TOPO-EUROPE – ILP's Program on Coupled Deep Earth and Surface Processes in Continental Europe and its Margins

Integrated studies of the full Earth system across space and time scales are rapidly advancing, such as exemplified by the recent conception of IUGS's first big science program on Deep-time Digital Earth (Oberhaensli, 2020). The International Lithosphere Program (ILP), the Inter-Union IUGG-IUGS program, connecting geophysical and geological sciences at their interfaces, promotes frontier research in Solid-Earth science, with high societal impact in the domains of geo-environment, geohazards and geo-resources.

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 (e.g., Cloetingh et al., 2007, 2013; Cloetingh, 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 ILP, these endeavors have in common the study of Earth's topography and the prediction of its origin and rates of change. Observations from surface studies, such as basin stratigraphy, geomorphology of landscapes, changes in surface elevation, and changes in sea level (Cloetingh and Haq, 2015), provide some of the principal constraints on geodynamic and tectonic models. 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 wavelength and creating new, shorter wavelength deformation; giving a surface response more complex than that of the mantle source.

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. The relevance of research conducted in both the deep Earth and surface regimes is thus strongly enhanced through a focus on their interaction.

Long-term inner Earth processes, such as mantle flow, drive the system of mantle-surface interaction. However, short-term outer Earth 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, sedimentation 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. At the same time, many modelling or theoretical studies suggest that erosion and sedimentation do impact the subsurface evolution of crustal deformation, changing flow patterns and magnitudes in the ductile crust and mantle through changing gravitational stresses or kinematics.

First Order Scientific Questions, Mission and Vision of TOPO-EUROPE

Many questions on inner Earth and outer Earth interactions remain to be addressed. For instance, what is the impact of erosion and surface mass redistribution on mantle flow? What is the influence of precipitation regimes on mountain building, and what is the budget of subduction in terms of sediments and water recycling? What are the sediment and tectonic loads 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 not fully resolved. For further progress, a close integration of quantitative modeling and high quality geophysical, geochemical and geological data is obviously needed. For this purpose, Europe with its rich data base resulting from a long history of geological studies and intensive probing of the crust, lithosphere and underlying mantle, provides an excellent natural laboratory. Data obtained from industrial and deep seismic reflection profiling (e.g. ECORS, CROP, NPF, DEKORP and BIRPS), designed to characterize the structure and architecture of basins and the crust are vital in this respect (Roure et al., 2010). It was thus natural that ILP, with its global mission, has selected the European continent and its margins as its pilot program for addressing coupled deep Earth and surface processes, providing seed funding to TOPO-EUROPE, significantly augmented by subsequent funding from other sources.

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 most times because of a lack of insight into the variability of the rates and scales of the underlying processes. TOPO-EUROPE has been exploring the dynamics of these processes and the role played by large-scale litho-spheric stresses. Clearly, understanding the processes and hence

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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 Earth resources and geohazards is the basic question of which processes define present topographic change, and at what spatial and temporal scales they are acting.

In its mission, 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; Cloetingh, 2020). The discoveries gleaned from TOPO-EUROPE have been augmented by parallel studies conducted around world in different geodynamic and climatological settings that illuminate the full spectrum of responses between the deep Earth and surface.

In this editorial, we present a compact review of the rationale of ILP's TOPO-EUROPE program as well as some examples of research approaches and research highlights.

Deep Earth and Mantle-Lithosphere Interactions

Seismic tomography has revolutionarised the capability to unravel the fine-structure of deep Earth (Fig. 1). Its findings have been crucial for understanding of 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. During the last few years, a large number of studies (e.g., Faccenna et al., 2014) have explored dynamic topography on plate scales, demonstrating its sensitivity to adopted crustal models.

Formation of sedimentary basins, resourcing mankind with geo-energy and fresh water, is fundamental in Earth's plate-tectonic evolution, and lithosphere dynamics (Cloetingh et al. 2015). Important advances have been made by integrating mantle structure, as a memory of Earth's dynamic evolution, with crust-lithosphere processes and tectonic reconstructions

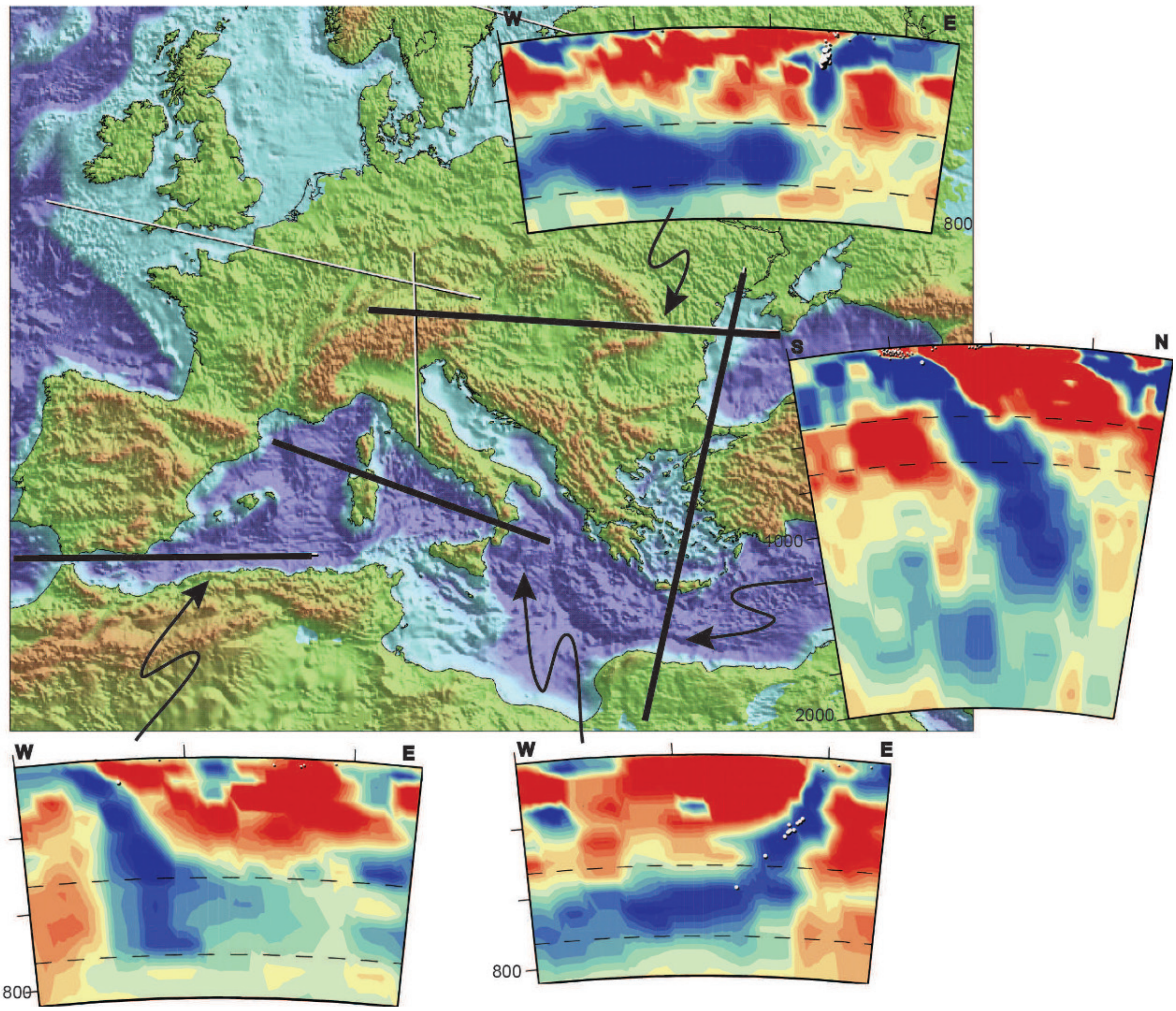

Fig.1. Tomographic cross-sections below Europe, illustrating heterogeneity in the upper mantle. Depth scale 600 km. Blue and red colours correspond to areas where seismic P-wave velocities are respectively higher and lower than the standard reference velocity model. The sections display distinct patterns of down-going slabs in convergent zones of Europe overlain by lithosphere with reduced seismic velocities, corresponding with areas of high heat flow and potential for geothermal energy exploration. The overall topography of Europe (central panel) is characterised by elevated areas (including Alps, Dinarides, Apennines, Carpathians, Pyrenees and Anatolian Plateau) in both convergent settings and intraplate areas such as Iberia (Tomographic sections: courtesy W. Spakman)

(Wortel and Spakman, 2000; van der Meer et al., 2010). Tectonic transitions are of key importance in 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.

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 (e.g. Rickers et al., 2013; Koptev et al., 2017).

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 (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.

Fully-consistent models of mantle-lithosphere interactions 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 analogue and numerical modelling integrated 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 subsurface thermal fields, 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.

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. Lithospheric and crustal stresses are responsible for the reactivation of pre-existing faults and affect fluid flow and reservoir characteristics, often across areas in continental interiors and their margins with contrasting strength and mechanical properties. Another factor significantly influencing subduction factories (Faccenna et al., 2014) 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. Matenco and Andriessen, 2013; 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 tectonics, 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. Finally, the sedimentary record of geodynamic processes is modulated by both paleoclimate change and the internal dynamics of drainage basins providing sediment to basins. Paleoclimate changes over the timescale of mountain building and basin formation can be significant (e.g. Ehlers and Poulsen, 2009; Botysun et al., 2020) such that changes in precipitation and temperature influence rates of weathering, sediment production, transport, and deposition. Understanding the individual contributions of geodynamics, paleoclimate change, and surface processes in the sedimentary record remains a frontier research area.

Surface Processes

TOPO-EUROPE research has applied insights gained about the deep Earth and lithosphere to improve our understanding of the linkages between geodynamics and surface processes. Earth's topography forms in response to complex interactions between the deep Earth, tectonic, (paleo)climate, and biologic processes. These interactions occur over diverse temporal scales ranging from millennia (e.g. earthquake cycle) to tens-of-millions of years (e.g. mountain building), and spatial scales of millimeters (individual rain drops or plant roots stabilizing hill slopes) to hundreds or thousands of kilometers (e.g. plume plate interactions and dynamic topography). Deep Earth and tectonic processes produce surface uplift and the generation of topographic relief. Topographic relief, in turn, increases rates of erosion via fluvial, hillslope and glacial processes. Thus, the evolution of topography represents a competition between geodynamic processes that uplift topography and surface processes that lower it.

However, the rates at which surface processes erode and provide sediment to adjacent basins is sensitive to paleoclimate (e.g. Lease and Ehlers, 2013). For example, increased precipitation can temporarily increase fluvial erosion until river channel slopes are decreased and a new equilibrium is reached with the rate of tectonic uplift. Furthermore, Quaternary glaciations in the Alps and elsewhere have resulted in accelerated mountain erosion over million-year timescales (Herman et al., 2003). Teasing apart if transients in observed erosion histories are the result of tectonics or climate change (or both) is challenging, and requires observational and modeling studies from both hinterland and basin environments (e.g. Whipple, 2009).

The complexities of climate-tectonics interactions are further increased due to a coupling between tectonic and atmospheric processes that occurs over million-year timescales (and longer). For example, surface uplift of the Alps (and larger orogens) constructs a topographic barrier to low-level atmospheric circulation and influences regional climate dynamics (e.g. Botysun et al., 2020). As a result, precipitation can become focused on the windward side of an orogen (i.e. the orographic effect) and lead to enhanced erosion and rock exhumation. The link between orography, erosion, and the geodynamics of mountain building occurs through different processes. For example, erosion and sedimentation result in the redistribution of mass on Earth's surface which modifies gravitational body forces and the state of stress in an orogen (e.g. Willett and Schlunegger, 2010). In addition, erosion and sedimentation, if fast enough, cause significant perturbations to subsurface thermal gradients thereby leading to thermal weakening or strengthening, respectively, of the lithosphere. The degree to which climate, tectonics, and surface processes are coupled to each other depends on erosion and convergence rates (e.g. Willett, 1999). However, despite twenty years of inquiry into this topic, the critical (or threshold) rates at which climate, erosion, and tectonic processes become strongly coupled to each other remains poorly understood from both observational and modeling studies.

Lastly, after the initiation of the TOPO-EUROPE research platform, growing interest has emerged over the linkages between the biosphere, solid Earth, and surface processes. These linkages are manifested in different ways. First, over the timescale of mountain building, the rise of the Andes and Himalaya-Tibet are thought to have provided a stimulus for producing some of Earths largest biodiversity hotspots observed today (e.g. Hoorn et al., 2010; Antonelli et al., 2018). Second, recent modeling and observational studies have identified a bi-directional response to vegetation's influence on erosion in orogens, whereby the effect of vegetation cover on erosion can be very different in dry, sparsely vegetated settings compared to wetter, more vegetated settings. This bi-directional response is the result from competing and non-linear interactions between precipitation and vegetation on erosion in each setting (e.g. Schmid et al., 2018; Starke et al., 2020). These biotic effects are important because the biosphere appears to function as a strong, and non-linear, filter to orographic effects on erosion, and sediment routing systems. While the previous interactions between the biosphere, tectonics, and Earth's surface were developed in orogens other than the Alps, they highlight the potential and need for future TOPO-EUROPE studies in the Alps to tackle similar problems.

Examples of Key Advances

European laboratory groups involved in the EU TOPOMOD and SUBITOP international training networks have all contributed at the international forefront of developments in their respective activities at the associated length scales. Using physical analogue experiments, these researchers have made

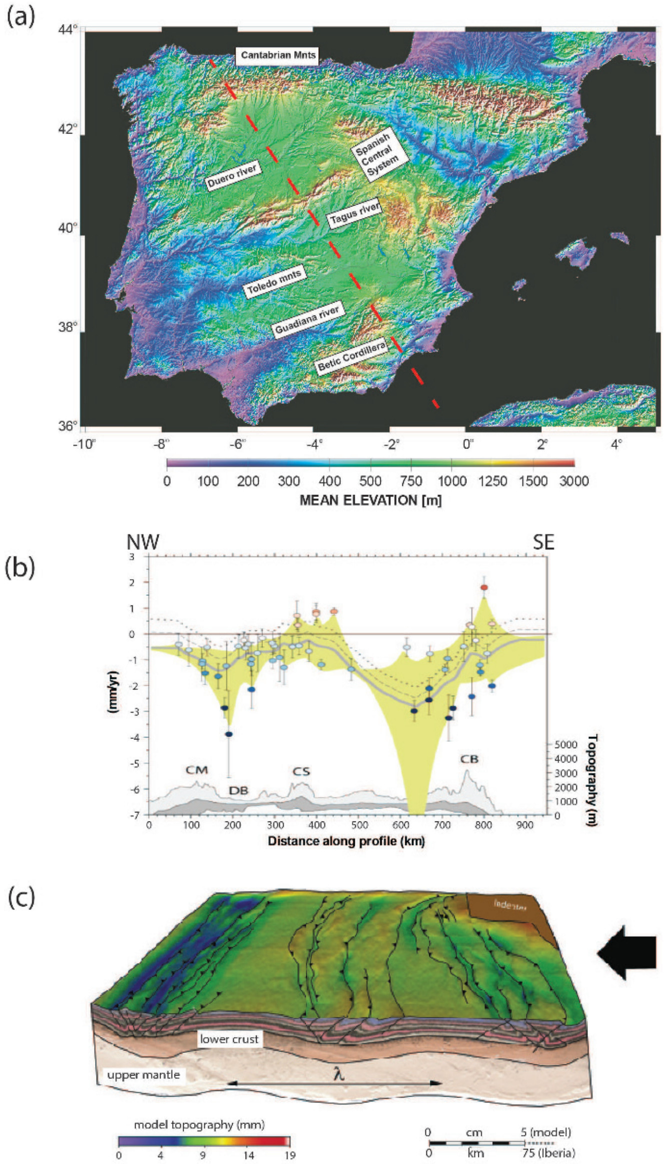

Fig.2. (a) Topographic map of Iberia. **(b)** Constraints from vertically derived GPS velocities on present day vertical motions in intraplate Iberia (Serpelloni et al., 2013), displaying differential patterns of subsidence and uplift of long-wavelength undulations, superimposed on an overall high topography associated with a decaying hot upper mantle thermal anomaly. Location of the profile is indicated by the red line in (*a*). **(c)** Results from analogue tectonic modelling adopting a model of lithosphere folding for Iberia, consistent with a wide range of geological and geophysical observations (Fernandez-Lozano et al., 2012).

key contributions to understanding tectonic processes and faulting at 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 thermo-mechanical 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 and analogue 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, see Fig. 2a,b) in space and time. Analogue modelling (Fernandez-Lozano et al., 2007, see Fig. 2a,c) 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 Iberian peninsula with an average elevation (Fig. 2a) higher than Switzerland. In this intraplate area intensively investigated in the context of the TOPO-IBERIA project (Cloetingh et al., 2011), the combination of lithosphere folding resulting in undulations of several 100's of km and an anomalously hot upper mantle appears the be the main driver for its anomalously high topography. An extensive database compiled in the TOPO-EUROPE project for the Alpine uplift and erosion history is now available (Fox et al., 2015) to further test different models and scenarios proposed for Late Neogene tectonics and climate of this key mountain system. Quantifying the elevation history of mountain belts is key to understanding the subsurface density structure, isostatic compensation and interactions of climate, tectonics and surface processes. Stable isotope paleo-altimetry is a key method in this respect. In recent work, Botsyun et al. (2020) have developed a novel approach to paleo-altimetry using a climate model with water isotopes implemented to explore the maximum precipitation signal of Cenozoic topographic and paleoclimatic change in the European Alps (Fig. 3). The results of their study suggest that integration of paleoclimate modeling, multiproxy approaches and low-elevation reference proxy records distal from a mountain belt can significantly improve topographic reconstructions.

TOPO-EUROPE research has revealed, amongst other things, 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. Plume-lithosphere interactions have also been shown to be key for better understanding in the processes controlling the initiation of continental lithosphere subduction (Burov and Cloetingh, 2010), a first order and hitherto not well understood question in geodynamics, with major impact for topography of the continents. Numerical models suggest that the thermo-tectonic age of the overlying lithosphere affected by plume impingement has a key control on the mode of subduction and subsequent slab detachment. Slab detachment and slab tearing processes exert pronounced effects on the 4D evolution of the Mediterranean, such as for instance a polarity swap in subduction beneath the Alps. This research has important spin-offs in the domains of geo-hazards (i.e. volcanism, earthquakes, landslides) and geo-resources, in particular the exploration and exploitation of geothermal energy, highly relevant for the

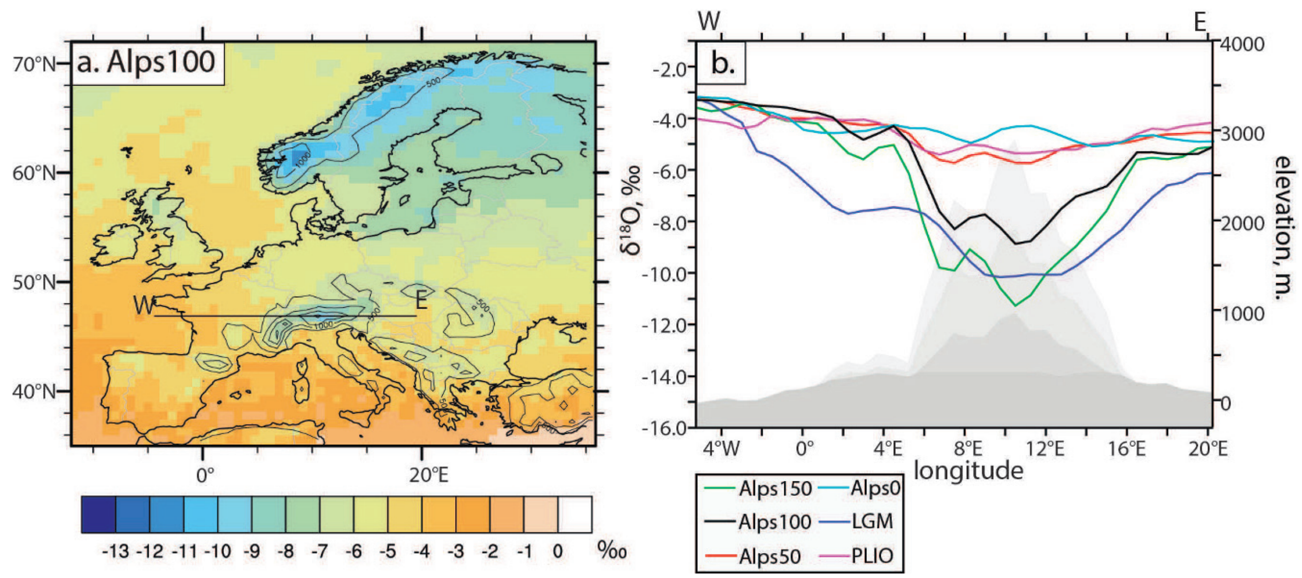

Fig.3. Results of high resolution isotope tracking general circulation model ECHAM5-wiso experiments.(*a*) Simulated mean summer (JJA) $\delta^{18}O_p$ values for the pre-industrial (Alps100) experiment (‰). **(b)** JJA $\delta^{18}O_p$ values across the Alps, averaged between 46°N and 47°N for topographic sensitivity (Alps0, Alps50, Alps100, Alps150) and paleoclimate (LGM, PLIO) simulations. Gray shading indicates the modeled alpine topography from Alps150 (light gray) to Alps0 (dark gray). For experiments with varied topography (Alps0, Alps50, Alps100, Alps150) the maximum change in $\delta^{18}O_p$ occurs over the highest alpine topography, while over the forelands the magnitude of difference between experiments with modern and modified topography is less and within 1–2‰. For experiments with paleo-boundary conditions (LGM and PLIO) pronounced changes in $\delta^{18}O_p$ over larger area are simulated. (after Botsyun et al., 2020).

present era of energy transition to a more sustainable world.

TOPO-EUROPE research has demonstrated the utility of diverse scientific communities working together. Wit the recent establishment in Europe of the European Plate Observing System (EPOS) and its implementation in the European Large Scale Facilities for Research Infrastructure (ESFRI), conditions are favorable for further advances and scientific breakthroughs in this domain. The integration of observations from seismology, tectonics, geodynamics, geochemistry, and surface processes (to mention a few) have been and will continue to be essential for advancing our knowledge of how the deep Earth and surface function as a system of interrelated processes.

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