The early stages of **subduction**

Dr Douwe J J van Hinsbergen reflects on his efforts to shed new light on the mechanisms of plate tectonics, attempting to determine the processes that lead to the formation of new subduction zones

From what context did your investigation into Subduction Initiation reconstructed from Neotethyan Kinematics (SINK) emerge?

During my PhD and first two postdoctoral positions, I studied the formation and evolution of mountain belts in the wider Neotethyan realm. The Neotethys was a major oceanic basin system that existed between Gondwana in the south (a major continental realm that contained Africa, Arabia, India and Australia) and Laurasia in the north (Eurasia, Greenland and North America). Its closure eventually formed the Alpine-Himalayan mountain belt.

During my third postdoctoral position at the University of Oslo in Norway, I started to make plate reconstructions of these mountain belts. Normal plate reconstructions assume that plates are rigid, they cannot deform and their motion is accommodated along narrow, discrete fault zones. Although this approach is very useful for reconstructing plate motion on a global scale, it is not directly applicable to regions where plates converge and where one plate subducts below another – in these places, plate boundary zones show distributed, spectacular deformation. Using structural geological and palaeomagnetic data, I have built detailed retro-deformation models of these mountain belts. From these models, I can derive when and where subduction zones started to form, and along what structures.

Can you provide an overview of your current project and outline the main aims of your research?

SINK mainly focuses on subduction zones that existed within the Neotethys Ocean, since these leave a very distinct rock record known as 'ophiolites' – pieces of oceanic crust that were thrust over continental margins and which are now exposed on land.

This particular project aims to create a breakthrough in our understanding of plate tectonics by identifying the processes that have led, and may lead, to the formation of new subduction zones. As common as subduction may be, and as long as we have known of its occurrence, this question has never really been asked and has not been analysed in detail. In more general terms, I aim to integrate the field of geology (that is, observational analysis of fossils, structures, rocks and minerals) with physics through numerical modelling.

Could you explain the importance of using an integrated geological and numerical approach to study the driving forces behind plate tectonics?

I have begun to collaborate with geophysicists, some of whom develop models for the structure of the Earth's mantle where former surface plates can be found that have subducted in the geological past; other partners create numerical models that try to explain elements of plate motion and subduction based on basic physical laws and principles. While geologists can only speculate about the causes and consequences of subduction, geophysicists can show what is theoretically possible. Much of the time, geophysicists do not know the details of what actually happened, so the application of their results alone is not always sufficient.

In your research, you reconstruct the geometry and orientation of a subduction zone at the moment subduction started. What questions are you hoping to answer and how do you combine these reconstructions with numerical models?

Given my interest in subduction zones and the ability to reconstruct their configuration back to the time of their onset, we aim to define what processes cause the formation of subduction zones. Is the collision between two continents sufficient to perturb the forces driving the plate tectonic cycle and develop a new subduction zone along a former mid-ocean ridge – or could this only happen under certain circumstances? Do these apply to the reconstructed history? We will combine the reconstructions with tailor-made numerical models to test whether geologists' speculations are physically possible and if the models actually match the observations.

What are your expectations for the future of your research?

By moving beyond studying generic aspects of Earth's behaviour, and isolating what exactly happened in terms of the geology and physics of subduction zone formation in the Neotethys, I hope we can better understand the physics of particular case studies. In the future, I would also like to include the more detailed geochemistry of mantle-derived rocks (volcanoes) in the analysis.

Solving the secrets of subduction

Using unprecedented multidisciplinary research methods, the SINK project based at Utrecht University is breaking new ground in its studies of the driving forces behind the initiation of subduction zones

OF EXISTING GEOLOGICAL theories, plate tectonics is one of the most revolutionary and influential. Supported by a weighty and diverse body of evidence, the theory mathematically describes the complex evolution of the Earth's lithosphere in terms of constantly shifting plates and their interactions. Understanding plate tectonics is not only important for explaining mountain formation and the creation of a wide range of georesources, but it is also vital for predicting natural hazards such as earthquakes.

Subduction of oceanic lithosphere into the Earth's mantle – the process by which one tectonic plate is pushed downwards beneath another as the two converge – is a key element of plate tectonics. Geophysical models demonstrate that forcing is required to initiate subduction at weakness zones, but mechanisms producing this forcing remain unexplored.

There is currently no widely accepted physical explanation for what drives plate tectonics. While there is broad agreement that the mechanism involves thermal convections in the Earth's mantle that result in interior cooling, it is only recently that technological advances have made it possible to reconstruct and explore the dynamic history of the mantle itself.

NEOTETHYAN KINEMATICS

Dr Douwe J J van Hinsbergen – a structural geologist, palaeomagnetist and field geologist – has dedicated his career to the tectonic reconstruction of mountain belts. Based at the Department of Earth Sciences at Utrecht University, The Netherlands, he is currently leading a research project that aims to further understand plate tectonics by identifying the mechanisms that force subduction initiation. A year and a half into the five-year project, entitled Subduction Initiation in Neotethyan Kinematics (SINK), van Hinsbergen employs a highly multidisciplinary approach that is essential to the work's success.

Once stretching between the two supercontinents – Gondwana in the south and Laurasia in the north – the Neotethys Ocean on which van Hinsbergen's study focuses contains many well-dated and well-exposed ophiolites (fragments of oceanic crust) that hold the best-preserved geological record of past subduction initiation events.

'Kinematics' refers to the mathematical calculation of past movements of the Earth's crust: "We are building a model that mathematically describes the motions of all crustal blocks that were involved in the closure of the Neotethys Ocean," explains van Hinsbergen. "The theory of plate tectonics is kinematic in that it describes the motion of

INTELLIGENCE

SINK

SUBDUCTION INITIATION RECONSTRUCTED FROM NEOTETHYAN KINEMATICS

OBJECTIVES

- To unravel the processes causing the formation of subduction zones – a key link in the plate tectonic cycle – through geological reconstruction and geophysical modelling
- To develop a predictive model for exploration of subduction-related georesource formation

KEY COLLABORATORS

Marco Maffione; **Ayten Koç** (Postdoctoral researchers); **Derya Gürer**; **Kalijn Peters**; **Peter McPhee** (PhD students) • **Wim Spakman**; **Cedric Thieulot**; **Liviu Matenco**; **Martyn Drury**; **Herman van Roermund**, Utrecht University, The Netherlands • **Fraukje Brouwer**, VU University, The Netherlands • **Nuretdin Kaymakci**, Middle East Technical University, Turkey • **Ercan Aldanmaz**, Kocaeli University, Turkey • **Paul Kapp**; **Peter Lippert**, University of Arizona, USA • **Fernando Corfu; Trond Torsvik**, Oslo University, Norway • **Morgan Ganerød**, Norwegian Geological Survey • **Stefan Schmid**, The Swiss Federal Institute of Technology, Zurich

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DR DOUWE J J VAN HINSBERGEN is Associate Professor at the University of Utrecht. He constructs plate tectonic restorations of mountain belts, including ophiolites within those, at subduction zones and uses these to constrain dynamic numerical models of subduction initiation and evolution.

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one plate relative to another. Kinematics is the expression of dynamics, the set of forces that explain why these movements occurred. That is our ambition: a dynamic explanation."

A NOVEL APPROACH

Subdivided into several smaller projects, SINK is integrating geology and geophysics in a way that will help to forge a deeper understanding of subduction initiation: "I have a team of talented people under my supervision, each with specific aptitudes and skills," van Hinsbergen enthuses. "Through the combination of our expertise we hope to gain insights that we wouldn't be able to develop individually."

Subduction initiation events, absolute and relative plate motions, continental subduction and mantle plumes can be reconstructed in the Alpine-Himalayan mountain belt, a natural laboratory that formed during the closure of the Neotethys Ocean. Its young age makes it an ideal study site, as the important features the team needs for its research remain present in the rock record. An added advantage is that the area is well studied, meaning there is already an existing wealth of information. A numerical laboratory has also been designed to conduct modelling experiments that test whether the geological incidents are causally related.

The combination of geological and geophysical techniques makes the project unique. Integration of geophysical modelling allows the team to test each step of their geology-based hypotheses: "If we can isolate those conditions, we can go back to our reconstruction, and from that to the field to test whether our inferences are possible, or whether we need to go back to the drawing board to test other key predictions made by the physical models," van Hinsbergen reveals.

SINK is also involved in several collaborations; the researchers work with colleagues at the Middle East Technical University and Kocaeli University in Turkey on the Anatolian projects, and with colleagues at the University of Arizona in Tucson, USA, on the Himalayan projects. They also have partners at the University of Oslo, Norway, and the Norwegian Geological Survey in Trondheim working on the dating of rocks.

RETRACING SUBDUCTION INITIATION

Subduction results in a very distinct set of geological features, generating volcanic belts and mountain chains that have specific chemistries, structures and rock types. During the process, rocks from the subducting plate can be offscraped and accreted to the overriding plate.

The researchers led by Van Hinsbergen build models of converging plates using modern-day ocean floors: "Our reconstructions begin in the present day and then recreate historical Neotethys plate movements step by step, to the best of our knowledge placing all the rocks that are now at the surface back into their position when they formed," he explains. Using these reconstructions it is possible to restore the geological units of a mountain belt to their configuration before subduction started to deform them. From this, the researchers can model the geometry and orientation of a subduction zone at the moment the process began.

Using advanced palaeomagnetic analyses, the team is able to map the spreading of the mid-ocean ridge at which ophiolites were formed. Determining the orientation of the Earth's magnetic field – which is frozen into these oceanic rocks – allows the researchers to predict the tilting and rotation an ophiolite may have undergone since its formation at the ridge. Using this information, they are able to derive the positioning of the lithosphere at the moment of subduction initiation. Conclusions can then be drawn about the relationship between the spreading ridge and the alignment of the subduction zone. This leadsvan Hinsbergen to believe that their research will also reveal other major processes that occurred elsewhere on the planet, for example, major volcanic episodes or continent-continent collisions.

FUTURE IMPLICATIONS

By iteratively integrating data obtained from the natural and numerical laboratories to further understand the processes driving subduction, it is hoped that a breakthrough will be made in developing a dynamic and quantitative model to explain plate tectonics.

Gaining a comprehensive and detailed understanding of the Earth's physical processes also has significant repercussions for the lives and security of future generations. Ultimately, SINK will pave the way for a more thorough assessment of seismic hazards, and for the identification of locations where ore deposits and hydrocarbons may be found: "An understanding of the physics of the Earth allows us to obtain predictive hypotheses of what we may expect to find where, how an area may behave in the future or must have behaved in the past," elucidates van Hinsbergen. "This is the Holy Grail of natural science."