, have a large control on fluid flow in conventional and unconventional hydrocarbon exploration, in geothermal energy exploration and in sequestration measures. The interaction between fractures and fluids, fracture network connectivity (Fig. 11), chemical reactions on fracture surfaces, and changes in seismic signature during fracturing has been and will be an important focus of our research (2 papers and PhD thesis (2014) by H. Fan).

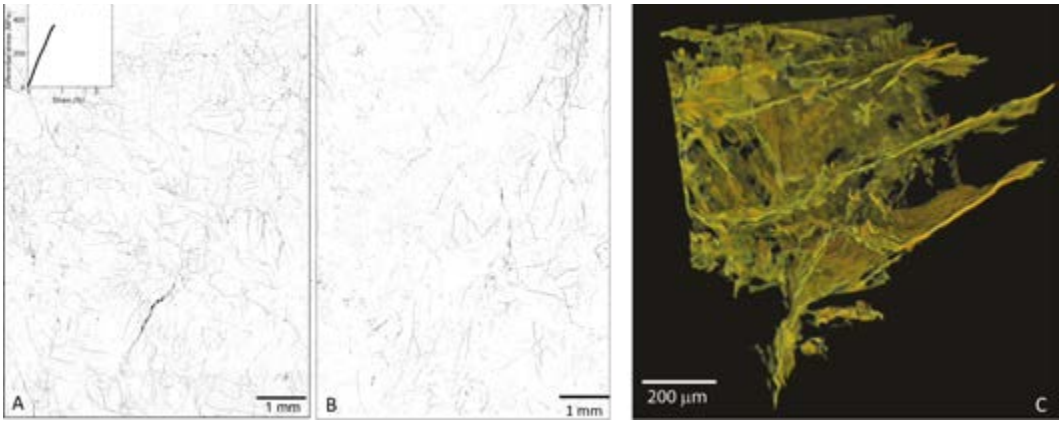



**Figure 11** Fracture network representation in an rock fracturing experiment due to (A) high stress conditions and (B) due to high fluid pressure conditions at the top of the sample. (C) Three dimensional micro CT image of a 3D fully connected fracture network. Connectivity of fractures in 2D slices has not yet been established.

Fracture network development research has been part of several initiatives, e.g., Top Sector Gas, CATO. A strong cooperation with the unit Geology and partners at Utrecht and Eindhoven Universities is part of this focus. Research on fracture control in permeable chalks, sponsored by Maersk, resulted in the experimental and theoretical development of a geochemical method to close fractures and create a wormhole complex as an alternative to keep a permeable zone for hydrocarbon transport (2 papers by Salimi).

**3D visualisation of rock structures and rock-fluid-gas interaction.** The purchase of a state-of-the-art micro-CT scanner enabled us to image rock structures at very high detail in three dimensions (up to 1 µm). We visualise individual grains, porosity, porosity infill and fractures at very high detail (Fig. 12) and image e.g. the effects of fluid/gas phases affecting pore frameworks (3 papers plus PhD thesis (2014) by Shojai Kaveh (pendant drop experiments), ongoing PhD research of Peksa (second phase $CO_2$-brine-EOR) and 2 papers by Salimi (chalk-acid flow behaviour), all in cooperation with the unit Geo-Resources). Currently, we perform in-situ tests (e.g. fluid flow tests and soon deformation tests) in the CT scanner and in pressure chambers while simultaneously imaging the samples. We strive to improve the texture resolution of our equipment so that petrophysical behaviour, like wettability and dielectric characteristics, can be studied at mineral scale.

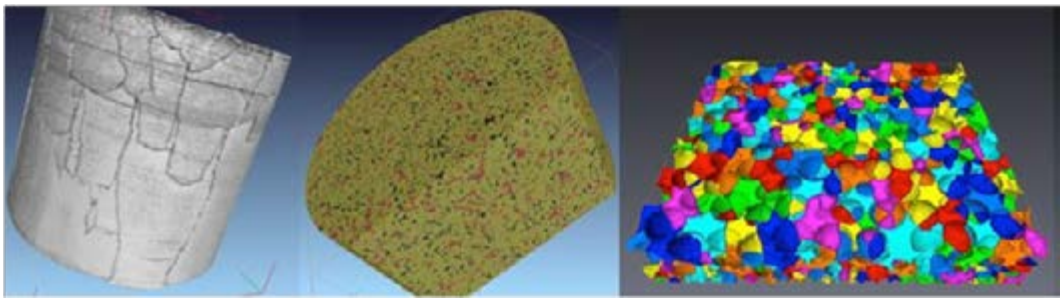


**Figure 12** Three dimensional micro-CT images of a fractured shale sample, of a sandstone that has naturally been exposed to prolonged $CO_2$ fluxes and pore visualisation and segmentation in an artificially created rock sample.

**$CO_2$ storage, clean coal/shale technologies**. Our petrophysical research is also focused on developing innovative methodologies for $CO_2$ storage, clean coal technologies and geothermal and reservoir engineering research. For $CO_2$ storage, a novel electrical-seismic laboratory facility is being developed to understand and utilise the signature of phase, saturation and pressure changes at potential leakage zones, and to understand accompanying key physical mechanisms (e.g. residual trapping, dissolution and precipitation on spectral induced polarization, and seismic velocity and attenuation). The interaction between coal/shale-brine-methane-$CO_2$/fluegas was studied in very special developed sorption and diffusion experiments. Wettability research was expanded to sandstones and shales. Finally, we focused on exergy and explained various types of $CO_2$ capture, transport and storage. This expertise is now extended to the FP7-TOPS project for a combination of in situ coal combustion with the improvement of injectivity for $CO_2$ storage.

Our research within the CATO programme was carried out in close cooperation with the units of Geo-Resources and Geo-Engineering (each two co-supervised PhD projects). It was a very productive programme in terms of publications and PhD theses. In total, 11 papers and 5 PhD theses were published under the (co-)supervision of Dr Wolf (Van Hemert (2009), Battistuta (2011), Eftekhari (2013), Shojai Kaveh (2014, cum laude), Khosrokhavar (2014), see also key publication by Mazumder & Wolf (2008)).

**Geothermal research** within the DAP and CATO programmes involved e.g. research on co-injection of $CO_2$ with the return water in aquifers and the development of a combined geophysical, static reservoir model for the prospected well on campus. The static reservoir model is the base for the prediction of $CO_2$ behaviour in an aquifer. The PhD work of Salimi produced a mathematical prediction tool for long term monitoring (2 papers, including key societal output by Salimi et al., 2012). We cooperate in a new Dutch-Indonesia geothermal research consortium (GEOCAP) that has started in 2014.

**Draganov, D**, Campman, X, **Thorbecke, J**, Verdel, A & **Wapenaar, K** (2009). Reflection images from ambient seismic noise. Geophysics, 74 (5), A63-A67.

**Mazumder, S** & **Wolf, KH** (2008). Differential swelling and permeability change of coal in response to $CO_2$ injection for ECBM. International Journal of Coal Geology, 74 (2), 123-138.

**Slob, E**, Sato, M & Olhoeft, G (2010). Surface and borehole ground-penetrating-radar developments: Geophysics, 75 (5), 75A103-75A120.

**Van Dalen, KN, Ghose, R, Drijkoningen, GG** & **Smeulders, DMJ** (2010). In-situ permeability from integrated poroelastic reflection coefficients. Geophysical Research Letters, 37 (12), L12303.

**Wapenaar, K**, Broggini, F, **Slob, E** & Snieder, R (2013). Three-dimensional single-sided Marchenko inverse scattering, data-driven focusing, Green's function retrieval, and their mutual relations: Physical Review Letters, 110, 084301.

**Figure 13** Key publications.

## 3.4 Summary of research quality

### Research products

The publication record of our unit has reached a high level of 47 journal articles per year which we want to keep or possibly even increase during the next years.

During the review period, the unit underwent some personnel changes. We were able to replace leaving staff members by and fill a new part-time position in cooperation with the GRS department with scientists with excellent reputation and track record (Prof. Slob (selected from international pool to become full professor of Geophysical EM methods), Dr Barnhoorn, Dr Evers).

### Use of research products

Our high H-indices reflect the quality of our publications (Appendix U2.4): Besides Wapenaar (30) and Slob (26), are especially remarkable the H-indices of part-time professors Mulder (19) and Evers (13), as well as our junior staff members Barnhoorn (12) and Draganov (14), all based on Scopus. Our research is of broader interest than just the "applied geophysics community", given our publications in physics- and geoscience-oriented journals.
Several of our staff members give high-qualified courses for international peers. For example, since 2012 Draganov, Thorbecke and Wapenaar contribute to SEG's Continuing Education programme.

Top-3 most cited papers in review period:

- M**azumder, S** & **Wolf, KH** (2008). Differential swelling and permeability change of coal in response to CO2 injection for ECBM. Int. J. Coal Geol., 74 (2), 123-138. (91 citations (Scopus))
- **Wapenaar, K, Slob, E,** & Snieder, R (2008). Seismic and electromagnetic controlled-source interferometry in dissipative media. Geophys. Prosp., 56 (3), 419-434. (82 citations (Scopus))
- **Draganov, D,** Campman, X, **Thorbecke, J**, Verdel, A & **Wapenaar, K** (2009). Reflection images from ambient seismic noise. Geophysics, 74 (5), A63-A67. (78 citations (Scopus))

#### Marks of recognition from academic peers

Funding by the National government is on a high level, including the private-public programmes of CATO, Lofar, and the Topsector Gas. Our success rate for STW proposals is 100% since 2000. We are proud of four PhD students/post-docs who received prestigious Veni, Vidi, and Toptalent grants. Three PhD students (co-)supervised in our unit graduated cum laude and one received the Springer thesis award.

Our staff has a high reputation in the academic community. Especially our research on seismic interferometry has been very productive (64 papers during the review period) and is world-leading. Marks of recognition during the review period include: Wapenaar received SEG's Virgil Kauffman Gold Medal (2010) and EAGE's Conrad Schlumberger Award (2013), Draganov received SEG's J. Clarence Karcher Award (2010) and obtained a Vidi grant (2012), Van der Neut received two SEG best presentation awards (2009, 2010) and the J. Clarence Karcher Award (to be presented to him in

2015) and Ruigrok received AGU's outstanding student paper award (2010). Three of our papers in Geophysics, The Leading Edge and Geophysical Prospecting belong to the most cited papers in those journals since 2006 (positions 2, 1 and 3, respectively, according to Scopus). Also the still very new field of Marchenko imaging has received considerable attention by spot light articles and numerous invitations for presentations, which resulted in other universities and companies taking up this theme.

Wapenaar and Slob both took 2 years' turn as Editor-in-Chief of Geophysics (which includes membership of SEG's Board of Directors). Many staff members serve as associate editor (Appendix U2.3). Slob has spent sabbaticals at Colorado School of Mines (6 months in 2009) and University of São Paulo (4 months in 2014). Staff members participate in the organisation of international workshops and special sessions and chair or take part in research and publication committees (e.g., Wapenaar was chairman of SEG's publication policy committee from 2012 until 2014, Draganov was chairman of SEG's continuing education committee from 2012 until 2014, Drijkoningen, Ghose and Wapenaar participate(d) in EAGE's research committee).

# 4 Relevance to society

The unit Geophysics pursues various ways of engagement with society, in order to facilitate the implementation of research results in industry, governmental bodies, and reach the general public.

## 4.1 Projects in cooperation with (and sponsored by) industry

A significant portion (roughly 50-60 %, Fig. 3) of our research is supported by oil and gas companies, service companies and large institutes, not only via programmes like CATO, Lofar, ISAPP, Delphi, TKI Gas, but also via direct individual projects. In projects funded by the national government (STW, NWO-Veni and FOM), the installation of user committees ensures guidance from company representatives. The time invested by these companies into the guidance also indicates their appreciation for our research. Furthermore, EU programmes with high societal relevance also build upon cooperation with large companies as well as (semi)governmental institutes like TNO and KNMI. Consequently, many of our projects have industry involved in one way or the other.

## 4.2 Part-time staff from industry and (semi)governmental bodies

Our research is further supported by industry and institutes via several part-time staff positions. These staff members form a bridge between research in our section and applications in industry:

- Prof. Mulder (Shell), geophysical imaging,
- Prof. Arts (TNO), seismic monitoring ('time-lapse seismic'),
- Dr Evers (KNMI), infrasonic investigations of the atmosphere,
- Dr Blacquiere (Delphi consortium), seismic acquisition.

Through these positions an efficient knowledge transfer is facilitated in both directions. In addition, these secondments are certainly a mark of recognition by the companies/institutes as they free their staff to do academic research in our unit.

## 4.3 Publications of research results and software

Some of our research results are not only relevant for experts in the specific field but are very suitable for related disciplines. Therefore, we strive to publish these results in journals that target a specific audience that might benefit from our results. Concerning software that we develop we also use ways of making it available for a broader public.

- The research in seismic interferometry (SI) has led to the proposal of a new technique for monitoring of $CO_2$-sequestration. The results were published in the Journal of International Greenhouse Gas Control (Draganov et al., 2012).

- Findings from Geothermal research were published in journals like Renewable Energy and International Journal of Greenhouse Gas Control (Salimi, Nick; see key societal output by Salimi et al., 2012).
- A finite-difference modelling software package that we developed for SI was published as freeware (Thorbecke and Draganov, Geophysics 2011). The modelling package has been downloaded and used around the globe, see the analytics.
- Together with Shell, field CSEM tests have been carried out to validate the use of vertical electric dipoles for monitoring the flow of gases in the subsurface. Investigations by Wirianto et al. (2010, key societal output) suggest that this type of configuration is the most favourable. First field data results on CSEM monitoring are expected in 2015.
- All research results acquired within the Delphi consortium are made accessible by distributing software to its sponsors.
- Our publications are cited in 120 patent applications by third parties (Scopus).

## 4.4 Research products made available to adjacent fields of societal application

We used our expertise and experience in seismic imaging for exploration geophysics to cross-fertilise other areas and address societal questions.

- In a project sponsored by the Argentina government and supported by the municipality of Malargüe we imaged the structure of the Moho, mantle, a subducting slab, and the subsurface next to an active volcano in the Malargüe region, Argentina (key societal output by Nishitsuji et al., 2014). This project was of great interest to the authorities as they aim to develop their risk assessment related to the volcano.

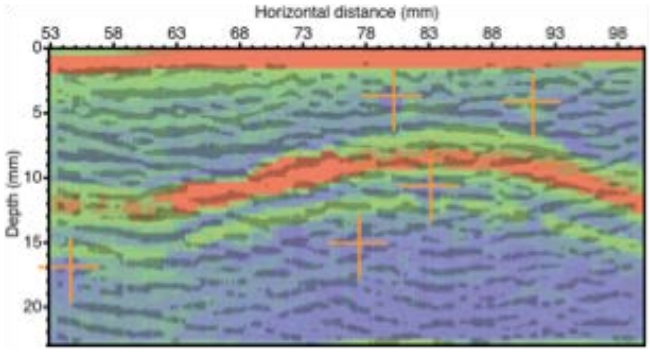



**Figure 14** Overlay of the depth images of an artwork mock-up obtained from X-ray computed tomography (colour) and from reflections retrieved with seismic interferometry (grey-level display).

- An interesting spin-off area is ultrasonic imaging of art objects for their conservation and restoration. We developed a new method for ultrasonic imaging of artworks (painting on wood, Fig. 14), frescoes, sculptures, etc.), using SI by multidimensional deconvolution.
- Small-throw seismogenic fault segments hidden in the Holocene sediments are crucial but difficult targets in seismic exploration. With shear-wave reflections, we detected a deformation pattern and a concealed fault segment in the unconsolidated sediments at Vila Franca Xira, Portugal (see key societal output by Ghose et al., 2013). Prior to this finding there was no evidence for Holocene activity of this fault, although this fault is considered to be the most probable source for the disastrous 1531 earthquake.
- We investigate the possibilities to use Marchenko imaging in medical imaging applications (cooperation with Dr Van Wijk, Auckland), in non-destructive testing of construction materials (such as fiber-reinforced metal laminates) and in ultrasonic imaging of highly scattering concrete.

## 4.5 Recommendations to governmental bodies

Some of our research projects target at safe and efficient engineering constructions, sustainable maintenance of environment, and natural or man-made disaster mitigation. These projects have a rather direct influence on societal decision making.

- Methods of $CO_2$-enhanced coalbed methane production (ECBM) were developed within the CATO programme and have been promoted in China and Australia, where the results are implemented in continuing research and in clean coal technology programmes (key publication Mazumder & Wolf, 2008).
- Results of our research into seismo-acoustic waves are used to verify the Comprehensive Nuclear-Test-Ban Treaty (see key societal output by Green, Evers et al., 2013). Dr Evers advises the Dutch Permanent Mission to the UN in Vienna.
- During the construction of the North-South metro line, a subwayline in Amsterdam, old houses at the Vijzelgracht were damaged due to subsidence generated by water inflow in the building pit. Prof. Slob was asked by Deltares to assess the quality of the geophysical fieldwork, data processing, and interpretation of the results performed by one of the companies involved.
- Prof. Slob has a long-standing relation with the national police of the Netherlands (KLPD) to aid them in the use of new geophysical methods for subsurface crime-scene investigations.

## 4.6 New societal relevant research lines

We keep our eyes open to developments of research fields that are highly societal relevant and where our unit can contribute with its geophysical expertise. One excellent example that was developed during the review period is the following:

- In 2007, Applied Earth Sciences students initiated the Delft Geothermal Energy Project (DAP-programme), with the objective to realise a geothermal doublet on campus to provide a sustainable, $CO_2$-neutral heating source for TU Delft buildings and likewise an in-situ laboratory. In a combined initiative between the units Geophysics, Geology and Geo-Resources, DAP was launched to develop an “Education-Application-Research” programme. The DAP-group received an exploration license to harvest geothermal energy. Throughout the years the initiative has grown into a new research direction in our Geo-Cluster, with a constant flow of limited funding (ca 150 kEuro annually), allowing to hire four post-docs/PhD students involving all units of the Department. In addition, many MSc theses were conducted. Until 2013, the programme was led by Dr Wolf of the unit Geophysics. Funding from industry and TU Delft alumni allowed setting up a new part-time chair in Geothermal Energy. When Prof. Bruhn took this chair in 2013, the research was transferred to the unit of Geo-Resources.

## 4.7 Contributions to the public debate

Because of their expertise and our responsibility to serve society, our staff members contribute actively to the public debate around societal issues. A full list of appearance in the media can be found on the website of our Department. To give a few examples:

- Dr Barnhoorn: Interview about injection of $CO_2$ in gas fields, “De Telegraaf” (a national newspaper) and invited lectures about shale gas research in Utrecht (for general public and industry) and at the Shale Gas World Europe meeting in Warschau (Poland) in 2014 (for industry and scientists).
- Dr Drijkoningen: Interview about induced earthquakes in the Northern part of the Netherlands due to gas extraction, “NOS journaal” (the daily news).
- Dr Wolf contributed manifold to the communication with the press and representatives of civil/environmental interest groups concerning $CO_2$-storage. Especially in the period 2009-2011 when a storage site was proposed in the city of Barendrecht and in the Northern provinces of the Netherlands, many hearings, radio and newspaper interviews, and clarifications of technical topics were given in the light of transparency. Also currently, the communication group of CATO (including Dr Barnhoorn, Dr Drijkoningen, Dr Ghose, Dr Wolf) is involved in environmental symposia, conferences, (governmental) hearings, newspapers and presentations to specific clubs, such as the

International Greenhouse Gas Program and special technical programs within the EAGE and IPCC (preparation Copenhagen treaty, 2008/2009).

- Dr Wolf: Interview about the mine disaster of May 13, 2014, in Turkey, national television and radio; Drs Wolf, Evers and Barnhoorn also contribute to national discussions about geothermal issues and the environmental effects of fracturing.
- PhD student Grobbe took part in a television programme for school children (watch "Het Klokhuis" video on our website) and a related Open Day in a museum. His installation, explaining geophysical exploration using surface seismic acquisition, was very well received by the audience and attracted press attention. Consequently, Grobbe was invited to set up an installation in the Science Centre of TU Delft that will be realised in 2016.

**Ghose, R.**, Carvalho, J., & Loureiro, A. (2013). Signature of fault zone deformation in near-surface soil visible in shear wave seismic reflections, Geophysical Research Letters, Vol. 40, 1074-1078.

Green, DN, **Evers, LG**, Fee, D, Matoza, R, Snellen, M, **Smets, P** & Simons, D (2013) Hydroacoustic, infrasonic and seismic monitoring of the submarine eruptive activity and sub-aerial plume generation at South Sarigan, May 2010. Journal of Volcanology and Geothermal Research, 257, 31-43.

**Nishitsuji, Y, Ruigrok, E,** Gòmez, M & **Draganov, D** (2014), Global-phase H/V spectral ratio for imaging the basin in the Malargüe region, Argentina. Seismological Research Letters, 85, 1004-1011.

**Salimi, H, Wolf, KH** & Bruining, J (2012). The influence of capillary pressure on the phase equilibrium of the CO2–water system: Application to carbon sequestration combined with geothermal energy. International Journal of Greenhouse Gas Control, 11S, S47–S66.

**Wirianto, M, Mulder, WA** & **Slob, EC** (2010). A feasibility study of land CSEM reservoir monitoring in a complex 3-D model. Geophysical Journal International, 181 (2), 741–755.

**Figure 15** Key societal output.

# 5 Viability

## 5.1 Positioning of the unit Geophysics within the applied geophysics landscape

Many university groups around the world pursue applied geophysics programmes, in which fundamental research underlies the development of advanced methodology for geophysical acquisition, imaging, characterisation and monitoring. Without claiming completeness, Figure 16 shows some of the main programmes, and the names of the main applied geophysicists in those programmes. Several of the programmes have their research sponsored via industrial consortia, e.g. the successful Stanford Exploration Project (SEP), established in 1973. The Delphi consortium in Delft, established in 1983, is another example of an industrial consortium. The programme of our unit Geophysics is complementary to the Delphi programme as the emphasis of our programme is primarily on fundamental research.

To our opinion, the research programme of our unit Geophysics is at competing level with the strongest programmes in Figure 16 when it comes to the development of innovative concepts/methods, the quality and quantity of the scientific output, and the societal relevance. Several of the consortium programmes have a stronger link with the exploration industry than we have now. In the coming period we will further increase our cooperation with industry through the new form of the Delphi consortium, in combination with ISAPP and RF.

**USA**
- Colorado School of Mines (Center for Wave Phenomena, R. Snieder, P. Sava),
- MIT (Earth Resources Laboratory, M. Fehler, N.M. Toksoz (em.)),
- Rice University (The Rice Inversion Project, W. Symes),
- Stanford Univ. (Stanford Exploration Project, B. Biondi and J. Claerbout (em.)),
- Univ. of Houston (Mission-Oriented Seismic Research program, A.B. Weglein),
- Univ. of Texas at Austin (Institute for Geophysics, M. Sen, P. Stoffa (em.)),
- Univ. of Texas at Dallas (The UTD Geophysical Consortium, G. McMechan).

**Europe**
- Delft Univ. of Techn. (Appl. Geophysics and Petrophysics, K. Wapenaar, E. Slob),
- Delft Univ. of Techn. (Delphi Consortium, E. Verschuur, A.J. Berkhout (em.)),
- ETH Zurich (Exploration and Environmental Geoph., J. Robertsson, H. Maurer),
- Heriot-Watt Univ. (Edinburgh Time-lapse Project, C. MacBeth),
- Imperial College (Center for Reservoir Geophysics, Y Wang, M. Warner),
- NTNU Trondheim (Rock Seismic Project, M. Landrø, B. Ursin (em.)),
- Univ. of Edinburg (Edinburgh Seismic Research, A. Curtis),
- Univ. of Hamburg (Wave Inversion Technology, D. Gajewski, T. Bohlen),
- Univ. of Joseph Fourier (Seiscope Consortium, S. Operto, J. Virieux),

**"Rest of the world"**
- KAUST Univ. (Center for Subsurface Imaging and Fluid Modeling, G. Schuster),
- Univ. of British Columbia (Seism. Lab. for Imaging and Modeling, F. Herrmann),
- Univ. of Calgary (Crewes consortium, G. Margrave, D. Lawton),
- Univ. of Campinas (Wave Inversion Technology, J. Schleicher),
- Univ. of Western Australia (Center for Petr. Geoscience & CO2 Seq., D. Lumley).

**Figure 16** Research groups (in alphabetical order) in exploration, environmental and engineering geophysics around the globe.

## 5.2 Benchmarking with Imperial College

The group at Imperial College, which compares best with the geophysics research of our unit Geophysics, is the Centre for Reservoir Geophysics, headed by Prof. Y. Wang. Research areas in this centre are Reservoir characterisation, Integrated reservoir geophysics, Integrated reservoir management, Time-lapse seismic, Seismic inversion and imaging, and Waveform tomography. The Centre has particularly a strong reputation for their research in the area of seismic inversion, which is witnessed for example by the books "Seismic amplitude inversion in reflection tomography" (Wang, 2003) and "Seismic inverse Q-filtering" (Wang, 2008), and by the many papers by Wang and Warner in this area.

The emphasis of the applied geophysics research at Imperial College is clearly directed towards the applicability of seismic methodology to large-scale problems of the oil and gas industry (a goal similar to that of the Delphi consortium), whereas the emphasis at our unit Geophysics lies on developing novel cutting-edge seismic and electromagnetic methodology for exploration, environmental and engineering geophysics. Apart from these different emphases, to our opinion the quality of our applied geophysics research programme can certainly compete with that at Imperial College. The scientific output and international academic recognition of the applied geophysics research at our unit is higher than that of the Centre for Reservoir Geophysics at Imperial College.

Within the Petroleum Engineering and Rock Mechanics group at Imperial College, headed by Prof. King, there are two research areas, which can be seen as the counterparts of our Petrophysics research. These are Porescale Modelling (Dr Blunt) and Rock Mechanics (Prof. Zimmerman). Both sections have a particularly strong reputation on advanced numerical modelling. The Porescale Modelling section focuses on numerical modelling of flow through three-dimensional porous media for upscaling to reservoir scales. The Rock Mechanics section focuses on the development of numerical constitutive models for the deformation and failure of rock on both macroscopic and microscopic scales for e.g. borehole instability, hydro-fracturing etc.

The research in these areas at Imperial College is internationally at the forefront. The petrophysics research in our unit Geophysics shrunk at the beginning of the review period due to the departure of two (out of three) associate professors. Due to financial constraints we could replace them by only one assistant professor. Consequently, we had to make choices. The new assistant professor (Barnhoorn) concentrates on the development of fracture networks by combining experimental rock fracturing, high-resolution 3D imaging of rocks and acoustic measurements. The petrophysics programme within our unit is, to our opinion, now well on its way to international leadership.

## 5.3 SWOT analysis

### Strengths

- Proven excellence in fundamental research for applied geophysics,
- Significant governmental funding, including personal grants for toptalents,
- High-quality group of PhD students and post-docs,
- Excellent infrastructure, in particular the petrophysics lab-facilities,
- Strong collaboration with Geo-Resources and Geology units,
- International recognition (awards, editorships, citations),
- Strong MSc student group (Idea-League programme).

### Weaknesses

- In the beginning of the review period the EM research was somewhat isolated,
- Cooperation with Delphi consortium not yet fully exploited,
- Unequal gender balance.

### Opportunities

- The energy transition asks for sustainable technology development for exploration and exploitation of gas hydrates, shale gas, geothermal energy, etc.; optimization and monitoring of storage of waste products; monitoring and assessment of induced seismicity and other production-related hazards,
- There is an increasing demand for geo-information on underground activities (subsurface infrastructures, geohydrology, catchment-scale water management, soil-atmosphere interaction, etc.). This asks for development of large-scale quantitative subsurface monitoring networks, interpretation of geoscientific “big data” etc.

### Threats

- Ever increasing reduction of open funding opportunities,
- If oil-price remains low the industrial funding opportunities will reduce.

We briefly indicate our strategy to cope with the weaknesses. (i) In 2010 we decided to give the EM research new impetus by establishing a chair Geophysical EM methods, see Chapter 2.2. (ii) With the plans to merge Delphi with ISAPP and RF (Chapter 2.3), the consortium will have a stronger basis in the Geo-Cluster, which will give new opportunities for closer cooperation. (iii) When hiring new staff, we actively search for female candidates, and the appointment committees always contain at least one female member. Moreover, we have approached candidates for the TU Delft initiative Dutch Technology Fellowship to attract female professors on a special five-year contract. Unfortunately our efforts to find female staff have so far not been successful. This aspect will have our full attention again when new vacancies will turn up.

To cope with the threats, in Chapter 2.3 we indicated that we will put continued effort in acquiring funding from NWO (Gravitation, Veni-Vidi-Vici, FOM, STW) and increase our efforts in acquiring European funds (Horizon 2020, ERC personal grants) and public/private funds (TNO, KNMI, TKI Gas).

Department
of Geoscience
& Remote Sensing

# 3
# Geodesy

# 1 Mission

The research program "Geodesy" is dedicated to the development and exploitation of geodetic and remote sensing techniques for measuring, monitoring, and modelling the Earth and objects at the Earth's surface. The research programme ranges from pure theory and methodology to the development of data retrieval algorithms, real data processing, quality control, geophysical interpretation, as well as the development of new applications.

*The mission of the research program is to advance technology and knowledge for monitoring and modelling the Earth in space and time, and to develop associated applications in science and society using opportunities offered by new observational platforms and sensors. This includes contributing to top-level MSc and PhD education in Geodesy and Remote Sensing embedded in the broader field of Geosciences.*

# 2 Strategy

## 2.1 Research strategy

**Review period**
The Geodesy research program is contributing to, and inspired by, the development of new satellite missions, which provide new data with higher accuracy and space-time resolution, offering new scientifically challenging applications in geoscience and engineering, and allowing to address problems of high societal relevance in the key fields of water, climate, safety, transport, energy, and infrastructure. The research activities range from mission analysis, theoretical studies, data acquisition, modelling, parameter estimation and quality control to interpretation and data assimilation. The research program is structured into four themes, which reflect the different objects of study and the key measurement techniques being used (cf. Fig. 1):

- Theme 1: Gravity
- Theme 2: Positioning, Navigation and Timing
- Theme 3: Geokinematics
- Theme 4: Remote Sensing

Theme 1, *Gravity*, focuses on the static and time-variable component of the Earth's gravity field and geoid on regional to global scales. Theme 2, *Positioning, Navigation and Timing*, relates to enabling accurate information on location and time, particularly via global navigation satellite systems (GNSS). Theme 3, *Geokinematics*, focuses on the time-variable geometry of the Earth's surface and objects on it. Theme 4, *Remote Sensing* aims at retrieving information on the properties and shape of land cover and man-made objects using imaging techniques in the optical and microwave domain. A common element of these themes is formed by their mathematical foundations. The 'Delft School' in geodesy is an internationally acclaimed trademark, steadily developing since the 1940's, with a strong conceptual basis in parameter estimation, prediction, filtering, testing, and quality assessment and control.

The scientific challenge of the Geodesy research program is to make fundamental contributions to new measurement system technologies, mathematical and physical modelling, numerical methods, the combination of data of different sensors with different space-time resolution and noise characteristics, and the integration & assimilation of data into geophysical models.

The Geodesy research program is well embedded in the disciplines of geosciences and civil engineering at TU Delft. Research activities on geophysical interpretation and data assimilation are partly done in collaboration with other units in the Geo-cluster and the water resources unit. Collaboration with the Geo-engineering unit and the Geophysics unit includes shallow sub-surface processes, volcano monitoring, and seismic imaging. A new theme on Climate modelling is being developed together with the Atmosphere unit. Related to civil engineering, joint research activities

have been initiated with several research units of CEG, e.g., on the monitoring of structures with the Department of Structural Engineering, on guidance and autonomous navigation with the Department of Transport & Planning, and on water defence infrastructure with the Department of Hydraulic Engineering.

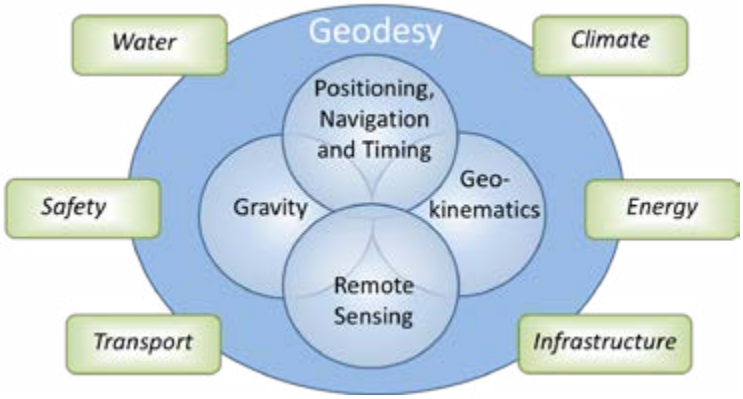



**Figure 1.** Challenges in key societal fields in relation to the four themes of the Geodesy unit.

**Coming period (2015-2020)**

The Geodesy research program is strongly driven by the major societal challenges of today and tomorrow, mainly centred around the themes Water, Climate, Safety, Infrastructure, Transport, and Energy, see Fig. 1.

The main natural hazards in the Netherlands are sea level rise, flooding, extreme weather, (induced) earthquakes, Earth's surface instability, and volcanic hazards (island of Saba). Sea level rise, river discharge, and increasing intensity and frequency of extreme precipitation events, in combination with vertical motion of the land (topography and bathymetry) require adaptations of Dutch society and multi-billion Euro investments to ensure safety. The Geodesy research program will address these issues by developing accurate models of the topography, bathymetry, and water levels using state-of-the-art measurement sensors, supported by the necessary theoretical and methodological research. This also includes studying the global and local driving forces of changes in land and water surfaces, such as the melting of glaciers and ice sheets, continental water storage variations, and dynamic processes in the solid earth. Local driving forces include past and present hydrocarbon and coal extraction. In the Netherlands, gas (and oil) production in several provinces leads to subsidence and induced earthquakes. Effects of former coal mining lead to unexpected uplift in the south of the Netherlands and sinkhole hazards. The Geodesy research program will contribute to provide answers to urgent questions such as the link between gas production and induced seismicity, risk assessment for infrastructural damage, and seismic remote sensing.

Encompassing various societal challenges, we address fundamental geodetic technology related to Positioning, Navigation and Timing. The rapid developments in the field of global navigation satellite systems (GNSS), particularly the realisation of a broader multi-frequency, multi-signal system-of-systems, requires further developments in theory and modelling, and we intend to broaden our scope beyond GNSS.

Another societal challenge is safe navigation through the shallow coastal waters of the Dutch Continental Shelf, depth maintenance in approach areas to the Rotterdam harbour, and integrated management of the vulnerable Dutch coastal zone. This requires fast, cheap, and accurate hydrographic data as well as accurate and easily accessible vertical reference surfaces at land and sea. We will intensify our research on innovative concepts of vertical reference frame realisations, improved bathymetric surveying, and more accurate vertical positioning of underwater vehicles.

Ageing of civil infrastructure is an important problem in western societies, where buildings and critical infrastructure such as dams, dikes, roads and railways reach a critical age, associated with increased

failure risk and maintenance cost. Structural health monitoring is challenging due to the sheer number of objects. New satellite radar missions, providing data free-of-charge at a near-daily basis and efficient point cloud sampling techniques implemented in, e.g., laser mobile mapping systems provide great opportunities to address this problem. We are the principal investigator of PanelSAR, a new Dutch satellite initiative designed specifically for infrastructure monitoring. We will work on the development of methods for such applications, and collaborate with end-users to facilitate the interpretation and proper use of the results.

We strive to increase the number of multi-disciplinary projects that address a particular societal challenge. An example of such a new overarching topic is climate and ice sheet modelling, which complements our efforts on ice sheet observations with the goal of advancing the understanding and quantification of processes of ice sheet and climate interaction and of providing improved projections of ice sheet, sea level and climate. Miren Vizcaino will take the lead. Together with colleagues of the Amosphere unit (Herman Russchenberg, Stephan de Roode), the Community Earth System Model (CESM) in the US (NCAR, Los Alamos National Lab) and Utrecht University (M. van den Broeke and colleagues from IMAU) we will pioneer the integration of ice sheets as a new and indispensable component of the next generation of climate models. In the coming period, we focus on the integration of observations, past climate and sea level records, and models of the solid Earth, climate system and ice sheets. In this way, we want to better understand ice-sheet/climate interaction and on-going ice mass changes, and provide reliable estimates of future sea level rise and climate change. Bert Vermeersen will establish the link with past ("paleo") records through his NIOZ affiliation and Riccardo Riva will establish the link with solid Earth modelling. Geodesy-unit activities on the remote sensing of ice sheets (altimetry, gravimetry, optical remote sensing, and SAR-based retrieval of glacier velocities) will contribute to model evaluation, provide improved input data for the models, and contribute to elucidation of processes of ice-sheet/climate interaction. Modelling efforts will benefit from the expertise of the Atmosphere unit, in particular on remote sensing of the atmosphere (Herman Russchenberg) and ice sheet surface energy budget, cloud simulation over ice sheets, and high-latitude precipitation (Stephan de Roode).
Other examples of multi-disciplinary projects requiring a collaboration between the different themes are i) closing the sea level budget at regional scale (all four themes), ii) the structural monitoring of infrastructure (themes 2, 3, and 4); and iii) the monitoring and interpretation of land subsidence (themes 1 and 2).

## 2.2 Personnel Strategy

### Review period

At the start of the review period the Geodesy research groups formed a department within the Faculty of Aerospace Engineering. As part of a university-wide reorganisation program, the Faculty proposed to terminate TU Delft's geodesy research as a whole. This lay-off scenario triggered a period of uncertainty between 2009 and 2010. Yet, mid-2010 TU Delft's executive board decided to the contrary- to strengthen earth science and engineering by clustering all geosciences research at the Faculty of Civil Engineering and Geosciences (CEG). Together with the department GSE and two atmospheric research groups, the Geodesy groups were tasked to form a new 'geo-cluster' within CEG. Yet, the budget of the Geodesy groups was to be reduced by 30% (0.5 M€), and therefore a significant reduction in (support) staff positions. Early 2012, the groups physically moved to CEG and started working as the Department of Geoscience and Remote Sensing, together with colleagues in the Atmosphere unit, in total 85 fte. Much emphasis in the period 2011-2013 was placed on the setup of a new educational program within CEG, which succeeded very well.

In the light of the reorganisation, the main strategic objective in terms of personnel was the survival of Geodesy as an academic discipline in the Netherlands and exploiting the new opportunities of interdisciplinary research and collaboration within the CEG geo-cluster. Considering the current status, this objective has been achieved, and the unit is in a healthy and ambitious state.

Other personnel changes in this period (only faculty staff):

- Early 2008, Ramon Hanssen was promoted to full professor on a prestigious Antoni van Leeuwenhoek chair

- Late 2008, Massimo Menenti was appointed as full professor in Optical and Laser Remote Sensing
- Mid 2008, Andy Hooper, a promising researcher with an excellent academic record in the field of geophysics and geodesy, joint the Geodesy unit. In 2012 he was promoted to associate professor. To our regret, but as a great personal achievement, he accepted an offer as Professor of Geodesy and Geophysics at Leeds University in May 2013.
- Since 2009, Peter Teunissen reduced his appointment to 0.2 fte, receiving a fellowship from the Australian Research Council to work for 0.8 fte as professor at Curtin University, Perth Australia. He is still strongly involved in the TU Delft Geodesy research program, supervises PhD students, and collaborates within the geodesy unit.
- Mid 2011, David Lavallee (assist. prof.) left the group to accept a senior geophysicist position at Shell in Houston.
- Mid 2011, Riccardo Riva (assist. prof.) joined the geodesy unit, with a strong background in geophysics and geodesy. He received a prestigious Vidi grant in 2014.
- Since 2012, Peter Hoogeboom joined the geodesy team at GRS as part time professor, with experience on SAR remote sensing. He led the radar research team at the Netherlands Organisation for Applied Scientific Research (TNO) and was already part-time professor at TU Delft's Electrical Engineering department.
- Christian Tiberius and Pavel Ditmar were promoted to associate professor in 2009 and 2012, respectively.
- Mid 2013, Brian Gunter (assist. prof.) accepted a faculty position at Georgia Tech, USA
- Since 2013, Miren Vizcaino joined the team as tenure-track assistant professor, in the Delft Technology Fellowship Programme. She is contributing author to the last IPCC report AR5, and has a well-cited record of published work on coupled ice sheet and climate evolution (GRL, Journal of Climate, Climate Dynamics). She is co-chair of the Land Ice Working Group and takes part in the Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6), which is linked with Climate and Cryosphere (CliC) and the World Climate Research Program (WCRP). She will take the lead in the new, overarching and department-wide topic on climate and ice sheet modelling (cf page 74).
- Mid 2014, Cornelis Slobbe joined as tenure-track assistant professor. With his cum laude doctorate on vertical reference surfaces (land and sea) and his experience in ICESat data processing and applications he became responsible for the research on satellite altimetry with applications to geodesy and hydrography, climate change, and hydrology.
- Mid 2014, Massimo Menenti retired as full professor Optical and Laser Remote Sensing.

Figure 2 depicts the development in personnel during the review period.

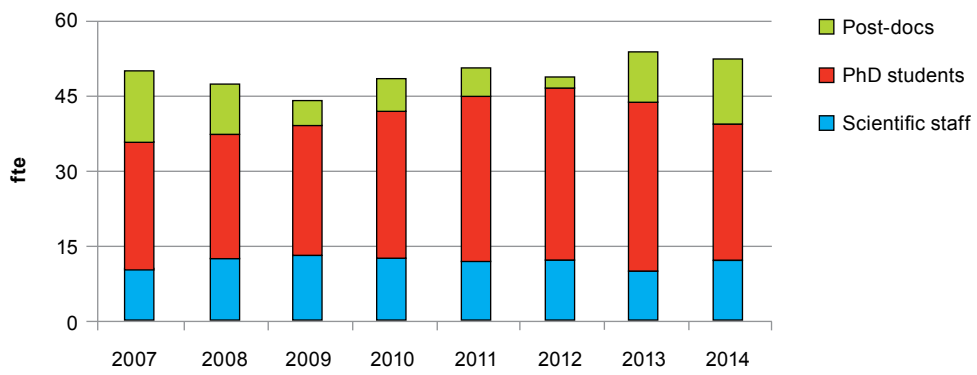



**Figure 2** Personnel (fte) Geodesy during the review period.

**Coming period (2015-2020)**

In the next period, the personnel strategy focuses on consolidation of the geodesy research programme after the previous reorganisation, and filling vacancies on geophysical geodesy, remote sensing of environment, and optical remote sensing technology with highly-qualified and ambitious researchers. We have adopted the strategy to search primarily for excellent candidates in these fields, irrespective of the specific niche or the level (assist., assoc., or full professor). PhD students and post-doctoral fellows are selected purely based on past performance, interviews, recommendations, and research potential.

The majority of them work on projects defined by the scientific staff in line with our research mission.

- Late 2014, Bert Vermeersen was appointed as full professor (0.1 fte) in the field of geophysics, with a research interest in geodynamics and Holocene sea level rise. He also pursues these research interests at the Royal Netherlands Institute for Sea Research (NIOZ) (0.2 fte). He is also appointed as professor in planetary exploration (0.7) at the faculty of Aerospace Engineering.
- We intend to appoint Miren Vizcaino and Cornelis Slobbe as tenured staff members in 2017 and 2018, respectively.
- We emphasize the need to increase the junior staff gradually to 3 full-time PhD students per staff and 10 post-doc positions. Quality remains the main criterion for appointments. In selecting new post-docs, we consider their capacity for being a potential Veni recipient as a crucial criterion.

## 2.3 Funding Strategy

The funding strategy reflects the research program, which is a mixture of methodology-driven and application-inspired research. Funding for the methodology-driven research comes primarily from personal grants (Veni and Vidi), the Netherlands Science Foundation (NWO), and specific programs such as the Integrated Solid Earth Science (ISES). Application-inspired research is primarily financed by EU (KP7 and regional programs), Space agencies, the Dutch Technology Foundation (STW), governmental organisations, and industry. Some PhD projects are financed by external scholarships. Since not all funding sources include overhead (such as the scholarships or NWO projects), we strive to have a healthy balance between these sources, as well as between academia, businesses, and the government.

Figure 3 depicts the funding of our unit during the review period.

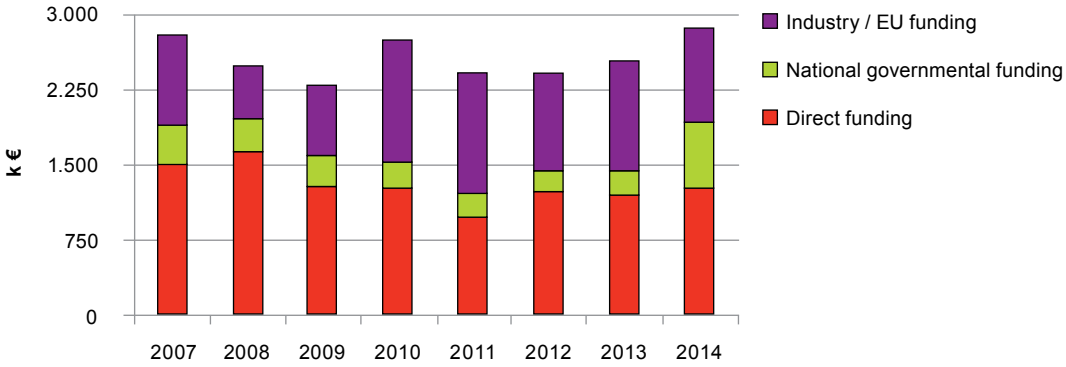



**Figure 3** Research funding during the review period.

### Review period

Our main funding sources are listed below.

**National Governmental Funding**

- **Veni-Vidi-Vici** is a competitive talent programme of NWO (also known as the Innovational Research Incentives Scheme), for top-researchers at different stages of their career. Postdocs and staff members are actively stimulated to apply for one of these grants. During the review period, Sandra Verhagen received a Veni and Riccardo Riva a Vidi grant.
- **NWO** The unit is successful in acquiring funds from NWO (nine PhD students/ postdocs received NWO funding during the review period), which underlines the strong fundamental character of our research.
- **STW** (The Dutch Technology Foundation), a subsidiary of NWO, finances excellent technological scientific research and realises the transfer of knowledge to the users. Through the years we have been quite successful in acquiring funds from STW. Five PhD students/postdocs received STW funding during the review period.

- **ISES** (Integrated Solid Earth Science) is one of six National Top Research Schools in the Netherlands, to bring together the top researchers in the field of solid earth science in the Netherlands. In Delft, the Geodesy unit has been involved in ISES from the start.
- **Ministry of Infrastructure and the Environment/Rijkswaterstaat and the Netherlands' Cadastre, Land Registry and Mapping Agency.** By its nature, the unit has long lasting and intensive collaborations with governmental organisations, such as ministries, cadastre, water management boards, state supervision organisations, or public work organisations. With some of them, such as Rijkswaterstaat, we work via multi-year framework contracts.

**European Funding**

- **EU FP7** was the research funding programme of the European Commission during the review period. The unit Geodesy participated in three programmes, Sigma (Marie Curie), CEOP AEGIS, and IQmulus, which funded 1 postdoc and 3 PhD students.
- **ESA** The Geodesy unit is seen by the European Space Agency as a centre of excellence in Geodesy, Navigation, and Remote Sensing. This lead to several contracts for fundamental and applied research executed by staff, postdocs and PhD students.

**Public-Private Funding**

- **CATO** programme The geodesy unit participated in the national CATO-2 programme on CO2 capture, transport and storage. CATO is a public-private partnership involving universities, research institutes, industry and government. In the review period, Pooja Mahapatra worked on the use of geodetic observations for monitoring $CO_2$ storage sites.
- **BE-Basic** is an international public-private partnership that develops industrial biobased solutions to build a sustainable society and to switch from fossil fuels to biomass. Remote Sensing is used to obtain information on land use changes. Two postdocs and one PhD student positions were funded.

**Industrial Funding**

- **Delphi** is a consortium project, sponsored by 35 companies from the oil and gas industry, dedicated to geophysical exploration research for the industry. One postdoc is funded.
- Industry in the **Energy sector** (Shell, Fugro, NAM, Liander). The Geodesy unit received funding via Integrated System Approach Petroleum Production (ISAPP) partnership program of TU Delft, Shell, and TNO (one PhD student).

## Coming period (2015-2020)

Although much of our current research will continue for a number of years, we will investigate possibilities for new GRS-oriented themes. We will continue to actively stimulate postdocs and staff members to apply for Veni-Vidi-Vici grants. The Veni-Vidi-Vici programme is an excellent opportunity to select future permanent staff members. In principle Vidi researchers (and higher) are offered a permanent position after finalizing their project. To support our methodology-driven research, we will continue applying for NWO grants. We intend to increase the number of STW grants to financially support the more application- and user-driven research.

**European Funds**

We will increase our efforts to apply for grants from the EU, in particular the EU Horizon 2020 programme. Both ITN, Marie Curie and the prestigious personal grants from the European Research Council ERC are being applied for. ESA will remain an important funding source for the development and exploitation of new satellites.

**Public-Private Funding**

- We participate in a National Initiative on Land movement (**NIB**), a 10 M€/y program to measure monitor and model surface motion in the Netherlands.
- We participate in setting up a cooperation programme between TU Delft and KNMI, see the report of the unit Atmosphere: water vapour mapping will be the main contribution of the Geodesy unit (1 PhD student).
- We are partner in the TU Delft-Rijkswaterstaat 5-year framework contract, which finances shorter innovative research projects (200 k€/y).

**Industrial Funding**

- We will continue working with industrial partners in various projects.
- Within the **Delphi** consortium, we will pursue our ideas for seismic remote sensing.
- We will participate as Principal Investigator in the development of a new Dutch radar satellite mission.

## 2.4 Publication strategy

### Review period

The Geodesy unit mainly publishes in high-impact peer-reviewed scientific journals, in particular Journal of Geodesy, Journal of Geophysical Research, Geophysical Research Letters, Geophysical Journal International, IEEE Transactions on Geoscience and Remote Sensing, Remote Sensing of Environment, and ISPRS Journal of Photogrammetry and Remote Sensing. The impact factor is one of the criteria we use to select the journal. The number of refereed conference papers has been reduced since 2008 due to a change of our publication policy, which prefers publication of original theory and methodology in peer-reviewed journals. Mainly for some fast-track research results peer-reviewed conference papers are published too. The main output of PhD research are refereed journal papers and PhD theses with a strong international standing. The unit is involved in several editorships (e.g., Roland Klees was the Editor-in-Chief of the Journal of Geodesy in 2007-2015), see the Appendix for a full overview.

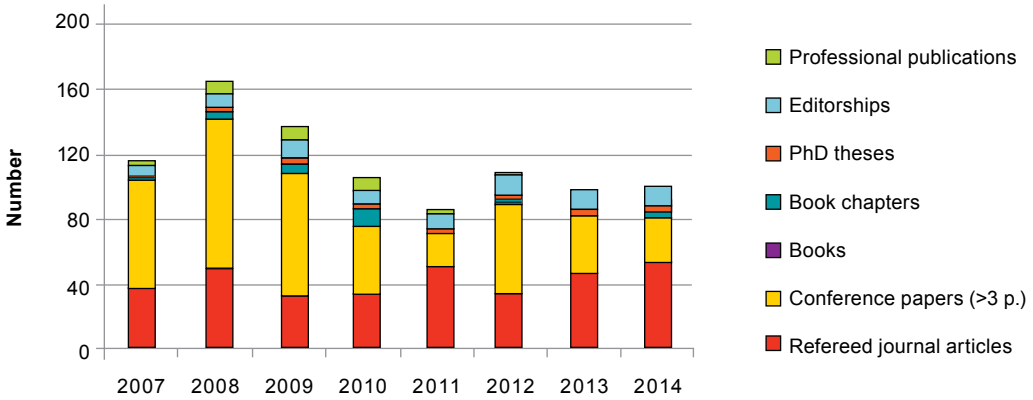



**Figure 4** Research output during the review period. (cf. appendix for numerical values).

### Coming period (2015-2020)

We will continue to publish in the major (high-impact) geodesy, geoscience, and remote sensing journals. We strive for 0.75 journal papers per PhD student per year, 1.5 papers per post-doc per year, and 1 paper per staff member per year (numbers refer to first-author journal papers, and staff generally manage and direct research portfolios rather than undertaking the research themselves), which comes to a total of 45-50 peer-reviewed journal papers per year. We continue to stimulate editorships of major journals, organisation of international workshops and special sections, and participation in research committees.

# 3 Research results and plans

## 3.1 Theme 1: Gravity

*Scientific staff: Roland Klees (1.0 fte), Pavel Ditmar (1.0 fte), David Lavallee (1.0 fte until 2010), Brian Gunter (1.0 fte until 2012), Riccardo Riva (1.0 fte, since 2011), Cornelis Slobbe (1.0 fte, since 2014).*

**Introduction.** We develop novel methodologies for modelling the static and time-variable gravity field from satellite, airborne, and/or terrestrial data on global to local scales. We follow an operational approach in which observations are coupled to a set of model parameters that are estimated using statistically-optimal techniques. We contributed to novel applications of static and time-varying gravity in continental hydrology, glaciology, hydrography, hydrocarbon reservoir modelling, and solid Earth geophysics. During the review period, we published 169 peer-reviewed papers on this theme, among which one in Science (Bamber et al 2009) and one in Reports on Progress in Physics (Wouters et al 2014).

**Satellite gravity modelling** encompasses the estimation of a set of parameters describing the Earth's gravity field using data from the dedicated satellite gravity missions CHAMP (2000-2010), GRACE (2002-now), and GOCE (2009-2013). The main developments during the review period concern refinements of functional models for GRACE and GOCE data, the development of data-driven weighting and regularization schemes based on statistical theory, and the validation of the estimated gravity models. In particular, a novel methodology for statistically-optimal filtering of temporal gravity field variations on the basis of full noise and signal covariance matrices was developed; the corresponding publication (Klees et al 2008) has 61 citations so far (Web of Science 31 August 2015). In combination with an accurate estimation of data noise, developed methodologies provided models of comparable or higher quality than those computed from the same data by other research teams. This concerns the Delft Mass Transport (DMT) models of temporal gravity variations, and the Delft Gravity Model (DGM-1S) of the static gravity field. A novel methodology for model validation was developed, which provided new insight into the performance per region of state-of-the-art combined high-resolution global gravity field models such as EGM2008.

We studied future concepts of satellite gravity missions. A novel methodology was developed, which allows the use of kinematic satellite orbits in gravity modelling even if the satellite is not equipped with an accelerometer to measure non-gravitational forces acting on the satellite. In this way, we paved the way to the use of non-dedicated satellites to study temporal variations of the Earth's gravity field. We were the first who applied this methodology to investigate the performance of satellite formations of opportunities, such as the IridiumNext constellation. We investigated the capability of Satellite Gravity Gradiometry (SGG) to observe temporal gravity field variations and showed that SGG may become one of the primary future techniques if a technically feasible improvement by one-to-two orders of magnitude upon the accuracy of the GOCE gradiometer is achieved.

**In the coming period**, we intend to continue our efforts on static and time-varying gravity field modelling on the basis of gravity data from GRACE, GRACE Follow-On (to be launched in 2017), and other suitable satellites. One of the main challenges and focus of our research is on producing dedicated optimally-filtered products tailored for specific applications in terms of spatial parameterization, temporal parameterization, and expected stochastic properties of the signal, which will facilitate, in particular, accurate modelling of mass redistribution in the Earth's system. We will put efforts in the further improvement of estimated low-degree spherical harmonic coefficients (i.e., those describing global gravity field features and geocentre motion), exploiting appropriate combinations of satellite gravity data and other information like ocean bottom pressure models. We will continue studying the optimal set-up of future satellite gravity missions to be launched in 10 to 20 years from now, keeping in mind a variety of different applications of those missions. We will continue the investigation of the noise budgets of satellite gravity data, which may facilitate both an improvement in processing of available data and a better design of future satellite gravity missions.

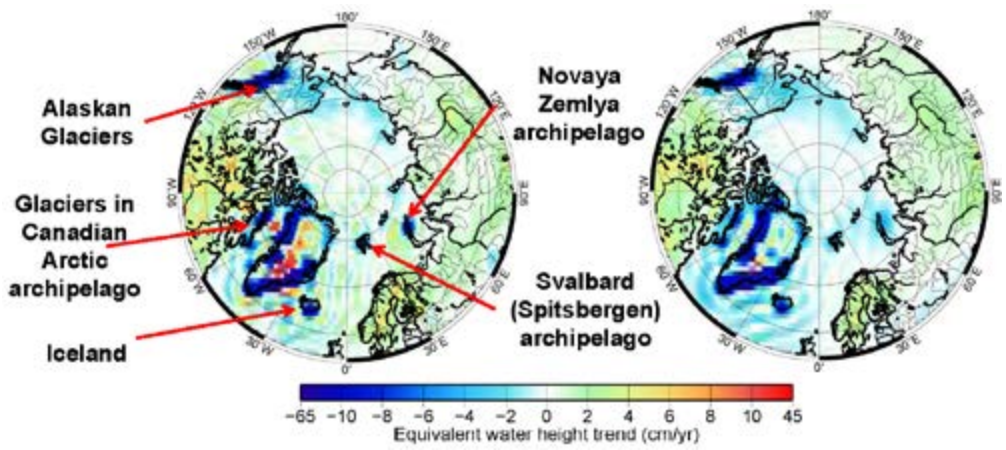



**Figure 5** Linear trend of mass variations 2003-2011 in the Arctic. Superior spatial resolution of a Wiener linear-trend-filter developed at our unit (left) compared to a state-of-the-art official Level-2 data product (right). Results of our fundamental research on mass distribution and re-distribution from GRACE satellite gravity data.

**Mass distribution and redistribution** encompasses the exploitation of geodetic data to model the distribution and redistribution of mass inside the Earth and at the Earth's surface. We used satellite gravity data to quantify hydrological processes in various river basins in Europe, Africa, and China in collaboration with hydrologists from TU Delft and Utrecht University. We developed a tailored retracking algorithm to extract lake level variations from high-resolution level-1b data provided by the Cryosat-2 satellite altimetry mission and applied this methodology successfully to monitor lake levels in the Tibetean Plateau and the Tian Shan. A novel technique was developed to process ICESat satellite laser altimeter data, and used to estimate volume variations of the Greenland Ice Sheet (GrIS). We combined these estimates with satellite gravity data and made for the first time estimates of individual contributors (snow and ice) to observed GrIS mass variations. This result was cited in the IPCC AR5 Assessment Report. We developed a novel filter technique for long-term mass trends of the GrIS, and demonstrated its superior spatial resolution compared to state-of-the-art processing techniques (cf. Fig 5).

We developed a new technique to monitor hydrocarbon reservoirs from a combination of time-lapse gravimetry, production data, and reservoir model data. This technique will be used by Shell for the future monitoring of the Groningen gas field.

Novel methodologies were developed for an estimation of the Moho geometry on the basis of gravity field data. This included: (i) efficient computational schemes to clean gravity anomalies and disturbances from nuisance signals related to terrain, bathymetry, and crust; (ii) validation of results by computing correlations between cleaned gravity field quantities on the one hand and geometry of Moho and other interfaces on the other hand; (iii) optimal weighting of gravity data and ancillary geophysical information. In this way, new Moho models were computed both for selected regions (Hellenic subduction zone, Red Sea area) and globally. We demonstrated that the new global Moho model improves upon existing models, particularly in areas poorly covered with seismic data, such as central Africa and northern South America.

We have used GRACE data to study mass redistribution inside the Earth due to (visco-)elastic deformation processes. In particular, we have done pioneering work on the determination of Glacial Isostatic Adjustment (GIA) over Antarctica through the combination of gravity and altimetry (ICESat) observations, which led to the first solution based on widespread observations of contemporary changes, cited 41 times in refereed journal articles (Web of Science, 31 August 2015) and in the IPCC AR5 Assessment Report (Riva et al 2009). We have also studied mass redistribution following large subduction earthquakes, including theoretical work on the effect on earthquake-driven ocean mass redistribution on satellite gravimetric observations.

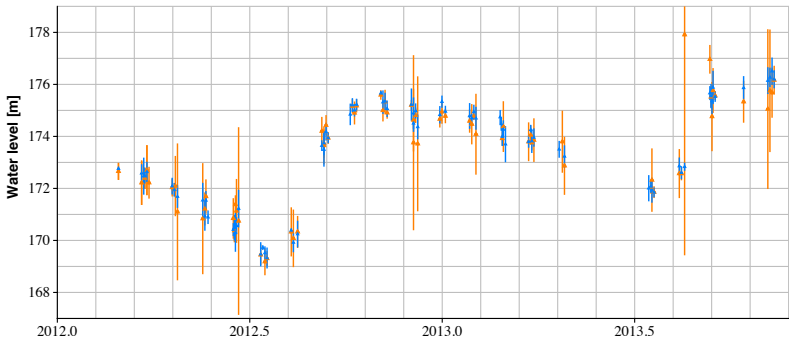



**Figure 6.** Cryosat-2 altimetry data processing over Lake Nasser, Egypt. Time series of lake levels obtained with the retracker developed at the Geodesy unit (blue triangles and error bars), and of the official Cryosat-2 level-2 data product (orange triangles and error bars). The length of the bars indicates the accuracy of individual lake level measurements. The proposed retracker delivers much more accurate results than the official level-2 data product, which is mostly explained by a more efficient handling of the waveforms that are polluted by reflections from surrounding land topography. Result of on-going research on mass distribution and redistribution.

**In the coming period** we will continue our research in this field with emphasis on the application of satellite gravity (in particular, GRACE and the GRACE-FO mission) and other remote sensing data (in particular, satellite altimeter data from Cryosat 2, ICESat 2, and Sentinel 3) to describe and analyse mass redistribution in various components of the Earth's system (cf. Fig 6). The focus will be on ice sheets and glaciers, river-basin-scale hydrology, permafrost, and GIA. We aim at tailored mass redistribution estimates that are i) based on a combination of various observation techniques, ii) fine-tuned to the needs of a particular application community, and iii) constrained by additional information from models and/or ancillary data provided by the application community; we also aim at the assimilation of satellite gravity and altimetry data in geophysical models developed by the geophysical community in an attempt to improve their spatial and temporal resolution.

**Vertical reference frames** refer to the realisation of surfaces to which heights/depths refer. We did pioneering work on the use of spherical radial base functions for regional quasi-geoid modelling. Using fundamental aspects of potential theory, we developed a new methodology to combine a gravimetric quasi-geoid with geometric height anomalies from GNSS, terrestrial gravity, and spirit levelling data, and applied this methodology successfully to the computation of a new quasi-geoid for the Netherlands and Germany with significant improvements upon the state-of-the-art models. We developed, in close cooperation with Deltares, an Dutch institute for applied research in the field of water and subsurface, a conceptual framework to realise a set of vertical reference surfaces (land and sea) by combining gravity data, radar altimetry data, and water levels at on- and offshore tidal stations with a regional hydrodynamic model in a feedback loop. The overall methodology comprises a number of novel ideas: i) the realisation of a coastal-waters-inclusive continuous separation model of chart datum without any spatial interpolation; ii) a methodology to vertically reference a regional hydrodynamic model to a particular quasi-geoid; iii) a reduction of altimeter-derived sea surface heights to geometric quasi-geoid heights using the properly referenced regional hydrodynamic model that includes astronomical tidal forcing, wind and pressure forcing, and baroclinic forcing, iv) a probabilistic design of chart datum, which is operational and much easier to implement and validate than all tidal vertical reference surfaces (cf. Fig 7). This new concept is currently being discussed within the International Hydrographic Society.

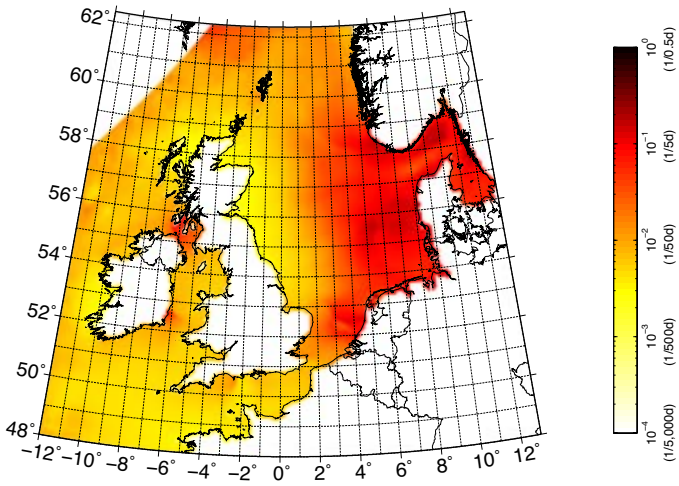



**Figure 7.** Probability that the minimum instantaneous water level in periods of tidal minima drops below Lowest Astronomical Tide (LAT). Result of our research towards a probabilistic design of depth reference surfaces.

**In the coming period**, we want to operationalise the conceptual framework to bring to society a new set of vertical reference surfaces (land and sea) for the Dutch mainland, Wadden islands, and Continental Shelf. For this, we recently acquired a STW grant for 1 PhD student and one PostDoc and made agreements with the Hydrographic Service of the Royal Netherlands Navy, the Ministry of Infrastructure and Environment/Rijkswaterstaat, and a broad user community comprising govern-mental agencies, surveying companies (among others Fugro), companies offering positioning services (among others QPS), and the dredging industry (among others Boskalis, van Oord).

We consider the integrated realisation of vertical reference surfaces (land and sea) in coastal regions as an emerging field with numerous benefits for accurate hydrographic surveys, coastal zone management, maritime vertical positioning, offshore dredging, and safety. For the coming period, we plan to apply the methodology to the coastal regions of Hong Kong and the South China Sea as part of the research activities of the TU Delft-Wuhan University Joint Research Centre. We also want to exploit the possibilities offered by proper vertically referenced hydrodynamic models for providing new services to the hydrographic community, including improved vertical positioning of underwater vehicles.
The developed methodology of quasi-geoid modelling in coastal areas will be improved by better models of noise in altimeter-derived sea surface heights (cf. Fig 7), incorporating GRACE/GOCE data as noisy data type, and a more sophisticated design of the spherical radial base function network. For the first time, we will investigate the use of shipboard GNSS data to close the 5-10 km gap between the area covered by (re-tracked) radar altimetry data and land for coastal quasi-geoid modelling.

**Sea level change** refers to the quantification of global and regional changes in the reference sea surface at temporal scales from years to centuries. We were the first to make use of GRACE data to determine trends in sea level driven by continental water mass redistribution (sea level fingerprints) and the resulting paper has been cited about 30 times (Riva et al 2010). We have modelled the effect on sea level of a collapse of the West Antarctic Ice Sheet in a study that was published in Science and cited about 150 times (Bamber et al 2009). We have also provided estimates of mass-induced sea level change to several international research groups, which resulted in 7 citations in the IPCC AR5 Assessment Report for (co-)authored papers about sea level (Bamber et al 2009, Bamber and Riva 2010, Riva et al 2010, Broerse et al 2011, King et al 2012, Slangen et al 2012, Perrette et al 2013).

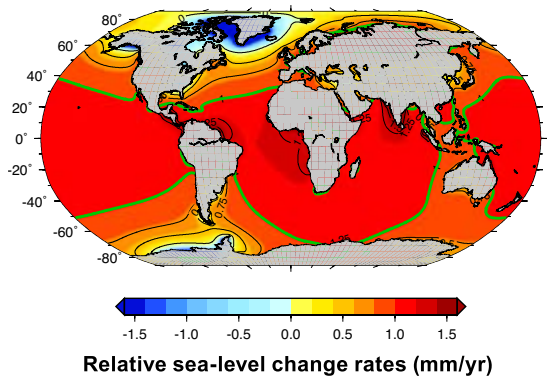



**Figure 8** Trend in sea level change driven by the redistribution of continental water, as estimated from GRACE data for the years 2003-2009. Mean sea level rise is equal to 1.0. Result of our research on regional sea level change.

**In the coming period** we will extend our research about sea level change by working on a data-driven multi-scale model that encompasses changes in both the sea surface and the solid earth, at global to regional spatial scales and at secular to annual temporal scales. This activity is financially supported by NWO through a Vidi grant received by Riccardo Riva (period 2014-2018, two PhD positions and one post-doctoral fellow position). We believe that studying processes that act at different spatial/temporal scales within a homogeneous and self-consistent framework will allow us to greatly improve our understanding of the size and causes of recent sea level change. A key role will be played by satellite gravimetry observations provided by the GRACE and GRACE-FO missions, which will ensure enforcing of mass conservation at all scales of interest. In particular, we aim at providing time-series of sea level change in coastal areas (from tide gauges) that are consistent with regional estimates over the oceans (from satellite altimetry). In addition, we will produce a global model of present-day GIA tuned to sea level studies, which will be made available to the geophysical and geodetic community.

## 3.2 Theme 2: Positioning, Navigation and Timing (PNT)

*Scientific staff: Peter Teunissen (0.2 fte), Christian Tiberius (1.0 fte), Hans van der Marel (0.7 fte), Sandra Verhagen (0.9 fte).*

**Introduction.** This decade will bring a proliferation of Global Navigation Satellite Systems (GNSS) that are likely to revolutionize society the same way as the mobile phone did. The promise of a broader multi-frequency, multi-signal GNSS ‘system of systems’ will enable a much wider range of demanding applications compared to the current situation. This PNT-programme aims to address these GNSS challenges by developing the theory and models necessary to fulfil high-accuracy and -integrity requirements (cf. Fig 9). During the review period, we published 163 peer reviewed papers and 1 patent on this theme.

### *Theory for PNT*

**Integer Inference and Validation**: We are the founders of the geodetic theory of integer inference, a key area for high-precision GNSS. Examples of our contributions are: integer bootstrapping, with its popular closed form success-rate; invention of integer-aperture (IA) and integer-equivariance (IE) estimation; and an extension of collocation- and Kriging-theory to the mixed-integer case. Although Kriging is one of the most popular spatial prediction methods, we have shown that it is suboptimal when the model of the spatio-temporal field contains an integer-parametrised multivariate trend. Within our new class of IE-predictors we were able to determine the best predictor and show that its mean squared prediction error is smaller than that of Kriging. We have also demonstrated that current integer ambiguity selection methods are not sustainable for future GNSSs and that they need to be replaced by our IA-theory based validation test procedures.

**Stochastic model:** Variance component estimation (VCE) is an important topic as our knowledge of the stochastic model is still at a rather rudimentary level in many modern geodetic measurement techniques. We have introduced Least-Squares (LS)-VCE as a method that unifies many of the existing

VCE methods. LS-VCE is attractive as it allows one to directly apply the existing body of knowledge of least-squares theory, such as statistical hypothesis testing, nonlinear estimation and curvature, and estimability with S-transformations. Our LS-VCE has been successfully applied to various GNSS models and measurement scenarios, from short-baseline to global network based models.

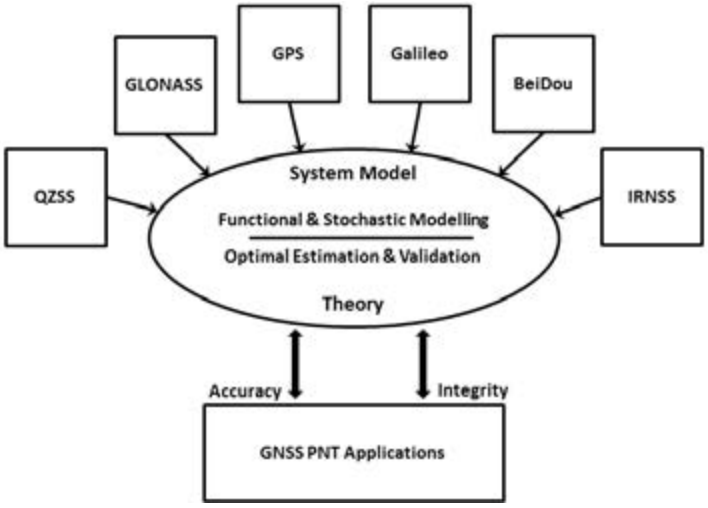



**Figure 9** Global Navigation Satellite Systems (GNSS) are linked to a wide range of Positioning, Navigation, and Timing (PNT) applications through system models and theory.

**Attitude Determination** GNSS attitude determination has a wide variety of challenging (terrestrial, sea, air, and space) applications. Until recently, the well-known LAMBDA method was universally used as the ambiguity domain attitude determination method. We have shown however that this method is not optimal for the highly nonlinear GNSS attitude model and that it should be replaced by our newly developed multivariate constrained (MC-) LAMBDA method. With its new ambiguity objective function, in which the nonlinear body-geometry is fully integrated, the method is currently the best performing attitude determination method as was demonstrated in land, sea and air experiments. As a maritime spin-off, an improved sinkage-monitoring method was also developed.

**Array processing:** The Array-aided Precise Point Positioning (A-PPP) concept was patented and introduced as a generalization of Precise Point Positioning (PPP). It is an array processing concept that uses data from multiple antennas in known formation to realise improved GNSS parameter estimation (position, time, equipment delays and atmospheric delays). The improvements can be exploited in different ways, e.g. to improve accuracy, to reduce convergence time, to achieve higher success rates, or to improve between-platform positioning. To enable fast, efficient and accurate A-PPP, a novel orthonormality constrained mixed integer least-squares problem was introduced and solved. The A-PPP principle is generally applicable. It applies to single-, dual-, and multi frequency GNSS receivers, as well as to any current and future GNSS, standalone or in combination. It is also not restricted to GNSS, as it applies for instance to acoustic phase-based positioning and other interferometric techniques as well.

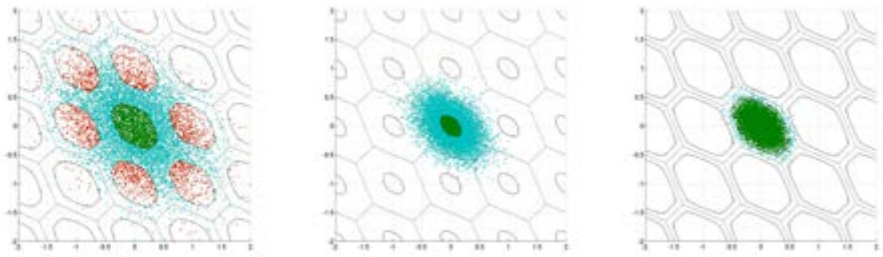


**Figure 10** A 2D illustration of three different cases of integer ambiguity ratio-test validation. The green and red dots result in correct and incorrect integer outcomes respectively, while blue dots result in a float solution as an outcome. The left panel shows poor performance (as the aperture pull-in region was chosen too large). The middle and the right panel show good performance; the fixed failure-rate approach was used, resulting the validation to adapt to the strength of the underlying model (they both do have the same guaranteed small failure-rate).

### *Modelling for PNT*

**New and Multi-GNSS:** We have been at the forefront of modelling, integrating and analysing the use of new and multi GNSSs for PNT. This includes the characterisation and initial assessment of the Chinese BeiDou (BDS) system and the first results of mixing GPS with Galileo and BDS, respectively. This work was also recognised by the European Space Agency (ESA) by means of a Galileo award. We also studied quadruple integration of GPS, BDS, Galileo and QZSS for long baseline RTK and single-frequency RTK. Our results show a remarkable robustness in satellite-deprived environments (urban canyons; open pit mines). And recently we successfully demonstrated how to L5-integrate the new Indian IRNSS signals with GPS, Galileo and QZSS for precise positioning.

**GNSS Bias Modelling**: New GNSS constellations come with system-specific bias characteristics. Inter-system biases (ISBs) need precise modelling if one is to take advantage of multi-GNSS 'mixing' to improve PNT solutions. We were the first to analyse un-differenced GPS-Galileo mixing and to determine their mixed receiver ISBs. We also discovered a new bias-type among the GEO, IGSO and MEO satellites of BDS. We have shown that this mixed receiver half-cycle inter-satellite-type-bias (ISTB) severely affects ambiguity resolution and we demonstrated how it could be calibrated. As acknowledged by the Chair of the Radio Technical Commission for Maritime Services (RTCM) SCI04, our discovery has enabled GNSS receiver manufacturers to modify and align their receivers such that now mutually consistent BDS extraction procedures are realised.

**PPP-RTK**: PPP-RTK is a relatively new positioning concept that combines the single-receiver positioning benefit of PPP with the ambiguity-fixing capability of network-RTK. We have used S-system theory to compare the different mechanizations that have been proposed in the literature. This enabled us also to identify the methods that cannot be accepted as proper PPP-RTK methods. The PPP-RTK development is still in its infancy, as studies focused on ionosphere-free, dual-frequency GPS so far. To do justice to the many different observation types of multi-GNSS, we have taken an un-differenced approach throughout. This allows for much greater flexibility, and, together with the S-system theory, for a proper PPP-RTK incorporation of next generation GNSSs in PNT. Our approach also applies to single-frequency users, thus enabling PPP-RTK even for low-grade GNSS receivers.

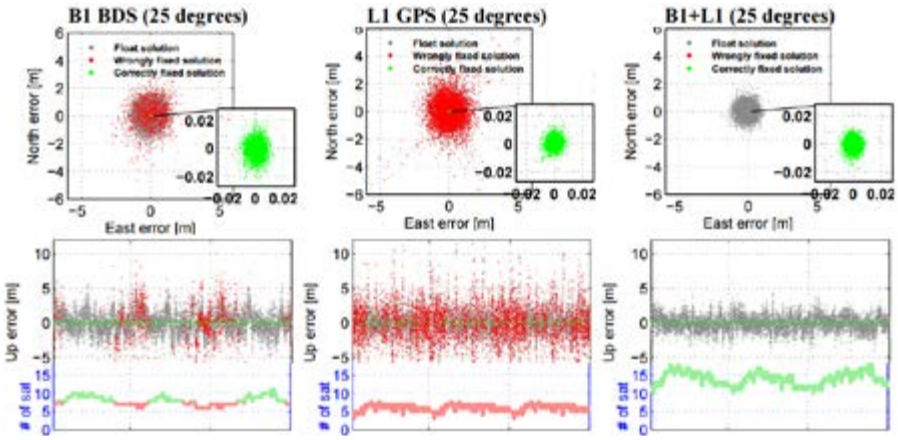



**Figure 11** Horizontal East-North instantaneous position scatter plots (upper panels), and vertical position time series (lower panels), for single frequency B1 BDS (at left), single frequency L1 GPS (middle), and B1+L1 BDS+GPS combined (at right). These results pertain to a 1 kilometre baseline, observed over a 3-day period, with a cut-off elevation angle of 25 degrees.

### *Future Plans for PNT*

**Theory and modelling**: Our work on multi-frequency, multi-GNSS, with associated theory and model development, will be continued and extended. Provision of a rigorous quality description for the ambiguity resolved GNSS-parameters is possible for integer-estimation, but not yet for the more complex integer-aperture-estimation. With regard to bias-robustness, we will work on model reduction methods to improve on the success-rates and partial ambiguity resolution performance. New theory is needed for mixed-integer model testing. This lack of appropriate theory has as a consequence that in practice still classical methods (e.g. statistical theory of hypothesis testing for linear models) are applied

to the mixed-integer model. With the advent of more demanding GNSS applications, the identified lack of testing theory is not acceptable, as one will have to satisfy the need for corresponding tighter quality control requirements.

**GNSS-complements**: Despite GNSS' huge success, the concept of satellite-based positioning also has its limitations (e.g. urban canyons, indoor, multipath). Indoor radio positioning and SuperGPS are the two GNSS-complementary concepts on which our research will be focussed. Recently we already started with the topic of indoor positioning, using wide band radio signals. This concept deserves also from the algorithmic point of view attention, as -unlike in satellite navigation- the problem is highly non-linear, due to the short ranges between transmitters and receiver, and the highly varying geometry. The second GNSS-complementary concept is SuperGPS, a new terrestrial radio-positioning concept in which an extremely accurate time reference is distributed over an optical network, and the 'last mile' to the user is covered by a very wide bandwidth radio signal (order of GHz). This should deliver pico-second timing and cm-positioning accuracy, and can be used for instance, to support vehicles driving autonomously on highways (see Fig 12). The extremely accurate time reference may also offer new opportunities in geodesy, beyond GNSS, as determining gravitational potential differences across the optical network.

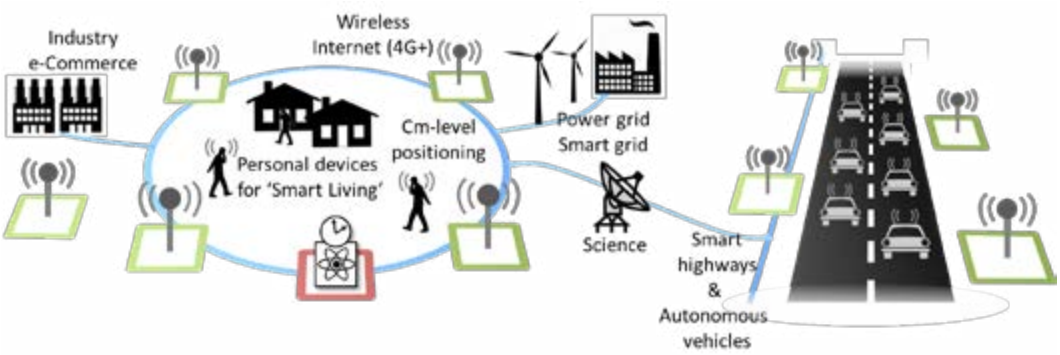



**Figure 12** The concept of SuperGPS: a hybrid optical-wireless system. A network of (existing) glass-fibre (in blue) distributes a highly accurate time reference (in the red square), to terrestrial wide-band transmitters (in green squares) providing radio-signals which allow users to position with cm-accuracy.

## 3.3 Theme 3: Geokinematics

*Scientific staff: Ramon Hanssen (0.9 fte), Andy Hooper (1.0 fte, until 2013), Miren Vizcaino (1,0 fte since 2013)*

**Introduction**. The geokinematics theme focuses on the development of methodology and algorithms to estimate motion of the earth or objects on earth, and the understanding of related driving mechanisms. Techniques such as InSAR are used alongside GNSS, ground-based observations and geophysical models to study processes such as land subsidence, earthquakes and volcanoes, dike stability, and structural health of objects. Improved processing techniques and the rapid development and availability of new satellite sensors lead to new applications of the technology, and require improvements of fundamental theory. During the review period, we published 139 peer reviewed papers on this topic, among which two in Nature, two in Nature Geoscience, and 1 patent.

**Methods and algorithms**. The main challenge in the use of satellite radar techniques is how to extract relevant information from the spatio-temporally variable reflections of signals transmitted by radar satellites. Intrinsically, the raw observations contain a multitude of contributions, and the geometric and kinematic information of interest needs to be deciphered by meticulous processing. During the review period, we elaborated on our radar interferometric software Doris, which is publicly available and used by hundreds of scientists around the world. We developed new software, DePSI, for persistent scatterer interferometry, and adapted this for all available satellite sensors. The DePSI core is now used as standard processing tool by ESA. In terms of methodology, we developed new methods to correct for

satellite orbit errors, for phase unwrapping (ambiguity resolution), DEM correction, hybrid processing, atmospheric correction, and time series analysis. We also pioneered and patented a technique for geodetic datum connection, using microwave transponders attached to permanent GNSS stations and tide gauges. We are principal investigator of a new Dutch X-band satellite SAR mission.

In the coming period we plan to optimally exploit the potential of new missions, such as ESA's Sentinel-1 mission, particularly in relation to parameter estimation over less coherent areas. This requires completely new processing techniques, related to the progressive scanning modes of these missions. Data availability will increase dramatically in the coming years, with world-wide coverage twice per week, and the main challenge will become how to process these data and estimate the relevant parameters. As principal investigator of PanelSAR, we expect the launch of this new (first) Dutch SAR satellite in the coming period. We will establish a first realisation of a national unified height system, the Dynamic DEM. Theoretical concepts related to hypothesis testing will be further studied.

**Geophysical geodesy**. Using the developed InSAR processing algorithms, we studied the dynamics of earthquakes (and if related, tsunami's) and volcanoes. Several studies led to publications in high-impact journals such as Nature (twice) and Nature geoscience (twice). We studied the deformation style of moderately active volcanoes, such as Eyjafjallajokull, Iceland, in 2010 where an explosive summit eruption caused exceptional disruption to air traffic, closing airspace over much of Europe for days. This eruption was preceded by an effusive flank eruption of basalt. We showed that deformation associated with the eruptions was unusual because it did not relate to pressure changes within a single magma chamber. Deformation was rapid before the first eruption, but negligible during it. For the Netherlands we have produced a national surface deformation map, using all available geodetic data, a worldwide novelty, see Fig. 13.

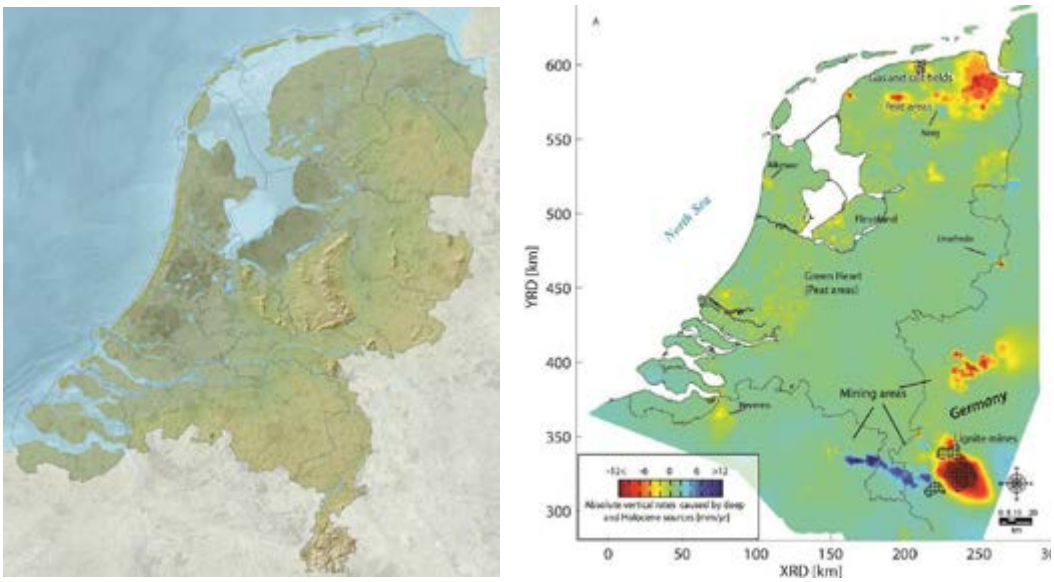



**Figure 13** Nation-wide surface elevation and deformation map derived from lidar, gravity, GPS, levelling, and InSAR.

In the coming period, we plan to focus on a few key geophysical application areas, dependent on filling a current vacancy. One new research direction is measuring the deformation of soft soils, such as pastures on peat soils, extremely relevant for the Netherlands, where we will use recently developed multi-sensor technology. We plan to develop methods for the continuous monitoring of strategic areas, such as the active volcano on the Dutch island Saba. Together with colleagues of the unit Geophysics, we explore combinations of seismic interferometry and satellite radar interferometry.

**Mining and natural resources** The unit has a long standing involvement with the monitoring of land subsidence (and uplift) due to the production of natural gas, oil, coal, salt, and water, in the Netherlands. Using InSAR, we have been monitoring the spatio-temporal behaviour of the surface, identifying time-dependent anomalies in the relation with production data. In 2009, in a letter to parliament, the Minister

of Economic Affairs adopted our technology, leading to its acceptance for operational monitoring. We continued to enhance the methodology to allow for coherent information over the more rural areas. We detected the uplift of several areas in the south and east of the Netherlands, some previously unknown, and assessed the associated risk.

In the coming period, we will focus on the discrepancy between geomechanical model predictions and geodetic data, which currently leads to much controversy, for the general public as well as in science. Second-order behaviour in space and time also shows potential to investigate relations with induced seismicity.

**Security and hazards**. The stability of dikes, bridges, and dams, is key for public safety in the Netherlands. Yet, reliable quantitative information on these structures is difficult to obtain due to the amount and size of such objects. We have developed and demonstrated monitoring strategies to measure this stability, which allowed infrastructure managers to assess their assets. This research has won an SBIR prize, which led the unit to start a spin-out company in 2008 to apply and offer this technology on an operational basis. The unit continues fundamental research on this topic. A recent success was related to the sudden occurrence of sinkholes in urbanized areas in the south of the Netherlands, where we demonstrated that there is precursory motion, preceding the collapse, which can be used to detect high-risk locations in the future.

In the coming period we will expand the application range for security and hazards, by incorporating buildings, railways and roads. We will elaborate on recent advances in hypothesis testing methods to identify hazardous situations related to infrastructure. This should lead to an automatic warning system based on continuous satellite-based monitoring.

## 3.4 Theme 4: Remote sensing

*Scientific staff: Massimo Menenti (1.0 fte), Roderik Lindenbergh (1.0 fte), Ben Gorte (1.0), Ramon Hanssen (0.1 fte).*

**Introduction**. We retrieve information on the properties and shape of natural land and man-made objects and on the processes modifying both, using measurements on the interactions of light with objects. We use imaging radiometers to measure radiative and hydro-meteorological processes over land. Satellite, airborne and ground-based laser systems are used to measure the detailed shape of observed objects. Imaging radiometers and laser systems help us to respond to questions emerging from both earth science and civil engineering. During the review period, we published 118 peer reviewed papers on this theme.

**Radiative and hydro-meteorological processes**. Research on this sub-theme has been boosted by a major FP7 project on the hydrology and climatology of the Tibetan Plateau using satellite data. This project aimed at developing a system to monitor water resources using satellite data, addressing multiple research questions related both to the observation of the required land surface properties and to the use of such observations to model the terrestrial water cycle and energy and mass exchange at the land-atmosphere interface. The research was carried out by 18 partners in 8 countries. The unit focused on:

a) lake levels using the ICESat Laser and Cryosat Radar Altimeter;
b) glacial thickness changes using the ICESat laser altimeter;
c) surface energy balance and evaporation using multiple satellite data, particularly the hourly observations of land surface temperature (LST) by a Chinese geo-stationary satellite;
d) surface albedo corrected for the effects of sub-pixel topography;
e) modelling and reconstruction of the hourly LST time series and retrieval of sub-surface soil thermal properties (cf. Fig 14);
f) use of multiple satellite observations to characterise glacier response to weather and climate; and
g) detection and delineation of large flooding events using the difference in brightness temperature at 37 GHz between horizontal and vertical polarization.

The topics (a-g) have been largely addressed by PhD projects (3 successfully completed in 2014 and 4 in 2015). In 2013 the French Ministère de l'Enseignement Supérieur et de la Recherche awarded to the project the prize *Etoiles de l' Europe* for the theme Environment. In 2010 and 2014 results of the project were used by the Group for Earth Observation (GEO) to produce a video show case to illustrate the benefits of Earth Observation at the 4 yearly World Ministerial Summit of the GEO Member Countries.

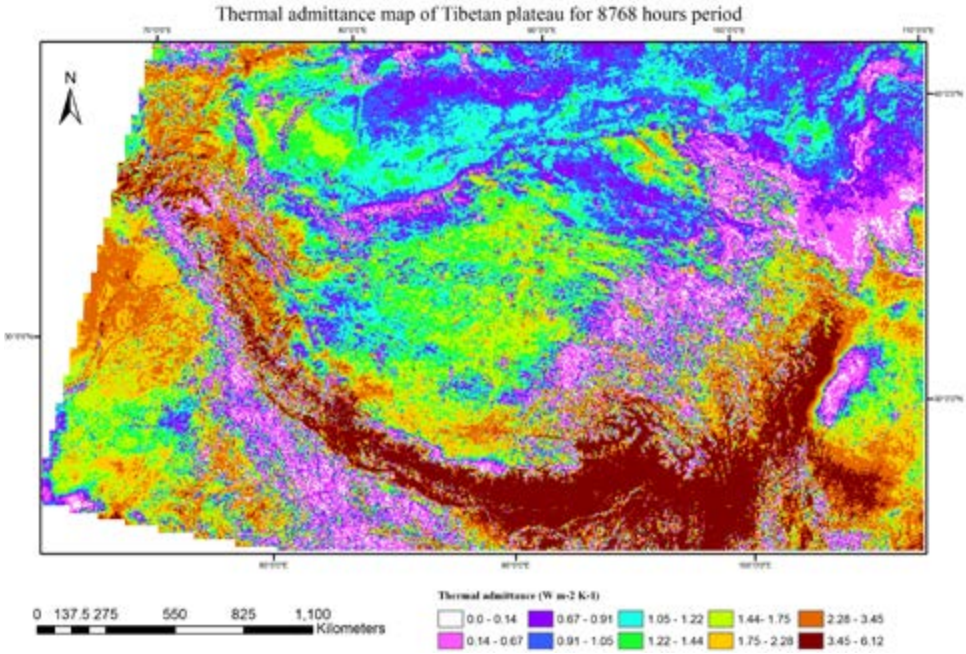



**Figure 14** Map of thermal admittance for the yearly component of soil heat flux derived from 3 years (2008- 2010) of FY-2 hourly observations of Land Surface Temperature ; Qinghai-Tibet Plateau.

**Retrieval of vegetation properties** by inverse modelling of spectral-directional radiometric data collected by space-borne imaging radiometers. This sub-theme addresses the core question of optical remote sensing: how to extract information on object properties from radiometric data at different wavelengths and viewing angles. Two topics have been addressed: (i) forward and inverse modelling of radiative transfer in the soil-vegetation-atmosphere continuum to retrieve simultaneously soil, vegetation and atmospheric properties, and (ii) retrieval of foliage water content and temperature to construct a forest fire hazard indicator. The synergy of a time series of optical satellite observations from a variety of sensors can be exploited to improve the retrieval of biophysical variables. Two PhD projects have been completed on these two topics and have resulted in high impact refereed journal publications.

**Metric information extraction with laser scanning**. Point clouds are discrete dense samples of the surface of 3D scenes and areas acquired by different geodetic measurement techniques. In our research we focus particularly on processing point clouds acquired by laser ranging. The principle of laser ranging has been implemented on both static and kinematic platforms. Local point clouds, of e.g., houses and vegetation can be acquired by a terrestrial laser scanner. We have our own terrestrial laser scanner which is actively used in research. One PhD project quantifies the influence of measurement geometry on the quality of the obtained laser scanner point cloud. Within another PhD project, finished in 2011, algorithms were developed to extract the structure of botanic trees sampled by a laser scanner. Results from both projects have been published in journals like the ISPRS Journal of Photogrammetry and Remote Sensing.

In recent years, laser rangers have also been incorporated in Laser Mobile Mapping systems, typically consisting of a car equipped with some laser profilers for range measurements, and GNSS and IMU equipment for positioning and orientation determination. Such systems, similar in operation as airborne laser systems, acquire huge point clouds sampling a large variety of objects in very short time. This calls for intelligent and notably very efficient processing methods. One ongoing PhD project considers the use of space division techniques like voxelization and octrees as a scalable strategy to extract

information from such point clouds. The TU Delft generally focusses on the design and testing of different strategies to process large laser scanner point clouds.

At the largest scale, laser ranging is applied in satellite missions. So far, the ICESat mission (2003-2009) is the only laser altimetry mission that has been operational on Earth. For this mission the full return signal as function of time is stored for each shot, the so-called full waveform. One PhD project was dedicated to the analysis of the potential of this ICEsat full waveform signal. One of the prime objectives of the ICESat mission is to map volume changes of the Greenland and Antarctic ice sheets. For this purpose methodology has been developed to extract elevation changes all over Greenland from ICESat data. It has also been demonstrated by our research that the full waveform signal can be used to distinguish land cover, both over The Netherlands and the cryosphere. A second PhD project, linking to the above mentioned CEOP-AEGIS project, has been used to extract lake level and glacial changes from ICESat data over the Tibetan Plateau (Fig 15).

In the coming period, it is expected that point cloud sampling systems will be used intensively to sample our 3D environment and its changes. Point clouds will be acquired repeatedly as requested by public stakeholders, such as cities and countries. In addition consumer products such as Kinect devices and smart phones in combination with drones or selfie sticks enable citizens to acquire their own point cloud data. Online platforms will be required that are able to almost instantaneously extract and update information hidden in newly available 3D data. Within this theme we will focus research on characterizing the quality of such different 3D point cloud data and on methodology to extract information near real-time from huge point cloud data sets while incorporating these quality descriptions.

**Image modelling and photogrammetric applications**. Spatial information has been extracted from image data for application in the domain of civil engineering. For example, hydraulic roughness is an important parameter in assessing flooding risks in washland areas. We demonstrated that hydraulic roughness can be estimated from a combination of image and point cloud data. Using a helicopter hovering over a highway, image sequences were obtained sampling the changing traffic situation. Methodology was designed and implemented to extract trajectories of individual cars from these image sequences which serves as input for research on driving behaviour. A new way of obtaining 3D data is by so-called structured light cameras, in which a projected pattern is analysed. Such a system was designed to monitor submerged terrain in a waterlab flume.

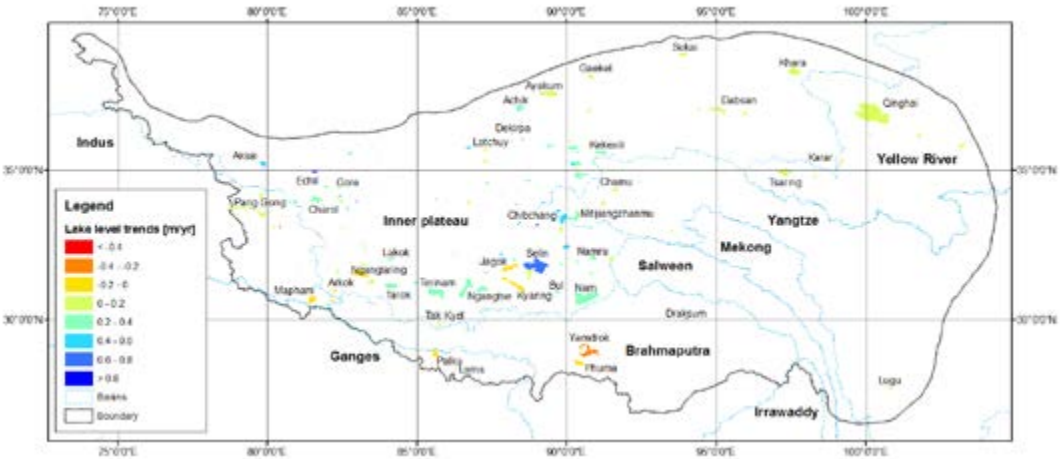



**Figure 15** Lake level trends on the Tibetan plateau between 2003 and 2009 derived from ICESat laser altimetry data.

**Land use change for bio-renewables**. Since 2013, a new research line started in the framework of Be-Basic, an international public-private partnership that develops industrial biobased solutions to build a sustainable society and to switch from fossil fuels to biomass. The unit develops a methodology to determine near real-time monitoring of land use, currently focussed to sugarcane production in Brazil. The novelty in the approach lies in the 'system-of-systems' combination of microwave and optical data

to provide continuous updates and classification reliability improvements. This research line currently involves two postdocs and a PhD student.

**Klees, R. E.A. Revtova, B.C. Gunter, P. Ditmar, E. Oudman**, H.C. Winsemius, and H.H.G. Savenije, 2008. The design of an optimal filter for monthly GRACE gravity models. *Geophysical Journal International*, 175 (2008), 417-432.

**Chang, L., Hanssen, R.F.**, (2014), Detection of cavity migration and sinkhole risk using radar interferometric time series, *Remote Sensing of Environment*, 147, pp. 56-64.

**Riva, R.E.M., B.C. Gunter**, T.J. Urban, **L.L.A. Vermeersen, R.C. Lindenbergh**, M.M. Helsen, J.L. Bamber, R.S.W. van de Wal, M.R. van den Broeke, and B.E. Schutz, 2009. Glacial Isostatic Adjustment over Antarctica from ICESat and GRACE satellite data, *Earth Plan.* Sci. Lett., 288 (2009), 516-523.

**Soudarissanane, S., R. Lindenbergh, M. Menenti, P.J.G. Teunissen**, 2011. Scanning geometry: Influencing factor on the quality of terrestrial laser scanning points. ISPRS *Journal of Photogrammetry and Remote Sensing*, 66 (2011), 389-399.

**Teunissen, P. J. G.**, 2010. Integer Least-Squares Theory for the GNSS Compass. Journal of Geodesy, 84 (2010), 433-447.

**Figure 16** Key publications.

## 3.5 Summary of research quality

### Research products

During the review period, the geodesy unit published some 360 peer reviewed papers, among which two in Nature, one in Science, and most others in the top scientific journals in our field. As such, we contribute at the highest international level within the geodetic discipline compared with other university research groups. The scientific staff ranges from senior scientists with the highest international reputation to high-potential, junior tenure-track scientists at the start of their careers. We made software products available for the community, such as the interferometric radar processing software Doris, as well as products such as the DGM-1S Delft static gravity model, the DMT monthly GRACE mass transport models, and the national surface deformation map.

### Use of research products

The use of our research products is can be measured from citations and H-indices, ranging from 11 for junior tenured staff to 28 (Menenti) and 26 (Teunissen) for the most senior staff. However, our research is of wider interest and its products are increasingly used by other disciplines, such as hydrology, transport, and national safety, i.e. for monitoring the safety of critical infrastructure such as dikes. This follows from the number of publications in journals of related disciplines.

Our open policy in terms of making software products available is very fruitful, judged by the hundreds of scientists using e.g. our radar processing software Doris on a daily basis. The European Space Agency used Doris as the core engine for its interferometric NEST software.

### Marks of recognition from academic peers

Our staff has a high reputation in the academic community. The theme leaders Peter Teunissen, Roland Klees, Massimo Menenti and Ramon Hanssen are leaders in their respective fields. Klees became fellow of the IAG and editor-in-chief of Journal of Geodesy. Teunissen became fellow of the U.S. Institute of Navigation (2013), the UK Institute of Navigation (2014), federation fellow of the Australian Research Council (2009), and is one of the few TU Delft members of the Royal Netherlands Academy of Sciences. He received an honorary doctorate from the Chinese Academy of Sciences (2014), and holds honorary professorships at Tongji University, Shanghai (2012), and Wuhan University (2000). Menenti is visiting research professor at the Institute of Tibetan Plateau Research of the Chinese Academy of Sciences (CAS), and guest Professor at Beijing Normal University. Hanssen was appointed to the Antoni van Leeuwenhoek professorship (2008), became senior-member of the IEEE-GRSS, is president of the

Netherlands IUGG committee, and was appointed as visiting professor at Wuhan University (2011). Andy Hooper was appointed full professor in Geodesy and Geophysics at Leeds University, Sandra Verhagen received a Veni and Riccardo Riva a Vidi grant. Verhagen is also member of the Executive Board of IAG, and was president of Commission 4 "Positioning and applications" of IAG (2007-2011). Bert Vermeersen was appointed full professor in 2014 and held several positions in the European Geosciences Union (EGU).

The three most cited publications produced by members of the unit during the evaluation period are:

Bamber, J.L., **Riva, R.E.M., Vermeersen, B.L.A.**, Lebrocq, A.M., (2009) Reassessment of the potential sea-level rise from a collapse of the west Antarctic ice sheet, *Science*, 324 (5929), pp. 901-903. (citations: 172 (Scopus)).

Sigmundsson, F., Hreinsdóttir, S., **Hooper, A.**, et al., (2010) Intrusion triggering of the 2010 Eyjafjallajökull explosive eruption, *Nature*, 468 (7322), pp. 426-432. (citations: 135 (Scopus)).

**Klees, R. E.A. Revtova, B.C. Gunter, P. Ditmar, E. Oudman**, H.C. Winsemius, and H.H.G. Savenije, 2008. The design of an optimal filter for monthly GRACE gravity models. *Geophysical Journal International*, 175 (2008), 417-432. (Citations: 61 (Scopus)).

Top-5 courses given to peers:

**Teunissen, P.** (2011-2014) GNSS workshops for Taiwan Institute for Information Industry (2011), Hong Kong Polytechnic (2012, 2014), and Nanyang Technological University (2014), Singapore.

**Riva, R.** (2014) TU Climate Institute Summer School 2014 "Sea-level change: observations and processes ". (Delft, the Netherlands) Organiser and lecturer.

**Lindenbergh, R.** (2014) MoLaS Technology Workshop 2014 on Key Technology Drivers in Mobile Laser Scanning, November 26 - 27, 2014, Fraunhofer IPM, Freiburg, Germany.

**Hanssen, R.F.**, (2009-2014 ) European Space Agency, Advanced Training Courses on Land Remote Sensing (Hanoi, 2008 Prague, 2009; Krakow, 2011; Valencia, 2014, Nanchang, 2014).

**Menenti, M.**, (2010-2014 ) European Space Agency, Advanced Training Courses on EO for the African water resources community (TIGER Capacity Building Facility) (Cairo, 2010; Delft, 2011; Frascati, Lusaka, 2012; Johannesburg, Nairobi, 2013; Tunis, Niamey, 2014).

# 4 Relevance to society

The research of the Geodesy unit focuses on a number of themes with high societal relevance. Closing the sea level rise budget at regional scale, integrated monitoring and modelling of land subsidence, development of vertical reference frames in coastal areas, quantification of trends in continental water storage, the integration of ice sheets in global climate models, indoor radio navigation and SuperGPS, or land use change for bio-renewables are just a few examples. They directly address challenges related to the key societal topics of climate, energy, safety, transport, and infrastructure. These topics are expected to be on the societal agenda for a long time and guarantee continuity of the research activities. In the following, we list various types of interaction with societal relevance.

## 4.1 Cooperation with non-academic partners and user committees

Regarding societal relevance, we strive to maintain a healthy balance between curiosity-driven and application-inspired fundamental research. This implies involving various societal partners. About one third of our research is funded via contracts with external (non-academic) partners. These include industry, such as oil and gas companies, utility companies, engineering firms, as well as various SME's. International space agencies such as the European Space Agency (ESA), the German Aerospace Center (DLR), and the French Space Agency (CNES) are important partners. Governmental partners include ministry's, the Dutch Cadastre, Rijkswaterstaat, the Hydrographic Service, and institutes such as National Aerospace Laboratory (NLR), TNO, the Royal Netherlands Meteorological Institute (KNMI), Geological Survey, the State authority for Mining, and the Netherlands Space Office (NSO). We participate in large research programmes such as CATO, ISAPP, and Be-Basic. In publicly funded

(NWO/STW) research programs, we install user committees to ensure direct links with representatives from industry.

Strategic cooperation with the Ministry of Infrastructure and the Environment (Rijkswaterstaat) is secured via large framework contracts, which ensure fast administrative start-up of new research projects, as well as more security in the overall budget.

The ESA TIGER Capacity Building Program targets non-academic organisations with a mandate to monitor and manage water resources in Africa. During the reporting period we have organised short training courses attended by about 200 participants from all over Africa and given a large fraction of the lectures and exercises. In the same period of time we have provided guidance to 12 research projects selected by ESA in the framework of the TIGER program. The same training approach was applied under the CEOP AEGIS project: we organised three courses, 2 in Beijing and 1 in Rourkela, India, attended by 150 participants from academic and non-academic organisations.

Three SME's participated as full-partners to the CEOP-AEGIS project. In the ESA project Thematic Exploitation Platform-Hydrology, we play the role of User Community Leader and we are expected to identify and engage in the project a large community of users worldwide, but with a focus on South East Asia and West Africa.

## 4.2 Part-time staff in industry, academia, and (semi)governmental bodies

The staff of the Geodesy unit includes no part-time positions which are shared with, or funded by, industry. Ramon Hanssen founded the spin-out enterprise SkyGeo in 2008, but is not involved in its daily management anymore. Several staff members of the geodesy unit are (guest) professors at other universities, for example at Wuhan University (Teunissen, Hanssen) and Curtin University (Teunissen). Vermeersen has a part time position at the Royal Netherlands Institute for Sea Research (NIOZ). Menenti holds a part-time position as (visiting research) professor at the Remote Sensing and Digital Earth Institute (RADI), Chinese Academy of Sciences (CAS) since 2011.

## 4.3 Publications of research results and software

Results of the research program are often direct input for adjacent disciplines. We strive to communicate our research results via dedicated journals, but also keep close direct ties to align with our partners. Algorithms and software developed for radar interferometric data processing is made available online, and is widely used throughout the world. Datasets derived from satellite sensors, such as the DGM-1S Delft static gravity model and the DMT monthly GRACE mass transport models are publicly available. A patent has been granted to our method for geodetic datum connection using radar transponders. Our LAMBDA-software for GNSS ambiguity resolution is publicly available, and used by most GNSS equipment manufacturers and research institutes.

## 4.4 Opportunities to make our results available to adjacent fields

The expertise and experience of the unit has been used to explore new fields. A particular example is the use of remote sensing for archaeology, where we collaborate with archaeologists from Leiden and Leuven University in exploration areas in Jordan and Egypt. Similar new fields are explored with colleagues from hydraulic and geotechnical engineering, focusing on the stability and safety of dikes and soils, from structural engineering, focusing on railways, and from geophysics, focusing on reservoir and overburden behaviour. Advancing these new geodetic application domains requires a close alignment with domain experts. Global and regional estimates of monthly mass variations are provided to the hydrology groups at TU Delft and the University of Utrecht for regional-to-global hydrologic modelling, and to the glaciology group at Utrecht University for the validation of surface mass balance models. We contribute to the further development of the RADS radar altimeter database, one of the

largest and most complete publicly available radar altimeter databases in the world.
The largest share of the Remote Sensing research is aimed towards hydrological science and water management. An example is the MOSES project which targets the integration of weather forecasts and remote sensing with hydrological modelling towards more efficient and productive use of water for agriculture.

## 4.5 Recommendations to governmental bodies

The scientific staff of the geodesy unit is frequently asked to advise governmental and public bodies, on a variety of topics. Examples include advice on the effects of gas production in the north of the Netherlands, on uplift of abandoned mines and on sinkhole risks, and on the future of the geodetic infrastructure in the Netherlands. Geodesy staff also act in the scientific advisory committees of new satellite missions, such as the Sentinel-1 mission. On another international level, Miren Vizcaino is a contributing author to the last IPCC report AR5 and contributor to the new Ice Sheet Modelling Intercomparison Project for CMIP6 (ISMIP6), sponsored by CliC (WRCP's Climate and Cryosphere Project). We act as certification agent for gravity observations and maintain a network of absolute gravity stations to control the vertical movement of the Netherlands first-order height network.

## 4.6 New societal relevant research lines

The geodesy unit has an agile attitude towards societal developments that require geodetic or remote sensing expertise. Although estimating land subsidence in Groningen has been a societally relevant research topic for many years, in recent years this gained momentum due to the increased occurrence of induced seismicity caused by gas production. Using our experiences in GNSS and radar techniques, we adapted research plans to allow for improved estimation of the surface movements in space and time, indicating differential compaction of reservoir units. Another example concerns the sudden collapse of a shopping mall in the south of the Netherlands, due to the sudden appearance of a sinkhole. Within one weekend, results were produced using InSAR showing that the collapsed building was actually deforming for a long time before the collapse, indicating a prior observable driving mechanism. The Be-Basic study on improved monitoring of land-use change is another example, where we adapt to requests from society to apply our expertise in new domains. During the review period we started a new research line on closing the sea level budget at regional scale with emphasis on the North Atlantic and North Sea. Together with Deltares, we intend to further intensify our research related to the assimilation of geodetic data in and the use of 3D high-resolution, high-accuracy regional shallow-water hydrodynamic models. They have the potential for a number of innovative applications in societal relevant areas: i) better quantification of risks in passage planning of ships in shallow coastal waters; ii) increased safety in navigation by a probabilistic approach to vertical referencing; iii) improved storm surge water levels; iv) increased efficiency and accuracy in bathymetric surveying, offshore construction works, and underwater acoustic positioning; and v) a better prediction of the impact of pile driving or dredging by improved modelling of acoustic propagation.

## 4.7 Engagement in the public debate

The geodesy unit has participated in the public debate on many occasions. Riccardo Riva responded to many media requests related to his publication on the range of anticipated sea-level rise. Andy Hooper appeared frequently in the international media after the 2010 Eyjafjallajökull explosive eruption, and published opinion pieces in leading international newspapers, including The Guardian, Telegraph and International Herald and Tribune. Ramon Hanssen was asked frequently by newspaper, radio and television, to comment on hazards related to land motion, and appeared on a special edition of Labyrinth, a scientific television show, and School-TV, aimed at primary school education. Anneleen Oyen appeared on the popular Dutch television show 'De Wereld Draait Door'.

**Hooper, A.J., R.F. Hanssen, A. Oyen, K. Spaans** (2010), Television and radio appearances on Volcano Eruption Iceland: CNBC (American TV - 19/04), Radio Europe (19/04), Sky News (UK TV - 20/04), CBC (Canadian TV - 21/04), Radio Netherlands (22/4) BNR Newsradio (17/5), Radio538 (17/5), De Wereld draait door (NL TV-20/4), VPRO TV documentary "Labyrint", on the stability of the Netherland, *March 2012*, subtitled https://youtu.be/m55ZjmtO6X0

**Caro Cuenca, M., A.J. Hooper, R.F. Hanssen, 2013**. Surface deformation induced by water influx in the abandoned coal mines in Limburg, The Netherlands observed by satellite radar interferometry, *Journal of Applied Geophysics*, 88 (2013), 1-11.

**Verhagen, S., B. Li, P.J.G. Teunissen, 2013**. Ps-LAMBDA: Ambiguity success rate evaluation software for interferometric applications. Computers & Geosciences 54 (2013), 361-376.

**Slobbe, D.C., R. Klees**, B.C. Gunter, Realization of a consistent set of vertical reference surfaces in coastal areas, *Journal of Geodesy* 88 (2014), 601-615.

Li, X., X.W. Li, K. Roth, **M. Menenti**, W. Wagner, 2011. Observing and modelling the catchment scale water cycle. Hydrology and Earth System Sciences 15 (2011), 597-601.

**Figure 17** Key societal output.

# 5 Viability

The research program has a strong fundamental component, and seeks to address problems of high societal relevance, which guarantees continuity for the next period. Although this covers a wide range of topics, the research program is well focused from a conceptual and methodological point of view. There is a good mixture of established senior researchers and high-potential junior researchers with a background in geodesy, geophysics, and mathematics. The informal style of leadership without internal management meetings and short lines of communication is increasing the collaboration between the various unit members, allowing potential synergies within the unit to be exploited, and generating additional coherence within the unit. Already two years after moving to CEG, there is a strong collaboration with other research units of CEG in order to address the key societal challenges indicated in Fig 1 following a multi-disciplinary approach. The network with leading (inter-) national academic institutions, governmental institutions, and industry is strong and continuously evolving. The financial basis is healthy. Our efforts to develop and implement the MSc track on Geoscience & Remote Sensing, which is open for students of two different MSc programs, starts paying off as seen in the increasing number of students.

## 5.1 Positioning of the unit Geodesy within the geodetic landscape

Top-ranked research in geodesy and remote sensing is performed at a number of universities and institutions in the world, see Table 1. Considering universities, in the fields of gravity, positioning, mathematical geodesy, and radar interferometry, we believe to be at a competing level in the top-5 world-wide in terms of scientific contributions and impact in the field.

**Europe**

- University of Bonn (Inst Geodesy and Geoinformation)
- Technical University of Munich (Inst Astronomical and Physical Geodesy; Inst Communication and Navigation)
- Technical University of Denmark (DTU Space-Geodynamics)
- Politecnico di Milano (Dipartimento di Elettronica ed Informazione)
- University of Leeds (School of Earth and Environment)
- ETH Zürich (Inst Geodesy and Photogrammetry)
- University of Bern (Astronomical Institute)
- Université Paul Sabatier Toulouse III (Center for the Study of the Biosphere from Space, CESBIO).

**International**

- Ohio State University (Division of Geodetic Science, School of Earth Sciences)
- Stanford University (GPS Lab; Department of Electrical Engineering)
- University of Calgary (Geomatics Engineering)
- Curtin University (Spatial Sciences)
- Wuhan University (GNSS Research Centre; School of Geodesy and Geomatics)
- University of Texas (Radionav Lab; Center for Space Research)

**Table 1** Peer academic institutions in Geodesy and Remote Sensing around the globe.

## 5.2 Benchmarking with MIT

In May 2015 we visited the Department of Earth, Atmospheric and Planetary Sciences (EAPS) at MIT to get a better understanding of the scientific culture. The focus of various talks with the head of EAPS, faculty staff, research scientists, PhD students, and the Vice President of Research was on the selection of staff, internal collaboration and communication, and instruments used to secure and maintain scientific quality. While at TU Delft the emphasis is on coherent research programs and 'design on content', at MIT the main emphasis is on the excellence of faculty staff, i.e., 'design on people'. The main instrument to achieve this is through a heavy 7-year selection procedure. Once tenured, there is no explicit quality control and the culture is characterised by trust and confidence that the best people will do excellent work. There is little programmatic steering. Internal collaboration and communication is organised through a large number of seminars separately for faculty staff and researchers/PhD students. High attendance is guaranteed, as the seminars are seen as the main mechanism to organise collaboration and to develop ideas for joint research projects and fund raising. Several aspects of the scientific culture at MIT are appealing and we will explore which aspects may be beneficial to the Geodesy unit.

## 5.3 SWOT analysis

**Strengths**

- A long record of proven excellence in fundamental and applied geodetic research ('the Delft school').
- Highly qualified and motivated, young academic staff.
- Strong network of collaboration with geoscientists at TU Delft and at the (inter-) national level.
- Close and solid ties with space agencies and industry.

**Weaknesses**

- Attracting enough highly qualified PhD students.
- Number of doctoral examinations, though increasing, is still below the target.

**Opportunities**

- Exciting new satellite missions will be launched in the next years, which will offer unique opportunities for fundamental and applied geodetic research.

- The integration of geoscience disciplines within CEG offers new opportunities for interdisciplinary research and collaboration with other units of the geo-cluster (atmosphere, geophysics, geo-engineering), and the units water resources, structural engineering, transport & planning, and hydraulic engineering.
- Current vacancies create the necessary space to set-up new research lines.
- Water, Climate, Energy, Safety, Transport, and Infrastructure are expected to be the key societal challenges for a long time; this aligns very well with our research portfolio and provides the necessary continuity for the further development of the program.
- The strong bachelor student base at CEG, and the embedding of our MSc track in two MSc programs at CEG will help increase the visibility of the Geodesy research program, stimulate CEG students to enter our PhD program, and secure the financial baseline.

**Threats**

- Reduction of the NWO open program budget and movement of research money from NWO to the EU reduces open funding opportunities and increases the administrative load.

In order to address the weaknesses, opportunities, and threats, several actions will be taken. Related to increasing the number of doctoral examinations, we will intensify our effort in acquiring funding from NWO (Veni-Vidi-Vici, STW), EU (Horizon 2020, ERC personal grants), European Space Agency (ESA), and public/private sources. A strict implementation of the new TU Delft graduate school procedure (go/nogo decision after the first year involving external referees) is expected to increase the success rate. To further reduce the risk of late termination of PhD projects, we complement the the TU Delft graduate school procedure by a program, which allows to attract potential PhD students on a temporary basis for a couple of weeks to months to demonstrate their qualification for entering the PhD program. To attract highly qualified PhD students, we will extend our effort in exploiting our scientific network. New satellite missions which have been launched recently or will be launched in the near future (e.g., GRACE-FO, Cryosat-2, Sentinel-1, Sentinel 2, Sentinel 3, Jason-3, ICESat-2, Metop-C) will generate an enormous amount of new data of great value to our research program and offers new opportunities for collaboration with other geo-science disciplines within CEG, as well as with external partners. We will constantly aim for increasing the visibility of the Geodesy research unit via various outreach opportunities.

Department
of Geoscience
& Engineering

# 4
# Geo-Engineering

# 1 Mission

The unit Geo-Engineering aims to improve the fundamental understanding of materials and processes in the shallow subsurface, with a particular emphasis on providing engineering solutions for a delta environment. To this end, we develop fundamental knowledge and innovative technology, which is essential to address current societal issues for:

- Safe constructions in, on and with ground materials (with a special focus on soft soils),
- Minimising the risk and impact of geo-hazards,
- Increasing the lifetime of existing soil structures (both man-made and natural),
- Sustainable use of the subsurface.

# 2 Strategy

## 2.1 Research strategy

### Review period

The unit Geo-Engineering focuses on "Geo-Engineering in a delta environment: on the ground, in the ground and under the sea". To address research related to the needs of society, in line with the unit's mission, we divide the research programme into 4 interconnecting themes (Fig. 1), which additionally have natural links to other units within the Department and wider Faculty. These are:

- Theme 1: Soil Mechanics,
- Theme 2: Geo-environmental Engineering,
- Theme 3: Subsurface Engineering,
- Theme 4: Dykes and Embankments.

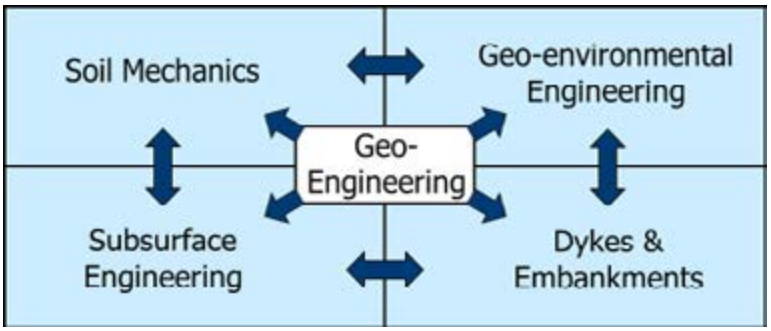



**Figure 1** Connecting research themes in Geo-Engineering.

The research of the unit Geo-Engineering focuses on the behaviour of, and engineering in and with, problematic deltaic soils. Particular scientific challenges include:

- The hydro-mechanical behaviour of fibrous soils (including wetting and drying),
- The behaviour and constitutive modelling of liquefiable soils at low stress levels,
- The characterisation and modelling of soil heterogeneity, and quantification of its impact on material and structure behaviour within a probabilistic reliability-based framework,
- Innovative engineering solutions for constructions in soft soils, with emphasis on soil-structure interaction in built-up areas, line infrastructure and ground improvement,
- The development of ecologically friendly subsurface solutions based on engineering with bio-geo-chemical processes,
- Reducing the negative impact of human interventions in the subsurface.

To tackle such challenges, the research involves a strong multi-disciplinary research team dedicated to the complex, coupled, non-linear and heterogeneous nature of geo-materials. This includes expertise in element testing, constitutive modelling, coupled processes, instrumentation, physical modelling, and

numerical and probabilistic modelling. There is a natural and strong connectivity between all themes, and it is common for staff members to contribute to more than one, or all, themes (Fig. 1).

The research strategy requires a commitment to a well-equipped laboratory, supported by appropriate academic and technical staff. The laboratory facilities are strong assets of the unit; they increase the potential for collaboration with other departments and industry, as well as being a unique selling point for hiring staff and research proposals. Foreseeing that construction and exploitation activities will move to more adverse conditions, e.g. deeper underground, as well as further and deeper offshore, to the arctic and less favourable subsurface conditions, our laboratory is well equipped to study such challenges.

During the reporting period, there have been significant staff changes within the unit Geo-Engineering, which has put a strain on research and education. At the same time, there has been the opportunity to reassess and strengthen the direction of research in the light of evolving societal needs. New chairs have been appointed to lead the fundamental research themes of Soil Mechanics and Geo-environmental Engineering, while there has been a change in emphasis in the application-inspired research themes including one new chair. In recognition of the increasing attention to safety against flooding, in particular relating to the continuous need to maintain and improve the geotechnical safety of dykes in delta regions throughout the world, the new theme Dykes and Embankments was started in late 2012. Meanwhile, the increasingly demanding technological and scientific challenges posed by growing demands on space, necessitating complex constructions on problematic soils as well as within the subsurface in urban areas, led to the new theme of Subsurface Engineering being introduced in 2014. This combines the previous themes of Foundation Engineering and Underground Space Technology (both chaired by part-time professors) into a wider cross-departmental initiative encompassing all aspects of underground (including offshore) construction, which will be led by a full-time professor (see next page).

### Coming period (2015-2020)

The above research themes will remain relevant in the coming period. The new themes of Subsurface Engineering and Dykes and Embankments will strengthen cross-departmental links, as well as links with Deltares, Rijkswaterstaat, STOWA, Dutch water boards, the oil and gas industry, and other semi-governmental and industry stakeholders. International collaborations (e.g. North America, Europe, China, Australasia), facilitated by recent staff appointments (Hicks, Vardon (UK); Jommi, Pisanò (Italy); Askarinejad (Switzerland)), will be further developed and new collaborations initiated. Our ultimate goal is to be a world-leading multi-disciplinary group in the multi-physics/multi-scale behaviour of engineering constructions in or on deltaic soils.

## 2.2 Personnel strategy

### Review period

In addition to the chair appointments, the unit has also appointed new assistant professors of very high calibre. Part of our hiring strategy was to appoint new staff with a broad (excellent) complementary network, as this will ease future collaboration, especially in the EU context. Although each assistant professor is nominally assigned to a particular chair, they interact with all themes, thereby ensuring a high degree of cross-unit cooperation.

According to this strategy, the staff changes during the reporting period are as follows:

- **Soil Mechanics:** A new chair in Soil Mechanics (Prof. Hicks, from the University of Manchester) was appointed in September 2009, following the retirement of Prof. Molenkamp in 2008. This was followed by the appointment of two new assistant professors: Dr Dijkstra in February 2011 (Experimental Soil Mechanics), as a replacement for Dr Allersma who retired in 2005; and Dr Vardon (from Cardiff University) in January 2012 (Computational Soil Mechanics), as a replacement for Dr Van Baars who took up a chair at the University of Luxembourg in 2010. Dr Dijkstra then took up an associate professor position in Chalmers University in 2013, and was replaced by Dr Askarinejad (from ETH Zurich) in April 2014 (Experimental Soil Mechanics). Mr Oostveen retired in 2012 and was not replaced.

- **Geo-environmental Engineering:** There have been the following changes in assistant professors: Dr Van Paassen was appointed in September 2009, following the transfer of Dr Storms to the Geology unit in 2008; Dr Hoogendoorn left the unit to join Deltares in March 2010; Dr Van Odijck was appointed in January 2011, but then transferred to the Geo-Resources unit in January 2012. A new chair in Geo-environmental Engineering (Prof. Heimovaara, formerly associate professor within the unit) was appointed in November 2012, following the retirement of Prof. Bruining in March 2012.
- **Subsurface Engineering:** The chair of Underground Space Technology (Prof. Bosch, 0.3 fte) left in July 2014, and the chair of Foundation Engineering (Prof. Van Tol, 0.4 fte) retired in May 2015. These two chairs were replaced by the new Subsurface Engineering theme. The unit appointed Dr Pisanò (from Politecnico di Milano) in November 2014, as assistant professor in Offshore Soil Mechanics, a joint position between Geo-Engineering (0.6 fte) and Offshore Engineering (0.4 fte).
- **Dykes and Embankments:** The chair of Groundwater Mechanics (Prof. Barends) retired in 2009 and the assistant professor in the same discipline (Dr Uffink) retired in 2012. It was decided to redefine this chair for the field of Dykes and Embankments, in order to strengthen the unit in this important strategic area. The new chair (Prof. Jommi, from Politecnico di Milano) was appointed in December 2012, and the position was upgraded from 0.3 to 0.8 fte in July 2013; the position is part-funded by Deltares and forms part of TU Delft's Flood Risk Centre.

Figure 2 depicts the development in personnel during the review period. Despite the many changes in scientific staff, the overall number of fte's was kept fairly constant, whereas the non-permanent staff doubled in number due to the successful acquisition of funds by the new scientific staff (see also Fig. 4). The relatively low number of graduating PhDs during the reporting period is partly because of the relatively high proportion of part-time PhD students registered in the earlier years (whose period of study is longer than 4 years), and partly because of the large number of new students who have not yet reached the end of their study period. Large numbers of students will graduate from 2015 onwards.

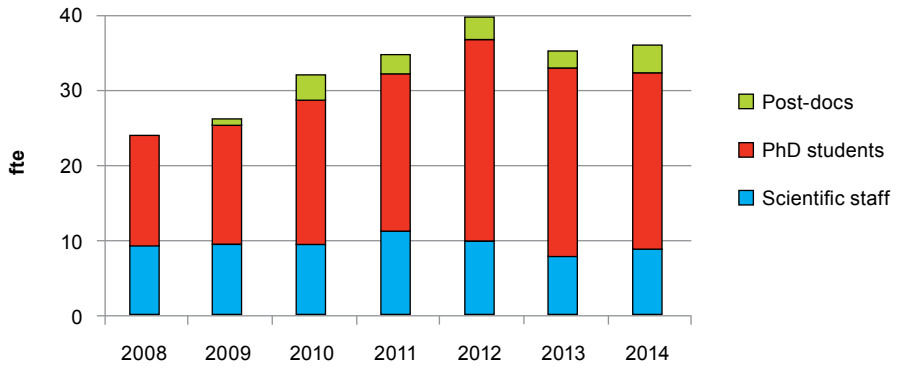



**Figure 2** Personnel during the review period (for numbers see Appendix U4.1).

## Coming period (2015-2020)

After these substantial changes in research focus and related personnel, the unit Geo-Engineering expects a more stable, though no less invigorating, staff environment in the coming years. The personnel strategy will be to continue seeking staff and researchers of the highest calibre. In particular, we will strive to strengthen the new research themes of Subsurface Engineering (which includes Offshore Engineering) and Dykes and Embankments. The following actions will be taken:

- A chair in Subsurface Engineering will be sought in 2015 (to be partly funded by Rijkswaterstaat and Deltares). We seek an individual with a high level of technical expertise in geotechnical engineering, with the remit to develop a strong international research theme in Subsurface Engineering linked to industry and the needs of society. This will be in close cooperation with colleagues from across the Faculty of Civil Engineering and Geosciences (in particular, the Departments of Geoscience and Engineering (GSE), Structural Engineering (SE) and Hydraulic Engineering (HE), as well as the Section of Offshore Engineering) (Fig. 3). The unit's staff will support the new chair strongly in order to ensure a quick and effective start-up period, especially as Mr Everts will retire in 2017.

- The unit will strive to increase the number of staff at the associate professor level, which currently stands at only 0.3 fte, either by new hire or as a career step for assistant professors.
- The unit will strive to increase the number of (preferably longer-term) post-docs, to improve the ratio between post-docs and PhD students to around 1:4 (now 1:6). This is to reduce the supervisory efforts of senior staff (that is needed for acquisition of funding and management of the research portfolio).

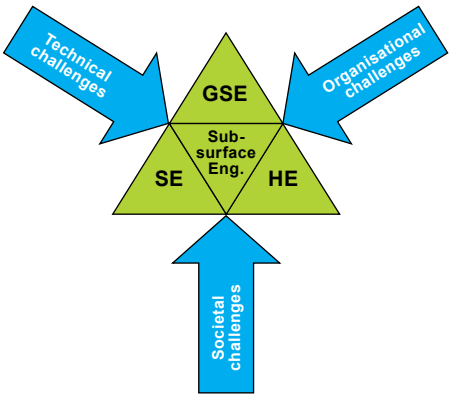



**Figure 3** Subsurface Engineering as a cross-departmental theme addressing technical, organisational and societal issues, involving the Departments of Geoscience and Engineering (GSE), Structural Engineering (SE) and Hydraulic Engineering (HE).

## 2.3 Funding strategy

### Review period

Our funding strategy serves our mission to execute fundamental geo-engineering research of societal relevance. We strive to cooperate with geo-engineers in the Netherlands and internationally, while aiming to found this on solid fundamental research. Staff are encouraged to apply for grants individually and in teams (i.e. from within the unit Geo-Engineering, or with national and international partners). Figure 4 clearly shows that our efforts have been successful. The acquired external funding increased by almost a factor of 2.5; this is a remarkable result when considering the changes in staff and rather recent appointments (see Chapter 2.2).

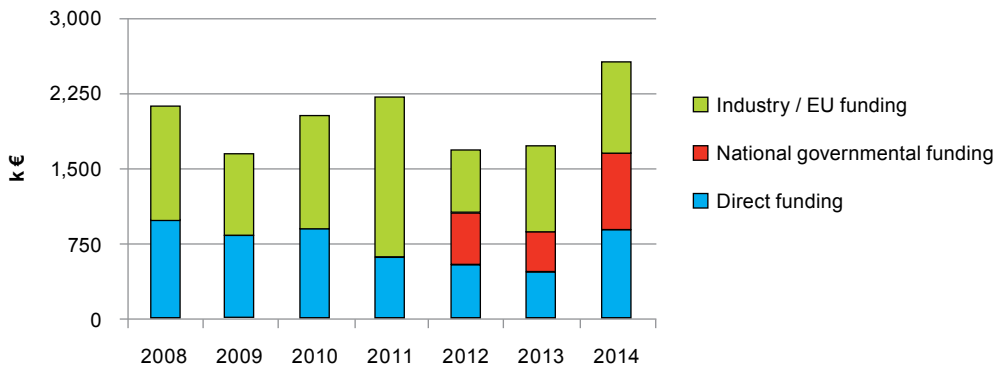



**Figure 4** Research funding during the review period (for numbers see Appendix U4.2).

#### National Governmental Funding

- Since 2012, the unit Geo-Engineering has been very successful in acquiring funds from STW (8 PhD students and 3 post-docs).

#### European Funding

- The unit Geo-Engineering participated in 6 FP7 programmes, which funded 5 post-docs and 1 PhD student, and an Erasmus Mundus exchange programme with India (3 PhD positions).

**Brazilian Funding**

- CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico), CAPES (Brazilian Federal Agency for Support)-Nuffic, "Ciencia sem Fronteiras" Programme.

**Industrial Funding**

- Funding is obtained via many industry-sponsored projects (Akzo, Arcelor Mittal, Boskalis, CATO, COB, COVRA, Deltares, DOW, Fugro, Inashco, Oldendorff, Plaxis, RPS, Sellafield Ltd., Shell, STOWA, Sustainable Landfill Foundation). This has included funding for 2 post-docs and several part-time PhD students, as well as numerous shorter-term projects.

### Coming period (2015-2020)

**National Governmental Funding**

- We are encouraging staff members and post-docs to apply for Veni (e.g. Askarinejad) and Vidi (e.g. Vardon) grants.
- We will continue our successful strategy in applying for STW grants, as well as NWO grants where applicable.

**European Funding**

- EU grants will play an important role in our future funding. We will continue to apply for EU grants, in particular the H2020 programme (e.g. climate, raw materials, security, cultural heritage).

**Public-Private Funding**

- In December 2014, the unit Geo-Engineering was awarded 2 large Top Sector Water grants, which will fund 2 post-docs and 6 PhD students. We will continue to apply for Top Sector funding. Within the future funding framework (KIBO) setup by the ministry of Infrastructure and Environment, together with our industry partners, the unit is working on a programme which builds on the results of the STW BioGeoCivil "Perspectief" programme.

**Industrial Funding**

- Our intensive and long-standing cooperation with the Dutch industry will ensure significant industrial funding in the future. We were recently awarded a research contract from COVRA for post-doc funding on the geological disposal of radioactive waste and further funding for a PhD student has been provisionally approved. In addition, Rijkswaterstaat has agreed to the funding of a first PhD student for researching the mitigation of slope liquefaction.

## 2.4 Publication strategy

### Review period

The research of the unit Geo-Engineering is primarily published in international peer-reviewed journals and conference proceedings. During the reporting period, there has been a strategy to place more emphasis on international journals, and less emphasis on conference proceedings and national publications (often professional publications for the Dutch civil engineering sector). This has resulted in a steady rise in the annual numbers of journal papers, despite the large turnover in staff during this time. Figure 5 depicts an enormous increase by a factor of 6. PhD students are encouraged to publish their findings in international journals and conference proceedings throughout their period of study. Although open access to publications is desirable, and TU Delft continues to discuss this issue with publishers, the unit's priority is to publish in international journals that have the highest impact factor for the intended audience (for Geo-Engineering, this typically means a range of 0.8-2.0). The portfolio of journals includes *Acta Geotechnica, Canadian Geotechnical Journal, Computers and Geotechnics, Ecological Engineering, Engineering Geology, Environmental Geotechnics, Geoderma, Georisk, Géotechnique, International Journal for Numerical and Analytical Methods in Geomechanics, International Journal of Rock Mechanics, Journal of Engineering Mechanics, Journal of Geotechnical and Geoenvironmental Engineering, Transport in Porous Media, Tunnelling and Underground Space Technology.*

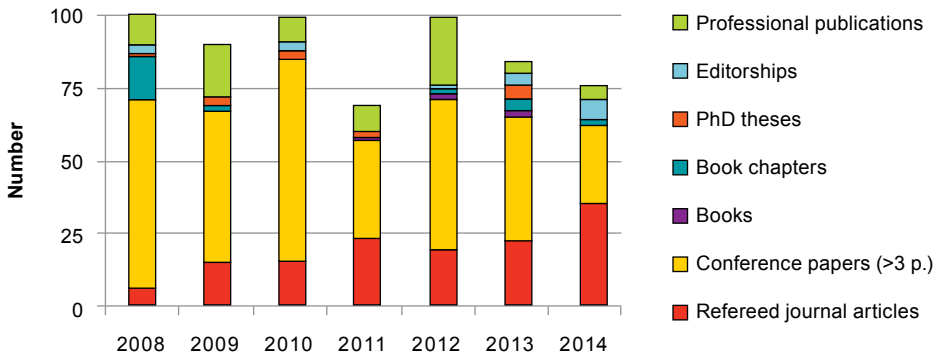



**Figure 5** Research output during the review period (for numbers see Appendix U4.3).

Scientific visibility is enhanced by staff taking editorial roles in major journals: Dr Broere is an editor of Tunnelling and Underground Space Technology; Prof. Hicks is on the editorial boards of Computers and Geotechnics, and Georisk; Dr Vardon is on the editorial boards of Computers and Geotechnics, and Environmental Geotechnics; Dr Askarinejad is on the editorial board of the International Journal of Physical Modelling in Geotechnics; Prof. Jommi is on the editorial board of the Italian Geotechnical Journal. The unit has also chaired 4 international conferences and workshops.

### Coming period (2015-2020)

To maintain the scientific visibility of the unit, we will continue to focus on publishing in major international journals in Geo-Engineering. We will strive for 0.75 journal papers per PhD student per year, 1.5 papers per post-doc per year, and 1 paper per staff member per year (numbers refer to first-author journal papers, and staff generally manage and direct research portfolios rather than undertaking the research themselves). The emphasis will be on maintaining the improvement in journal numbers achieved during 2008-2014, while targeting high quality potentially prize-winning papers. We will continue to attend and participate in the organisation of scientific conferences, workshops, committees, and so on.

# 3 Research results and plans

Research in Geo-Engineering concerns the combination of geomechanics, geochemistry and flow in porous media. In particular, it focuses on the challenging area of complex interactions in the sub-surface between the hydro-mechanical system and thermal, electrical, chemical and biological processes. An essential component of all research themes is the experimental laboratory.

## 3.1 Experimental facilities

During the reporting period, the area of laboratory element testing and physical modelling was strengthened by the appointments of Dr Van Paassen (2009) and Dr Dijkstra (2009), and the more recent appointments of Prof. Jommi (2012), Dr Askarinejad (2014) and post-doc Dr Zhao (2014) have ensured that the development of laboratory-based research remains a top priority.

During 2009-2010, Dijkstra led the total rebuild of the geotechnical centrifuge and supporting facilities (including a new sand raining device and major maintenance on the consolidation centrifuge). The facility formed a major part of the PhD research of Beijer-Lundberg (Theme 3). Dijkstra also developed a new full-field photo-elasticity setup, and had an important role in the development of a high speed electrical resistivity tomography setup (including software development) which was used for the PhD project of Korteland (Theme 2). Significant investments were made to acquire equipment for the characterisation of soil properties, including automated facilities for unsaturated flow properties and a state of the art Time Domain Reflectometer, which will mainly be used for research in the areas of landfill emissions and bio-geo-civil engineering (Theme 2).

## 3.2 Theme 1: Soil mechanics

*Scientific staff: Prof. Hicks (0.7 fte since 2009), Prof. Barends (0.3 fte until 2009), Dr Askarinejad (0.5 fte since 2014), Dr Van Baars (1.0 fte until 2010), Dr Brinkgreve (0.2 fte), Dr Dijkstra (1.0 fte 2011-2012), Mr Oostveen (1.0 fte until 2012), Dr Pisanò (0.3 fte since (2014), Dr Uffink (0.5 fte until 2012), Dr Vardon (0.7 fte since 2012).*

**Introduction**: Research in Soil Mechanics focusses on the characterisation, testing and modelling of, and engineering in, problematic soils. Particular attention is paid to:

- The short and long term behaviour of deltaic soft clays and organic soils such as peat,
- The liquefaction and internal erosion of loose sands and other estuarial deposits, and the behaviour of stiffer clays associated with geological disposal,
- Geomaterials arising from industrial processes,
- The impact of soil heterogeneity on material behaviour and geo-structural response.

A feature of this theme is the development of innovative numerical and stochastic techniques, validated by high quality theoretical formulations, laboratory testing, physical modelling and field data.

**Heterogeneity and Uncertainty**: The unit Geo-Engineering specialises in the research, development and application of novel numerical and probabilistic methods for geotechnical engineering. It previously initiated the development of the commercial finite element code PLAXIS (Brinkgreve) and, in June 2014, it hosted the “8th European Conference on Numerical Methods in Geotechnical Engineering” (Hicks, Brinkgreve). Prof. Hicks (recently with Vardon) continues to develop a major research line in the stochastic modelling of soil heterogeneity and geotechnical uncertainty and, with Prof. Jommi, coordinated the 2014 ALERT Geomaterials Doctoral School on “Stochastic Analysis and Inverse Modelling” and edited the published School book.

The unit Geo-Engineering (Hicks) participated in two EU programmes in this area. IRIS was a large integrated programme for developing an “Integrated European Industrial Risk Reduction System” (2008-2012). A strategy for assessing the liquefaction potential of tailings dams, hydraulic fills and underwater slopes was developed, involving the stochastic characterisation of in situ data and modelling of slope reliability using the Random Finite Element Method (RFEM). Slope liquefaction slides that occurred during construction of the Jamuna River Bridge in Bangladesh were analysed and results demonstrated a direct link between larger vertical correlation distances of the soil properties and an increased tendency for slope liquefaction. Meanwhile, GEO-INSTALL, a Marie Curie Industry-Academia Pathways and Partnerships Project (2009-2013), demonstrated the relative performance of different construction and soil improvement methods on sand state, spatial variability and liquefaction potential, using a large CPT database obtained from artificial sand islands used as oil exploration platforms in the arctic. A new approach was developed for optimising the characterisation of in situ spatial variability, based on linking CPT data and conditional random fields (Fig. 6), and the resulting journal paper (key publication Lloret-Cabot et al., 2014) won the Georisk 2014 Best Paper Award.

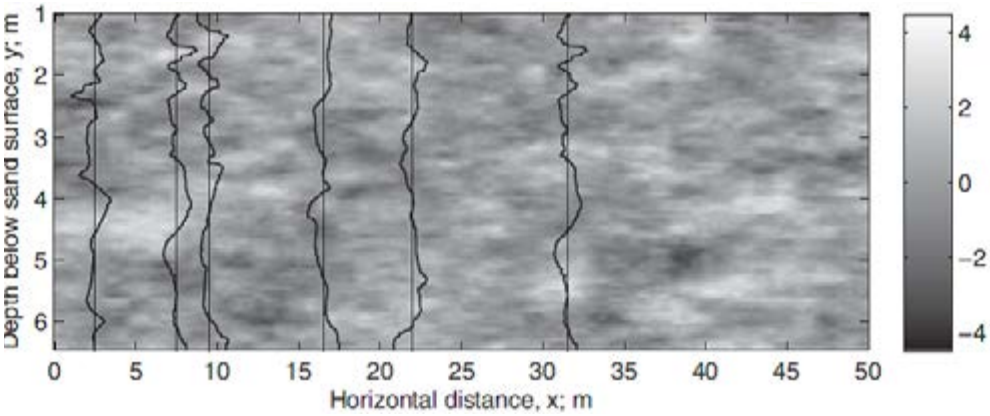



**Figure 6** Typical conditional random field of normalised de-trended CPT tip resistance (from key publication Lloret-Cabot et al., 2014).

Other research investigates the influence of heterogeneity on the performance of different types of slope subjected to various external loadings (Hicks, Vardon). Hicks & Spencer (2010, key publication), nominated for the Keverling Buisman Prize (2011), demonstrated three categories of 3D slope failure, depending on the magnitude of the horizontal correlation distance of the soil shear strength compared to the slope height and length. Based on this ground-breaking work, PhD students Nuttall and Li used 3D RFEM to investigate the influence of soil heterogeneity and slope length on the reliability of slopes that are very long in the third dimension (Fig. 7). The research is being used to benchmark and upgrade simpler probabilistic tools (some of which have been shown to be un-conservative at small spatial scales of fluctuation) for practical dyke safety assessments. PhD students Arnold and Liu have used simple unsaturated soil models to investigate the influence of heterogeneity on rainfall-induced slope failure and dyke instability due to seepage (through and beneath the structure), and have linked in situ measurements with inverse modelling to reduce soil parameter uncertainty (and thereby optimise designs) in collaboration with Plaxis and Deltares. Research in heterogeneity and uncertainty is closely related to the theme Dykes and Embankments, and, in 2014, the unit was awarded a large Top Sector Water grant, “Reliable Dykes”, to fund 1 post-doc and 4 PhD students (see Theme 4 for details).

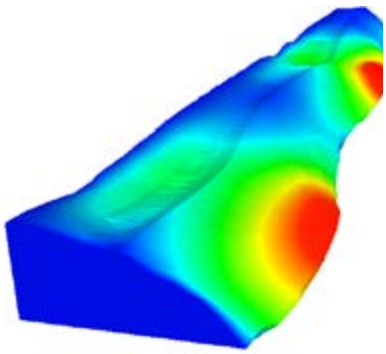


**Figure 7** Influence of soil heterogeneity and length effects on embankment failure mechanisms and reliability (by the Random Finite Element Method).

PhD student Wang (with Hicks, Vardon) has developed a dynamic “Implicit Material Point Method” to investigate the influence of heterogeneity on the risks posed by post-failure mechanisms (e.g. rotational, translational and retrogressive) in very long slopes. Research has demonstrated the importance of large deformations and soil heterogeneity on the extent to which a slide may retrogress in sensitive clay (Fig. 8). The research is also being linked to the earthquake- and rainfall-induced failure of mountain slopes in China, to be studied in a new collaboration with the State Key Laboratory of Geomechanics and Geotechnical Engineering, Chinese Academy of Sciences, Wuhan. It is also related to the danger posed to offshore installations by submarine flow slides (including collaborative research into simpler methods of analysis, carried out with Dr Nadim from the Norwegian Geotechnical Institute (NGI)), as well as with the unit’s research into underwater slope liquefaction (Hicks, Molenkamp, Askarinejad).

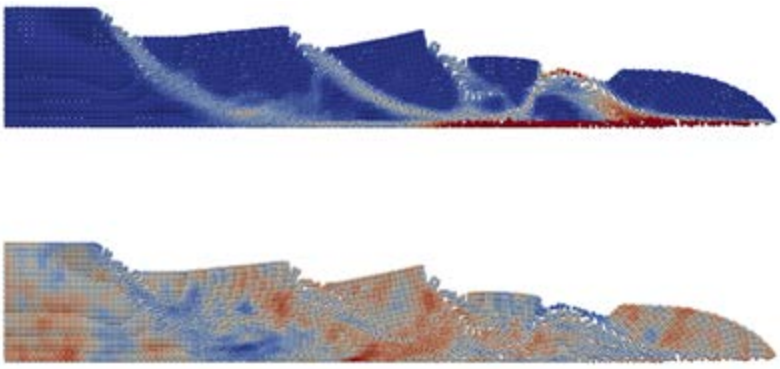


**Figure 8** Influence of soil heterogeneity and large deformations on propagation of retrogressive failure in a sensitive soil (by the Random Material Point Method): Deformations with shear strain invariant contours (upper) and heterogeneity of peak shear strength (lower).

Academic visitors included Mr. Rodriguez-Ochoa (University of Oslo), researching hazards posed by seismic submarine slope instability, and Mr. Huber (University of Stuttgart), researching reliability-based design. Prof. Fenton from Dalhousie University (Canada), a world leader in probabilistic methods and reliability-based geotechnical design, joined the unit on a 1-year sabbatical during 2011-12. The unit hosted a 1-day international workshop on “Safety Concepts and Calibration of Partial Factors in European and North American Codes of Practice” in November 2011, centred on a series of invited presentations by international leaders from Europe and North America. This led to publication of the book “Modern Geotechnical Design Codes of Practice” (Arnold et al., 2013).

**Soil Behaviour and Constitutive Modelling**: The unit historically has a very strong basis in fundamental soil mechanics. In 2014, emeritus Prof. Verruijt received the ASCE’s prestigious Maurice A. Biot Medal for his pioneering contributions to the theory of poroelasticity and the development of original analytical and numerical methods for solving problems of poroelasticity in soil mechanics and groundwater flow. In the same year, the unit published a ground-breaking paper on stress measures for describing the deformation of granular soils, involving, not only inter-granular stress, but also what happens in the pores (key publication Molenkamp et al., 2014). This paper provides a unified elastoplastic framework for saturated and unsaturated soils that may be utilised in the future development of unified constitutive models, and builds on the earlier pioneering work of Verruijt based on elasticity theory.

The unit continues to develop new facilities to test fibrous materials, including a prototype Rowe cell to study the electrical and geomechanical properties of peat (Ngan-Tillard, Slob (Geophysics), PhD Ponziani), and a unique direct simple shear/axial shear device for measuring the anisotropic behaviour of peat accounting for both the average orientation of fibres and very low stress levels (Molenkamp, PhD student Mathijssen) (Fig. 9). Moreover, Molenkamp and PhD student De Jager have designed and constructed a major new “tank” testing facility for investigating underwater slope liquefaction (Fig. 9). This research is funded by STW and the first tests are scheduled for 2015. The research includes the development of a novel triaxial apparatus to measure material properties at very low stress levels, and the development and implementation of advanced (state-parameter-dependent) constitutive relationships within a dynamic finite element code for the purpose of assessing liquefaction potential at larger scales. The tank is a crucial asset in future PhD research relating to current national concerns regarding the numerous historical and recent large underwater liquefaction slides that have occurred near the Oosterschelde storm surge barrier. Other possible application areas are landslides and the development of new types of site instrumentation. Future research will be linked to further constitutive model developments, as well as to numerical research using the Random Finite Element and Material Point Methods (Hicks, Askarinejad, Vardon, Pisanò, Jommi).

**Figure 9** Axial shear device for testing fibrous soils (left) and liquefaction tank under construction (right).

New experimental research, funded by Shell, includes the development of a strategy for the enhanced dewatering of soft sediments to improve soil strength, focusing on dewatering techniques and the modelling of this process (Van Tol, Van Paassen, Vardon, PhD students Yao and Tollenaar). This is relevant for the management of mine tailings, oil sands and deposits of dredging sludge, and for their

application as alternative building materials. Meanwhile, numerical research on ground improvement by electro-osmosis (Hicks and PhD student Yuan) has resulted in the development of a fully coupled formulation incorporating large deformations, elastoplasticity and nonlinear variations in soil transport parameters. This has been used to demonstrate efficiency gains possible with current intermittence, current reversal and various multiple electrode configurations, and is expected to be linked with future experimental research into improving embankment stability (Jommi).

The unit has also conducted a series of small-, medium- and large-scale experiments on backward erosion piping in collaboration with Deltares and the University of Ghent (Barends, Hicks, and PhD student Van Beek). This research investigated the conditions needed for the initiation and progression of piping beneath dykes; in particular, it highlighted limitations in the existing standard analysis used in design and developed a new improved method applicable to a wider range of sand types.

**Plans**: Our world-leading research on heterogeneity and reliability-based methods for geotechnical engineering will be used to develop practical geomechanical assessment tools for industry: advanced techniques such as RFEM will be used to benchmark and develop simpler probabilistic design methods, while other research will focus on reducing uncertainty through developing strategies for linking probabilistic methods with various forms of measurement and observational data. Research on the influence of heterogeneity on material behaviour and structure performance will be extended and integrated with research on soil-atmosphere applications, fibrous soils, soil liquefaction and piping. Research on liquefaction will focus on mitigation measures, as well as methods for upscaling detailed experimental data (e.g. from the liquefaction tank) to the field scale (e.g. using numerical methods and/or centrifuge modelling). The behaviour, constitutive modelling and improvement of soft, fibrous and liquefiable soils will remain a priority area.

## 3.3 Theme 2: Geo-environmental Engineering

*Scientific staff: Prof. Heimovaara (1.0 fte), Prof. Bruining (1.0 fte until 2011), Dr Hoogendoorn (1.0 fte until 2010), Dr Ngan-Tillard (1.0 fte), Dr Van Paassen (1.0 fte since 2009), Dr Van Odijck (1.0 fte 2011).*

**Introduction:** During the review period, Geo-environmental Engineering research focussed on two themes where the sustainable use of the shallow subsurface is central:

- Reducing the environmental impact of human activities in the subsurface,
- The development of bio-geotechnical approaches to change the in-situ properties of the subsurface.

Understanding the complex interplay of coupled bio-geochemical and hydro-mechanical processes, in both natural and human-influenced subsurface environments, is an important driver for this research theme. Several research lines have been successfully initiated and continued; the appointment of Prof. Heimovaara as chair increased the focus towards utilizing biological processes as engineering tools.

**Reducing the environmental impact of human activities:** Prof. Bruining led the following research into environmental impact. These projects were carried out mostly in cooperation with colleagues of other units and have been continued by them also after Bruining's retirement in 2012.

Projects aimed at reducing the natural arsenic contamination of groundwater were carried out with Donselaar (Geology) and partners from the University of Dhaka (Bangladesh), the Department of Technology Development and Sustainable Development (TU Delft), and the University of Patna (India). The EU Erasmus Mundus programme (EurIndia) supported 3 PhD students. The main research result is that the deep water (Pleistocene aquifers) was initially essentially arsenic free, but that large-scale water extraction withdraws contaminated water from shallower depth. Dr Donselaar continues the research.

Research into $CO_2$-sequestration in coal layers, aquifers and shale, in collaboration with Dr Wolf (Petrophysics), led to 6 PhD theses. The work was largely experimental and was so successful that we were invited to participate in Round Robin projects (identical studies carried out in different EU research

laboratories). A spin-off of this research was a comprehensive experimental error evaluation that went beyond the traditional random/systematic error approach. In addition, a fundamental study was carried out on enhanced mass transfer from carbon dioxide to the underlying brine layer. The study, in collaboration with Prof. Zitha (Geo-Resources), resulted in a greatly accelerated sequestration process and an unprecedented 10 refereed journal papers within the PhD project of Farajzadeh, who was awarded the PhD "cum laude". Another PhD study was devoted to visualising, for the first time, natural convection flows in brine-$CO_2$ systems. The work is being continued by Dr Wolf.

Exergy analysis of energy conversion processes was carried out in collaboration with Dr Van der Kooi (Laboratory of Chemical Thermodynamics, TU Delft) (PhD Eftekhari). As the developed methodology can be generically used for different energy conversion processes, to identify bottlenecks and how to affect the efficiency of a particular process, Springer invited Eftekhari and his co-workers to write a book about the exergy analysis of energy conversion processes and their carbon footprint, which is under preparation and soon to be published).

Work on enhanced oil recovery methods that can be used for environmental applications was carried out on combustion (PhD Koshnevis Gargar, cum laude), upscaling using homogenization (PhD Salimi, cum laude), and solvent enhanced gravity drainage (PhD Chahardowli). Salimi and Chahardowli showed that gravity and diffusion can bring solvents more rapidly into the rock matrix from fractures than would be expected from conventional dual-porosity simulations; thus oil recovery by injection of gases can go much more quickly than was previously thought. Two further PhD students will graduate in 2015 and the work is being continued by Prof. Van Kruijsdijk (Geo-Resources).

Mathematical modelling of flow in porous media was carried out in collaboration with Prof. Marchesin of the Institute Nacional de Matemática Pura e Aplicada (IMPA, Brazil) and Dr Salimi (Geo-Resources). This research benefited from significant funding from Brazil, and resulted in one of the first publications on the natural convection of $CO_2$ saturated water in aquifers. As part of the cooperation, Bruining co-supervised PhD students at IMPA.

Due to his excellence both in education and research, Prof. Bruining won the Society of Petroleum Engineers Distinguished Achievement Award for the Petroleum Engineering Faculty in 2012. This prestigious award is given each year to one faculty member in the world.

Within the Environmental Impact theme, Prof. Heimovaara led the research programme on the Emission Reduction of Landfills. The research is funded by a large STW project (2011-2015) (3 PhD/post-doc positions: Konstantaki, in collaboration with Draganov and Ghose (Geophysics), Van Turnhout, Bun). Also, 1 PhD student is funded by an Erasmus Mundus Exchange programme with India (Baviskar). Within this program we develop an in-depth understanding of the hydrological and biogeochemical processes, and landfill heterogeneity, with which we can quantify the (remaining) emission potential of a waste body. This programme has led to a stochastic framework (post-doc Bun), in which the emission potential can be quantified using simply obtainable data such as rainfall, potential evaporation, cumulative leachate discharge and leachate quality. The framework is an integration of models quantifying (multi-phase) preferential flow through the (unsaturated) waste body (PhD student Baviskar), bio-geochemical kinetics within the waste body and subsequent development of leachate quality (PhD student Van Turnhout). Probability density functions obtained with this framework can be verified using a high resolution quantitative geophysical assessment of landfill heterogeneity (PhD student Konstantaki). The results are also very valuable for optimizing landfill treatment methods such as irrigation/recirculation, to stimulate anaerobic degradation processes and landfill aeration in order to stimulate aerobic aeration processes. Konstantaki et al. (2013, key publication) showed the potential for using shallow depth seismics to map the heterogeneity of waste bodies. The major innovation in this study is the use of seismic interferometry (SI) to enhance the signals. Using SI opens up the opportunity to do a physical interpretation of the seismic images obtained.

The research of PhD Korteland aimed to develop a quantitative method to monitor in-situ mixing of injected reactants in groundwater in in-situ soil remediation projects. This research led to the development of a new high-speed laboratory Electrical Resistivity method. Korteland developed methods for improving the quantitative analysis of ERT data.

Also within this theme, Dr Ngan-Tillard initiated research in order to study the impact of large infrastructural projects on archaeological sites. The aim is to develop insights which lead to improved ways of preserving and exploiting archaeological resources in the subsurface, a topic that is a new challenge to Dutch geo-engineers. The aim is to investigate the impact of changing environments on buried archaeology in wetlands (Ngan-Tillard, Dijkstra, Brinkgreve). Wetland environments provide perfect acidic anaerobic conditions to conserve archaeological remains below the ground water table as long as their multi-physics equilibrium is not disturbed by human activities. Wetland archaeological sites are used as large-scale laboratories for research on ageing of structures and materials and mitigation of degradation (PhD student Afanasyev). The research involves computer and laboratory simulations of archaeological artefacts embedded in soils.

**Bio-Geotechnical Engineering:** The STW-sponsored "Perspectief" programme Bio-Based Geo & Civil Engineering for a Sustainable Society (BioGeoCivil) aims to develop biology-based processes and products in order to substantially mitigate the pressure from the Geo & Civil Engineering activities on the environment. The challenge is to develop biology-based materials, technology and processes that solve engineering challenges such as resource depletion, material production, strength, permeability, climate control, air quality improvement and more, while at the same time reducing the impact on the environment compared to traditional solutions. Prof. Heimovaara is the programme director, and the unit Geo-Engineering participates with 3 projects, in cooperation with groups at TU Delft, Wageningen and Utrecht Universities, and NIOO-KNAW. It is supported by Deltares, a water board and industry.

For his PhD, Dr van Paassen conducted pioneering research into using microbial induced carbonate precipitation (MICP) for ground improvement (key societal output Van Paassen et al., 2010) (Fig. 10). This research had earlier been published in the 17th International Conference on Soil Mechanics and Geotechnical Engineering (2009), in a paper for which Van Paassen won the Young Member Award of the International Society of Soil Mechanics and Geotechnical Engineering. The research formed the basis of the first full-scale field trial of MICP for ground improvement in 2010, and was incorporated into a review paper on MICP, "Biogeochemical processes and geotechnical applications: Progress, opportunities and challenges.", summarising the outcomes of the Bio-Soils Workshop at Cambridge in 2011, which Van Paassen co-organised with De Jong (University of California, Davis), Soga (University of Cambridge), Kavazanjian (Arizona State University) and Burns (Georgia Institute of Technology).

**Figure 10** The exposed cemented sand body of the 100m$^3$ experiment reported by Van Paassen et al. (key societal output, 2010).

The BioFix project (PhD students Pham, Bergwerff, Md Zain) is a follow-up of Van Paassen's PhD project, where in-situ precipitation of $CaCO_3$ is used to cement sand or gravel in order to increase the strength of the soil (Fig. 11). The approach which Van Paassen used turned out to be very costly because bacteria had to be grown in a bioreactor and the ammonium produced by the process had to be removed. Within BioFix, an alternative approach based on nitrate reduction is being investigated, with the added benefit of reducing the liquefaction potential of loose sands and susceptibility for piping

under dykes. Results so far have indicated that the alternative process has potential, not only because soils are strengthened by precipitation of $CaCO_3$, but also because the production of (micro) bubbles of $N_2$-gas can act to reduce the water saturation and permeability due to denitrification.

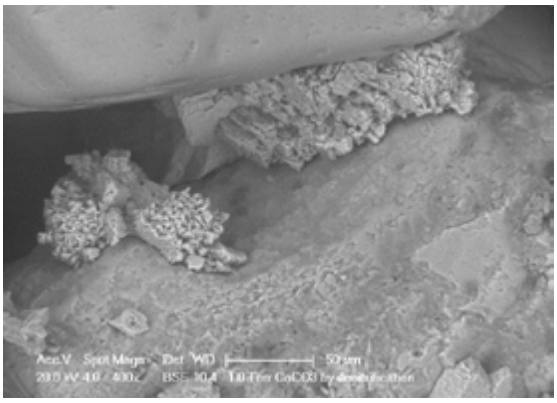


**Figure 11** ESEM image of sand cemented by calcium carbonate crystals precipitated by micro-organisms as a bi-product of their metabolism.

In the BioCoPro project (PhD student Afanasyev), biogeochemical processes involved in the corrosion of metal objects in the subsurface are investigated. The ambition is to understand the interaction between the corroding steel object and the microbial ecosystem processes in the soil in the direct surroundings, and thereby identify those processes and microbial communities which may prevent corrosion of steel. Novel experimental and numerical methods have been developed to visualise and quantify the effect of the microbial corrosion process on the characteristics of porous media, and some of the results may lead to novel approaches for preventing corrosion.

The Lift-Up of Lowlands project (PhD student Tollenaar, with PhD student Hazwani and post-doc Wijdeveld from an EU InterReg project) focuses on understanding the processes involved in the ripening of dredged materials and the impact these processes have on the mechanical stability of the ripened sludge.

An additional project, related to but not part of BioGeoCivil, on biofilm growth in fractured tight gas reservoirs (2010-2013, post-doc Bottero), was funded by DOW Chemical and carried out in cooperation with Prof. Van Loosdrecht (Environmental Biotechnology, TU Delft). The research developed visualisation experiments to show flow diversion by biofilms.

Prof. Heimovaara chaired the First International Conference on Frontiers in Shallow Subsurface Technology (Delft, 2010), attracting professionals from academia, governmental bodies, and industry.

**Plans:** In October 2015 a so-called “green deal” will be signed between the Dutch ministry of Infrastructure and Environment (I&M) and the landfill operators in the Netherlands. This will lead to changes in national regulations which will allow for pilot projects at three landfills where emission reduction approaches are to be tested at full-scale. Prof. Heimovaara is currently planning a follow-up program to the STW project on landfill emission reduction. Close collaborations are being set-up with groups from the University of Southampton and the Technical University of Vienna to embed this initiative in the international research community.

In September 2015 a new STW-funded project started focussing on in-situ technologies for permeability reduction. This project is part of the STW Top Sector Water program. The aim of this project is to develop in-situ technology for reducing the permeability of targeted layers in the sub-surface, using concepts derived from the natural process of podzol formation. This is a joint project with Dr Jansen from the University of Amsterdam and funds (at TU Delft) 1 PhD and 1 post-doc, as well as some laboratory investments. In addition, a close collaboration is being developed with Prof. Kalbitz of the Technical University of Dresden.

Discussions with industry partners are under-way in order to further develop the ideas developed within the STW-BioGeoCivil programme. The I&M funded KIBO programme will be an important source of alternative funding. Setting up a European consortium is an important goal to acquire significant funds from the EU framework programmes.

## 3.4 Theme 3: Subsurface Engineering

*Scientific staff: Prof. Van Tol (0.4 fte), Prof. Bosch (0.3 fte), Dr Broere (1.0 fte), Dr Pisanò (0.3 fte since 2014), Prof. Hicks (0.1 fte since 2009), Dr Brinkgreve (0.1 fte), Dr Vardon (0.1 fte since 2012).*

**Underground Construction**: Research in underground construction has focussed on the process of constructing diaphragm walls, following incidents with leaking diaphragm walls during the construction of the North-South metro line in Amsterdam. The research includes detailed numerical and experimental modelling of the flow of bentonite in the slurry-filled trench and its subsequent replacement by concrete. This has been supplemented by field observations during the construction of diaphragm walls at the site of the new railway station in Delft (Bosch, Broere, PhD student Van Dalen). Additionally, several geophysical measurement techniques (including tomography and electrokinetic measurements) have been adapted to find bentonite inclusions and locations at risk of promoting leaks in the diaphragm walls at Delft station (Van Tol, Bosch, Broere, PhD student Spruijt). Both research projects are incorporated in the national Geo-Impuls research programme and updated design guidelines and cross-hole sonic defect detection techniques have already been implemented in recent construction projects, such as at Delft station and the A2 highway in Maastricht.

Current research in tunnelling deals with the interaction between the Tunnel Boring Machine (TBM) and the surrounding soil, and indirectly with surface constructions. It uses actual monitoring data, from the Hubertus tunnel in The Hague and the North-South metro line in Amsterdam, to describe the kinematic behaviour as the TBM moves through the soil (Broere, Bosch, PhD student Festa). The research forms the starting point for a new project aimed at reducing the required cover for TBM driven tunnels in very soft soils (Broere, PhD student Vu Minh).

In 2011, the unit Geo-Engineering led a successful top-ranked proposal (with partners TNO and NRG) for researching the feasibility of the Dutch Radioactive Waste Repository Concept. The project developed a reliability-based approach combining analytical techniques, finite elements and probabilistic methods such as Monte Carlo simulation and the First Order Reliability Method (FORM) (Hicks, Vardon, Brinkgreve, Broere, post-doc Arnold). By analysing the excavation and construction of tunnels and galleries, as well as pre- and post-closure scenarios, within a probabilistic framework, the research highlighted influential design parameters requiring further in-depth investigation. In 2014, agreement was reached on further research (post-doc Yuan), in particular relating to the design and construction of tunnel crossings, and utilising new laboratory data obtained by the British Geological Survey (who have joined the consortium team). There are plans for further laboratory-based research funded by COVRA (1 PhD student), linked to a proposed Intercontinental Scientific Drilling Programme (ICDP) Cenozoic Drilling Project in the Netherlands led by the unit Geology (Luthi).

**Foundation Engineering:** Early in the reporting period, the centrifuge modelling and photo-elastic simulation of pile installation by PhD Dijkstra was ground-breaking in obtaining both stress and strain data from the same sample at the same time; the research produced 5 journal papers and the PhD was awarded cum laude. Subsequent research in piled foundations has centred around an STW project that resulted in numerical schemes to model pile installation effects via a Lagrangian finite element code (Brinkgreve, Van Tol, PhD Engin) and centrifuge model simulations of pile installation (Van Tol, Dijkstra, PhD student Beijer-Lundberg).

The design of piled embankments and, in particular, the load transfer in geosynthetic reinforced embankments was researched using experiments and monitoring data from field projects. Simulations with analytical as well as numerical models were performed (Van Tol, PhD student Van Eekelen). The work of Van Eekelen got significant recognition in the scientific community, including several prizes: her

2011 paper (key societal output Van Eekelen et al., 2011) in the international journal Geotextiles and Geomembranes, the journal with the highest impact factor in geotechnics, was given an honourable mention as one of the four best papers in Geotextiles and Geomembranes in 2011 and was awarded the Keverling Buisman Prize in 2011, and Van Eekelen et al. (2012, key publication) won the prize for best paper in Geotextiles and Geomembranes in 2012 (Fig. 12). Her whole PhD research, based on five journal papers, was awarded with the highest prize by the International Geosynthetics Society in 2014.

In March 2013, the unit chaired the “International Conference on Installation Effects in Geotechnical Engineering” (Hicks, Dijkstra, Lloret-Cabot).

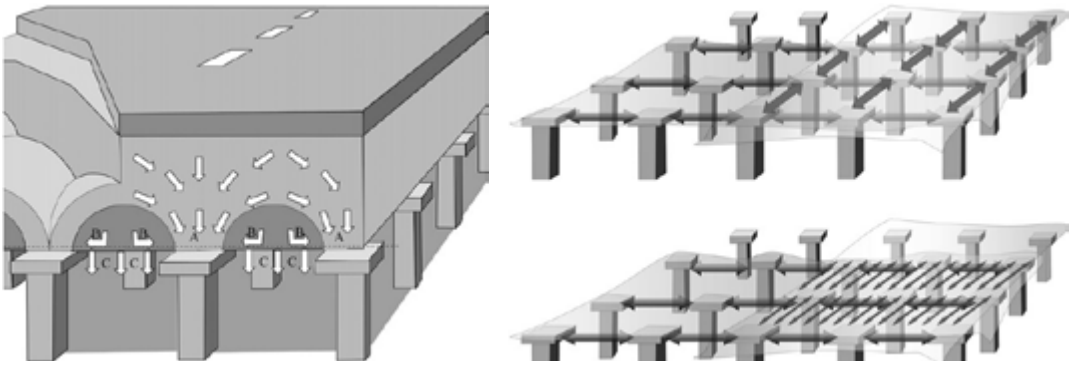


**Figure 12** Load distribution in piled embankments (left) and two possible mechanisms for load transfer in reinforcement of two layers of uniaxial grid (right) (from key publication Van Eekelen et al., 2012).

**Plans**: The new chair in Subsurface Engineering will be responsible for the detailed development of the research theme for the coming period. Nevertheless, research will continue on the installation of, and long term performance of, (often piled) foundations and (temporary) support for deep building pits in built-up areas. Alongside existing research on underground construction, a new line of research will be the maintenance of existing underground structures, especially tunnels, as many of the road tunnels in the Netherlands have passed half of their design lifetime and are in need of extensive renovation and maintenance. The installation and performance of offshore foundations, with the behaviour of dynamic and cyclic, axial and lateral loading of piles will also be a major topic of interest.

## 3.5 Theme 4: Dykes and Embankments

*Scientific staff: Prof. Jommi (0.8 fte since 2012), Prof. Hicks (0.2 fte since 2009), Dr Askarinejad (0.5 fte since 2014), Dr Vardon (0.2 fte since 2012).*

**Introduction**: This new research theme is being developed with the aim of bridging fundamental research on materials, processes and structures with the societal needs of construction, maintenance and safety of the national and international infrastructures. The present focus is the Dutch water system and European research lines on transport and climate action. Deltaic areas are specially addressed. The research is characterised by a strong multi-disciplinary approach, involving hydraulic, mechanical and biochemical processes, and by a wide spectrum of methodologies, including experimental research on materials and models, theoretical developments on materials and structure behaviour, and numerical modelling of soil-structure interaction under lifetime and exceptional loads.

There is collaboration with Geophysics for non-invasive studies, the GRS department for exploiting satellite data, and the HE department for innovative monitoring techniques. Research initiatives are starting with the section of Road Engineering on transportation infrastructures, and with the universities of Utrecht, Wageningen and Twente, to address fundamental research on the relevant coupled physical processes. A close working relationship with STOWA and the Dutch water boards and provinces has been developed.

**Initial results and plans**: At the international level, the unit Geo-Engineering is already participating in two EU FP7 projects. MAGIC supports the development of monitoring systems for geotechnical infrastructure subjected to climatic hazards and the training of young industrial and academy fellows (Jommi, post-doc Zhao). The COST TU1202 Action aims to develop a collective understanding of the impact of climate change on engineered slopes for infrastructure. It includes sharing techniques, facilities and data, and working jointly in disseminating results, ultimately enabling infrastructure asset owners to make evidence based investment and adaptation decisions to improve resilience and safety (Jommi, Vardon).

There is a fundamental need for a deeper comprehension of the bio-hydro-mechanical behaviour of organic soils, as a basic requirement to understand, monitor, predict and assess the behaviour of infrastructure in time. Therefore, special attention is being paid to the systematic development of dedicated experimental devices for investigating dyke construction materials and the subsoil. This includes biogenic degradation effects and soil-atmosphere-vegetation interaction processes that are being tackled experimentally at different scales, including micro-CT analysis, centrifuge and field models. Advanced theoretical models are being developed to provide scientific understanding of the behaviour of fibrous soils, including pre-failure deformation, and to assist in the developing of testing techniques. Research also aims at providing simple, but reliable, indications on operational parameters and calculation procedures to address proper maintenance and assessment of infrastructures.

**Figure 13** The Leendert de Boerspolder environment, full-scale natural test site.

In 2014, the unit Geo-Engineering (Jommi, Hicks, Vardon, Askarinejad) was awarded a contract to design and oversee technical aspects of a full-scale field test of a dyke at Leendert de Boerspolder (Fig. 13) (part-funding 2 PhD students, De Gast and Muraro; see also Chapter 4.1). The project is funded by STOWA and the Dutch water boards and provinces, with additional in-kind support from Deltares and Plaxis. Within the Top Sector Water (STW), the group was awarded a large project (linked to Leendert de Boerspolder) on Geomechanical Assessment Tools for Dykes and Embankments. This proposal was top-ranked (out of 26 proposals) and will fund 1 post-doc and 4 PhD students.

**Hicks, MA** & Spencer, WA (2010). Influence of heterogeneity on the reliability and failure of a long 3D slope, *Computers and Geotechnics*, 37, 948-955. [Nominated for Keverling Buisman Prize in 2011]

**Van Eekelen, SJM**, Bezuijen, A, Lodder, HJ & **Van Tol, AF** (2012). Model experiments on piled embankments. Part 1, *Geotextiles and Geomembranes*, 32, 69-81. [Best Paper in Geotextiles and Geomembranes in 2012]

**Molenkamp, F, De Jager, R & Mathijssen, FAJM** (2014). Stress measures affecting deformation of granular materials, *Vadoze Zone Journal*, 13(5), 17 pp.

**Konstantaki, LA**, Draganov, D, **Heimovaara, T** & Ghose, R (2013). Imaging scatterers in landfills using seismic interferometry, *Geophysics*, 78(6), EN107-EN116.

**Lloret-Cabot, M, Fenton, GA & Hicks, MA** (2014). On the estimation of scale of fluctuation in geostatistics, Georisk, 8(2), 129-140. [Georisk 2014 Best Paper Award]

**Figure 14** Key publications.

## 3.6 Summary of research quality

### Research products

The unit Geo-engineering has undergone a substantial development in terms of staff, funding and output (Figs. 2, 4, 5). The hire of high calibre scientific staff has resulted in higher funding rates from national and EU sources (increased by a factor of 2.5) and in higher numbers of junior research staff (which has about doubled). Consequently, the number of peer-reviewed journal papers has also risen enormously, by a factor of 6. Our strategy to focus more on journal papers and less on conference papers has thus been very successful.

Not only has the number of peer-reviewed papers risen, but also their quality is very high. We publish in high-impact journals in geo-engineering, such as *Computers and Geotechnics* (1.63), *Engineering Geology* (1.74) and *Géotechnique* (1.87). (Note that geo-engineering journals have lower impact factors than journals from the geosciences and that this impacts other metrics such as H-index and citation count.)

### Use of research products

H-indices are respectable for our field of discipline (6-15 for full-time full professors, see Appendix U4.5) and these will inevitably increase in due course due to the improvement in the quantity and quality of journal papers.

Our highly cited journal publications include:

- **Van Paassen, LA,** Ghose, R, Van der Linden, TJM, Van der Star, WRL & Van Loosdrecht, MCM (2010). Quantifying biomediated ground improvement by ureolysis: large-scale biogrout experiment. *Journal of Geotechnical and Geoenvironmental Engineerin*g, 136 (12), 1721-1728. (59 citations (Scopus));
- **Farajzadeh, R,** Ranganathan, P, Zitha, PLJ & **Bruining, J** (2011). The effect of heterogeneity on the character of density-driven natural convection of $CO_2$ overlying a brine layer, *Advances in Water Resources*, 34 (3), 327-339. (39 citations (Scopus));
- **Van Eekelen, SJM, Bezuijen, A** & **Van Tol, AF** (2011). Analysis and modification of the British Standard BS8006 for the design of piled embankments, *Geotextiles and Geomembranes*, 29, 345-359. (31 citations (Scopus)).

Organising international conferences, workshops and high level courses has been an important activity throughout the review period. We were honoured to be invited to host the important international NUMGE VIII conference (2014), and honoured to attract so many world leaders to contribute to our international workshop on “Codes of Practice” (2011). The international conferences on “Frontiers in Shallow Subsurface Technology” (2010) and “Installation Effects in Geotechnical Engineering” (2013) were highly successful in attracting senior international academics as well as many participants from industry. We were also honoured to be invited to coordinate the internationally important ALERT Geomaterials 2014 Doctoral School on “Stochastic Analysis and Inverse Modelling”.

### Marks of recognition from academic peers

Several papers have won prizes or were nominated for prizes; including three out of the key publications and two of the key societal output. We are especially proud that these papers are often written by junior staff, with PhD student Van Eekelen being a highlight (4 prizes/nominations). The number of PhDs awarded cum laude is significant (4 during the review period), and the PhD thesis of Eftekhari forms the basis of a book specially commissioned by Springer.

The quality of our research is also proven by the fact that, on the one hand, staff of our unit were appointed to prestigious positions elsewhere in academia, e.g. Van Baars and Dijkstra, while, on the other hand, we were able to attract high-quality staff from renowned universities to take positions in Delft, e.g. Jommi, Askarinejad, Pisanò and Vardon. We believe that our excellent laboratory facilities play an important role in this. Other indicators of quality include the sabbatical of Prof. Fenton in our group, and that two emeritus staff members received prestigious international “lifetime achievement” awards (Prof. Verruijt and Prof. Bruining).

Several of our staff have editorial roles on leading international journals and chair international conferences and workshops (see above). Prof. Hicks is a member of the board of Directors of the major European network, ALERT Geomaterials; the Alliance of Laboratories in Europe for Education, Research and Technology.

# 4 Relevance to society

In Geo-Engineering there are new challenges as we strive to build a sustainable society. We increasingly need to build on, in, under and with soils that may be classed as problematic: such as very soft soils, saturated soils, reclaimed soils and polluted soils. We increasingly need to reassess the stability of existing structures: for example, due to rising sea level and degradation of soils under changing environmental conditions. There are new “soils” that need to be characterised, modelled and stored; such as waste materials arising from domestic and industrial processes. There are also the increasing demands of society for codification and for quantifying and managing risks effectively.

Much of the research in Geo-Engineering examines risk, risk reduction and uncertainty reduction. Identifying and quantifying uncertainty in geotechnical engineering will result in reducing uncertainty, and thereby costs, in design. Hence it is of obvious interest to society. The better use of resources is another clear link between several projects: the better management of waste, re-using materials and in situ ground improvement all lead to better use of resources and therefore help to answer societal questions. The unit Geo-Engineering develops detailed knowledge of the fundamental behaviour of soil and other geomaterials in order to improve the sustainable assessment of geotechnical infrastructure. This includes the characterisation of the soil-atmosphere interaction and the impact of changing climate on geotechnical infrastructure, which is, at present, not readily assessed.

The unit Geo-Engineering uses several ways to ensure that the results of our highly societally-relevant research are indeed embedded within industry and governmental bodies.

## 4.1 Projects in cooperation with (and sponsored by) industry

We strive to ensure that the scope and results of our research are appropriate for society, and will thus be implemented, by involving industry partners from the beginning of projects. The importance of our research is highlighted by the considerable funding that has been received from industry, which equates to around 50% of the unit’s total annual funding (Fig. 4). In particular, there is a strategic cooperation with the research institute Deltares with respect to research, laboratory facilities and teaching. Within all our industry-sponsored projects, the approach is to answer the fundamentals of any problem, so that, through increased knowledge, the solutions can be more easily transferred to other projects and challenges.

In the following, we highlight a few research projects that are driven by pressing societal challenges and carried out in cooperation with industry:

- The construction of a new experimental facility (Fig. 9) to study liquefaction processes, financed by STW with a significant contribution from Boskalis, has attracted considerable interest from other potential industry partners. Rijkswaterstaat approached us to undertake long-term research into the causes of, and possible mitigation measures for, major slope liquefaction problems due to the formation of scour holes in the river bed near the Oosterschelde Storm Surge Barrier.
- Dutch landfill operators, the Dutch Ministry of Infrastructure and Environment, and the Dutch provinces seek to reduce the emission potential of sanitary landfills. Together with these partners, Heimovaara initiated a STW programme in order to develop methods and regulations. He now leads a group of specialists that advises the operators on how to implement the emission reduction technology that was proposed as a result of the research. In October 2015 a “green deal” will be signed. This will lead to “regulatory space” which enables the landfill operators to carry out three pilot projects to test emission-reducing technologies. The landfill operators intend to have a scientific programme parallel to the three pilot projects.

- Shipping and mining companies are searching for methods to prevent liquefaction of iron ore in bulk carriers during sea voyages. Van Paassen was asked to investigate measurement techniques to assess the water content of the ore, as well as methods for drying it onshore, or in the carrier.
- As more and more waste is being incinerated in the Netherlands, the bottom ash of municipal solid waste incinerators is increasing in volume. A company involved in valorising the bottom ash has asked the unit to carry out a series of experiments to understand the physical properties of the ash, in order to develop methods for enhanced drying of the material.
- A very pressing issue in the EU is the absence of any deep geological disposal for radioactive waste. The unit Geo-Engineering is heavily involved in this topic on a national and EU level. On a national level, Prof. Hicks leads a consortium of partners (TNO, NRG, BGS) researching geo-mechanical aspects of the proposed disposal in Boom Clay. This research is within the OPERA programme coordinated by the Dutch Central Organisation for Radioactive Waste (COVRA).
- Flood protection has always been a critical issue for Dutch society and the unit, with its new chair in Dykes and Embankments (Jommi), is the major academic player in the Netherlands in geotechnical aspects. Financed by Deltares, the unit carried out the first detailed study into the role of biochemical processes on the hydro-mechanical performance of organic materials used in flood defences. Although the research was born at the national level, it has considerable potential for development in many other countries, where infrastructures on organic soils are common. Future research is aimed at providing criteria to predict the influence of biochemical degradation on the deformation and strength of infrastructures made of, or founded on, organic soil layers.
- The Foundation for Applied Water Research (STOWA), mainly composed of the Dutch Waterboards, wants to improve the reliability of regional dykes, under both daily working conditions and exceptional loads. In order to study the response of clay dykes founded on soft organic layers, peats and clays, a full-scale natural test site (Fig. 13) has been made available that offers the unique opportunity of developing understanding of the different factors and processes involved. The unit Geo-Engineering (Jommi, Hicks, Vardon, Askarinejad) designed the research proposal and developed work packages to address the societal needs raised during continuing exchanges with public bodies and authorities.

## 4.2 Involvement of staff in industry

Several members the Geo-Engineering staff have active roles in industry, either being mainly employed at TU Delft with a part-time (e.g. seconded) position in industry, or vice versa. In addition, the unit Geo-Engineering also receives direct funding for staff from industry. Through these part-time chairs we enable direct knowledge transfer to industry at an early stage of research; similarly, the research questions from industry get easily incorporated into our research programme.

- Prof. Hicks has a 0.2 fte secondment at Deltares (since 2012), while Prof. Van Tol and Prof. Barends had appointments at Deltares (0.6 fte and 0.7 fte, respectively), and Prof. Bosch had a 0.7 fte appointment at Rijkswaterstaat.
- The chair of Underground Space Technology has been supported by 130 kEuro per year from the COB: this covered the appointment of Prof. Bosch (0.3 fte), as well as the part-funding of Dr Broere and various support staff and student assistants. The same level of funding will continue during the next reporting period. The funds will in the future come from Rijkswaterstaat and Deltares, and support the new chair in Subsurface Engineering.
- The chair of Prof. Jommi is part-funded (0.3 fte) by Deltares.
- Dr Brinkgreve (0.3 fte at TU Delft) is the full-time Research Manager of Plaxis BV.

## 4.3 Embedding research into teaching

At TU Delft, research and teaching are closely related. By introducing actual research subjects with industrial involvement into our educational programmes, for MSc and PhD students, we contribute to the embedment of recent knowledge into society via well-educated engineers.

- Most MSc projects have a significant industrial involvement, with industry often taking an active role in initiating the thesis topic and thesis supervision.

- All PhD students have regular contact with industrial partners. This is realised by the direct involvement of the industrial sponsor or, if funded by STW, via user-committees, which typically meet twice per year and have a significant industrial membership. Moreover, most of the latter PhD projects are counter-financed by industry. A feature of the unit Geo-Engineering is that many of our PhD students, around 25%, have joint industry appointments, meaning that they are directly funded by their industrial employer and seconded to TU Delft for their thesis.
- Dr Vardon is very much engaged in the training of (PhD) students. Together with the TU Delft Reactor Institute, he will organise a summer school on radioactive waste disposal (in 2016) that is based on the joint efforts of the Dutch OPERA programme and the EU PETRUS consortium. COVRA has co-funded his EU activities to allow implementation of specific MSc/PhD courses at TU Delft. Vardon is also a member of the EU Technology Platform on Implementing Geological Disposal (IGD-TP) where he specifically works within the sub-group on “Competence Maintenance, Education and Training” (CMET).

## 4.4 Engagement in professional committees and code development

Through engagement in various committees we create chances of direct influence on policies being developed and technical standards being issued. A few examples are as follows:

- PhD student De Jager was asked to sit in a working group of young engineers appointed by Rijkswaterstaat. The group reconsidered the original design philosophy of the Oosterschelde Barrier, recalibrated the failure probability, and transferred and secured the knowledge of the original design project team. Its conclusions and recommendations were incorporated in the strategy of Rijkswaterstaat to secure the safety of the Barrier and adjacent primary sea defence.
- Brinkgreve is a member of the NAFEMS Geotechnical Committee (based in the UK, but with an international membership and remit), which provides recommendations on the proper use of numerical methods in geotechnical engineering. As a result of his work on the committee, he is the author of the book *Validating numerical modelling in geotechnical engineering*, published by NAFEMS (key societal output Brinkgreve, 2013).
- Ngan-Tillard has developed novel approaches to site investigation and laboratory index testing, which have been adopted by the construction and dredging industries and are being integrated into CUR and ISRM guidelines.
- Heimovaara is a member of the Soil Protection Technical Committee, a committee based on the Dutch Soil Protection Act; in addition, he is a member of the board of SKB (Sustainable development of the subsurface in the Netherlands) and he serves on the MER committee of Shale Gas.
- The research on piled embankments (Van Tol, PhD student Van Eekelen) (key societal output Van Eekelen et al., 2011) has been incorporated in the Dutch design code for piled embankments (CUR, 2015).
- The research on the rapid (quasi-static) pile load tests (Van Tol, PhD students Huy and Chi Nguyen Thanh) has led to a draft version of the Eurocode for the execution of rapid pile load tests. This draft is now the basis for the standard on this topic in CEN TC 341 and was issued together with an international guideline for the interpretation of these kinds of tests.
- The research on diaphragm walls (Van Tol, Bosch, Broere, PhD students Van Dalen and Spruijt) has been incorporated in the Dutch design code for diaphragm walls (CUR, 2014). In particular, the research on cross-hole sonic logging (CSL) has already reduced the risk profile of D-wall construction significantly and has been adopted for large projects already, as reported by Spruit et al. (key societal output, 2013).
- To study the impact of large infra-structural construction on archaeological sites, Dr Ngan-Tillard set-up a joint research programme with the Dutch Cultural Heritage Agency and Leiden University. She is also coordinator for our Faculty in the Centre for Global Cultural Heritage and Development, established by the universities of Leiden, Rotterdam and Delft in 2013.

## 4.5 Contributions to the public debate

Although our efforts in knowledge transfer to society are mainly geared towards industrial partners and (semi-)governmental bodies, we also take the opportunity to contribute to the public debate.

- Related to his appointment at Rijkswaterstaat/Gemeente Amsterdam, Prof. Bosch was involved in the construction of the North-South metro line in Amsterdam. Therefore, he gave interviews to Dutch media when the bored tunnels in Amsterdam were completed (Parool, 2012) and on the use of underground space (NPO Radio Hoe?Zo!Radio, NPO3 Labyrinth, Telegraaf, 2013).
- As an expert on radioactive waste disposal in geological formations, Dr Vardon was invited to conduct a Q&A session after the film Into Eternity, a documentary regarding the first radioactive waste repository being constructed in Europe, that was shown at the Movies That Matter film festival at the same time as the Nuclear Security Summit took place in The Hague (March, 2014).
- Dr Van Paassen has done over 30 interviews for radio stations, newspapers, websites and other popular media, since 2008, on issues relating to bio-cement and subsidence (key societal output Van Paassen et al., 2010).
- After the inaugural lecture of Prof. Heimovaara a feature article on his research was published in "De Volkskrant". Prof. Heimovaara has had three interviews on national radio; one on the topic of subsurface engineering, one about the soil contamination in Russian industrial towns and one about the resulting soil contamination after the "Chemiepak" explosion and fire in Moerdijk.

## 4.6 Publications and products for societal use

In general, the unit Geo-Engineering does not seek to patent ideas; rather, it generates knowledge and publishes papers in open literature, so that knowledge is available early for everyone's benefit. This also holds for advances in modelling and characterisation of complex soil processes that are incorporated into state-of-the-art numerical simulation programmes.

- Accepted manuscripts are put on the TU Delft repository and the university library is negotiating hard for open access.
- Professional publications include contributions to Cobouw, L+W, Verkeerskunde, Geotechniek.
- New insight into the thermo-hydro-mechanical behaviour of the various repository components for radioactive waste disposal has been incorporated into a single model, allowing new insights into safety performance (key societal output Thomas, Vardon & Cleall, 2013).

**Spruit, R, Van Tol, F, Broere, W**, Slob, E & Niederleithinger, E (2013). Detection of anomalies in diaphragm walls with crosshole sonic logging. *Canadian Geotechnical Journal*, **51**, 369-380. [Editor's Choice Award]

Thomas, HR, **Vardon, PJ** & Cleall, PJ (2013). Three-dimensional behaviour of a prototype radioactive waste repository in fractured granite rock. *Canadian Geotechnical Journal,* **51**, 246-259.

**Brinkgreve** (2013). Validating Numerical Modelling in Geotechnical Engineering. NAFEM. download.

**Van Eekelen, SJM, Bezuijen, A** & **Van Tol, AF** (2011). Analysis and modification of the British Standard BS8006 for the design of piled embankments, *Geotextiles and Geomembranes*, 29, 345-359. [Keverling Buisman Prize, 2011]

**Van Paassen, LA**, Ghose, R, Van der Linden, TJM, Van der Star, WRL & Van Loosdrecht, MCM (2010). Quantifying biomediated ground improvement by ureolysis: large-scale biogrout experiment. *Journal of Geotechnical and Geoenvironmental Engineering*, 136 (12), 1721-1728. [Cited 46 times (Scopus feb 2015).]

**Figure 15** Key societal output.

# 5 Viability

## 5.1 Benchmarking with Imperial College

The Geotechnics Group of Imperial College (IC) is internationally recognised as a world leader in geotechnical research. It is of a similar size to the unit Geo-Engineering and resides within a Civil Engineering department of similar high standing: in the 2015 QS World University Rankings, Civil Engineering at IC was ranked 4th and, at TU Delft, Civil Engineering was ranked 2nd. It covers a broad spectrum of geotechnical research, including numerical methods, laboratory testing and field testing, as does the unit Geo-Engineering; however, it does not include geo-environmental engineering.

The unit Geo-Engineering's numerical research is world-leading and (at least) on a par with IC; the unit's focus is on the development of cutting-edge numerical and stochastic techniques for researching fundamental problems in geomechanics, whereas IC's focus is mainly on the continual development and application of an in-house code (the Imperial College Finite Element Package, ICFEP) for both research and industry. IC's experimental research has a targeted direction; they are focused (and very good at) element testing, for which they have a well-equipped laboratory. In contrast, the unit is less focused; it currently has fewer facilities for element testing than IC, but it does have excellent facilities for physical modelling including some unique facilities.

Overall, although Imperial College does have a broad range of research, the unit's research is broader still. Contributing factors to this difference are that the unit serves both Civil Engineering and Applied Earth Science programmes at TU Delft, whereas the Geotechnics Group of IC serves only Civil Engineering; in addition, the unit is the only Geo-Engineering group in the Netherlands and therefore attracts a broad range of opportunities, whereas there are many geotechnical groups in the UK so that different universities tend to focus more. It should also be noted that, although the two groups have similar numbers of academic staff, the group at IC represents 22% of Civil Engineering staff, whereas at TU Delft it is around 6-7% of the Faculty of Civil Engineering and Geosciences. Bearing in mind the much larger number of students taught by the unit Geo-Engineering than the Geotechnics group of IC, this has implications for the relative workloads of the two groups.

The Geotechnics Group of IC has been established as a world-leader for several decades, and this is partly reflected by the large number of high quality publications, including numerous prize winning papers. The publication rate of the unit was lower than IC over the reporting period as a whole, but, due to the big increase in publication rate, it is now at a similar level. IC has a long history of high quality research, a high level of staffing and is politically well placed within the UK (in particular, through the Institution of Civil Engineers which is highly regarded internationally), and it has therefore built-up a big reputation over the years. TU Delft also has a distinguished reputation in Geo-Engineering, although it tends to have been previously based on a smaller number of individuals rather than on a larger multi-disciplinary team, and its international impact has more lately been less significant. However, although the unit is not currently at the same level regarding reputation and output as IC, it is not far behind. The objective of the unit Geo-Engineering is to attain a similar world-leading status to IC during the next reporting period. Given the changes the unit has implemented in recent years (in particular, the appointment of excellent staff who will continue to develop and flourish) it is certainly feasible to achieve this.

## 5.2 SWOT analysis

**Strengths**

- Visibility/brand of TU Delft, with Civil Engineering 2$^{nd}$ in the 2015 QS World University Rankings.
- Strong bachelor/master student base (in both Civil Engineering and Applied Earth Sciences).
- Ability to hire excellent new staff and talent.
- Increasingly international staff, with international networks in academia and industry.
- Large group with a relatively young age profile, a wide and complementary skill and knowledge base (coupling numerical, experimental and theoretical expertise), and the potential for growing

as an internationally leading multi-disciplinary group in the multi-physics/multi-scale behaviour of engineering constructions in or on deltaic soils.
- Strong strategic partnerships with companies and research institutions (e.g. Boskalis, COB, COVRA, Deltares, Fugro, Plaxis, Rijkswaterstaat, Sellafield Ltd., Shell, STOWA, TNO, Van Oord).
- Focus on participation in large national and international research projects.
- There is an obvious link between the research portfolio and the needs of Dutch society.
- The research portfolio includes initiatives on, and/or research developments towards, some of the key themes of H2020 (i.e. climate, raw materials, security, cultural heritage).
- Large laboratory shared with other units in the Department of GSE, equipped with a broad variety of facilities, many of them unique, run by excellent staff.

**Weaknesses**
- International staff are less able to directly/easily interact with the Dutch Civil Engineering industry. There are initiatives in place to rectify this (e.g. through exploiting the links developed between Deltares and Prof. Hicks).
- Relatively new staff; thus relationships within the unit and with industry are not yet fully mature.
- Problem of keeping very good students from our master track as PhD students, due to strong economy in our sector.

**Opportunities**
- Strong bonds with industry (both for financing and stimulation of research), including part-time employment and secondment in both directions, that raises opportunities for implementation and valorisation of research.
- Research into societally relevant subjects; e.g. construction in the delta, flood defence, offshore engineering, “earthquakes” in Groningen.
- Exporting Dutch expertise to the rest of the world.
- Large Faculty of Civil Engineering and Geosciences, which increases opportunities for inter-disciplinary research between departments and individual units.
- Thematic STW calls and the governmental Top Sector strategy.
- EU-funding, e.g. H2020.

**Threats**
- Company willingness to finance medium-term (e.g. PhD) projects. Companies often have a shorter-term view on funding.
- Temptation to chase short-term research opportunities, rather than be selective and focus on topics aligned to our strengths.
- Restriction of the growth in staff numbers, especially at a time in which teaching loads per staff member are increasing.

Department
of Geoscience
& Engineering

# 5

# Geo-Resources

# 1 Mission

The Geo-Resources unit is focussed on research into the exploitation of fluid and solid subsurface resources for the benefit of society. The resources can be oil and natural gas, solid minerals, or heat. We also apply these innovative exploration and production technologies to subsurface sequestration of $CO_2$ and other greenhouse gases. Exploitation of subsurface drinking water resources and remediation of polluted soils is the field of other groups in our Department and Faculty. Combining geosciences and engineering, we focus on selected subsurface and fluid-flow aspects of petroleum, geothermal and mineral resource engineering rather than surface facilities or the mechanical aspects of drilling or mining.

The research programme of in the Geo-Resources unit is divided into four themes, namely

- Theme 1: Rock-Fluid Flow Processes
- Theme 2: Advanced Reservoir Simulation and Optimization
- Theme 3: Resource Engineering
- Theme 4: Geothermal Engineering.

Both Themes 1 and 2 come within the broader heading of Petroleum Engineering.

*The mission of the research programme of the Geo-Resources unit is to conduct excellent fundamental research directed towards developing innovative technologies to recover subsurface fluid and solid resources or to store (greenhouse) gases. Our application-driven research has a strong fundamental character, corresponding to the Technology Readiness Levels (TRL) 1-6 as defined by the EU.*

# 2 Strategy

## 2.1 Research strategy

### Review period

In the review period we expanded our research portfolio in two directions, Resource Engineering (in 2012) and Geothermal Engineering (in 2013). Resource Engineering has always been part of the educational programme of our department, but for several years no research was conducted. Due to a strong demand of the international mining industry, we decided to re-establish a research programme in this field. Research on Geothermal Engineering was led by the Geophysics until 2013 (DAP). Once the Chair in Geothermal Engineering was established, the theme became part of the unit Geo-Resources, since it has many common research questions with petroleum engineering (specifically, fluid flow in porous media). With this theme, we also expand our expertise towards sustainable energy technologies.

Research on **Rock-Fluid Flow Processes** proceeded in two major directions, i.e. enhanced oil recovery (EOR) and subsurface sequestration of $CO_2$, along with continuing research in well-inflow performance and visualisation techniques. A major research effort was in foam EOR and chemical EOR. A major focus of this theme is on the mechanisms of mobility of foam and oil displacement by surfactants used to reduce oil-water interfacial tension. We also developed capabilities in micro-CT scanning applied to multiphase flow in porous media.

Research on **Advanced Reservoir Simulation and Optimization** was performed in two areas: One focussed on the control and optimization of subsurface flow in the **Closed-Loop Reservoir Management** (**CLRM**, a.k.a. “Smart Fields”) program, and one focussed on reservoir simulation in the **Delft Advanced Reservoir Simulation** (**DARS**im) program. CLRM research was carried out during the entire period, mainly within two large industry-funded programmes, the ISAPP (Integrated Systems Approach to Petroleum Production) consortium and the Recovery Factory (RF) programme. Within these programmes, concepts and technologies for CLRM were developed, i.e., optimization applied to reservoir model updating and (robust) optimal control of oil recovery under geological uncertainty (Fig. 1). Both ISAPP and RF are performed in close cooperation with the Delft Institute of Applied

Mathematics (Faculty of Electrical Engineering, Mathematics and Computer Sciences), the Delft Centre for Systems and Control (Faculty of Mechanical, Maritime and Materials Engineering) and the control systems group of Eindhoven University of Technology, especially to investigate the underlying fundamental systems and control-theoretical aspects of porous media flow (Fig 2.).

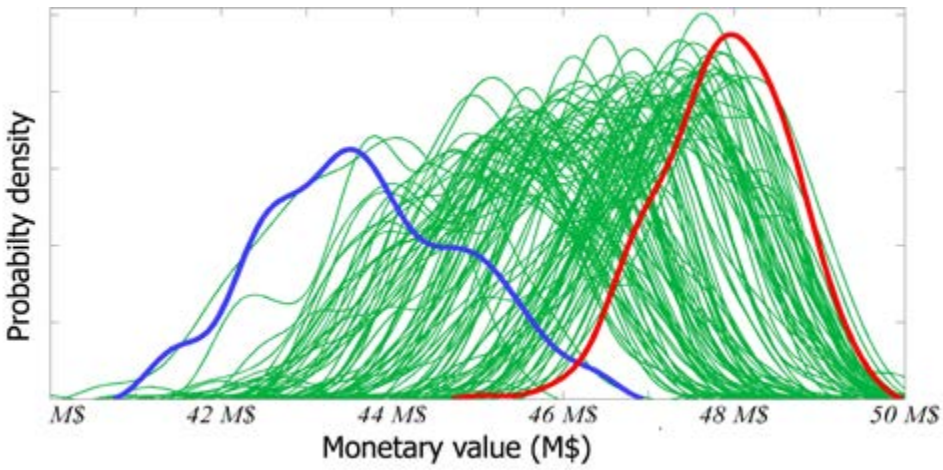



**Figure 1** Increased monetary value through robust waterflood optimization. Blue: Probability density function (PDF) of monetary value (Net Present Value, NPV) resulting from reactive control as applied to an ensemble of 100 geological realisations. *Green*: 100 PDFs of NPV resulting from 100 *individual optimizations* of 100 single realisations as applied to all 100 ensemble members. *Red*: PDF of NPV resulting from a single *robust optimization* over the entire ensemble as applied to all 100 ensemble members. (After Van Essen et al 2009.)

With the arrival of a new assistant professor, Hadi Hajibeygi, an expert in reservoir simulation, we established the DARSim group in 2013. This group develops next-generation modelling and computational methods addressing current and future challenges in reservoir simulation. The developments include in particular multi-scale, multi-physics modelling and methods for efficient and accurate large-scale simulations of reservoirs with complex fluid-rock physics (Fig. 2). In pursuit of this aim, DARSim also aims to deepen collaboration with other geoscientists within the Department. DARSim is fully aligned with the CLRM group, and, in addition, maintains close contacts with other strong numerical-simulation groups at TU Delft, such as those of Prof. Vuijk in the Faculty of Mathematics, Electrical Engineering and Computer Sciences and Prof. Sluys in the Faculty of Civil Engineering and Geosciences. It also connects with the researchers who focus on the fundamentals of porous media flow in our unit.

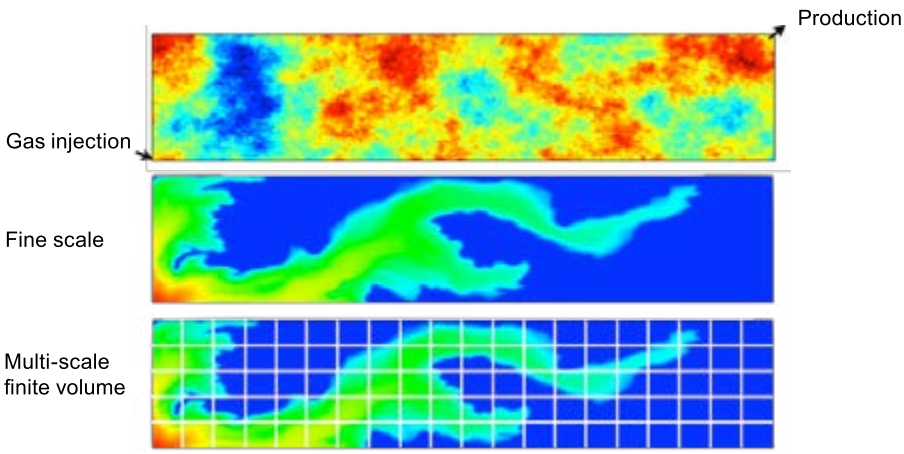



**Figure 2 Top**: Heterogeneous permeability field for a reservoir, with 220x55 grid cells. **Middle**: Fine-scale reference numerical solution for a gas-injection process. **Bottom**: The multiscale approach applies only 20x5 grid cells to solve the same problem, while its results are quite accurate for such a nonlinear test case.

For **Resource Engineering** the focus is on developing, facilitating and implementing key enabling technologies to enhance the performance and competitiveness of the European mineral resource industry. Our research is focussed on the development of innovative "Real-Time Mining" methods for on-line sensor-based mineral characterisation and real-time resource-model updating and extraction optimization (in analogy to the CLRM approach in petroleum engineering). The approach combines sensor-based material characterisation, geostatistical resource modelling and data integration to achieve risk-based mine-planning optimization, to create one holistic closed-loop framework.

### Coming period (2015-2020)

In the coming period, we will continue and expand our research on the **Rock-Fluid Flow Processes**. In particular, we are in negotiations with Shell to open a University Technical Centre ("INPERM") to focus on developing experimental tools to study pore-scale and interfacial phenomena at the micro and nano-scales. This topic is of interest for both EOR and near-well phenomena in geothermal wells. We are also in negotiations with the an Iranian geotechnical research institute for the petroleum industry regarding a major cooperative agreement regarding environmental issues related to EOR. It would be a department-wide programme combining geology, petroleum engineering and petrophysics, with a major laboratory effort.

We will continue to pursue and expand the research programme on **Advanced Reservoir Simulation and Optimization**, especially as it could be applied to EOR, the use of time-lapse geophysical imaging methods (in collaboration with the unit Geophysics), and the control of production-induced seismicity. We will incorporate multi-scale numerical methods developed in DARSim to assimilation and control and geophysical imaging. The new phase of the Delphi consortium will further deepen this collaboration in the field of reservoir characterisation and modelling (see Chapter 3.2).

Through DARSim, we will continue to develop advanced reservoir simulation (multi-scale, multi-physics) tools for application to complex subsurface processes related to oil reservoirs, geothermal power plants, $CO_2$ sequestration, and water resources. As of September 2015 Denis Voskov, an expert in advanced reservoir simulation research, will join as associate professor. His experience in compositional modelling, reactive flow and geomechanics will allow us to expand our simulation and CLRM research to address geothermal challenges.

The newly formed section **Resource Engineering** will focus on the development and demonstration of concepts for efficient mineral resource extraction using online data, and in particular "Real-Time Mining" methods. Utilizing the European research grants awarded already and developing industrial collaboration, the main focus will be on the maturation of this theoretical concept through to a TRL 6.

Research activities in **Geothermal Engineering** will be centred around the plans for a geothermal injector-producer doublet on the TU Delft campus. The doublet will serve as a national research facility and will at the same time be used to harness geothermal energy for heating. Specific research aspects of geothermal heat production that are important to the Netherlands include hydrocarbon co-production, injectivity decline (scaling) and evaluation of optimal breakthrough times and well patterns.

## 2.2 Personnel Strategy

### Review period

The personnel in the unit Geo-Resources grew substantially in this period, as described below and shown in Fig. 3.

Whereas Dutch universities traditionally work in hierarchical structures, the Geo-Resources unit has adopted the PI model that is followed at most US universities, where several of our staff have experience. This is also in line with HR policy at TU Delft, where the tenure system requires all assistant and associate professors to demonstrate that they can establish and fund a distinct research programme within 4 to 5 years. Therefore, our strategy in hiring has been to value quality over a specific research area in cases where a distinct difference exists between candidates. Hence, with outstanding

candidates in reservoir simulation available in 2013 and 2015, our research programme has increased its effort in modelling and simulation.

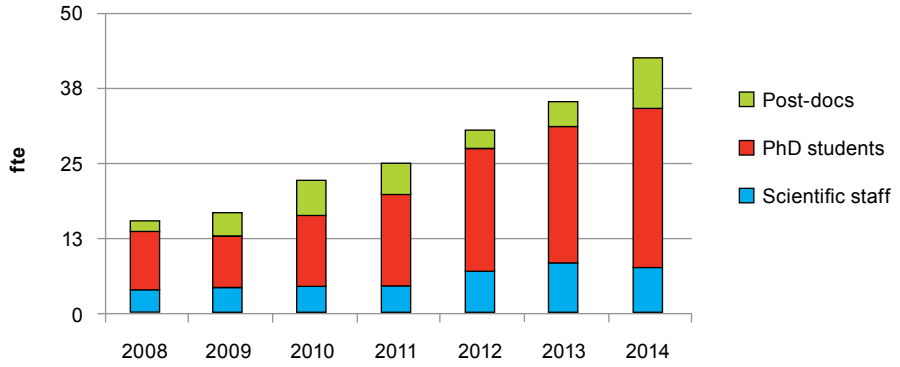



**Figure 3** Personnel during the review period (for number see Appendix U5.1). Note that in 2012 and 2013, respectively, the groups of Resource Engineering and Geothermal Engineering started. The staff on the petroleum engineering themes (1 and 2) also gradually increased over the years.

Three assistant professors left us during this period. In two cases it was because the individuals were unable to fund their research programmes. We have learned to evaluate potential and ambition to maintain a research programme in our search for new staff. In 2013, we made an excellent hire in the person of Dr Hadjibeygi, who was named best PhD graduate of ETH Zurich in 2012. Dr Buxton was recruited in August 2011 from the South African mining industry to revive the **Resource Engineering** group and establish a viable research portfolio. His position is sponsored by an industrial consortium comprising Dutch natural-resource-extraction companies. In order to support and ensure the sustainability of the group, the Board of the University agreed to sponsor the recruitment of an additional tenure-track position. This was fulfilled by the recruitment of Dr Benndorf from the German mining industry in April 2012 and by the transfer of Dr Voncken from the unit Geology.

**Geothermal Engineering** research at TU Delft was initiated 2007 with the establishment of the "Delft Aardwarmte Project" (Delft Geothermal Project, DAP), led initially by the Geophysics unit. In 2013, Prof. David Bruhn was recruited from the International Centre for Geothermal Research at the GFZ in Potsdam (Germany) as a part-time Professor of Geothermal Engineering to set-up and coordinate the research and education. Bruhn is has more than 10 years' experience in generating and managing European projects. He was heavily involved in setting up the joint programme on geothermal energy within the European Energy Research Alliance and was its first scientific secretary. His international network and experience are vast, which will be crucial for connecting the department's geothermal research activities with other programmes in the world. This Chair is funded by a voluntary subscription of contributions of Geoscience and Engineering alumni of TU Delft.

## Coming period (2015-2020)

In **Advanced Reservoir Simulation and Optimization**, a newly recruited associate professor, Dr Voskov, formerly a Senior Research Associate at Stanford University, arrived in September 2015. This addition will further strengthen the DARSim and CLRM research programmes.

In **Resource Engineering**, an additional lecturer position (0.6 fte) was filled in February 2015 to meet the increasing teaching load and free current staff for research. Our aim is to continue to expand the group by building upon the outcomes and funding of current research projects. As of August 2015, Dr Buxton has received a permanent position, a year ahead of plan, which is a recognition of the success of the group in re-establishing a successful research programme.

The further growth of the group of **Geothermal Engineering** depends on the success in obtaining approval for the envisioned geothermal doublet on campus. Once finances for the wells and the related research facilities are in place, an extensive investigation of the geothermal system to be exploited will require more personnel than the 0.3 fte currently assigned. The short-term goal is to acquire funding for 5-10 years to enable the recruitment of an assistant or associate professor. In the near-term, a small research group will be sustained on project funding.

## 2.3 Funding strategy

Our funding strategy is to pursue sources of funding which enable us to fulfil our mission and that are compatible with conducting excellent fundamental, applications-driven research. The division of the funding from among the different funding schemes is shown in Fig 4.

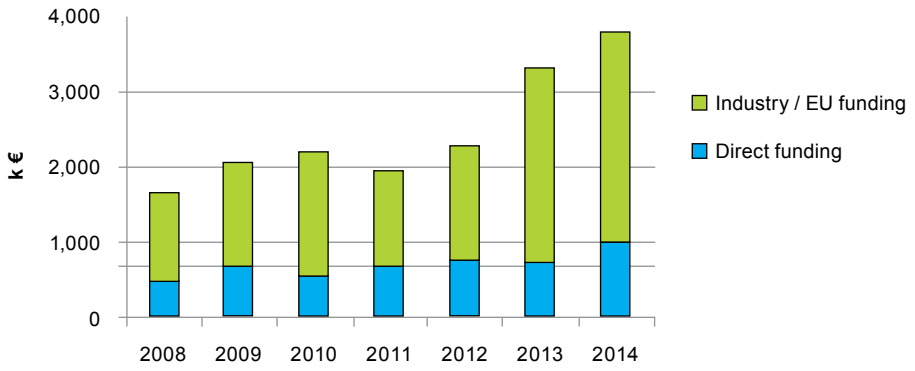



**Figure 4** Research funding during the review period (for numbers see Appendix U5.2). Note that the sudden funding increase after 2012 is due to newly established Resource Engineering group.

### Review period

Our main funding sources have been the following:

**Industrial Funding**

As most government research programmes exclude petroleum engineering from consideration, most of the funding for research in petroleum engineering comes from industrial sources.

The largest programmes are the ISAPP Consortium and the Recovery Factory (RF) programmes on CLRM. The first phase of ISAPP, funded by Shell and TNO, ended in 2012 and was succeeded by a second phase of ISAPP, funded by Petrobas, Statoil, Eni, and TNO, and the RF programme, funded by Shell. Both programmes will conclude at the end of 2016. Over the evaluation period a total of 18 PhD students were funded by these programmes. All of them had a Petroleum Engineering staff member as (co-)promotor (Prof. Jansen), while 8 of them were directly on the Petroleum Engineering payroll.

In addition to ISAPP and Recovery Factory, Shell funds a wide variety of research on EOR, and provides three part-time adjunct staff (Prof. Van Kruijsdijk, Dr Farajzadeh and Dr Vincent-Bonnieu). PhD and post-doctoral research is often also funded by smaller projects (1 to 3 positions) sponsored by the oil and gas or mineral resources industries, either in one-to-one or joint projects. We received funding for chemical and foam EOR from Shell, Maersk, Saudi Aramco, Conoco Phillips, GDF Suez, PEMEX, Equión Energia, and Petronas. The establishment of the DARSim group was funded by grants to Dr Hajibeygi from Chevron, Schlumberger and PI/ADNOC. Funding in Resource Engineering came from, e.g., Barrick Gold and IHC Merwede.

**Public-Private Funding**

Within the CATO programme, 2 post-docs and 3 PhD students worked on reservoir-engineering aspects of $CO_2$ storage. Besides that, 1 PhD student studies polymer EOR funded by the Dutch Polymer Institute.

**European Funding**

In just the short time since the group was established in 2011, our staff from Resource Engineering has been remarkably successful in attracting European funding. It is involved in 4 programmes with 8 positions for PhD student and post-doc's, respectively (2 in FP7, 2 from the European Research Fund For Coal & Steel, and 4 in H2020, starting 2015). TU Delft acts as coordinator for 6 projects.

**National Governmental Funding**
The Geothermal group has succeeded already in getting funds for two PhD candidates within the Geothermal Capacity Building Programme (GEOCAP), funded by the Dutch Ministry of Foreign Affairs. This programme concerns capacity-building in Indonesia, and the Delft part is executed in close collaboration with the unit Geophysics (Barnhoorn) and TNO. Moreover, the Geothermal group recently got awarded two European Union (H2020) proposals for a total of 1.2 mEuro. These grants have been awarded but are not reflected in funding during the review period (Fig. 4).

## Coming period (2015-2020)

We continue to engage in large programmes, whether purely industry-sponsored, EU or national programmes, or public-private partnerships. The latter two funding sources are likely to increase the coming years, partly due to the new research themes in Resource Engineering and Geothermal Engineering, and partly due to our efforts to focus on research that is seen as societally relevant by the Dutch FOM and STW foundations: in particular, shale oil and gas, including safety aspects, and geomechanics during gas production. Next to the large programmes, we will continue to build our research programmes through increased industrial contacts and funding in all fields of research.

**Industrial Funding**
While the ISAPP and RF programmes will end in 2016, we seek to keep funding on a high level and expand the research programme on **Advanced Reservoir Simulation and Optimization**. This will mainly be realised through the merger of the ISAPP, RF, and Delphi. With this new joint geophysics/reservoir engineering consortium, we aim to transform our Advanced Reservoir Simulation and Optimization programme into one or more conventional consortium(s) with lower fees but with a larger number of sponsoring companies and without a predefined end date. The **Resource Engineering** group will focus on complementing EU funding with industrial funding. We aim at establishing an industrial consortium, building on our strong industry relations in the field of education (European Mining Programmes) and the group of companies that currently funds Dr Buxton's position.

We will continue to fund research on **EOR** funded by a variety of companies. As noted above, we are in negotiations with Shell to establish the centre "INPERM" on fundamental research on interfaces and flow in porous media.

**Public-Private Funding**
In the **Rock-Fluid Flow Processes** theme, our contribution to the CATO programme will be to focus on $CO_2$ utilization in $CO_2$ EOR projects. Prof. Zitha is leading the discussion with several companies (Statoil, NW, Petrobras, Brazil, etc.), universities (e.g. University of Bergen, NW), and research institutes (TNO, IFP France, etc.). This is done in cooperation with Dr Wolf of the unit Geophysics. We are also in negotiations with a geotechnical research institute in Iran regarding a major cooperative agreement that would fund several PhD students and post-docs in petroleum engineering, geology, and petrophysics studying environmental issues related to EOR. For Shale Oil research, we plan to seek funding from sources such as EU H2020, NWO and STW to pursue innovation in the area of green chemicals and smart proppants used for environmentally friendly drilling and hydraulic fracturing. We also plan to cooperate with Chinese academic and industrial partners who in the future can give us access to field implementation of the technologies developed. Initial contacts have been established with Qingdao University of Science and Technology, China University of Petroleum and Petrochina.

We will further develop the **Advanced Reservoir Simulation and Optimization** group, and in addition to establishing one or more international consortia of industrial sponsors, we will step up our efforts to secure funds from industrial, national, and international granting agencies: STW/FOM, STW and the EU, among which the recently announced NWO program on fundamental deep-subsurface aspects of production-induced seismicity which will offer opportunities to expand our CLRM and DARSim research lines to include control of coupled fluid flow and geomechanics.

In **Resource Engineering**, we will continue to pursue public-private funding through the EU H2020 programme. In addition, we will seek funding in collaboration with national industrial partners through STW. We will expand our efforts to seek industrial funding through collaborative consortia of international industrial partners. Dr Benndorf will apply for a Vidi grant.

To finance the envisioned **Geothermal** doublet on campus, funding is sought from private partners (ca. 10 mEuro). The related scientific infrastructure will most probably be requested by a proposal submitted to NWO (funding scheme for large research infrastructure, ca. 4 mEuro). This will enable us to set up a national research centre on geothermal energy. Additional STW and EU H2020 proposals are in preparation to cover the actual costs of research(ers). The research facility of a university-owned geothermal well will be very exceptional and will make TU Delft highly attractive for EU researchers. We are therefore convinced that the probability of receiving EU funding is high once the funding for the geothermal doublet is acquired. In addition, Prof. Bruhn has been involved in several H2020 proposals and a concept study on large-scale research infrastructure coordinated by Karlsruhe Institute of Technology (KIT). In the event that wells on campus are not drilled, communication has been established with the deep geothermal project in the Westland to include a STW-funded coring programme in their well (to be deepened in 2016).

## 2.4 Publication strategy

### Review period

Our research is published in international peer-reviewed journals, conference proceedings and PhD theses (Fig. 5). Most journal papers appear first as a conference paper. We encourage PhD students to compile their theses as far as possible from journal papers and our MSc thesis students to prepare a paper from their thesis. We expect PhD students to produce 3 to 4 peer reviewed journal papers as first author during the course of their research.

The top research journal for the petroleum-engineering research (themes 1 and 2) in the Geo-Resources unit is the *SPE Journal*. In past years, the funding mechanism of our university (which recognised *SPEJ* as a top-tier journal and rewarded publishing there) led us to focus perhaps too much on that one journal. However, in the last few years we have diversified our journal selection to other high-impact journals. During the review period Prof. Jansen published a small text book entitled *A Systems Description of Flow Through Porous Media* (key societal output Jansen 2013). Prof. Rossen co-authored the revision of the classic text book *Fundamentals of Enhanced Oil Recovery*, with three colleagues from The University of Texas at Austin (key societal output Lake et al. 2014).

The top journal in **Resource Engineering** is the *Transactions Mining Metallurgy & Materials*. Our research has also been published in journals including *Minerals Engineering and Mathematical Geology.*

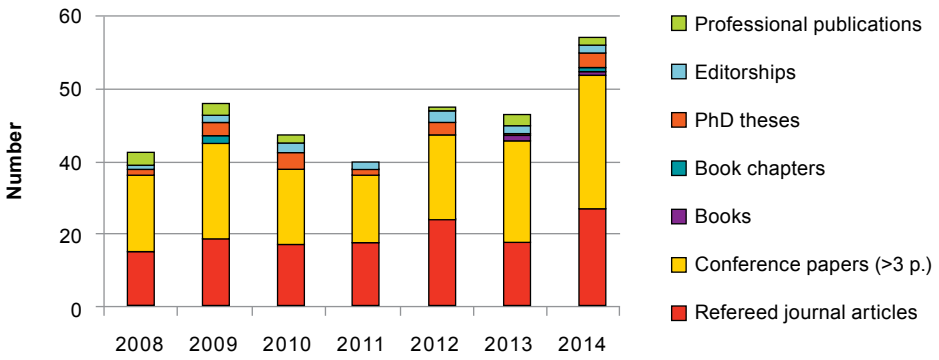



**Figure 5** Research output during the review period (for numbers see Appendix U5.3).

### Coming period (2015-2020)

We will continue to publish in the major geoscience, fluids and engineering journals and present our work at major international conferences. We will continue to strive for 3 to 4 refereed journal publications per PhD student in high-impact journals during the course of the PhD study. In addition, we publish the results of MSc thesis research when possible. We will continue to hold editorships of major journals, organise international workshops, etc. Resource Engineering and Geothermal Engineering will expand its publication record based on ongoing results of the newly established research programmes.

The Advanced Reservoir Simulation and Optimization groups (CLRM and DARSim) will jointly host the next European Conference on the Mathematics of Oil Recovery, in 2016.

# 3 Research results and plans

## 3.1 Theme 1: Rock-Fluid Flow Processes

*Scientific staff: Prof. Rossen (1 fte), Prof. Zitha (1 fte), Dr Rudolf (1 fte until 2010), Dr Berentsen (1 fte until 2012), Dr Farajzadeh (0.2 fte since 2012)*

The research program on rock-fluid flow properties at TU Delft is noted for combining state-of-the art laboratory methods interpreted and extended by modelling. The laboratory facilities for coreflood testing of flow processes and analysis of fluid/rock properties in our Department are excellent. In the review period a major advance in laboratory techniques was the innovative use of imaging of fluids in porous media on both the cm and pore scale, as discussed below. For the coming period, we will continue to build on this foundation and expand into innovative laboratory techniques to study interfacial and compositional fluid properties in situ, especially through the proposed Shell University Technical Center INPERM.

Foam and other chemical EOR: Prof. Rossen's research focused on development of simplified models for foam EOR that maximise physical insight while minimising needless complication. His group extended the method of characteristics for foam EOR to non-Newtonian flow, three-phase flow with oil, and gravity segregation. After developing the only current model that explains the jumps between multiple foam states seen in the laboratory, the group showed the implications of this model for the feasibility of long-distance propagation of foam in the field (key publication Ashoori et al. 2012). Using simple analytical models they identified the simulator artefacts that distort reservoir simulation of foam EOR (Fig. 6).

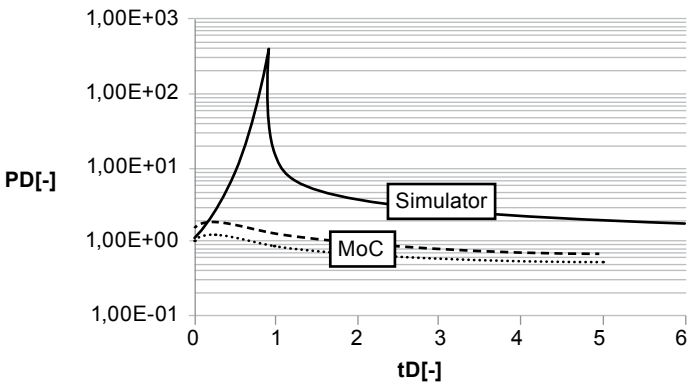



**Figure 6** Comparison of pressure drop during foam injection estimated using conventional simulation methods and using the more-accurate method of characteristics (MoC) in grid blocks of 5 and 50 m radius. Conventional simulation methods grossly overestimate the rise in injection-well pressure (PD) during gas injection.

Practical applications of this work include identifying the key role of injectivity in a process involving viscous foam and development of improved injection strategies to optimise injectivity. They also developed simple methods to fit simulator model parameters to laboratory foam data. The group published 27 journal articles and 27 conference papers during this period, together with co-authors from The University of Texas at Austin, Rice University, The University of Manchester, The University of Aberystwyth, and IMPA (Brazil).

Prof. Zitha also conducted ground-breaking work on foam EOR, focusing especially on CT imaging, the effect of oil on foam and use of foam as a mobility-control agent for surfactant flooding (key publication

Simjoo et al. 2013). He demonstrated a possible mechanism of oil recovery with foam by emulsification that would not depend on capillary number. Together, Profs. Zitha and Rossen showed that flowing-gas fraction with foam can be up to 70 times less than estimated by previous methods (Fig. 7).

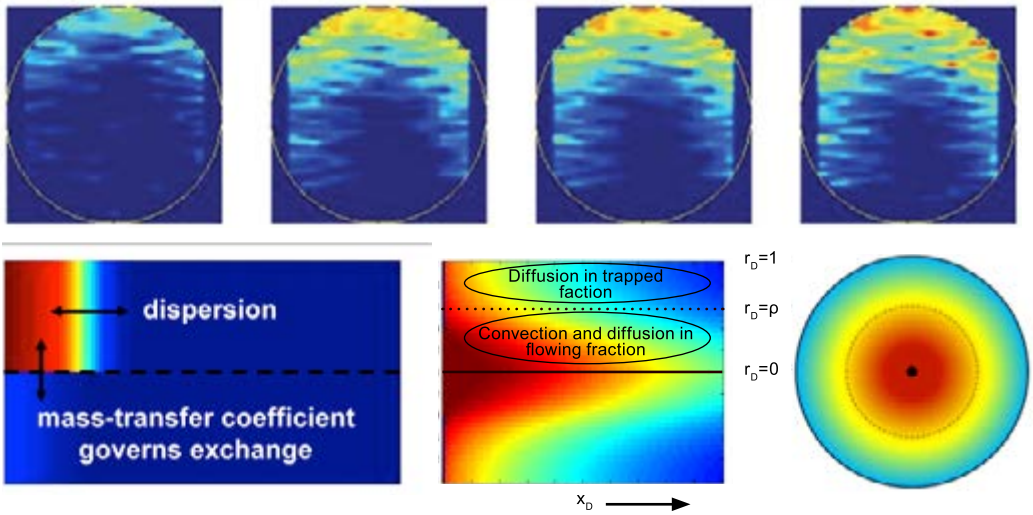



**Figure 7 Top**: CT (cross-section) image of xenon tracer penetrating a foam-filled core in study of gas trapping with foam. Tracer, transported in flowing bubbles, penetrates core in many small pathways surrounded by trapped gas bubbles. Bottom left: conventional model for interpretation of tracer experiments (axial view along core). At each position along core, there is a single flowing concentration of flowing gas and one of trapped gas. Top figure disproves this assumption. **Bottom center**: improved model, where tracer flows in a small finger surrounded by trapped gas. **Bottom right**: result of model: tracer appears in cross-section around each finger as it does in many individual locations in the CT image. Analysis of CT images like these led to a reduction in the estimate of flow-gas fraction by a factor of 70 from previous techniques.

Prof. Zitha conducted a series of studies in coupling of two-phase flow and phase-behaviour-related phenomena, inspired by and relevant to chemical EOR. CT-scan-aided experimental studies culminated with the establishment of alkali-surfactant-foam (ASF) as a possible extension of alkali-surfactant-polymer (ASP) EOR. This work has resulted in 5 conference and journal articles.

For his achievements in EOR research, Prof. Rossen was named an IOR Pioneer at the 2012 Tulsa Symposium on Improved Oil Recovery, the oldest and most prestigious international symposium in that field. This award is given to between 3 and 5 recipients worldwide every two years. Prof. Zitha received the SPE Regional Reservoir Description and Dynamics Award for his contributions in rock-fluid physics and its bearing upon hydrocarbon recovery.

**$CO_2$ storage and $CO_2$ EOR**: $CO_2$ storage in aquifers and waterflooded reservoirs was the main focus of our contribution to the CATO project, starting 2010.

The first PhD project (Shojai Kaveh, cum laude 2014) investigated the wettability of reservoir rocks similar to those encountered in depleted gas storage sites. The research evaluated the wetting properties of rock surfaces in the presence of $CO_2$ and/or synthetic flue gas at high pressures and elevated temperature (up to 16 MPa and at 318 K). PhD student Khosrokhavar focused on enhanced mass-transfer of $CO_2$ from the gas phase into brine or oil, as a model for $CO_2$ storage in saline aquifers or waterflooded oil reservoirs (Fig. 8). The Schlieren technique was applied to visualise natural convection fingering patterns induced by $CO_2$ dissolution in brine or oil. Furthermore, Khosrokhavar investigated the competitive sorption of $CO_2$ and methane for $CO_2$ storage into shale formations combined with enhanced methane production. PhD student Roels undertook modelling and micro-CT-scan-assisted experimental studies on salt precipitation and injectivity impairment induced by $CO_2$ injection into aquifers. We were among the first to establish a direct correlation between salt precipitation and resulting permeability impairment. This resulted in 4 publications in high-impact journals by Roels and post-doctoral researcher Van Hemert.

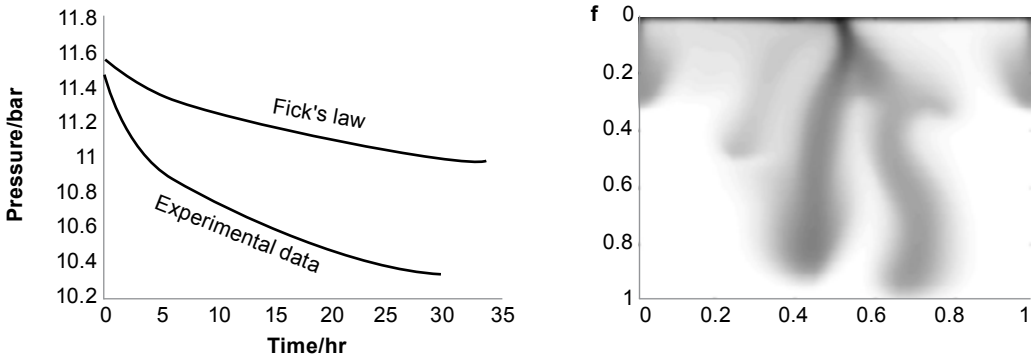



**Figure 8** Two figures from study of density effects in mass transfer of $CO_2$ into water and oil, in the lab, in aquifers and in oil reservoirs. Left: initial experiment: rate of pressure decrease as $CO_2$ entered water phase was unexpectedly high. The reason was density-driven circulation of $CO_2$-rich water to and from the interface. Right: scale-up of this mechanism to aquifer or reservoir scales, resulting in accelerated transport of $CO_2$ from override zone to rest of reservoir.

**Well-inflow performance**: Our research related to water and sand control continued the investigation of oil-soluble chemicals which form gels in the presence of water. This research involved phenomenological modelling and CT- and MRI-aided porous-media flow experiments. Prof. Zitha led the work in cooperation with Eindhoven University (Pel, Kopinga). It led to significant progress in the fundamental understanding of two-phase flow coupled with reactive mass transfer. Research on formation damage during produced-water reinjection continued with modelling and CT-scanning experiments on deep-bed filtration. This work led to improved models of the process. The research was supervised by Profs. Currie and Zitha in cooperation Prof. Bedrikovetsky (U. of Rio de Janeiro/U. of Adelaide) and Petrobras. This work produced 5 conference and journal publications.

**Advanced visualisation techniques**. Noteworthy in this period is remarkable progress of our group from a fast-follower to a leadership position in CT scanning and micro-CT scanning in petroleum research. In 2009, through a joint effort of several groups of the Faculty, we acquired a micro-CT scanner with much greater spatial resolution (better than 1μm ) than conventional CT scanners, but at lower temporal resolution. Using our previously acquired conventional CT scanner and the new micro-CT scanner, we expanded considerably the domain of application of these advanced visualisation tools, making several significant discoveries, such as

- identification of mechanisms of foam generation, trapping and flow in porous media in absence and in presence of oil, with application to foam (Fig. 9): see key publication Simjoo et al. 2013

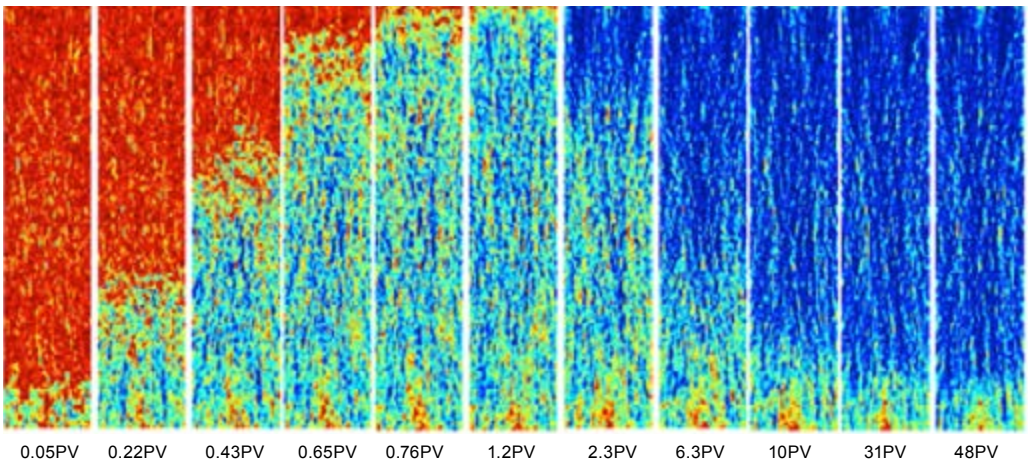



**Figure 9** Sequence of CT images of foam (green/blue) displacing brine (red) from a Bentheimer sandstone core. A foam with modest mobility reduction propagates from the core inlet (bottom) to the outlet (top). After it arrives, a stronger foam (lower water saturation, with lower mobility) is created near the outlet, which propagates over time upstream to the inlet. This creation and upstream propagation of strong foam is confirmed by sectional pressure-difference measurements along the core.

- investigation of two-phase flow coupled with mass transfer between phases and chemical reactions, with applications to selective blocking of water layers, sand control, and salt precipitation induced by $CO_2$ injection into aquifers: 4 publications by PhD students Elewout and Al-Muntasheri
- 3D visualisation of the development of hydraulic fractures, with application to tight and shale gas and shale oil exploitation (together with the unit Geophysics): 2 publications by PhD student (later post-doc) Dong
- visualisation and quantification of the retention of solid particles in porous media (formation damage, produced water re-injection, drilling fluids): 6 publications by MSc students van Overveldt, Frequin, S.S. Yerramilli and R.C. Yerramilli.

## 3.2 Theme 2: Reservoir Simulation and Optimization

*Scientific staff: Prof. Jansen (1 fte), Dr Hajibeygi (1 fte since 2013), Dr Van Odyck (1 fte until 2013)*

**Closed-loop reservoir management (CLRM):** Over the past decade, we have developed into one of the word-leading groups in CLRM research, focusing on fundamental and algorithmic aspects of control and optimization of subsurface flow (Figs. 1 and 10). In this review period we extended the functionality of this concept by adding “robust” optimization under geological uncertainty (key publication Van Essen et al. 2009), “hierarchical” optimization, “multi-level” optimization to reconcile reservoir management with short-term production optimization, multiscale regularization, model-reduced history matching and value of information assessment in CLRM. Moreover, we widened the scope of applicability from waterflooding to EOR applications. We expanded our efforts in recovery optimization to include ensemble optimization where we deepened the theoretical understanding (optimal ensemble size, covariance matrix adaptation) and scale up of the computational aspects (e.g., a case study for Eni). We further deepened the insights in observability and controllability of subsurface flow, identifiability of reservoir parameters, reduced-order modelling, control-relevant upscaling (SPE Ferguson medal 2011 for Vakili) and the emerging use of fiber optics for well monitoring (2014 mini-workshop). For the coming period, we aim at expanding into control of coupled flow and geomechanics, in particular aimed at production-induced seismicity, and application of our system-theoretical understanding to geophysics (time-lapse seismics) in cooperation with the Geophysics staff in our Department and in the Faculty of Applied Sciences.

Within the evaluation period, 10 PhD students obtained their doctoral degree on a Smart Fields-related topic (with Prof. Jansen), while another 14 started their PhD research. The group published 18 journal publications, 30 conference papers, and two patents and gave numerous invited presentations, notably keynote speeches at the 2013 *SIAM Conference on Computational Science and Engineering*, Boston, USA, a 2011 *Institute for Mathematics and Applications* (IMA) *invitational workshop* (Minneapolis, USA) and the 10th *Conference on Numerical Methods for Fluid Dynamics* 2010, Reading, UK, and many others. We had PhD-student and scientific-staff exchanges with IRIS (Norway), Tulsa University, and Stanford University.

**Advanced reservoir simulation:** Newly arrived Dr Hajibeygi’s research focuses on numerical methods, and in particular on multi-scale, multi-physics modelling and methods for efficient and accurate large-scale simulations of reservoirs with complex fluid-rock physics (key publication Wang, Hajibeygi et al. 2014; Figs. 2 and 11). His grant from PI/ADNOC was one of 9 grants made from 107 international proposals. In additions to links to researchers at TU Delft facilitated by DARSim, Dr Hajibeygi continues strong collaboration with his former colleagues at Stanford University. With the arrival of Dr Voskov, with in-depth expertise in compositional simulation and geomechanics, in September 2015 we will further expand our simulation research to include compositional simulation, reactive flow and geomechanics. In particular, we envisage the development of specific geothermal simulation capabilities for the Dutch geothermal community.

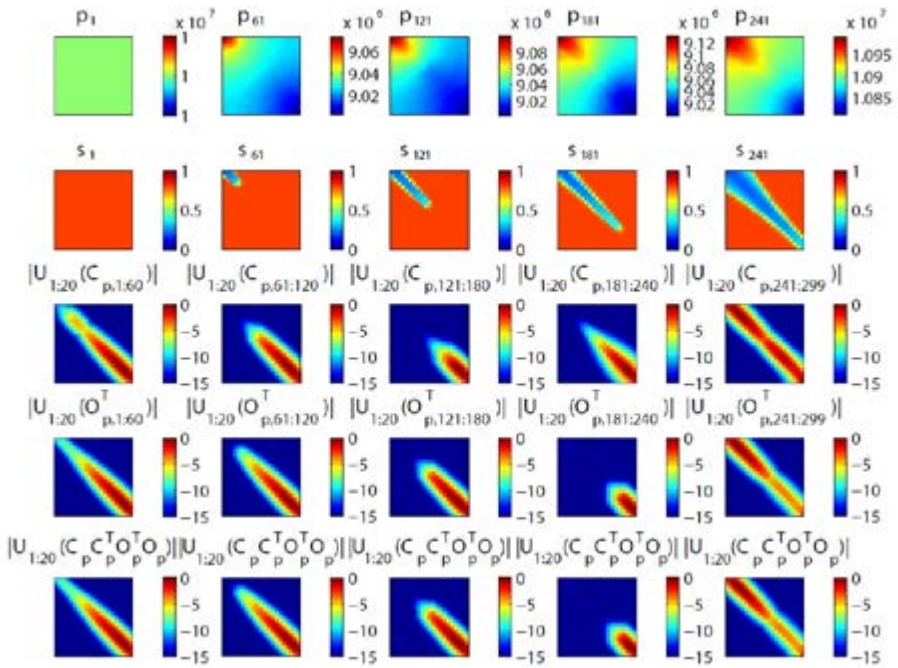


**Figure 10** Observability and controllability of pressure states for two-phase (oil-water) flow in a heterogeneous reservoir (Injector top-left and producer bottom-right) connected by a high-permeability streak. Columns indicate five consecutive time intervals. The top two rows display the pressure and saturation fields. The three bottom rows display the (base 10) logarithm of the 'weighted singular vectors' corresponding to the empirical controllability Gramian, the empirical observability Gramian and the balanced Gramian, illustrating the limited controllability and observability of pressure outside the immediate vicinity of the wells and the high-permeability streak, and their increased values after water-breakthrough. (After Van Doren et al. 2013).

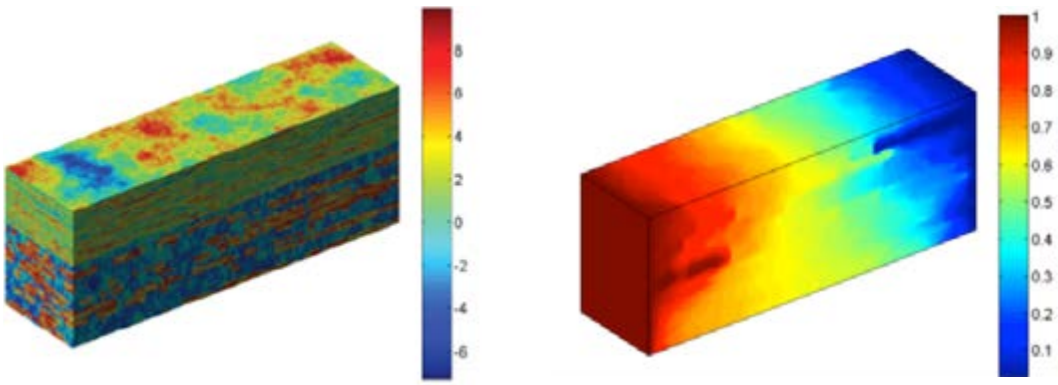


**Figure 11** **Left**: three-dimensional permeability field of a heterogeneous reservoir with 1.1 million grid cells. Our multiscale method employs only 1100 grid cells to solve this problem. **Right**: Pressure field in reservoir using only 1100 grid cells.

## 3.3 Theme 3: Resource Engineering

*Scientific staff: Dr Buxton (1 fte since 2011), Dr Benndorf (1 fte since 2012), Dr Voncken (1 fte since 2012)*

The overarching, integrating research theme in Resource Engineering is the development of a framework for real-time process reconciliation and optimization of mineral resource extraction in highly complex geological settings, particularly for selective mining scenarios (key publication Benndorf & Dimitrakopoulos, 2013; see also Fig. 12). Complex deposits are characterised by a low continuity in grade and high irregularity in the geometry of the ore boundaries. As a result, the profitable exploitation of the deposit becomes much more challenging. This results in underutilization of valuable sources of raw materials in the European Union.

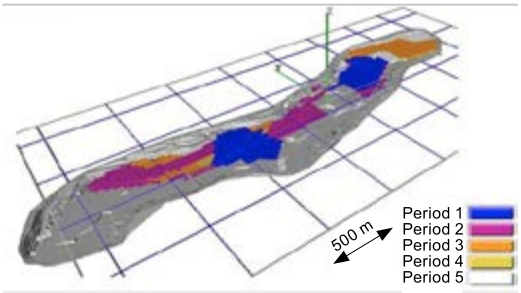



**Figure 12** Example of an optimised schedule for exploitation of a mineral resource.

To be able to better utilise such unconventional mineral resources of the future, smart autonomous mining systems are needed, which integrate local exploration of spatially varying material characteristics in–situ and have the ability to follow and extract the pay zones in the ore body while optimising the sustainable value of extraction. The main barriers to overcome for the successful economic exploitation are

- effective grade control, which will maximise resource potential along the whole value chain
- minimization of handling of zero-value material introduced by dilution, thus reducing unnecessary expenditure of energy and financial resources
- management and control of the geological uncertainty due to limited information available, thus optimising resource utilisation.

The key concept of the research promotes the change in paradigm from discontinuous, intermittent process monitoring and control to a continuous closed-loop process-management system (Fig. 13, lower part).

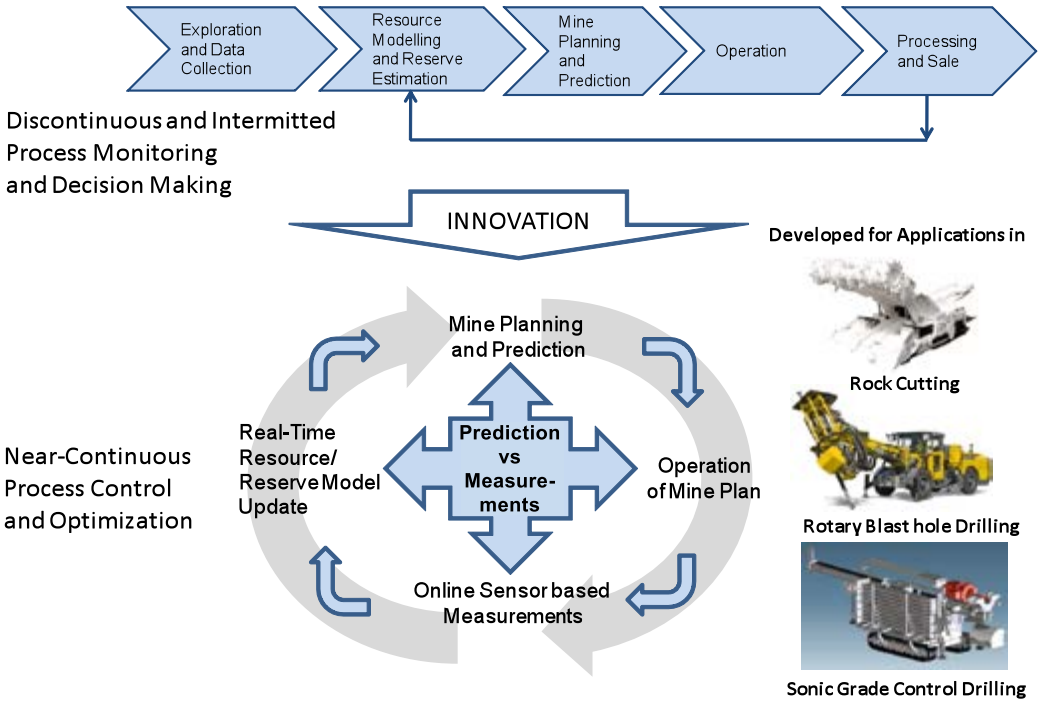



**Figure 13** Schematic of a Closed-Loop Process-Management System.

The development of such an integrated framework in the context of mineral resource management is novel and involves significant scientific challenges, since it has to integrate the following distinct scientific disciplines into one coherent process optimisation framework:

- underground equipment positioning
- sensor-based material characterisation
- sensor-based machine control monitoring
- methods of spatial grade prediction using geostatistical approaches and rapid updating
- optimization of short-term planning.

## 3.4 Theme 4: Geothermal Engineering

*Scientific staff: Prof. Bruhn (0.3 fte since 2013)*

Though initiated late in the reporting period with only 0.3 fte scientific staff, the Geothermal effort has made an impressive start and laid plans for the coming period. In the course of 2013 and 2014, Prof. Bruhn finalised his work on induced seismicity in the framework of the EU project GEISER and became a partner (with GFZ Potsdam) in the EU project IMAGE on novel geothermal exploration approaches. TU Delft is involved in IMAGE through the interpretation of ambient noise (seismic) data acquired at an Icelandic site within the project (post-doc Weemstra). Post-doc Nick's work addresses the quantitative assessment of heat recovery, sweep efficiency, injectivity enhancement, and effects of cold mixed $CO_2$-water injection within deep fluvial sandstone and Triassic fractured formations. This work has resulted in 2 journal papers, with four more under review, and 3 conference papers so far. The mechanical properties of geothermal reservoir rocks in the context of enhanced geothermal systems (EGS) and hydraulic stimulation are at the centre of our cooperation with Indonesia, TNO and Utrecht University. A major new topic approached by the geothermal group, including PhD student Willems, is the potential interference of several geothermal operations in one aquifer. This is a question of great relevance for the further development of geothermal projects in the Netherlands.

The deep geothermal wells to be drilled on the campus of TU Delft will provide an excellent opportunity and location for the installation of a national infrastructure for the investigation of the deep subsurface, primarily – but not exclusively – for geothermal development and operations. There is no comparable infrastructure in the world allowing subsurface monitoring during operations in a sedimentary environment. The scientific objectives of the envisioned geothermal doublet, are, amongst others, to reduce geological uncertainty, reduce operational risks, test innovative well completion, install innovative monitoring and optimization methods, support co-generation of electricity and heat, control geochemical processes occurring during water production and injection, evaluate the option of $CO_2$ sequestration with the water pumped back into the aquifer, and validate novel geophysical approaches to characterise a geothermal reservoir with wellbore and surface imaging methods

Several of the proposals prepared for EU-H2020 and STW include tasks that directly address relevant work for the envisioned deep geothermal wells. Within these projects, we will study the testing of the next-generation (high-temperature) composite casing (with Acquit BV) and the prevention of corrosion and scaling (with Prof. Zitha). We will also perform direct measurements of thermal properties of the rocks below Delft down to the Triassic sandstones (the potential deep reservoir) and calculate the resulting heat flow. Such measurements have not yet been performed for any well in the Netherlands.

## 3.5 Interdisciplinary research and synergies between themes

Although accomplishments are listed above according to theme, there are numerous large and small collaborations between themes, with other units in our Department and elsewhere at TU Delft. Some of these, listed below, are small efforts now, which might grow into larger programmes.

- The CLRM programmes (ISAPP and RF) have long kept close collaboration with the units Geophysics and Geology, seeking to integrate new methods of reservoir characterisation into data assimilation and production optimization. This relation is now formalised in a link to the Delphi consortium.
- The CATO programme brings together reservoir engineers and petrophysicists in a joint effort to understand and optimise the subsurface storage of $CO_2$.
- Research in the theme Resource Engineering shares many of the tools of ISAPP, in characterizing reservoir deposits under uncertainty.
- Research in the theme Geothermal Engineering combines expertise and staff from the units Geophysics, Geo-Resources and Geology.
- A joint effort with the unit Geophysics on shale fracturing and production of shale gas and oil is seeking funding to grow.

- DARSim is pursuing efficient multi-scale and multi-physics simulation of miscible and foam EOR and of geomechanics during oil recovery.
- DARSim collaborates closely with ISAPP and the unit Geophysics unit in order to develop Multi-scale Integrated Reservoir Management.
- A joint effort with the Department of Chemical Engineering seeks to relate polymer rheology in viscometers, microfluidic devices and EOR applications.
- Joint efforts with the unit Geology seek better ways to characterise flow in naturally fractured reservoirs, starting with geomechanics.

To promote better coordination between staff and students working on diverse topics in the Petroleum Engineering themes (1 and 2), we conduct weekly seminars attended by all research staff.

**Van Essen, GM, Zandvliet, MJ**, Van den Hof, PMJ, Bosgra, OH and **Jansen, JD** (2009). Robust waterflooding optimization of multiple geological scenarios. *SPE Journal* **14** (1) 202-210. DOI: 10.2118/102913-PA.

**Ashoori, E**, Marchesin, D, & **Rossen, WR** (2012). Multiple Foam States and Long-Distance Foam Propagation in Porous Media. *SPE Journal* **17**, 1231-45.

**Simjoo, M, Dong, Y**, Andrianov, A, Talanana, M & **Zitha, PLJ** (2013). Ct scan study of immiscible foam flow in porous media for enhancing oil recovery. *Industrial & Engineering Chemistry Research* **52**, 6221-6233.

Wang, Y, **Hajibeygi, H** & Tchelepi, HA (2014). Algebraic multiscale solver for flow in heterogeneous porous media. J. *Computational Physics*, (ISSN 0021-9991), **259**, 284-303.

**Benndorf, J** & Dimitrakopoulos, R (2013). Stochastic long-term production scheduling of iron ore deposits : Integrating joint multi-element geological uncertainty. J. *Mining Science*, 49 (1), 68-81.

**Figure 14** Key publications.

## 3.6 Summary of research quality

### Research products

The more established research themes 1 and 2 are highly productive. From the number of papers mentioned throughout this chapter, we would especially highlight the research on Chemical EOR and CLRM, with 41 and 18 journal papers, respectively, throughout the review period.
Our publication strategy was directed towards diversification and, besides *SPE J*, we published in high-impact journals (impact factors): *Langmuir* (4.38), *International Journal of Greenhouse Gases* (3.82), *Fuel* (3.41), *Energy and Fuels* (2.73), *Journal of Supercritical Fluids* (2.57), *Journal of Computational Physics* (2.49), *Colloids and Surfaces A* (2.35), *Ind. Eng. Chemistry* (2.23), *Physics of Fluids* (1.94), *Computational Geosciences* (1.87) and *Computers and Geosciences* (1.56). Some of these journals also underline the fundamental character of our research. Resource Engineering (theme 3) research was published in *Transactions Mining Metallurgy & Materials, Minerals Engineering* (1.71) and *Mathematical Geology* (1.0).

Our most cited papers published in the review period are:

- **Essen, GM van**, **Zandvliet, MJ**, Van den Hof, PMJ, Bosgra, OH & **Jansen, JD** (2009). Robust waterflooding optimization of multiple geological scenarios. *SPE Journal*, 61 (3), 202-210. (76 citations (Scopus))
- **Farajzadeh, R**, Andrianov, A, **Zitha, PLJ** (2010). Investigation of immiscible and miscible foam for enhancing oil recovery. Industrial & Engineering Chemistry Research 49 (4), pp. 1910-1919. (66 citations (Scopus))
- **Jansen, JD**, Bosgra, OH & Hof, PMJ van den (2008). Model-based control of multiphase flow in subsurface oil reservoirs. *Journal of Process Control*, 18 (9), 846-855. (57 citations (Scopus))

Whereas the extension of the unit can be clearly seen in the fte's and funding, starting 2012, the number of publications only started increasing substantially in 2014 and is expected to grow the coming years (Fig. 5).

Jansen made publicly available the “Egg model” benchmark study (based on key publication Van Essen et al. 2009) in open access (3TU DataCenter and *Geoscience Data Journal*), and filed two patents.

### Use of research products

Our full-time professors have H-indices from 15 to 22 (Scopus), and it is remarkable that assistant professor Farajzadeh has an H-index of 11, despite his young age and his part-time position (6 years after PhD).

### Marks of recognition by academic peers

For his achievements in EOR research, Prof. Rossen was named an IOR Pioneer at the 2012 Tulsa Symposium on Improved Oil Recovery, the oldest and most prestigious international symposium in that field. This award is given to between 3 and 5 recipients worldwide every two years. Being invited to co-author the recent edition of the classical text book on EOR (Lake et al. 2014), also honours Rossen’s reputation in this field. Prof. Zitha received the SPE Regional Reservoir Description and Dynamics Award for his contributions in rock-fluid physics and its bearing upon hydrocarbon recovery.

Our CLRM group has developed into one of the word-leading groups over the past decade, on par with, and in some aspects exceeding, Stanford University’s, NTNU’s and Tulsa University’s efforts in this field. The fact that we were able to attract two young high-potentials from Stanford University is attributable to our reputation in this field. Numerous invited presentations and several notably keynote speeches support our standing, as well as the research staff exchanges with IRIS (Norway), Tulsa University, and Stanford University.

Due to his outstanding contribution to the research field, Prof. Jansen received several marks of recognition. He was awarded a one-year Cox Visiting Professorship at Stanford University for the academic year 2010-2011. He was named to the external review committees of the Department of Energy Resources Engineering of Stanford University (2012) and the Energy and Sustainability Research Institute of the University of Groningen (2014). During the entire review period he was a member of the Technical Committee for the Integrated Operations consortium at NTNU, Norway. In 2014 he was appointed to the Board of Professors of TU Delft, advising the Rector Magnificus on university strategy and all TU Delft full professor appointments.

We are also very proud of our PhD students Ashoori and Shojai Kaveh who received their PhD cum laude. Ashoori was also nominated for TU Delft Dewis Award (for best female PhD student). PhD student Vakili won the SPE Ferguson medal for the best peer-reviewed young-author publication in 2011, and MSc student Noordstrand the UfD-EBN Geo Energy Master Award (1st prize) for best MSc thesis in the Netherlands (2013).

Our staff are invited to participate in editorships of international journals and organising committees for numerous symposia. Some examples include the following: Prof. Jansen was Editor-in-Chief of *Computational Geosciences* (2009-2013), Associate Editor since 2014, and Member of the editorial board of Springer Briefs in Earth Sciences. He served on the scientific programme committees of the industry’s two prime reservoir simulation conferences, i.e. the *European Conference on Mathematics in Oil Recovery (ECMOR)* (Chair in 2008) and the *SPE Reservoir Simulation Symposium (RSS)* throughout the whole review period, and was co-chair/initiator of the *SPE Advanced Technology Workshop* on *Closed-Loop Reservoir Management*, Bruges, Belgium (2008). Since 2011, he is Board member of the Dutch National Committee for the World Petroleum Congress. Prof. Rossen was an Associate Editor of *SPE Journal* and a member of the scientific programme committee of *EAGE European Symposium on Improved Oil Recovery*, the most important European conference in improved/enhanced oil recovery. Prof. Zitha has served on the programme committee of the *SPE European Formation Damage Conference* for 8 years (chairman in 2011 and 2013). This is one of the top two conferences on formation damage in the world.

As is obvious from Figure 4 on funding, the theme of Resource Engineering was quite successful in acquiring EU funding, which supports their level of recognition within the European research community.

# 4 Relevance to society

For decades, society will still depend on extraction of subsurface resources for its welfare and prosperity. Foreseeable increases in efficiency of end-use and recycling of subsurface resources and foreseeable reductions in cost of renewable energy resources cannot meet worldwide demand without a significant reduction in standards of living. As the efficiency of resource-recovery processes increases, the number of extraction projects and therefore the magnitude of environmental impact of these industries is reduced, while the prosperity and welfare of society is improved.

Our research on efficient extraction of solid natural resources contributes to the benefit of society by maximising utilisation of natural resources and allowing extraction of previously inaccessible or uneconomic resources. This is achieved by optimisation of extraction, reduction of energy required for extraction, enhanced safety through automation, subsurface storage of waste products (e.g. $CO_2$ - see key societal outputs Farajzadeh et al. 2011 and Roels et al. 2014), and reduction of the use of water and the emission of greenhouse gases.

Our involvement in the DAP project greatly contributed to the discussion about Geothermal Energy resources in the Netherlands. This is reflected in the supporters of the DAP research programme (EBN, Hydreco and Eneco, KIVI chapter Mijnbouw and a subsidiary of EFRO) and the great success of, and the 192 participants in, the bi-annual DAP Symposium in February 2015. Moreover, the establishment of the part-time Chair in Geothermal Engineering through contributions of Geoscience and Engineering alumni of TU Delft reflects society's recognition of the importance of this Geo-Resources research. This crowd-funding of a university chair generated lots of attention in the Dutch media.

Our unit ensures the societal relevance and impact of its research mainly by the following approaches.

## 4.1 Cooperation with and products for industry partners

The large fraction of the research funding for this unit provided from industry (74%, see Tab. 2) testifies to the relevance of our work to their operations and the impact they perceive from our work. Our research results in products that we share with sponsors and/or make available to academic as well as industrial R&D staff through publications.

- The CLRM concept developed in the group of Prof. Jansen was instrumental in the establishment of a Quantitative Reservoir Management R&D team within Shell Global Solutions. This has resulted in a marked increase in the number of optimization and assisted-history-matching studies being performed within Shell. Moreover, algorithms developed in the Prof. Jansen's group were implemented in Shell's in-house reservoir simulator Dynamo-MoReS. Other industrial spin-offs from our CLRM research include the development of a reservoir optimization toolbox at TNO, and optimization and assisted-history-matching workflows and field studies in Statoil, Eni and Maersk.
- Multi-scale reservoir solvers developed by Dr Hajibeygi were prototyped in the Chevron/ Schlumberger Intersect simulator.
- The EOR research results of Profs. Rossen and Zitha have led to spinoffs within Shell, including field implementation of chemical EOR projects and new research.
- Due to our emphasis on fundamental, applications-driven research, we continue to present papers at international conferences attended by both academic and industry R&D researchers. This enhances peer-group recognition, ensures dissemination of the results towards the end users, and eventually leads to implementation.
- Prof. Jansen published the small textbook *A Systems Description of Flow Through Porous Media*, and Prof. Rossen co-authored *Fundamentals of Enhanced Oil Recovery* (see key societal outputs, and Chapter 2.4.

## 4.2 Employment of (part-time) staff from industry

To ensure fast implementation of research into practice and being up-to-date with challenges that industry faces, we involve part-time staff based in industry. At present, Shell seconds to TU Delft three part-time staff members (Prof. Van Kruijsdijk, 0.2 fte; Dr Farajzadeh, 0.2 fte; and Dr Vincent-Bonnieu, 0.2 fte). In addition, Prof. Jansen held a joint TU Delft/Shell position (0.5/0.5 fte) until mid-2010 when he took up a full-time position at TU Delft.

For staff vacancies, we consider not only candidates from academia, but also those who previously worked in industry. By hiring staff who know the issues and the working environment of industry, we are better equipped to set up partnerships and research programmes that involve partners from industry. This strategy has been particularly effective in the reestablishment of the group of Resource Engineering; both Buxton and Benndorf have worked in industry.

## 4.3 Training of skilled graduates for the R&D sector

Our unit trains significant numbers of MSc and PhD students that enter the R&D sector after graduation. Their R&D work in industry multiplies the impact of our in-house research. We held three ISAPP workshops for industry professionals (two in Delft in 2012 and 2013, and one in Brazil in 2013), and taught various courses at summer schools on data assimilation in Indonesia (2012) and Romania (2013). In 2013 and 2014 we presented the Delft Summer School on EOR to industry professionals, academic staff, and PhD students. Applications for the class went beyond capacity (40 participants) both years and we attracted instructors from Rice University, Stanford University, The University of Texas at Austin, and the University of Bergen. The CLRM program organised the ISAPP Course “Closed-Loop Reservoir Management and Production Optimization - From Theory to Application” for Petrobras in Rio de Janeiro, Brazil, in May 2013.

## 4.4 Capacity building

Within the Geothermal Capacity Building Programme (GEOCAP), funded by the Dutch Ministry of Foreign Affairs, two PhD candidates will engage in capacity-building in Indonesia. Prof. Zitha took part in the mission to Mozambique, Tanzania and Zanzibar as part of the Aid and Development mission led by the Minister Foreign Trade and Development Cooperation, Mrs. Ploumen, in 2014. One result is the recently published NUFFIC tender for improving local education in Geosciences and Petroleum Engineering & Renewable Energies.

## 4.5 Contribution to public debate and government consultation

As experts in the field of geo-energy, we consider it our duty to also engage in the public debate. Many of the activities listed below have been initiated or coordinated by the Delft Energy Initiative, a TU-broad network of energy experts that seeks to enhance visibility of TU-energy expertise in the Dutch and EU context. Since 2011, Prof. Jansen has been theme leader for Geo-energy within this initiative. Examples of our activities include the following:

- Prof. Jansen was invited by members of the Dutch Parliament and the Provincial Government of Brabant to advise them on shale gas development. To this end, he wrote a briefing (key societal output Jansen 2013) and took part in public hearings.
- Prof. Jansen was appointed by the Ministry of Economic Affairs as one of the two Dutch members in an international Scientific Advisory Board on seismicity induced by natural gas production in the North of the Netherlands.
- We gave several public lectures and interviews on the Gulf of Mexico oil spill disaster, Dutch exploration successes, advances in the technology of petroleum production, shale-gas development, and gas hydrates.

- Prof. Bruhn was invited by the ministry of Economic Affairs as an external expert to make suggestions for a medium- to long-term geothermal development and the required research infrastructure.
- Prof. Zitha gave several interviews, including on Dutch TV, about the potential for exploitation of natural gas hydrates.
- Prof. Rossen gave a lecture at the Fysica meeting for Dutch physics educators in 2014 on hydraulic fracturing.
- Resource Engineering were involved in the compilation of an EU report for DG Mare entitled "Study to investigate the state of knowledge of deep-sea mining".
- Dr Voncken gave several expert interviews to governmental agencies with respect to critical raw materials, specifically Rare Earth Elements. In addition, he gave a lecture to the Dutch Chemical Society on this subject.

**Jansen, JD** (2013). "Standpunten Hoorzitting Schaliegas, J.D. Jansen, TU Delft." Testimony prepared for Netherlands Parliament, September 2013.

**Farajzadeh, R,** Ranganathan, P, **Zitha, PLZ, Bruining, J** (2011). The effect of heterogeneity on the character of density-driven natural convection of $CO_2$ overlying a brine layer. *Advances in Water Resources* **34** (3), 327-339.

**Roels, SM, Ott, M & Zitha, PLJ** (2014). CT analysis and numerical simulation of drying effects of $CO_2$ injection into brine-saturated porous media. *Int. J. Greenhouse Gas Control* **27,** 146-154.

**Jansen, JD** (2013). *A systems description of flow through porous media*. SpringerBriefs in Earth Sciences, Springer. ISBN: 978-3-319-00259-0 (print), 978-3-319-00260-6 (online). DOI: 10.1007/978-3-319-00260-6.

Lake, LW, Johns, RT, Pope, GA, and **Rossen, WR** (2014). *Fundamentals of Enhanced Oil Recovery.* Society of Petroleum Engineers, Richardson, TX, USA. ISBN:978-1-61399-328-6.

**Figure 15** Key societal output.

# 5 Viability

## 5.1 Positioning of the unit Geo-Resources within the international research community

The top-ranked university research programmes in petroleum engineering include The University of Texas at Austin, Stanford University, Texas A&M University (USA), Imperial College (UK), and the University of Bergen (Norway). All of these universities fund their research with a mix of industrial support and government funding. In our opinion, our programme competes with the strongest of these programmes, especially in pore- and core-scale displacement processes (experiments and modelling) and CLRM. With our two new staff in numerical methods as of 2015, we expect to come into prominence as a centre of reservoir-simulation research. With a much-smaller staff than most of the programmes mentioned above, we focus on fewer topics than those programmes, specifically topics at the interface of geosciences and engineering, as noted in our mission.

The top ranked university research programmes in mining engineering include Colorado School of Mines (USA), Queens University (Canada), University of British Columbia (Canada), University of Queensland, and University of New South Wales (Australia). These universities generate funding from industry and government. The Resource Engineering programme is competitive with these programmes. Because of the relatively small size and new/developmental status of the group, we specifically focus on addressing integrated themes related to resource characterisation, resource definition and mine-planning optimisation. By means of this specialisation, we avoid direct competition with "traditional" mining schools and thereby create a valuable niche that is strongly supported by multi-partner industry and EU funding.

Our programme in Geothermal Engineering is newly started (2013) and still relatively small. We benefit from the prominence of Prof. Bruhn and the connections of Prof. Bruhn to the larger Geothermal Engineering research community. Thus we enjoy greater prominence than a programme of this size and short history would normally enjoy.

## 5.2 Benchmarking with Imperial College

The group at Imperial College that corresponds to our Petroleum Engineering programme (themes 1 and 2) is the Petroleum Engineering and Rock Mechanics (PERM) group, led by Prof. Peter King. The research interests of that group (pore-level processes, core-level study of oil displacement and EOR, and field-scale simulation) are similar to ours. The PERM group is larger than our Petroleum Engineering Section, even after excluding staff focusing on rock mechanics, which at TU Delft resides in the Geophysics and Geology units. The PERM programme is very well funded by industry at the moment, especially by Shell, Qatar Petroleum and Total.

The international reputation of the programme at Imperial College is comparable to ours, but perhaps a bit higher overall. In the specialties in which we focus, especially smart fields and chemical EOR, TU Delft excels the programme at Imperial College.

The PERM group follows the “PI model” described in Chapter 2.2 above, with individual staff allowed to follow their own research interests. New staff are hired primarily for overall quality and potential, not research specialty. Informally, Prof. King and other staff try to develop collaborative research projects among the staff. We are introducing informal presentations into our weekly staff meetings this fall to keep ourselves more up to date on each other’s research and plans, and thereby encourage more collaboration between staff and with other units. There is no prohibition against funding petroleum research in UK government research programmes, but, according to Prof. King, informally the assumption of review panels is often that such research doesn’t need government funding because it can be funded by industry. One can, however, craft a successful proposal to the government emphasizing the basic science behind research rather than the application. If industry funding becomes harder to obtain because of lower oil prices in the near future, we will increasingly adopt a similar strategy to increase EU and NL funding of our research.

The group at Imperial College that compares best with Resource Engineering is the Department of Earth Science and Engineering, which includes research on energy, environment, modelling and minerals. Specifically, an objective is the sustainable production of metals and earth resources and mitigating environmental impacts. Much of the focus is on aspects of coal gasification, coal-bed methane and carbon sequestration. However they have strong expertise in geostatistical modelling and simulation of geological and environmental systems and assessment of risk and uncertainty in engineering. Historically, they were represented by the Royal School of Mines; however, gradual restructuring has split the mining-specific competencies into other groups. They have a strong focus on financial and economic modelling.

At present, they have a stronger international reputation than Resource Engineering at TU Delft, but this is primarily due the relative newness of the Resource Engineering section. Going forward, the competence within Resource Engineering is expanding, in contrast to a more static scenario at Imperial College.

## 5.3 SWOT analysis

### Strengths

- Solid ties to industrial sponsors, especially Shell, and Dutch natural resource extraction companies (e.g. Tata Steel, IHC, Akzo Nobel)
- Proven ability to obtain funding from EU as a result of alignment of research themes with the strategic objectives of the EU during the H2020 programme

- Solid reputation: we are “preferred partner” of several major companies
- Strong support of alumni and industry contacts for geothermal research
- High visibility in the national geothermal sector
- Strong international ties in the geothermal research community
- Synergy between engineering and geosciences in one Department
- Stream of MSc thesis students available to conduct research as part of funded projects or to explore new, as-yet unfunded, topics

### Weaknesses

- Relatively small size of the unit will make it difficult to the grasp new funding opportunities and sustain preparation of multi-partner research proposals
- Cost structure of TU Delft which makes PhD projects more costly than, for instance, at many excellent American Universities

### Opportunities

- Production of shale gas in US, combined with possible risks with Russian-supplied gas, make government more interested in research on shale gas
- Government is also interested in research on geological risks from gas production from the Groningen field. Understanding and minimising these risks requires better science, more data, and multi-scale, multi-physics simulation models
- Declining production of oil in many fields worldwide increases interest in EOR
- Political pressure to reduce greenhouse-gas emissions increases interest in geothermal research

### Threats

- Public resistance to $CO_2$ sequestration has reduced funding for research
- Poor societal perception of resource extraction due to environmental and social impacts
- If oil price and commodity prices fall further and remain low, it may be difficult to raise industrial research funding for research in petroleum and resource engineering
- EU and NL government definitions of “energy” exclude most petroleum-related research from research programmes
- If there is no investor for the DAP, this may lead to reduced support for geothermal research within TU Delft
- Geothermal research infrastructure is not adequately funded nationally and internationally; industry support is also not strong

Our strategies to meet the weaknesses and threats are described in Chapter 2. We have been successful in raising EU and government funds for resource engineering and geothermal research. If industry support for petroleum engineering research (themes 1 and 2) decreases because of a period of low oil price, we will increase our efforts to define our research in terms of fundamental engineering science and pursue government funding.

Department
of Geoscience
& Remote Sensing

# 6
# Atmosphere

# 1 Mission

The atmosphere is of vital importance for mankind: the atmospheric composition, climate, and weather determine the environmental conditions for human life. Although global circulations determine the climate, the societal impact of the atmosphere is mostly experienced at local and regional scales. It is on these scales where the atmosphere program is focussed: the study of the atmospheric water cycle, trace gases and aerosols by developing atmospheric models, simulation tools as well as new observation methodologies. The results have to be used for improving climate models, and for increasing our ability to monitor and forecast urban air quality, extreme weather, wind and solar power.

The unit Atmosphere defined its mission as 'to perform cutting edge research and development in atmospheric modelling and remote sensing, aiming at local and regional scales.'

# 2 Strategy

## 2.1 Research strategy

The atmosphere program is rooted in two disciplines:

- Atmospheric modelling and simulation with the focus on high-resolution simulation of thermo-dynamic processes, wind, turbulence, clouds, rainfall and radiation. Key activities are *direct numerical simulations, large eddy simulations, regional modelling and developing conceptual models*.
- Atmospheric remote sensing with the focus on developing new methodologies to measure atmospheric parameters, from space or ground. Key activities are signal and data processing, the development of retrieval algorithms, sensor synergy, calibration and validation. We cover the complete chain from sensor development to information products.

**Figure 1** MULTI-GPU Simulation of clouds above Netherlands (500kmx500km @ 100m resolution).

The atmosphere program is curiosity driven, but strongly embedded in the context of social relevance. The researchers have to be intrinsically motivated by the science of atmospheric modelling and remote sensing, but with an open eye to the application domain.

Two of the main challenges the modern society faces are the consequences of *climate change* and *urbanisation*. The upward trend of emission of greenhouse gases into the atmosphere will continue to increase the global mean temperature and most likely have adverse weather-related consequences as increased extreme rainfall, droughts and heat waves. Globally, economic developments make people move towards the cities. This is leading to a strong increase in the local emission of trace gases and

aerosols, and consequently in a deteriorating *air quality*. The atmosphere program has been designed to address the following underlying research questions:

- What is the role of the atmospheric water cycle, trace gases and aerosols in the regional climate system?
- How does the emission of trace gases and aerosols affect the urban air quality?
- How can we improve our ability to forecast the weather and radiation on local scales?

While in the past modelling and observational activities have, more or less, independently developed in different departments of the university, we now start to benefit from a synergetic approach by:

- Improving the representation of processes and parametrisations in atmospheric models based on the observations;
- Using the observations for process studies, (quasi)real time evaluation and validation of model predictions or forecasts;
- Data assimilation in high-resolution (urban scale) forecast models;
- Improving methodologies for the interpretation of the ground-based and satellite observations;
- Developing new observation/sensor methodologies.

Our long-term challenge in the application domain is the development of high-resolution weather and air quality forecast systems for water management, wind and solar energy plants as well as (extreme) rainfall.

The advanced CESAR Observatory in Cabauw will be used as research and development site. We will use the city of Rotterdam as a field laboratory and showcase of results. More opportunities for implementation of results can be found within the framework of the Advanced Metropolitan Solution Institute (situated in Amsterdam), recently founded by the universities of Delft and Wageningen and MIT.

Key to the atmosphere program is observational and computational infrastructure:

- The world-class CESAR Observatory in Cabauw (www.cesar-observatory.nl, PI: prof. Russchenberg) is widely recognised as one of the most advanced sites for atmospheric studies. TU Delft owns and operates the high-resolution radar systems IDRA and TAR A.
- The OMI satellite instrument (PI: prof. Levelt) and the new TROPOMI instrument (PI: Veefkind, to be launched in 2016) gives detailed information on global trends in regional and global air quality and climate related issues.
- The Rotterdam testbed, including a network of weather stations, high-resolution rainfall radar and in situ sensors, and remote sensing sensors for air quality is under development.
- The PARSAX S-band radar at the campus of TU Delft.
- The KNMI Parameterisation Test Bed. Results of a variety of numerical models, ranging from GPU-accelerated large-eddy simulations, limited area models and single-column model versions are compared continuously with in-situ data as obtained from the CESAR Observatory.

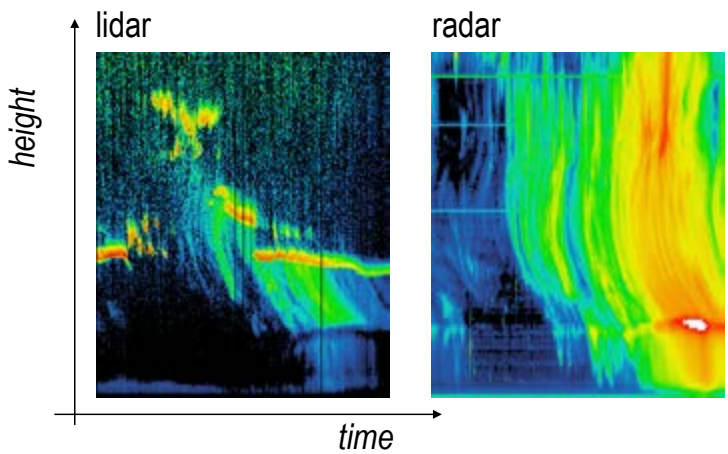



**Figure 2** Observation of light rain with different instruments.

## 2.2 Personnel strategy

### Review period

The two research groups 'atmospheric remote sensing' and 'clouds and climate', initially located at different faculties, took the initiative to join forces to strengthen atmospheric research. The university's reorganisation of 2012 opened a good opportunity to realise this by moving to the Faculty of Civil Engineering and Geosciences and setup the current atmosphere program, and to get tighter connections with the earth science and water-research groups of TU Delft.

Being independent groups at the time, there was no common personnel strategy before 2012. Also, the chemical atmospheric domain, based on part time personnel since 2011, was only recently strengthened with the tenure track position of Vlemmix, since 2012. Prof. Hoogeboom's appointment was renewed in 2014.

### Coming period (2015-2020)

We aim at achieving a mix of experienced tenured and non-tenured staff with excellent academic records, post-docs and PhD students for the different themes with high scientific potential. For the tenured positions we comply with the personnel policy of the Faculty which aims at a good balance between scientific quality, teaching, valorisation and organisation. We also strive towards collaboration with external partners via part-time positions, most notably with the Royal Netherlands Meteorological Institute.

Figure 3 depicts the development in personnel during the review period.

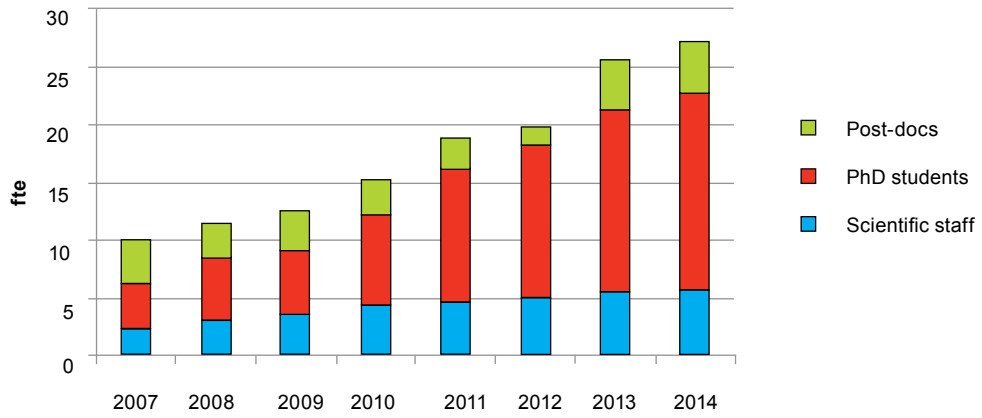



**Figure 3** Personnel during the review period.

In 2015 Prof. Harm Jonker will reduce his appointment at the university from full-time to 0.2 fte to start a spin-out company in high-resolution forecasting for wind and solar energy generation. Dr Yann Dufournet will leave academia to explore the possibilities to commercialise rainfall forecasts. In 2015 Dr Van de Wiel will strengthen the atmosphere unit. He has acquired an ERC Consolidator Grant to investigate the collapse of turbulence in the stable boundary layer. In line with the aim for quality and coherency in the research program, we will open

- a tenure track position in the field of atmospheric radar remote sensing,
- and aim at a position for full professor in atmospheric modelling of thermo-dynamic processes including the interaction with aerosols.

Furthermore, we are in the process of strengthening collaboration with KNMI and commence a long-term commitment: KNMI and TUD will both allocate additional staff and resources to well-defined goals of common interest. We have identified four themes:

- high resolution atmospheric modelling
- model-observation infrastructures
- geo-seismics (cf. Geophysics programme)
- atmospheric chemistry

TUD and KNMI will commit themselves to long-term collaboration with an period of at least ten years in these areas. Not only does this collaboration aim at strengthening external collaboration, but also at the internal synergy between the Geo-departments of the Faculty, as well as with the hydrological departments.

## 2.3 Funding Strategy

### Review period

Atmospheric research is of multi-disciplinary nature. International scientific networks are therefore very important Collaboration has been one of the focal points of the funding strategy:

- Initiate and participate in international networks and programs. Successful examples are ACTRIS, ITARS, EUCLIPSE, OMI, and Raingain.
- Participate in national programs, like Knowledge for Climate.
- Such programs are usually more than purely science driven (educational or socio-economic requirements also need to be fulfilled). We have therefore also given priority to acquisition of PhD or post-doc projects from NWO with a strong scientific focus.

Figure 4 depicts the funding of our unit during the review period.

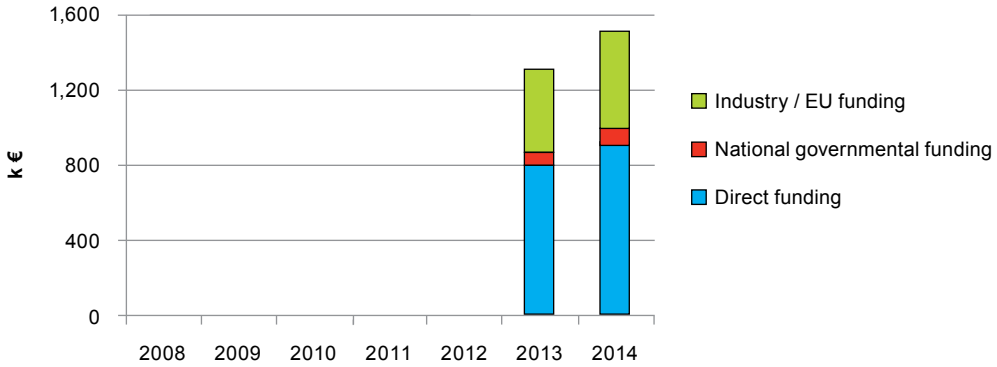



**Figure 4** Research funding during the review period (2013 and 2014 only).

### Coming period (2015-2020)

In the vision of the Dutch government scientific research should be closer connected to societal and industrial needs than it was in the past. This will affect the allocation of governmental resources and require a change of strategy to acquire sufficient funding. We adopt the following strategy:

- Set the research agenda of national and international funding agencies by initiating ideas for new programs, attend relevant committees, actively approaching the relevant ministries, companies and agencies.
- Continue the pursuit for (inter)national funding by NWO, NSO, ERC and Marie Curie (as of sept 1st 2015 Bas van de Wiel has joined our unit with an ERC grant).
- Join and/or initiate international consortia for Horizon 2020 and ESA programs.
- Join and/or initiate (inter)national consortia for infrastructure programs like ESFRI, the National Roadmap for Large Scale Infrastructure and NWO-Large. (pursued in 2015 for ESFRI).
- Initiate the formation of a national public-private fund for long term climate monitoring.
- Use the means and instruments of the TU Delft Climate Institute and DRI Infrastructure and Mobility for external communication and networking when appropriate.

With this strategy we aim at a healthy financial basis for recruiting high quality scientific staff and the operation/maintenance of the research infrastructure. Current examples of strategic planning are:

- The initiative for the Ruisdael Observatory: a nation-wide atmospheric facility for high resolution modelling and monitoring of the atmosphere. We are leading this national initiative.
- The NWO Large proposal for expanding the capabilities of the CESAR Observatory.
- Exploring the potential of the governmental Toekomstfonds (‘Future Fund’) for securing long term funding of climate monitoring.
- Setting a cloud radar calibration facility as part of the European ESFRI Infrastructure ACTRIS.

### Strategic partnerships

These scientific and societal challenges are of a multi-disciplinary nature. Hence, national and international cooperation is a necessity. We strive for strategic partnerships with selected partners, characterised by exchange of staff, mutual use of infrastructure, a joint-programmatic approach, and defined for longer terms than separate projects:

- KNMI (Royla Netherlands Meteorological Institute) on the themes earlier mentioned.
- CESAR Consortium, consisting of the universities of Delft, Utrecht and Wageningen as well as Royal Netherlands Meteorological Institute KNMI, the National Institute for Public Health and Environment RIVM, the Netherlands Energy Research Centre ECN, the Netherlands Organisation for Applied Scientific Research TNO and the European Space Agency ESA for measuring the atmosphere at CESAR Observatory.
- The European ACTRIS network for embedding the CESAR research infrastructure in long-term European programs.
- The National Center for Atmospheric Research (US) for high resolution simulation of atmospheric boundary layer processes.
- The University of Warsaw, specialised in cloud micro-physics modelling and measurements, for linking aerosol physics with our cloud dynamics simulations.
- Indian Institute for Technology Delhi for the study of climate change and air quality in non-European settings with strategic funding from the Board of the University.
- International collaboration via the satellite projects OMI and TROPOMI (amongst others ESA, NASA, EUMETSAT. ) where for both project a staff members is Principal Investigator.
- At TU Delft level: the departments of Mathematics, Computer Science and Electrical Engineering: profs. Heemink, Yarovoy, Rehdig, Eisemann for data assimiliation, radar technology, mathematical physics and data visualisation.

## 2.4 Publication strategy

### Review period

The research of the unit is primarily published in international peer-reviewed journals, conference proceedings and PhD theses (Fig. 5).

### Coming period (2015-2020)

We will continue to publish the relevant journals (most notably those published by the AMS, AGU and EGU) of our scientific domains. The PhD students will be expected to write and submit two to three manuscripts during their graduation period. While we support striving for more open access journals, we will give priority to impact above open access. This policy may be revised when the market for open access journals get more established.

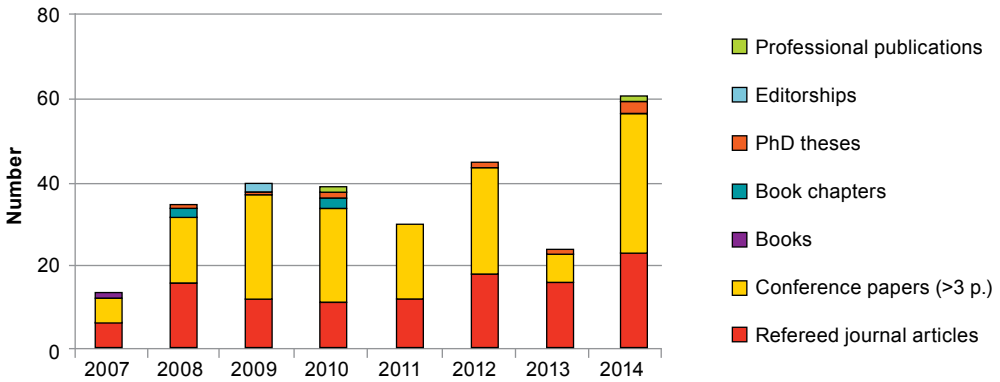



**Figure 5** Research output (number of publications) during the review period.

# 3 Research results and plans

The Atmosphere program and the composition of its groups is in place since 2012. We therefore only show the results since 2012.
*Scientific staff: Herman Russchenberg (1 fte), Harm Jonker (1 fte), Pier Siebesma (0.2 fte), Pieternel Levelt (0.2 fte, since 1-9-2011), Peter Hoogeboom (0.0 fte), Stephan de Roode (1 fte), Yann Dufournet (1 fte until 2015) Tim Vlemmix (1 fte, since 1-11-2012), Pepijn Veefkind, (0,2 fte, since 1-9-2011), Christine Unal (1.0 fte).*

## 3.1 Theme 1: Clouds and climate

**Ground based-retrievals of water cloud parameters**. New techniques, using cloud radar, lidar and microwave radiometry, have been developed to measure the microphysical structure of liquid water clouds. It was shown how important a priori information is to such retrieval techniques and that representative cloud models are crucial. The techniques came out as the most accurate in a European blinds test. The technique was validated with surface radiation measurements.

**Cloud-aerosol interaction**. New approaches using the space-based MODIS and ENVISAT instruments were developed to measure aerosol and cloud properties simultaneously. Especially the effects of biomass burning in Africa on clouds off the coast from Namibia were studied. While satellites give the large-scale overview from above, most cloud-aerosol processes occur, however, at the cloud base. New techniques to measure the interaction were developed, using the ground-based instruments at CESAR Observatory. The techniques will be implemented in the European ACTRIS network.

**Mixed-phase clouds**. Mixed-phase clouds – with super-cooled liquid water layers embedded in ice clouds – are common at mid-latitudes. Detection of these liquid layers is difficult, because the droplets are very small. Only lidars have the required sensitivity, but in many cases the laser beams are blocked by cloud layers below. Indirectly, Doppler-polarimetric cloud radars have the potential to observe these layers by measuring the changes ice crystals undergo when passing through the liquid layers. It was shown that especially the Doppler-spectrum carries the information to describe ice crystal growth. In Autumn 2014 an excellent data set was collected during the ACCEPT campaign at CESAR Observatory in cooperation with TROPOS, Leipzig, and LMU, Munich.

**Clouds and Climate**. The effect of global warming on the change of subtropical low cloud amount was assessed with large-eddy simulation (LES) and single-column model (SCM) versions of climate models. Idealised experiments were carried out in which the models were run towards an equilibrium state, including a perturbed set in which the temperature of the sea surface and the atmosphere were increased by 2K. The LES results suggest a decrease in cloudiness, which will tend to amplify the down-welling radiation reaching the ground surface. The SCM results show much scatter. However, for this family of models it is found that the change in cloudiness is strongly controlled by the change in the intensity of cloud-top mixing as triggered by the increased surface forcing.

**The Grey Zone Project**. As a result of the ever increasing computer resources, more and more numerical weather and climate models are operating in the so called “Grey Zone” at horizontal resolutions in the range of 1~10 km. As these resolutions exceed the depth of the atmosphere (~10 km), they allow for numerically resolved vertical turnover behaviour. Indeed at these resolutions, clouds and convective transport are partly resolved, but this has led to the wrong perception that models operating in the grey zone might operate satisfactory without (deep) convective parameterizations. LES models are used to gain insight and understanding of model behaviour in the grey zone with and without conventional convection parameterizations, and to provide guidance and benchmarks for the design of new scale-aware convection parameterizations that can operate in the grey zone.

**Real weather** LES. Through a fruitful collaboration with the Faculty of Informatics, we recently managed to port our Large-Eddy Simulation program to run completely on Graphical Processing Units

(GPUs, e.g. Schalkwijk et al, BAMS, 2012). As a result, one can perform runs with a much longer timespan than previously feasible. This made it feasible to conduct a single, continuous Large-Eddy Simulation of actual weather conditions during the timespan of a full year. The simulation was coupled to a regional weather model in order to provide an LES dataset that is representative of the daily weather of the year 2012 around Cabauw, the Netherlands.

In this theme, we produced 3 PhD theses and 15 journal papers during the review period.

## 3.2 Theme 2: Wind and turbulence

**Wind and turbulence.** Both the variability of fall speeds and orientation angles of raindrops are affected by turbulence, with large drops being more inert than small ones. Combined Doppler and polarization radar measurements were shown to be a promising tool for the measurement of boundary layer turbulence, as both atmospheric dynamics as microphysical variability are sampled.

**Global wind fields.** Improved measurement of wind speed and direction over the oceans by use of satellite wind-scatterometry. Extreme situations (high windspeeds) can be covered with better radar models and the additional use of cross polarised radardata. Research is ongoing with ESA-ESTEC. Turbulence-resolving forecasts on country scale. By combining 256 parallel running GPUs, it became possible to perform turbulence resolving simulations on the scale of a small country (Netherlands). This exercise presents a proof of concept of LES-based, turbulence-resolving forecasting. It was shown that LES can explicitly resolve a realistic cloud field over the Netherlands, and furthermore, that meso-scale effects like sea-breezes are also well represented.

In this theme, we produced 6 journal papers during the review period.

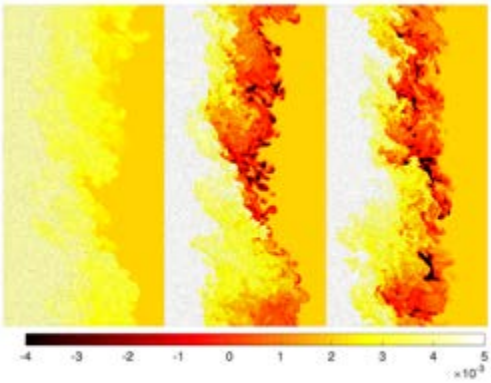



**Figure 6** Snapshot of buoyancy field for simulations ML5-ML7 after 11 seconds.

## 3.3 Theme 3: Rain

**Rainfall microphysics and estimation**. The parameterization of the raindrop size distribution is key to accurate rainfall retrievals with radar. Using the unique three-antenna beam radar system TARA new techniques were developed to measure the distribution. Combination with polarimetric measurements enables the observation of raindrop shapes as well. A unique dataset was collected during the HYMEX campaign in France (2013). The high-resolution X-band radar system at CESAR Observatory was compared with the standard operational weather radars of KNMI. It was found that operational weather radars are not suited for urban applications. Their coarse resolution makes them 'miss' the extremes, which leads to sub-optimal urban water management. Also the occurrence of intense cores in squall lines were studied and found to resemble the features of (much larger) super cells. This can be used in early warning system to detect the development of extremes in an early stage.

**Extreme Precipitation**. Events of convective extreme precipitation are highly disruptive to society and are likely to intensify with global warming. With increasing temperatures, the moisture-holding

capacity of the atmosphere increases. Therefore, when sufficient moisture is available, precipitation extremes are expected to be thermodynamically related to surface temperature. Analysis of a sub-hourly dataset of rainfall rates with 10-min resolution over the Netherlands has confirmed a 14%/0C increase in the extreme rainfall events. Using a simple entraining plume model, an idealised deep convective environmental temperature profile is perturbed to analyse extreme precipitation scaling from a frequently used relation based on the column condensation rate. It is discussed that atmospheric stability changes, which are expected to be dependent on the latitude, may well play a key role in the behaviour of precipitation extremes in the future climate.

In this theme, we produced 6 journal papers during the review period.

## 3.4 Theme 4: Fundamental development of model and technology

**Model Quality Verification.** The coarse spatial resolution used in weather forecast and climate models requires the parameterization of the (boundary-layer) cloud fraction and the effect of clouds on the vertical turbulent transport of heat, moisture and momentum. Observations from aircraft and CESAR, in addition to large-eddy simulations of observed cases, are used to verify and improve the representation of boundary layer clouds in large-scale models (intercomparison studies such as ASTEX, CGILS, phase space experiments, entrainment of vertical velocity).

**Radar development.** New signal processing and array antenna techniques were developed to enable flexible scanning for the observation of rapidly changing atmospheric phenomena, like extreme storms.

**Small scale turbulent flows.** The behaviour of small droplets in turbulent flows has been modelled, taking into account inertial and sedimenting effects. This leads to a better understanding of rainfall formation.

In this theme, we produced 2 PhD theses and 12 journal papers during the review period.

## 3.5 Theme 5: Air quality

**Atmospheric Composition satellite based retrievals**: The OMI NO2 product has been validated and future improvements have been developed. The validation has focussed on the stratospheric column, which is an essential step in the operational NO2 retrieval. The stratospheric column was compared to observations of NO2 profiles from satellite limb sounders. This work led to improvements in the OMI operational NO2 code. Further NO2 product improvements focusses on corrections for the presence of aerosols, which often spatially co-vary with NO2 due to the underlying common emission sources. The effect of aerosols is especially large in urban emission regions. A new technique was developed to derive NO2 profiles from data above clouds. The results show that there are significant discrepancies with NO2 profiles from current state-of-the-art models, possibly due to errors in the convection in the models.

**Emission calculations based on Atmospheric Satellite Data**: Emission calculations based on OMI satellite data using the DESCO algorithm developed by KNMI were performed for the Youth Olympic Games held in Nanjing in China in 2014. Several model improvements were implemented in the DESCO algorithm, which is a Kalman filter based inversion model. First tests on emission calculations above Europe were performed.

**Figure 7** TROPOMI ( courtesy Dutch Space).

**Atmospheric composition ground based retrievals and validation**: comparison of ground based measurements of tropospheric nitrogen dioxide using the DOAS technique and determination of the limitations of this retrieval technique for vertical profile information. Next step is to create in Rotterdam area a new testbed centre for nitrogen dioxide measurements, using the existing in-situ network and dedicated remote sensing ground based instrumentation. This testbed will also be used to study air quality in that area, and investigate the spatial, vertical and time dependencies of in-situ, ground based remote sensing and satellite retrievals.

In this theme, we produced 13 journal papers during the review period.

**Schalkwijk**, J, Griffith, EJ, Post, FH & **Jonker, HJJ** (2012). High performance simulations of turbulent clouds on a desktop pc. *Bulletin of The American Meteorological Society*, 93(3), 307-314.

**Veefkind, JP,** Aben, I, McMullan, K, Forster, H, Vries, J de, Otter, G, Claas, J., Eskes, H.J., Haan, J.F de, Kleipool, Q., Weele, M van, Hasekamp, O., Hoogeveen, R., Landgraf, J, Snel, R., Tol, P., Ingmann, P., Voors, R., Kruizinga, B., Vink, R, Visser, HC & **Levelt, P.F.** (2012). TROPOMI on the ESA Sentinel-5 Precursor: A GMES mission for global observations of the atmospheric composition for climate, air quality and ozone layer applications. *Remote Sensing of Environment: an interdisciplinary journal*, 120(Special Issue), 70-83.

**Dussen, JJ van der, Roode, SR de & Siebesma, AP** (2013). Factors Controlling Rapid Stratocumulus Cloud Thinning. *Journal of the Atmospheric Sciences*, 71(2), 655-665.

**Anitori, L**, Maleki, A, Otten, M, Baraniuk, RG & **Hoogeboom, P** (2013). Design and analysis of compressed sensing radar detectors. *IEEE Transactions on Signal Processing*, 61(4), 813-827.

Ducrocq, V., **Dufournet, Y** et al (2014). HYMEX-SOPI The Field Campaign Dedicated to Heavy Precipitation and Flash Flooding in the Northwestern Mediterranean. *Bulletin of The American Meteorological Society*, 95(7), 1083-1102.

**Figure 8** Key publications.

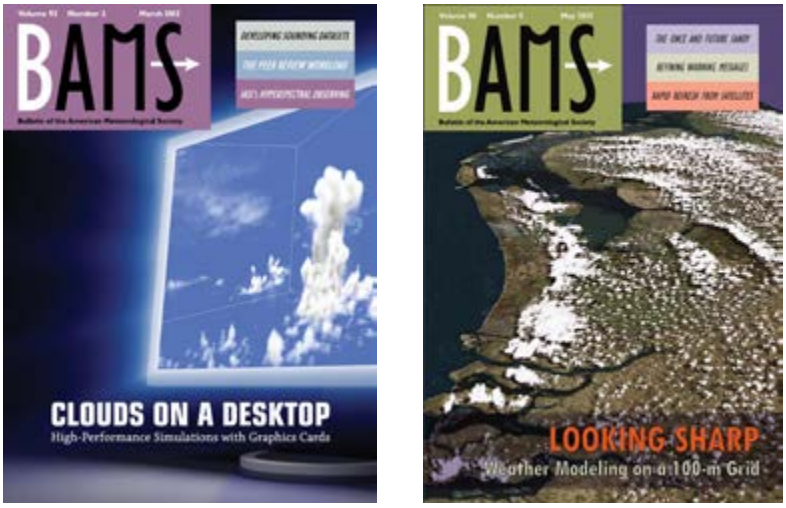



**Figure 9** Research output (Bulletin of the American Meteorological Society).

## 3.6 Summary of research quality

This unit originated from two other faculties. Within these faculties they were assessed during this assessment period. Jonker's group was assessed, as integral part of the MSP programme, over the period 2004 – 2009, with a site visit in 2011. In March 2012 they received the following marks: Quality: 4; Productivity: 4; Relevance: 4; Viability: 4. Russchenberg's groups was assessed as part of the Electrical Engineering assessment (2005-2010).( Radar and Remote Sensing Programme). In December 2012 they received the following marks: Quality: 4; Productivity: 4; Relevance: 5; Viability: 4.

### Research products

The number of peer-reviewed articles have steadily increased from 5 to 20 per year. The data collected with the radars at CESAR Observatory has been made publicly available Software for real-time LES is in the open source domain.

### Use of research products

We publish in the journals for fundamental and applied research. The papers are on average well received. The Scopus-based Hirsch indices of the tenured staff members vary between 10 and 27.

The data of the in-house designed IDRA rainfall radar at CESAR Observatory is archived in the 3TU Data Centre. It is one of the few high-resolution rainfall radar systems in the world. The data is used by groups in The Netherlands, France and the United Kingdom to simulate the impact of extreme rainfall events on urban environments. The CESAR data is used within the ITARS and ACTRIS network. The IDRA data is also used by the KNMI for the study to improve forecasts of extremes in squall lines. The data of the TARA radar system obtained during the HYMEX and ACCEPT campaigns is used by groups in Germany and France to study the processes in mixed-phase clouds. In particular the high level of detail that our radars achieve raise interest in the community.

The Large Eddy Simulation (LES) software tools have been installed at the Indian Institute of Technology in Delhi to simulate cloud formation, and in a later stage, the dispersion of air quality. Note that the LES model has been made publicly available (http://www.knmi.nl/~siebesma/LES/) and can be freely used. The real-time aspects of the models in combination with the long-term observations at CESAR Observatory enable a thorough evaluation of model performance. This philosophy, which originated at TUD and KNMI, is now finding its way in the US and elsewhere in Europe.

Supported by the transnational access program of ACTRIS European scientists visit CESAR Observatory to make use of the radar systems there in combination with their own and other available equipment.

Satellite data are obtained via the regular satellite data portals and from KNMI processing systems, most notably for OMI data. Ground based data used are from KNMI owned mini-MaxDoas systems, or obtained from validation campaigns KNMI lead or participated in.

### Marks of recognition from academic peers

Our staff has a strong reputation in the scientific community. Prof. Jonker was awarded the "*NWO/ SARA Wim Nieuwpoort prize*" for supercomputing in the Netherlands. In addition he holds an *affiliate scientist* position at the National Center for Atmospheric Research, Boulder (CO), US. The staff members are regularly invited for key note presentations are guest lectures, serve on international program and advisory committees. Prof Levelt is member of the International Ozone Commission and chair of the international OMI Science Team. Dr Veefkind is PI of the TROPOMI mission. Prof. Siebesma is member of the GEWEX Global Atmospheric System Studies Panel. Prof. Russchenberg is chairman of the Netherlands Committee for Atmospheric Remote Sensing. Prof. Russchenberg is guest editor of the Atmospheric Chemistry and Physics journal.

The three most cited publications produced by members of the unit during the evaluation period are:

- Manney, G., Santee, M.L., Rex, M., …, M.C, **Veefkind, J.P**. …, **Levelt, P.F**. et.al. (2011). Unprecedented Arctic ozone loss in 2011. Nature, 478(7370), 469-475. (citations: 179 (Scopus)).
- Wulfmeyer, V, **Brandau, CL, Dufournet, Y & Russchenberg, HWJ** (2011). The Convective and Orographically induced Precipitation Study (COPS): the scientific strategy, the field phase and research highlights. Royal Meteorological Society. Quarterly Journal, 137(S1), 3-30. (citations: 152 (Scopus)).
- Illingworth, AJ, Hogan, RJ, O'Connor, …, **Russchenberg, HWJ**, at. al. (2007). Cloudnet continuous evalution of cloud profiles in seven operational models using ground-based observations. Bulletin of The American Meteorological Society, 88(6), 883-898. (Citations: 149 (Scopus)).

**Top-5 courses given to peers:**

- Prof. Herman Russchenberg, Courses at the ITARS Summerschool in Juelich, Germany, 2014.
- Prof. Peter Hoogeboom, SAR/ satellite workshops upon invitation with China Academy of Space Technology in Beijing, China (2015).
- Prof. dr. Pieternel Levelt, GEMS meeting, lectures on OMI and TROPOMI for PhD students and postdocs, Seoul, October 2013.
- Dr. Stephan de Roode, Summerschool(s) EUCLIPSE.
- Prof. Harm Jonker, Summerschool *Bridging the gap between atmospheric scales*. Wageningen 2012.

# 4 Relevance to society

Our modern urban society demands high standards for the quality of life. The developed world has committed itself to the long term goals of clean air, reduced greenhouse gas emissions, more sustainable energy, mitigation of climate change and adaptation against its consequences. This regularly leads to a balancing act between economic growth and environmental circumstances. Atmospheric research plays a key role here: it provides the information and knowledge for the assessment of the effectiveness of policy, adaptation and mitigation measures. Of specific relevance are:

- Long term monitoring to reveal trends of air quality and essential climate variables;
- High resolution modelling of extreme precipitation and the urban climate;
- High resolution forecasts of wind and solar radiation to optimise the integration of sustainable energy;
- Fog and wind forecasts for traffic – through the air or on the road;
- Global wind fields radar modelling for wind scatterometers to improve global forecasts.

These information demands stimulate innovation. In Europe the number of SME's – either in the sensor industry, or service consultancies – is increasing. They commercialise new technologies and develop decision support services for public and private institutions.
These societal developments are regarded as crucial to the research program of the atmosphere unit. We seek to play an active role here through interacting with policy makers, partnerships with public

institutions and industrial partners. Concrete examples are the Knowledge for Climate program, projects like Raingain, UFO, SHINE, OMI and TROPOMI. These projects are targeting urban climate, air safety and air quality. The consortia encompass municipalities, ministries, water boards and industry. We are also actively involved in the organisation of public symposia, climate debates and have significant media profile.

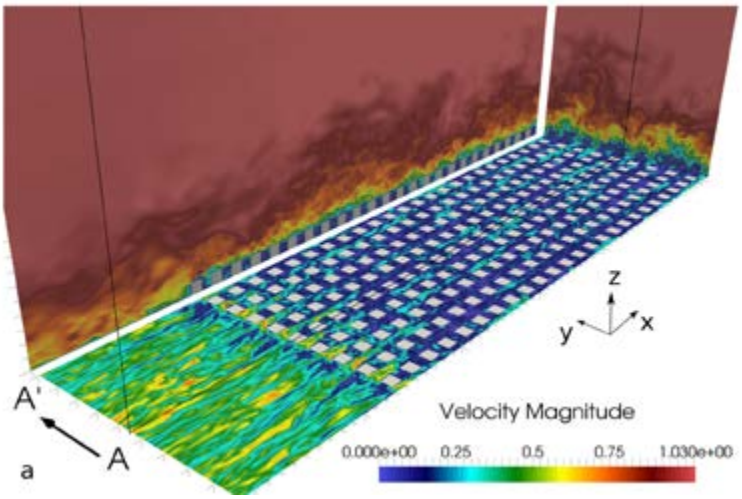



**Figure 10** Flow approaching an idealised urban geometry.

## 4.1 Projects/Consortia in cooperation with societal groups or companies

We are the leading institute of the CESAR Consortium, consisting of the universities of Delft, Utrecht and Wageningen as well as Royal Netherlands Meteorological Institute KNMI, the National Institute for Public Health and Environment RIVM, the Netherlands Energy Research Centre ECN, the Netherlands Organisation for Applied Scientific Research TNO and the European Space Agency ESA. This mix of scientific organisations and governmental agencies maximises the impact of observational work at CESAR Observatory.

The RainGain project is conducted by a European consortium of universities, municipalities and water authorities. Once a year the wider user community, consisting of public and private weather agencies, hydrologic consultancies and companies is invited to give their stakeholder's input. TU Delft is the coordinator of the project. The RainGain project is sponsored by the municipality of Rotterdam and the Province of South-Holland. They sponsor the acquisition of a high-resolution radar system to be installed in the centre of the city. With this system we will study the added-value of such system for urban water management

Two of our staff members are PI's for respectively the OMI and TROPOMI projects. In these projects both universities and space agencies as well as enterprises take part.

## 4.2 Staff with part-time position/secondment in company/societal group

We offer formal hospitality to guest scientists from the industry, implying that they get access to our facilities and get the opportunity to sharpen their scientific skills. In 2013 and 2014 we have welcomed Dr Alexander Los (Eko-power) and mr Placidi (Metasensing). On average they spend two days per month at the laboratory.

There are strong links with the KNMI with secondments of Prof. Levelt, Prof. Siebesma and Dr Veefkind. KNMI has co-financed the chair Prof. Siebesma and Dr Veefkind.
Also from TNO there was a long term secondment of Prof. Hoogeboom. TNO has co-financed the position of Prof. Hoogeboom. Prof. Hoogeboom was employed by TNO until September 2014, now under appointment by TU Delft.

## 4.3 Artefacts, datasets, software tools

The developed software tools for LES calculations enable high-resolution forecasts of wind and solar radiation. This is important to optimise the economic value of wind farms and solar power plants. In 2015 Prof Jonker started a spin-off company to commercialise the concept.

The IDRA radar serves as a prototype for urban rainfall radars. The spin-off company Metasensing (director Dr Meta, Meta's promotor: prof. Hoogeboom) plans to produce these systems for the global market. In 2015 a high resolution rainfall radar will be installed in the centre of Rotterdam. In combination with a network of weather stations and a sensor network in the water run-off system data will be collected for the optimization of urban water management procedures.

The weather station network in Delft is incorporated in the school educational programs. In this 'Waterlab' program school children learn about meteorology in practice.

By using data of the OMI satellite long term trends of air quality across the globe can be assessed: especially concerning the impact of developing economies and environmental policies. It has revealed the striking regional differences of the constituting components of air quality in Asia, Europe and the US

The results of the RainGain and the SHINE program, combining physical with social sensing, find their application in the recently started institute for urban studies AMS: Advanced Metropolitan Solutions in Amsterdam.

## 4.4 Contributions to public debate and popularisation of science

Prof. Russchenberg regularly gives public lectures as well as interviews for radio, television, and newspapers. He is also involved in the organisation of climate-oriented debates and symposia of the TU Delft Climate Institute. He is chairman of the advisory board of Climate Dialogue, a web-forum where climate scientists from all sides of the spectrum discuss 'hot' issues of climate change. Climate Dialogue is an initiative of the Dutch parliament.

Prof. Jonker has also contributed to several Dutch television, radio and newspaper interviews. One of the highlights was a full article featuring the group in the *National Geographic* (2012, Benelux version). Prof. Levelt and dr. Veefkind contributed to several Dutch television, radio and newspaper interviews. Recent highlight was TROPOMI in the NOS journal in July 2015, radioprogram "Met het oog op morgen", March 2014 on 10 years of OMI data (Levelt), and the television program "koffietijd" on TROPOMI in April 2014 (Levelt).

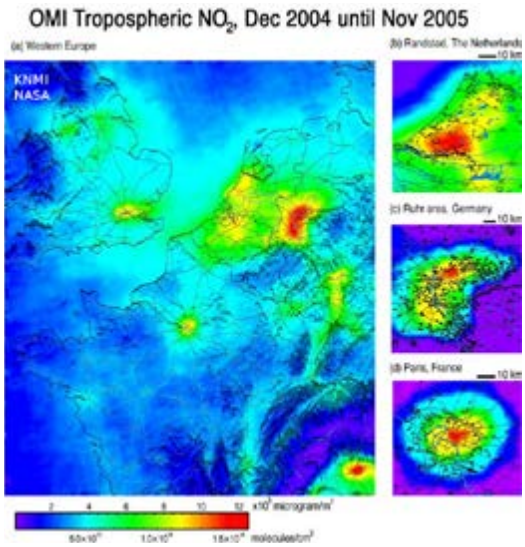



**Figure 11** $NO_2$ map of Western Europe.

## 4.5 Strategic cooperation

Apart from the cooperation within the CESAR Consortium, we also value the long-term structural collaboration with KNMI via the part-time positions of dr Veefkind and profs Siebesma and Levelt. In view of the recent shift of emphasis of the strategy of the KNMI – more research targeted at specific requests from external stakeholders at the expense of fundamental science – this strategic cooperation becomes all the more necessary.

**Russchenberg, H.**, 'Waterlab' educational program for school children Delft, to learn about meteorology in practice.

**Russchenberg, H.** regular public lectures as well as interviews for radio, television, and newspapers.

**Russchenberg, H.** Climate Dialogue, an initiative of the Dutch parliament: a web-forum where climate scientists from all sides of the spectrum discuss 'hot' issues of climate change. (Chairman of advisory board).

**Jonker, H.**, National Geographic (2012, Benelux version): full article featuring the group.

**Levelt, P. and P. Veefkind** NOS journal in July 2015, on TROPOMI, radio show Met het oog op morgen, March 2014, on 10 years of OMI data (Levelt), and the television show "Koffietijd" on TROPOMI in April 2014 (Levelt).

**Figure 12** Key societal output.

# 5 Viability

## 5.1 National and international position of unit Atmosphere

In the Netherlands the universities of Utrecht and Wageningen also perform atmospheric research. In Utrecht the emphasis is put on fundamental atmospheric chemistry and the development of in situ measurement technology. This is complementary to the satellite-based approach of our program. The research program of Wageningen University focusses on boundary layer meteorology and air quality. While there are strong common grounds in the methodologies used, our program distinguishes itself through the emphasis on the cloud-climate feedback as well as the development of new techniques – computational and observational. Together with our strategic partnership with KNMI, this triangle of national universities offers many opportunities for joint programs. Examples are the NWO Large program for CESAR Observatory, the new initiative for the Ruisdael Observatory and the urban rainfall programs in Rotterdam and Amsterdam.

The available expertise of real-time LES modelling and the observational capacity of CESAR Observatory has put the atmospheric unit in a leading position through the demonstration of the added value of real time model-observation comparisons. This gives the atmospheric unit a strong position in the international arena. Cooperation is in place in the framework of the long–term European ACTRIS (ESFRI) program and the US ARM program.

## 5.2 Benchmarking with MIT

In May 2015 we visited MIT institute of earth and atmospheric sciences in Boston to get a better understanding of the scientific 'culture'. The emphasis of the visit was mainly put on organisational matters: selection of staff, expectations, evaluations, programmatic strategy, balance between research, education and other duties etc. Our main goal was to learn how we can improve the quality of our own laboratory. While in our system we seek to achieve quality through programmatic planning and selection, at MIT this notion is far less prominent. Heavy weight is put on the selection procedure to hire the best people. Once selected, the culture and corresponding quality control is mostly based on trust

and confidence that the 'best people will do the best work'. Programmatic steering is mostly absent. The work floor culture is one of seminars and open academic debates. This is currently less prominent in our system. We tend to focus our work and attention within a narrower field of view and communicate less outside our domain. The MIT culture has several appealing facets: we will explore how to incorporate these in our culture.

## 5.3 SWOT analysis

### Strengths:

- The multi-disciplinary expertise, ranging from fundamental atmospheric sciences to electromagnetic theory, system design, data analysis, and information products makes the program almost unique in Europe.
- Expertise of atmospheric models ranging from Direct Numerical Simulation, Large-Eddy Simulation and Limited Area Weather Forecast Models.
- Expertise in massive supercomputing and GPU-computing.
- Excellent and extended national and international network, industrial and scientific; visibility due to the large societal importance.
- Excellent experimental facilities.
- Scientific leadership, as is evident from our role in European programs

### Weaknesses:

- Small number of full-time permanent researchers
- Maintenance of the experimental facilities puts pressure on available resources.

### Opportunities:

- The TU Delft Climate Institute opens many ways to put atmospheric science in a broader and tighter context on campus.
- The strategic partnership with KNMI offers additional opportunities for external funding, and to fulfill the requirements for our ambitions.
- Pursue opportunities that arise from more connectivity with the water-oriented departments of the Faculty.
- The new MSc program Environmental Science and Engineering (starting 2016) will educate more students in atmospheric sciences
- The spin-off company of Prof. Jonker creates good opportunities for industrial outreach.
- Strong cooperation with the microwave technology group at the Electrical Engineering, Mathematics and Computer Science department for new and existing radar instruments.
- Strong cooperation with the mathematics and computer science groups at TU Delft for data assimilation, social sensing, modelling and visualisation.

### Threats:

- Declining governmental funds for science and engineering will lead to more time spent on acquisition and less on science.
- The large number of flexible contracts threatens continuation of key-knowledge.

# List of Abbreviations

| | |
|---|---|
| **2D** | two-dimensional |
| **3D** | three-dimensional |
| **AAPG** | American Association of Petroleum Geologists |
| **AGU** | American Geophysical Union |
| **ALERT** | Alliance of Laboratories in Europe for Research and Technology |
| **ALW** | NWO Earth and Life Sciences division |
| **A-PPP** | Array-aided Precise Point Positioning |
| **BDS** | Chinese BeiDou system (GNSS) |
| **BP** | British Petrol |
| **BSc** | Bachelor of Science |
| **CATO** | Research programme on $CO_2$ capture, transport, and storage in the Netherlands |
| **CEG** | Faculty of Civil Engineering and Geosciences of TU Delft |
| **CESAR** | Cabauw Experimental Site for Atmospheric Research |
| **CLRM** | Closed-Loop Reservoir Management |
| **COB** | Netherlands Center for Underground Construction |
| **COVRA** | Dutch Central Organisation for Radioactive Waste |
| **CPT** | Core Penetration Test |
| **CSEM** | controlled-source electromagnetic |
| **CT** | Computed Tomography |
| **CTG** | Research School Centre for Technical Geoscience |
| **CUR** | Guideline committee (Civieltechnisch Centrum Uitvoering Research en Regelgeving) |
| **DAP** | Delft Geothermal Project (Delft Aardwarmte Project) |
| **DARSim** | Delft Enhanced Reservoir Simulation |
| **Deltares** | Dutch institute for delta technology |
| **DGM** | Delft Gravity Model |
| **DMT** | Delft Mass Transport |
| **DPGA** | Dutch Permanent GNSS Array |
| **E&P** | Exploration & Production |
| **EAGE** | European Association of Geoscientists and Engineers |
| **EBN** | Energie Beheer Nederland (Dutch Gas) |
| **EC** | European Commission |
| **ECBM** | enhanced coalbed methane |
| **ECN** | Netherlands Energy Research Centre |
| **EGU** | European Geophysical Union |
| **EGU** | European Geosciences Union |
| **EM** | electromagnetic |
| **EOR** | Enhanced Oil Recovery |
| **ESA** | European Space Agency |
| **ESA** | European Space Agency |
| **ETH** | Swiss Federal Institute of Technology (Eidgenössische Technische Hochschule), Zürich, Switzerland |
| **EU** | European Union (and its various funding schemes) |
| **FEM** | Finite Element Method |
| **FOM** | Foundation for Fundamental Research on Matter (Physics division of NWO) |
| **FP** | Framework programme of the EU |
| **fte** | full time job equivalent (w.r.t. 38 hours per week) |
| **GFZ** | German Research Centre for Geosciences |
| **GNSS** | Global Navigation Satellite Systems |
| **GPR** | Ground penetrating radar |
| **GrIS** | Greenland Ice Sheet |
| **GRS** | Department of Geoscience and Remote Sensing |
| **GS** | Graduate School of TU Delft |
| **GSE** | Department of Geoscience and Engineering |
| **GTI** | Large Technological Institute |
| **H2020** | Horizon 2020 programme of the EU |
| **HR** | Human resource (management) |

| | |
|---|---|
| **IC** | Imperial College, London (UK) |
| **ICDP** | International Continental Scientific Drilling Program |
| **IDRA** | IRCTR Drizzle Radar (x band) |
| **IFP** | IFP Énergies nouvelles, former Institut Français du Pétrole (France) |
| **IMPA** | Instituto Nacional de Matemática Pura e Aplicada, Rio de Janeiro, Brazil |
| **InSAR** | Interferometric SAR (Synthetic-aperture radar) |
| **IOR** | Improved Oil Recovery |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **ISAPP** | Integrated System Approach Petroleum Production programme |
| **ISES** | Netherlands Research Centre for Integrated Solid Earth Science |
| **ISO** | International Organisation for Standardisation |
| **ISSMGE** | International Society for Soil Mechanics and Geotechnical Engineering |
| **ITN** | International Training Network (funding scheme of the EU) |
| **k** | kilo, thousand |
| **KIVI** | The Royal Institute of Engineers in the Netherlands (Koninklijk Instituut Van Ingenieurs) |
| **KIWA** | Netherlands Waterworks' Testing and Research Institute |
| **KNAW** | Royal Netherlands Academy of Arts and Sciences |
| **KNGMG** | Royal Dutch Geological and Mining Society |
| **KNMI** | Royal Netherlands Meteorological Institute (Koninklijk Nederlands Meteorologisch Instituut) |
| **LAMBDA** | Least-squares AMBiguity Decorrelation Adjustment method |
| **LES** | Large-Eddy Simulation |
| **LOFAR** | Research programme on Low Frequency Array |
| **m** | million |
| **MIT** | Massachusetts Institute of Technology (USA) |
| **MRI** | Magnetic Resonance Imaging |
| **MSc** | Master of Science |
| **NAC** | Dutch Earth Sciences congress (Nederlands Aardwetenschappelijk Congres) |
| **NAM** | Nederlandse Aardolie Maatschappij BV |
| **NCR** | The Netherlands Centre for River Studies |
| **NEN** | Nederlands Normalisatie-instituut |
| **NIOO-KNAW** | Netherlands Institute of Ecology |
| **NIOZ** | Royal Netherlands Institute for Sea Research |
| **NMR** | Nuclear Magnetic Resonance |
| **NUFFIC** | Expertise and service centre for internationalisation in Dutch education |
| **NVAO** | Dutch-Flemish Organisation for Accreditation in Higher Education (Nederlands-Vlaamse Accreditatieorganisatie) |
| **NWO** | Netherlands Organisation for Scientific Research |
| **NWO-ALW** | NWO Earth and Life Sciences division |
| **NWO-WOTRO** | Global development division of NWO |
| **OMI** | Ozone Monitoring Instrument |
| **OPERA** | Research programme of COVRA (Onderzoeksprogramma eindberging radioactief afval) |
| **PhD** | Doctor of Philosophy, doctoral degree |
| **PI** | Principle Investigator |
| **PNT** | Positioning, Navigation and Timing |
| **QZSS** | Quasi-Zenith Satellite System (GNSS) |
| **R&D** | Research and Development |
| **RF** | Recovery Factory programme |
| **RFEM** | Random Finite Element Method |
| **RIVM** | National Institute for Public Health and the Environment (Rijksinstituut voor Volksgezondheid en Milieu) |
| **RTK** | Real Time Kinematic |
| **RWS** | Directorate-General for Public Works and Water Management (Rijkswaterstaat) |
| **SAR** | Synthetic-aperture radar |
| **SBIR** | Small Business Innovation Research |

| | |
|---|---|
| **SEG** | Society of Exploration Geophysics |
| **SEP** | Standard Evaluation Protocol (for Research Evaluation in the Netherlands) |
| **SPE** | Society of Petroleum Engineers |
| **STOWA** | Foundation for Applied Water Research (Stichting Toegepast Onderzoek Waterbeheer) |
| **STW** | Dutch Technology Foundation (applied science division of NWO and the technology programme of the Ministry of Economic Affairs) |
| **TBM** | Tunnel-boring machine |
| **TC** | Technical Committee |
| **TKI** | Top consortia for Knowledge & Innovation (as part of the top sectors) |
| **TNO** | Geological Survey of the Netherlands |
| **TRL** | Technology Readiness Level |
| **UU** | Utrecht University |
| **VCE** | Variance component estimation |
| **VSL** | Dutch Metrology Institute |
| **VU** | VU University Amsterdam |
| **WRCP** | World Climate Research Programme |
| **XRF** | X-ray fluorescence |