Carbon: captured!

Anthropogenic emission of carbon dioxide is a key influence on the global climate change that has been observed over the last century. While government agencies set long-term goals to cut carbon emissions, pioneering research is exploring ways of dealing with today's problem today. Carbon capture and storage (CCS) represents one promising fix to this challenge: we're familiar with extracting oil, gas and water from deep subsurface reservoirs, so why not inject our waste emissions back underground and make use of some spare space? Dr Monika Ivandic, a post-doctoral researcher in geophysics at Uppsala University in Sweden, is using seismic imaging methods to monitor CCS operations as part of the CO_2SINK and CO_2MAN projects, making sure that captured carbon stays well-and-truly captured.

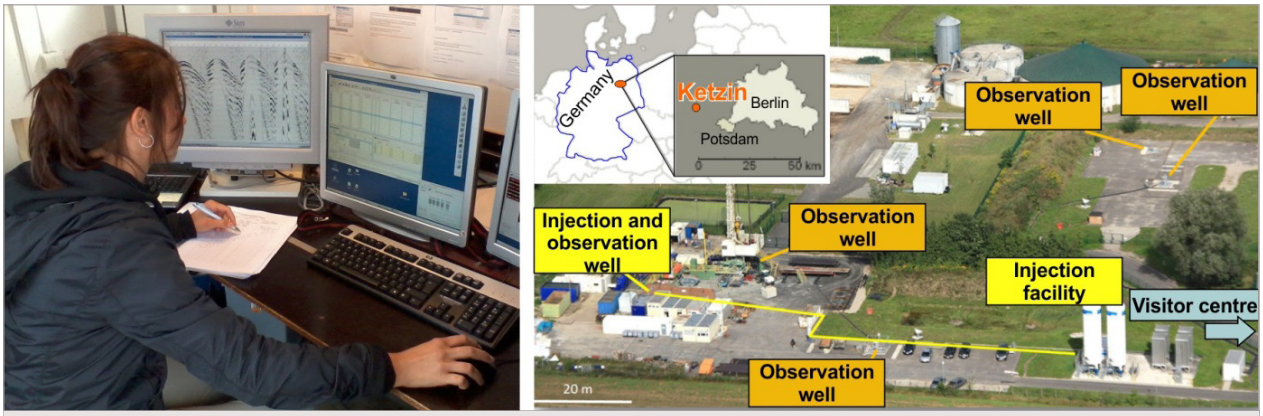
"Our projects examine whether geological storage is an option for reducing CO_2 emissions," Ivandic says. "A critical component of long-term CCS is our ability to adequately monitor the movement of CO_2 in the subsurface." So how is this done? In essence, Ivandic conducts time-lapse photography of the subsurface CO_2 plume, only at the seismic scale. By repeating a seismic survey at the same site, she builds up a series of images from which the growing subsurface volume of CO_2 can be monitored. "Time-lapse seismic surveys have been widely adopted for measuring subsurface fluid flow," she tells me. The general trick is that gas injection changes the physical properties of the subsurface reservoir – for example, reducing its bulk density – which in turn changes the reservoir's seismic response. Careful seismic data acquisition and processing can then map where those changes are taking place.

The gas injection in question takes place west of Berlin at the Ketzin CCS study site, Europe's first and longest-lived on-shore CO_2 storage facility (Martens et al., 2011). Since 2008, Ketzin has been pumping CO_2 into saline sandstone aquifers, sealed beneath impermeable mudstones some 640 m below the ground. In 2005, prior to the start of CCS operations, researchers performed a baseline seismic survey and then repeated it for comparison in 2009 and 2012, in which time over 65,000 tonnes of CO_2 had been injected.

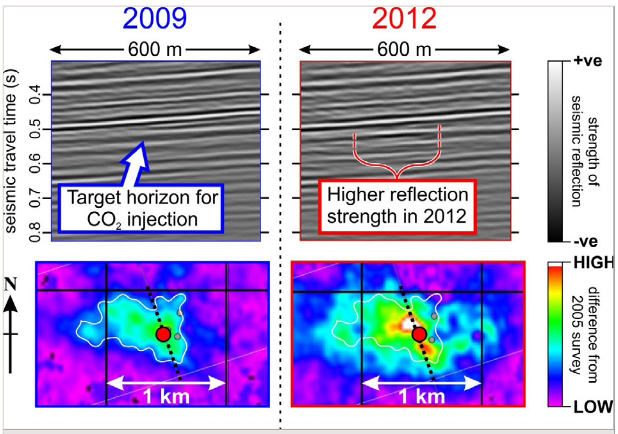
With some pride, Ivandic states that "the monitoring methods used at Ketzin are among the most comprehensive in the field of CO_2 storage." Injection will cease this year, marking the first time that a CCS reservoir has been monitored throughout and beyond its operational cycle.

Ivandic's seismic images (next page) show clear changes in the subsurface – both in cross-sectional (upper) and plan (lower) views – which are directly attributable to the growing gas plume. Of course, there's a real need for such comprehensive study: the problem with injecting thousands of tonnes of free-spirited gas into the ground is that it doesn't always stay where you need it to. In fact, Ketzin itself proves that you should always expect the unexpected. Theoretically, the CO_2 was expected to migrate north into the highest part of the reservoir. "That's not what we're observing at the moment," says Ivandic, who tells me that lithological variations in the reservoir are causing the gas to head west. "In spite of very detailed data, fine-scale reservoir structure can be difficult to discover and can seriously affect the CO_2 migration. That's why time-lapse seismic imaging of the CO_2 plume evolution during and after injection is crucial." The next seismic survey is scheduled for 2015, and Ivandic is "really curious to see how the reservoir and plume will behave once the site is closed. An exciting period is ahead of us!"

Despite its unexpected migration, the good news at Ketzin is that the CO_2 looks to be locked away. But such operations are clearly not without risk, and Ivandic's group has navigated a fine line between scientific discovery, environmental legislation and societal impact. "The safety of the sequestration process is the most crucial aspect, for both man and nature, and thus for other CCS projects." Some commercial injection operations have encountered strong opposition from local German stakeholders, but Ketzin has been well-accepted by local politicians and public alike. While this is partly down to its non-commercial scale, it is also related to the fact that Ivandic's group has actively engaged with the local community, for example by holding weekly outreach and education events at a visitor centre.



Left: Dr Monika Ivandic oversees seismic acquisitions at the experimental site in Germany. Right: Aerial view over the Ketzin CCS facility, close to Berlin, Germany (Adapted from http://www.co2ketzin.de/en/pilot-site-ketzin/summary.html)



Time-lapse seismic data from the Ketzin CCS site, from 2009 and 2012 acquisitions (from Ivandic et al., in preparation). In cross-section (upper images), stronger seismic reflections are observed in the target aquifer but the rest of the data remains identical. This shows that the CO_2 volume in the aquifer has increased, but that it is contained. Map-view images (lower) reveal the size of the 2009 and 2012 CO_2 plumes compared to the 2005 baseline survey and suggested that it has migrated west from its injection site (red circle). The black dashed line shows the intersection with the cross-sections above.

Worldwide, interest in CCS is growing – something Ivandic has experienced first-hand. Many countries, including her homeland of Croatia, have no CCS operations but have estimated their potential storage capacity from data archives or from regional distributions of suitable reservoirs. Such estimates keep increasing, but The Worldwatch Institute suggests that today's seven active and planned CCS operations could only store 0.5% (35 million tonnes) of the CO_2 emitted in 2010 – hence CCS does not yet provide the answer to the global emissions challenge. Nonetheless, CCS expertise is in demand and, this year, Ivandic has completed a marathon schedule of workshop and conference attendance presenting CO$_2$MAN's latest observations (including at April's EGU General Assembly). Indeed, she was surprised to find that "the work and results attracted the attention of scientists not even involved in CCS projects!" Clearly, the world is becoming fascinated by grounded gas.

Adam Booth

Post-doc at Imperial College London, UK

More information

Monika Ivandic obtained her PhD from IFM-GEOMAR (Kiel, Germany) in 2008, then worked back in her native Croatia on a variety of geophysical projects for geotechnical and civil engineering applications, and started her post-doc at Uppsala in 2011. For those embarking on a post-doctoral career, Monika has the following advice. "Be ready for short-term contracts. More than a third of academics are on temporary contracts, a situation which results in frequent changes of job and city." However, such diversity also brings rewards. "It brings a lot of excitement and dynamics to your life! And as for the science, that's always a new page in your career."

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The real Silicon Valley

On the pathways of silicon on its way to the sea

Everybody knows Silicon Valley, but how many people can tell you about the importance of silicon in nature? One who surely can is Dr Wim Clymans. He is a young post-doctoral scientist at the Geology Department of Lund University in Sweden who dedicates his research to silicon and its biological role. "Silicon is highly underappreciated!" he starts. "People know oxygen, carbon, maybe nitrogen and phosphorus, but hardly anybody has heard of silicon as an important nutrient. Yet, it is vital for plankton in the oceans and other small forms of life in rivers. Silicon forms one of the base components for a well-balanced food system and is, therefore, very relevant," he explains. "Silicon travels from the land to the ocean via rivers and over-land flow in the valleys but, on its way, it can be fixed by vegetation. In our research, we delve deeper into the pathways of silicon on its road to the sea. This is important because, due to human interventions and climatic changes, the supply of silicon from the land to the sea may become distorted and the precious food system in rivers and seas may be altered."

Clymans and his colleagues have monitored several river catchments. In the old Meerdaal Forest in Belgium, for example, they took measurements for three years, equipping the area with devices to monitor the rainfall, the flow in the main stream and the presence of silicon in water samples. They examined this element in more than 800 samples of soil and river water that were collected in the course of this three-year period, which included some storm episodes.

Clymans detected notable differences in the amount of silicon in the stream in winter/spring and in summer/autumn. In a recent paper published in Biogeochemistry, he elucidated the reasons for this variation: "In contrast to larger and less densely forested areas, water stays only a few hours in the stream before it leaves our catchment and the stream is largely shaded. Biological activity in the river is thus low, and so is the uptake of silicon within the river. This led us to conclude that the seasonal variation must be related to processes that occur on the land, and to the connection between the land and the river." Moving the focus to the land, Clymans explains the varying link between the water in the soil around the stream and the stream itself: "In winter and spring, the soil water is in close contact with the stream because the soil is wet. Thus, rain easily drains via the soil to the river. In summer and autumn, the soil is drier and the connection between the soil water and the stream is much weaker." This is one explanation for the varying amount of silicon in the river over the seasons.

In addition, the researchers also revealed that the amount of silicon in the soil water – affected by vegetation and soil disintegration – itself varies. Soil disintegration results in the release of silicon while uptake by vegetation can temporarily hold it. The dominance of one process over the other is highly dependent on temperature and differs among the seasons. Yet, for a long time, there has been a balance between the uptake and release of silicon over the years in old forests. "It is not inconceivable that global warming can distort this balance in the future," reasons Clymans.

Wim Clymans probing the forested 'silicon valleys' at Forêt de Houssière, Belgium. (Credit: L. Fondu)

Exciting storms

More exciting than the rippling water during most of the year were the occasional storms. During these events, the team automatically collected samples covering the entire storm period. They found that during a heavy rain shower, the amount of silicon in the river did not decrease drastically. This may sound counterintuitive because we could expect that heavy rainfall, which can temporarily increase the volume of water leaving the catchment up to 100 times, would wash down the catchment and lead to a drop in silicon following the first rain peak. "We observed that the amount of silicon in the river water only drops slightly and recovers quickly after a storm," explains Clymans. "Thus, silicon is not merely washed out of the soil by rain water." The researchers realised that there should be a second mechanism in action, keeping the element at a roughly constant concentration in the river. When it rains, silicon-poor rainwater flushes 'old' silicon-rich soil water out of the soil and into the river water, which maintains the supply of silicon.

Despite this tendency towards a constant silicon concentration in the river, Clymans fears that disturbances of the natural balance can have a large impact. "From our study, it is clear that the age-old water cycle in the forest is the major control factor on the pathways of silicon. We, humans, can have a large impact on this through the expansion of agricultural land or climatic changes induced by the emission of greenhouse gases. This inevitably alters the transport of silicon to the oceans. At the bottom of the food chain, changes in silicon supply can get a whole cascade going: a known consequence is the harmful bloom of algae, which lowers the oxygen in the river and leads to the death of fish."

And could these changes in the silicon cycle affect Silicon Valley, or at least the production of the silicon-based microchips used in our computers and smartphones? "No, they are quite unrelated, Clymans answers. "Our research focuses on the biological form of silicon while microchips are made of pure silicon crystals, which do not disintegrate easily and will probably never run out. But the biological form of silicon is of interest in our daily lives in another way. Humans profit from silicon uptake as it strengthens bone structure, lowering the incidence of osteoporosis and fractures. A principle dietary source of silicon is beer! Belgian colleagues of mine have shown that the complexity and length of the Belgian brewing process causes Belgian beers to be especially rich in silicon. So, cheers!"

Eline Vanuytrecht

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Icequakes!

Scientists at the British Antarctic Survey are monitoring the rumbling of ice streams to discover what makes them flow

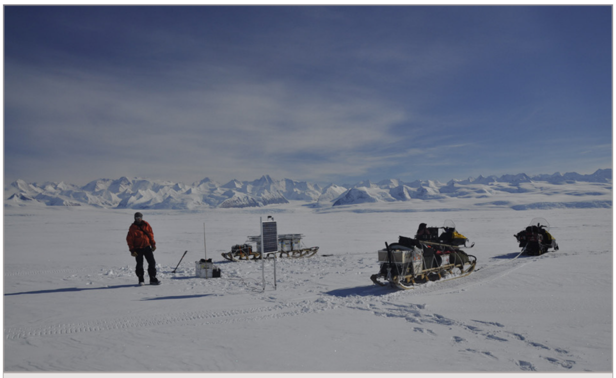
Antarctica is a hostile continent. For half of the year not even the Sun dares to show its face. On the surface the white wilderness appears frozen in time but underneath it there is a stirring world that scientists are only just beginning to uncover.

Woven through the giant ice sheet, which consumes an area bigger than Europe, are networks of ice streams. These are fast flowing passages of ice that, like arteries that move blood around the human body, are a main mechanism for transporting fresh water off the continent and into the ocean.

Ice streams and outlet glaciers are considered to be significant if not dominant causes of the recent Antarctic ice sheet mass loss (Rignot et al. 2008). Some suggest the flow could even speed up in response to warming oceans as ice streams are the fastest responding component of an ice sheet system.

Buried

Understanding the dynamics of ice streams is important to help predict their future contribution to global sea level rise. However, the



Recording icequakes at Rutford Ice Stream. (Credit: Andy Smith)

ice-bed interface, which accommodates the movement of the ice stream, is difficult to access. In situ measurements are challenging as the bed is usually buried under kilometres of ice.

Emma Smith, PhD candidate at the British Antarctica Survey (BAS) is using seismic data to study icequakes – microseismic movement – at the Rutford Ice Stream, West Antarctica. After starting a career in engineering, she moved into exploration geophysics and spent several years working in the oil and gas industry before returning to research.

Antarctica is divided into East and West by the stretch of the Transantarctic Mountains. The West Antarctic Ice Sheet reaches out like a tentacle to the southern tip of South America and contains enough water to raise global sea levels by five meters.

The Rutford Ice Stream is a typical Antarctic outlet glacier sitting in a deep trough. It moves about one meter a day.

"By far, it is not one of the fastest flowing," says Smith. For example the Pine Island Glacier, the longest and fastest moving glacier in Antarctica, can move almost 10 meters a day.

Varying in width from 20 to 30 kilometres and being over two kilometres deep in places, the Rutford Ice Stream flows for more than 150 kilometres before it reaches the Ronne Ice Shelf and starts to float. It drains a land area of 49,000 square kilometres in the West Antarctic Ice Sheet.

Listen closely

To study the stream, Smith uses a technique derived from classic earthquake monitoring called passive microseimic monitoring. It consists in placing geophones – devices that convert ground motion into voltage – on the ice stream surface to record the icequakes produced as it moves over its bed.

Using the data obtained in this way, Smith can then get information about the basal conditions and physical properties of the ice. Ice streams generally have water present at the bed. This water is either surface meltwater that has reached the base or results from the fact that the ice at the bottom is under so much pressure that it has melted at the pressure melting point. "The water allows movement of the ice by providing lubrication – otherwise the ice would be frozen onto solid rock," she says.

Rumbled

However, what the stream is sitting on also controls the speed of its movement. Motion at its bed can change depending on whether the ice stream is moving across soft sediment or sliding over hard rock. Smith found icequakes to be clustering at particular sources at or near the ice-bed interface. "This is telling us the mechanism for accommodating movement is happening in a repeating manner," she says.

Analysis of these data is allowing Smith to build up a picture of the mechanisms that cause the icequakes to occur, meaning she can then better understand how the stream moves. Using the information from the icequakes, Smith can also construct models to illustrate the basal dynamics over space and time.

Parts of the bed deform as the ice moves over and can form large mounds – some as high as 500 meters wide and 50 meters high. In other parts, the ice stream slides over its bed with little deformation. For example, areas of the ice stream bed interpreted as basal sliding show a greater roughness than those with a deforming bed. A rougher bed could be an indication of higher basal friction and so this could explain the increased levels of seismicity detected in those areas.

Looking back

For the past 25 years, BAS have been busy working around Rutford to try and create a full representation of what is happening in this polar area. "The research we are doing can be combined together to get a bigger picture of what's going on," Smith says.

Palaeo-ice streams could give us a glimpse into the future. Comparing present ice streams with previous glaciations can give clues on the Rutford Ice Stream condition. O'Cofaigh and collaborators found in 2005 that deglaciation of deep marine troughs can occur rapidly over just 100 to 1000 years.

However, there are significant differences between past and present. Past ice streams have exposed bedrock but no evidence has been found of this at Rutford. This could be by chance or it may indicate high erosion rates and deep scouring events that characterise the final demise of an ice stream. A process that palaeo-ice streams have already suffered and a fate the Rutford Ice Stream may have yet to come.

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Freelance science writer

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