TOPO-EUROPE – From the Deep Earth to the Surface of Continental Europe and Its Margins

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Definition

Linking different spatial and temporal scales in coupled deep Earth and surface processes is a prime objective of the multidisciplinary international research program TOPO-EUROPE. The research approach of TOPO-EUROPE integrates active collection of new data, reconstruction of the geological record, and numerical and analog modeling. The results of the program focus on closely interrelated topics: deep Earth, lithospheric structure, mantle-lithosphere interactions, and sedimentary basins and geo-resources. Quantitative understanding of topographic evolution in space and time requires study of processes from the upper mantle through the lithosphere and crust and acting on the Earth's surface. The overview presented here demonstrates the opportunities for further understanding of topography through integrated studies of the full Earth system across space and timescales.

Introduction

One of the important developments in Solid-Earth science over the past decade has been recognition of the importance of linking deep Earth dynamic processes with surface and near-surface geologic processes (e.g., Cloetingh et al. 2007, 2013). Deep Earth research, encompassing fields such as seismology and mantle geodynamics, has traditionally operated distinctly from fields focusing on dynamics of the Earth's surface, such as sedimentology and geomorphology. However, these endeavors have in common the study of Earth's topography and the prediction of its origin and rates of change. Observables from surface studies, such as basin stratigraphy, geomorphology of landscapes, changes in surface elevation, and changes in sea level, provide some of the principal constraints on geodynamic and tectonic models. Conversely, deep geodynamic processes give rise to the topography, erosion, and sediment generation that are the basis of surface geology. The lithosphere, due to its stratified rheological structure, acts as a nonlinear "filter" for deeper sources, attenuating long deformation wavelength and creating new, shorter wavelength deformation, giving a surface response more complex than that of the mantle source.

Surface manifestations of these deep geodynamic processes modified by multifaceted mantle-lithosphere interactions have societal impact by (1) creating natural hazards, such as earthquakes and mass movements, and (2) controlling the distribution of natural resources such as fossil fuels or geothermal energy. The relevance of research conducted in both the deep Earth and surface regimes is thus enhanced through a focus on their interaction.

Long-term processes such as mantle flow drive the system of mantle-surface interaction. However, short-term processes such as erosion and climate tune the response. The continental lithosphere transforms deformation generated at its base by mantle flow, but surface processes control many of the observables such as topography, sediment, and exhumation rates, and thus further filter the source and even tune the response through cyclic processes such as climate. However, little is known on how far these interactions may go, or how these different processes are coupled or feed back into the dynamic system. Many modelling or theoretical studies show that erosion and sedimentation should have an impact on the subsurface evolution of crustal deformation, changing flow

H. K. Gupta (ed.), *Encyclopedia of Solid Earth Geophysics*, Encyclopedia of Earth Sciences Series,
https://doi.org/10.1007/978-3-030-10475-7_275-1

patterns and magnitudes in the ductile crust and mantle through changing gravitational stresses or kinematics.

This leads to many questions that remain to be tested. For instance, what is the impact of erosion and surface mass redistribution on mantle flow? What is the influence of protracted precipitation regimes on mountain building? and what is the budget of subduction in terms of sediments and water recycling? What is the sediment and tectonic load incidence on thermicity and sediment blanketing and on foreland flexure? How and on what timescales does the build-up of topography impact atmospheric circulation processes? How does the creation of topography modify shallow crustal stress fields and how does this impact seismicity and fault kinematics? How can we differentiate between geodynamic, tectonic, and surficial displacements of the Earth's surface if all processes are active? These and many other questions are still unsolved.

Tectonic, surface, and external forcing processes are responsible for the growth and decay of continental topography and sedimentary basins, i.e., the interplay between sediment supply and mass (re)distribution with the full range of deep Earth to surface processes. However, the mechanisms that link exhumation, formation of topography, and sedimentation are still poorly understood because of a lack of insight into the variability of the rates and scales of the underlying processes. TOPO-EUROPE explores the dynamics of these processes and the role played by large-scale lithospheric stresses. To this end, lateral variations of tectonic and erosion/sedimentation evolution through time are incorporated into dynamic models of topography evolution by integrating deposition in sedimentary basins with topography formation and evolution in neighboring source areas. This will provide new opportunities to analyze and quantify the interplay between deep Earth and surface processes, which is critical for novel evaluation of geo-resources and natural hazards.

Scientifically, the role of topography in the Earth's system is as a dynamic, active permeable boundary layer between solid Earth processes occurring at different depths and atmospheric processes. Clearly, understanding the processes and hence predicting rates and signals of topographic change over the planet is a first-order challenge to the Earth Sciences.

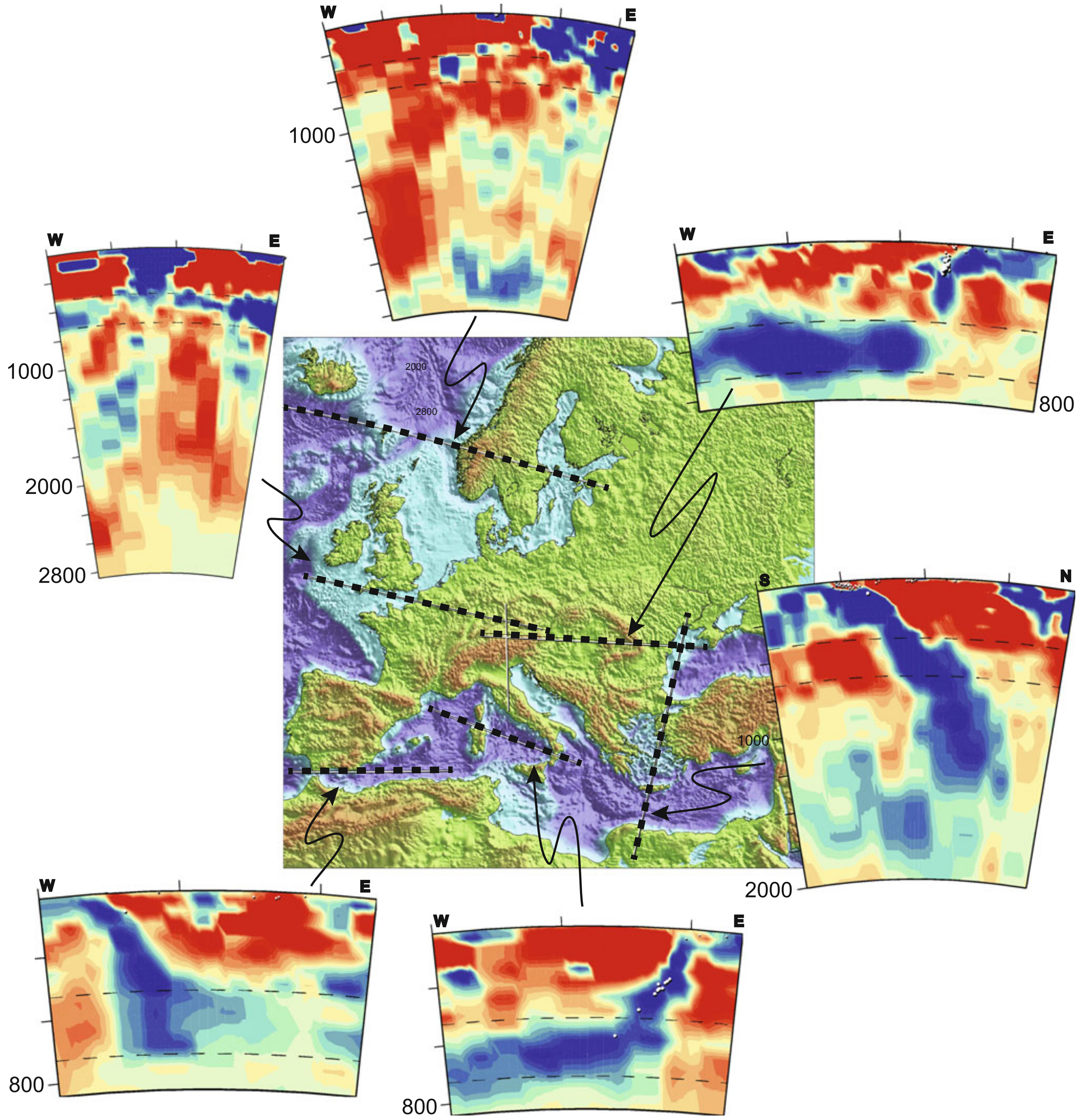
Underpinning many of the pure and applied issues concerning resource and hazards is the basic question of which processes define present topographic change, and at what spatial and temporal scales they are acting. Processes such as so-called dynamic topography (e.g., Faccenna et al. 2014; Colli et al. 2018) driven by mantle flow, lithospheric partitioning of stress and strain, and the thermal structure of the mantle and overlying crust remain only partly understood.

The TOPO-EUROPE program has been designed to serve as a platform for integration of deep Earth and surface processes studies, taking the Europe continent and its margins as a natural laboratory. TOPO-EUROPE has focused on collaborative research projects in specific areas such as the Norwegian continental margin, the Pyrenees, the Alpine-Carpathian system, the western Mediterranean, the Anatolian Plateau, and Europe as a whole. Results of TOPO-EUROPE research have been published in a number of special topical volumes and publications therein (Cloetingh and Tibaldi 2012; Cloetingh et al. 2009, 2011, 2018). TOPO-EUROPE has been building on a rich database on the deep crustal structure of key sectors of the European continent, and on data obtained from industrial and deep seismic reflection profiling programs (e.g., ECORS, CROP, NFP, DEKORP, and BIRPS), which were set up to characterize the structure and architecture of sedimentary basins and the crust (Roure et al. 2010; Laubscher 2010). Here we present a brief review of the rationale of TOPO-EUROPE as well as some examples of research approaches and research highlights.

Deep Earth

Plate reconstructions and absolute plate motions based on seismic tomography from research within the context of the TOPO-EUROPE project have led to a new reference frame to determine absolute plate motions from remnants of past subduction, as imaged by seismic tomography (Fig. 1). This novel approach is crucial for future understanding of the deep Earth controls on dynamic topography, formed in response to the interaction of the lithosphere and crust with thermal perturbations and convective movements in the Earth's mantle. Several studies (e.g., Faccenna et al. 2014) have explored dynamic topography of the Mediterranean area, demonstrating its sensitivity to adopted crustal models.

Formation of sedimentary basins is an intrinsic corollary to the Earth's planetary evolution, particularly of its lithosphere (Cloetingh et al. 2015). At present, knowledge on the evolution of the Earth's lithosphere is assembled in kinematic reconstructions at regional to global scales. The state-of-the-art in the fields of tectonic reconstructions and coupling deep Earth processes to surface evolution is of high international level. TOPO-EUROPE researchers have combined efforts in regional scale reconstruction with global reconstructions, utilizing Gplates (freeware, see www.gplates.org). These modern quantitative reconstructions provide an interface with thermo-mechanical modelling of plate tectonics coupled to the underlying mantle. Important advances have been made by integrating mantle structure, as a memory of Earth's dynamic evolution, with crust-lithosphere processes and tectonic reconstructions of complex plate boundary regions (Wortel and Spakman 2000) and with global tectonic reconstructions linked to mantle evolution (van der Meer et al. 2010). Crucial is the knowledge of precise mantle structure obtained from tomography. Tectonic transitions are considered to be of key importance in



TOPO-EUROPE – From the Deep Earth to the Surface of Continental Europe and Its Margins, Fig. 1 Tomographic cross-sections for the upper mantle below Europe, illustrating heterogeneity in the upper mantle. Depth scale 600 km. Blue and red colours correspond to areas where seismic P-wave velocities are respectively higher and lower than the standard reference velocity model. The sections display distinct patterns of down-going slabs in convergent zones of Europe overlain by lithosphere with reduced seismic velocities, corresponding with areas of high heat flow and high potential for geothermal energy exploration. The overall topography of Europe, depicted in the central panel, is characterised by elevated areas (including the Alps, Dinarides, Apennines, Carpathians, Pyrenees and the Anatolian Plateau) not only in the convergent settings, but also in intraplate settings such as Iberia and the southern Scandes. (Tomographic sections: Courtesy W. Spakman) controlling, for instance, the preservation of hydrocarbon reservoirs and the formation of ore deposits as they lead to strong changes in the crustal stress-field, local thermal pulses from the asthenosphere, and mantle-driven crustal flow of mineral-rich fluids. In contrast to its importance, process-based understanding of basin and plate boundary deformation or tectonic transitions is one of the weak links in current tectonic reconstructions.

Crucial for creating detailed process-based models of natural laboratories coupled to deep processes is the capability to embed regional modelling in a global dynamic lithosphere-mantle framework. This provides the necessary (realistic) constraints on regional mantle flow and the stress field resulting from global plate-mantle interaction. Global and regional tomography models can now be used to estimate mantle composition, temperatures, and mantle flow, resolving deep Earth structure in great detail and demonstrating the existence of side lobes of the Iceland Plume under intraplate areas in northwestern Europe with elevated topography (Fig. 2) (e.g., Rickers et al. 2013; Koptev et al. 2017). This potentially can be coupled to tectonic reconstructions in an absolute plate motion frame (Torsvik et al. 2010). To this aim, 3D numerical mantle modelling assimilating models of lithospheric age and thickness and incorporating evolving subduction systems, ocean spreading, and other plate boundary processes is required. The strategy of establishing a global dynamic reconstruction model is essential for predicting the impact of global plate-tectonic and mantle processes on the evolution of local subduction and other plate boundary systems as well as past tractions and temperatures at the base of lithosphere plates crucial for lithosphere-stress modelling.

Lithosphere Structure

On a completely different scale, new approaches have been developed to quantify plate rigidity on a full continental scale, resolving controversies regarding end-member rheological models for continental lithosphere (Tesauro et al. 2009). This work has also led to the insight that lower crustal flow in Europe's lithosphere and mechanical coupling between individual crustal layers is crucial for linking deep Earth processes and mantle-lithosphere interactions to surface deformation (Fig. 3) (Burov et al. 2007). Subsequent work has enabled a comparison of inferences for the effective elastic thickness of the lithosphere from admittance functions with spatial variations in integrated strength based on rock-mechanics data – on a global scale. The resulting strength maps display a robust pattern of variations in lithospheric strength, crucial for understanding localization of deformation in the interior of plates and basins, and for an assessment of stress propagation away from plate boundaries into these continental interiors.

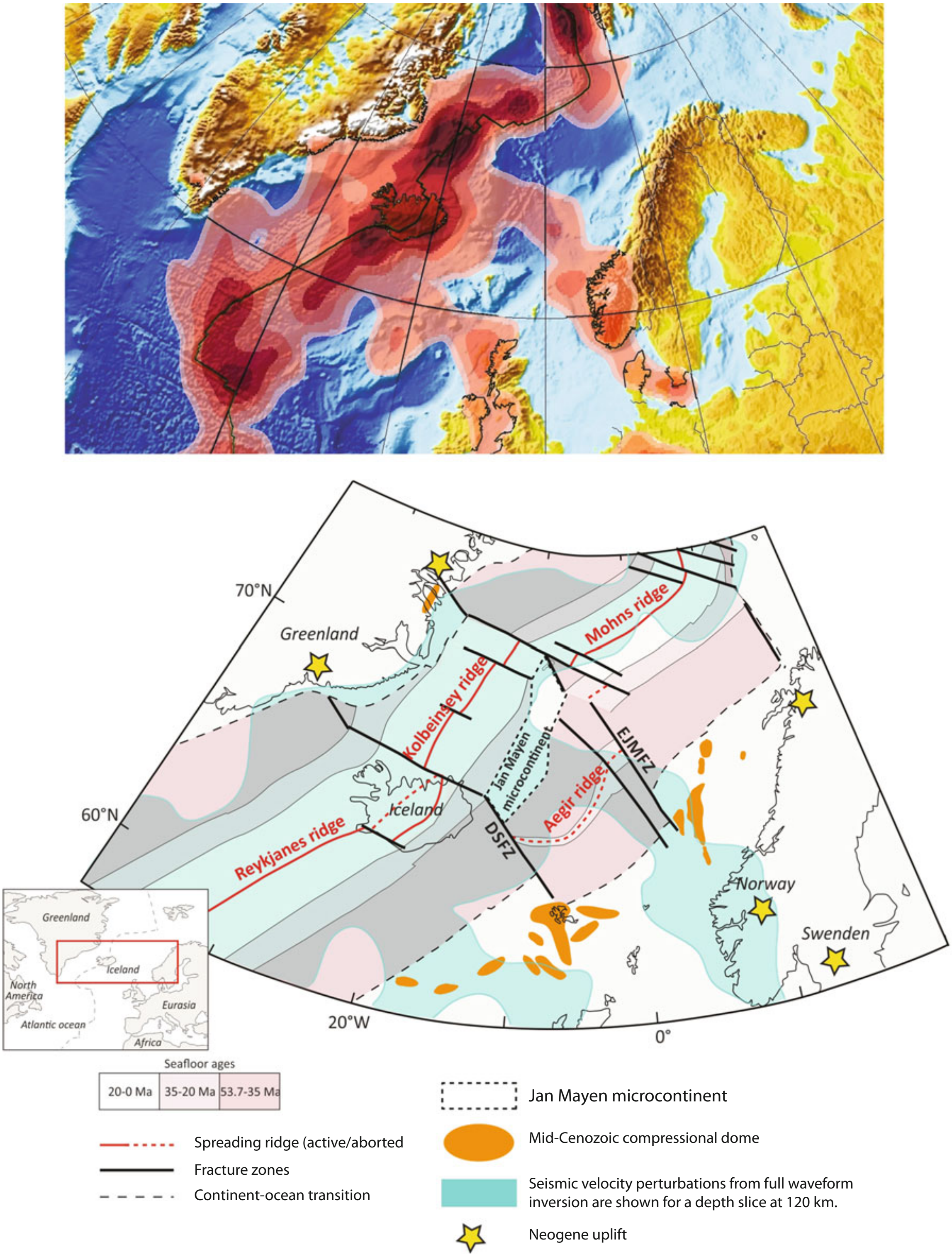
In the context of TOPO-EUROPE, temporal changes in stress regime have also been investigated in terms of transient changes in tectonic regime in the Pyrenees (see also Erdös et al. 2014) and at the southern margin of the European continent where it interacts with the northern African margin (Faccenna et al. 2014). These models have demonstrated strong mechanical control on sedimentary basin systems and their intrinsically polyphase behavior. Stress and strain relationship and rheology are important ingredients in this context.

Mantle-Lithosphere Interactions

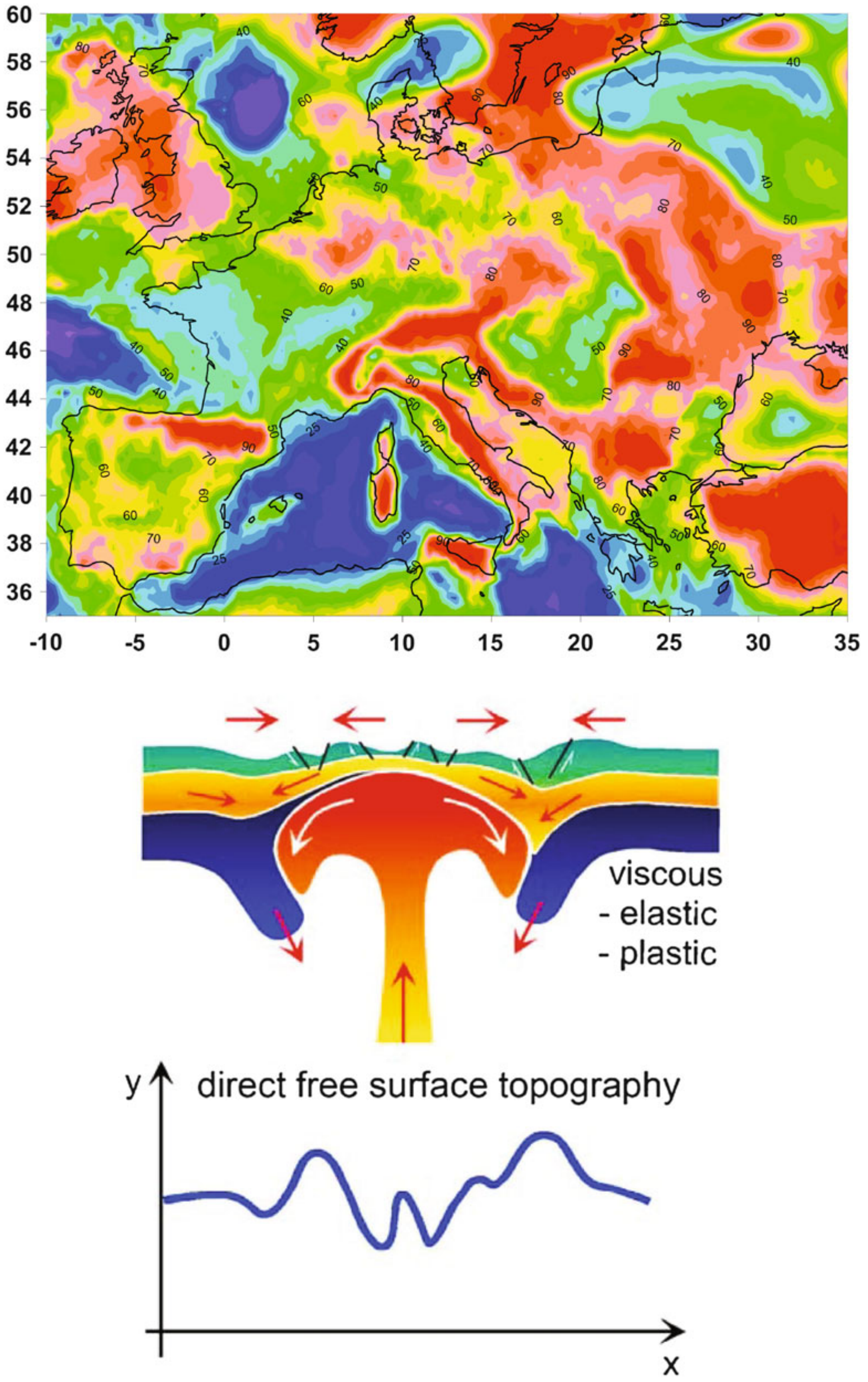
New fully consistent models of mantle-lithosphere interactions (Fig. 3) and stable and even unstable lithospheric deformation (such as lithospheric folding) adopting realistic rheologies and integration into sedimentary basin studies (Cloetingh et al. 2015) have recently been developed. Advances in tectonic modelling and its integration with observational studies have allowed quantification of the time constants involved in the temporal succession of mantle/lithosphere interactions and of rifting and lithospheric folding by stress accumulation in intraplate continental crust and lithosphere. The results have been shown to be of critical importance for quantitatively assessing thermal regime, the record of differential vertical motions, and the faulting characteristics of super-deep basins created by the lithospheric folding and its interaction with phase changes in the crust. Key in this approach has been the integration of realistic models for Earth rheology in numerical studies of large-scale deformation and faulting and its role in intraplate structure and processes. Fully consistent 2D and 3D geodynamic numerical models incorporating thermo-mechanical, thermodynamic, and surface process (via implementation of free surface boundary or similar solutions) will play a key role in testing hypotheses on the topographic impact of deep processes and in separating tectonic components of deformation from dynamic topography. The latter task becomes extremely challenging since it is evident that tectonic and deep Earth processes are so interlinked that the notion of the dynamic topography will probably undergo significant changes in the nearest future.

Sedimentary Basins and Geo-Resources

By their nature, sedimentary basins develop and evolve in a plate tectonic setting, characterized by a strong mechanical coupling between plate boundaries and plate interiors. Of particular relevance in this context is the subduction factory, being the prime engine for build-up and release of stresses in the crust and lithosphere (Faccenna et al. 2014).



TOPO-EUROPE – From the Deep Earth to the Surface of Continental Europe and Its Margins, Fig. 2 (*top panel*) Horizontal cross-section through a high resolution S-velocity model of the North Atlantic region, derived from full-waveform tomography. Highlights of the model in the upper mantle include a well-resolved Mid-Atlantic Ridge and two distinguishable strong low-velocity regions (indicated by the red colors) beneath Iceland and beneath the Kolbeinsey Ridge west of Jan Mayen. A sub-lithospheric low-velocity layer is imaged beneath much of the oceanic lithosphere, consistent with the long-wavelength bathymetric high of the North Atlantic. The low- velocity layer extends locally beneath the continental lithosphere of the southern Scandinavian Mountains, the Danish Basin, part of the British Isles and eastern Greenland. (After Rickers et al. 2013). (*bottom panel*) Tectonic setting of North Atlantic region and low velocity anomaly at 120 km-depth. The side lobes of the Iceland plume (top panel) and plume channeling through fracture zones explain the joint occurrence of Late Neogene uplift in the southern Scandes and northwestern part of the British Isles and compressional intraplate doming in the offshore part of the Northern Atlantic volcanic rifted margin system (Koptev et al. 2017)



TOPO-EUROPE – From the Deep Earth to the Surface of Continental Europe and Its Margins, Fig. 3 (*top*) Map of Europe with colour contours indicating the relative contribution of the crust to the rheological strength of the entire lithosphere (after Tesauro et al. 2009). Dark blue colours indicate that the strength distribution is dominated by the mantle lithosphere, whereas red and yellow colours indicate lithosphere were strength is primarily concentrated in the crust ("crème brûlée" model). Green and light blue coloured areas indicate a stratified lithosphere with rheologically strong layers in both crust and upper mantle lithosphere ("jelly sandwich" model). (*middle and bottom*) Models that include a plate rheology and multilayer lithosphere structure predict a complex surface topography with several short-wavelengths generated by intraplate deformation, tectonic-style deformation at surface and strong lithosphere mantle erosion at depth. The short wavelengths are controlled by the thickness of the lithosphere and intra-lithospheric layers. (After Burov et al. 2007)

Crucial in this context is the need to quantify the mechanisms for far-field stress propagation, away from plate boundaries and the localization of the resulting deformation in critical zones for resource formation in the interior of continents and their margins. At a regional scale, lithospheric and crustal stresses are responsible for the reactivation of preexisting faults and affect fluid transfers and reservoir characteristics, in particular across areas of contrasting strength and mechanical properties. The second so far underestimated factor significantly influencing subduction factories refers to the presence of structural heritage in the subducting and overriding plate (e.g., subduction of old terrains causing poly-phase subduction and metamorphic exhumation). The interplay between deep Earth and surface processes has distinct consequences for the record of vertical motions and sedimentary basin architecture (e.g., Cloetingh et al. 2015). As a result, the impact of these processes is a key for a quantitative assessment of resource and storage potential (i.e., aquifers, ore deposits, geothermal energy, hydrocarbons, and greenhouse gases). Sedimentary fluxes are often characterized by episodic moments of rapid changes in tectonic, drainage network distribution, oceanic circulation, or connectivity between basins. The latter are, however, commonly studied in isolation and require constraints on their temporal evolution frequently beyond the resolution of existing dating methods. As a result of the current mismatch between their intrinsic temporal and spatial scales, incorporation of these elements in predictive models for geo-resources is far from complete.

Analogue Tectonic Modeling

European laboratory groups involved in the EU TOPOMOD international training network have all contributed at the international forefront of developments in their respective activities at the associated length scales. Using physical analogue, or scale model experiments, these researchers have delivered major contributions to understanding tectonic processes and faulting at the basin scale, providing a basis for unravelling geological and geophysical observations on basin and crustal structure, and for testing and improving numerical models of basin evolution (e.g., Cloetingh et al. 2015).

Novel tectonic concepts and their implementation in coupled numerical and analogue modelling have opened new approaches to study the thermomechanical behavior of the Earth's lithosphere and to assess the role and interaction of parameters such as intraplate stress, rock rheology, and lithosphere structure. Advanced numerical methods have been implemented for the quantitative analysis of dynamic models that address the link between lithosphere deformation processes and vertical and horizontal motions, including constraints from GPS data (see, e.g., Serpelloni et al. 2013) in space and time. Analogue modelling has been shown to be particularly useful in qualitative and quantitative studies of lithosphere deformation in settings with a complex 3D geometry, such as present in the European Alps where seismic tomography interpretations have yielded evidence for a flip in the polarity of the down-going slab (Fig. 4) (Luth et al. 2013). An extensive database compiled in the TOPO-EUROPE project for the Alpine uplift and erosion history is now available (Fig. 5) (Fox et al. 2015) to further test different models and scenarios proposed for Late Neogene tectonics and climate of this key mountain system.

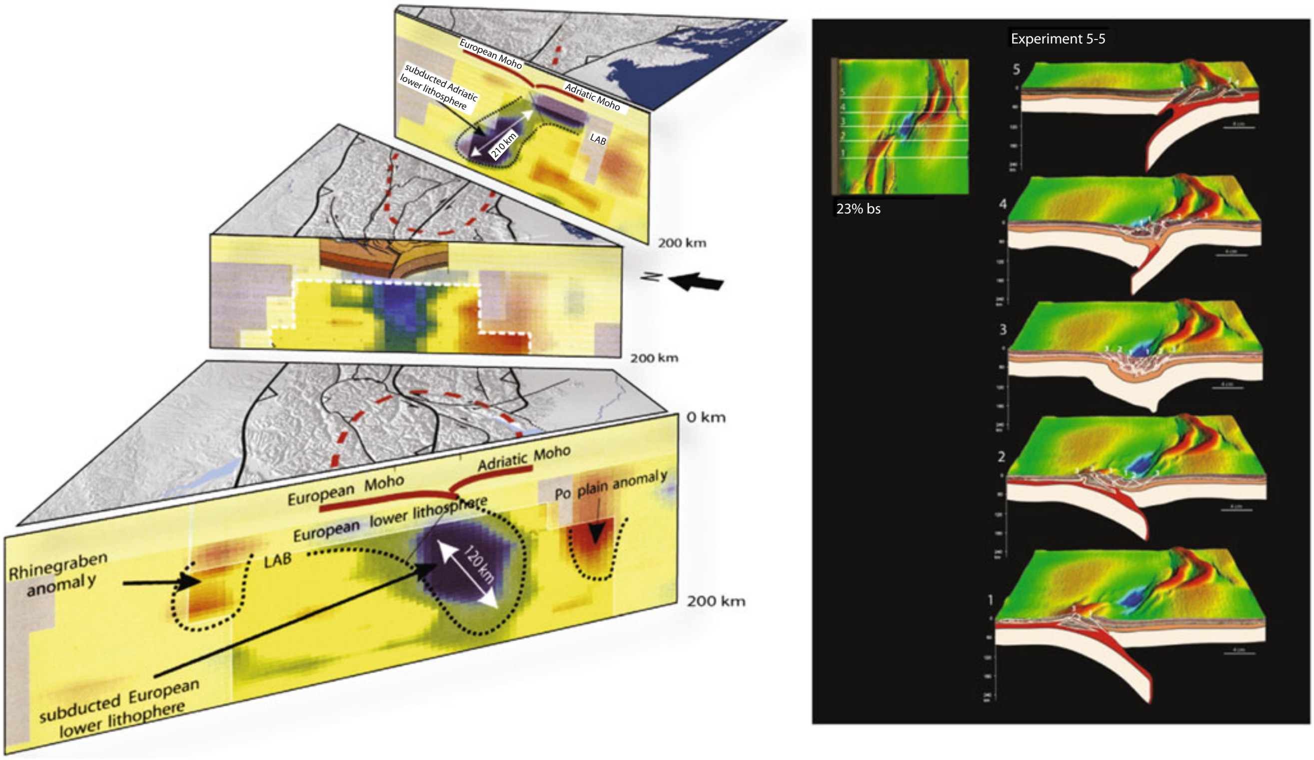
Coupling of experimental predictions from analogue models into numerical models has led to a better understanding of the interplay between the formation and evolution of sedimentary basins and of the mechanisms that control stress and strain distribution at crustal and lithospheric scale. This has resulted in novel predictions of depositional system behavior and hydrocarbon reservoir architecture.

It has been clearly demonstrated that sedimentary basin systems cannot be treated in isolation but should be treated by connecting their basin fill architecture to the evolution of adjacent basins and topographic highs, accounting for their hydrological connectivity (Matenco and Andriessen 2013). This research has allowed quantification of how different types of basin connectivity affect budgets and pathways of sedimentary fluxes, including source magnitudes and mechanisms of sediment depocenter shift across basins. Spatial variations in the rheology of the underlying crust appear to be key to basin connectivity and the sediment storage capacity of individual basins. These findings are also important for assessing the impact of differential vertical motions in highly populated areas affected by flooding events, regional landslides, and active seismicity (Matenco and Andriessen 2013).

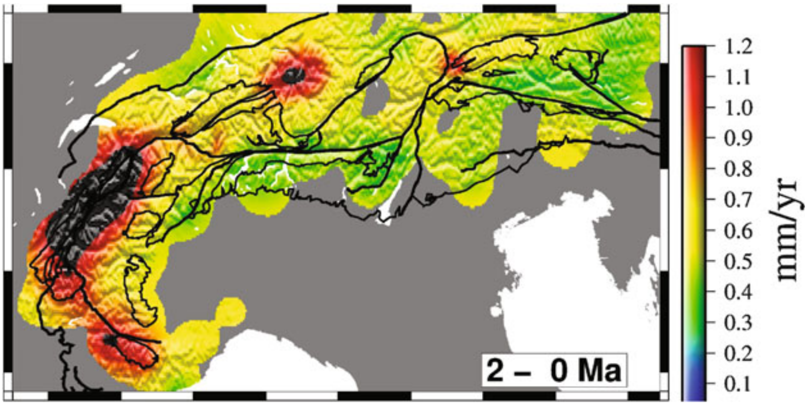
Summary and Conclusions

Research on coupled deep Earth and surface processes has developed as a frontier in integrated solid Earth science. The European continent and its margins provide an excellent natural laboratory to test in particular process-oriented models, such as for instance the effects of spatial variations in lithosphere strength on the mode and surface expression of mantle-lithosphere interactions. This research is by its nature multiscale and requires a close integration of observations, monitoring, and modelling.

TOPO-EUROPE research has demonstrated, amongst others, an important control by side-lobes of the Iceland mantle plume on anomalous topography of the Southern Scandes of Norway and the offshore Northern Atlantic compressional domes. Slab detachment and slab tearing processes exert pronounced effects on the 4D evolution of the



TOPO-EUROPE – From the Deep Earth to the Surface of Continental Europe and Its Margins, Fig. 4 (*left*) Tele-seismic tomographic cross-sections display along-strike variations in continental subduction polarity. Blue and red colors refer to relatively high and low P wave velocities, respectively. Top views show the major tectonic boundaries as black lines and the outline of the subducted slabs between 135 and 165 km depth in dashed red lines transposed on a DEM. (**a**) (bottom) Lower lithosphere transects through western Central Alps imaging in blue the SE-dip of subducted European lower lithosphere. Bold dashed line indicates lithosphere–asthenosphere boundary. (**b**) (middle) TRANSALP crustal section transposed on a deep tomographic transect disclosing a steep dipping slab. (**c**) (top) Lower lithosphere transect through Eastern Alps imaging NE-dip of subducted Adriatic lower lithosphere. (*right*) Cross-sections located along white profile lines shown in top view inset. Within the cross-sections white material corresponds to mantle lithosphere, beige to strong lower crust, red to weak zone, and colored sand to upper crust. Black line represents Moho. White lines are interpreted faults, which are chronically numbered. A DEM overlies the cross-sections (both panels after Luth et al.



TOPO-EUROPE – From the Deep Earth to the Surface of Continental Europe and Its Margins, Fig. 5 Alpine exhumation rates over the past 2 My, inferred by analysis of over 2500 thermo-chronometric ages. (After Fox et al. 2015)

Mediterranean, such as for instance a polarity swap in subduction beneath the Alps. In Iberia, lithospheric folding is a key contributor to differential topography with an average anomalous elevation due to the interaction of intraplate deformation with plate edge driven thermal anomalous in the upper mantle. This research has important spin-offs in the domains of geo-hazards (i.e., volcanism, earthquakes, and landslides) and geo-resources, in particular the exploration and exploitation of geothermal energy, highly relevant for the present era of energy transition to a more sustainable world.

Acknowledgments This review is based on the dedicated research efforts of the TOPO-EUROPE community. Funding by 23 national research councils in Europe and the European Community is gratefully acknowledged. ESF provided valuable coordination during the TOPO-EUROPE EUROCORES program. The International Lithosphere Program and the Academia Europaea are thanked for continuous support during various phases of the lifespan of TOPO-EUROPE. Constructive criticism by François Roure is greatly appreciated. Wim Spakman and Fred Beekman are acknowledged for suggestions and technical support.

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