UNCOVERING AN INVISIBLE WORLD

GEOLOGICAL SURVEY OF THE NETHERLANDS

100 YEARS OF GEOLOGICAL MAPPING

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TNO innovation for life

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"DISCOVER THE FASCINATING STORY OF THE DUTCH SUBSURFACE. OUR KNOWLEDGE ABOUT THIS HIDDEN WORLD IS UNRIVALLED."

TIRZA VAN DAALEN, DIRECTOR, GEOLOGICAL SURVEY OF THE NETHERLANDS

MAKING THE **SUBSURFACE** WORK

Tirza van Daalen

Director, Geological Survey of the Netherlands

The Geological Survey of the Netherlands, part of TNO, has a unique character and a long history. A history shaped by a varied subsurface that is suitable for many applications and has given Dutch society an abundance of resources.

The Netherlands is a flat country. On the surface, our geology is barely visible. We had to find other ways to map sturdy shallow layers to build on, discover deep reservoirs of fossil fuels, and understand worrisome land subsidence. Numerous boreholes and countless kilometres of seismic profiles are still our most important sources of information. For more than 100 years, they have enabled us to make ever-better visualisations of the subsurface.

Originally, we drew colourful paper maps using information stored the old-fashioned way: in filing cabinets. That all changed about 30 years ago, when we started digitising our data. Since then, 2D mapping has turned into 3D modelling, and our growing database has become a key resource in its own right. Data mining enables us to provide tailor-made information to an increasingly diverse group of end users. Every day, sophisticated models of the shallow and deep subsurface are used by decision makers from governments and businesses alike.

Using an arsenal of tools and models, the Geological Survey of the Netherlands is able to explain the implications of new national and global developments, such as the energy transition, for the use of the subsurface. We understand how much money can be made or saved, and how to minimise the risks involved. By making it easy for others to use our models, new opportunities are created and innovation is stimulated. With national as well as international partners and stakeholders, we are getting ready for tomorrow's questions.

The Dutch government has systematically invested in centralised, state-of-the-art expertise of the subsurface. This investment has paid off. Our country has a robust high-quality geological knowledge base. In introducing you to the captivating world below, we show how the Geological Survey of the Netherlands makes geology work in your favour.

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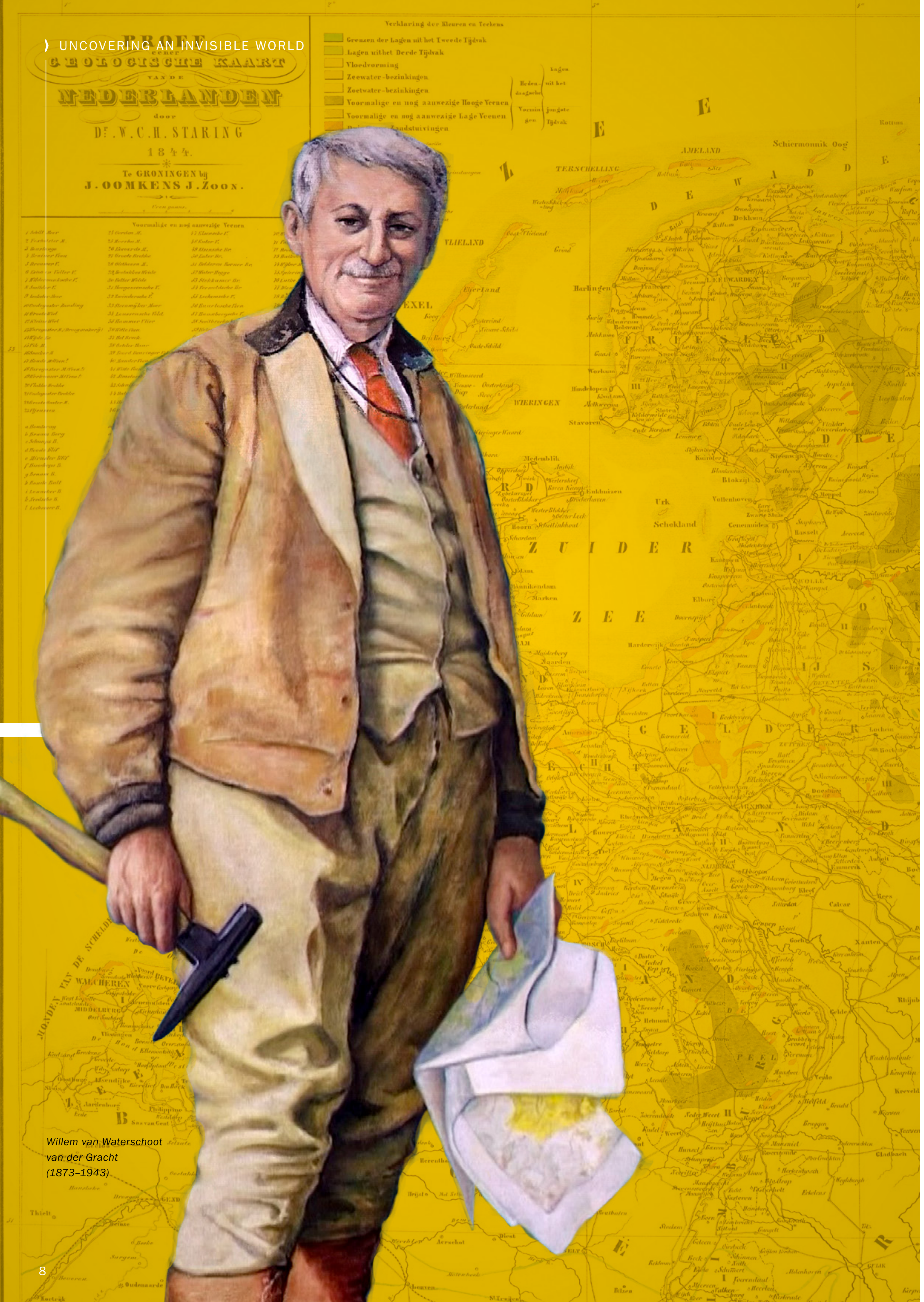


Willem van Waterschoot van der Gracht (1873–1943)

WHY A **GEOLOGICAL SURVEY** MATTERS

It is hard to imagine a world without geological surveys. The contribution of systematically collected subsurface knowledge to society's prosperity and well-being is undisputed. In the Netherlands, the foundations for geological surveying were laid in 1852. Much-needed improvements in agricultural productivity, as well as the increasing need for turf, sand, gravel and clay, prompted the mapping and characterisation of surficial layers. Winand Staring, son of a well-known Dutch poet, was tasked by Royal Decree to develop the very first geological map of the Netherlands. Starting close to his castle near the German border, Staring travelled all across the country on foot and on horseback to make observations and talk to locals. In only eight years, his surveying culminated in 28 highly detailed and remarkably accurate map sheets. They were published in 1860.

BLACK GOLD

The first geological exploration aimed specifically at the deeper subsurface was conducted between 1903 and 1916. Its aim was to find new economically extractable coal in the Netherlands. Early results were disappointing. That all changed when Willem van Waterschoot van der Gracht, patriarch of our survey, took over. His refined research and innovative interpretation of geological information led to the discovery of vast coal reserves at relatively shallow burial depths, well north of existing privately operated mines. This discovery gave a big impulse to the Dutch economy.

EVER-CHANGING ROLE

To reinforce the importance of systematic geological research in the Netherlands and ensure its permanence, Van Waterschoot van der Gracht advised the government to establish a geological survey, following the example of neighbouring countries. He was successful: the Geological Survey of the Netherlands was inaugurated in 1918. The newly established organisation was instructed to systematically store and update all subsurface data, information and knowledge, and to ensure its public availability. That mission hasn't changed. We are proud of what we have contributed these past 100 years, and eager to continue our work.

We understand better than anyone how the subsurface has made the Netherlands the thriving modern nation it is. Turf, coal, oil and gas have kept our houses heated and our industry running. An abundance of sand has ensured the safety of our coastal lowland and the stability of our infrastructure. Fertile marine clay has nourished our crops. Fresh groundwater has been instrumental to our health. But our role changes constantly. We are witnessing the transition to renewable energy and the dawn of a circular economy for raw materials. As the subsurface is starting to be used for new and innovative applications such as geothermal heat and carbon capture, the geological knowledge we have acquired through time remains incredibly useful. Not only for economical gain and environmental considerations, but also for risk management.

SYSTEMATIC AND CONSCIENTIOUS

Our methodical surveying approach – asking and answering applied questions while building up an accessible knowledge base – has been a core strength. Our independence is also a major asset. We are able to assess highly complex issues relating to the supply and demand of subsurface potential and resources, taking into account multiple stakeholders that may have conflicting interests. In this capacity, we are an important advisor to the Dutch government and society.

“AS AN **INDEPENDENT KNOWLEDGE CENTRE**, WE HAVE ALL OF THE INSTRUMENTS TO TACKLE SOCIETY’S SUBSURFACE ISSUES.”

INDISPENSIBLE ADVICE TO SOCIETY

In all subsurface-related matters, the Dutch government turns to the Geological Survey of the Netherlands for advice. To fulfil this delegated function properly, we need to be transparent and independent. Society expects us to provide clear guidance on often complex, abstract and controversial topics.

Without easily accessible geological information, the national government, provinces, regional water authorities, businesses and public at large are unable to use the subsurface safely and efficiently. Knowledge-based decision making is absolutely essential. Both the deep and the shallow subsurface are getting more and more congested, forcing us to think in terms of risk management, sustainable solutions and environmental consequences.

Our main strength is that we have the highest data density in the world. Hundreds of thousands of borehole descriptions, for example, provide information on sediment or rock type and age. Being part of TNO, the Netherlands Organisation for Applied Scientific Research, makes it easy to work across disciplines, a great asset. We are also the first geological survey to undertake systematic 3D mapping and modelling, which provides exceptional added value when it comes to solving societal issues.

THE FUTURE STARTS UNDERGROUND

The subsurface is a crucial pillar for Dutch prosperity. Deep down, we have abundant natural gas and geothermal energy. At shallower depths, there has been plenty of fresh groundwater for drinking, gardening and agriculture. Onshore and offshore, the upper tens of meters are increasingly important for construction, infrastructure, food, chemicals and raw materials. The use of these and other subsurface resources evolves continuously as environmental conditions are changing, societal interests are shifting, and regulations are being adapted. We are ready for the geological challenges that await us.

STATUTORY DUTY

The Geological Survey of the Netherlands is a designated partner of the Dutch government. Our main tasks are the careful management of subsurface data and information, the interpretation of these digital resources for applied purposes, and the dissemination of resulting knowledge and data products such as maps and models. Currently, we are building and managing the Dutch Key Registry of the Subsurface (BRO) on behalf of the Ministry of the Interior and Kingdom Relations. This core task is embedded in law. A separate section of our Survey, focussing on the deep subsurface, works exclusively for the Ministry of Economic Affairs and Climate. Given the substantial economic interests that are at stake, we handle all information with great care and, if needed, with confidentiality. During the past decade, advice on permits, oil or gas extraction, hydrocarbon reserves, storage options and subsidence has been supplemented with recommendations related to renewable energy, groundwater and safety.

The subsurface has never been as intensely used as right now. We provide knowledge-based support. How? Read on and see for yourself.

A **KINGDOM** TO SURVEY

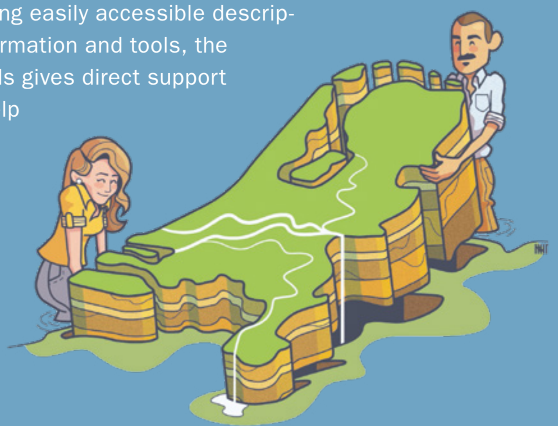
We don't limit ourselves to the 40,000 or so square kilometres of lowland bordering the North Sea. Our geological inventory and research address the entire territory of the Netherlands, including the Dutch section of Europe's continental shelf (57,000 square kilometres of the North Sea) and the Caribbean Netherlands. We focus on the upper seven kilometres of the earth's crust: the section of the subsurface that is suitable for human use.

A SEPARATE WORLD

To a lot of people, the subsurface doesn't seem to exist. Even when travelling underground, most of us are unaware of the sediments or rocks around us. As a geological survey, we help to make this fascinating world more accessible and understandable. We can explain why there are so many bumps in roads through peaty landscapes, why houses on clay are built on piles anchored in sand, and how rain provides much-needed replenishment of our heavily used groundwater system.

Collection of field data is expensive, especially for depths that cannot be hand-augered and for our tidal and marine waters. Although the Geological Survey of the Netherlands has a budget and programme for coring and for acquisition of geophysical profile data, field surveys are mainly undertaken by contractors that build houses, roads or railways, by businesses looking for raw materials, and by petroleum companies. Long ago, the Dutch government enacted legislation ensuring that this priceless information is provided to a central service, where it is stored and unlocked. This political decision has enabled the Survey to build a rapidly growing database. In doing so, we are shining a brightening light on our subsurface.

If you want to use the subsurface sustainably and safely, you need to combine subsurface data with geological expertise. In providing their cumulative know-how, our mappers and applied geologists are illuminating the complexities of modern subsurface use. Increasing concerns about safety are compelling us to bring the surface and subsurface together. By providing easily accessible descriptive, explanatory and predictive information and tools, the Geological Survey of the Netherlands gives direct support to spatial planners. Together, we help policy makers to compare scenario-based projections for different governmental plans and strategies, and to make the best choices. The applications are infinite – on the Dutch mainland, in the North Sea and in the Caribbean.



"GRADUALLY, WE ARE RAISING THE CURTAIN ON THE SUBSURFACE."

THE NORTH SEA: SPRINGBOARD FOR COOPERATION

The North Sea is a crossroads of pipelines, connecting platforms for oil and gas extraction with the mainland. This infrastructure can play a role in a successful energy transition. When adapted, it can be used for transport and storage of CO_2 captured onshore by Dutch industry. The reservoirs and pipes may also be suitable to store and transfer wind energy after its conversion into fuel such as hydrogen. Along with the ongoing establishment of offshore wind farms, this potential has made the North Sea a testing ground for the supply of sustainable energy. Our expertise on reservoir characteristics, borehole and pipeline behaviour, and the shallow seabed subsurface offers opportunities for new economic developments.

VOLCANIC HAZARD: STANDING UP FOR SAFETY

We are actively researching effects of past volcanic activity, such as earthquakes and landslides, on the islands of Saba and Sint Eustatius. In the event of a volcanic eruption, water and energy provision could be compromised. And to what extent would a harbour still be accessible? For effective measures, we need to be prepared. Extra support from the government and research-funding bodies will enable us to upscale our operations in the Dutch Caribbean, starting with the systematic assemblage, collection and management of existing and new geological data.

A BRIEF HISTORY OF THE **MINING ACT**

How do you manage the deep subsurface: its use, its resources and the associated income? How do you allocate the proceeds fairly and how can you ensure sustainability? And how do you ensure thorough public consultation and a proper balancing of interests?

In the Netherlands, all of this is established in the Mining Act, which was written under French rule in the early 19th century. Signed by Napoleon, it laid the foundation for an open and trustworthy system that encourages new initiatives to research and extract our buried natural resources. It has stimulated economic activity and growth, allowing all citizens to share in the knowledge of and revenues from the subsurface. The Dutch section of the North Sea was included in the Mining Act much later, in 1965. The name of the Act suggests that it only relates to mining. That was true for the original law. Nowadays, it has much broader coverage, following successive updates to accommodate new applied issues related to the deep subsurface.

At present, the Act stipulates that petroleum and minerals extracted at a depth of more than 100 metres (or geothermal heat from 500 metres or deeper) belong to the state. A landowner involved must grant access to the licensed operator responsible for the extraction, and the responsible minister determines the payment for all parties involved. There is a duty to share research data, following a confidentiality period to give the initial investor an advantage. After five or ten years, the data are made public. More and more, citizens and local governments are being involved in decision-making.

Because the Dutch subsurface was found to be rich in oil, gas and minerals, many seismic investigations have been conducted, and boreholes drilled, over the years. Both onshore and offshore, the density of Dutch subsurface data is unmatched. We are still benefitting from Napoleon's Act today, using it for an increasing number of applications.
To supplement the Mining Act, a new national law covering the deep as well as the shallow subsurface was recently passed. This Key Registry of the Subsurface strengthens our continued development and society's broad utilisation of easily accessible geological data and information.

BY LAW, THE GEOLOGICAL SURVEY OF THE NETHERLANDS STORES AND SAFEGUARDS PUBLIC SUBSURFACE DATA AND INFORMATION.

Thanks to our statutory basis, we have all the tools to make sure that policy development and planning for a sustainable, safe and efficient use of the subsurface are based on knowledge and facts. Because of our independence, we are also free to help the rest of Europe and particularly our neighbouring countries with subsurface-related questions and problems. Geology doesn't stop at national borders. A mountain of geological data and information shows that the Dutch subsurface is anything but two-dimensional.

"FEW COUNTRIES KNOW AS MUCH ABOUT THE SUBSURFACE AS WE DO."

SUBTLE AND EXPLOSIVE GEOLOGY IN ONE

You won't find deep fjords, high mountains or vast tundra in the Netherlands. Our European territory is mostly coastal lowland, intersected by rivers and fringed by hills. In the south, some rare exposed Carboniferous rock is more curious than relevant. As a small country with a large population, urban geology and intelligent use of space for different purposes are much more important to us. They make our work challenging and interesting. On the other side of the Atlantic Ocean, six Caribbean islands and surrounding seas are home to volcanoes and coral reefs that are a world away from ice-pushed ridges and barrier islands. They ask for different kinds of expertise.

THE NORTH SEA EXPOSED

Looking at the seabed, we see a constantly changing terrain of sand and mud beneath commonly murky waters. Nothing is ever the same. Underwater sand dunes can be moved dozens of metres a year by waves and tides. We also find drowned landscapes, remnants of past Ice Ages. Dogger Bank for example, in the far northwest, was formed some 27,000 years ago when the North Sea area was dry and a terrestrial ice sheet advanced southward one final time. It disappeared about 20,000 years later, when it was flooded by the rising sea. From a present water depth of 50 metres, Doggerland rises up to 15 metres below sea level and is around 300 kilometres long.

FIGHTING FOR SPACE IN THE DUTCH SUBSURFACE

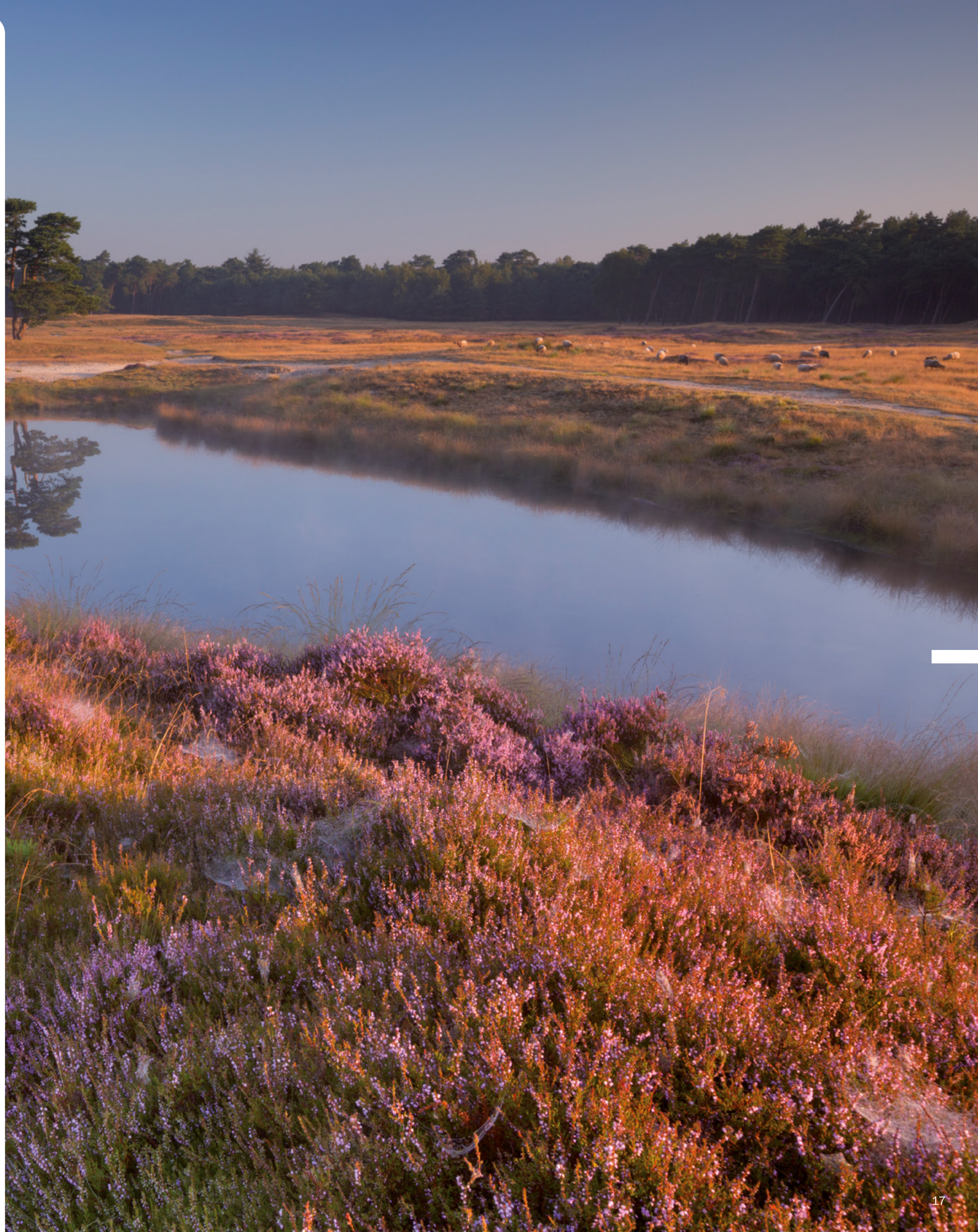
And what about the geology on the mainland? You could say that people have reshaped practically the entire upper layer of the Netherlands in one way or another. From Roman times onward, peat has been extracted and dykes have been built. Our activities have accelerated land subsidence, changed river courses, and led to the formation of an inland sea that was later converted into a freshwater lake. Homes, infrastructure, industry and agriculture all require specific subsurface properties. Natural where present, man-made if needed. Dykes and purposely heightened dunes protect an economically thriving area up to 7 metres below sea level. It is under pressure from rising sea level along our shores and from increased peak discharge in our rivers.

LUCKY THROUGH TIME

Much of our country is part of a large sedimentary basin, a slowly subsiding area that has filled up with sediment from seas, rivers and glaciers over millions of years. The prehistoric origins of the Netherlands can be seen in unevenly stacked subsurface layers. A substrate made of rock, including chalk and coal, lies at more than a kilometre depth in some areas and rises up to the surface in the extreme southeast. In much of the Netherlands, it is covered by thick layers of clay, sand and gravel. The top layer is dominated by soft clay and peat from the past 10,000 years. Because of the way the layers are structured, the Dutch subsurface has substantial reserves of oil, gas, freshwater and salt. Not every country is so lucky. In the Caribbean, the subsurface is completely different. Here, rock-solid surficial geology is adorned with two dormant volcanoes. Unlike our two deeply buried European volcanoes, they were active as little as 300 years ago.

HIDDEN HIGHS AND LOWS

Deep below the flat surface of the Netherlands, a faulted landscape of raised and depressed blocks tells a story of gradual change. Rocks deep in the earth's crust have been reorganised by faulting, folding and erosion, deformed by viscously flowing salt, and covered by young sediment. Thousands of borehole descriptions and numerous seismic profiles, acquired for oil and gas exploration, have been used to visualise these deep-subsurface structures. The resulting models of fractures and salt domes are vitally important in many respects. They help predict the flow of warm groundwater when extracting geothermal energy, for example, or the long-term stability of potential locations for underground storage. Thus, the Geological Survey of the Netherlands provides insight into abstract and complex matters influencing everyday life.



QUICKSCAN OF GEOLOGICAL HIGHLIGHTS

Despite its overall subtlety, Dutch geology has plenty to offer. From young to old and from surficial to deeply buried, the diversity is surprising. Ten highlights give you an impression.

1 At the end of the last Ice Age, riverbeds were dry much of the time, and the North Sea bed had turned into a vast polar desert. Dry sand was everywhere. It was picked up by westerly winds and redeposited as a thick blanket of coversand that still shapes the morphology in part of the country. During the Holocene, much of this sand was either flooded or sealed up by vegetation. In the Middle Ages, overgrazing by sheep destroyed the shrub and tree cover, especially in the central Netherlands. The newly exposed sand began to drift again, creating **highly mobile inland dunes**.

2 The **Dutch Water Line**, a series of water-based defences, is testament to our status as a wetland country. This 17th- and 18th-century fortification, modernised and strengthened in the 19th and 20th century used the geology to its advantage. One of the fortifications was transformed into an interactive science centre where children and adults can find out about old and new geotechnologies in a fun way, mainly focussing on maps and positioning.

3 During an exhibition in 1938 about the Dutch East Indies, today's Indonesia, an oil company wanted to demonstrate how oil wells were drilled on Sumatra. A replicate of a typical bamboo drilling rig was put into service at the exhibition site. To everyone's surprise, oil was discovered at a depth of 461 metres. A **monument in The Hague** marks this special place. Since then, many productive wells have been drilled, both onshore and offshore.

4 In 1887, rock salt was discovered at a depth of 470 metres in the northeast. People were actually searching for drinking water, to be used at a local castle. Salt has been extracted in this region ever since. **Green salt cabins** protect the valves capping boreholes. These boreholes are used to pump water down and to transport the salt, dissolved in water, back to the surface. Via a closed system, it ends up in a production facility.

5 Several megalithic structures, **prehistoric burial chambers**, can be found on top of a remarkably linear megaflute in the northeast. This elongate glacial landform, dating from the penultimate Ice Age, became the first UNESCO Geopark in the Netherlands. It is a beautiful area where Ice and Stone Ages come together.

6 Not far from the **megaflute**, oil is extracted from a specific type of sandstone present between 650 and 900 metres depth. It crops out farther east, just across the German border. The **sandstone**, fondly named 'Bentheimer Gold', was widely used as a building stone. Through time, weathering has turned gold into grey or black.

7 In a generous count, the Netherlands has four volcanoes. Remnants of two extinct volcanoes are deeply buried under the Wadden Sea and North Sea. One of them was recently named Mulciber. Two dormant volcanoes are located in the Caribbean. One of these, **Mount Scenery**, dominates the island of Saba. It offers astonishing views, but what would happen if the volcano erupted...?

8 A small, circular lake in the central Netherlands occupies one of our largest **pingo remnants**. During the peak of the last Ice Age, the Dutch subsurface was frozen. Throughout the region, earth-covered hills with growing ice cores emerged. When the permafrost melted, circular depressions remained. Now filled with water, they are home to some of the best climate records.

9 There are thousands of faults in the subsurface of the Netherlands. They extend into the North Sea. Most of them have no surficial expression, but there are some exceptions. **Knickpoints in road surfaces, cracks in walls and differences in groundwater levels and saturation give away their locations**.

10 In the southeast, along the river Meuse, it is possible to see chalk in a quarry used by the Dutch cement industry. The nearby city of Maastricht gave the last Age of the Cretaceous its name. In 1849, the Belgian geologist André Hubert Dumont described the chalk and proposed the term **Maastrichtian**. This is how a small piece of the Netherlands ended up in the internationally used geologic timescale. Its top marks the demise of the dinosaurs at the infamous Cretaceous–Paleogene boundary.

AIMING FOR **IMPACT**

As the Geological Survey of the Netherlands, we characterise the subsurface with expert knowledge from all possible earth-science disciplines. From large-scale geological structures to millimetre-level laminae, we have used our skills for more than 100 years of socio-economic benefit.

"WE'RE USING THE PAST TO ANSWER TOMORROW'S QUESTIONS."

THE KEY IS THE SUBSURFACE

When Winand Staring first mapped the subsurface of the Netherlands, he was mainly interested in surficial properties relevant to agricultural land use. From 1903 onward, the lure of potentially huge coal reserves generated a national interest in deeper layers. Our focus on characterising the deep subsurface intensified when oil and gas were found, especially after the discovery of the enormous Groningen reservoir in 1959. New techniques, in particular seismic profiling, were instrumental in localising natural resources on land and at sea. Now, sixty years later, we operate a unique database of seismic data and borehole descriptions.
Gradually, our focus is shifting from oil and gas exploration to subsurface use for the generation of geothermal energy and the storage of CO_2 as well as other substances. Much attention is being focussed on associated risk management.

A PERFECT COUPLE

The common thread running through all these developments is that, once collected, data can be used many times. The knowledge base generated by the Geological Survey of the Netherlands during its century-long history can now be used to answer new questions and tackle current societal issues. We have consistently and continuously built on our core asset: a digital, centrally stored subsurface database. By standardising it, managing it properly and enriching it with interpretations, we are ready for the future.

Aside from boosting knowledge and understanding of the Dutch subsurface, information is disseminated in the form of subsurface models. The geological maps of the past have been replaced by flexible visualisations tailored to specific end users. Thus, we are making geology accessible to decision makers from all walks of life.

We help society deal with complex issues such as the energy transition, land subsidence, landslides, induced seismicity and sustainable groundwater management. Drinking water, food and energy are daily business. We do this with and for many stakeholders, such as ministries, provinces, municipalities, regional water authorities, drinking water companies, knowledge institutes and universities.
We also work closely with the geological surveys of neighbouring nations, where similar issues are at play. The subsurface, after all, does not care about country borders.

INFORMED CITIZENS

In addition to the specific issues addressed above, we are also working on:
- Climate effects in general, and for the Caribbean Netherlands in particular. We are actively looking for organisations that want to join forces with us to map landslide risk on Saba and Sint Eustatius.
- Predicting subsidence. We already know a great deal about the causes of this vertical land loss. We now want to make the transition from monitoring and explaining to forecasting.
- Public information. More and more government agencies, civil organisations and individual citizens are coming into direct contact with subsurface issues and information, both as a result of the shift in executive responsibilities and through the availability and mandatory use of the Key Registry of the Subsurface. These parties are less familiar with our data and information than traditional stakeholders. This new user group calls for well-explained data products and new forms of dissemination targeting a wider audience.

NO **ENERGY TRANSITION** WITHOUT THE **SUBSURFACE**

Like all nations dependent on fossil fuel, our country faces a difficult task: making a smooth transition to sustainable energy. Less oil, less gas and more clean energy from sun, wind and geothermal heat. We feel a direct result of CO_2 emissions: sea-level rise.

So, what can be done? How can we reduce our dependence on oil and gas wisely? How can we ensure that alternative sources of energy are produced and extracted safely and affordably? How do we plan facilities for energy storage and production in an intensively used subsurface? What are feasible long-term scenarios? And above all: how do we secure the reliable supply of energy without outages or shortages? At the Geological Survey of the Netherlands, we are searching for answers to these questions, advising the Dutch government on the steps to be taken where and when. In providing policy makers and administrators with carefully balanced and independent guidance, we enable them to make the right knowledge-based decisions for the future of our country. The same knowledge is made available to innovative organisations and individuals that want to be at the cutting edge of the energy transition.

FROM FOSSIL PAST TO CLEANER FUTURE

Since the Groningen gas field was discovered, one of the largest reservoirs in the world, the Netherlands has been living on natural gas. Much of our energy system is tuned to it. Security of supply is guaranteed, even with sharp fluctuations in demand. The transition to sustainable energy will require a major rebuild of the system in use today. Our infrastructure for energy transport and storage will be subject to radical change. Solar, wind and geothermal energy are our main alternatives to fossil fuels. The Netherlands has no reservoirs for hydroelectricity, and the market share of nuclear power is limited. Our challenge with renewables is supply security.

We never needed to be concerned about this with gas and, earlier, coal. Unfortunately, the sustainable sources are not always producing what we need and where or when we need it. After all, the sun only shines during the day, turbines stop humming when the wind dies down, and the subsurface is not uniformly suitable for the extraction of geothermal energy. We must find ways of buffering surplus energy to cope with later peaks in demand. Whereas the capacity for storage aboveground offers only a fraction of what we need, there are feasible options for large-scale storage in the subsurface.

The potential storage capacity for excess clean energy in former gas fields, salt caverns and possibly coal mines is unique in northwest Europe. To determine their suitability for this purpose, we need to combine subsurface information and knowledge with expertise from other research fields. Along with many other organisations and together with our TNO colleagues, we are therefore looking at the system as a whole from a scope that extends beyond the subsurface of the Netherlands. By working in conjunction with our northwest-European neighbours, we make sure that no solutions and potential locations are left on the table. The energy system of the future aligns different kinds of supplementary energy generation and storage that will still include fossil fuels in the short term. It needs to be flexible to accommodate the reduction of oil and gas in the coming decades. By understanding and weighing mid- and long-term options and consequences, we can help governments make better decisions on investments and divestments pertaining to old and new energy.

WE FIND OURSELVES IN EXCEPTIONAL CIRCUMSTANCES...
Our deep subsurface offers plenty of storage capacity. Thanks to past oil and gas exploration, we have a lot of detailed information, helping us to select the best spots. Having all this information is a good thing because there is no guarantee that as much drilling and seismic prospecting will be done for renewables. In the world of sustainable energy, there is less capital for expensive surveys. As geothermal energy may be possible or desirable in places where there are no oil and gas reserves and thus few existing surveys, there are places for which detailed new data must be collected. This opportunity to fill existing data gaps will further complete our picture of the deep subsurface.

If we also look beyond the limits of traditional disciplines and country borders, we can jointly move forward and make a transition in the way data and information are put together. The oil and gas sector identifies hotspots of geothermal energy. Hydrologists look at renewable energy from a groundwater-management perspective. Geologists and engineers work closely together to facilitate CO_2 capture, H_2 production, and the storage of these gases. When it comes to solar and wind energy, a geological contribution is also necessary, not least because the required foundations and cable infrastructure are underground.

The Geological Survey of the Netherlands is uniquely qualified to look at the feasibility and impact of the energy transition from a broad perspective. Knowing the subsurface, we can quantify opportunity and risk. By combining our geoscientific knowledge with extensive experience in the energy domain, we create models and develop technological innovations for optimising designs and for accelerating the implementation of clean-energy facilities. By cooperating with transnational partners, we are in prime position to modernise the energy system in northwest Europe.

RESCUING THE **SINKING** NETHERLANDS

Large parts of the Netherlands suffer from subsidence caused by human activity. Primary causes are extraction of gas, oil, and salt, and lowering of the groundwater table to keep our feet dry and our land arable. In constructing residential areas and roads on soft ground, we accelerate compaction. In areas of the Netherlands with lots of clay and peat in the shallow subsurface, subsidence has been a problem for decades. By keeping the groundwater level artificially low, we have inadvertently created a societal problem that is expensive to mitigate.

SINKING THROUGH HUMAN IMPACT?

Which processes contribute to subsidence? What is its extent? And how can we predict the amount of subsidence yet to come? By investigating these issues together, we are better able to minimise the problem and alleviate its effects. The most important shallow-subsurface processes currently causing subsidence are the shrinkage of clay and the oxidation of peat. We are in a vicious cycle. As our land sinks, we need to follow suit by further lowering the groundwater table. Indirectly, long-term drainage of our lowland has led to sinking roads and bridges, damaged dykes and houses, and flooded fields and streets. For each plan involving the shallow subsurface, it is imperative to look critically at potential subsidence. Policy and regulations can then be aligned to avoid mistakes of the past and to foster a sustainable and safe living environment.

RAISING AWARENESS

We have extensive knowledge on the processes that cause subsidence in both the shallow and deep subsurface. By having access to a database going back a century, it is possible to link cause and effect through time. This enables us to reconstruct the changing rate of subsidence for different sinking regions. Nowadays, we measure, monitor and model subsidence to optimise our forecasting capability. Better risk analyses are just what policy makers need.

QUANTIFYING SUBSIDENCE

Many activities in and on the subsurface require a subsidence-impact assessment. Understanding and predicting subsidence is a key objective of the Geological Survey of the Netherlands. By coupling data and knowledge, shallow and deep, monitoring and modelling, we show where and how much the land is prone to subsidence, so that land management and policy can be adjusted accordingly.

OF FLOODS AND DROUGHTS

The relatively soft subsurface of the Netherlands is sensitive to changes in ground- and surface-water levels. Unsurprisingly, flooding and water shortages are important issues, impacted by changes in water systems and land use. Climate change, translated into sea-level rise and changing weather patterns, leads to more and more environmental pressures.

To ensure the continued prosperity, well-being and safety of our citizens, the government pays lots of attention to managing the coast and maintaining the dykes. Geological input in their decision making is indispensable. Dunes, dykes and other barriers protecting us from seas and rivers are inextricably linked to the subsurface.

SAND FOR SAFETY

Sea level along the Dutch coast is rising by an average of two millimetres every year. At first thought, it is nothing to be worried about. Over our lifetime, though, it becomes noticeable. Combined with more frequent and higher storm surges, peak water levels are going up. If we let nature run its course, many Dutch people would get wet feet sooner rather than later. Little by little, the coastline would shift landward. To protect the Netherlands and to limit coastal erosion, we use North Sea sand. Far from the coast, sand has been extracted from the seabed since 1990. The extracted sand is pumped or rainbowed onto beaches or into shallow nearshore waters. This governmental nourishment programme requires more than 10 million cubic metres of sand each year. The Geological Survey of the Netherlands helps to find suitable sand. By researching and mapping North Sea sediments, we localise sand reserves that can be extracted with minimal environmental impact.

DYKES UNDER PRESSURE

We are also helping with research into the soundness of dykes. Stable dykes need to be built on a strong natural foundation. The composition, particle-size distribution and permeability of the subsurface are crucial. When the water level in rivers is high, some dykes are at risk of breaching triggered from the land side. Initially small ruptures, created by excess water pressure and most common in ditches, may grow into conduits of weakened sand below a dyke in a process known as piping. The stability of dykes is further compromised from below if overall water pressure in the underlying layers increases and both the dyke and the subsurface are saturated with water. Major dry spells can also cause a failure of a dyke, if cracks grow into major fissures. We develop models predicting the stability of dykes on the basis of subsurface-related risk factors quantified from soil-mechanical analyses, probability calculations and research into sediment characteristics. Key questions include: what are the geotechnical and hydrological properties of the subsurface, and how do subsurface properties change during flooding and desiccation? Decision makers cannot do without a reliable assessment framework for these and other water-related issues. Indirectly, our citizens depend on it.

FRESH GROUNDWATER: MORE PRECIOUS THAN WE THINK

Aside from flooding and water shortages, we also work specifically on fresh groundwater. As the Geological Survey of the Netherlands, we are acutely aware that this invaluable resource is not as plentiful as most people assume. We make sure that all of our data and knowledge are converted into accessible and understandable information for the likes of water managers, drinking water companies and the agricultural sector.

SIMPLIFYING A COMPLEX SUBSURFACE WATERWORLD

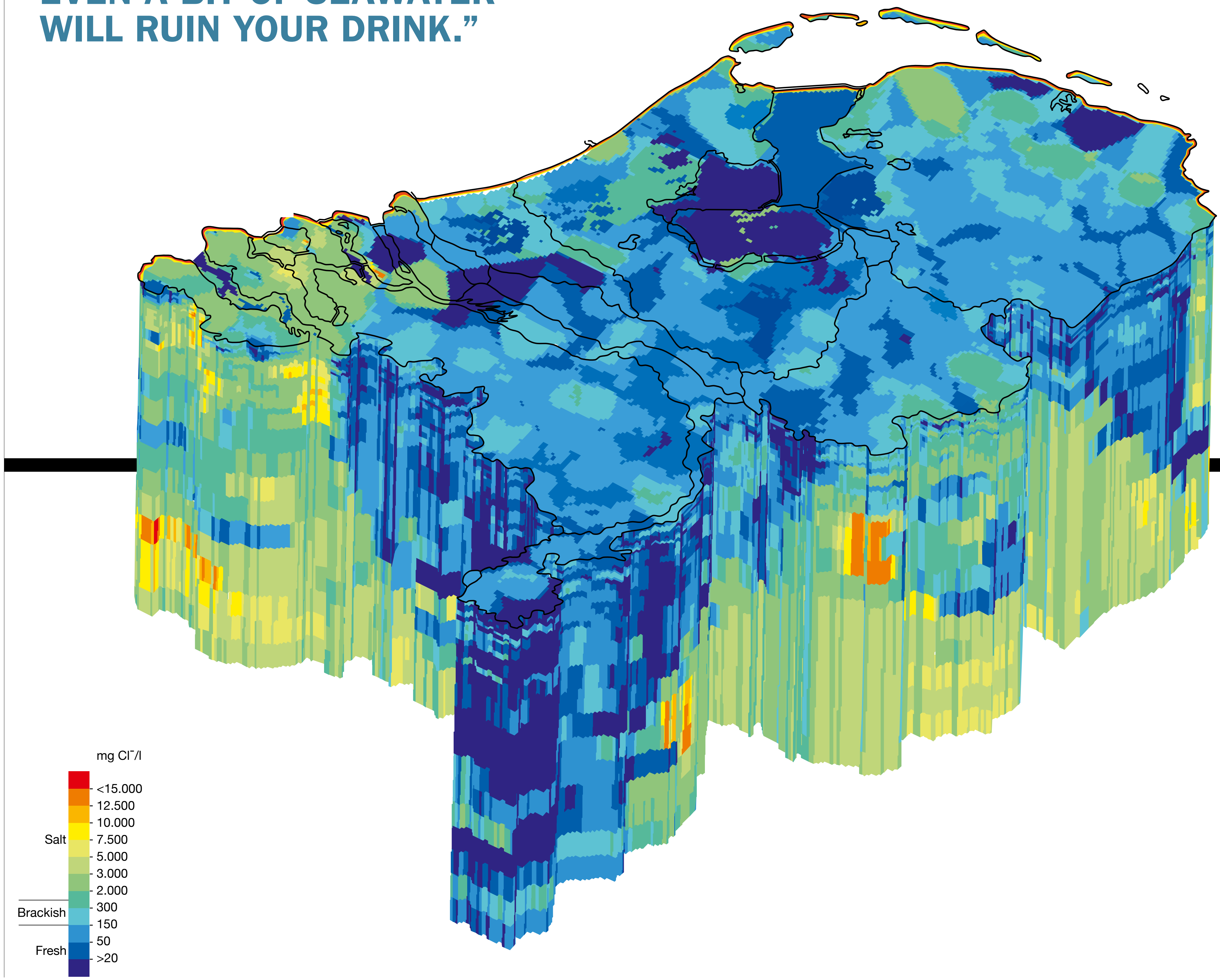
We are closely involved in all kinds of issues relating to the use and protection of fresh groundwater. This is surprisingly varied and often highly complex work. Next to obvious questions about droughts, groundwater management or agricultural and drinking-water provision, we analyse and solve problems with seepage and pollution. In addition, we use our groundwater knowledge to facilitate the energy transition and thus mitigate effects of climate change. We enter all of our groundwater data and knowledge into advanced models that have been developed over many years. The primary groundwater model of the geological Survey of the Netherlands is REGIS II, which divides our subsurface into aquifers, which are water-bearing units, and low-permeability layers.
We also map the spatially varying and temporally changing groundwater salinity. We can even do that from the air. State-of-the-art equipment mounted on helicopters enables us to measure and monitor groundwater salinity much more accurately and rapidly than before, as well as deeper below the land surface.

WATER CROSSING BORDERS

We apply our expertise globally. With our European neighbours, for example, we have been developing a cross-border hydrogeological model. This kind of project involves more than just a consistent and harmonised description of the subsurface. Common values and standards relating to the use of groundwater also play a role. The result: an international, state-of-the-art mapping initiative generating results applied in concrete transnational application matters.

Whether dealing with provinces, regional water authorities, the national government or international clients and partners, our models, analyses and expertise are used to make fact-based choices. Together, we are working on sustainable and responsible groundwater use.

"EVEN A BIT OF SEAWATER WILL RUIN YOUR DRINK."



TREASURE TROVE OF MINERAL RESOURCES

The Dutch subsurface delivers plenty of buried natural resources. We mentioned drinking water and the energy potential of the subsurface, but there is more. Our subsurface is also rich in surficial aggregate resources for the construction industry. Clay is used for bricks and roof tiles, and sand and gravel for concrete and infrastructure-related levelling. And let's not forget the large reserves of rock salt deep in our subsurface. Luckily, the subsurface of the Netherlands offers much more benefit than risk.

CLAY, SAND AND GRAVEL

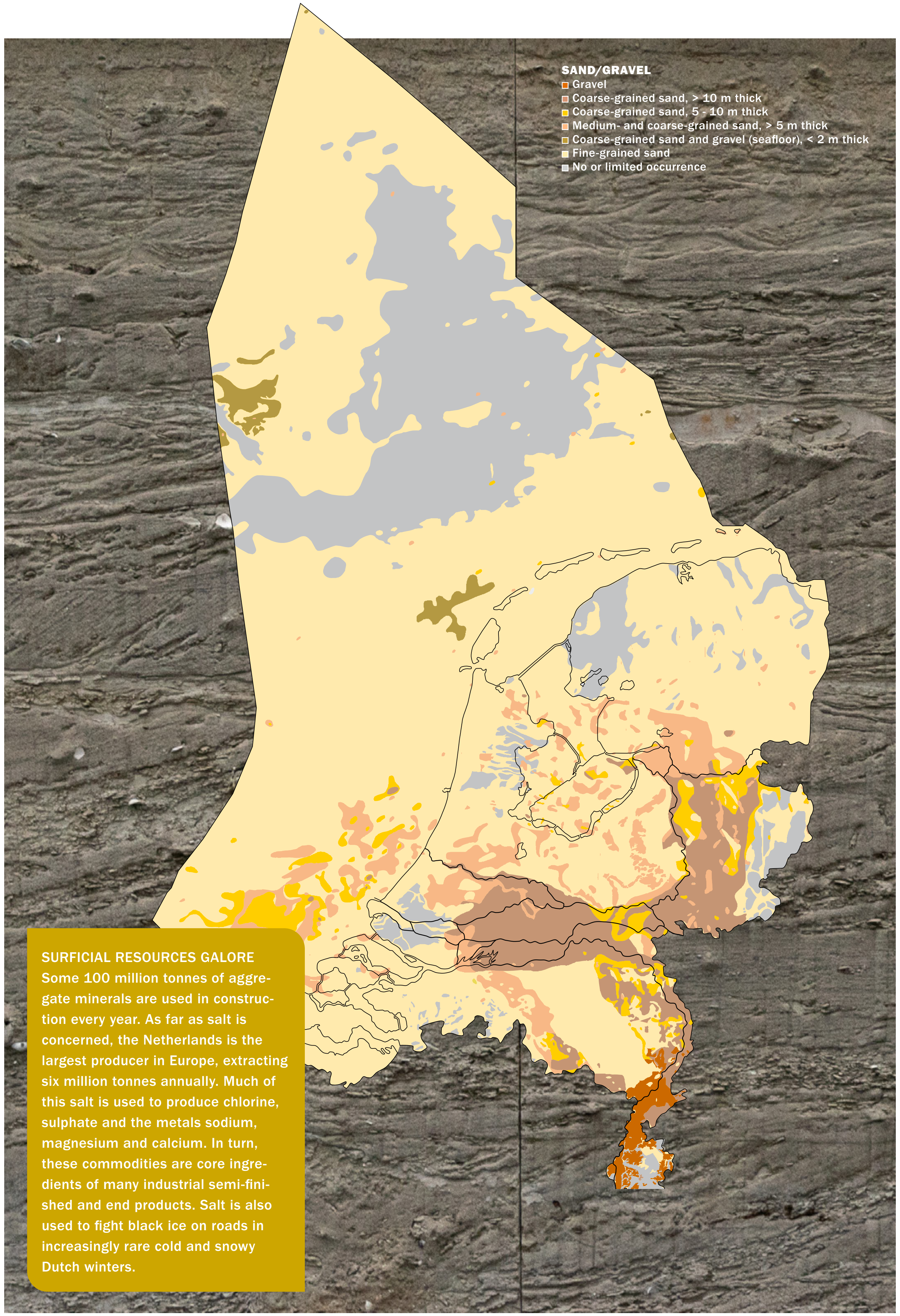
Owing to our lowland setting with rivers, seas and glaciers, thick and variable depositional sequences have accumulated over many millions of years. River deposits form the most important source of gravel, sand and clay. The Geological Survey of the Netherlands has lots of information about extractable stocks. A large database on particle-size distribution, for example, is used to determine how material can be used most effectively. This information is especially important for the construction sector. Nowadays, the extraction of clay, sand and gravel is bound by rules created to decrease pressures on the Dutch landscape associated with an increasing lack of space. For sand extraction, we have been making a move to the North Sea.

SALT

Much farther down in the subsurface, rock salt abounds. In the north of the country, this salt layer is almost a kilometre thick. Its typical depth range is 1,500 to 2,500 metres. The salt formed just over 200 million years ago as a result of long-term evaporation in a vast inland sea that once stretched from Great Britain to Poland. After its formation, other deposits covered the salt layer. Locally, the salt is pushed significantly upwards to form salt pillars (diapirs). In these places, it is easier and cheaper to extract this resource.

WHY THE NEED TO KNOW?

Our subsurface resources are plentiful but finite. It is one of the reasons why we need to treat the subsurface with great care. As an important adviser to government, we bear great responsibility, enabling decision makers to draft properly considered, sustainable and safe policies and regulations. Take the caverns that are formed when salt is extracted. They can reach hundreds of cubic metres in size. The Geological Survey of the Netherlands has developed models to monitor these caverns and to simulate their behaviour as a function of salt extraction. This is just one of the endless applications.



SURFICIAL RESOURCES GALORE

Some 100 million tonnes of aggregate minerals are used in construction every year. As far as salt is concerned, the Netherlands is the largest producer in Europe, extracting six million tonnes annually. Much of this salt is used to produce chlorine, sulphate and the metals sodium, magnesium and calcium. In turn, these commodities are core ingredients of many industrial semi-finished and end products. Salt is also used to fight black ice on roads in increasingly rare cold and snowy Dutch winters.

SUBSURFACE AND POLICY

As an independent organisation, the Geological Survey of the Netherlands provides the government with objective knowledge and information about the deep subsurface (500 metres and deeper). Part of our role is to advise the Ministry of Economic Affairs and Climate about the risks and effects of mining activities.

Effects of mining are frequently in the public eye, much of the time in a negative way. They dominate discussions about present and future energy policy. Subsidence and earthquakes resulting from the extraction of natural gas in the northeast are causing structural damage. The impact is not limited to houses and other buildings. Many residents are worried, and this feeling of unsafety should not be ignored.

LESSONS ON SAFETY

To quantify the effects of mining, the Geological Survey of the Netherlands combines its subsurface expertise with TNO's knowledge on the strength of buildings and structures. The lessons we learn are important both nationally and internationally. The extraction of resources – whether gas, oil, water, salt or geothermal heat – can bring major risks and security-related issues in urban and rural areas.

BAD VIBRATIONS

We develop models that predict the number and magnitude of earthquakes expected under different extraction scenarios. We analyse how vibrations triggered by seismic waves move from an earthquake's origin, deep in the subsurface, to the surface. The composition and mechanical properties of the deep and particularly the shallow subsurface are crucial. They are the parameters we use to explain and predict surficial ground motion and its effect on buildings. Our models are calibrated with laboratory experiments. Jointly, they tell us how houses are best reinforced and how future damage can be limited.

RAPID AND FLEXIBLE RESPONSE

An understanding of the effects of mining is crucial to the Dutch energy policy. Armed with our expertise, we are able to provide clear, knowledge-based advice now that the Netherlands plans to reduce gas extraction. Up-to-date knowledge is essential if gas production has to be increased temporarily, for example during a cold winter. In choosing where and when to extract, the safety of residents has top priority. With the subsurface being used more and more intensively, the well-being of our citizens will become a guiding principle in much more of the work we do. In order to react quickly to unexpected events and new information, we are making sure that our models get better while computing times get shorter.

OUR FUTURE WITH **OPEN DATA**

Open data are data freely accessible to everyone. In many countries, users are still charged for accessing subsurface data. The Netherlands has one of the most extensive open-data policies, and geological data are no exception. All of our data are machine-readable and can be downloaded for free, even when supplied to us by industry. As stipulated by the Mining Act, businesses in the oil and gas sector have to share their subsurface data with the Geological Survey of the Netherlands. Following a confidentiality period, they become open to everyone. The philosophy of open data is bearing fruit. In the old days, we were getting paid for data and information. Now, we are asked to explain the free data distributed through our digital portal. Questions by data users have become one of the best ways to gain knowledge in areas such as the energy transition and spatial planning.

COLLECT ONCE, USE MANY TIMES

If you want to say something about human interference in the subsurface or right on top – on land or at sea – and if you want to make decisions from a longer time perspective, you need all the existing data you can get. Collecting new subsurface data is very expensive, especially at sea. The legal obligation of data delivery to the Geological Survey of the Netherlands, under the Mining Act and the Key Registry of the Subsurface, has been instrumental in keeping down societal costs for many projects. Lots of old and new data are secured and made accessible to all. Our specialists are primary users of these data, in keeping with our mission: facilitating the sustainable management and use of the Dutch subsurface.

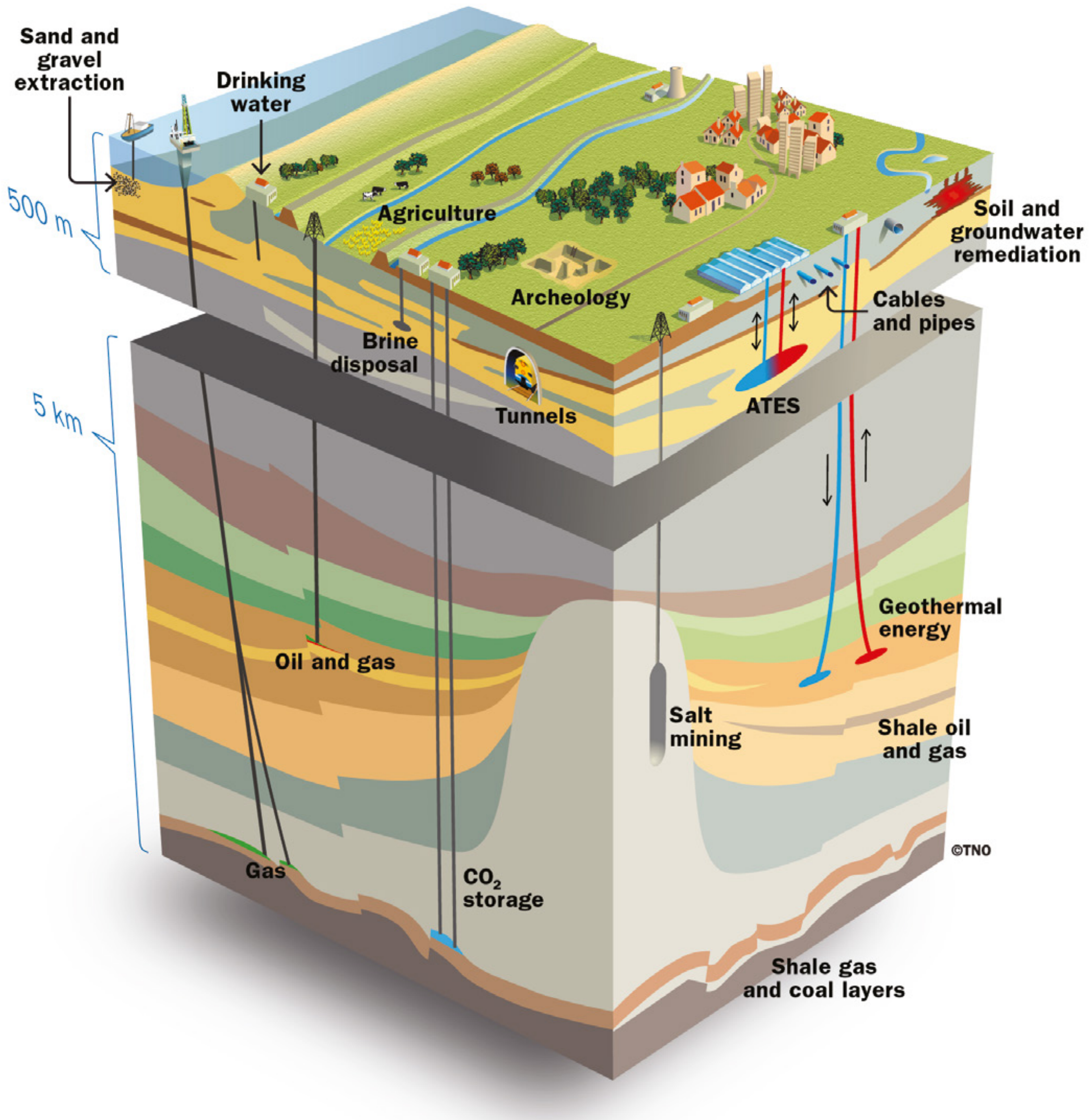
VERSATILE PORTALS

Taking full advantage of the open-data principle, we share subsurface data, tools, maps, models and knowledge that are constantly evolving. The following portals are operational:

- DINOloket.nl and BROloket.nl – a plethora of subsurface data and models for consultation and retrieval.
- NLOG.nl – aimed specifically at data, public information and innovative developments related to the deep subsurface; operated in conjunction with the Ministry of Economic Affairs and Climate.
- Thermogis.nl – information system aimed at assessing and extracting geothermal energy.
- Grondwatertools.nl – lots of hydrogeological and geological information, with interactive tools and maps for spatial planning and other subsurface-related matters.
- Delfstoffenonline.nl – information system on surficial and shallow-subsurface aggregate resources.

FROM NATURAL GAS TO GEOTHERMAL ENERGY

The use of geothermal energy is set to increase spectacularly in the coming years. It is a sustainable, local source of heat for houses, offices, greenhouses and industry. We identify opportunities, which are plentiful because it is easy to make boreholes in the soft upper hundreds of metres. We also quantify associated risks. Our data and models provide direction to parties developing a broad range of small and large initiatives. Equally importantly, we advise the government on the development of effective policy instruments. Finally, we are an important sounding board for municipalities and provinces that want to stimulate geothermal energy projects.



EXPORTING OPENNESS

We notice that surveys and other agencies from a growing number of countries want to know more about our open approach to managing and providing subsurface data. We get many questions on how this openness is embedded in law. Our foreign colleagues are keenly aware that national stipulations on the provision of newly collected data to our database and on the mandatory use of this database under public law have boosted our subsurface expertise and its visibility. We share this knowledge and experience with more than forty European geological surveys in a joint research programme, GeoERA. Its harmonised deliverables contribute to the sustainable use and management of the European subsurface. Openness and strong collaboration are two pillars underpinning the use of geological knowledge in decision making.

Open data, especially when plentiful like for the Dutch subsurface, are indispensable for education and research.
The portals of the Geological Survey of the Netherlands are popular with national as well as international users. They have grown into much more than data-access points alone. Interpretative models, analytical tools and explanatory documents are increasing the accessibility and applicability of our information.

From an international perspective, the Netherlands has a high data density, reflecting our extensive use of the space above and below ground. In an absolute sense, we still know very little. To answer the current, complex questions thoroughly, we need to develop a stronger predictive capability. New data, in large part provided by third parties under the Dutch subsurface laws, make all the difference. The more we know, the better we can calculate benefits, address safety issues, and optimise our overall subsurface management.

DEEPER AND DEEPER

Older, deeper and therefore less accessible layers of the subsurface offer unique opportunities. The Dinantian, part of the Carboniferous that has brought the Netherlands its coal, is particularly interesting. Its geology echoes major climatological and evolutionary changes during this part of the Palaeozoic era. Dinantian limestone is potentially interesting as a geothermal energy reservoir. At the same time, some Dinantian deposits deep under the North Sea are an important source of hydrocarbons. The Geological Survey of the Netherlands is the driving force behind various partnerships combining all available knowledge for large-scale, cross-border research. Parties from different countries have joined forces in the Ultra-Deep Geothermal Energy programme, part of Europe's Green Deal. In Paleo-Five, we make sure that promising deep petroleum plays aren't forgotten. We lead the way in processing and interpreting large quantities of seismic data, in bringing together deep-subsurface knowledge, and in developing state-of-the-art reservoir models.

Databases by themselves don't tell you much. First, you need to turn them into information through querying and analysis. Next, you need to know what this information means, developing knowledge. Geoscientific and geotechnical knowledge are the basis of meaningful advice. It is as much about the big picture as about specific details. Every day, the Geological Survey of the Netherlands generates new knowledge and makes it available to society. You can only talk about the real wealth of data after adding interpretative, explanatory and predictive value.

PLANNING WITH GEOLOGY

Essentially, we have always been subsurface pioneers. Trying to make full use of a good and accessible database, we are continuously developing and exploring new querying and processing technologies. In 1997, we took our first steps toward 3D modelling. Although it was sad to say goodbye to the classical mapping programme and the related data collection for the shallow subsurface, this radical change in approach has paid off. It has increased the consistency of our mapping, facilitated updates, allowed us and others to create subsurface-geological products tailored to specific end users, and enabled us to do uncertainty analyses. This 3D development has unlocked the secrets of a 2D country.

3D MODELLING: MORE INSIGHT, BETTER FORECASTING

Various models with different capabilities offer separate insights into the fascinating world of the subsurface. The models have been developed and are updated systematically. Built on experience, some of them are unique in the world:

- GeoTOP: the types of sediment in the uppermost 50 metres of Dutch coastal provinces, river areas and southern provinces, visualised in volume blocks of 100x100x0.5 metres.
- DGM: the geological layers of the Netherlands up to 500 metres deep.
- REGIS II: the permeability of our subsurface up to 500 metres deep on average.
- DGM-deep: the geological layers of the Netherlands (including the Dutch North Sea) up to 6,000 metres deep.

DYNAMIC CHANGE

As the Geological Survey of the Netherlands, we know full well that the subsurface is far from static. Just think of the groundwater that slowly migrates through pores, and of subsidence and sediment transport causing existing data to become obsolete. The step from 3D to 4D modelling cannot be taken soon enough. On a human timescale, it is important to allow our models to capture these and other changes in the subsurface. In light of these changes, we need to collect new data even for locations with existing information.
The statutory duty to deliver subsurface data and, for us, to make them publicly available under the Key Registry of the Subsurface is timed perfectly.

A TRANSPARENT SUBSURFACE

Models and new data increase our capability to show geology reliably. Up-to-date 3D models in particular offer better insight into subsurface processes that are not directly visible. You could say that the models make the subsurface 'transparent'. Such transparency is needed to raise public awareness.
After all, today's and tomorrow's questions are not simple, and may even deal with controversial topics. Using our models and data, government policies and public opinions can be properly aligned with the dynamic characteristics of the subsurface.

SOCIETAL DILEMMAS

Spatial planning and the construction of large-scale infrastructure come with predicaments. How and where, for example, should the dykes along the Rhine be reinforced? Or take energy transition: how can we use the subsurface to make sure that energy supply and demand are matched without glitches? We are also conducting a lot of research into induced seismicity and other risks associated with resource extraction. The complexities of these processes preclude easy answers. Any answer should be based on the reliable and accurate data and models provided by the Geological Survey of the Netherlands.

Employees of the Geological Survey of the Netherlands have long been used to an accessible, knowledge-supported subsurface database. Although it feels entirely normal, it is a real goldmine. We owe it in part to Napoleon, who laid the foundations for the Dutch Mining Act, and to the shallow successor of this law: the Key Registry of the Subsurface.

GEOLOGY EMBEDDED IN LAW

The Dutch Key Registry of the Subsurface (BRO) is a worthy twin of the much older Mining Act. Whereas the Mining Act focusses on shared data and information concerning the deep subsurface, the BRO is mostly about the shallow subsurface. Since 2018, administrative bodies such as municipalities, provinces and regional water authorities have delivered their subsurface data, mainly collected by third parties, to a central database. Use of this growing database in their policy making has become mandatory. Reusing subsurface data saves society money. Imagine if you had to keep drilling new boreholes because existing data were hidden in local or regional archives: that would be unnecessarily costly.

UNIQUE: STATUTORY KEY REGISTRY

The BRO's history starts and ends with the Geological Survey of the Netherlands. One hundred years of systematic mapping of the subsurface forms the heart of the BRO. Our pioneering role makes us proud. With the BRO, we are much better able to show the value of subsurface data for the Netherlands. And it's all because of Willem van Waterschoot van der Gracht, our founder.

FROM NON-BINDING TO MANDATORY

We spent much of our history collecting data, storing it, interpreting it, digitising it, and making it publicly accessible. The transition from loose documents in filing cabinets to digital interconnectedness was made decades ago, following a prescient decision made from a strategic point of view. The BRO has formalised, strengthened and broadened it. Our government believes that subsurface information is so important that it should be harvested, documented and reused from a central point, unambiguously and in accordance with joint agreements enshrined in law.

Commissioned by the Ministry of the Interior and Kingdom Relations, we are developing exchange standards and a technical system ensuring interoperability, but we are not doing it alone. Along with many other stakeholders, we are making excellent progress in this prestigious mission. The BRO will make our sustainable future a little more affordable.

A FRAMEWORK OF OPPORTUNITY

The BRO does not stand by itself. It is part of a family of key registries, offering opportunities in efficiency and application. All standards are aligned with European guidelines, facilitating cross-border cooperation. After all, many rivers run right across geographical boundaries, and the clay in our deep subsurface was originally deposited on a continent without borders that looked far different from today's Europe.

The bottom line? Never before has geology been so important. We need all subsurface data we can get. The BRO is a potential blueprint for a pan-European data infrastructure.

WELCOME TO THE DUTCH SUBSURFACE

The Netherlands and its geological survey are on the eve of some exciting subsurface-related opportunities. There is no escaping from the relevance of geology. To illustrate the importance of innovation in geological mapping and modelling, we want to share some characteristic stories. Hopefully, they will inspire you to do more with the subsurface, with less impact. Join us underground...

EXPEDITION NORTH SEA

One of our research projects focuses on the question how the North Sea refilled with water after the last Ice Age. To answer this question, researchers from the Royal Netherlands Institute of Sea Research (NIOZ), Deltares, Utrecht University and the University of Leeds set sail on the NIOZ research vessel Pelagia.

DROWNED LANDSCAPE

The North Sea area fell dry during the last Ice Age because sea level dropped by more than a hundred metres. Some 12,000 years ago, as ice sheets in regions such as Scandinavia and North America began to melt quickly, the lowest parts of the present North Sea started filling up again. But how quickly did sea level rise between 12,000 and 9,000 years ago? And how did vertical movements of the earth's crust affect that rise just after the end of the last Ice Age? With coring and seismic profiling, experts in geology, chemistry, biology and groundwater are refining their knowledge about a period of extremely rapid sea-level rise. Their findings may offer insight into our own climate-influenced future.

SEARCHING FOR PEAT

To gather this knowledge, the crew started looking for drowned peat layers that mark the transition from terrestrial to marine conditions. The boundary between sand and peat, easily recognisable in cores and on seismic profiles, tells us that the land subsurface became wet under the influence of rising groundwater, creating a marshy wetland. A second boundary, between peat and brackish clay, marks the full submergence within a tidal basin. There was water overhead. Our borehole-description database and a corresponding subsurface model were used to identify suitable sampling locations in advance. Further refinement and final site selection were based on newly collected seismic profiles during the cruise.

The researchers returned with a large set of undisturbed cores, almost all with the targeted peat and clay. These cores are being examined as if they were medical patients, visually as well as with modern equipment such as scanners. They have been photographed, analysed for their chemical composition, and sampled for radiocarbon dating. Some of this work was carried out in our own lab. It has yielded a lot of valuable information.

APPLYING FUNDAMENTAL KNOWLEDGE

We are learning how quickly the North Sea region flooded after the last Ice Age. Our information helps geophysicists to improve models quantifying the magnitude of vertical movements of the earth's crust, and to understand gravitational effects triggered by the disappearance of enormous ice masses. Expedition results also clarify interactions between climate, ice sheets and sea level for a time period marked by exceptionally rapid change. As such, our research is crucial to understanding and preparing Europe for expected future climate change. It combines basic and applied aspects.

LUCKY WITH THE NORTH SEA

Basal peat and tidal clay covering the Pleistocene surface have been sampled up to 65 metres below present-day sea level. Our cores document more than 12,000 years of change, taking us back to the Stone Age. Aside from telling us how and when the North Sea region filled up with water, the cores also enable us to reconstruct the early Holocene landscape and vegetation. Holocene peat layers as deep as ours are rare. Their sporadic occurrence on earth makes this joint research even more special.

AMAZON OF THE NORTH

Up to a depth of a few hundred metres, the subsurface of the Netherlands is dominated by deposits formed by rivers. Knowing how these rivers flourished and faded during hundreds of thousands to millions of years, matters for lots of reasons. It provides insight into climate change, helps us to reconstruct former coastlines, and explains the observed layer sequences. The queen of our past rivers is the Eridanos, also known as the 'Amazon of the North'.

RISE AND FALL OF ERIDANOS

The largest river leaving sediment in the Dutch subsurface in the past ten million years was the Eridanos. It was comparable in size to the current Amazon and is named after the legendary eponymous river from Greek mythology. The Eridanos brought huge volumes of sand and gravel from the Baltic region and even northern Russia. Some of this material was deposited in the northern half of the Netherlands. At the same time, precursors of the Rhine, the Meuse and a number of smaller rivers delivered sediments from the Alps, the Ardennes and the German uplands. About a million years ago, the first serious glaciation heralded the demise of the Eridanos. Its drainage basin was completely disrupted by advancing land ice. Farther south, the Rhine, Meuse and small Belgian and German rivers have survived to this day.

RIVERS TO THANK

The old river deposits in the subsurface are now very valuable. Most of us won't realise, but we benefit from them every day. Thick sand and gravel deposits from the Eridanos and other rivers are home to our largest volumes of fresh groundwater. They are also used in the construction industry. Both literally and figuratively, river geology forms the foundation of the Netherlands. Everything we know about this firm base is in our public subsurface models.

USING THE GEOLOGICAL RECORD

The better we understand the origins of the Netherlands and the more we refine subsurface models, the better we can help governments and organisations to manage our densely populated and intensively used country efficiently and effectively. From preventing flooding to drafting policies on raw materials and renewable energy, knowing our geological past makes all the difference.

NO MORE **BUMPY ROADS**

Over time, smooth roads on clay or peat can develop lots of unwanted ups and downs. Bumpy asphalt leads to high maintenance costs. In order to meet minimum government-set requirements for longitudinal evenness, the maximum acceptable height difference over a certain stretch of road, contractors building motorways and other high-speed roads are contractually obliged to make repairs if needed. The guiding principle: damage to cars must be prevented and road safety must be ensured at all times. Contractors benefit from accurate estimates of expected differential settlement following road construction, which cannot be made without subsurface data.

COUNTING ON GEOLOGY

We present our subsurface data in such a way that users can make calculations with them. The prediction of differential settlement under roadbeds is a successful example. A dedicated model translates 3D subsurface characteristics into total expected lowering of the surface, identifying locations where minimum flatness requirements are not satisfied.

HIGHWAY PATROL

One of our main traffic arteries, a ten-lane motorway between Amsterdam and Utrecht, traverses polders dissected by local rivers. Here, subsurface sequences of compactable peat and clay meet a tangled network of sandier channel belts. Because the sensitivity of this area to load-induced compaction is so variable, it has been an ideal spot for testing. Our predictions have turned out to be accurate.

ADDING VALUE

The smart combination of geological, geotechnical and geostatistical knowledge has fed a model guiding pre-construction measures, limiting unpleasant post-construction surprises, and keeping costs down. Similar interdisciplinary approaches answer different sets of questions. Interconnectedness with other knowledge institutes is the way to go.

RIVERS **BELOW** US?

In many places, more than one third of the Dutch subsurface consists of groundwater. This water is located in the open spaces between gravel, sand and clay particles, and between plant fragments in peat layers. Do we have ‘underground rivers’? Not really, but there are good reasons to make this comparison. After all, groundwater tends to flow downslope, be it through interconnected pores.

MODELLING AQUIFERS

The size, shape, number and interconnectedness of pores govern the speed at which groundwater flows. These characteristics depend on soil type. Most gravel and sand layers are permeable. They are aquifers suitable for groundwater extraction.

Around 60% of Dutch drinking water comes from groundwater. For the supply of this drinking water, we need to know where aquifers are located, how thick they are, and which specific hydrological properties they have. Similar information on less permeable layers is just as important. Mapping and characterising aquifers and low-permeability layers is a core task of the Geological Survey of the Netherlands.
Our knowledge is captured in a 3D hydrogeological model, REGIS II, covering the entire country. The model subdivides the subsurface into 125 aquifers and less permeable layers, up to an average depth of 500 metres.

FROM REGIONAL WATER BOARD TO ENERGY TRANSITION

As part of our systematic hydrogeological reconnaissance, we release new, improved versions of REGIS II every once in a while. The next step is modelling in 4D. Groundwater moves, and pollutants or other unwanted dissolved substances with it. To ensure optimum groundwater levels and safeguard groundwater quality, water managers from regional and provincial water authorities are in desperate need of this temporal information. So, too, are hydrologists hired to keep building sites dry, and designers of energy-saving ground-coupled heat exchangers. Knowledge of ‘underground rivers’ is good for our planet and wallet.

STORING THE DUTCH SUBSURFACE

In essence, the Central Core-Storage Facility of the Geological Survey of the Netherlands is the sample library of the Dutch subsurface. This paradise for earth scientists houses an impressive collection of sediment and rock samples collected at sea and on land for more than 100 years, along with some interesting geological artefacts. The samples originate from boreholes, excavations and construction sites. There are important reasons to keep these samples. They are unique, and their replacement value is prohibitively high.

CORES OF ROCK AND BAGS OF SAND

We have core samples from oil and gas reservoirs, shale from which gas can be produced, limestone, rock salt and layers containing coal from the Carboniferous period. All geological units that are important for the Netherlands are well represented. Our collection also contains a core sample from the Zuidwal volcano that was active 145 million years ago. Its almost-forgotten remnants lie deep beneath the Wadden Sea.

Many shallow boreholes have been drilled for geological modelling, research into groundwater, or prospecting for gravel, sand and other minerals. Material from these boreholes is generally loose, unconsolidated sediment. It is stored either as complete cores or as bagged samples from borehole intervals of approximately one metre.

AMPLIFIED STRUCTURES

In addition to thousands of borehole samples, our core-storage facility has a rich collection of lacquer peels. These physical prints - cross-sections - of the subsurface enhance the sedimentary structures and layering that characterise the subsurface. They tell us a lot about the physical environments in which the layers were formed. Some of the peels have archaeological value. Plough marks and remnants of old habitation layers are cherries on sedimentological cakes.

KEPT FOR RESEARCH

Borehole samples provided to us under the Mining Act are documented and stored immediately. Samples from shallow boreholes are first described and, if necessary, analysed in our laboratory. The most unique and special cores and bagged borehole samples are stored for reference, because re-drilling is expensive. In this way, they remain available for research, potentially with yet-to-be-discovered methods.

GETTING ACCESS

In our opinion, this precious library can never be used enough. You are welcome to discover what we have in store. Most of our collection is freely available for research by anyone with a relevant interest. However, within the framework of the Mining Act, samples from the exploration for gas, oil or salt remain confidential for a number of years. With enough patience, even these can be studied.

IF YOU WANT TO KNOW **MORE**

This brochure covers the way we work and share our data, information and knowledge, as well as the reasons for doing it. It also highlights why working with others is so important. Our use of the subsurface is changing rapidly, and your expertise or question can make a real difference.

We make our specialist geological know-how available to everyone: the subsurface data as well as the models. Free of charge. And for good reason: together, we can take big steps toward a more sustainable use of the resources our subsurface has on offer. Our focus is on the Netherlands, but we look well beyond the border. Many national and international research institutes and educational centres already know where to find us.

How about you?
It is also possible to use our expertise directly. We can participate in research projects or specific case studies. Where possible, we contribute expertise or advice on the innovative use, management and design of the subsurface and its resources, nationally and internationally. As a guardian and as a pioneer.

Have you become curious about our work? Don’t hesitate to contact TNO - Geological Survey of the Netherlands. Call +31 (0) 88 - 866 43 00 or send an e-mail to info@dinoloket.nl/en/contact. Are you speaking Dutch? Discover more about our work by visiting www.grondwatertools.nl.

WEB FULL OF DISCOVERY

Discover the data and models of the Dutch subsurface at www.dinoloket.nl/en, or dive into the world of the deep subsurface and read about near-limitless opportunities for exploring and extracting new forms of energy in the Netherlands: www.nlog.nl/en.