European Review, Vol. 31, No. 4, 328–355

doi:10.1017/S106279872300008X

GOLD MEDAL LECTURE GIVEN AT THE ACADEMIA EUROPAEA BUILDING BRIDGES CONFERENCE 2022

Bottom-up Probing Earth System: A Journey in Deep Time and Space

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The quantitative understanding of processes operating in the earth system has advanced significantly over the last few decades. This has led to the realization that a close interaction between deep earth and surface processes is a key element in earth dynamics and its impact on geo-environment, geo-energy, geo-resources and geo-hazards in general. The European continent and its ocean-continent margins provide an excellent natural laboratory to examine the impact of geodynamics and climate on topography at the earth's surface. The overview presented here demonstrates the need for a further understanding of the earth system across space and timescales. Cross-border scientific cooperation on a full pan-European scale, benefiting from funding opportunities offered by the European Commission and a pro-active role in bottom-up self-organization involving members of the Earth and Cosmic Sciences section of Academia Europaea, is needed more than ever.

Introduction

To have received the Gold Award at the Building Bridges Conference of Academia Europaea in Barcelona (Figure 1), means a lot to me, especially thanks to the

Figure 1. Sierd Cloetingh receives AE Gold Medal after laudation from Robert-Jan Smits (right) and introduction by Carl-Henrik Heldin (left).

Figure 2. AE Foundation meeting, Cambridge 1988.

wonderful laudation and the very warm and personal words by Robert-Jan Smits. To be part of this community, the Academy of Europe, which I joined in 1993, has always been a source of inspiration for me. Our Academy is very close to my heart, because it is a bottom-up initiative of a group of people (amongst them Ole Petersen, see the group picture – Figure 2 – of the foundation meeting in 1988 in Cambridge). They decided that Europe needed an academy at the time of major changes in the European landscape, and this bottom-up spirit is still there today. Currently, we are a truly pan-European academy with 5000 members from all fields of science and scholarship, including the social sciences and humanities. A recent highlight was the celebration of our 30th anniversary at the Royal Society (Figure 3). It is this mix of scholarship and diversity in nationalities that has positioned us well for our role in the Scientific Advice Mechanism of the European Commission (SAM), designed by Robert-Jan Smits in his capacity as Director-General for Research and Innovation

https://doi.org/10.1017/S106279872300008X Published online by Cambridge University Press

Figure 3. Thirtieth anniversary of AE, celebrated at the Royal Society in London in 2018. Front row from left: Lars Walloe, Founding President Arnold Burgen, Eva Kondorosi, Robert-Jan Smits with Gold Medal, Richard Catlow, Jürgen Mittelstrass, Sierd Cloetingh. Second row: Nicole Grobert, Johannes Klumpers and Ole Petersen. Back row: Executive Secretary David Coates and Ortwin Renn.

of the European Commission. As a member of the SAPEA (Science Advice for Policy by European Academies) consortium, Academia Europaea has been the lead academy for the preparation of a number of SAPEA's Evidence Review Reports (see Figure 4) supported very effectively by the Academia's knowledge hub in Cardiff, directed by Ole Petersen. I am also very grateful to the Academia Europaea for enabling me to synergize two of my passions – earth science and the European project. It was within Academia Europaea that many of the developments that I have been involved in were born. In a bottom-up spirit, this article reports on a brief journey into our earth system. (Thus, it likely comes as no surprise that 'bottom-up' is in title of this paper.) I will reflect deeply into the earth, to the core–mantle boundary at a depth of 3000 km. The deep earth might sound remote to most of us, but it nevertheless has a strong impact on our lives on the earth's surface.

The Plate-tectonic Revolution in the Earth System

I have been very fortunate to have started my bachelor's degree study in earth sciences at the time when very important changes in the field were taking place. The classical view of the structure of the inner earth had always been a spherically symmetrical object, with a silica-rich crust, underlain by a silicate mantle and an iron/nickel-rich core. It was widely accepted that there is heterogeneity in the crust, with pronounced differences between the oceans and the continents, but at the deeper levels the earth's structure was assumed to be homogeneous. This somewhat static picture changed completely with the plate-tectonic revolution, which took place around the time I entered the Earth Science building at Groningen University in the

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Figure 4. Delivery of the third scientific opinion of the SAM Group of Chief Scientific Advisors and the SAPEA Evidence Review Report (ERR) "Food from the Oceans" (FFO) to the European Commission in 2017. Front row from left to right: Poul Holm (Chair SAPEA FFO Working Group), Carina Keskitalo (Member Group of Chief Scientific Advisors), Karmenu Vella (EU Commissioner for Environment, Maritime Affairs, and Fisheries), Rolf-Dieter Heuer (Chair Group of Chief Scientific Advisors), Carlos Moedas (EU Commissioner for Research, Science, and Innovation), Günther Stock (President ALLEA).
Top row from left to right: Janusz Bujnicki (Member of Group of Chief Scientific Advisors), Dag Aksnes (Chair SAPEA FFO Working Group), Pearl Dykstra (Co-Chair Group of Chief Scientific Advisors), Sierd Cloetingh (President of SAPEA's lead academy for FFO). (Photo: European Commission.)

northern Netherlands. Plate tectonics was born in the oceans (Vine and Matthews 1963; Le Pichon *et al*. 1973). It was a by-product of the Cold War resulting from the efforts by the US and some western European countries to map the ocean floor, particularly in the context of finding safeguards for nuclear submarines. The concept of plate tectonics mostly focused on the horizontal motions of the tectonic plates. The basic idea is simple. Hot material coming up from the deeper earth creates spreading ridges and volcanism in the ocean, solidifying at the surface. Next, the oceanic floor material is carried laterally to the sides, where, at a certain moment when it has cooled enough and is gravitationally unstable, it will descend back into the mantle (Figure 5). This downgoing movement of a tectonic plate with its physico-chemical recycling in the underlying mantle, and its creation of a convergent plate boundary with an ocean trench and zones of intensive seismicity and volcanism, is known as "subduction". In the first years after the plate-tectonics revolution, the popular paradigm was that all deformation occurs at the plate boundaries without affecting the rigid plate interiors. By its very nature, as a theory born in the oceans and by studying ocean-floor spreading and subduction, its focus was on the horizontal plate motions. Relatively little attention was given to the interiors of the continents. Apart from ideological reasons, as these ideas were born in the western world, this theory had limited impact in the former Soviet Union, partly because it

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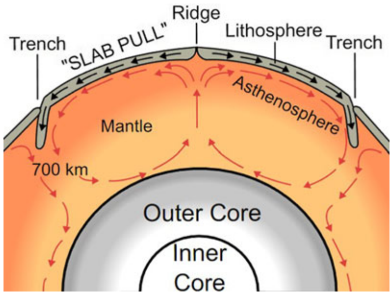

Figure 5. Conceptual drawing of assumed convection cells in the mantle. Below a depth of about 660 km, the descending slab begins to soften and flow, losing its form. (US Geological Survey).

did not contribute much to the understanding of the geological evolution of the Russian platform and vast areas of the Siberian continental shield and the surroundings. It was only at the time of Gorbachev's Perestroika and Glasnost that plate tectonics became accepted in the Soviet Union (Lobkovsky *et al.* 1996; Nikishin *et al.* 1993; Burov *et al.* 1993). Another fortunate development was the disappearance of the iron curtain in Europe at that time, enabling extensive scientific cooperation in earth science on a full pan-European basis. Geology is by its nature cross-border science, often involving PhD-student traffic circulating within and between western and eastern Europe (Horváth and Cloetingh 1996).

The Deep Earth: Recorder of Birth and Death of Tectonic Plates

We are fortunate that deep earth can be probed with several different tools. Drilling the Earth crust, however, is limited to ca. 10 km depth. Vastly more information on the deep earth can be obtained from seismology. Seismology has provided the fundamental information on the structure of the deep earth, resulting in the understanding and acceptance that the Earth is composed of crust, mantle, and core. With further advancements in seismology this first order subdivision was refined by dividing the crust, mantle and core into distinct layers. With the advent of plate tectonics, the concept of the lithosphere has emerged, juxtaposing the crust and the more viscous part of the upper mantle. Originally, it was assumed that the heterogeneity of the earth's structure is limited to the crust, while the mantle and core were considered as a simpler, homogeneous radial structure. This view has dramatically changed during the past few decades. I was lucky that when I joined a masters programme at Utrecht University, I could be part of an active research group in theoretical geophysics headed by Nico Vlaar, with a focus on seismology and later also on tectonophysics. Figure 6 displays a picture taken many years later after Vlaar's retirement, with him standing amidst a group of his former PhD students. He not only initiated a very vigorous research programme in geophysics with many doctoral students, but he also involved the master's students. One of the

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Figure 6. Group picture reunion of former PhD students of theoretical geophysics group Utrecht with their promotor Professor Nicolaas Vlaar (middle).

very first papers I was involved in was on the core–mantle boundary (Van den Berg *et al*. 1978). What we found was a result we did not understand at that time. We detected inhomogeneity near the core–mantle boundary at depths of 3000 km. We used information from seismic waves propagating through the mantle and core and waves scattered in the lower mantle recorded by seismic networks operated by the UK Atomic Energy Authority (Figure 7). These stations were located in the UK, Australia, India and Canada to monitor nuclear tests in the former Soviet Union. Today, we have a much better resolution of the earth's structure at these levels in the very deep mantle. Many years after we published our paper, the solution came from seismic tomography, a more three-dimensional tool, pioneered by Guust Nolet (Nolet 2008), one of the students of the Utrecht group who guided me in the early 1980s in seismological studies of the crustal structure of the Mediterranean and continental margins (Cloetingh et al. 1980). Figure 8 shows a tomographic section from the earth's surface to a depth of around 3000 km, where the abbreviation CMB means the core–mantle boundary. Another boundary with a phase change and a density jump at a depth of around 660 km, marks the transition between the upper and the lower mantle. In the early days of plate-tectonics, the prevailing idea was that these downgoing plates will never go down deeper than this level of 660 km. Today, we know from seismic tomography that this transition zone might be a graveyard for the downgoing plates. The latter are characterized by higher seismic velocities than predicted by the standard model for a homogeneous spherical earth, as they are colder than the surrounding mantle. In contrast, areas with lower seismic velocities, correspond to zones where temperatures are higher than the standard model. As evident from Figure 8, slabs can also descend to much deeper levels in the mantle, reaching depths of around 3000 km. It appears, therefore, that we have two levels of graveyards for the subducting, downgoing plates: one at a level of 660 km, and another one at the core–mantle boundary. The latter now explains the enigmatic

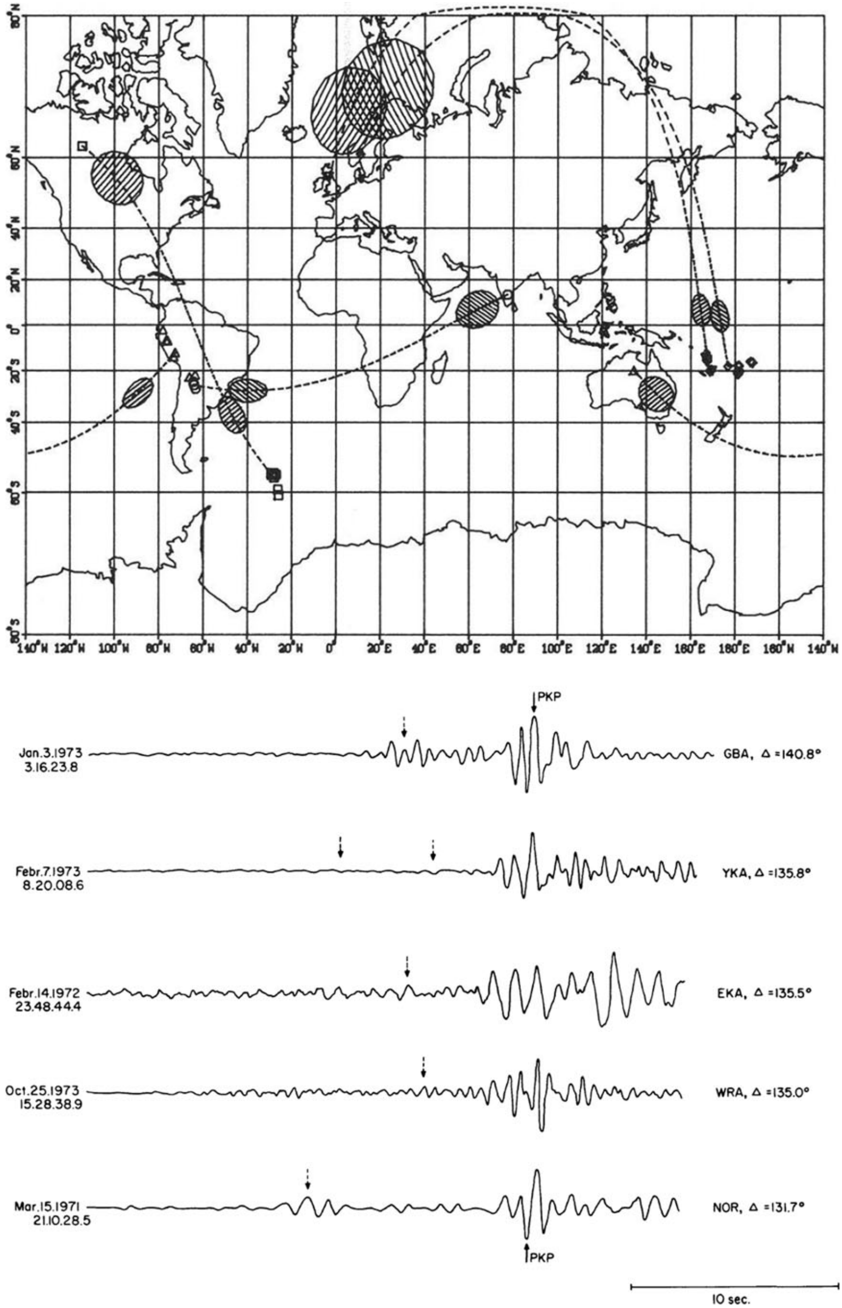

Figure 7. Seismological study of the lower mantle close to the location of the Core Mantle Boundary (CMB), utilizing precursors to seismic waves traversing the earth's core. These precursors are the result of the scattering of these waves by heterogeneities in the lowermost mantle and recorded by seismic networks operated by the UK Atomic Energy Authority sampling different locations in the lower mantle around the globe (Van den Berg *et al.* 1978).

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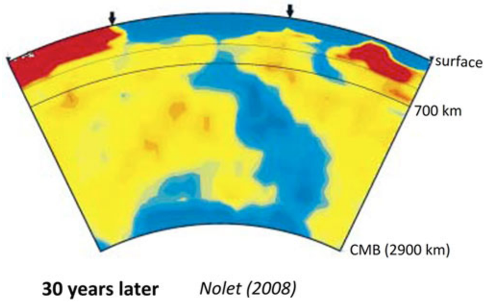

Figure 8. Seismic tomography resolving deep earth structure, demonstrating of descendant cold tectonic plates (marked in blue, detected by seismic velocities higher than predicted by the standard model for velocities in a spherical symmetric earth) to depths close to the location of the core–mantle boundary, as well as plates stagnated at depths around 660 km at the earth's transition layers, separating the upper and lower mantle, corresponding to phase changes in the silicate mantle. Red areas correspond to a hot upper mantle with reduced seismic velocities (Nolet 2008).

outcome of the study I was involved in as a Master's student. This is a striking example of curiosity-driven research. Another important development which has accelerated inexorably is the field of computational geodynamics. Simulations in this field have made it evident that downgoing plates can descend all the way from the earth's surface to the core–mantle boundary – providing, in turn, a recycled source for subsequent upwelling of hot material. Evidently, the process of subduction is the key in the downward movement of the plates into the deep earth. The initiation of subduction – this fascinating and still unresolved problem – was the topic of my PhD. Here, I was very fortunate to have close interaction with and guidance by Rinus Wortel, leading to many joint papers on lithospheric stress fields (Wortel and Cloetingh 1981; Cloetingh *et al.* 1985). Although the paper on the initiation of subduction resulting from my PhD project was accepted by *Nature*, it was a kind of negative result, because I demonstrated that it was very difficult to initiate subduction, consistent with the notion that at present we hardly see it occurring (Cloetingh *et al.* 1982). Actually, I was somewhat relieved, when soon after my PhD I met one of the greatest geologists of his generation, Peter Ziegler, at that time head of global geology of Royal Dutch Shell, who suggested to me that with the same methodology I could do something of even greater significance, i.e., the study of sedimentary basins.

From Initiation of Subduction to the Formation and Evolution of Sedimentary Basin Systems and Continental Topography

Sedimentary basins contain mankind's primary natural resources, including hydrocarbons, fresh water and geothermal energy. They are also indispensable for unravelling earth history as contained in the record of the interplay of tectonic

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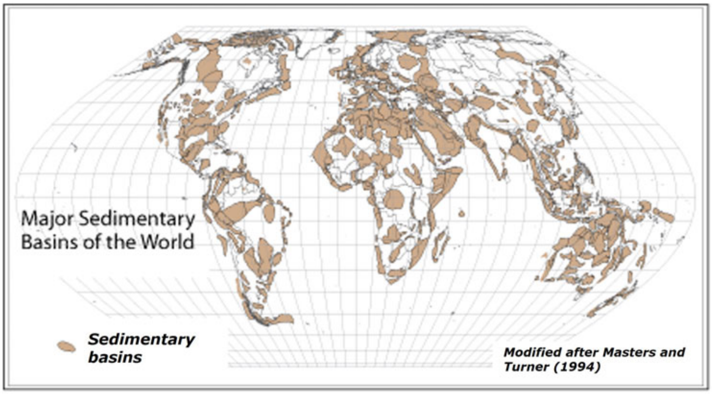

Figure 9. Global distribution of sedimentary basins. Inset: Peter Ziegler.

processes, sea level change and climate (Cloetingh *et al.* 1985; Cloetingh and Ziegler 2007). The earth has a very good memory, allowing us to reconstruct its past, and thereby feeding quantitative predictions for the future of our planet (Cloetingh *et al.* 2005). Figure 9 displays a map of the global distribution of the sedimentary basins of the world, covering vast areas of the earth's surface. The sedimentary basins also provide us with clues to quantify the vertical motions of the earth's crust, with a direct connection to the earth's topography. In a paper I published with Bilal Haq a few years ago, we made the point that inherited landscapes are very closely linked to past and present sea level change (Cloetingh and Haq 2015). This finding provides another example of the memory of the earth system with a driving force deep in the earth for many of these surficial landscapes. In that paper we also suggested that ocean water entrainment at downgoing subduction zones and its expulsion, with a time lag, at the mid-ocean ridges can be a feasible mechanism for long-term sea level variations.

TOPO-EUROPE: Coupled Deep Earth and Surface Processes with Europe and its Continental Margins as the Natural Laboratory

The above provided the motivation to develop a pan-European large-scale collaborative research programme called TOPO-EUROPE. TOPO-EUROPE considered continental Europe and its adjacent ocean–continent margins and oceanic basins (such as the Mediterranean and northern Atlantic) as a natural laboratory to investigate the interaction between the processes operating deep in the earth, on the surface and also in the atmosphere (Cloetingh *et al.* 2007). Figure 10 displays seismic tomographic cross-sections through a number of key areas in Europe, provided by Wim Spakman, to a depth of 800 km. The areas in the upper mantle in red are the zones where we have upwelling of hot upper mantle material and the areas in blue are the areas where we have subduction and down-thrusting of the lithosphere to greater depths. The first occurs, for example, below the Pannonian

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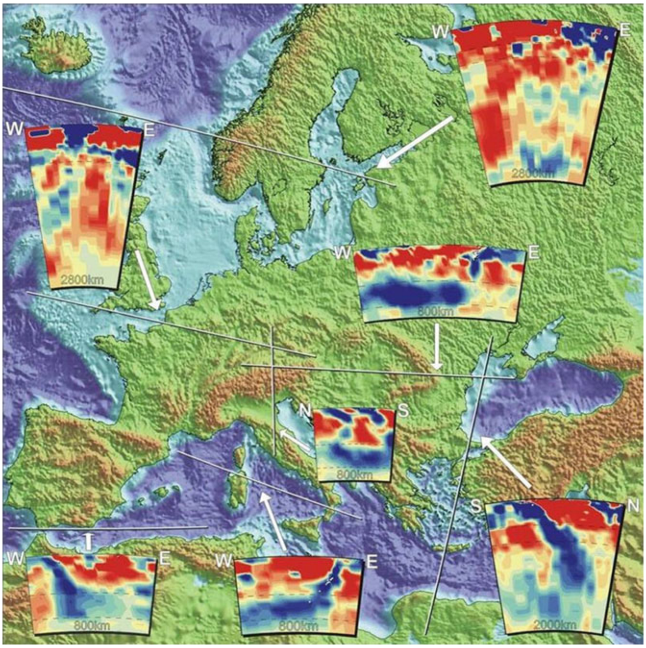

Figure 10. TOPO-EUROPE fundamental premise. Inset: Images from seismic tomography for different slices through Europe's upper mantle, demonstrating pronounced heterogeneity. Figure conventions as in Figure 8 (Courtesy Wim Spakman.)

Basin of Hungary. The latter occurs, for example, below the Romanian Carpathians, below Crete, the Tyrrhenian Sea, and in the Gibraltar area. This is a striking illustration of heterogeneity in the earth's mantle underlying the European continent with major consequences for its surface topography. According to the paradigm of plate tectonics, in its early phase, mountains in Europe are basically by-products of the interaction of tectonic plates in the Mediterranean, where Europe meets Africa. However, in Europe we have also substantial topography far away from the plate boundaries, as in southern Norway. Also fascinating is Iberia as a microcontinent with an average elevation higher than the average elevation of Switzerland. For a long time, the causal mechanisms for this intraplate topography have remained enigmatic. However, the earth science community now has the tools to reconstruct the evolving continental topography and to link it to processes operating at deeper levels. With the TOPO-EUROPE programme, developed with the support of the International Lithosphere Project, we received ca. €15 million funding for a large-scale European Collaborative Research Effort (EUROCORES) coordinated by the European Research Foundation (ESF) (Cloetingh and Willett 2013). In addition, a TOPO-EUROPE inspired programme on the topography of Iberia (Topo Iberia) obtained an additional €8 million from the Spanish National Research Council, CSIC. In the EUROCORES project with 23 participating European countries, we were able to employ 60 young researchers, forming a community that still exists. I am

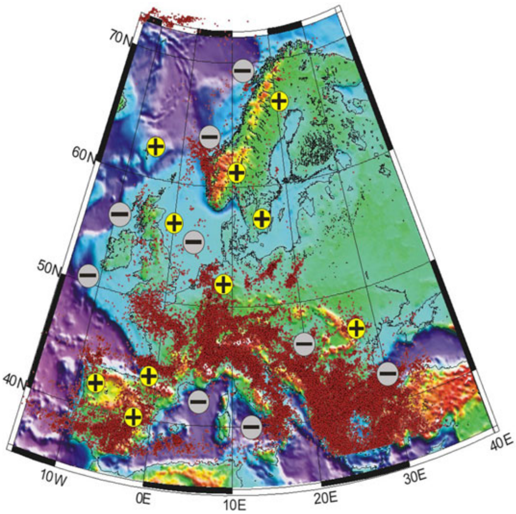

Figure 11. Intraplate seismicity and vertical movements of the European continent (Cloetingh *et al.* 2007). Red dots indicate epicentre locations of earthquakes. + signs indicate current surface uplift; – signs indicate current surface subsidence.

very pleased that among the members of the Young Academy of Europe, several young members have grown up in this community. Europe has a pronounced topography, a significant part of which is at first sight enigmatic, while Europe's crust and lithosphere are not exactly rigid. In the early paradigm in plate tectonics, deformation was considered to be concentrated at the plate boundaries. From the distribution of earthquakes in Europe we see that this is evidently not the case (Figure 11), and earthquakes occur far from the plate boundaries. In addition, we have a very rich spectrum of differential motions in Europe, where some areas are observed to go up, while other areas continue to go down (Figure 11). These earthquakes evidently have an impact on the assessment of seismic hazards, as illustrated by the seismic hazard map of Europe, displayed in Figure 12, financed by the European Commission. High seismic risk is characteristic for areas around the Mediterranean, but also for the Romanian Carpathians area, very close to the city of Bucharest, and also elsewhere. This is illustrated in Figure 13 for the Rhine Rift which formed the Rhine Valley, a site of major concentration of infrastructure in Europe (see also Figure 14 for other natural hazards associated with differential topography).

Synergy between TOPO-EUROPE and Academia Europaea

It should therefore come as no surprise that the TOPO-EUROPE programme was born in the Rhine valley area in a workshop organized by the Earth Science section of Academia Europaea hosted by the Klaus Tschira Foundation, with excellent

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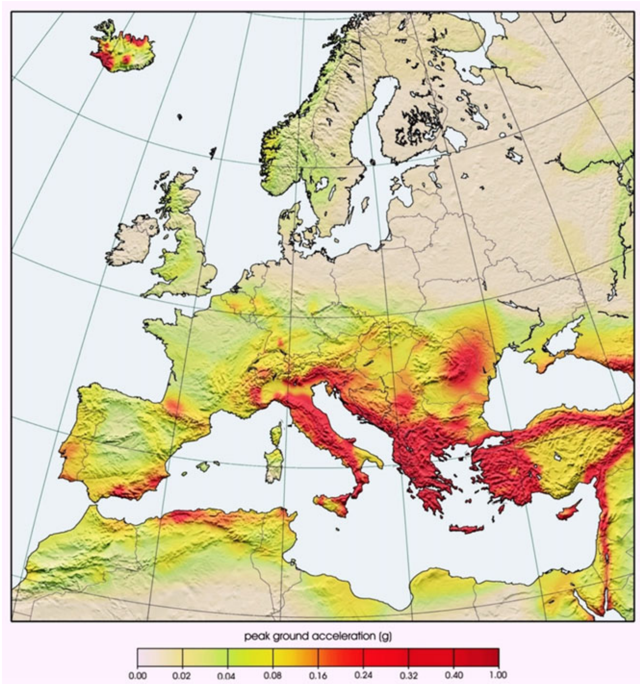

Figure 12. Seismic hazards maps of Europe. Red areas mark sites of high seismic hazard (Giardini *et al*. 2014).

support provided by David Coates. At this very moment (Figure 15), Academia Europaea brought the community together to pave the way for the next generation of solid earth science research in Europe. In doing so, we were standing on the shoulders of a number of giants in our field (Figure 16). I have already mentioned Peter Ziegler, but I would also like to mention Karl Fuchs, Stephan Mueller and Alan Green. Stephan Mueller was the founding president of the European Geophysical Society. I also had the great fortune to stand shoulder to shoulder with colleagues and friends of my own generation, and even a little bit younger. All of them were members of the Earth Science section of Academia Europaea. Therefore, in our community, Academia Europaea, in addition to being inspirational on general issues, has also played a key role in the community building process in the earth science area.

TOPO-EUROPE benefits from European research facilities and know-how (e.g., the European Plate Observing System EPOS), essential to advancing the understanding of the role of topography in earth system dynamics. The principal objective of the network, initiated within the Earth and Cosmic Science section of Academia Europaea, has been twofold. Namely, to integrate national research programmes into a common European network to integrate activities among TOPO-EUROPE institutes and participants. As such, it has served as an interdisciplinary forum to share knowledge and information in the field of the neo-tectonic and topographic evolution of Europe, to promote and encourage multidisciplinary

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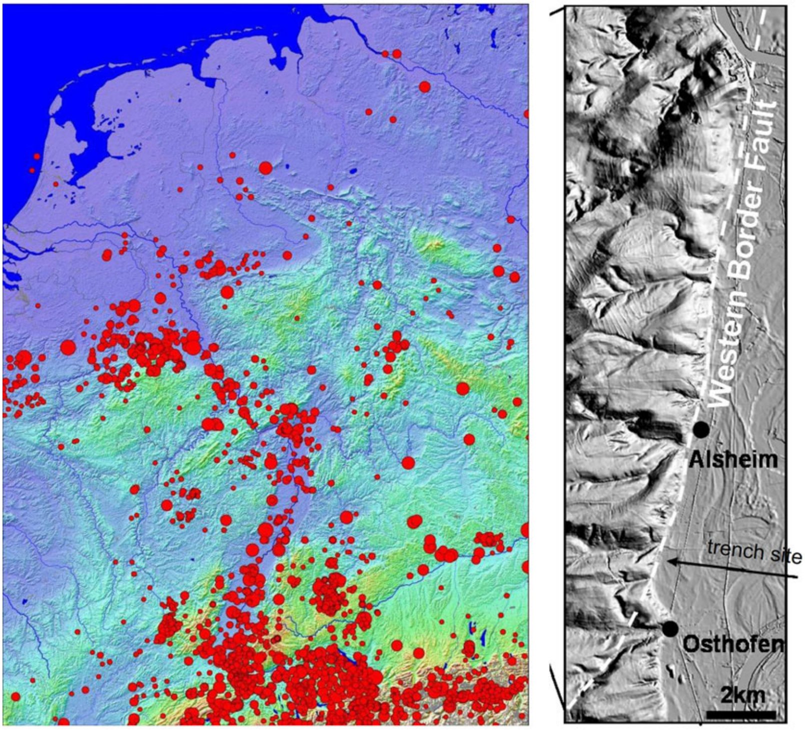

Figure 13. Neotectonics, fault structures (for the upper Rhine rift, right panel) and seismicity in the Alpine foreland. Red dots mark location of earthquakes (Cloetingh *et al.* 2007).

research on a truly European scale, to increase the mobility of scientists and to train young scientists.

Within Europe, we selected a number of sub-regions where we could investigate some specific problems. Because of space limitations, I will focus on the Northern Atlantic Ocean and the transition to Scandinavia. In addition, I will briefly discuss the Massif Central of France and the Eifel Region, both volcanic areas in northwest Europe where our predecessors have witnessed enigmatic volcanic activity in the middle of our continent.

Fingerprinting Plumes in the Earth's Mantle

Figure 17 shows an exciting result from an ERC-funded project carried out by the seismology group in Utrecht. As is well-known, ERC aims at breakthrough science and that was certainly the case with this work that is displayed here as a depth slice through the northern Atlantic and adjacent areas between 100 and 200 km depth. Red areas represent upper mantle manifesting the uprise of a hot mantle plume. It is not surprising that this area also underlies the Northern Atlantic spreading ridge, and Iceland, known for its continuous volcanic activity. Iceland is also a site of interest

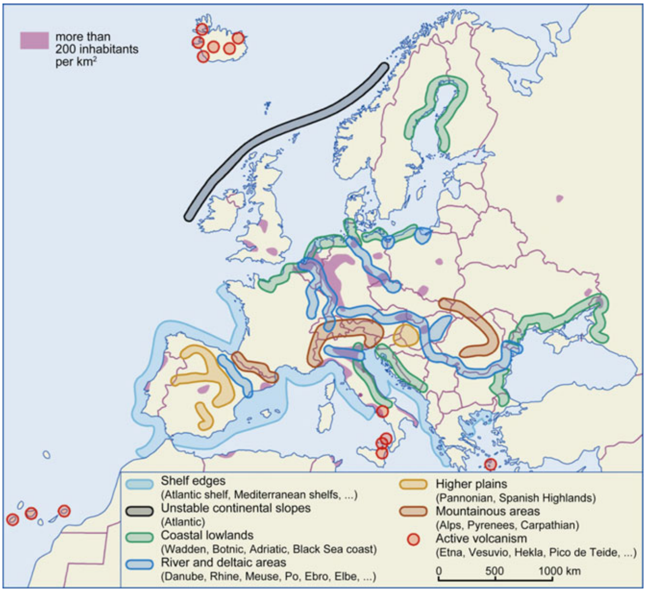

Figure 14. Role of topography in natural hazards (Cloetingh *et al.* 2007).

Figure 15. Group picture TOPO-EUROPE meeting Heidelberg 2006, organized by Academia Europaea (courtesy David Coates).

for deep drilling for geothermal energy (World Energy Council (WEC)) (Cloetingh *et al.* 2023). Interestingly, one of the side lobes of the plume extends all the way to the base of the mountains of southern Norway, far away from the plate boundaries. This side lobe of the plume provides an explanation for this enigmatic feature as a hot upper mantle is pushing up the overlying plate. A hot upper mantle is also present below northwest Britain, with recent volcanic activity, and seismic tomography has

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Figure 16. Standing on the shoulders of giants (upper row) and shoulder to shoulder with AE members of my own generation.

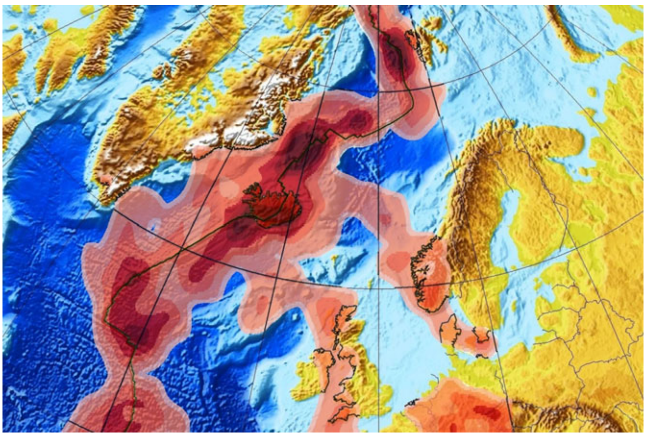

Figure 17. Seismic tomography depth slice through the Northern Atlantic at depths between 100 and 200 km, demonstrating the existence of a mega plume under Iceland and with side lobes extending to the mountains of Southern Norway, western Britain and the Eifel volcanic area of northwest Germany, marked by low seismic velocities (indicated in red) (Rickers *et al.* 2013).

also detected a hot upper mantle below the Eifel region of northwest Germany characterized by very recent intraplate seismic and volcanic activity. In addition to probing the depths of the earth with seismological methods, we can also resolve earth structure with information from earth-oriented space satellite missions. Researchers from the German Helmholtz Centre for Geosciences in Potsdam (GFZ) have made fundamental contributions in this domain. In Figure 18(a) the so-called Potsdam potato is displayed, showing areas with a deficit in density in the deeper earth, also detected by seismic tomography, including the northern Atlantic, but also major parts of the Alpine Himalayan belt. In other areas such as the Congo basin of Central

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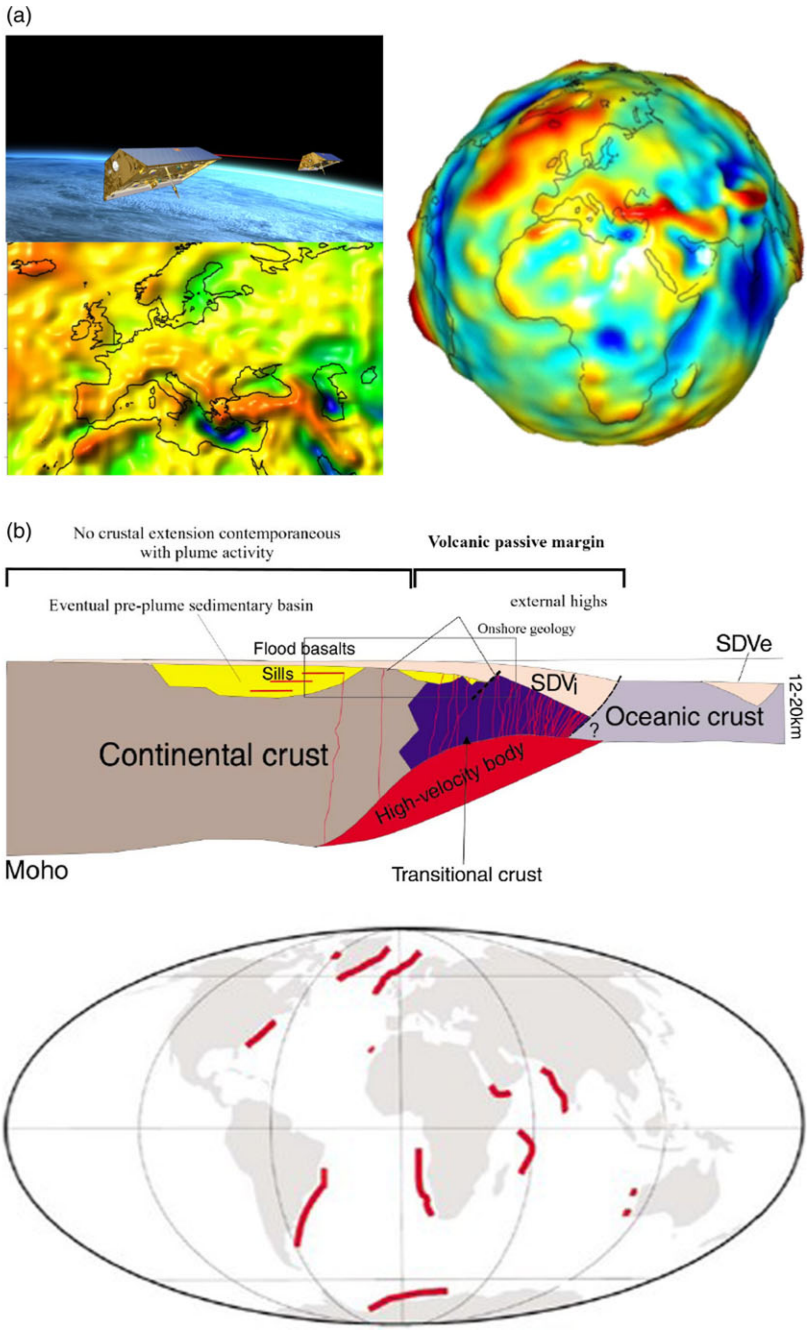

Figure 18. (a) Satellite derived density anomalies in the mantle under Europe and adjacent areas (left panel) and for the globe (the so-called Potsdam potato). Red/brown colours mark areas with mass deficit. Blue areas mark areas with mass excess. (Courtesy: German Helmholtz Centre for Geosciences (GFZ), Potsdam.) (b) Volcanism in plate interiors and ocean–continent margins in the plate interiors, demonstrating massive upwelling of mantle material. More than half of these so-called passive continental margins are of volcanic nature (Geoffroy 2001).

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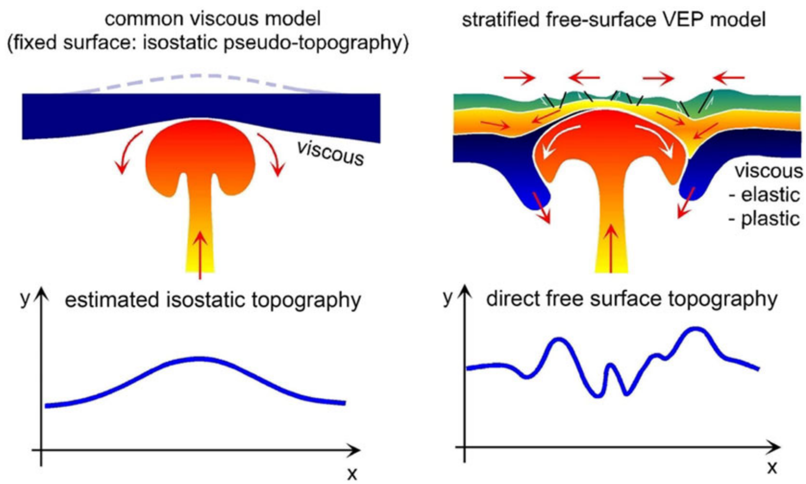

Figure 19. Role of plumes in intraplate deformation. Left: Topographic response to plume emplacement (top) resulting in a broad zone of uplift of overlying oceanic lithosphere. Right: Topographic response to plume emplacement, resulting in ductile flow in the lower crust and down thrusting of continual plates (top) and differential topography with highs and depressions at the earth's surface (bottom) (Cloetingh *et al.* 2021).

Africa and the northeast Indian Ocean, an excess of mass at deeper levels is detected. In the zoom-in on Europe, areas interpreted as upper mantle are visible that are not only of low density but also of high temperature. These domains include the mega-plume under Iceland and areas such as the Anatolian Plateau of Turkey, the Pannonian Basin of Hungary, the Atlas Mountains of northern Morocco (Figure 18(a)) and also many rifted continental margins around the globe (Figure 18(b)). Evidently, the inner earth is far from static, with subduction zones where the downgoing tectonic plates are recycled in the mantle but also areas where hot mantle material comes up all the way from 3000 km and, in addition, many smaller secondary plumes rise up from a level of 660 km. As only recently realized, a fundamental difference occurs in the mode of interaction of these rising plumes and the overlying tectonic plates in oceanic and continental settings. In oceanic settings, such as the oceanic plateaus in the Pacific Ocean, the surface expression of a plume is a large-scale topographic uplift of the ocean floor, called an oceanic swell. In contrast, an uprising plume under a continent causes a differential topography with both uplift and subsidence, the latter is capable of producing sedimentary basins (Figure 19). Plume interaction with the continental lithosphere can even lead to down-thrusting of the continent into the adjacent underlying mantle, providing a hitherto overlooked mechanism for initiation of subduction (Cloetingh *et al.* 2021). Proposing this alternative mechanism for subduction initiation more than 30 years after I finished my PhD topic is an illustration of the importance of pursuing curiosity-driven research, leading to unexpected outcomes. This finding was a by-product of our investigation on the mechanics of plume–lithosphere interactions.

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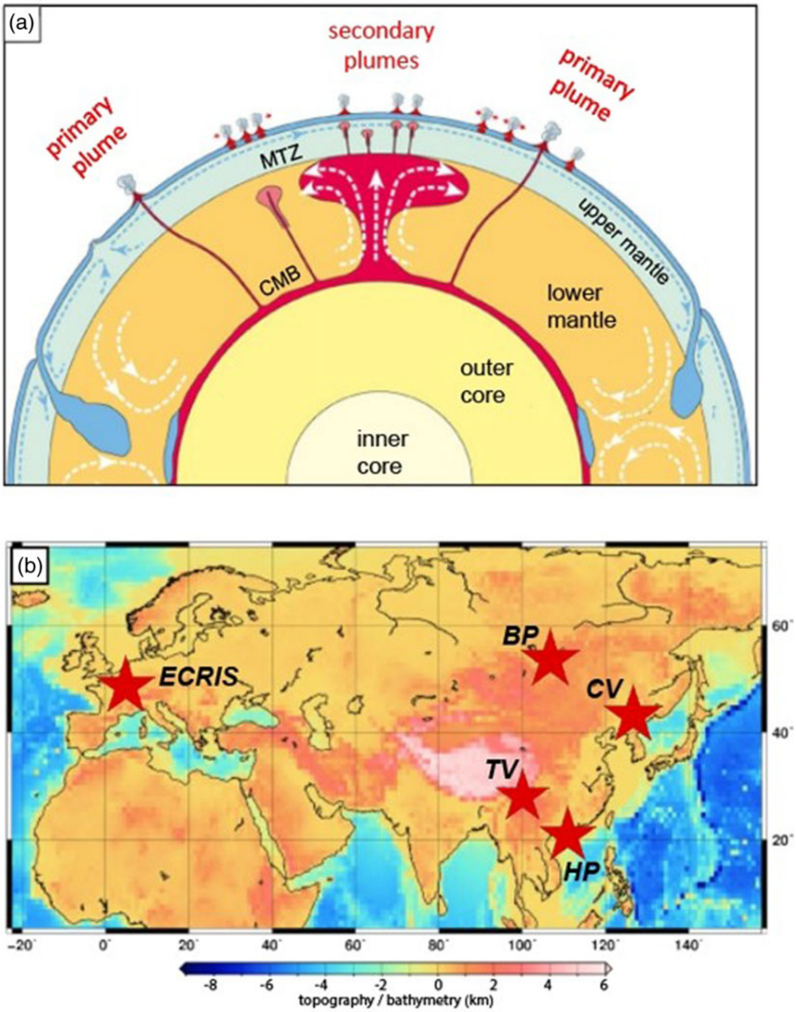

Figure 20. Distribution of secondary plumes (locations marked by red stars) analysed for mode of penetration in the overlying lithosphere (bottom). The top panel illustrates connections between secondary plumes in the upper mantle and primary plumes rising upward from the Core Mantle Boundary (Courtillot *et al.* 2003).

More recently, we further elaborated on this process not only for large primary plumes, but we also examined what we call secondary plumes, which are rising upward from the transition zone in the mantle at a depth of around 660 km (Figure 20) (Morgan 1971; Courtillot et al. 2003). These small plumes were first detected by seismic tomography in Europe (Figure 21) (Granet *et al.* 1995; Ritter *et al.* 2001). They have been called baby plumes, not because they have been geologically only recently emplaced, but because of their small diameter of approximately 100 km (Cloetingh and Ziegler 2009). In a recent paper, we analysed observations on secondary plumes from Europe, where they were initially detected,

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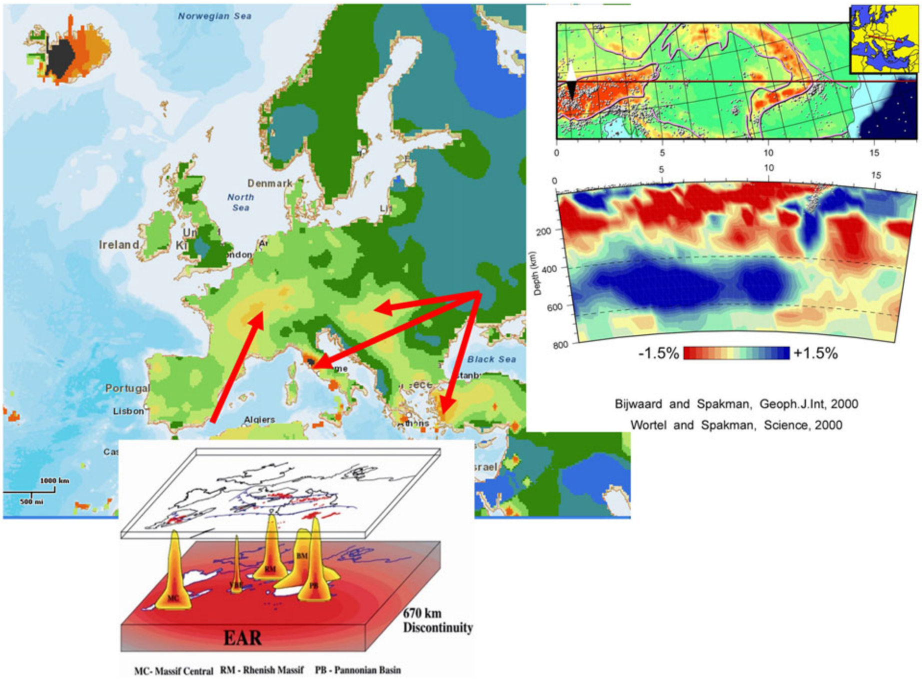

Figure 21. Hot upper mantle under Europe detected by seismic tomography for areas such as the Pannonian Basin (right panel) and various areas including the French Central Massif and the Eifel region underlain by secondary plumes (Granet *et al.* 1995).

and subsequent observations from China and Japan (Figure 20), to examine the mechanisms of their penetration to shallow depths in the overlying lithosphere, sticking up like fingers (Cloetingh *et al.* 2022). In general, Europe is characterized by a hot upper mantle, such as detected under the Pannonian Basin of Hungary. In the case of the Eifel area, the secondary plume (of hydrous nature) makes it all the way to the surface. In the case of the secondary plume detected under Southeast Asia, we observe a mode of arrowhead penetration of the lithosphere, whereas Figure 22 shows an example of a plume that is already dying and where we missed the moment where the plume interacted with the lithosphere at an earlier stage. We performed numerical experiments to understand these very intriguing different modes of penetration from finger-shaped to arrowhead. This has provided novel insights in the emplacement processes and their impact on earth structure and the thermal regime at or near the surface. As a spin-off, the findings of TOPO-EUROPE have contributed to the science base for research on geothermal energy exploration.

A Forward Look on Coupled Deep-earth and Surface Processes

Integrated studies of the full earth system across space and time scales are rapidly advancing, such as exemplified by the recent conception of the International Union

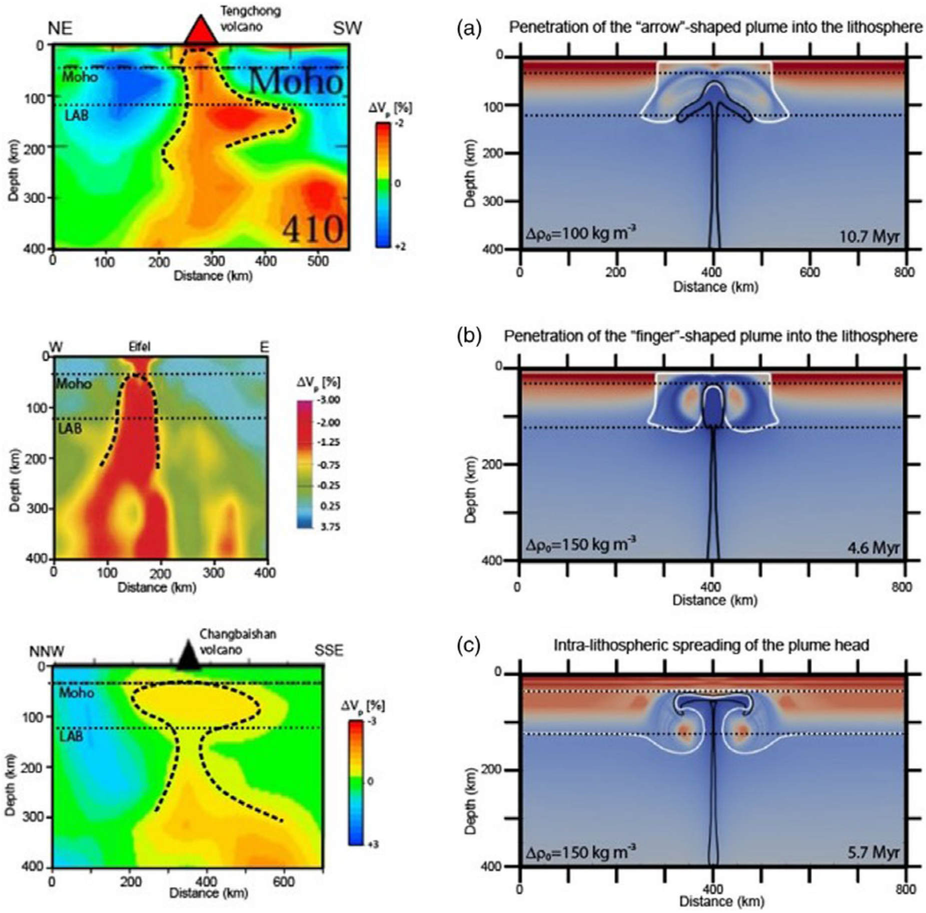

Figure 22. Comparison of modelled plume-emplacement modes (left panels) with natural examples of seismic velocity anomalies in the upper mantle (right panels). (a) Modelled 'arrow'-shaped plume versus asymmetric 'arrow' beneath the Tengchong volcano. (b) Modelled 'finger'-shaped plume versus columnar structure in the sublithospheric and lithospheric mantle below the Eifel volcanic fields. (c) Advanced stage of the 'finger' scenario with intra-lithospheric spreading of the plume head versus intra-lithospheric 'mushroom' underlying the Changbaishan volcanic area (Cloetingh *et al.* 2022).[27]

of Geosciences' (IUGS) first big science programme on Deep-time Digital Earth (Oberhänsli, 2020). Probably one of the important developments in solid-earth science over the past decade has been the recognition of the importance of linking deep earth dynamic processes with surface and near-surface geologic processes (Cloetingh *et al.* 2007; Cloetingh *et al.* 2020). Deep earth research, encompassing fields such as seismology and mantle geodynamics, has traditionally operated distinctly from fields focusing on dynamics near the earth's surface, such as sedimentary geology, geomorphology, and climate/paleoclimate. However, as realized by the International Lithosphere Program (ILP), these endeavours have

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one thing in common, i.e., the study of earth's topography and the prediction of its origin and rates of change. Observations from surface studies, such as basin-wide stratigraphy, geomorphology of landscapes, changes in surface elevation, and changes in sea level, provide some of the principal constraints on geodynamic and tectonic models (Cloetingh and Haq 2015). Conversely, deep geodynamic processes give rise to topography, thereby modifying regional climate, erosion, and sediment generation that are the basis of surface geology. The lithosphere, due to its stratified rheological structure, acts as a non-linear "filter" for deeper sources, attenuating long deformation wavelengths and creating new, shorter wavelength deformation, giving a surface response more complex than that of the mantle source (Cloetingh *et al*. 2021; Koptev *et al*. 2021).

TOPO-EUROPE and EPOS: A Solid Science-base for Earth System Science on a European Scale

It is the surface manifestations of these deep geodynamic processes modified by mantle–lithosphere interactions that have significant societal impact by (1) creating natural hazards, such as earthquakes and mass movements, and (2) controlling the distribution of natural resources including fossil fuels and geothermal energy (Cloetingh *et al.* 2020; Limberger *et al*. 2014, 2018). The relevance of research conducted in both the deep earth and surface regimes is thus strongly enhanced through a focus on their interaction. Research on enhanced geothermal systems has developed as a vigorous focus for networking European earth science research institutions and provides an illustrative example of connecting basic research in coupled deep earth and surface processes with societal relevance in the current era of energy transition to a more sustainable world.

In the EU-funded ENGINE project on enhanced geothermal energy systems (EGS), many of the findings described above were applied. Research such as that carried out in TOPO-EUROPE has yielded insights in the location of prospective areas with high heat flow, such as the Pannonian basin of Hungary, Western Turkey, the Massif Central of France and the western Mediterranean region (Figure 23). Europe has a high potential for geothermal energy in areas such as Iceland, where extremely high heat flow enables electricity generation, but also primarily heating for areas with more modest heat flow. Here we benefit from extensive knowledge on the structure of the subsurface of Europe owing to more than 100 years of intensive geological and geophysical research. The sedimentary basins of Europe have been mapped in great detail in the search for hydrocarbons, providing an extremely valuable database for geothermal energy exploration and production. Figure 24 provides a cost basis prediction for geothermal energy made some years ago (Limberger *et al*. 2014). From this, we can identify a number of areas where the costs are relatively low, while the perspective is even brighter for the future. As illustrated by Figure 24, in the framework of ongoing energy transition, when we compare geothermal energy to hydrocarbons, a reversal will take place in the focus of the

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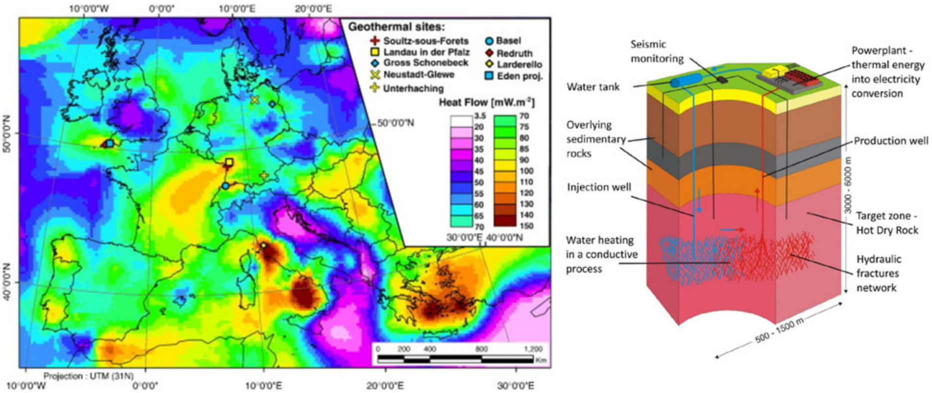

Figure 23. TOPO-EUROPE science base for energy resources. Left: Observed heat flow distribution for the European continent (Cloetingh *et al.* 2010). Right: Main elements of an Enhanced Geothermal System (EGS) consisting of production and injection wells drilled in a deep fractured rock and surface units for heat and power generation (Moska *et al.* 2021).

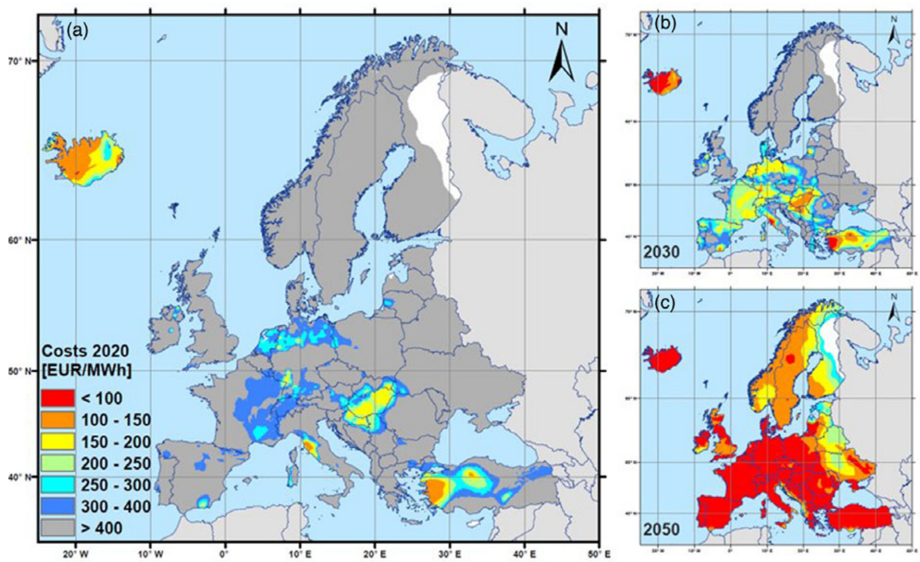

Figure 24. Geothermal energy potential for Europe: maps depicting the calculated minimum levelized cost of geothermal energy in (a) 2020, (b) 2030 and (c) 2050 (Limberger *et al.* 2014).

source areas for energy. The areas that now hold some of the major hydrocarbon resources are not always the areas which are associated with the hot upper mantle with a high potential for geothermal energy. Within Europe, the European Cenozoic rift system and the Pannonian basin have excellent conditions for the development of EGS systems. The first successful EGS stimulation in Europe was the Soultz project

https://doi.org/10.1017/S106279872300008X Published online by Cambridge University Press

Figure 25. European Plate Observing System (EPOS website: https://www.epos-eu.org/).

in eastern France (Gérard *et al.* 2006). Since then, further projects have been developed in the Upper Rhine Graben near the Soultz site (e.g., Landau, Insheim). The Basel EGS project in Switzerland, which was terminated after an induced earthquake, is a good example of the potential risks associated with reservoir stimulation (Deichmann and Giardini 2009). Such risks may be reduced with seismic monitoring and in-depth studies based on local stress conditions and the assessment of the pre-existing fracture network. The number of operating EGS sites in Europe has not increased significantly in the past years, and the share of electricity generation from EGS within Europe is not comparable to other renewables such as wind, solar and hydroelectric power (IEA 2021). To achieve a significant increase, exploration and technology developments in EGS and further successful demonstration sites are necessary in the future.

Apart from the development of new concepts, the European solid earth science community has been very fortunate that the European Commission has funded a major large-scale research infrastructure in this domain. The ESFRI project EPOS, the European Plate Observing System (Figure 25), is integrating distributed infrastructure in the solid earth sciences where different countries in Europe often have very complementary infrastructures. In EPOS, this not only creates the conditions for further progress for probing the earth system, but also for dealing with its societal impact for issues such as induced seismicity, unstable coastlines and carbon dioxide sequestration. This has also motivated major investments in EPOS infrastructure on a national level, such as in the case of the Netherlands (Figure 26). Also here, a close connection exists with the research agenda of TOPO-EUROPE, illustrating that in earth sciences, basic science and applied science are closely linked to mutual benefit. The successful integration in earth system science in the last decades will also facilitate the realization of effective cooperation between earth sciences with other sciences, including social sciences as had been advocated for (Holm *et al.* 2013).

Figure 26. EPOS-NL, the Earth Simulation Laboratory of Utrecht University, part of EPOS and EPOS-NL. Three examples of its experimental facilities.

Conclusion

Earth science is on the move. Following the plate tectonics revolution, now 50 years old, it is characterized by a high level of integration between its sub-disciplines. Its present momentum has set the stage for further scientific breakthroughs and building the knowledge base to address societal challenges in the earth environment and the role of geo-energy in the current energy transition.

Obviously, teamwork will be essential to make further progress in better understanding the earth system and its impact on geo-environment and geo-energy. Apart from thematic funding opportunities, brain circulation, networking and funding opportunities for individual researchers at different stages of their career ladder, by other funding instruments such as COST and ERC offered through Horizon Europe, have changed the European research landscape and will be essential to remain at the forefront of earth system research. Self-organization and commitment to community building by members of the Earth and Cosmic Sciences Section of Academia Europaea and members of the Young Academy of Europe are essential in this bottom-up endeavour facing earth system science on a pan-European scale.

Acknowledgements

I am very grateful to Academia Europaea for honouring me with its Gold Award. It has been a privilege to be part of our academy from my very first moment of membership onward. Working closely together with different generations of researchers and building a community in earth sciences, has been a great source of inspiration. Particular thanks go to all my co-workers, and the almost 80 PhD students from 18 different nationalities who completed their degrees with me, for joining me in my journey through system earth.

Technical assistance in the preparation of this manuscript, offered by Fred Beekman, Maureen van den Bosch and Juliet Davies, is highly appreciated, as well as thoughtful and constructive feedback by Don Dingwell, Bilal Haq and Eva Kondorosi.

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Sierd Cloetingh is Utrecht University Distinguished Professor. His research field is Earth Sciences. He has published more than 380 papers in international peer-reviewed journals (Scopus: 19,640 citations, h-index 77) and has been promoter of close to 80 PhD students of 18 different nationalities. Currently, he serves as Chair Regional Coordinating Committee Europe of the International Lithosphere Programme. Past functions include President of the Academia Europaea, Member and Chair of the Board of SAPEA (Scientific Advice for Policy by European Academies), President of the Association for European Cooperation in Science & Technology (COST), Membership of the Scientific Council (2009–2015) and Vice-President of the European Research Council (ERC), President of the European Geophysical Society (1998–2000), President of the International Lithosphere Programme (ILP, 2004–2017), Distinguished Professor of the Royal Netherlands Academy for Arts and Sciences (KNAW, 2006–2015), Editor-in-Chief of the international journal *Global and Planetary Change* and Chairman of the TOPO-EUROPE collaborative research programme. Sierd Cloetingh has received honorary doctorates from six European universities and numerous medals and awards. He is a member of the Royal Netherlands Academy of Sciences, the Royal

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