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Invited Review Article

Coupled surface to deep Earth processes: Perspectives from TOPO-EUROPE with an emphasis on climate- and energy-related societal challenges

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ABSTRACT

Understanding the interactions between surface and deep Earth processes is important for research in many diverse scientific areas including climate, environment, energy, georesources and biosphere. The TOPO-EUROPE initiative of the International Lithosphere Program serves as a pan-European platform for integrated surface and deep Earth sciences, synergizing observational studies of the Earth structure and fluxes on all spatial and temporal scales with modelling of Earth processes. This review provides a survey of scientific developments in our quantitative understanding of coupled surface-deep Earth processes achieved through TOPO-EUROPE. The most notable innovations include (1) a process-based understanding of the connection of upper mantle dynamics and

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absolute plate motion frames; (2) integrated models for sediment source-to-sink dynamics, demonstrating the importance of mass transfer from mountains to basins and from basin to basin; (3) demonstration of the key role of polyphase evolution of sedimentary basins, the impact of pre-rift and pre-orogenic structures, and the evolution of subsequent lithosphere and landscape dynamics; (4) improved conceptual understanding of the temporal evolution from back-arc extension to tectonic inversion and onset of subduction; (5) models to explain the integrated strength of Europe's lithosphere; (6) concepts governing the interplay between thermal upper mantle processes and stress-induced intraplate deformation; (7) constraints on the record of vertical motions from high-resolution data sets obtained from geo-thermochronology for Europe's topographic evolution; (8) recognition and quantifications of the forcing by erosional and/or glacial-interglacial surface mass transfer on the regional magmatism, with major implications for our understanding of the carbon cycle on geological timescales and the emerging field of biogeodynamics; and (9) the transfer of insights obtained on the coupling of deep Earth and surface processes to the domain of geothermal energy exploration.

Concerning the future research agenda of TOPO-EUROPE, we also discuss the rich potential for further advances, multidisciplinary research and community building across many scientific frontiers, including research on the biosphere, climate and energy. These will focus on obtaining a better insight into the initiation and evolution of subduction systems, the role of mantle plumes in continental rifting and (super)continent break-up, and the deformation and tectonic reactivation of cratons; the interaction between geodynamic, surface and climate processes, such as interactions between glaciation, sea level change and deep Earth processes; the sensitivity, tipping points, and spatio-temporal evolution of the interactions between climate and tectonics as well as the role of rock melting and outgassing in affecting such interactions; the emerging field of biogeodynamics, that is the impact of coupled deep Earth – surface processes on the evolution of life on Earth; and tightening the connection between societal challenges regarding renewable georesources, climate change, natural geohazards, and novel process-understanding of the Earth system.

1. Introduction

The advent and establishment of the theory of plate tectonics in the second half the 20th century, providing an integrated explanation for the bathymetry of oceans, the relative motion of continents, the formation and evolution of orogenic belts and sedimentary basins, glaciations, greenhouse gases concentration changes over geological timescales and related evolution of oceanic and atmospheric circulation patterns embodies the last major revolution in the Earth Sciences. One of the most important recent developments of such theory and coeval improvement of mantle tomography models (Nolet, 2008) have been the recognition that processes occurring at the Earth surface and those taking place deep within its interiors are inherently linked. Since this recognition, the understanding of how the Earth's topography evolves has been pursued through joint investigations of the Earth's surface through sedimentology and geomorphology, and of the deep Earth through seismology and geodynamics. More and more commonly, modern geologists interpret basins' stratigraphy, volcanic and hydrothermal activity, ore formation and distribution, the morphology of landscapes, changes in sea level and surface elevation also in terms of deep geodynamic and tectonic processes (Cloetingh and Haq, 2015). Similarly, modern geophysicists explain topographic anomalies as well as erosional and sedimentary changes via data that reports on the deeper Earth structure and dynamics. Because the surface-deep Earth processes coupling is the means for the geological cycling and storage of fundamental elements such as carbon, hydrogen, oxygen and metals, it links the evolution of life and climate to that of plate tectonics, also involving favourable aspects such as the geological conditions that allow our present-day society to function and prosper into the future. This aspect requires, amongst other, knowledge on the distribution of rock formations suitable for extraction and storage of natural compounds such as hydrocarbons, carbon dioxide, hydrogen, heat, nuclear waste to develop strategies for production of energy and/or mitigation of climate and environmental changes. It further involves natural hazards related to earthquakes, volcanic eruptions and the redistribution of the surface masses of rocks, water and ice. The relevance of research pertaining to the deep and surface Earth are thus enhanced through a focus on their interaction, particularly considering the impact of climate changes on society.

The International Lithosphere Program (ILP) launched a European multidisciplinary program in Europe under the umbrella name of TOPO-EUROPE with a workshop in 2005 and a white paper (Cloetingh et al., 2007) describing its scientific scope. The program represents a bottom-up, community effort to self-organize and cross-fertilize the disparate fields within the geological and geophysical communities. Throughout the last fifteen years the program has continued to grow. The core of the TOPO-EUROPE research activities was supported through funding of a European Collaborative Research (EUROCORES) program administered by the European Science Foundation (ESF), with 14.5 M€ allocated by 23 different member states to better understand and quantify the evolution of topography in Europe, the accompanying changes in sea level and their surface and deep Earth driving mechanisms. The ESF EUROCORES provided funding for the training of more than 60 European young researchers with widespread results published in several special volumes and papers of high-impact international journals and papers. Since the establishment and start of the TOPO-EUROPE programme in 2006, a significant number of scientific results from collaborative research projects have been published in several special volumes (Cloetingh et al., 2007, 2009, 2011, 2013, 2018; Cloetingh and Tibaldi, 2012; Matenco and Andriessen, 2013). Highlights include amongst others:

- Novel models for the connection of upper mantle dynamics and absolute plate motion frames.
- Integrated models for sediment source-to-sink dynamics, demonstrating the importance of mass transfer from mountains to basins and from basin to basin.
- Demonstration of the key role of polyphase evolution of sedimentary basins and the impact of pre-rift and pre-orogenic structures and evolution of subsequent lithosphere dynamics and impact on topography.
- Demonstration of variability of relative role of tectonics and climate along strike of mountain belts, such as the Alps.
- New concepts for temporal change from back-arc extension to tectonic inversion and onset of subduction.
- First models for integrated strength of Europe's lithosphere.
- Novel concepts for interplay of thermal upper mantle processes and stress-induced intraplate deformation.
- New constraints on record of vertical motions from high-resolution data sets obtained from geo-thermochronology for Europe's topographic evolution.
- Recognition and quantifications of the forcing by erosional and/or glacial-interglacial surface mass transfer on the regional magmatism,

with implications for our understanding of the geological carbon cycle and the emerging field of biogeodynamics.
- Acquisition of deep seismic reflection and refraction data for a number of TOPO-EUROPE's natural laboratories.
- Transfer of insights obtained on the coupling of deep Earth and surface processes to the domain of geothermal energy exploration.

TOPO-EUROPE has been extraordinarily successful in capacity building on a pan-European scale and inspiring large scale collaborative research in Europe. Several International Training Networks (ITN) funded by the European Commission for training and networking young researchers followed. The ITNs SUBITOP and TOPOMOD, for instance, have funded more than 20 young researchers together. On a national level, programs such as the TOPO-IBERIA (Gallart et al., 2015; Garate et al., 2015; Cloetingh et al., 2011) program funded by the national research council of Spain (CSIC) with an amount of 8 M€ to unravel the structure and evolution of the Iberian topography, with an average elevation higher than that of Switzerland. TOPO-EUROPE also demonstrated the need for integrated European Solid Earth Scientific infrastructures and accomplished the realization of the European Plate Observing System (EPOS, https://www.epos-eu.org/) coordinated by the Italian National Institute of Geophysics and Volcanology (INGV) as part of the European Scientific Research Infrastructure (ESFRI) program. Other examples of community building in the Solid Earth science inspired by TOPO-EUROPE are the AlpArray, AdriaArray and Topo-Iberia programs for deployment of dense networks of seismic stations to address first order questions about intra-crustal heterogeneities and coeval regional seismicity, orogenies and lithosphere dynamics. Overall, TOPO-EUROPE served as a trigger to bring integrative Earth Science to a position where it could more easily branch out to synergies with other disciplines such as Environmental and Climate science.

The interaction between surface and deep Earth processes is far more reaching than anticipated at the onset of the TOPO-EUROPE program and the global nature of the themes addressed by TOPO-EUROPE does not restrict its findings to Europe and its continental margins (Fig. 1). Despite the advances made so far, major challenges for frontier research in the domain of coupled surface-deep Earth processes have emerged, requiring scaling up present collaborative and individual research efforts as well as the integrated research approach and methodologies. In this contribution, we review several recent breakthroughs in the domain of the interaction between surface and deep Earth processes. To this aim, we follow a bottom-up sequence, starting with perspectives from the deep mantle, followed by findings from lithospheric and surface processes research. As evident from this overview, these topics cannot be treated in isolation but are intrinsically linked. Recent breakthroughs lay a solid foundation for the next TOPO-EUROPE agenda which, apart from pursuing further frontiers of research in integrated Earth Sciences, will also focus on interfacing with the biosphere, environment, and climate research.

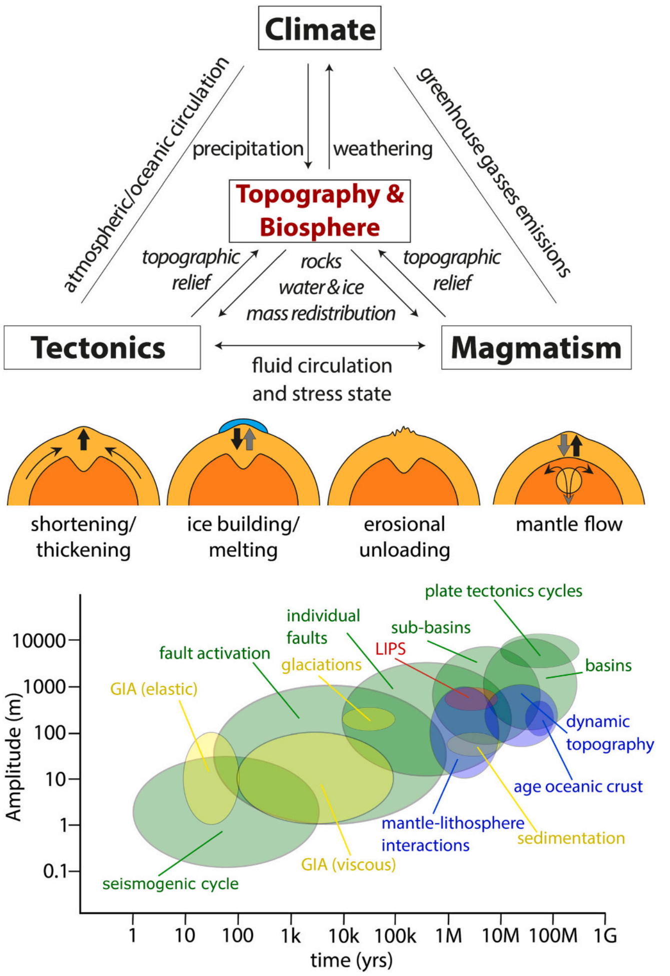

Fig. 1. (top panel) Schematic representation of the Earth System Triangle (EST), showing the main components of the Earth system and dynamic interactions. Tectonics, magmatism, and climate are intrinsically coupled with joint expressions on Earth topography. Forcings external to the EST include orbital changes as well as sun activity. (Modified after Sternai et al., 2020.) (bottom panel) Temporal and spatial variability of the main mechanisms that link surface and deep Earth processes. LIPS - Large Igneous Provinces; GIA - Glacial Isostatic Adjustment. (After Matenco et al., 2022.)

2. Examples of recent breakthroughs in linking deep and surface earth dynamics

2.1. Mantle structures, dynamics and interactions with the lithosphere

Seismology has always been a fundamental source of information on the deep Earth, resulting in the widespread acceptance of an Earth structure composed of crust, mantle, and core. With further developments in seismology this first order subdivision has been 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 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 picture has dramatically changed during the past decades. Advanced seismic tomography is capable now to detect crust/mantle seismic velocity differences of only a few percent (Rickers et al., 2013; Plomerová et al., 2016), corresponding to temperature anomalies in the order of tens of °C and subtle compositional changes. This allowed imaging of downgoing lithospheric slabs and uprising mantle plumes throughout the entire mantle and has provided new constraints on plate reconstructions and has also shown that there is rich diversity in the mode of subduction and mantle ascent (Arnould et al., 2020) (Fig. 2).

Importantly, the sources of vertically continuous low-velocity anomalies (Ritsema et al., 1999), interpreted as classic Morgan-type plumes originating at the base of the lower mantle (Morgan, 1971), are not randomly distributed across the core-mantle boundary but are preferentially localized within or at the boundaries of two large low shear wave velocity provinces (LLSVPs) located beneath the African continent and the Pacific Ocean (French and Romanowicz, 2015). Such "primary" superplumes can also stagnate below or within the mantle transition zone (MTZ, 410–660 km) and cause numerous thermal perturbations in the upper mantle, corresponding to so-called "secondary" plumes (Courtillot et al., 2003). The MTZ might also serve as a barrier to the descent of oceanic slabs, which tend to stagnate in its lower part (Kuritani et al., 2019; Yang and Faccenda, 2020) due to the jump in

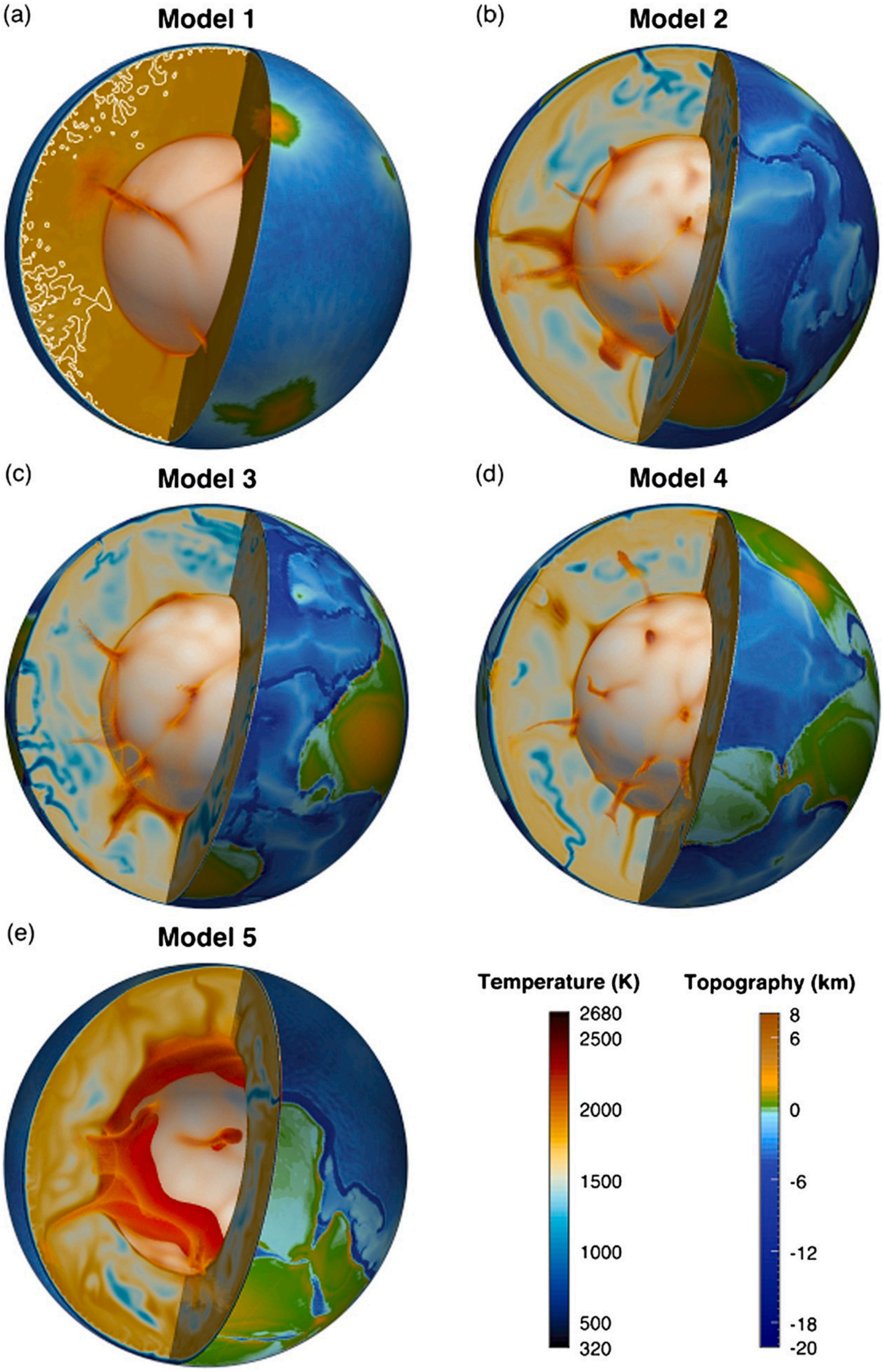

Fig. 2. 3D snapshots of five different numerical simulations of global mantle convection based on different plausible parameter settings to highlight the role of plate tectonics and mantle convection in driving mantle plumes' shape and dynamics (modified after Arnould et al., 2020). Temperature is shown in the interior of the shells and topography at their surface. The white isotherm on (a) highlights small-scale convection. The red isosurface on (e) delineates basal thermochemical heterogeneities. (For interpretation of the colours in the figure(s), the reader is referred to the web version of this article.) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

mantle viscosity at about 660 km depth (Forte and Mitrovica, 1996). A chemical (hydrous) component attributed to water originated from stagnant slabs (Richard and Bercovici, 2009) enhances the buoyancy of "secondary" plumes rising from the MTZ (Zhao, 2009). Despite the relatively small size of these thermo-chemical anomalies (sometimes referred to as "baby" plumes (Koptev et al., 2021a)), these have been shown to be capable of penetrating to shallow levels near the base of the crust (Cloetingh et al., 2022), forming "finger" and "mushroom"-like structures inside the overlying continental lithosphere (Fig. 3), as detected in regional seismo-tomographic studies across the globe (Ritter et al., 2001; Lei et al., 2009).

Seismic tomography has yielded fundamentally new insights into the regional geodynamics, providing an unprecedent image in terms of resolution and coverage of the upper mantle beneath Europe and its margins, including areas such the northern Atlantic rift province (Lebedev et al., 2018; Steinberger et al., 2019), Anatolia (Medved et al., 2021; Kounoudis et al., 2020), central Europe (Zhu et al., 2012; Karousová et al., 2012). The Mediterranean area, with its rich spectrum of down going slabs and the creation of young and well-preserved back-arc systems provides an excellent natural laboratory for detailed imaging of upper mantle structures. Rappisi et al. (2022) (Fig. 4) present the first three-dimensional (3D) anisotropic teleseismic P-wave tomography model of the upper mantle covering the entire Central Mediterranean. The tomography model is dominated by numerous fast anomalies

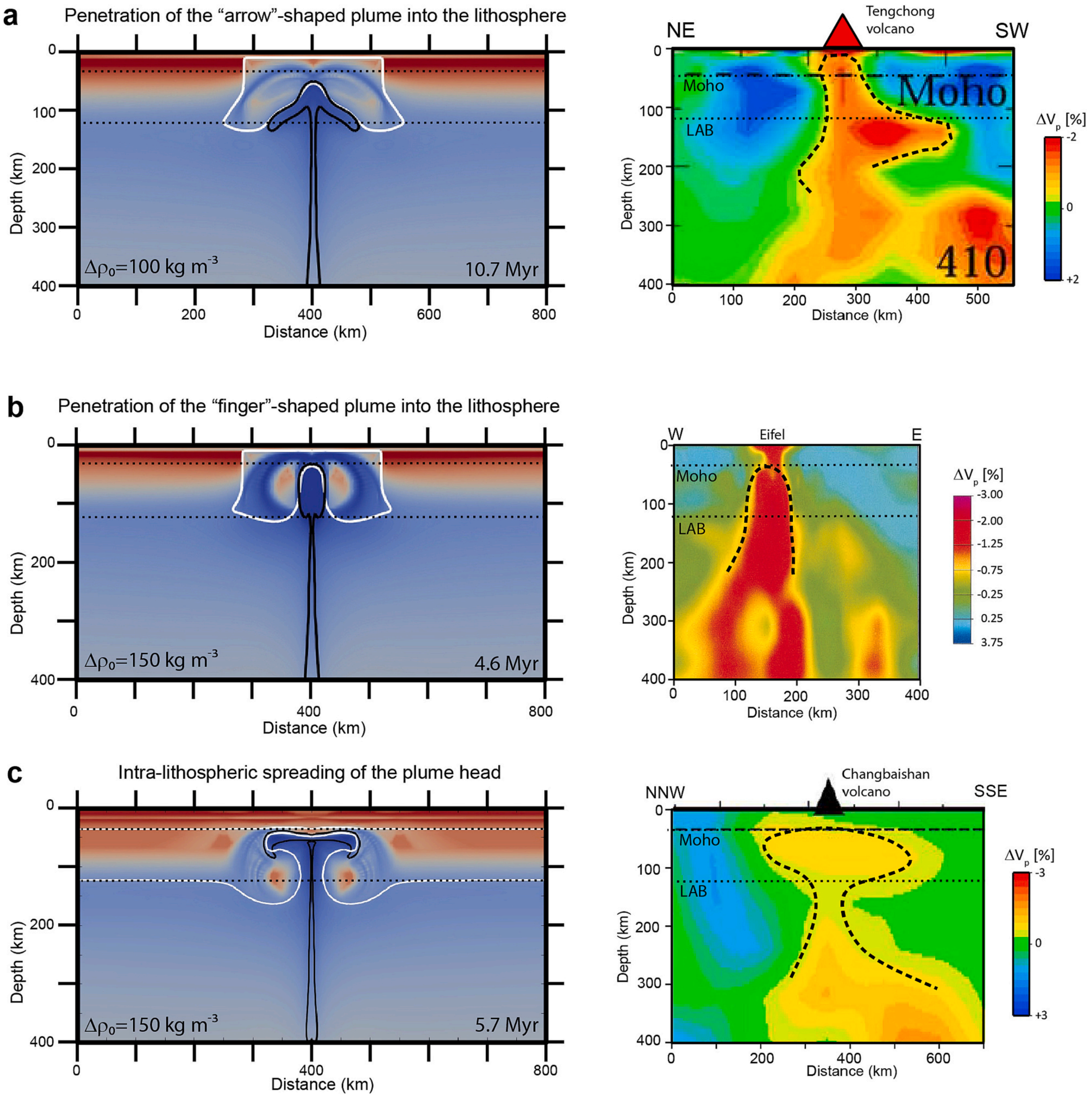

Fig. 3. Comparison of modelled plume-emplacement modes (left panels) with natural examples of seismic velocity anomalies in the upper mantle (right panels). a) Modelled "arrow"-shaped plume vs. asymmetric "arrow" beneath the Tengchong volcano. b) Modelled "finger"-shaped plume vs. columnar structure in sublithospheric and lithospheric mantle below the Eifel volcanic fields. c) Advanced stage of the "finger" scenario with intra-lithospheric spreading of the plume head vs. intra-lithospheric "mushroom" underlying the Changbaishan volcanic area. (Modified after Cloetingh et al., 2022.)

associated with retreating, stagnant, and detached slab segments as well as relatively slower mantle structures related to slab windows and back-arc basins. P-wave seismic anisotropy in the Central Mediterranean upper mantle is strongest at 200–300 km depth and interpreted as the result of asthenospheric material flowing primarily horizontally around Cenozoic slabs that rollback, while sub-vertical anisotropy may reflect asthenospheric entrainment by downwelling slabs.

Tomography underneath the Paris Basin has documented the occurrence of a remnant of the Hercynian slab still accounting for a deep density anomaly at the base of the lithosphere, resulting in the long living subsidence observed in this intraplate sedimentary basin over the entire Mesozoic and Cenozoic (Averbuch and Piromallo, 2012). Tomography beneath the SE Carpathians in Romania has demonstrated the occurrence of ongoing delamination of the Moesian lithosphere, its lithospheric mantle being subducted at great depth, accounting for extremely high subsidence rates and deep focal mechanisms below the Focsani Depression, whereas its upper crustal basement and sedimentary units are progressively uplifted underneath the outer Carpathians in the Vrancea area (Bocin et al., 2013). Similar dynamics have also been proposed for the Apulian lithosphere beneath the Southern Apennines (Roure et al., 2010a; Koulakov et al., 2015). In this context, the paleo-bathymetry and geodynamic evolution of the Eastern Mediterranean should be revisited, as alternative models involving the progressive delamination of the continental lithosphere of North Africa could be more realistic than models which are based on an oceanic crustal structure of the Eastern Mediterranean basin.

The lithosphere-asthenosphere boundary (LAB) is a first-order structural discontinuity accommodating differential motion between

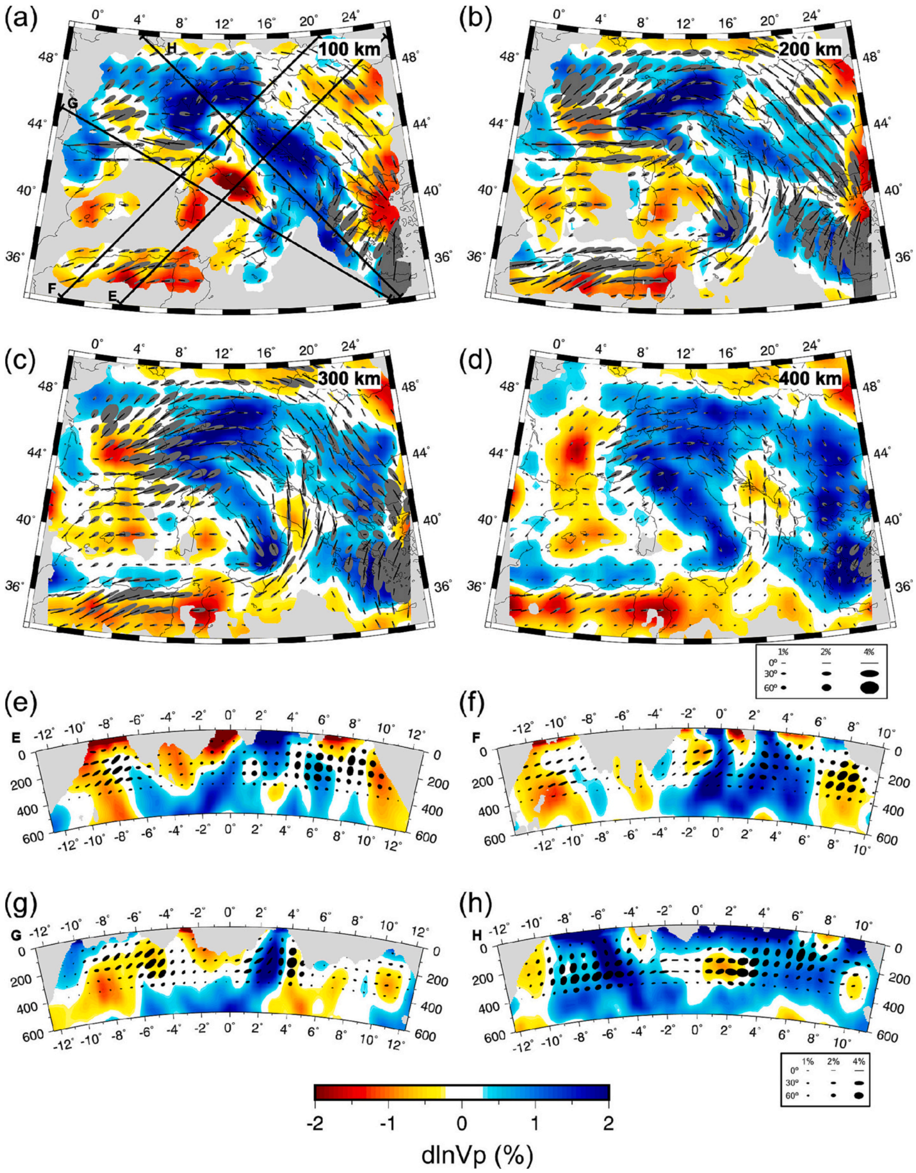

Fig. 4. Horizontal and vertical cross-sections of the ani-NEWTON21 tomography model for the central Mediterranean (Rappisi et al., 2022). Areas of poor coverage are masked in grey.

tectonic plates and the underlying asthenospheric mantle (Eaton et al., 2009). A fundamental question formulated at the dawn of plate tectonic theory has been the nature and importance of drag at the base of the lithosphere arising from mantle convective flow (Forsyth and Uyeda, 1975) versus slab pull (Conrad and Lithgow-Bertelloni, 2002) and ridge push (Artyushkov, 1973) forces. Different definitions exist on the LAB varying from a thermal definition equating it to an isotherm between ~1200–1350 °C (Artemieva, 2006; Koptev and Ershov, 2010, 2011) and a seismological definition based on a decrease in seismic velocities (Rychert et al., 2005; Chen et al., 2006) and change in seismic anisotropy (Gung et al., 2003). In addition, a petrological definition has been formulated pursuing the hydrous nature of the mantle below the LAB (Kovács et al., 2020). Previous attempts have been made to reconcile these different definitions (Artemieva, 2010). These attempts also led to the formulation of the '*pargasosphere*' hypothesis, where pargasitic amphibole (a hydrous double chain silicate with ~1.5–2 wt% of H_2O) is stable (i.e., at pressures and temperatures less than 2.8–3 GPa and 1000–1100 °C, depending on the presence of K_2O and on the activity of H_2O (Green, 1973; Niida and Green, 1999; Fumagalli et al., 2009)) making the lithosphere mechanically stronger (Kovács et al., 2021). The lack of melts/fluids and the lower structural hydroxyl content in nominally anhydrous minerals (Girard et al., 2013; Tielke et al., 2017) both strengthen the rheology of the shallow upper mantle where hydrous minerals, especially pargasitic amphibole, are stable. This contributes significantly to the contrast existing between the stronger and rigid outer shell (the lithosphere) and the underlying mechanically weak and ductile asthenosphere.

Besides the LAB, another important horizon in older and colder plates are the mid lithospheric discontinuities (MLD) of which discovery goes back only little more than two decades (Thybo and Perchuć, 1997). The origin of MLDs is still a controversial issue as it is linked to various factors including the presence of hydrous layers ('water collector'; (Fu et al., 2022)), pargasite-rich horizons (Kovács et al., 2021) and channel flow (Yang et al., 2022). Regardless their origin, it became clear that MLDs may play a fundamental role in continental subduction initiation and evolution (Cloetingh et al., 2021), delamination of the lower continental lithospheric mantle and removal of cratonic roots (Wang et al., 2017; Wang and Kusky, 2019; Liu et al., 2018; Shi et al., 2021; Shi and Morgan, 2022; Wang et al., 2022). The LAB and MLD may also be genetically linked, since with the age and secular cooling of tectonic plates LAB can be transformed into MLD as 'frozen' in or 'fossil' LAB (Fischer et al., 2010; Kovács et al., 2017; Rychert et al., 2020).

2.2. Rheological structure of the lithosphere and intraplate seismicity

An early breakthrough in our understanding of the lithosphere mechanical properties was achieved by Goetze and Evans (1979), who first extrapolated inferences from experimental rock mechanics on olivine to geological timescales to assess the rheology of the oceanic lithosphere. Subsequent work on ocean lithospheric flexure under seamount loading and at subduction trenches validated this concept, showing that oceanic intraplate seismicity is restricted to depths shallower than the isotherm of 750 °C whereas the effective elastic thickness corresponds to the depth of isotherms between 400 and 600 °C (Wiens and Stein, 1983; Bodine et al., 1981). The mechanically strong part of the lithosphere resides in the upper part of the lithosphere in oceanic domains. A similar approach was used to assess the rheology of the continental lithosphere. Experimental mechanic studies applied to rocks and minerals characteristic of the continental crust and upper mantle (Brace and Kohlstedt, 1980), analyses of intraplate seismicity, and quantifications of continental flexure (Cloetingh and Burov, 1996) led to a better understanding of spatial variations in the mechanical behaviour of the continental lithosphere, allowing for the definition of the effective elastic thickness (*Te*) as a proxy parameter for the rigidity and integrated strength of the lithosphere (Burov and Diament, 1995; Ershov, 1999; Burov, 2011). Europe, with its wide coverage of seismological studies shedding light on the Moho and crustal as well as upper mantle structures, served as the first area to construct continental scale maps of *Te* (Tesauro et al., 2013). These maps were obtained determining temperature distribution from inversion of new seismic tomography models improved by an a-priori correction of the crustal effect (Koulakov et al., 2009). The new temperature estimates were used together with the updated European crustal model EuCRUST-07 (Tesauro et al., 2008) to calculate the strength distribution within the European lithosphere (Tesauro et al., 2009a). Differently from previous estimates, the new strength model adopted lateral variations of lithology and density, which were also derived from EuCRUST-07. The strength distribution was the input for the calculation of the *Te*. Both strength and *Te* models show that in western and central Europe the lithosphere is more heterogeneous and characterized by mostly mechanically decoupled crustal and mantle lithospheric layers, relatively low strength, and $Te < 30$ km (Tesauro et al., 2009a, 2009b), whereas eastern Europe is generally more uniform, stronger, and with higher *Te* values.

These findings have led to recognition that the spatial distribution of intraplate seismicity in Europe is focused on the European Cenozoic rift system (ECRIS) and the Pannonian/Carpathian system, both characterized by relatively weak lithosphere. These concepts have been subsequently expanded to other continents including North America and Australia (Tesauro et al., 2014; Tesauro et al., 2020). In North America, a high proportion of intraplate seismic events are concentrated at the edge of the cratons (Mazzotti and Stein, 2007), in areas characterized by sharp lateral variations in the lithospheric thickness (Mooney et al., 2012) and integrated strength (Tesauro et al., 2015). A correlation between seismicity and cratonic edges is also reported for the Siberian and Congo craton (Craig et al., 2011; Sloan et al., 2011). On the other hand, the intraplate earthquakes in the western part of Australia do not show a strong correlation with the edges of the cratons, but many of them occur in areas characterized by weak crust, such as the southwestern part of the Yilgarn craton. Other seismic events are located along the transition zones between the weak and strong crust, as those at the margins of the Officer basin and Musgrave Province (Beekman et al., 1997; Tesauro et al., 2020).

The most seismically active areas around the globe are in proximity of plate boundaries, where around 90% of earthquakes occur (Sbar and Sykes, 1973). This led to the assumption of limited deformation within plates in the early formulations of the plate tectonic theory (Isacks et al., 1968). However, several seismic events in intraplate regions testify stress accumulation far from plate boundaries, in areas commonly considered tectonically stable (Haldar et al., 2022). Notable regions for intraplate earthquakes include the New Madrid seismic zone (Nuttli, 1973; Page and Hough, 2014), West Malaysia (Nazaruddin and Duerrast, 2021), Costa Rica region (Tary et al., 2021), India (Haldar et al., 2022), central Brazil (Rocha et al., 2016) and Bohemia (Mittag, 2003). Typically, these regions are affected by low to moderate seismic activity, although examples of earthquakes with magnitude higher than 6 still occur. In historical times, notable examples of large earthquakes are the well-studied 1811–1812 New Madrid events in the Mississippi valley of the Central U.S., the 1988 Tennant Creek earthquakes in Australia, the 1819 and 2001 earthquakes in the Kachchh rift basin (Western India), and the 1690 Manaus and 1955 Parecis basin earthquakes in Brazil (Calais et al., 2016), and references therein). Regarding Europe, relevant examples of historic earthquakes that shook relatively stable regions are the Basel (1356), Verviers (1692), Lisbon (1755) and Nice (1887) earthquakes.

Intraplate earthquakes occur preferentially in areas of rifted crust, with over half of all events associated with either interior rifts or rifted continental margins, where most earthquakes with magnitude ≥7 occurred (Schulte and Mooney, 2005). Several models have been suggested to provide an explanation for seismicity in stable cratonic regions. The first models suggest the presence of factors causing stress concentration, such as weakened intrusions (Campbell, 1978), intersections of faults (Talwani, 1988) and shear zones in the lower crust (Zoback, 1983). Other factors include pre-existing weak zones below the fault (Kenner and Segall, 2000), topography load change due to surface erosion (Calais et al., 2010), glacier removal (Grollimund and Zoback, 2001) and fluid flow along the fault plane (Audin et al., 2002). The important contribution of fluids at near-lithostatic pressures has also been suggested for seismic activity in southern Italy (Lavecchia et al., 2022), where recent studies highlight a strength drop and rheological switch for the Gargano promontory lower crust, causing a diffused micro-seismicity at depth greater than 20 km, in contrast to the almost totally aseismic upper basement and sedimentary cover in the region (Fig. 5). High crustal temperatures have also been suggested as a driver of seismic activity by raising the depth of the brittle ductile rock transition (Liu and Zoback, 1997). A fundamental contribution to intraplate seismicity is ascribed to far-field tectonic stresses and large-scale plate interactions, which may control the recurrence of intraplate earthquakes depending on the viscosity ratio between the two plates and the far field to local fault stress regime (So and Capitanio, 2017).

Earthquakes at crustal depth can also be triggered by mantle flow, as in the case of the 1811–1812 New Madrid seismic sequences, an unprecedented sequence involving at least three main events with magnitude ≥7 (Hough et al., 2000). Several studies invoked the descent of the Farallon slab as the main source for high localized mantle flow below the New Madrid seismic zone (Forte et al., 2007; Becker et al., 2015), suggesting that variations in mantle flow related dynamic topography (see also section 2.3) can contribute to seismicity where convective vertical normal stress are modulated by lithospheric strength heterogeneities. It thus appears that mantle flow needs to be considered to properly quantify seismic hazard in intraplate regions.

Because seismic reflection profiles acquired by the petroleum industry have only been rarely made available to seismologists, most seismo-tectonic maps show only the surface projection of earthquakes. Few studies using 2D or 3D seismic imagery provide accurate cross-sections where individual seismic event can be confidently plotted at depth on specific fault segments (i.e., in the Po Plain, (Turrini et al., 2014)). Intraplate deformations and diffuse seismicity in the forelands of the Alps, the Pyrenees and the Apennines imply the remobilization of fluids within the ductile lower crust; if strong coupling exists between the orogen and its foreland, far field reactivation of high angle upper to middle crustal faults at large distance from the suture may occur as long as high angle structures are still connected with the lower crust (Ziegler

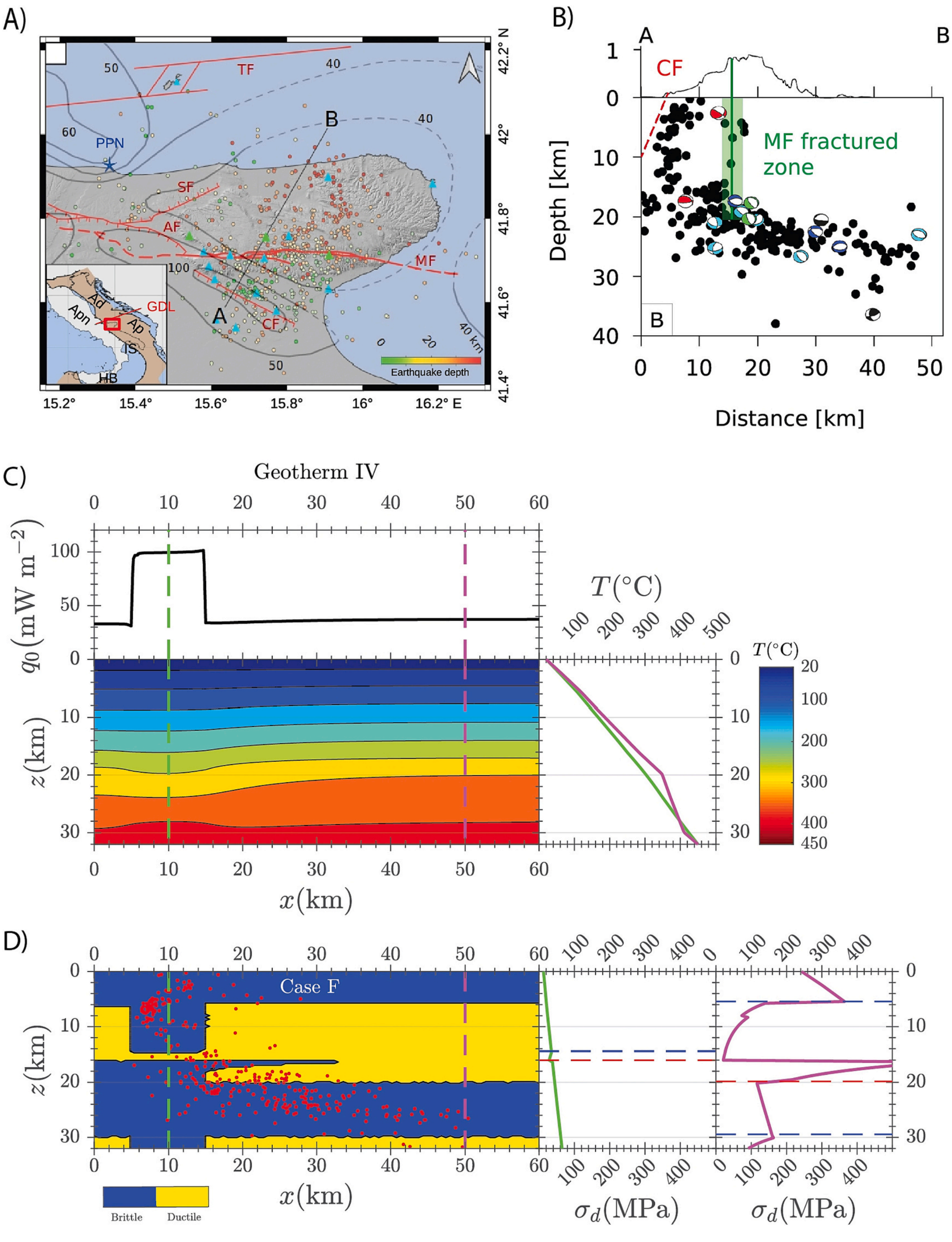

Fig. 5. A) Map of the Gargano promontory of southern Italy. Inset shows its location (red square) with respect to the Adria and Apulian microplates Coloured circles indicate the depth of the earthquake hypocentres. The A-B black segment is the trace of the vertical crustal section in panel B. B) Vertical cross-section along the A-B section. Hypocentres (black circles) and focal mechanisms are projected over the vertical plane (red = normal; green = transcurrent; light blue = transpressive; dark blue = compressive; black = unknown). C) Heat flow, geotherm, and D) rheological behaviour for the Gargano promontory. Further details are given in Lavecchia et al., 2022. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and Dèzes, 2006; Koptev et al., 2021b; Lavecchia et al., 2022). The construction of accurate 3D structural models at crustal scale, outlining the fault trajectories between the surface and the lower crust, still requires the acquisition of regional deep seismic reflection profiles, whereas denser seismic networks would be also required to plot individual events on the active fault segments (Roure and Howell, 2022). Ultimately, prediction of both horizontal and vertical intra-crustal fluid transfer and modelling of associated pore-fluid pressure cycles would provide a new approach to better understand and predict seismic hazard at distance from plate boundaries.

2.3. *Interactions between surface processes and lithospheric dynamics*

Shortening or stretching the continental lithosphere due to horizontal tectonics involve their thickening or thinning and thus vertical deformation of the Earth’s surface and, thus, surface uplift or subsidence. The dismantling of uplifted terrains via erosion and the filling of subsiding basins with sediments contribute to the horizontal motion of plates and the associated strain (Sternai, 2023). Within this framework, convergent mountain belts have been considered as crustal scale accretionary wedges in which lithospheric deformation and erosion are linked in a feedback loop that plays a particularly important role for exhumation of deep crustal and metamorphic rocks normally exposed as metamorphic complexes in the internal zones of orogenic belts (Burkhard and Sommaruga, 1998; Willett, 1999; Malavieille and Konstantinovskaya, 2010) and, as more recently recognized, landscape evolution (Sembroni et al., 2016; Reitano et al., 2022), magmatism (Sternai, 2020; Sternai et al., 2021; Stuewe et al., 2022; Muller et al., 2023), climate and biodiversity (Favre et al., 2015; Sarr et al., 2022; Botsyun et al., 2019; Tian et al., 2022; Xing and Ree, 2017). Probably the best example of the role of surface processes in affecting the deeper dynamics is provided by exhumation of the high-grade metamorphic

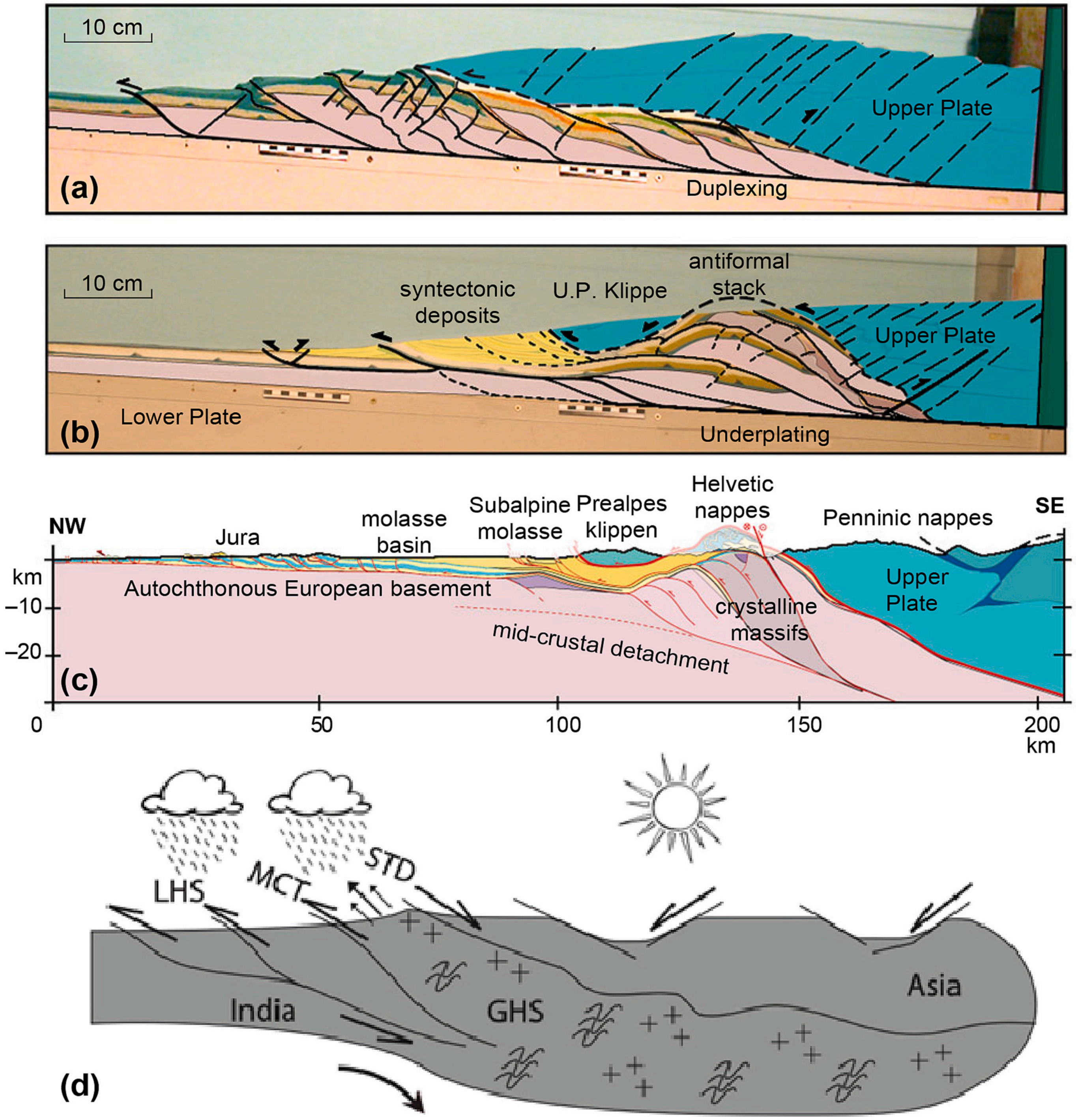

Fig. 6. (a) Analogue models of crustal convergence and orogenic wedge evolution without (a) and with (b) erosion and syntectonic sedimentation (Malavieille and Konstantinovskaya, 2010). Modelling results are compared to a classical cross section of the Swiss Alps (c) from Burkhard and Sommaruga, 1998. (d) Crustal tectonic framework of the Himalaya and Southern Tibet where erosion at the mountain front contributes to localized exhumation of weak lower crustal material (e.g., Wu et al., 1998; Burchfiel et al., 1992; Beaumont et al., 2001). LHS, Lesser Himalayan sequence; MCT, Main Central Thrust; STD, South Tibetan Detachment; GHS, Greater Himalayan Sequence.

Greater Himalayan Sequence, interpreted as the southward 'extrusion' of the Tibetan middle to lower crust ductile flow in the middle to lower crust facilitated by focused erosion along the Himalayan front (Burchfiel and Royden, 1985; Royden, 1996; Grujic et al., 1996; Wu et al., 1998; Beaumont et al., 2001; Zeitler et al., 2001; Thiede and Ehlers, 2013) (Fig. 6). Finally, parallel to the previous solid Earth studies are paleoclimate modelling studies designed to identify time periods when climate change can induce significant erosional change in tectonically active orogens (Mutz et al., 2018; Mutz and Ehlers, 2019) or to aid in the interpretation of paleoclimate versus surface uplift signals in paleoaltimetry studies (Ehlers and Poulsen, 2009; Botsyun and Ehlers, 2021) (see also section 2.7). More of these types of scientific investigations are needed because often the regional modern climate configurations are used as long-term proxy to infer past climate forcing on landscape and topography evolution.

The previous theoretical considerations have stimulated a diverse array of observational studies aimed at identifying when and where climate and tectonics operate and may be linked (Whipple, 2009; Whipple, 2014). A fundamental challenge for these communities has been the diverse timescales over which climate and tectonic may be linked, and which methods are best suited for quantifying those interactions. Observational and modelling studies have targeted one or more of several approaches. These include: bedrock (hinterland) studies quantifying temporal changes in erosional exhumation over millions of years (e.g., via multiple thermochronometric systems and numerical inverse modelling approaches; (Ehlers and Farley, 2003; Herman et al., 2013, Eizenhöfer et al., 2021)); basin analysis studies investigating the sedimentary record of changes in sedimentation and climate reconstructions from proxy data (Whittaker, 2012; Chen et al., 2018) and (lastly) investigations of recent (millennial timescale) catchment scale sedimentation and erosion rates (e.g., from cosmogenic isotopes, DEM analysis, etc) (Schaller et al., 2016; Starke et al., 2017), and thermokinematic forward modelling (Eizenhöfer et al., 2023). Together, these types of approaches have been successfully applied to quantify temporal and spatial variations in surface processes, along with inferences on the relative contributions of climate change and tectonic processes in controlling them (Champagnac et al., 2012; Champagnac et al., 2014). One of the best case-studies within the TOPO-EUROPE program, would be the European Alps with more than 20 years of scientific research dedicated to the interplay between internal and external forcing mechanisms in Alpine topography evolution (Kuhlemann et al., 2002; Willett, 2006; Champagnac et al., 2007; Fox et al., 2016; Fox et al., 2013; Valla et al., 2021). However, it should be noted that most observational studies focus on identifying spatial or temporal correlations between observed erosion/sedimentation rates with changes in climate and tectonics. Ultimately, these studies benefit significantly when linked with dynamic, process-based modelling studies where causal relationships can be rigorously tested with physics-based modelling approaches (Sternai et al., 2012; Winterberg and Willett, 2019).

The European Alps have long served as a natural laboratory to highlight relationships between localized thrusting and the topographic/architectural evolution of accretionary mountain belts during convergence. These relationships are well expressed in the Internal Crystalline Complexes (ICC) of the western European Alps (e.g., Monte Rosa, Gran Paradiso and Dora Maira), along with the Monviso ophiolite, where oceanic and continental plate fragments subducted down to ~120 km depth are currently exposed at more than 4500 m above sea level (Schmid et al., 1996; Rosenbaum and Lister, 2005; Handy et al., 2010; Manzotti et al., 2018). The main driver of the exhumation is the shift from subduction to collisional tectonics at ~35 Ma (Schmid et al., 1996). The localization of brittle deformation along major structures such as the Insubric and Periadriatic lines exerts a major influence on topography and, thus, on erosion (Janots et al., 2009; Malavieille and Konstantinovskaya, 2010). In turn, erosion and sedimentation decrease the topographic slope favouring a change from overcritical to stable to undercritical mechanical state of the wedge (Willett, 1999; Reitano et al., 2022). Alpine models highlight particularly tight relationships between many of the main structures within classical geologic sections across the Swiss Alps and erosion and/or sedimentation during convergence (Malavieille and Konstantinovskaya, 2010) (Fig. 6).

In response to shortening without surface processes, an analogue basement is commonly subject to initial thrusting and imbrication upon inherited structural and sedimentary weaknesses. Then, the homogenous part of the basement underthrusts and a high friction wedge is originated. With erosion and sedimentation, convergence leads to initial thrusting and frontal accretion in the foreland basin, followed by formation of an antiformal stack of duplexes in the internal part (Willett, 2006). Here, protracted strain localization, erosion and exhumation isolates a frontal synformal klippen of formerly imbricated thrust units and the antiformal structure eventually outcrops as a tectonic window, as observed in the natural case studies (Burkhard and Sommaruga, 1998). Climate changes, involving glaciation and precipitation gradients amongst other effects, play a similar role to that of strain regime changes in affecting the exhumation history of tectonic units across the Alps. The External Crystalline Massifs (ECM), for instance, are Paleozoic magmatic and metamorphic complexes of European affinity that were rapidly exhumed during the Pliocene along the strike of the western Periadriatic Line and currently form the highest topography of Europe (e.g., the Mont Blanc). Fast exhumation occurs in the last ~1 Ma by erosion of ~1 km of rocks through glacial valley carving (Valla et al., 2011; Sternai et al., 2012; Fox et al., 2015) across terrains subject to uplift due to mantle dynamics such as slab-break off and/or slab rollback (Fox et al., 2015; Lippitsch et al., 2003; Kästle et al., 2020). The influence of surface processes on orogenic dynamics in the European Alps is also expressed at short timescales. Catchment-wide quantification of millennial-scale erosion rates has suggested a potential "steady-state" between tectonic rock uplift and surface erosion for the Western and Central Alps (Wittmann et al., 2007; Champagnac et al., 2009), in contrast to the Eastern Alps (Norton et al., 2011). Ongoing efforts in further quantification of both modern rock uplift and millennial-scale erosion at the scale of the entire Alps have revealed higher modern uplift rates compared to catchment-wide erosion rates, potentially suggesting ongoing surface uplift for the Central Alps (Delunel et al., 2020). Overall, the influence of surface processes on orogenic dynamics in the European Alps is also expressed at short timescales since at least ~50% of the geodetically measured present-day vertical displacements are currently ascribed to the deglaciation of the Last Glacial Maximum ice sheet and Pliocene-Quaternary erosion of the belt (Sternai et al., 2019).

Another important aspect of the interaction between deep and surface processes in orogenic systems has been the documentation of important drainage pattern modifications associated with horizontal movements (Castelltort et al., 2012; Goren et al., 2015), as well as the possibility of large-scale landscape re-organization (Willett et al., 2014). These works have often been benchmarked with numerical and physical models (Guerit et al., 2016; Guerit et al., 2018), but they raise the need for further research on the implications of horizontal advection in mountain ranges, notably for the interpretation of exhumation thermochronometers.

Recently developed state-of-the-art numerical techniques allow thermo-mechanical experiments to be combined with simulations of realistic (including sedimentation and/or fluvial erosion) landscape evolution, not only in 2D (Burov et al., 2014; Ballato et al., 2019) or in a 2 + 1 D approach where the in-plane surface process is averaged across the width to account for the cross-sectional thermo-mechanical model (Beucher and Huismans, 2020; Neuharth et al., 2022; Wolf et al., 2022a; Wolf et al., 2022c), but also in true 3D geodynamic-geomorphological modelling (Braun and Yamato, 2010; Collignon et al., 2014; Thieulot et al., 2014; Ueda et al., 2015; Nettesheim et al., 2018) in both general (Koptev et al., 2022a; Munch et al., 2022; Wolf et al., 2022b, 2022c) and regional (Koptev et al., 2022b) contexts (Fig. 7).

Moreover, surface processes appear to be linked not only to crustal and lithospheric deformation, but also to magmatic activity. This is

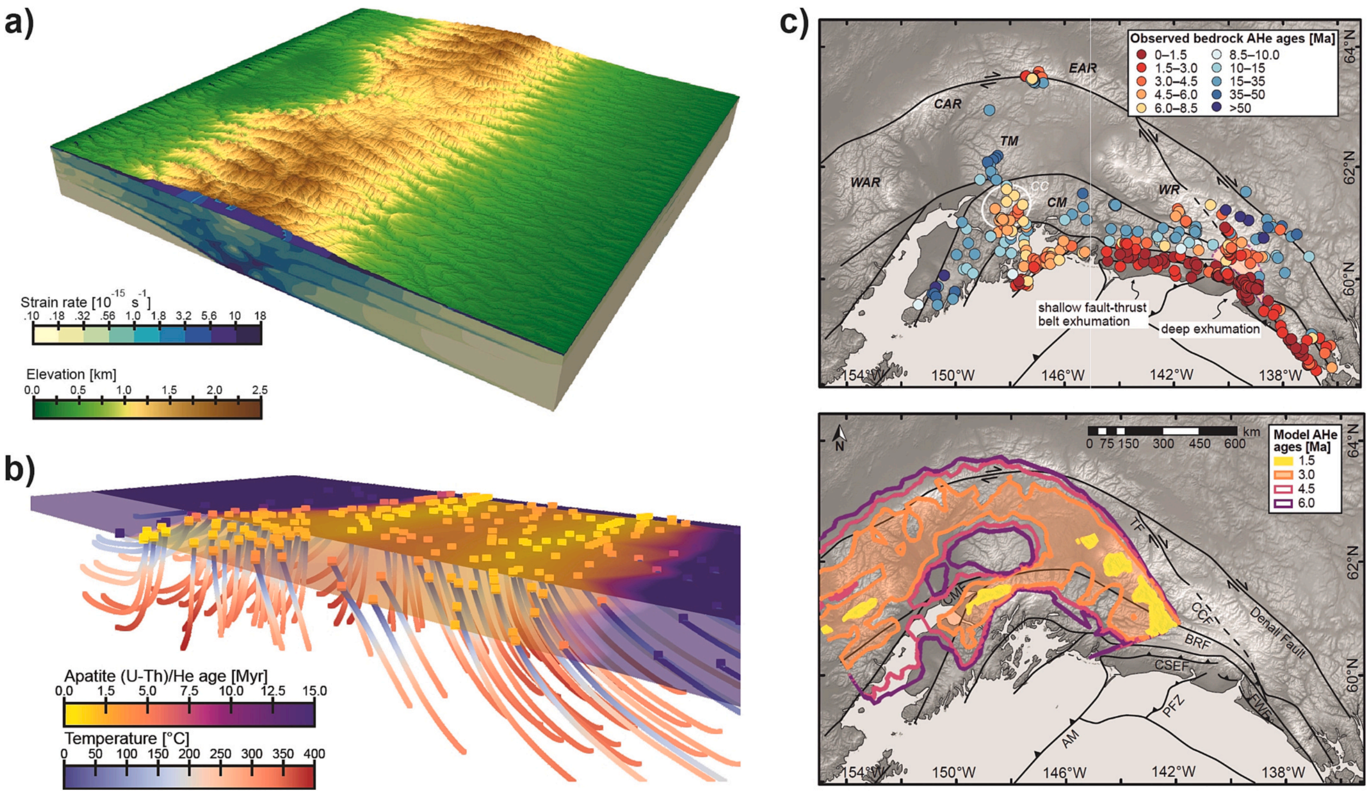

Fig. 7. (a) Example of a 3D geodynamic-geomorphologic model (Koptev et al., 2022a) created using the thermo-mechanical code DOUAR (Braun et al., 2008; Thieulot et al., 2008) coupled with the landscape evolution code FastScape (Braun and Willett, 2013). (b) Example of a thermochronometric age distribution calculated from the time-temperature history of tracer particles (Koptev et al., 2022a). (c) The first regionally applied true 3D geodynamic- geomorphologic modelling: comparison of modelled and observed spatial distributions of thermochronological ages overlaid on the topography of southeast Alaska (Koptev et al., 2022b).

increasingly being recognized and explored, and represents an example of a remarkable breakthrough in a particularly promising area of research. The straightforward concept behind these links is that changes in the crustal stress and strain fields due to variations of the surface load associated to erosion/sedimentation, ice building-melting and/or sea level changes can affect the magma production and upwelling towards the surface. As a result, subaerial volcanic activity can increase during interglacials due to the reduction of surface load by ice melting and erosion (Pagli and Sigmundsson, 2008; Singer et al., 1997; Rivera et al., 2012; Swindles et al., 2018; Sternai et al., 2016), whereas submarine volcanic activity can be inhibited by the downstream effect of sea level rise (Crowley et al., 2015; Schindlbeck et al., 2018; Kutterolf et al., 2019). These links pertain not only to individual volcanic edifices but also to entire volcanic arcs, where surface erosion/sedimentation can modulate the production of magmas (Sternai, 2020) and orographic erosion can force an upwind magma ascent toward regions of enhanced surface unloading (Sternai et al., 2021; Stuewe et al., 2022; Muller et al., 2023).

An impressive amount of research performed in just a few decades establishes that deformation, surface uplift or subsidence, erosion or sediment deposition (these latter may act in addition to ice-building/melting or sea level changes), and the magmatic/volcanic activity comprise a dynamic and complex system with feedbacks that links plate tectonics and continental drifting to the evolution of the surface topography.

2.4. Glaciers, bedrock adjustment and landscape evolution

Extensive studies on deep sea sediment cores have shown that the climatic evolution of the Cenozoic was characterised by gradual cooling after the climatic optimum of about 50 Ma, culminating in the Pleistocene glacial cycles of the last few million years (see Fig. 8). Superposed on this cooling of about 10 K were cycles and events of shorter duration. The Antarctic Ice Sheet formed about 35 Ma ago (e.g., Barrett, 1996; De Boer et al., 2010). It underwent periods of expansion and shrinking, but probably never disappeared completely.

During the Pleistocene, large ice sheets, with a cross section of up to ~2000 km and a thickness of up to ~3000 m, were growing and disappearing quasi-periodically on the continents of the Northern Hemisphere. Ice sheets also formed in Australia, New Zealand and Patagonia, but these were much smaller because of the limitations set by the land-ocean distribution. Our knowledge about the dynamics of the Pleistocene climatic fluctuations stems mainly from three types of sources: (i) isotope records from deep-sea sediment cores (e.g., Raymo et al., 2018), (ii) information from mapping of glacio-geomorphological features (e.g., Chandler et al., 2018), and (iii) records retrieved from the long ice cores drilled in Greenland and Antarctica (e.g. EPICA Community Members, 2004). The combined information shows that the amplitude and duration of the glacial cycles has been increasing over the past few million years. Global mean sea level changes associated with the waxing and waning of the big ice sheets are of around 100 m. However, regional differences are very large. Close to the centre of the big ice sheets, the Earth's crust has been depressed by up to ~1000 m. The interaction between ice sheet dynamics and delayed bed response is complex but of crucial importance for understanding the Pleistocene climate evolution (e.g., Lambeck, 1995).

Glacial isostacy and Glacial Isostatic Adjustment (GIA, sometimes also referred to as postglacial rebound) is an important process that underpins many of the other processes discussed in this paper, especially those relating to climate. Since a great deal of the current deformation of the Earth is a result of the redistribution of ice (e.g., melting of the Laurentide, Fennoscandian and Polar ice sheets), GIA has become a

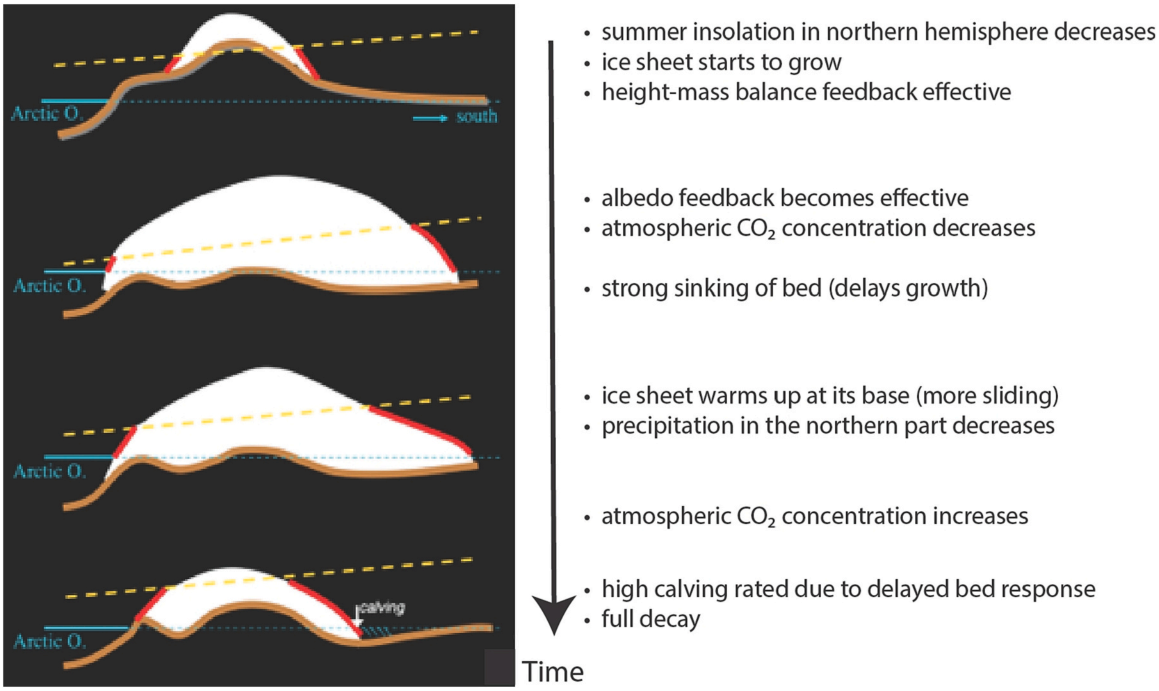

Fig. 8. The ice age cycle represented by north-south cross sections (northern hemisphere) at different phases. To the left is the Arctic Ocean, in the middle the higher grounds of Scandinavia and/or northern Canada. At its maximum size the ice sheet is typically 2000 km long. The dashed yellow line is the equilibrium line. The red sections on the ice-sheet surface represent the ablation areas (mass loss). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

specialized field. GIA is not only important anywhere there is and has been ice, at high latitudes and altitudes, but also away from these regions because continental glaciation/deglaciation affects sea level, with a resulting distal and global scale GIA response. Feedbacks between GIA and ice dynamics depend on the rate at which the Solid Earth responds to ice-sheet change, which, in turn, depends on the rheological properties of the mantle. In fact, the choice of the rheological model has a particularly large effect on the modelled GIA response. The response of the Earth to changing surface loads has generally been described using a linear Maxwell viscoelastic rheologic model, with an instantaneous elastic response superposed on a longer-term Newtonian viscous relaxation (Spada et al., 2011). However, non-Newtonian rheologies may also be important to understand and quantify the postglacial rebound across spatial and temporal scales (Adhikari et al., 2021; Blank et al., 2021; Lau et al., 2021). Seismic evidence underneath Antarctica (Heeszel et al., 2016; Whitehouse et al., 2019), for instance, indicates that there are spatial variations in mantle viscosities, and hence relaxation timescales that may vary across several orders of magnitude. In the northern Antarctic Peninsula, geodetic evidence suggests that contemporary ice loss is triggering a viscous rebound on decadal, rather than millennial, timescales (Nield et al., 2014), which can foster feedbacks on the ice sheet dynamics (Pollard et al., 2017; Gomez et al., 2015, 2018). This implies that, regardless of the choice of rheological model, lateral variations in rheological structure of the Earth suggested by differences in the response of the Earth to surface loading/unloading around the world, are crucial to GIA assessments. The need for future modelling and observational efforts to accounting for lateral variations of the Earth's rheology beneath large continental ice sheet is clear (Whitehouse et al., 2019; Kachuck et al., 2020; Weerdesteijn et al., 2022).

Until today, the central question in the ice-age story remains *how very small insolation fluctuations can lead to such big ice sheets, and, once they are there, why they disappear again.* Many theories exist and relevant processes have been identified, but a comprehensive Earth System model (including dynamic ice sheets), that generates the glacial cycles from astronomical forcing alone without imposing many constraints and 'ad hoc parameterizations' has not yet been constructed.

A qualitative overview of the processes thought to be most important in shaping a typical Pleistocene ice-sheet cycle is given in Fig. 8. The built-up of a large ice sheet starts when the equilibrium line, separating the accumulation zone and the ablation zone) lowers due to decreasing summer insolation at high latitudes. As soon as sufficient high terrain is above the equilibrium line, an ice sheet forms and will grow due to the height – mass balance feedback: the thickening ice sheet expands and grows upward into the cold atmosphere. Through albedo feedback the regional climate, and later the global climate, is cooled which facilitates further growth of the ice sheet and an expansion of glaciated terrain.

However, there are also processes that slow down the growth of an ice sheet. Isostatic bedrock sinking reduces the surface elevation, making the mass balance less positive. The base of an ice sheet slowly warms up because of the upward thermal heat flux and frictional heating in the basal layers where most of the shear takes place. The ice sheet thus prepares itself for decay when a summer insolation maximum (high equilibrium line) is on the way.

When an ice sheets decays, bedrock rebound is delayed by the slow viscous flow of the underlying mantle, and large lakes / estuaries are formed. The related calving at the margins may strongly accelerate the shrinking of the ice sheet. The bed response is thus a very important factor in the evolution of a Northern Hemisphere ice sheet. It is the primary reason for the *asymmetric* nature of an ice sheet cycle (slow build up and fast decay). The precise adjustment of the bed to a retreating ice margin differs significantly from a local isostatic response, depending on the flexural length scale. In future modelling studies the inclusion of lateral variations in rheological parameters is of crucial importance to get the interaction with ice sheet dynamics right. This is particularly relevant with respect to the current (in)stability of the Antarctic ice sheet and its subtle grounding line dynamics.

The erosive capacity of glaciers is enormous, and typical 10 times more efficient than that of weathering or running water. Erosion at the glacier base by abrasion and plucking increases with the ice overburden pressure. This constitutes a potential instability of the bedrock – ice system: when an ice-filled valley becomes deeper due to erosion the overburden ice pressure will increase and strengthen the 'scraping mechanism'. Over-deepening is the result, and fjords are the most dramatic products of this process. When the eroded material is deposited further away, local isostatic uplift will lead to a more pronounced topography with high plateaus intersected by deep U-shape valleys. The first attempt to simulate this mechanism by means of a numerical model (coupled ice – bedrock model) is described in Oerlemans (1984). Although the computer simulation was very primitive by todays standard, the experiments suggested that fjords can form over time scales of a few hundred thousand of years. Again, the details of the deformation process as determined by the rheology of the lithosphere play a crucial role.

Also, on smaller spatial scales glacier erosion shapes the landscape. Almost all freshwater lakes on the Earth are the result of glacial erosion. In Europe, all scales are present: from the numerous smaller lakes in Finland, the medium size lakes in Norway, Sweden, Scotland, and England, to the large lakes in the Alps.

In summary, the redistribution of mass by the process of glacial erosion constitutes an important link between climate variations, sea level, and the dynamics of the solid earth. Earth System Models aimed to simulate the evolution of climate over millions of years should deal with processes of glacial erosion and deposition.

2.5. Beyond dynamic topography, sea level change, glaciation

The Earth's topography is shaped by external and internal processes that continually shape interact at various time and spatial scales (Sternai, 2023). Mantle flow generates topography through the transport of temperature and density anomalies resulting in deformation of the surface, a mechanism first proposed by Pekeris (1935). Over the last few decades, the community of geodynamic models realized the potential implications of mass flow in the upper mantle for vertical motions at the surface of the overlying lithosphere. Major research efforts have been made to advance this field resulting in the concept of 'dynamic topography' as the regional relief generated by the flow-related vertical stresses and/or thermal anomalies acting at the base of the lithosphere resulting from the mantle flow.

Global models of mantle flow and density can be used to predict the Earth's dynamic topography. Current mantle flow models often include density anomalies derived from seismic tomography models (Conrad and Husson, 2009; Hager et al., 1985; Steinberger, 2007), and these density anomalies can be advected backward to several Myr ago (Conrad and Gurnis, 2003; Ismail-Zadeh et al., 2004). Some mantle flow models use reconstructed surface plate velocities as upper boundary conditions and plate assimilation techniques in forward models (Bower et al., 2015; Liu et al., 2008). Using a wealth of different techniques, previous studies attribute topographic anomalies at wavelengths greater than 10^4 km to convection across the entire mantle (Hager and Richards, 1989; Becker et al., 2014; Arnould et al., 2020). Such large-scale dynamic topography is expected to change at relatively slow rates between 1 and 80 m/Myr (Flament et al., 2015). Regional observational constraints, however, suggest the existence of transient (<10 Myr) and local (<3000 km) dynamic topography related to pulses of mantle upwelling or strong local upper mantle convection (Al-Hajri et al., 2009; Hartley et al., 2011). Interpretation of river drainage patterns based on continental margin uplift or subsidence (Pritchard et al., 2009; Roberts et al., 2012) or carbonate platform analysis (Czarnota et al., 2013) indicates rates of dynamic surface elevation change between 75 and 400 m/Myr. Regional models of dynamic topography and relative sea level change associated with small-scale convection (Petersen et al., 2010) predict surface topography at wavelengths as short as 250 km and on timescales of approximately 2–20 Myr. Petersen et al. (2010) showed that small-scale mantle convection can sweep across the surface with an amplitude of about ±300 m and induce a high-frequency stratigraphic sequence with period between 2 and 20 Myr and lateral wavelength of about 200 km.

A global model of present-day topographic anomalies based on global seismic data collected primarily at passive plate margins confirms that the magnitude of the remnant topography is significant at wavelengths as short as 1000 km (Hoggard et al., 2016). However, if near-surface tomography is not accounted for, most global mantle convection models predict negligible dynamic topography at wavelengths shorter than 5000 km (Hoggard et al., 2016) due to the limited resolution of global scale seismic tomography. Furthermore, the spatial variability of the seismic velocity-density conversion factors to predict mantle flow is uncertain, and chemical effects in the uppermost mantle are often ignored. In addition, lithospheric density anomalies are commonly not accounted for when dynamic topography is calculated from global or regional upper or whole mantle flow models (Flament et al., 2013; Lithgow-Bertelloni and Silver, 1998; Steinberger, 2007). More recently, Steinberger et al. (2019) showed that accounting for density heterogeneities in the uppermost mantle from a high-resolution near-surface tomography model in combination with a global S-wave model allows resolving dynamic topography at spatial scales as low as a few hundreds of km. However, it is worth pointing out that there is still considerable mismatch between predictions of the longest wavelengths dynamic topography (i.e., degree-two) (Steinberger et al., 2019). Because degree-two dynamic topography is mostly controlled by the dynamics of the lower mantle, poor predictions reflect a lack of understanding of lower mantle dynamics. Overall, the amplitudes of dynamic topography can be predicted across a wide range of spatial and temporal scales, if sufficient geological and geophysical observations are available. Improving predictions of dynamic topography at both specific locations and globally is an area of intense active research.

Studies have also been conducted on European regional scales and a testbed has been the Alpine-Mediterranean area due to the complex plate configuration and associated mantle dynamics. As shown by e.g., Boschi et al. (2010) for the pan-Mediterranean area, and by (Sternai et al., 2019), for the greater Alpine region, models' predictions are very sensitive to the adopted lithospheric structure and mantle, showing major differences when global low-resolution or regional high-resolution crustal and mantle tomographic data are used. Indeed, considerable debates exist on the magnitude of the mantle contribution to the surface vertical displacements as reviewed by Molnar et al. (2015) and Hoggard et al. (2016). These issues are important also in the context of linking inherited topography to the record of sea level change (Cloetingh and Haq, 2015), and continuing efforts are made to obtain insights in the connection between long-term sea level changes from Solid Earth processes, including the contribution from dynamic topography (Young et al., 2022) (Fig. 9).

Building upon the research done in the Alpine-Mediterranean domain (Faccenna and Becker, 2020; Sternai et al., 2019; Faccenna et al., 2014; Sternai et al., 2014), the AlpArray and AdriaArray research projects are providing the community with a great deal of new data including seismic anisotropy (Liptai et al., 2022; Rappisi et al., 2022; Lo Bue et al., 2022), Moho and LAB geometry, gravity maps, S- and P-wave structures (Bianchi et al., 2021; Sadeghi-Bagherabadi et al., 2021; Link and Rümpker, 2021; Scarponi et al., 2020) and other geophysical measures.

Improving quantifications of the patterns and magnitudes of mantle contributions to topography changes and vertical displacements is thus a major endeavour in the agenda of future surface-deep Earth research initiatives.

2.6. Deciphering the interplay between internal and external forcing in sedimentary basins dynamics

Sedimentary basins are our largest reservoirs of natural resources. Apart from fresh water, hydrocarbons have been a major target of intensive research by both academia and industry. Industry data, including multi-channel seismic reflection data and borehole data, have been an important source of information for deciphering the link

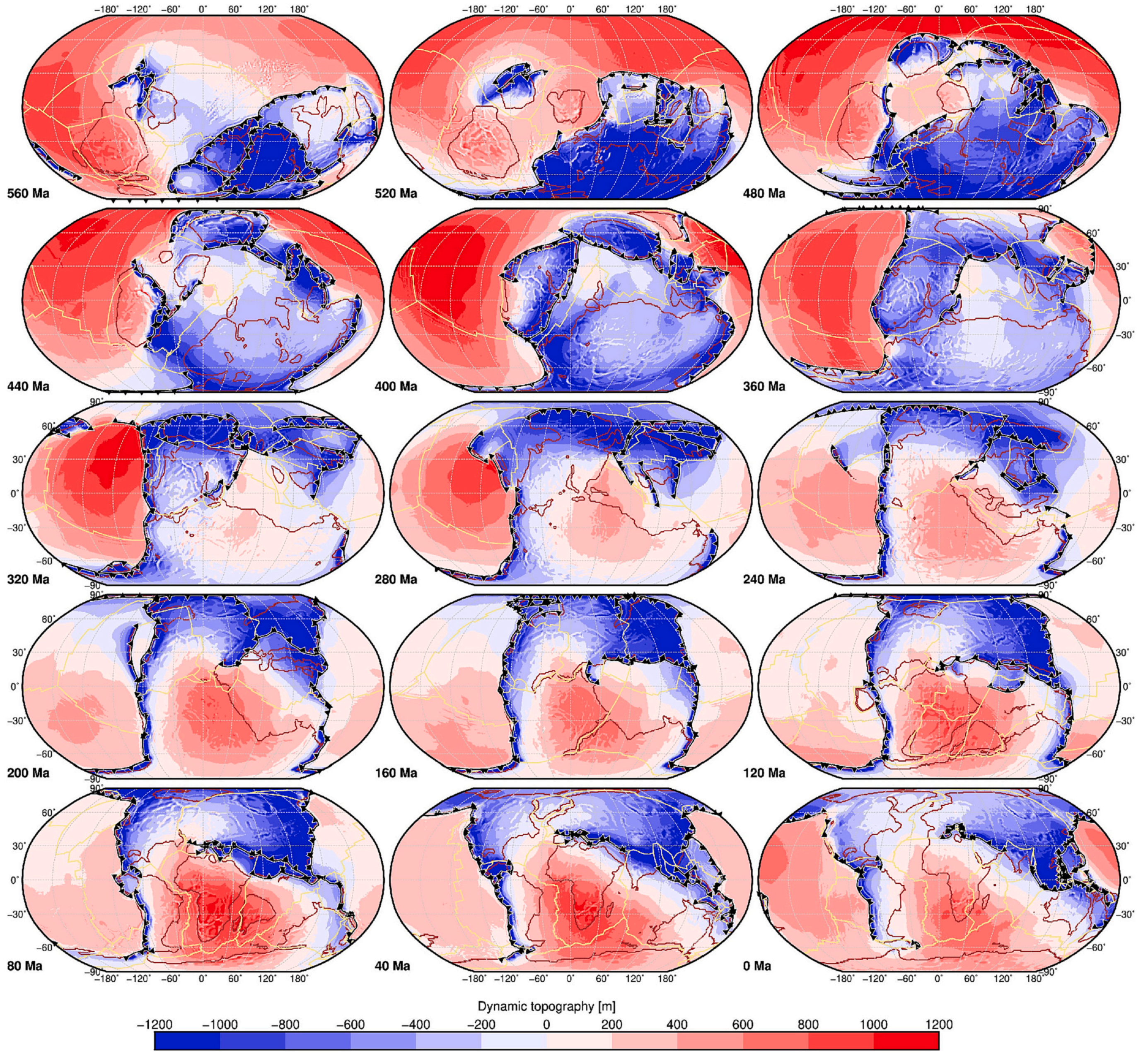

Fig. 9. Dynamic topography estimates since 560 Ma in 40 Myr increments, for sources of buoyancy deeper than 350 km, free-slip boundary conditions and preserving lateral viscosity variations at all depths (Young et al., 2022). Reconstructed subduction locations in black, reconstructed mid-oceanic ridges and transform faults in khaki, and continent-ocean boundary in brown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

between deep Earth and surface processes recorded in sedimentary basin systems (e.g., Roure et al., 2010a, 2010b; Cloetingh et al., 2015). Geodynamic concepts have also been utilized to develop basin classification for schemes for application in hydrocarbon exploration (e.g., Beglinger et al., 2012a, 2012b, 2012c). Understanding the structure and evolution of sedimentary basins is relevant to many societal issues (see also Section 4), especially as repositories for subsurface georesources such as geothermal energy or as reservoirs for carbon or hydrogen (Haszeldine, 2009; Cloetingh et al., 2010; Limberger et al., 2018a; Jolie et al., 2021). It has been realized since the early days of plate-tectonics that forces such as slab pull and ridge push generated at plate boundaries exert a fundamental control on plate motions (Forsyth and Uyeda, 1975) but also on the orientation and magnitude of stresses in the interior of the plates (Cloetingh and Wortel, 1985; Heidbach et al., 2019). As such, they are of first order importance for the formation of sedimentary basins, continental rifting and the creation of topography (Cloetingh et al., 2015). The orientation and magnitude of stresses inside the lithosphere is of great societal importance for assessment of natural hazards (e.g. seismicity) and for assessment of the impact of faults and fault re-activation on the stability and leaking of fluids from reservoirs, including reservoirs for geothermal energy and storage sites (e.g., Cloetingh et al., 2010; Limberger et al., 2018b). Insights in the feedback mechanisms between internal and external forcing acting in orogens and sedimentary basins systems is essential to quantify causal processes, such as linked exhumation and uplift in mountain belts with subsidence in neighbouring basins generating societal-relevant natural hazards (Roure, 2008; Seranne et al., 2015; Matenco et al., 2016; Bernard et al., 2019; Sautter et al., 2019). The interaction between deposition in sedimentary basins with processes in the neighbouring orogens driving erosion and transport is in particular challenging because it requires a multi-scale approach where the meters to tens of kilometres scale observations are integrated with numerical modelling across the entire orogen-basin system, including the underlying lithosphere (Fig. 10a) (Cloetingh and Haq, 2015; Gibson et al., 2015; Noda, 2016; Matenco et al., 2022).

Recent breakthroughs have shown that multi-scale vertical movements associated with erosion control the deposition in sedimentary basins, modulated by sea-level variations and the local climate, or in the case of endorheic basins the balance between precipitation and evapotranspiration (Nichols, 2011; Andric et al., 2018; Balázs et al., 2017; Ballato et al., 2019; Matenco and Haq, 2020). No matter the specific setting, tectonic drivers of vertical motions controlling the creation or destruction of accommodation space are made up of a wide number of processes that vary in time and space from upper crustal faulting and its individual moments of activation during the seismogenic cycle, the creation of individual basins or their connection in larger sedimentation domains, to the long-term thermo-flexural effects that are usually grouped in the generic term of dynamic topography, driven either by tectonics or mantle convection (Fig. 1) (Gurnis, 2002; Ventura et al., 2007; Conrad and Husson, 2009; Braun, 2010; Munteanu et al., 2012; Flament et al., 2013; Bercovici and Ricard, 2014; Sato et al., 2017; Faccenna and Becker, 2020; Tartaglia et al., 2020).

The sedimentation patterns observed have a wide range of temporal and spatial scales, creating an often quasi-cyclic deposition than can be observed in the 10 kyr – 200 Myrs and metres to hundreds of kilometres scale, depending on the balance between the rate of creating accommodation space and the rate sediment supply, modulated by a wide range of parameters, such as the distribution of faulting, thermal structure of the lithosphere, glacio-isostatic adjustment, the rate of creating the oceanic lithosphere, conditioned by climate and sea-level variations (Sigmundsson and Einarsson, 1992; Cobbold et al., 1993; Garcia-Castellanos et al., 2003; Cederbom et al., 2004; Haq, 2014; Cloetingh and Haq, 2015).

Among the observed large-scale variability of sedimentary basins, tectonic-driven sedimentation can ultimately be defined as being sourced from multiple directions in a quasi-cyclic deposition filling an asymmetric depositional space with an overall triangular geometry that contain steep slopes prone to mass-wasting deposition, creating ultimately generic tectonic successions that are spatial, temporal and sea-level independent (Fig. 10b) (Matenco and Haq, 2020). While the influence of climate and eurybathic variations, analysed by the classical means of sequence stratigraphy (Van Wagoner et al., 1990; Hardenbol et al., 1998; Catuneau et al., 2009), is undeniable in many tectonically-driven sedimentary wedges, such deposition takes often place in areas located too far in the continental interior, too deep in the oceans or too high in the mountains to be characterized by a global shoreline-fixed terminology (Fig. 10a). Therefore, the conceptual approach of multi-scale tectonic succession based on the identification of succession boundaries and point of reversals separating source-ward and basin-ward shifting facies tracts (Fig. 10b) is more appropriately employed for facies predictions in the large variability of syn-kinematic deposition observed. This terminology can be efficiently employed in all types of tectonic settings, from continental rifting and extensional, to transtensional, contractional and foredeeps, with relevant observational or

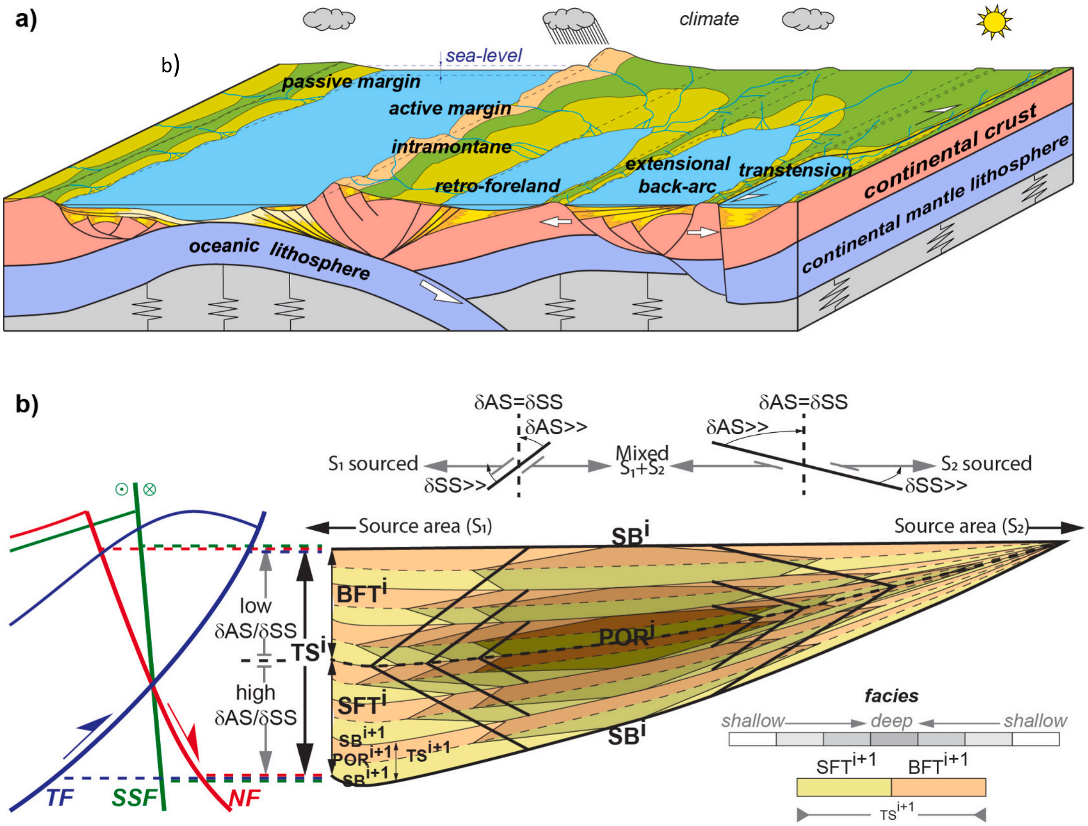

Fig. 10. The multi-scale depositional concept of tectonic successions driven by the coupled evolution of sedimentary basins, orogens and their underlying lithosphere (Matenco and Haq, 2020; Matenco et al., 2022). a) Sketch showing various types of plate tectonic regimes, the formation of depositional space and its infill in sedimentary basins; b) Conceptual definition of low (i) and high order (i + 1) tectonic successions (TS) in fault bounded sedimentary basin, which are composed of a source-ward-shifting facies tract (SFT) and a basin-ward-shifting facies tract (BFT). NF - normal fault(s), TF - thrust fault(s), SSF - strike-slip fault(s) with their sketched offset creating a wedge-shaped depositional space. SB = succession boundaries, POR = point of reversal, δAS = rate of creating accommodation space, δSS = the rate of sediment supply. For further details we refer to Matenco and Haq (2020) and Matenco et al. (2022).

modelling examples that can be applied to the Pannonian Basin, Western Mediterranean, Pyrenees, Alps, Carpathians or various types of south-eastern Asia basins (Matenco et al., 2010; Suades Sala, 2016; Balázs et al., 2016; Andric et al., 2018; Matenco and Haq, 2020; Balázs et al., 2021).

2.7. *Quantifying present-day vertical motions*

Satellite-based geodesy, and particularly global navigation satellite system (GPS), has rapidly developed in the last two decades, becoming the prime source of information on horizontal motion of the lithosphere. Examples of early regional scale horizontal surface velocity measurements are the studies of Reilinger et al. (2010), on the westward movement of Anatolia, and Grenerczy et al. (2005) on the north-westward movement of Adria and its impact on the adjacent lithosphere of the Dinarides Pannonian Carpathian region. This topic has also been an area of active research of TOPO-EUROPE, especially in the Fennoscandia region (van der Wal et al., 2013) and the Mediterranean area (Faccenna et al., 2014). Today, thanks also to the development of pan-European global navigation satellite system (GNSS) initiatives (e.g., EPOS, https://gnss-epos.eu), for large part of the Africa-Eurasia plate boundary zone it is possible to use horizontal geodetic velocities to constrain strain-rates, fault kinematics and lithosphere dynamics with unprecedent spatial details (Piña-Valdés et al., 2022; Pintori et al., 2022; Serpelloni et al., 2022).

A breakthrough has been the development of the capability to extract vertical motions from GPS observations. It is widely known, in fact, that the precision of vertical positions determined by GPS is typically about 3–5 times lower than for the horizontal. Moreover, GPS measurements of vertical surface motion are susceptible to numerous potential errors and local processes, besides the geometric weaknesses in the height component of GPS in general. However, the increasing GPS series length and stations spatial density now allows to extract spatially consistent, in a statistical sense, features of the vertical geodetic velocity field (Serpelloni et al., 2013; Pintori et al., 2022; Serpelloni et al., 2022; Kreemer et al., 2020). Also in this case, the Alpine-Mediterranean area has been at the forefront (Fig. 11). (Serpelloni et al., 2013) detected major differential vertical motions across the Betics, the Apennines and the Alps. In the Iberian micro-plate, for example, (Serpelloni et al., 2013) describe differential vertical motions with a wavelength and spatial pattern consistent with inferences from studies carried out in the context of Topo-Iberia (Fernández-Lozano et al., 2012; Cloetingh et al., 2002) proposing lithospheric folding and a decaying upper mantle thermal anomaly as a prime mechanism for explaining differential vertical motions during late Neogene to present times. (Faccenna et al., 2014), compared vertical GPS velocities and estimates of the crustal isostatic topography along the Apennines to show that a large fraction of the orogens topography is related to the mantle dynamics, particularly the formation and enlargement of a slab window underneath the central Apennines. GPS measurements of surface vertical displacements of the European Alps have also been carefully analysed (Sternai et al., 2019). Here, a correlation between rock uplift rates and topographic features exists, with uplift at rates of up to ~2–2.5 mm/a in the North-Western and Central Alps and ~ 1 mm/a across a continuous region from the Eastern to the South-Western Alps. Proposed mechanisms of rock uplift rate include isostatic response to the last deglaciation and/or long-term erosion, detachment of the Western Alpine slab, and surface deflection due to the sub-lithospheric mantle flow. The plausible range of model estimates is large. However, the isostatic adjustment to deglaciation and erosion may explain the full observed rate of uplift in the Eastern Alps which, if correct, precludes a contribution from horizontal shortening and crustal thickening and suggests lateral escape of the incoming crustal material toward the Pannonian and Dinaric domains. Alternatively, uplift is a partitioned response to the deglacial/erosional isostatic rebound and crustal shortening and thickening. In the Central and Western Alps, the lithospheric adjustment to deglaciation and erosion likely accounts for roughly half of the rock uplift rate, which points to a noticeable contribution by mantle-related processes such as detachment

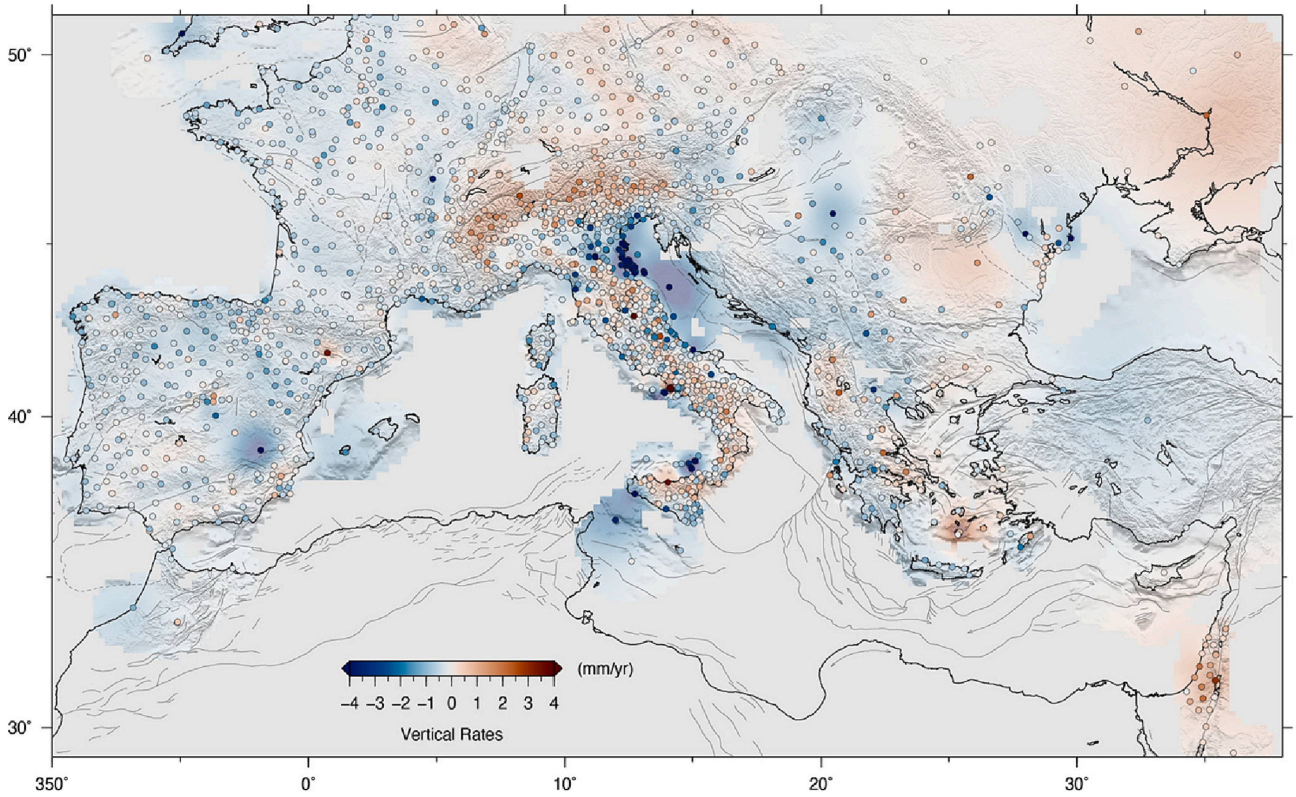

Fig. 11. Map of the absolute observed (coloured circles) and continuous vertical GPS velocities of the Mediterranean region (modified after Serpelloni et al., 2022).

of the European slab and/or asthenospheric upwelling. Thus, interacting tectonic and surface mass redistribution processes, rather than an individual forcing, best explain ongoing Alpine elevation changes, which is a further indication of the tight link between the Earth's surface and deep dynamics.

Vertical geodetic velocities provide key information for tectonic and seismogenic potential studies, with important implications, for example, in the Eastern Alps, where tectonic shortening and glacial isostatic adjustment, at least, are certainly simultaneously active (Anderlini et al., 2020). Since different multiscale processes are contributing to the total geodetically measured budget of vertical velocities in the Mediterranean and since each process is characterized by different spatial footprints, the availability of accurate and dense measurements of spatial velocity gradients is important to discriminate among their relative contributions. To achieve this goal, it is mandatory to increase the precision and accuracy of vertical and horizontal ground velocity measurements, other than increasing the density of measuring stations. It is now possible to exploit the large number of available stations with longer position time-series lengths to estimate spatially correlated common mode errors and common mode signals (mainly associated with hydrological processes occurring at different spatial scales), which can be filtered out resulting in a significant improvement in the precisions and accuracy of GPS velocity estimates (Kreemer and Blewitt, 2021; Pintori et al., 2022) (Fig. 12). Moreover, the increase in the number of active full-GNSS

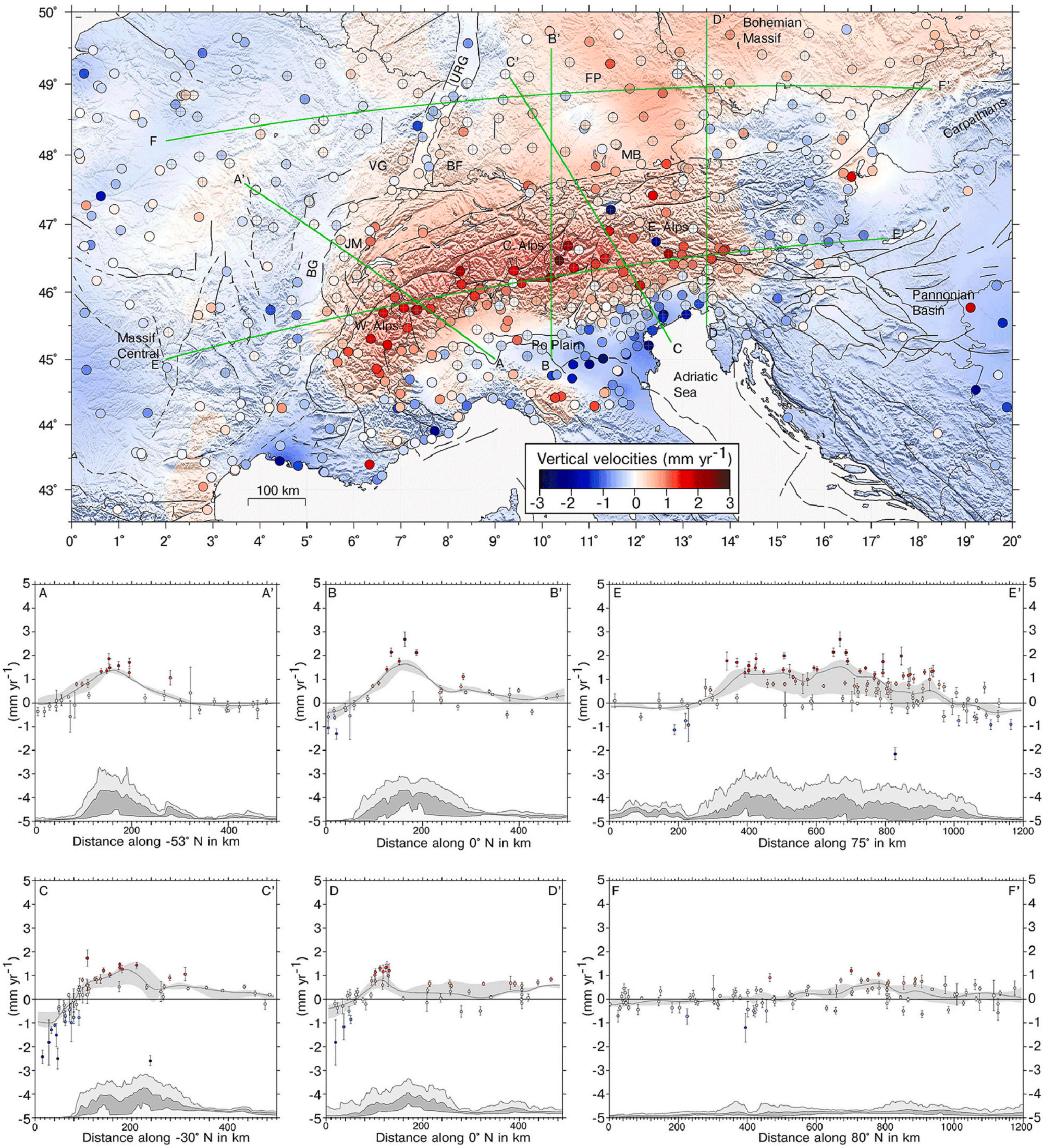

Fig. 12. Map of the common mode signal filtered (coloured circles) and continuous vertical GPS velocities of the Alps and velocity cross-section showing the positive correlation between velocities and topography in the western and eastern Alps (from Pintori et al., 2022).

stations, capable of recording all the GNSS constellations, other than GPS, and the development of new processing techniques, will certainly help improving the accuracy and precisions of vertical and horizontal measurements. Together with the desirable continuous increase in the density of GNSS stations, spatially detailed information on ground deformation at regional or even European scale can be now provided by synthetic aperture radar (SAR) measurements, with a key role played by the Copernicus Sentinel observations (https://sentinels.copernicus.eu). A recent example of the use of multitemporal interferometric SAR observations for the measure of mountain uplift in the western Alps is shown in Mathey et al. (2022), whereas pan-European InSAR velocity measurements are made available through the Copernicus Service for Ground Motion Mapping and Monitoring (https://land.copernicus.eu/pan-european/european-ground-motion-service; (Costantini et al., 2022)). All together, these recent and ongoing developments in the pan-European space geodetic infrastructures will provide new key information to improve our knowledge on the interactions between surface and deep Earth processes.

2.8. *Quantifying past mountain elevations*

Quantifying the uplift history of orogens, including orogenic plateaus and their margins, is essential for understanding the subsurface density structure of orogens, their isostatic compensation, and the interactions between climate, tectonics, and surface processes (Clark, 2007; Molnar et al., 2010; Clift et al., 2010). A wide range of methods have been developed for quantitative estimates of past mountain elevation, e.g., based on geomorphological evidences, such as river of marine terraces (Hergarten et al., 2010; Legrain et al., 2014), paleontological methods using fossil flora and fauna remains (Forest et al., 1999; Wei et al., 2016; Fauquette et al., 2015), and geochemical methods, such as biomarkers (Hren et al., 2010) and stable water isotopes. Among these methods, paleo-altimetry based on stable isotopes of water is the most widely used. This technique has been extensively applied to Earth's largest mountain ranges, such as the Himalayas and Tibetan Plateau (Ding et al., 2014; Rowley and Currie, 2006), the North America Cordillera (Cassel et al., 2014; Chamberlain et al., 2012), the Andes and Andean Plateau (Garzione et al., 2017; Mulch et al., 2010), but also to smaller mountain ranges such as the Pyrenees (Huyghe et al., 2012), the Tauride Mountains in Anatolia (Meijers et al., 2018), the Southern Alps in New Zealand (Zhuang et al., 2015), the Cascade Mountains (Methner et al., 2016), and the European Alps (Campani et al., 2012; Krsnik et al., 2021). For example, Krsnik et al. (2021) apply the stable water isotope paleo-altimetry approach to the Central Alps and suggest that the region surrounding the Simplon Fault Zone attained surface elevations of >4000 m by the middle Miocene. They propose a change in landscape from a uniform pre-middle Miocene to a more complex one with highly variable topography at the latest in the middle Miocene and attribute this change to the exhumation of the Aar Massif at ∼ 20 Ma and the associated reorganization of the Alpine drainage network. Complementary, Fauquette et al. (2015) used pollen data in combination with other sedimentological and provenance proxy to reconstruct the topographic evolution of the southwestern Alps since the Eocene. They showed that this region already had topographic elevations over 1900 m as early as the Oligocene, resulting from orogen tectonic building and coincident with a previously documented event of rapid erosional exhumation during the mid-Oligocene. Despite these quantitative studies, little is still known about the topographic evolution of the European Alps over the last 20–30 Myr (e.g., review in Valla et al., 2021 and citation therein).

Despite the success of these data-based paleo-altimetry methods, recent studies have highlighted that a variety of paleoclimate processes can contribute to the isotopic composition of a measured signal used in elevation reconstructions. In some cases, these processes can overprint the elevation signal sought in the proxy data and preclude robust elevation reconstructions (Poulsen et al., 2010; Botsyun et al., 2016). These processes can include: regional, global, and topographic variations in paleotemperature, environmental conditions of an air mass prior to orographic ascent, evapotranspiration, water vapor recycling, and changes in the vapor source. To overcome these uncertainties, it has been proposed to apply isotope-tracking climate models allowing to estimate changes in paleoclimate during orogen development and associated changes in paleo stable water isotopes due to both climate and topographic changes (Botsyun et al., 2019; Botsyun and Ehlers, 2021). In a recent paper by Botsyun et al. (2022) on middle Miocene climate in Europe and stable isotopes composition of water, the authors apply a climate model with isotope tracking and designed experiments with variable elevation configurations of the European Alps. This work not only reconciles models and proxy data for European paleotemperature and paleo-precipitation (Fig. 13), but also suggests that only a small fraction of stable water isotope variations in middle Miocene Europe is linked to changes in global climate, thus supporting high elevation of the central Alps in the middle Miocene.

Since the NSF Margins Science Plan (MARGINS Office, 2004), source-to-sink studies have proliferated over the last decades (e.g., Matenco and Andriessen, 2013), in industry and academia, providing concepts and tools for improved understanding of the uplift history of source terranes preserved in sedimentary basins, in particular with distinction to climate drivers (Helland-Hansen et al., 2016; Romans et al., 2015). Among others, these S2S studies have delivered important outcomes on the tectonic history of orogens through 1) the development and refinement of methodologies to estimate sediment budgets at the scale of entire orogen-basin systems (Guillocheau et al., 2012; Ortiz et al., 2022),; 2) the widespread development of detrital zircons dating for fingerprinting source areas, their exhumation, and their tectono-magmatic origin (Mason et al., 2022); 3) grain size signals; and 4) geochemical signals.

3. Perspectives and examples of emerging fields

3.1. *Surface-deep Earth processes coupling in extensional settings*

Much of what we know about the climate-tectonics interactions comes from the study of mountain building in convergent tectonic settings. However, prominent topographic ridges and basins generated by dominant extensional tectonics make divergent settings valuable contexts too (Armijo et al., 1996; Petit et al., 2007; Sembroni et al., 2016) and it seems somewhat intuitive that a thinning lithosphere transmits surface stress changes at depth more easily than a thickening one. Numerical experiments indicate particularly that syn-extensional sediment deposition within rift basins produced opposite mechanical and thermal effects (Burov and Cloetingh, 1997; Burov and Poliakov, 2001; Buiter et al., 2009; Sternai, 2020; Sternai et al., 2021). The increase in vertical stress involved by the deposition of sediments within rifts basins enhances the lithostatic pressure and, thus, the brittle strength of crustal and mantle rocks. On the other hand, thermal blanketing by sediment deposition prevents crustal rocks to lose heat, thereby enhancing the viscous strain of the lithosphere. By inhibiting localized brittle strain and favouring distributed ductile flow of viscous rocks, sediment deposition above a stretching lithosphere favours lateral migration of the extensional strain, in turn allowing for prolonged stretching and delayed continental lithospheric breakup. In a recent contribution Sternai et al. (2021) investigate how asthenospheric upwelling and orographic precipitation influence the slip along lithospheric shear zones accommodating far-field extension, associated topographic growth, and lithospheric rupturing. The authors derive a relationship between the location of lithospheric rupturing with respect to the asthenospheric plume axis and the lithosphere effective elastic thickness Te (Burov and Diament, 1995), accounting for asymmetric surface erosion due to orographic precipitation, recognizing striking similarities with the spatial pattern of lithospheric rupturing, rock exhumation, magmatic activity and topographic evolution of the East African Rift

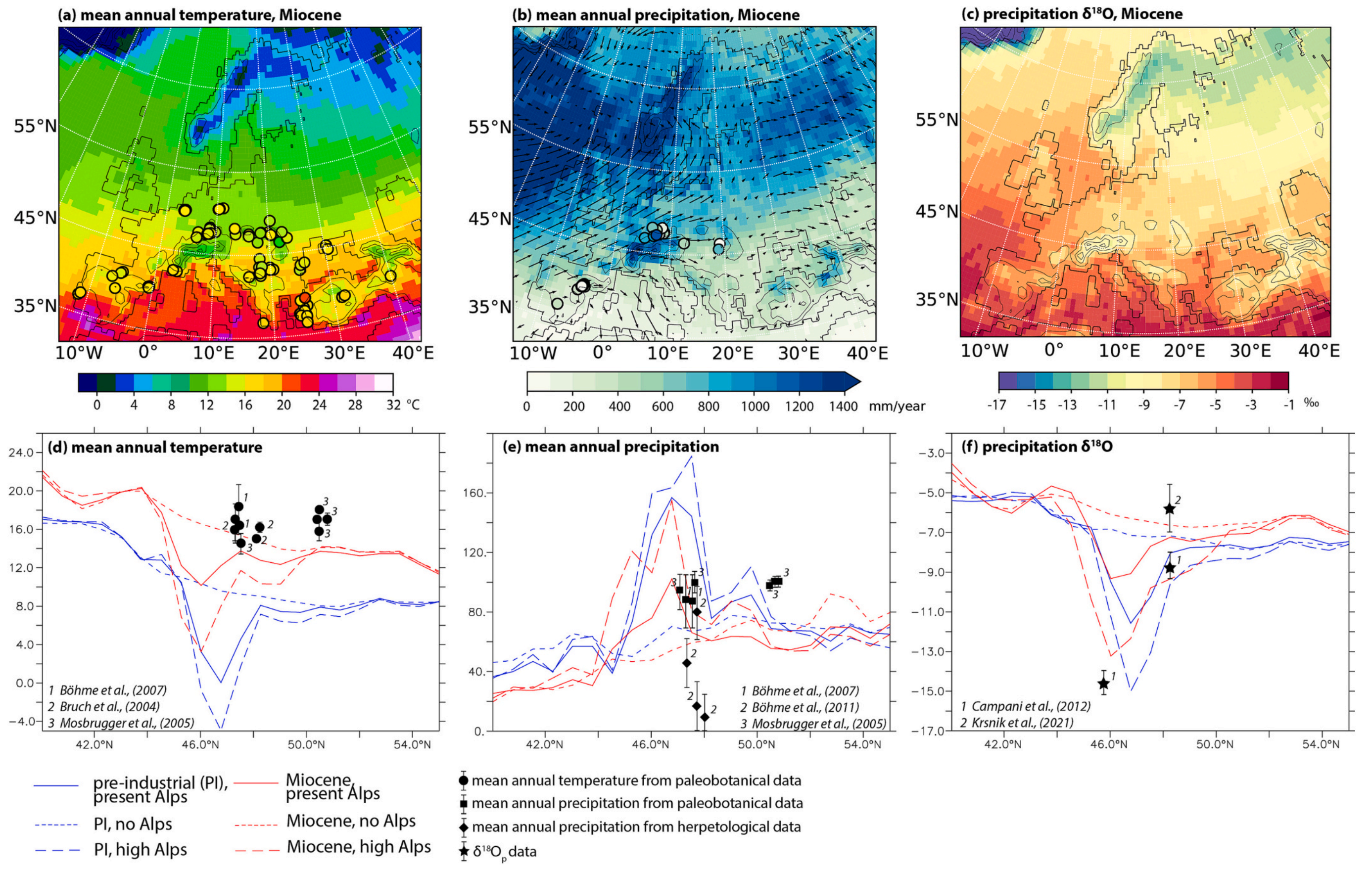

Fig. 13. Results of high-resolution isotope-tracking general circulation model ECHAM5-wiso experiments with Middle Miocene boundary conditions (modified after Botsyun et al., 2022). Maps show Middle Miocene mean annual temperature (a), mean annual precipitation and surface winds (b), and precipitation δ^{18}O (c). S-N profiles show Middle Miocene and pre-industrial mean annual temperature (d), mean annual precipitation (e), and precipitation δ^{18}O (f) for experiments with varied topography of the Alps. Color points on subplots (a,b) and black points on on subplots (d,e) show temperatures and precipiation derived from palentological proxy data. Black starts on subplot (f) show δ^{18}O from carbonate/silicate archives.

system.

Syn-extensional and post-breakup magmatic units are nearly ubiquitous in extensional settings and in some cases particularly voluminous (White and McKenzie, 1989; Franke, 2013). A particularly promising research direction in the field of the surface-deep Earth processes coupling is provided by the recent recognition that surface processes in extensional settings can significantly affect the magmatic activity (Fig. 14) (Sternai, 2020). Magmatism likely provides a substantial contribution to lithospheric rupturing (Kendall et al., 2005; Lavecchia et al., 2016) because extensional stresses alone are estimated to be at most just enough to rupture the continental lithosphere (Bott, 1991; Buck, 2004). The magma supply within fracture zones increases the pore fluid pressure, thereby lowering the plastic yield strength of fractured rocks and further localising the strain and topographic uplift or subsidence along weakening fault zones (Turcotte, 1982; Spence et al., 1987; Connolly and Podladchikov, 1998; Gerya and Yuen, 2003; Katz, 2008;

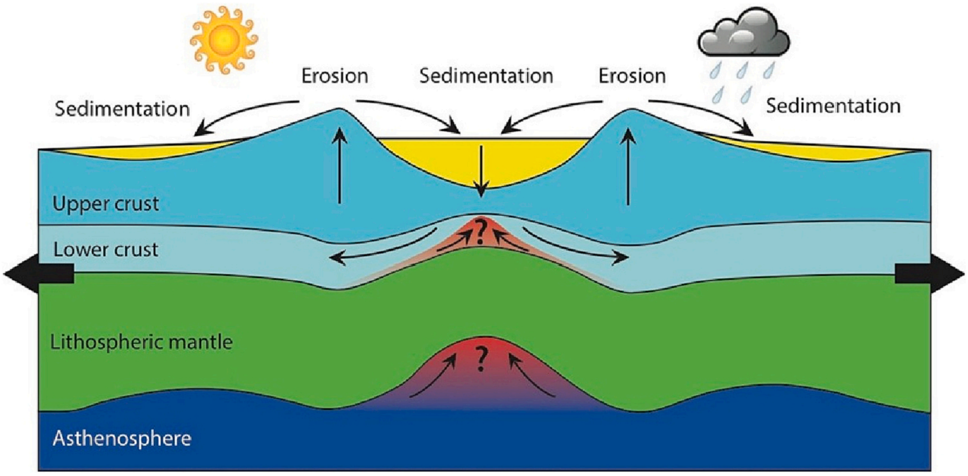

Fig. 14. Schematic representation of the interactions between surface processes and magmatism in an extensional setting (not to scale, modified after Burov and Cloetingh, 1997; Sternai, 2020). Sediments derived from erosion of rift shoulders load the rift basins. The rigid upper crust and lithospheric mantle flex and weaken, while more ductile lower-crustal material flows from the centre of the rift outward, facilitating uplift and erosion of the rift shoulders. The associated effects on extensional magmatism (reddish material) are to date poorly constrained and represent a promising emerging research field.

Sternai, 2020; Koptev et al., 2021b).

In this frame, peaks of igneous activity due to enhanced mantle decompression melting have been ascribed to surface unloading by the deglaciation (Jull and McKenzie, 1996; Singer et al., 1997) and/or erosion (Sternai et al., 2016) or sea level lowering (Crowley et al., 2015; Sternai et al., 2017). However, the sensitivity of extensional systems to surface processes and the mechanisms that allow these latter to affect the production, transfer and emplacement or eruption of magma are poorly constrained. Numerical modelling suggests that flexural bending of the Moho due to efficient sediment delivery into a rift basin is an efficient mechanism to enhance crustal melting in a stretching and warming lithosphere (Sternai, 2020). On the other hand, surface loading due to efficient filling of the rift basin dampens asthenospheric decompression partial melting by an amount proportional to the rate of basin deepening/filling, the sediment density, and the surface-to-depth stress change transfer of the rift system. For a given erosion/deposition rate, the modulation by surface processes to rock melting in natural rift settings is inversely correlated to the extensional velocity, mantle potential temperature (sensu McKenzie and Bickle, 1988) and initial Moho depth. Increasing observational evidence corroborates these modelling results, showing that surface load changes in the order of the tens of MPa due to sea level changes during glacial interglacial cycles can modulate the extensional magmatism (Crowley et al., 2015; Schindlbeck et al., 2018; Kutterolf et al., 2019; Satow et al., 2021). Along the Red Sea, convex channel profiles with concave swath profiles west side of the divide, systematic morphologic changes from north to south and the post-12 Ma basaltic volcanism are well interpreted through feedbacks between the onset of ocean spreading, uplift of the rift shoulders, associated coastal magmatism, and strong orographic rainfall (Stuewe et al., 2022). The recent seismic evidence for failed rifting in the Ligurian basin (Dannowski et al., 2020) can also be explained by the high rate of synrift sediment delivery from the western Alpine domain, fostering distributed rather than localized strain and preventing the extensional system to reach the ocean spreading stage.

The main point of these research breakthroughs is that typical changes in the temporal and spatial pattern of surface mass redistribution may result in protracted variations of the strain rate by up to a few orders of magnitude that reach down to sub-lithospheric levels. Such variations imply changes in the location and amount of partial rock melting, with further feedbacks on the strain pattern and topographic evolution. The resulting chain of cause-effect relationships between surface, lithosphere and asthenosphere dynamics are highly non-linear. We thus anticipate that unravelling the substantial modifications to the architectural evolution of extensional systems involved by ever-changing surface processes will be a highly rewarding challenge for future research.

3.2. *Surface-deep Earth processes coupling and the geological cycling of carbon and other life-essential elements*

At timescales of millions to tens of millions of years the Earth's life-essential elements, among which carbon is of primary relevance, flows between the atmosphere, lithosphere, and mantle in an exchange called the geological volatile cycle (Berner, 2003; Broecker, 2018; Bodnar et al., 2013; Hayes and Waldbauer, 2006). This cycling, therefore, embodies the coupling between tectonic and climatic changes in that by preventing, for example, all of the Earth's carbon and water from being released into the oceans and atmosphere or to be stored within rocks, it acts as a global long-term thermostat, linking the evolution of climate and life to plate tectonics. Geological emissions from volcanic arcs above subduction zones or at divergent margins are a critical input of carbon and oxygen into the atmosphere, whereas the chemical weathering of silicate rocks exhumed at the Earth's surface through erosion of tectonically uplifted terrains (Lee and Lackey, 2015; Kelemen and Manning, 2015; Mason et al., 2017; Bodnar et al., 2013; Vitale Brovarone et al., 2020a), and trapping of organic matter in sedimentary basins (Galy et al., 2007; Hage et al., 2022), consume the atmospheric carbon. Recently, analyses of hydrocarbon-rich fluids entrapped in quartz veins in the Swiss Alps have revealed significant fluxes of methane and CO_2 linked with the tectonic burial of organic matter during Miocene nappe emplacement and exhumation (Mangenot et al., 2021). Water-rock interactions at various geodynamic settings spanning mid-ocean ridges and convergent margins can produce fluxes of energy sources and nutrients for microbial life among which natural H_2, methane, ammonia, and hydrogen sulphide are of primary importance (Holm and Charlou, 2001; Kelley et al., 2005; Etiope and Sherwood Lollar, 2013; Vitale Brovarone et al., 2020a). Mineral inclusions in super-deep diamonds indicate that a large amount of water on Earth is stored in the mantle (Pearson et al., 2014; Nestola and Smyth, 2016). Analyses of the sedimentary archives allow reasonable estimates of the carbon outflux from the atmosphere through erosion, chemical weathering, and preservation of organic matter. Instead, the uncertainty regarding the amounts and driving mechanisms of carbon recycling and emissions from the Earth's interior (Fig. 15) stands out as one of the most vexing problems facing us in understanding the geological volatile cycle (Berner and Lasaga, 1989; Dasgupta et al., 2007; Burton et al., 2013; Kelemen and Manning, 2015; Orcutt et al., 2019). Available estimates of current carbon fluxes between the Earth's deep and surface reservoirs, for instance, vary by several orders of magnitude (Dasgupta et al., 2007; Kelemen and Manning, 2015; Plank and Manning, 2019), which is indicative of how little we know about this branch of the carbon exchange cycle. Multidisciplinary integrations of geological data and modelling to quantify variations in global emissions due to fundamental geodynamic events throughout the Earth's history and their critical effects on climate change represent a top-priority challenge for future research on the cycling of carbon and other life-essential elements, the quantitative understanding of which is also a fundamental objective of the International Panel on Climate Change - IPCC (www.ipcc.ch).

Mountains are key drivers of global weathering. They represent the main long-term sink of surface CO_2 as they are dominated by rapid mechanical erosion, which increases the amount of minerals available for chemical weathering (Raymo et al., 1988). The proposal that the India-Eurasia collision and uplift of Tibet led to greater global weathering rates and long-term Cenozoic climate cooling (Raymo and Ruddiman, 1992; Molnar and England, 1990) drove research efforts within and outside the TOPO-EUROPE community toward quantifications of past weathering rates (Goddéris et al., 2014) to explain the Cretaceous to Tertiary climate proxy record (Zachos et al., 2001). The currently established weathering-dominated climate paradigm, however, cannot explain the ~10 Ma climate warming preceding post-50 Ma cooling and overlooks changes in volcanic/magmatic /metamorphic CO_2 emissions in driving early Cenozoic climate (Sternai et al., 2020; Chu et al., 2019).

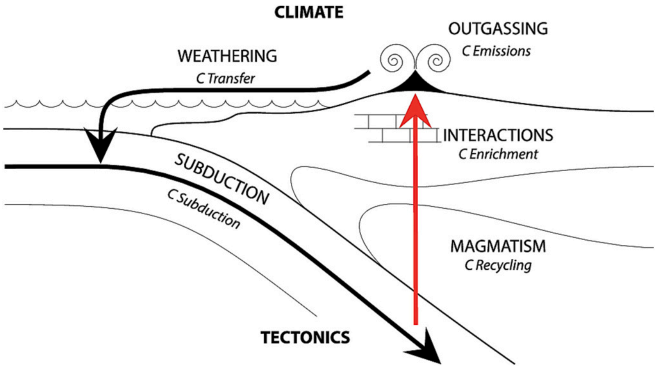

Fig. 15. Schematic representation of the geological carbon cycle (modified after Sternai et al., 2020). The recycling of carbon along subduction zone is a particularly poorly constrained branch of this cycle, but it provides and additional means of linkage between tectonic-magmatic events, climate and surface processes changes.

This is even more important in the light of recent reinterpretations of Cenozoic climate proxies suggesting overall higher and more variable temperatures than previously determined during the early Eocene (Meckler et al., 2022). Also, recent work further suggests that weaker than previously thought global Cenozoic silicate weathering fluxes (Rugenstein et al., 2019; Tipper et al., 2020) are to some extent compensated by weathering of accessory carbonate and sulphide minerals, a geologically relevant source of CO_2 (Bufe et al., 2021). It is also plausible that elevated rates of 'reverse weathering' - the consumption of alkalinity and generation of acidity during marine authigenic clay formation - enhanced the retention of carbon within the surface reservoirs, leading to elevated past CO_2 concentration baselines (Isson and Planavsky, 2018).

The large uncertainty that still exists regarding present-day and past CO_2 and other greenhouse gas emissions from volcanic arcs, the primary natural input of carbon into the ocean and atmosphere, is currently our greatest limitation to the quantitative understanding of the geological carbon cycle. Reconstructing the time history of greenhouse gas emissions thereby marking a turning point in the research about the surface-deep Earth processes coupling will be a priority in the future agenda of TOPO-EUROPE. Ground-breaking techniques that can be used to determine temporal changes in greenhouse gas emissions and assess their geologic drivers and climatic effects are: (1) studies of melt inclusions within magmatic rocks and subsurface fluid records (e.g. calcite/quartz veins), (2) geochemical and organic characterizations of accretionary systems to provide proxies of carbon recycling at subduction-collision zones (3) coupled petro-thermo-mechanical geodynamic, landscape evolution, Earth system and climate carbon cycle numerical modelling to constrain plausible changes in magmatic-volcanic-metamorphic emissions (CO_2 source) as well as weathering and exhumation of silicate minerals but also of organic matter and the trapping of organic material into sedimentary basin (CO_2 sink). To enhance the understanding of the sedimentary record, it is also important to adopt source-to-sink (S2S) strategies which allow better assessment of the relevant time and space scales, as well as of the potential signal buffering within the sediment routing system (Romans et al., 2015). Engaging into this research allows us to better quantify natural carbon fluxes, assess the drivers of natural climate variability and, by comparison, the climatic consequences of current anthropic emissions.

Another important aspect of the surface-deep Earth processes coupling that involves effects on the geological carbon cycle and has yet to be explored is the role of magmatism in affecting global climate through the intrusion of magmas into organic rich sedimentary basins or, more generally, crustal material. A telling example is the hypothesis formulated by Svensen et al. (2004), stating that the intrusion of magmas into organic rich sedimentary rocks of the Norwegian margin during NAIP activity is a potential trigger of a massive and very brief pulse of light Carbon injection into the atmosphere that is a possible responsible for the PETM hyper thermal event. Current research focuses on the tracing of volcanic activity, primarily through mercury concentration (Jones et al., 2019; Tremblin et al., 2022) or mercury isotopes (Jin et al., 2022) among other tracers, into ancient successions to test such hypothesis of deep-surface-climate relationships with impact on the biosphere.

Global estimates on geological carbon emission focus on active volcanoes but disregards diffuse CO_2 emissions away from active volcanoes which may originate in the mantle and travel to the surface through deep shear zones (Caracausi et al., 2015). With this regard, the pargasosphere concept (section 2.1) may provide a new generic model for CO_2 emissions from intraplate settings distant from active volcanic areas. Diffuse gas emissions with upper mantle origin may remain active in formerly active rifted regions long after the cessation of magmatism and volcanism (Kennedy and Van Soest, 2007). The chemical and isotopic composition of CO_2-rich gas emissions from these areas often show a direct upper mantle origin and a moderate signature of shallow crustal magma chamber processes or carbon reservoirs (Vaselli et al., 2002; Boudoire et al., 2018), which the 'pargasosphere' can help explaining. During gradual cooling of the partially molten asthenosphere beneath young oceans and continents, a small amount (<1 ν/v %) of H_2O- and CO_2-bearing basaltic silicate melts or supercritical fluids crystallize or react with the shallower upper mantle respectively (Berkesi et al., 2019). Although small proportion of carbon may be incorporated in apatite (Riker et al., 2018), most of the carbon is stored as CO_2 in fluid inclusions of silicate minerals or in free fluids at grain boundaries (Berkesi et al., 2019; Frezzotti and Touret, 2014). The source of CO_2 (and other volatiles) is the in-situ partial melt or incipient fluid present in the cooling asthenosphere a process that can be effective until the 1100 °C isotherm reaches the bottom of the 'pargasosphere' at 100 km depth. The CO_2-rich fluids trapped in fluid inclusions or along grain boundaries eventually migrate to the surface from the upper mantle and contribute to the global carbon cycle (Kovács et al., 2021). In case of CO_2-rich inclusions in upper mantle rocks, the effect of fracturing has been investigated (Yamamoto et al., 2011). These studies suggest that during deformation of the host minerals, fluid inclusions and fluids present at grain boundaries may be mobilized via diffusion or dislocation creep. CO_2-rich fluids can also be liberated along cleavages and migrate quickly toward the surface. The regional stress/strain field and the migration of CO_2-rich fluids thus appear to be tightly related, which is why CO_2 (and associated noble gas) monitoring is tentatively used in earthquakes prediction research (Szakács, 2011).

Water, besides carbon, is an indispensable ingredient of life on planet Earth. There is also a deep-water cycle which connects the atmosphere, hydrosphere and the Earth deep interior and ensures that Earth is still a living planet in the solar system with active plate tectonics. Living plate tectonics is associated with active volcanism and regular earthquakes especially in the vicinity of plate boundaries which is in large part made available by the presence of water even in small quantities in the Earth's interior. Water has disproportionally large effect on lowering the solidus temperature (e.g., Green et al., 2010; Green, 2015), viscosity (Dixon et al., 2004) and increasing the electrical conductivity (Fullea, 2017) of rocks. In the last decade there have been several studies (e.g., Peslier, 2010; Peslier et al., 2017; Demouchy and Bolfan-Casanova, 2016; Xia et al., 2019) summarising the water content of the different main reservoirs in the Earth interior. There is general consensus that the deeper part of the lithosphere contains only up to a few hundred ppm wt. bulk water with the exception of subduction zones, where it may be enriched up to thousands or wt% levels. In these deeper shells of the Earth water can be stored in melts/fluids, hydrous minerals (amphibole, phlogopite) or as structural hydroxyl in nominally anhydrous minerals (NAMs) (e.g., Demouchy and Bolfan-Casanova, 2016). The observation from upper mantle xenoliths, volcanic phenocrysts and experiments suggests that the partially molten asthenosphere beneath the lithosphere contains more water in accord with the presence of partial melts regardless the geological setting (Xia et al., 2019; Kovács et al., 2020; Liptai et al., 2022; Hua et al., 2023). It has been recently discovered that the top of the upper mantle transition zone (MTZ) can be a globally significant water rich layer containing up to wt% of water (e.g., Ohtani et al., 2004; Pearson et al., 2014; Kuritani et al., 2019; Freitas and Manthilake, 2019). At the MTZ it is thought that remnants of previously subducted slabs are accumulated, and therefore the water enrichment along this zone is mainly due to subduction recycling. It is still a hot topic how much water can be retained in subduction slabs and how subduction recycling into the Earth's deep interior impacts the secular equilibrium of the global water budget. A recent study (Hermann and Lakey, 2021) highlighted that the geochemical composition and P-T path of subducting slabs are the main factors controlling the amount of water that can be recycled into the deep upper mantle. The main conclusion of this novel experimental study is that the occurrence of colder subductions in the past few hundred million years enhanced the recycling of water back to the upper mantle lowering the global sea level. This also raises the possibility that the deep-water cycle may not be in secular equilibrium. On the other end, the hydrous MTZ can be the source of hydrous plumes which can recycle considerable amount of water back to the shallower upper mantle and contribute to the formation of magmas feeding volcanoes on the surface (Wang et al., 2015; Kuritani et al., 2019; Kovács et al., 2020; Liu et al., 2017, 2022; Cloetingh et al., 2022).

Carbon is mainly recycled into deep upper mantle in the form of various carbonates (calcite/aragonite, dolomite and magnesite). There is still significant uncertainty on how much carbon can actually be recycled into the deep upper mantle without having been expelled from the subduction slab by dissolution, devolatilization and precipitation in shallower levels of the subduction system (e.g., Kelemen and Manning, 2015; Hilton et al., 2002; Schmidt and Poli, 2003; Barry et al., 2019). In a recent study Farsang et al. (2021) found that solubility of carbonates in aqueous fluids is an important factor controlling carbon recycling and estimated that this dissolution is responsible for mobilising 10 to 92% of carbon in the subducting slab. In addition, the authors also pointed out that enrichment of carbonates in Mg expands their stability field and enhance their transport back to the deeper upper mantle.

An important aspect of the shallow and deep carbon cycle (and their links) is that the main fluxes are governed by redox reactions since carbon may occur in different valence states both in minerals and in fluids. The fate of carbonates (C^{4+}) and organic carbon (C^0), as well as methane-bearing fluids (C^{4-}) in modern subduction zones is still largely unconstrained and the carbon transfer from subducting slabs to the overlying mantle wedge is almost always mediated by fluids (Tumiati and Malaspina, 2019, and references therein). For this reason, the fluid-mediated processes occurring at the slab-mantle interface are of particular importance, along with the deep-water cycle, which involves subduction, volatilization, and deep recycling through volcanic arcs, is of utmost importance in comprehending the exchange of elements between the Earth's interior and the exosphere. The fluids released from subducted slabs are likely responsible for initiating mantle wedge melting and, as a result, play a role in arc volcanism (Ringwood, 1974). This is demonstrated by the unusual geochemistry of arc lavas (Tatsumi et al., 2006) and by tomographic images displaying low seismic velocities in the mantle wedge, which are interpreted as either the partially molten or hydrated mantle wedge (Zhao et al., 2009). From a petrologic point of view, hydrates coexisting with carbonates and C polymorphs have also been found in multiphase inclusions hosted by garnet and orthopyroxene of deep mantle wedge peridotites (Malaspina et al., 2010). Similarly, in the subcratonic mantle, far from active subduction zones, cloudy diamonds host inclusions derived by carbonatitic melts, aqueous fluids, brines, and silicate melts (Izraeli et al., 2004), revealing that the fates of C-O-H components are intimately related throughout the mantle.

Obviously, the transport of water in hydrous minerals at great depths has a significant impact on the Earth's volatile budget, the chemical development of the Earth, and the composition and rheology of the deep mantle. Petrological and thermal models can be combined to investigate the various metamorphic reactions that release fluids from the subducting plate (Syracuse et al., 2010; Wada et al., 2012). These models show that the depth at which the dehydration of the slab occurs depends on numerous factors that affect the thermal structure of the subduction zone, including slab age, slab thickness, slab dip, subduction velocity, and the lithology and initial water content of the slab. Estimates suggest that the quantity of water released in the first 150 km from the slab varies between approximately 40% to 70% (Rüpke et al., 2004; Parai and Mukhopadhyay, 2012). As a result, 30% to 60% of the rock water content can be transported deep into the mantle and recycled over extended geological time frames. The significant uncertainty regarding the amount of recycled water is mainly due to the limited constraints on some of the critical factors mentioned above and their evolution through space and time. The temperature of the mantle is another factor that affects the effectiveness of slab dehydration and thus volatile recycling. While various hypotheses on the cooling of the Earth propose different mantle temperature values, it is generally accepted that the Archean mantle was hotter by around 100–300 °C (Herzberg et al., 2010). This implies that, since temperature plays a significant role in slab dehydration, it may have been challenging to transport water deeply into the mantle during the early stages of the Earth's development.

Magni et al. (2014) used the compilation of subduction zones by van Keken et al. (2011) to estimate an average flux of water entering worldwide trenches of 2.63109 Tg/Myr. Many uncertainties exist on the initial hydration state of an incoming plate, and different authors used different settings in their calculation of the global water influx to produce very wide range of possible values: 0.7–2.13109 Tg/ Myr (van Keken et al., 2011), 1.33–2.43109 Tg/Myr (Hacker, 2008), 2.41–3.763109 Tg/Myr (Faccenda et al., 2012), 0.8–1.83109 Tg/Myr (Rüpke et al., 2004). About 26% of the water entering the trench at present day can be retained in the slab, particularly in the lithospheric mantle, and carried deep into the mantle and models with a 100–200 °C mantle thermal anomaly show that, if the plate is old and fast enough, it is still possible to have some water retained in the slab (Magni et al., 2014). Predictions further suggest that the global water flux deep into the mantle from 4 Ga until today is about one present-day ocean mass in the case of constant plate age and velocity, 60% of the ocean mass if the plate velocity was generally lower than today, and two ocean masses if the plate velocity was generally higher than today (Magni et al., 2014). Interestingly, all models indicate that deep water recycling in the early Earth is possible. Nowadays only a few subduction zones (Andes, Tonga-Kermadec, Solomon, and Java- Sumatra-Andaman) are responsible for carrying almost 60% of the total return flux of water in the mantle (Hacker, 2008). These results clearly indicate that the deep-water cycle can affect sea level, and thus paleogeography, life, and surface processes in time. Assessing (im)balance between subduction of water and degassing by volcanism is, therefore, a primary and promising matter of ongoing research.

3.3. Surface-deep Earth processes coupling and direct effects on life

3.3.1. Biogeodynamics

Several elements and nutrients useful to life (besides carbon) are cyclically transferred through surface and deep reservoirs during geological timescales. This implies that, beyond climate and landscape evolution (Antonelli et al., 2018), geodynamic events are intrinsically linked to the biosphere and increasing evidence suggests the establishment of modern-style plate tectonics contributed to the development of complex life on our planet (DePaolo et al., 2008; Sobolev et al., 2011; Stern, 2016; Zaffos et al., 2017; Lee et al., 2018; Hagen et al., 2021a; Hagen et al., 2021b; Large et al., 2015; Dehant et al., 2019). A global continuously evolving mosaic of lithospheric plates, likely established gradually during the geological past (Gerya, 2014; Gerya, 2019; Sobolev and Brown, 2019), supplies and withdrawals nutrients resulting in variations of environmental conditions that foster genetic modifications (Zerkle, 2018; Descombes et al., 2018). In this respect, modern-style plate tectonics with its continuously evolving global mosaic of lithospheric plates (Bercovici and Ricard, 2014) is often viewed as a strong promoter of biological evolution (Leprieur et al., 2016; Stern, 2016; Pellissier et al., 2017; Descombes et al., 2018; Zerkle, 2018).

Over geological timescales, volcanic activity of different duration, volume, and origin (e.g., from Large Igneous Provinces to ignimbrites flare-ups) contributed to changes in the composition and availability of trace elements required by life for metabolic functions. Life on Earth uses a small set of proteins to carry out most redox chemical reactions required for its survival. These proteins, called oxidoreductases enzymes, contain diverse trace elements as catalytic centres used to control redox chemistry. Elements used by life for this purpose include a diverse array of metals and some non-metal (Fe, Cu, Ni, Co, Mo, W, Mn and S among others; (Giovannelli et al., 2022). The environmental availability of these elements is linked to a variety of deep and surface Earth processes, including volcanisms (Edmonds et al., 2018; Liu et al., 2021), redox changes during planetary history (Anbar, 2008) and erosion of diverse rocks (Middelburg et al., 1988; Robbins et al., 2016). The onset of plate tectonics and variations in the coupling of deep and surface Earth processes influencing environmental trace element availability have likely had an effect on the emergence and distribution of life in deep-time, influencing the emergence of modern biogeochemistry and thus influencing climate (Giovannelli, 2022). Besides the effects through the recycling of nutrients and elements, the redistribution of continents, the growth of mountains, the rise and demise of volcanic and magmatic arcs, the opening and closing of marine gateways also produce moderate environmental 'stress' that stimulates populations to adapt and evolve (Stern, 2016). Indeed, some of the characteristic timescales of biological evolution are comparable to those at which geodynamic reorganizations occur (Giovannelli et al., 2022), which may be taken as further evidence of the coupling between internal and external dynamics (DePaolo et al., 2008; Hagen et al., 2021b). The influences of global tectono-magmatic style are at least twofold and regulate (i) the supply and withdrawal of nutrients (for instance, via mantle degassing/ingassing, rock weathering and erosion, sedimentation and burial, subduction-related recycling) and (ii) space-time variations of environmental pressures (including evolution of landmass distribution, landscape, atmosphere, ocean and climate). Zerkle (2018) and Stern (2016) summarized the nutrients-tectonics and environmental pressures-tectonics relations. First, they recognized that life is sustained by a critical set of elements contained within rock, ocean and atmosphere reservoirs and cycled between Earth's surface and interior via various tectonic, magmatic and surface processes. Over geologic time scales, tectono-magmatic processes play a critical role in providing bioactive elements to the ocean-biosphere system, via outgassing, volcanism, uplift and erosion (Zerkle, 2018). Second, they highlighted that tectonic processes such as the redistribution of continents, growth of mountain ranges, formation of land bridges, and opening and closing of oceans provide continuous but moderate environmental pressures that isolate and stimulate populations to adapt and evolve without being capable of extinguishing all life. In addition, mantle plumes and large bolide impacts provide episodic but potentially extreme environmental pressures capable of causing global mass extinctions. A planet with oceans, continents, and modern-style plate tectonics maximizes opportunities for speciation and natural selection, whereas a similar planet without plate tectonics provides fewer of such opportunities (Fig. 16) (Stern, 2016).

3.3.2. *Plate tectonics and biodiversity evolution*

It is obvious that both nutrients and tectonics aspects are intimately related and must be considered together for better understanding of life evolution and biodiversity distribution. It is important to point out that timescales of biological evolution estimated based on the analysis of phylogenies and/or fossils are rather long and comparable to geodynamic timescales (Alroy, 2008; Marshall, 2017). In a constant rate birth-death model (Kendall, 1949), new species originate with speciation rate, and species become extinct with extinction rate, typically expressed as rates per lineage per million years ($L^{-1}Myr^{-1}$). Typically, estimates of speciation and extinction rates fall within the range 0 to 1 $L^{-1}Myr^{-1}$ (Marshall, 2017) and rarely exceed 1 $L^{-1}Myr^{-1}$, except within intervals of crisis (Alroy, 2008). The timescales of biological evolution are therefore similar to the timescales of tectono-magmatic lithospheric and mantle processes in general and subduction and plate motions timescales in particular. This creates a natural possibility for the coupling of geodynamical simulations with life evolution modelling. Some recent examples of biogeographical modelling coupled to reconstructed plate motions that show strong potential of this modelling direction are shortly described hereafter.

Leprieur et al. (2016) investigated numerically possible roles of plate tectonics in driving tropical reef biodiversity dynamics. The Cretaceous breakup of Gondwana strongly modified the global distribution of

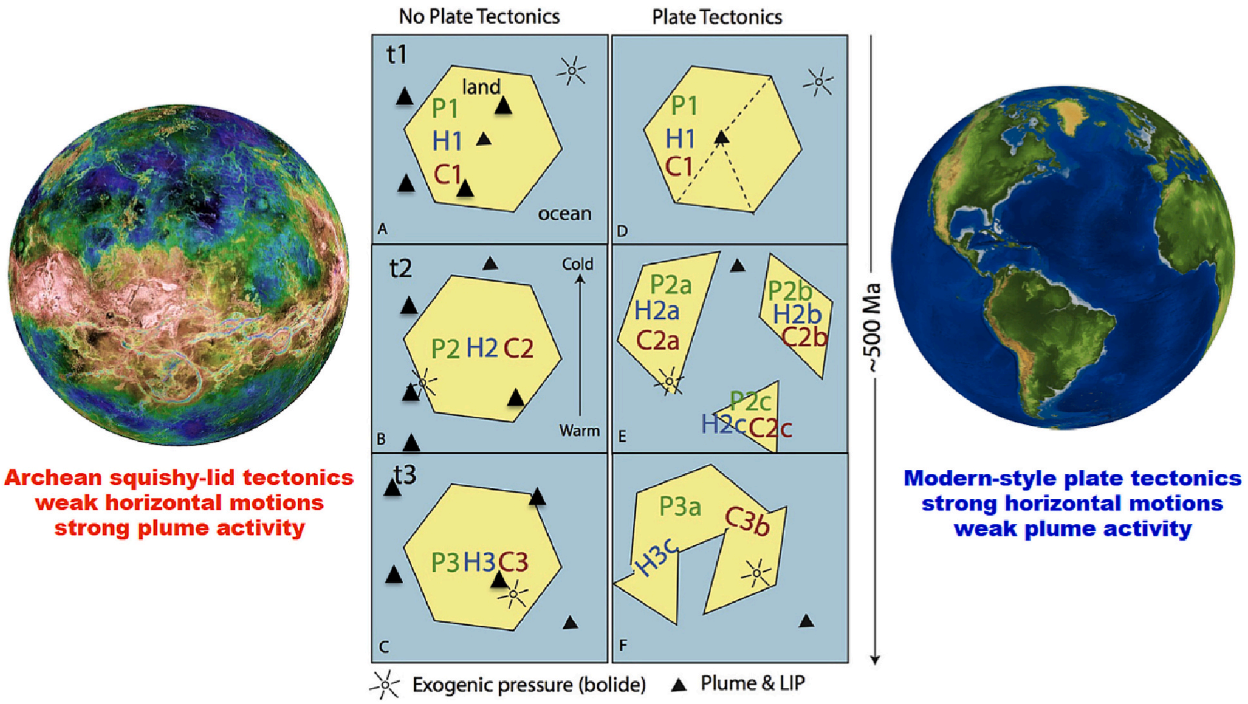

Fig. 16. Cartoon illustrating potential influence of global terrestrial tectonic styles on life evolution (modified after Stern, 2016). Two idealized Earth-like planets without (left, analogous to Hadean-Archean Earth) and with (right, analogous to modern Earth) plate tectonics are compared that possess continents (yellow) and oceans (blue) and three interdependent evolving life forms (plant "P", herbivore "H", and carnivore "C"). Three panels from top to bottom show three different times at ~100 million year intervals (characteristic timescales of the supercontinent cycle). It is assumed that exogenic evolutionary pressures (causing e.g., global mass extinction) depend on meteorite impacts and mantle plume activity including Large Igneous Provinces (LIPS). Plate tectonics causes breakup and movements of continents that provides many opportunities for isolation and diversification under different (geographic, climatic) conditions of natural selection, and evolution. On the other hand, when continents collide, different species comingle, and complete and new ecological systems are established that further accelerate life evolution (Stern, 2016). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

shallow tropical seas reshaping the geographic configuration of marine basins. Leprieur et al. (2016) showed that a spatial diversification model constrained by absolute plate motions for the past 140 million years can predict the emergence and movement of diversity hotspots on tropical reefs. The simulated spatial dynamics of tropical reefs explains marine fauna diversification in the Tethyan Ocean during the Cretaceous and early Cenozoic and identifies an eastward movement of ancestral marine lineages towards the Indo-Australian Archipelago in the Miocene. A mechanistic model based only on habitat-driven diversification and dispersal yields realistic predictions of current biodiversity patterns for both corals and fishes. Leprieur et al. (2016) therefore concluded that plate tectonics played a major role in driving tropical marine shallow reef biodiversity dynamics.

Pellissier et al. (2017) investigated how changes in the position, connectivity and topography of continents during the last 100 Myr could have shaped the current location of hotspots of endemic richness across the globe. They used palaeogeographies in a numerical model that quantifies, through time and space, the potential dispersal between disconnected habitat areas. As the dynamic coupling to changing plate tectonic environment, Pellissier et al. (2017) used palaeoreconstructions of the position of continents, coastlines and palaeobathymetry from the Early Cretaceous (140 Mya) to the present in 1 Myr steps as boundary conditions for their biogeographical models. They further developed a numerical biogeographical model based on habitat dynamics, which quantifies the amount of potential dispersal into each geographical cell from disconnected patches separated by unsuitable areas (i.e., of sea for terrestrial species or deep sea and land for marine species). Rare dispersal across such geographic barriers should allow the establishment of new populations, but gene flow is subsequently almost non-existent, leading to in situ speciation. Classical examples of long-distance colonization of remote areas such as islands (Guzmán and Vargas, 2009; Gillespie and Roderick, 2014) followed by local speciation support the possibility of dispersal across straits on geological time scales (Cowie and Holland, 2006), i.e. on the timescales of subduction and plate mosaic evolution. Pellissier et al. (2017) evaluated whether their biogeographical model could pinpoint the locations of hotspots of endemic richness computed from the ranges of 181′603 species across 14 taxonomic groups. As a result, Pellissier et al. (2017) found the significant spatial congruence between the model results and the observed present-day biodiversity, thereby providing important quantitative evidence of the contribution of plate tectonics in shaping global biodiversity pattern. Remarkably, the signal of plate tectonics was independent from those of the Quaternary glaciation, topographical heterogeneity and contemporary productivity and was stronger for terrestrial than freshwater and marine taxa (Pellissier et al., 2017). Complex tectonic regions, predominantly located at the confluence of major lithospheric plates such as the Mediterranean, Mesoamerica, Madagascar and South-East Asia likely provided favourable environments for allopatric speciation and the emergence of new species across straits (Pellissier et al., 2017). Non-coincidentally, these are also areas strongly affected by various subduction, collision and plate tectonics processes and complex landscape evolution.

Descombes et al. (2018) presented the new process-based numerical modelling tool SPLIT that allows to simulate the evolutionary dynamics of species ranges by spatially linking speciation, extinction and dispersal processes to paleo-environmental habitat changes over geological time periods. The SPLIT model provides a mechanistic expectation of speciation and extinction assuming that species are ecologically identical and not interacting. The likelihood of speciation and extinction is equivalent across species and depends on two dispersal parameters interacting with habitat dynamics (“d” a maximum dispersal distance and “ds” a distance threshold beyond which gene flow is absent). The SPLIT model tracks biodiversity dynamics under paleo-environmental changes and provides multiple expectations that can be compared to empirical patterns. Descombes et al. (2018) illustrated potential real-world applications of SPLIT by whether habitat changes caused by plate tectonics explain the current biodiversity patterns of mangroves. Simulations of the last 100 Myr successfully reproduced the observed longitudinal gradient in species richness, the empirical pattern of beta-diversity and also provided inference on diversification rates (Descombes et al., 2018).

Hagen et al. (2021b) presented the next generation biogeographical modelling tool GEN3SIS aimed at simulating eco-evolutionary processes coupled to plate tectonics and long-term climate variations. This tool allows to simulate species ranges, alpha- and beta-diversity patterns, ecological traits as well as phylogenies that can be compared to observations. This allows to evaluate different paleoclimatic and paleogeographic hypotheses by simulating different Earth history scenarios and comparing numerical results with available observations. As a case study, Hagen et al. (2021b) explored the cold-adapted plant biodiversity dynamics throughout the Cenozoic history, based on topo-climatic reconstruction for the India-Asia collision during the last 55 Myr. In this highly elevated region, the first cold niches of the Cenozoic appeared, demanding adaptation from the local living flora. The GEN3SIS model successfully predicted the emergence of current cold-species richness patterns and indicated that cold-adapted flora emerged in the Oligocene, first in the Himalayas, followed by a spread to the Arctic. The later agrees with observed low species richness and high nestedness of Arctic assemblages compared to those of the Himalayan Mountain range (Hagen et al., 2021b). Development and validation of GEN3SIS is thus an important step toward coupling of biogeographical and climate models.

3.3.3. Beyond continental drifting and the evolution of life

This very short overview highlights that bio-geodynamical numerical modelling (i.e., coupled modelling of Earth’s interior, climate, environment and life evolution) stands out as one of the frontier research tasks in geodynamics, biology, ecology and evolution as well as related disciplines. This is a promising future field, which will explore connections between deep Earth processes, surface processes, and the diversification of life. Accelerated development and application of new global- and regional-scale computational bio-geodynamical numerical modelling tools is needed, that will couple (i) available global and regional geodynamic models of subduction and plate tectonics processes (Crameri et al., 2012; Gerya et al., 2015), (ii) landscape evolution models (Braun and Sambridge, 1997; Braun and Willett, 2013; Goren et al., 2014), (iii) atmospheric, ocean and climate change models (Donnadieu et al., 2006; Donnadieu et al., 2009) and (iv) spatially-explicit models of species speciation, evolution and extinction (Gotelli et al., 2009; Leprieur et al., 2016; Pellissier et al., 2017; Descombes et al., 2018; Hagen et al., 2021b). The resulting hybrid bio-geodynamical numerical modelling tools will be used to explore systematically various subduction and plate tectonics scenarios and understand their potential effects for the evolution of the environment, landscape, climate and the diversification of life. To this aim, TOPO-EUROPE will encourage geodynamicists, geologists, (geo)biologists, ecologists, geochemists, palaeontologists, geomorphologists, and climate experts to cooperate and integrate/interpret biological data with geodynamic, landscape evolution, carbon cycle and climate (*sensu lato*) modelling.

Looking beyond continental drift and the evolution of life (Spencer et al., 2022), biota have been recognized as providing important controls on erosion and weathering processes (Langbein and Schumm, 1958; Istanbulluoglu and Bras, 2005; Heimsath et al., 2012) and river morphodynamics (Métivier and Barrier, 2012; Ielpi et al., 2022). Conversely, the development of topography over geologic timescales creates and destroys ecosystems and influences biodiversity (Antonelli et al., 2018; Hoorn et al., 2013; Boucher et al., 2021). Biota influence erosional processes through interactions with the hydrologic cycle (e.g., interception, infiltration, and runoff), as well as bioturbation and biotic weathering of rocks (Übernickel et al., 2021; Viles et al., 2021). In the absence of climate (or vegetation) change, topography can reach an equilibrium, or steady state, such that the mean of erosion rates over sufficiently long (millennial to million year) time scales reflects that of rock uplift rates (e.g., flux steady state of (Willett and Brandon, 2002)). Superimposed on this tectonic forcing on the landscape are transients in catchment erosion driven by internal dynamics such as river capture (Yanites et al., 2013; Willett et al., 2014), climate change (Tucker and Slingerland, 1997, Mutz and Ehlers, 2019), and vegetation (Starke et al., 2020). The effects of vegetation on erosion are linked to climate change, whereby climate (and topographic) change can lead to variations in the distribution of different plant functional types which then influence catchment average erosions by 5–25% depending on the ecosystem experiencing the change (Langbein and Schumm, 1958; Schmid et al., 2018; Starke et al., 2020). Finally, biota has also long been postulated to exert a strong influence on landscape morphodynamics, such as on river channel patterns and mobility, with potential impact on the transfer of the products of erosion from their source to their ultimate repository in sedimentary basins. Thus, although erosion rates, on the long-time scale, are consistent with uplift rates, over shorter timescales climate and vegetation can introduce transients in erosion rates that can potentially obscure the calculation of tectonically driven erosion rates. The previously described interactions highlight that tectonics, and climate and vegetation change have some degree of coupling with each other. More specifically, tectonic processes (from continental drift to mountain building) lead to changes in biomes and ecosystem composition, whereas climate (e.g., orography) and vegetation change influence erosion rates and landscape morphodynamics. Our knowledge of these interactions has grown in the past decade with the rebirth of biogeomorphology as a research area. However, the linkages and feedback between the biosphere, surface processes and solid Earth dynamics remain largely unexplored to date and, as such, present fertile grounds for future research.

In addition to the coupling and direct effects of surface-deep Earth processes on life at the surface of the planet, coupled processes between deep Earth processes, topography, climate and deep subsurface life have been discovered in the last decade of research (D'Hondt et al., 2019; Barry et al., 2019; Vitale Brovarone et al., 2020b). Recent advances in environmental microbiology have shown the presence of a vast, diverse and extremely active subsurface biosphere (Magnabosco et al., 2018). The distribution of subsurface life, which is entirely microbial, in the oceanic and continental crust is typically controlled by the 122 °C – 150 °C isotherms (122 °C is the maximum temperature for life growth in laboratory conditions –the so-called "biotic fringe" (Takai et al., 2008)) together with a variety of other parameters (e.g., pore space availability, water activity, presence of electron acceptor and energy sources). Data collected in the last 20 years of subsurface research show that life can penetrate the crust up to 3–5 km (Magnabosco et al., 2018; Kallmeyer et al., 2012), with theoretical studies suggesting that in areas of low heat flow such as those present in cold subduction zones the habitability zone can reach 15–20 km depth (Plümper et al., 2017). Given its global prevalence, diversity and slow but consistent biogeochemical impact over geological time scales (Giovannelli et al., 2022), deep microbial life has been shown to significantly alter the quantity and quality of volatiles recycled through the crust by plate tectonics (Giovannelli et al., 2020; Fullerton et al., 2021) and impact rock weathering through bio-leaching, bio-dissolution and bio-precipitation of minerals in diverse rocks (Lian et al., 2008; Heim, 2011; Samuels et al., 2020). While the extent of the effects of subsurface life on climate-relevant volatile is not constrained, recent papers suggest a tight relationship between deep Earth processes, topography and subsurface microbial communities interactions with element cycling. Recent work on the forearc region of the Costa Rica convergent margin have shown that calcite precipitation in the subsurface can account in a reduction of up to 19% of the carbon originally believed to be delivered to the mantle (Barry et al., 2019). In the same area, subsurface microbes remove through chemolithotrophy an additional 2 to 22% (Fullerton et al., 2021), which combined with the calcite precipitation described by Barry et al. (2019), brings the total amount of carbon removed from deep sequestration up to ~40%. Calcite and other calcium carbonate minerals are known to be microbially precipitated, either directly or indirectly (Stocks-Fischer et al., 1999) with the microbes acting as nucleating agents (Pacton et al., 2014) or altering the chemical equilibrium (Seifan and Berenjian, 2019). While these papers are focused on the forearc region of the Central American Volcanic Zone, similar processes might be at play in other convergent margins, and their relative intensity might change in relationship to topographic features and deep Earth processes. In the South American Central Volcanic Zone, the inventory of volatiles recycled through volcanism both in the volcanic arc, forearc and backarc correlates with crustal thickness and heatflow (Barry et al., 2022). The presence of reduced heatflow, for example linked to stable cratons, cold orogenic belts and cold subduction zones, can promote a deeper subsurface ecosystem, allowing for extensive interaction between rock, fluids and microorganisms at depth. Cold thermal regimes do not only favour habitable conditions to depth, but also allow geological processes necessary for microbial life to extend to greater depths and, possibly, to have emerged on Earth. Olivine hydroxylation, also called serpentinization, is a simple, yet fundamental fluid-rock interaction that has attracted broad scientific interest in communities spanning geology, petrology and geochemistry, microbiology, astrobiology, and geo-energy research. Serpentinization is known to produce reduced fluid species such as H_2 and abiotic CH_4 that act as sources of energy for microbial life (Kelley et al., 2005; Martin et al., 2008), as well as key building blocks of life (Ménez et al., 2018). Cold subduction thermal regimes, which result from the interconnection of multiple surface-deep interactions, favour the extension of serpentinization reaction and H_2 and abiotic CH_4 to greater depths (Vitale Brovarone et al., 2020b). This feature sets deep convergent margins fluid-rock reactions as a major feeder of energy for deep –or the deepest–life form on Earth and potentially beyond (Mottl et al., 2003; Ohara et al., 2012; Vitale Brovarone et al., 2020b).

While this is a new area of inquiry and data is lacking for diverse tectonic settings globally, the presence of a pervasive subsurface biosphere has the potential to significantly alter volatile cycling over geologic time scales. The feedback mechanisms between deep and surface Earth processes and the biosphere (both surface and subsurface) might have contributed significantly to diverse tipping point in Earth planetary history, and the coevolution between geosphere processes and the biosphere constitute a ripe area of future research.

4. Impact on societal challenges

4.1. Current climate change

Observations of present-day and recent warm climates (e.g., Mid-Piacenzian Warm Period) help understanding climate dynamics and constraining predictions of future climate conditions in response to human activity (Robinson et al., 2008; Haywood et al., 2011). However, these observations provide limited information about the climatic response to the massive amount of CO_2 that our societies release into the atmosphere and ocean. To assess climate projections, it is desirable to study past climate changes associated with high atmospheric CO_2 concentrations, similar to those predicted for the near future (i.e., 550 ppm in the next 30–80 years and $>$ 1500 ppm in just a few centuries if anthropogenic emissions continue unabated (Caldeira and Wickett, 2003)) and longer than global ocean overturning (i.e., a few millennia). In addition, the tangible narratives of past climate perturbations preserved in rocks, and the story they reveal of their impact on landscapes, biota and even human populations (Zaki et al., 2021) are *per se* efficient communication tools to channel important and complex knowledge to the society (Pancost, 2017), without invoking predictions and the uncertainties they bear that are often misunderstood by the broader public. TOPO-EUROPE is highly interdisciplinary, pooling not only on Solid Earth sciences, but also on paleoclimatology and climate sciences. That topography influences climate has been known since the beginning of civilization, but only recently have we been able to model its effects in regions where good (paleo-)topographic and climatologic reconstructions are available. The present state and future evolution of climate is a consequence of processes operating over a wide range of temporal and spatial scales such as the behaviour of river systems, the residual effects of the ice ages on crustal movement, and the powerful anthropogenic impacts of the last century. If we are to understand the present state of the climate system, to predict its future and to engineer our use of it, this spectrum of processes, operating concurrently but on different scales, needs to be better understood.

Within this framework, the Miocene period provides an ideal paleo-example of future climate (Steinthorsdottir et al., 2021), as paleoclimate proxy records document high atmospheric $p\mathrm{CO}_2$ values of up to ~600 ppm, with over 1000 ppm permissible during the Miocene Climatic Optimum (Rae et al., 2021). Recent modelling efforts to simulate global

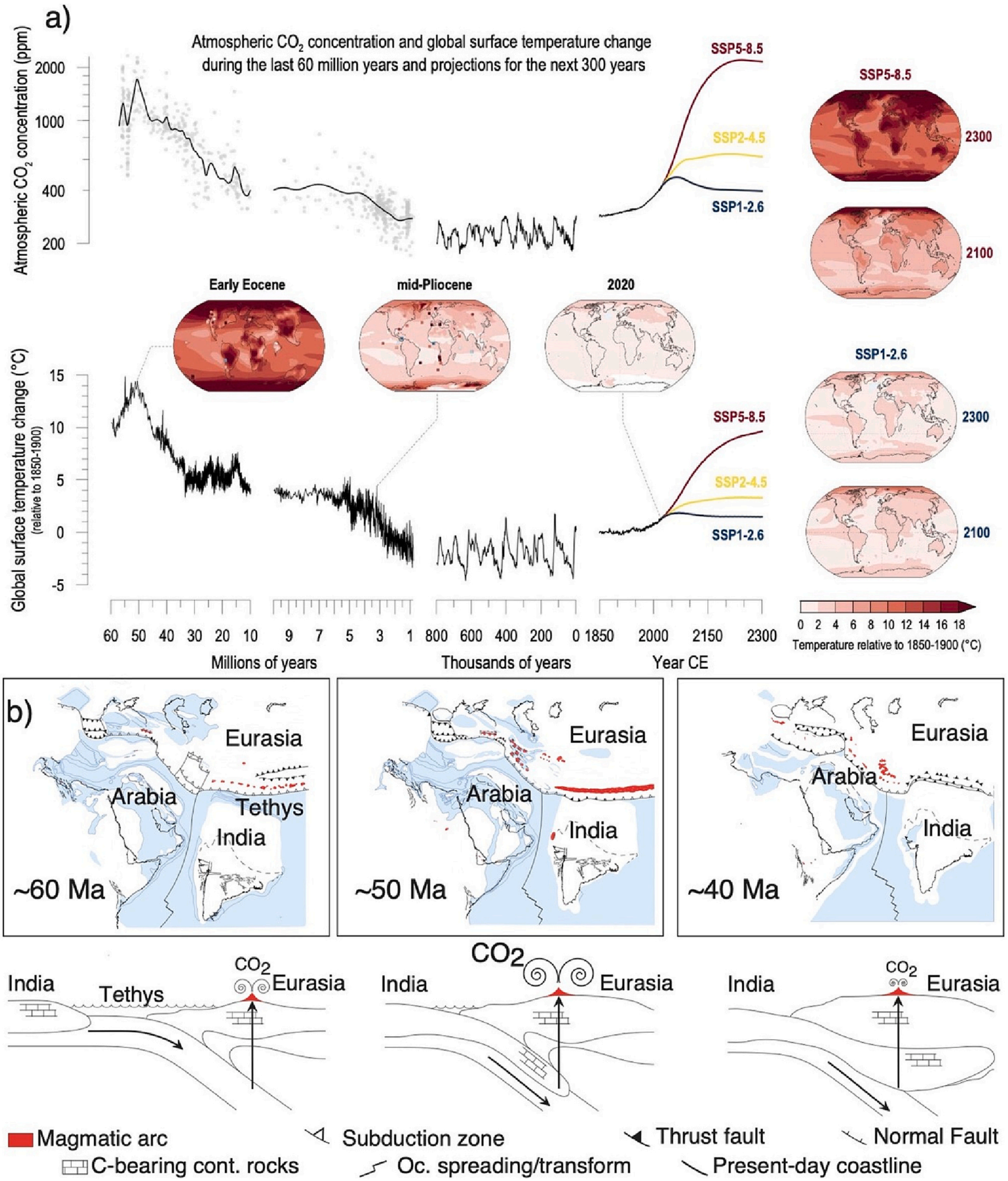

Fig. 17. (a) Changes in atmospheric CO2 and global surface temperature (relative to 1850–1900) throughout the Cenozoic and for the next 300 years (modified after IPCC 2021 report, to which the reader is referred for details on sources and data analyses). (b) Paleotectonic maps and cross-sections of the Neo-Tethyan margin during the lower Cenozoic (modified after the paleotectonic reconstructions by the DARIUS program, 2018, http://istep.dgs.jussieu.fr/darius/maps.html and Sternai et al., 2020).

Miocene climate (MioMIP1 project; (Burls et al., 2021)) show that during the Miocene, the stronger polar greenhouse effect (due to CO2, water vapor, and lapse rate) and decreased surface albedo, are the dominant contributors to the Polar amplified warming – a result consistent with the literature on future climate change (Pithan and Mauritsen, 2014). For Europe, the Miocene is characterized by strong precipitation "bi-directional" precipitation change (Fig. 17), with a precipitation decrease over the Southern Europe and the Mediterranean and an increase over Scandinavia and Northern Russia (Botsyun et al., 2022). It was also highlighted that paleoclimatic modelling studies are sensitive to the choice of geological boundary conditions (e.g., paleogeographic reconstruction including surface topography). Therefore, adequate paleoclimate modelling studies require direct integration of latest state-of-the-art of plate tectonic, crustal and paleomagnetic reconstructions, paleotopography, and paleobathymetry.

Another paleo example of what the future climate be like is the Early Eocene Climatic Optimum (EECO), between around 53 and 50 million years ago, characterized by much higher CO_2 concentrations and warmer global temperatures (Fig. 17) (Meckler et al., 2022). At timescales shorter than a few tens of thousands of years, early Eocene hyperthermals show that atmospheric CO_2 concentration and temperature can increase abruptly driven by natural forcing (Barnet et al., 2019). The most prominent hyperthermal, the Palaeocene-Eocene Thermal Maximum (PETM, at ~55 Ma) involving a global temperature increased by more than 5 °C in less than 10 kyr (McInerney and Wing, 2011), is to all effects the most similar known climate aberration to the ongoing global warming (Fig. 17). Several paleoclimate modelling studies of the PETM (Rush et al., 2021; Shields et al., 2021), have now successfully demonstrated how elevated CO_2 levels could trigger important hydrological response, in particular with atmospheric rivers and shifts in storm tracks, highlighting the potential of future couplings of solid Earth models and high-resolution coupled climate ocean-atmosphere simulations. The early Cenozoic thus includes an ideal ensemble of natural experiments to elucidate the mechanisms and drivers of climate changes and assess by comparison the role of human activity in setting the overall conditions and transience of the global climate (Lunt et al., 2021). The occurrence of past abrupt warming events provides an opportunity to test theories about the physical and biogeochemical interactions in rapidly shifting systems. To achieve this goal, however, it is pivotal to develop a deeper understanding of the complex interactions between the climate system, the biogeochemical cycles and the characteristic processes of the solid Earth, with particular focus on positive and negative feedbacks acting on short geological timescales.

4.2. Stability of the Greenland and Antarctic ice sheets and future sea level

Changes in the shape of the Greenland and Antarctic ice sheets are of great concern, because an amount of 67 m of sea-level equivalent is stored here in the form of ice. Even a 1% decrease in the ice volume, corresponding to a sea level rise of 67 cm, obviously has huge consequences for coastal regions.

Mercer's alarming paper about the possibility of a runaway deglaciation of the West Antarctic ice sheet (WAIS, Fig. 18) initiated by anthropogenic greenhouse warming (Mercer, 1978), generated a great deal of research on marine ice sheets, grounding line stability, and interactions of ice sheets with the ocean. In recent decades we see signs that the threat of a retreating WAIS may become a reality. Also, runoff and ice discharge from the Greenland ice sheet shows a clear upward trend since about 1980 (King et al., 2020).

Much of the concern is due to the fact that mean sea level was about

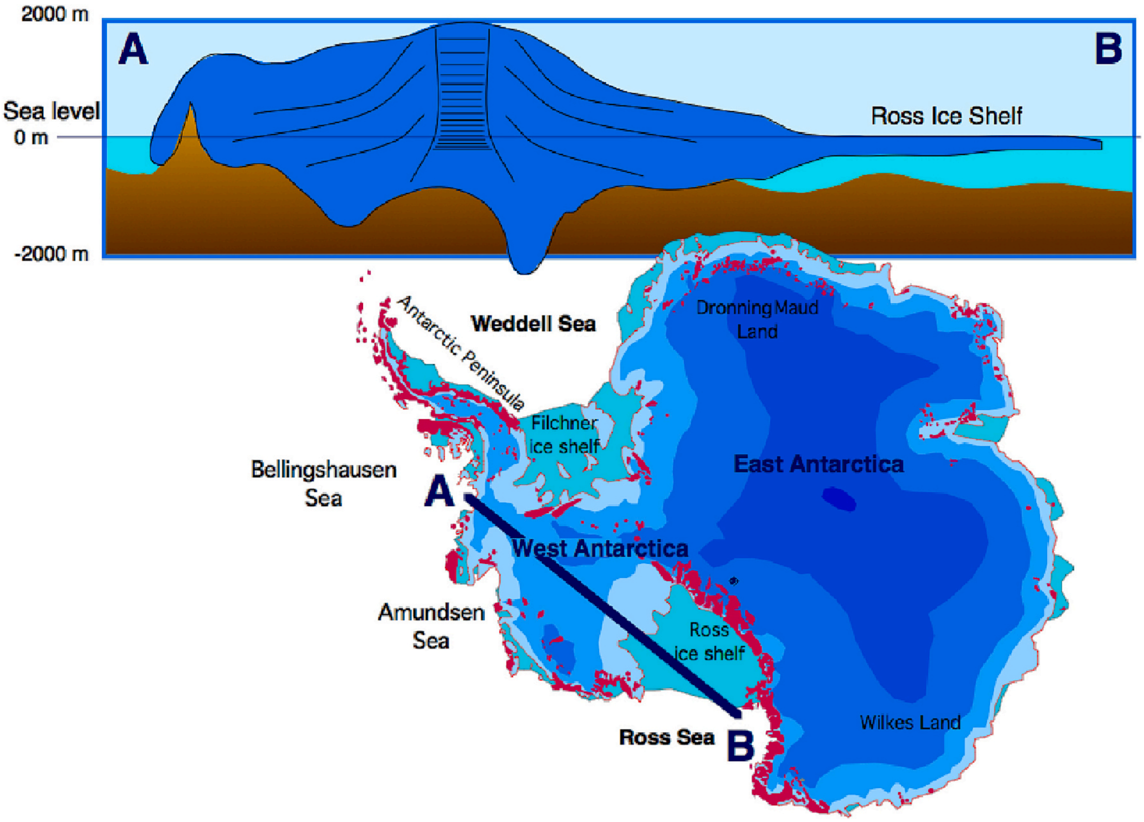

Fig. 18. Profile through the Antarctic ice sheet (A) Bellingshausen Sea – West Antarctic ice sheet – Ross ice shelf – Ross Sea (B). The profile shows that most of the West Antarctic ice sheet is grounded below sea level which makes it sensitive to sea level rise. If the contact of the ice to the bottom rocks is lost seaward of the grounding line, the ice sheet becomes significantly thinner (some 100 m), forming a shelf ice. (After Davies, 2020).

5 m higher during the Eemian interglacial (130,000–115,000 BP) (Dutton and Lambeck, 2012). During this period temperatures were a few degrees higher than today, notably at higher latitudes. The absence of the Greenland ice sheet as well as the WAIS could explain the 5 m difference in sea level west Antarctic Ice Sheith the present day. However, there is convincing evidence from deep ice cores that the Greenland ice sheet was largely intact during the Eemian (e.g. Helsen et al., 2013), suggesting that at least a part of the higher sea-level stand must have been due to a considerably smaller WAIS.

At the peak of the last glacial about 18,000 BP, grounded ice was present where now the Ross ice shelf is found (Fig. 18) (Kuhn et al., 2012). The grounding line was not far from the edge of the continental shelf and started to retreat at the beginning of the Holocene. Increasing ocean temperature (higher calving rates), as well as sea-level rise due to the melting of the Northern Hemisphere ice sheets, are thought to have been the most important factors causing the retreat of the grounding line to its present position. It is not known if the current grounding line is close to a steady state position, i.e., if it would remain there in a world without anthropogenic warming.

Investigations on deep sea sediment cores suggest that the WAIS disappeared several times during the past million years. Other studies claim that at least the West Antarctic ice divide has been stable for at least 1.4 million years. Numerical simulation with advanced ice sheet models may help to constrain the envelope of future sea-level contributions from the WAIS. Assimilation of palaeodata of a very different nature (e.g., deep-sea sediments, geomorphological studies, exposure dating, ice-core records, radar mapping of horizons in the ice sheet) is a real challenge but may greatly improve the reliability of projections. Another challenge is dealing with the large spatial variability of Earth rheological parameters in the zone where the WAIS is bordered by the East Antarctic ice sheet (Busetti et al., 1999; Coulon et al., 2021; Reading et al., 2022) have recently demonstrated the impact of geothermal heatflow on Antarctic tectonics and ice-sheet dynamics.

4.3. Energy

Many of the renewable energy and climate mitigation actions are inherently linked to the deep and surface Earth interactions at the very heart of the TOPO-EUROPE initiative. For instance, the long-term security of geothermal or nuclear plants can be threatened by natural hazards such as volcanic activity as well as earthquakes or ‘anthropic’ seismicity arising from extraction of hydrocarbons or water injection associated with the exploitation of geothermal systems. The development and maintenance of these infrastructures should thus be accompanied by careful monitoring and better understanding of intraplate stresses, 3D fault trajectories, fault reactivation, and both natural and anthropogenic induced pore pressure cycles nearby driving the migration of natural fluids in the crust.

4.3.1. Geothermal energy and natural H_2

Geothermal resources are commonly classified based on temperature and thermodynamic properties (Haenel et al., 1988; Hochstein, 1990; Muffler and Cataldi, 1978) which are the most relevant parameters in terms of estimating the amount of energy that can be recovered from a system. An alternative classification scheme referred to as geothermal play types (Moeck, 2014) focuses on the geological and geodynamic controls that have major influence on the thermal, structural, hydrogeological and geochemical characteristics of geothermal reservoirs. Quantitative knowledge of the crust and upper mantle structure and their thermal regime, as well as tectonic regimes and faults structures, enable to link geothermal systems to their plate tectonic settings (e.g., Cloetingh et al., 2010). Therefore, these studies are key for geothermal exploration.

Geothermal energy has high potential for providing sustainable energy, particularly in continents with a relatively hot upper mantle such as Europe. In the past few decades, there has been a significant increase in both direct heat utilization and geothermal power generation within Europe and worldwide (Huttrer, 2020; Lund and Toth, 2021). The increasing trend in Europe is also predicted for the future, especially when considering the current energy crisis and climate change mitigation actions. By 2050, Dalla Longa et al. (2020) foresee a level of 880–1050 TWh/yr and_100–210 TWh/year in heating applications and electricity generation, respectively.

Geothermal reservoirs that can provide temperatures of at least 70 °C, suitable for direct heat applications exist in many locations throughout Europe (Limberger et al., 2018b), and technologies to utilize such hot sedimentary aquifers (HSA) are already well-established (e.g. Van Wees et al., 2012). Hot sedimentary aquifers are characterised by relatively high levels of natural permeability from both porosity and fractures in sedimentary formations. A HSA is exploited by pumping up hot reservoir brine water to the surface through a production well, after which the heat is extracted from the often corrosive and toxic reservoir water using a heat exchanger. The cooled water is pumped back into the reservoir through a second injector well, thus limiting the change in reservoir pressure and thereby reducing the risk of induced seismicity, i.e. reactivation of nearby faults. On the other hand, stress changes related to thermal contraction caused by injection and spreading of cooled reservoir water might lead to an increased risk of induced seismicity (Buijze et al., 2019). Due to mechanical compaction, porosity of a HSA rapidly declines with increasing burial depth, limiting the maximum depth of a HSA to 4–5 km. The exploitable heat stored in a HSA is determined by the porosity, permeability, thickness and temperature of an aquifer. The geothermal resource potential of a HSA will therefore differ regionally or locally as a result of gradual or abrupt variations in these reservoir characteristics. These lateral variations are the result of the long-term and often complex thermo-tectonic evolution of sedimentary basins, such as passive margin basins, foreland basins and intracratonic rift basins (Cloetingh et al., 2010).

Examples of sedimentary basins with hot sedimentary aquifers that currently are exploited in Europe include the intraplate Paris Basin (heat used for electricity generation for Paris and surrounding), the molasse basin in south Germany (heat used for district heating in the greater Munich area) and the Mesozoic rift basins in the Netherlands (heat used for greenhouse heating). Quantitative studies of the tectonic evolution of sedimentary basin systems (e.g., Cloetingh et al., 2015) are therefore a key component in the exploration and resource assessment of geothermal energy stored in hot sedimentary aquifers.

Geothermal systems that are suitable for economic power generation with temperatures of at least ~120 °C and relatively high flow rates (preferably >100 L s^{-1}) are rather limited within Europe and are located for instance close to plate boundaries and or in volcanic provinces such as Italy, Greece and Iceland. In these regions with high heat flow and hydrothermal fluid circulation, the reservoir is economically exploitable and geothermal energy production is often sufficient to power large parts of the nation. Apart from these locations, high temperature basement formations commonly do not have sufficient porosity and permeability to host and readily extract hydrothermal fluids, and thus require stimulation to create fluid pathways necessary for economic heat recovery, a technology called Enhanced Geothermal System (EGS) (Breede et al., 2013; Lu, 2018; Olasolo et al., 2016). The EGS concept consists essentially of drilling at least two boreholes into deep fractured rock, extracting hot fluid from a production well and injecting the cooled fluid back into the fractured reservoir through an injection well (Fig. 19). To this end, both boreholes have been stimulated to connect the two wells to the natural surrounding geothermal reservoir by artificially enhancing the permeability of the natural network of fractures in their vicinity (Lamur et al., 2017; Eggertsson et al., 2020).

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 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.,

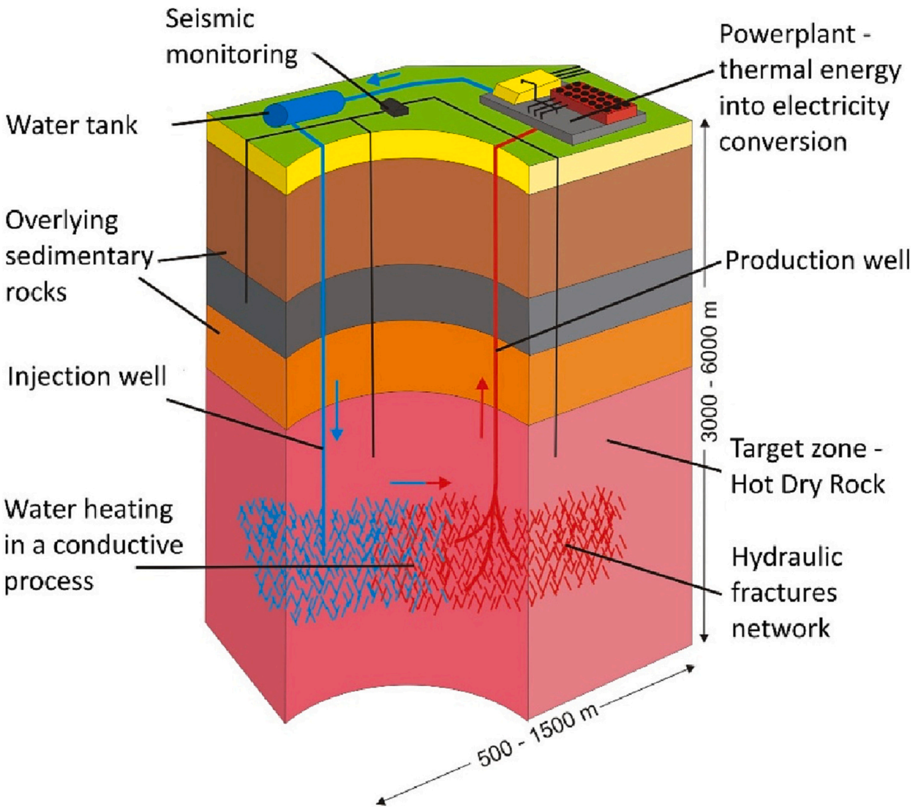

Fig. 19. Main elements of an EGS system consisting of production and injection wells drilled in a deep fractured rocks and surface units for heat and power generation. (after Moska et al., 2021).

Landau, Insheim). The Basel EGS project in Switzerland, which was terminated after an induced earthquake (Deichmann and Giardini, 2009), is a good example on the potential risks associated with reservoir stimulation. 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 hydropower (IEA, 2021). To achieve a significant increase, explorational and technological developments in EGS and further successful demonstration sites are necessary in the future.

The key element of EGS development is the creation of the reservoir, mostly through hydraulic stimulation. For this operation, prediction of the local stress field orientation and magnitude is essential. Success in hydraulic stimulation is dependent on the thermo-mechanical and physical properties of the crust. Critically stressed regions, marked by active deformation, require little excess pressure for stimulation and are therefore favourable (Xi et al., 2022). In addition, such regions are marked by pre-existing faults and fractures, forming preferential pathways for stimulated flow.

On the exploration side, geological information, world stress map data (Heidbach et al., 2019) and natural seismicity can be used to identify active deforming basins and basement areas which are critically stressed. Cloetingh et al. (2010) and Moska et al. (2021) demonstrated the importance of tectonic processes in EGS site selection and development. They point out that distinguishing between local and regional heat flow anomalies is essential for the proper extrapolation of temperature and heat flow data to areas without well control. Tectonic models are able to constrain crustal rheology and stress regime, highlighting actively deforming areas and fault/fracture zones with favourable conditions for hydraulic stimulation.

In recent years, several studies in various regions of Europe utilized regional-scale input data such as lithosphere and crustal thickness and composition models, regional heat flow, structural data and models to highlight potential areas for geothermal exploration (Békési et al., 2018; Freymark et al., 2017; Limberger et al., 2018b). Such approaches may shed light on geothermal targets that would have been overlooked without an integrated lithosphere-scale approach.

Volcanic provinces are more easily identifiable than EGS and are a tremendous source of energy. In active volcanic regions, mechanical stimulation is commonly not required, owing to the magnitude of reservoir rock storage capacity and the vigour of hydrothermal fluid circulation, and because the cooling fluids necessary to drill a well thermally stimulate geothermal systems, generating distributed fracture networks to channel fluids. These geothermal systems can reach extreme temperatures in excess of 900 °C (Axelsson et al., 2014), as they near their heat source—magma—providing a lucrative geothermal energy output. In the active volcanic island of Iceland, geothermal energy is responsible for 60% of the nation’s energy portfolio, including 90% of energy required for heating and 28% of the electricity input in the grid (World Energy Council, WEC). This corresponds to immense economic savings in excess of 1600€/year per capita, compared to the price of oil-based energy. The average geothermal well output in Iceland produces around 5 MW, generally from fluids sourced at depths between 1 and 2 km.

Recently, in the search for more energetic fluids, the Icelandic Deep Drilling project (IDDP) sought to drill deeper in the crust and harness energy from supercritical, high-enthalpy fluids (i.e., very high pressure and temperature beyond the termination of the boiling curve that separates liquid from vapor (Elders et al., 2014)). Serendipitously, during drilling of the first well (IDDP-1) aimed to reach ~4.5 km) (Friðleifsson et al., 2014), they intersected magma at a depth of 2.1 km (as our ability to detect magma remains insufficient; see 4.4. Hazard). Despite practical and engineering challenges with this encounter, their efforts resulted in a number of key discoveries: 1) It provided the first exact location of a magma reservoir below a volcano; 2) the magma reacted to drilling activity but was not prone to erupt; 3) the rocks surrounding the magma reservoir were unexpectedly highly-permeable, and importantly 4) successful flow tests from the magma well produced >30 MWt of energy, that is 5-10× more than the average well in Iceland and 10-15× more than the average "conventional" well in the Krafla geothermal system (WEC) (Eichelberger et al., 2018). The reasons for the high energy output are twofold: the fluids were sourced from the heat source and near-magma rocks were preferentially permeable due to their propensity for jointing during cooling contraction. Thermal contraction is unavoidable during cooling and crystallisation of magmatic bodies (Lamur et al., 2018) and is radically accentuated by drilling fluids (Lavallee et al., 2019), making magmas ideal candidates to harness hydrothermal fluids to an extent that would drastically improve the contribution of geothermal resources to our energy portfolio worldwide. Considering that quenching one litre of magma (at 1000 °C) generates approximately 1 MWt and that magma reservoirs can reach a few thousand cubic kilometres, the potential of magma energy is tremendous; it is regarded as a means to provide more energy at a reduced cost.

Several European countries host active volcanoes (e.g., in Iceland, Greece, Italy, Spain) and so does the majority of developing countries listed in the Official Development Assistance (ODA) program of the international Organisation for Economic Co-operation and Development (OECD). The prospect of exploiting magma, notwithstanding a better understanding of the hazard they present, raises the necessity to expand our strategy to monitor and forecast magmatic and volcanic processes.

In light of the findings from IDDP-1, the volcanology and geothermal communities are now rallying to scope out, and thrust forward, the development of magma energy exploitation via the Krafla Magma testbed (KMT). KMT aims to establish the first *magma observatory* – an international, open access, scientific platform to advance our understanding, monitoring, and use of magmatic and superhot hydrothermal systems, to transform volcanic hazard mitigation strategies (see Section 4.4) and develop next-generation, geothermal energy solutions. KMT research activities revolve around a research and education infrastructure consisting of multiple wells to monitor and manipulate magma, produce energy, and track the response of magma to thermomechanical stimulations and geothermal operation. The ability to manipulate magma raises the viability of alleviating volcanic activity, a vision at the heart of the on-going project MODERATE funded by the European Research Council (ERC). The development of magma energy requires innovations in engineering practices, materials, monitoring capabilities, and magma manipulation strategies, and it demands elaboration of new guidelines to ensure safe operations. KMT aspires to provide transferable solutions to enable magma exploitability at other volcanic centres worldwide, necessary to expand the landscape of geothermal energy.

Apart from EGS systems and magma-hydrothermal systems, deeply buried, fractured and/or karstified carbonate formations can also provide sufficiently high temperatures and flow rates for power generation in Europe. The utilization of such systems for electricity production has already been initiated for instance in the German Molasse Basin (Dussel et al., 2016) in the Pannonian Basin (Velika Ciglena power plant in Croatia, Tura power plant in Hungary) (Huttrer, 2020). Such projects can also benefit from basin-scale tectonic and geomechanical models to highlight major fracture zones and understand the state of stress in locations where no crustal indicators are available (Ziegler and Heidbach, 2020).

Finally, as a promising renewable energy option, H_2 is receiving increasing attention across several scientific and industrial communities. Although natural H_2 has long been neglected in geological fluids (Smith et al., 2005), discoveries and investigations on natural H_2 shows are increasing fast and set a new horizon in geo-energy research (Moretti and Webber, 2021; Truche and Bazarkina, 2019; Zgonnik, 2020). Natural H_2 has been identified in multiple forms such as free gas, in inclusion, and dissolved in water, and in several geological contexts, from mid-ocean ridges, ophiolites, Precambrian shields, coal basins, in terranes ranging in age from Archean to the present day, and from surface to deep mantle conditions (Smith et al., 2005; Zgonnik, 2020; Cannat et al., 2010; Lollar et al., 2014; Vitale Brovarone et al., 2020b; Smith et al., 2016). Some shows are associated with large reservoirs (Prinzhofer et al., 2018). Although the detection of natural H_2 and the determination of the associated H_2 fluxes is still preliminary, identified sources clearly highlight a high potential for future collaborative research among geobioscientists to quantify the mechanisms, fluxes, migration pathways, and reservoirs of this natural resource.

4.3.2. Geological storage of CO_2 and H_2

The rising concentrations of greenhouse gases and the related rising of global temperatures prompted attempts of storing CO_2 in geological reservoirs (Carbon Capture and Storage, or CCS). The basic concept of CCS is to capture CO_2 at a location of anthropogenic emission and inject it underground into a geological formation to prevent emissions into the atmosphere. In many cases, the adopted strategies and reaction pathways mimic natural processes of fluid-rock interaction identified over a broad range of conditions, from shallow to deep. Suitable host geological formations for CCS may be found in sedimentary basins, such as aquifers or depleted oil and gas fields. In these cases, the injected CO_2 is stored in the pore space of the reservoir formation, coexisting with the naturally accumulated fluid phases (brine, hydrocarbons, naturally accumulated CO_2), and relies on seal (low permeability) formations and trap structures for keeping the injected CO_2 underground. The injected CO_2 is first trapped by the trap structure, and, with time, becomes increasingly consumed by residual trapping, by dissolving into reservoir brines, and by mineralization (Metz et al., 2005). The presence of an extensive subsurface microbial community can directly alter the fate and success of CCS efforts. Microorganisms can in fact use CO2 both as carbon source to produce biomass or as electron acceptor in microbial respiration forming methane and acetate as by products (Tyne et al., In review). While the former, the conversion of CO2 into biomass, can promote sequestration by locking carbon into organic matter at depth, methanogenesis, referred to as CO2 methanation in the field of CCS (Strobel et al., 2020), can alter the chemical and physical properties of the injected carbon, rendering more difficult to predict the long-term fate of the CCS efforts. Microbial methanation depend on multiple factors, including reservoir temperature, availability of hydrogen and redox conditions. A recent paper has demonstrated rapid microbial methanogenesis in CCS reservoir (Tyne et al., 2021), suggesting that deep biosphere interaction with the injected gases might play a key role in the future success of this mitigation technology.

CCS in sedimentary basins has been trialled for decades in frontier projects, such as the Sleipner CCS project, located in offshore Norway, and operating since 1996 (Baklid et al., 1996; Torp and Gale, 2004). Experiences also from other industrial test sites (e.g., In Salah, Snøhvit projects) so far show the general suitability of CCS in porous formations, but also highlight the need for detailed geological models, knowledge of mechanical properties and advanced monitoring-modelling techniques (Chadwick et al., 2010; Eiken et al., 2011; Ringrose, 2020; Williams and Chadwick, 2017). Early successes have been followed by further European initiatives, including research projects focusing on both the aspects of carbon capture (e.g. NANOMEMC2 project, (Ahmadi et al., 2018) and its subsequent geological storage (e.g. ENOS project) (Sohal et al., 2021).

Alternatives to CCS in sedimentary basins are geological formations that undergo relatively rapid chemical reactions in the presence of CO_2. Such rock types are mafic and ultramafic rocks (basalts, peridotites, serpentinites), which may be considered for mineral (reactive) CO_2 storage. The result of mineral storage is the incorporation of the carbon into the mineral structure of carbonates, which results in a much desired "permanent" deposition in the lithosphere and separation from the atmosphere (Oelkers et al., 2008; Snæbjörnsdóttir et al., 2020). Natural examples of such processes include large-scale carbonation, i.e., replacement of silicate by carbonates, of ultramafic rocks in at mid-ocean ridges, in ophiolites and orogenic peridotites such as Oman, Norway, and Newfoundland among others (Kelemen and Matter, 2008; Matter and Kelemen, 2009; Ludwig et al., 2006; Boschi et al., 2009; Beinlich et al., 2012; Menzel et al., 2018), and possibly large portions of the mantle wedge above subducting slabs (Kelemen and Manning, 2015). Onshore areas in Europe with such oceanic rock types exposed on the surface are not abundant. However, Iceland offers an ideal location for testing and developing this method. This gave rise to the projects CarbFix and CarbFix 2, where reactive mineral storage facilities were established and developed on Iceland, unravelling the optimal conditions and great theoretical potential of this method (Clark et al., 2020; Gislason et al., 2010; Matter et al., 2009). Results have shown that young basalts (not yet affected by weathering) are especially suitable for storing large amounts of carbon (Wiese et al., 2008), making mid-ocean ridges giant potential reservoirs, theoretically capable of storing more carbon than the carbon content of all fossil fuels on Earth (Snæbjörnsdóttir et al., 2020).

CCS projects in sedimentary basins as well as in oceanic rocks have demonstrated the vast geological potential of this method. While improving risk evaluation, technological and monitoring techniques are still essential, the largest barrier for meaningful contribution to climate change mitigation appears to be the lack of attractive business models that would allow for large-scale implementation.

As renewable energy sources become more important, the need for balancing their fluctuating energy output (especially in case of solar and wind energy), which results in periodic energy excesses and deficits, is also growing. One of the possible solutions for this is Underground Hydrogen Storage (UHS), which allows to convert excess electricity to hydrogen through electrolysis (“Power to Gas” method), to store the hydrogen in a geological object, and then to use it later in a period of higher energy demand. UHS is possible in the porous formations of sedimentary basins (aquifers and depleted hydrocarbon fields), in salt caverns or in artificially lined rock caverns.

Storage in low-permeability salt caverns is a proven method, with a Teesside facility in England successfully operating since 1972 (Stone et al., 2009), and new initiatives for example in the Netherlands (Hystock project) and France (Storengy-HyPster project) are further developing the technique. However, suitable salt formations are of limited extent and occurrence in Europe, making the method itself a limited prospect on the scale of European energy transition.

Artificially lined rock caverns also appear to be safe solutions for hydrogen storage: the pilot project HYBRIT in Sweden is building on the experiences of natural gas storage in such facilities (Tengborg et al., 2014) and trying to develop the methodology for hydrogen. While the low risk of hydrogen escape in a lined cavern is an advantage, the cost of cavern mining and artificial lining would certainly require substantial investment when upscaling this technique.

Hydrogen storage in porous formations of sedimentary basins offers far larger theoretical capacity than cavern storage methods. Such potential storage sites require a porous reservoir, a sealing caprock and a trap structure, similarly to hydrocarbon fields. However, the physical-chemical characteristics of hydrogen significantly differ from those of hydrocarbons (Pan et al., 2021), which requires more careful examination of flow patterns, potential chemical (and microbial) reactions and storage integrity (Heinemann et al., 2021). Apart from rising academic interest in this topic, pilot projects for implementation have also started, for example the RAG Underground Sun Storage project in Austria (AG RAG, 2020).

Also, in the case of hydrogen as for CO2, deep microbial communities can impact the results and efficiency of the storage process. Hydrogen is one of the key electron donors in microbial metabolic reactions (Greening et al., 2016), and can be used together with a wide array of electron acceptors some of which might be present in UHS reservoirs (Dopffel et al., 2021). Beside lowering the total amount of hydrogen available for recovery with direct consumption, deep microorganisms are also responsible for the production of unwanted by products, such as sulphide that can sour the recovered gas, affect the infrastructure and alter the pore space structure favouring the precipitation of sulphide minerals. Given the link between the distribution of deep subsurface microbial communities and deep and surface Earth processes, understanding the feedback between microbial and geological processes is a key area of future investigation with potentially multiple contributions to diverse societal challenges.

4.4. Geohazards

Much of TOPO-EUROPE research has been dedicated to the analyses of the relationships between lithospheric stress and geohazards, including seismic, hydrogeological and volcanic hazard. Stress fields are also of paramount importance to the understanding of differential vertical motions in the lithosphere and in the discrimination of tectonic and climatic controls on relative sea level variations (Cloetingh and Haq, 2015). In addition, stresses and their interaction with the geomechanics of the lithosphere (Zoback, 1983; Zoback, 2007) are crucial in setting up conduits for fluid transport and melt movements inside the lithosphere, also put forward in a series of recent papers (Sternai et al., 2021; Sternai et al., 2016; Stuewe et al., 2022; Tibaldi et al., 2010) as tectonic and/or surface stresses changes guide the processes of magma ascent and emplacement. The resulting magma stress field can produce changes in the basement fault geometry and kinematics. Similarly, the anomalous heat flow in volcanic regions can contribute to modifying the dominant deformation style in the substratum and promote regional changes that trigger eruptions. Thus, understanding the state and distribution of thermal and mechanical stresses in the crust are central to improve our understanding of geohazards and establish adequate risk mitigation strategies. This is especially needed for volcanic provinces, considering that nearly 10% of the Earth’s population live within 100 km of an active volcano (Brown et al., 2017), and that eruptions can impact the weather system and climate globally. Beyond the primary volcanic hazards, understanding intraplate and plate-margin volcanism is also critical for nuclear waste storage or carbon capture repositories, which needs to remain structurally stable for hundreds of thousands of years. Increasing our ability to assess how likely a volcano, even a small one, will erupt in the next few decades or centuries is important for placement of storage facilities for geothermal energy systems. In fact, geothermal energy is easiest to collect in areas with high heat flow (see section 4.3), which are often volcanic areas. Since volcanic eruptions are a major threat to our lives and society, they represent a primary connection between surface and deep Earth processes that future TOPO-EUROPE activities will certainly tackle.

Research carried out in the context of ILP (Tibaldi et al., 2008), through an integrated approach that combines field studies flanked by analogue and numerical modelling, has resulted in a major progress in understanding the tectonic controls on volcanism exerted by a large extent through the interplay of thermal perturbations and stress fields. Milia et al. (2012) focus on a possible link between faulting, cryptodomes and lateral collapses at the Vesuvius volcano (Italy). The Vesuvius is an active volcano that has been affected by late Quaternary lateral collapses and tectonic faults. Cryptodomes and two debris avalanches, 18 ka-old and 3.5 ka-old, were previously documented and for the younger avalanche a link between onshore and offshore stratigraphy was reconstructed. Stratigraphic data reveal a remarkable difference between the architecture of the northern and southern volcano sectors that is compatible with the occurrence of the older debris avalanche in the southern volcano sector, broadening the horizons of the Vesuvius volcanic hazard. In a complementary study, Nomikou et al. (2012) addressed submarine cones in the Kolumbo Submarine Volcanic Zone of the Hellenic Arc (Aegean Sea, Greece). The seafloor northeast of the Santorini volcano consists of a small, elongated rifted basin within the Cyclades backarc region of the present Hellenic subduction zone, where the seafloor of the eastern Mediterranean Sea is descending beneath the

Aegean microplate. Nineteen submarine volcanic cones occur within this small rift zone, with Kolumbo, the largest of these, which last erupted explosively in 1650 AD, causing significant damage and fatalities on the nearby island of Santorini. In general, the domes/craters northeast of Kolumbo were found to be sediment-covered and showed little evidence of recent volcanic activity. Another observation by the authors was that volcanic rocks were outcropping in the crater walls and slopes of some of the cones. However, they typically consist of volcanic fragments of pumice and lava that have been cemented together by biological activity, indicative of the lack of recent eruptions. Geochemical analysis of samples collected by Nomikou et al. (2012) on the northeast cones showed evidence of low temperature hydrothermal circulation on the summit and upper flanks in the form of stream-like manganese precipitates emanating from pits and fractures. These case studies in Italy and Greece show the importance of characterising the state of stresses and the presence of fluids in tectonically and volcanically active provinces.

Understanding the state of magma and surrounding crust is vital to understanding active volcanoes and improving our risk mitigation strategies and preparedness to the many hazards they present. In the past decades, we have deployed a breadth of sophisticated geophysical and geochemical monitoring equipment which have provided us with rich multi-parametric datasets to examine the magmatic pulse of the Earth and resolve volcanic unrest. The simple reason underlying this data surge is that we know *WHERE volcanic activity takes place.* Despite this convenience, we lack an understanding of and *WHEN* and *HOW volcanic activity will occur.* We need to improve our ability to forecast *when an eruption begins and ends* and *how the eruption will proceed.* In fact, one of our most important lacking's is our inability to detect and image magma in the crust using current datasets and existing modelling tools; this inability has led, for instance, to the serendipitous drilling of a magma body at 2.1 km below the Krafla volcano, Iceland, during IDDP-1 (see 4.3. Energy), despite being one of the most thoroughly monitored volcanoes worldwide, where data seemingly suggested magma at ~5 km depth. The aforementioned shortcomings (where, when, how) point to two important needs for the volcanological community; we need to 1) ground-truth our observations, and 2) develop robust, quantitative, predictive tools that comprehensively integrate magma generation, transport and eruptions in the Earth system.

The Krafla Magma Testbed (see 4.3. Energy) is an international initiative which aims to establish the first *magma observatory* to advance our understanding, monitoring, and use of magmatic and superhot hydrothermal systems, to transform volcanic hazard mitigation strategies and develop next-generation, geothermal energy solutions. The KMT infrastructure is innovatively established around multiple wells dedicated to monitor and manipulate magma, to improve our quantitative knowledge of the subsurface. Using surficial and underground stimulations along with surface, downhole and *in-situ* magma monitoring, a series of research activities are designed to directly quantify subsurface conditions (in the crust and magma), develop new monitoring tools and technologies, and groundtruth/improve our methods to quantify the state of, and conditions extant in, magma and the crust at active volcanoes (Eichelberger et al., 2019; Papale and Marzocchi, 2019). This includes (though not exclusively): 1) thorough petrological, petrophysical and geochemical characterisations of the rock-magma interface via regular sampling campaigns, 2) direct, continuous measurements of stress and strain above a magma reservoir, including how they change during unrest or anthropogenic (drilling) activity, 3) direct, continuous measurements of temperature across the rock-magma interface to examine natural and induced changes, 4) direct measurements of signal propagation in magma and the surrounding crust to constrain which signals transfer through the crust (or not) and reach the surface, etc. The research activities include strategic manipulation experiments to assess the response of magma and constrain the evolution of magma properties (e.g., viscosity, density) and acting processes (crystallisation/melting, degassing, convection, etc) through time (Lavallee et al., 2019), whilst assessing the geophysical and geochemical signals monitored and ensuring that these manipulations do not elevate the geological risk (Ilic et al., 2020). If systematically and successfully undertaken, these manipulations may allow the establishment of guidelines to degas and cool magma and one day, perhaps, alleviate the likelihood or explosivity of volcanic eruptions – a commendable task which will require due diligence and a robust understanding of magma which can be achieved via KMT innovations. Such an interdisciplinary initiative, dedicated to quantifying and improving our knowledge of the state of magma in the crust, is essential to develop predictive tools. Just like we all make use of daily weather forecast tools, it is now time for the volcanological community to develop a comprehensive quantitative model capable of predicting the lifecycle of magma; from its genesis to its differentiation, storage, transport, and eruption, considering the general impact of volcanic emissions to the atmosphere, the hydrosphere, the biosphere, and climate. Such a predictive tool is direly necessary for communities, stakeholders, policy makers and the industry to increase our preparedness and build a more resilient future.

Existing meteorological time-series are commonly too short to capture climate oscillations that spans century or millennia and can help modelling and forecasting future climate (Kondrashov et al., 2005; Pèlachs et al., 2011). At such timescales, however, rivers can showcase extremely high sedimentation rates (>1 cm/yr), allowing for the creation of detailed chronology of humid/arid periods and flood events (Knox, 1993; Benito et al., 2015) and the tracking, through mineralogical and geochemical analysis, of the source area of the floods (Mologni et al., 2020). The stratigraphy of deposits formed over century-to-millennial time scale can thus be used as proxies to study the climate variability. The information derived on rainfall dynamics and their localization is not only crucial for paleoclimatology but is also extremely precious for predictions of future climate conditions and extreme meteorological events, long-term planning of agriculture and energetic infrastructures, city zoning and management (Hendrix and Salehyan, 2012; Brunetti et al., 2019). Detailed analysis of surface processes and sedimentary archives are key source of information to bridge across the time scales of direct measurements of Earth observables and those of the underlying geological processes and Earth dynamics.

5. Conclusion and forward look

All these examples of frontier research demonstrate the need for a multi-scale approach linking new observational constraints reporting on the Earth's structures and characteristic rates with numerical and experimental modelling of surface and deep Earth processes. They also demonstrate that teamwork and connecting advances in different fields is an intrinsic aspect of research efforts to linking deep Earth and surface processes. The recent advances in this domain have set a stage to build future interfaces with other exciting fields such as research on the biosphere, climate and energy. New frontiers in coupled – deep Earth – surface processes include:

(1) Obtaining a better insight in the initiation and evolution of subduction systems, the role of mantle plumes in continental rifting and (super)continent break-up, and the deformation and tectonic reactivation of cratons.
(2) Assessing interaction between geodynamic, surface and climate processes (e.g., interactions between glaciation, sea level change and deep Earth processes); the role of rock melting in the interplay between climate and tectonics; and the sensitivity, tipping points, and spatio-temporal evolution of the interactions between climate and tectonics.
(3) Advancing biogeodynamics studies: impact of coupled deep Earth – Surface processes on the evolution of life on Earth.
(4) Tightening the connection between societal challenges in renewable georesources and natural geo-hazards, and novel process-understanding of the Earth system.

The realization of these ambitions requires a dedicated effort for community building from all individuals involved. This Science Agenda has the ambition to provide an up-to-date review of high potential building blocks and opportunities for synergy at their interfaces. Further breakthroughs in coupled surface-deep Earth processes research are a pre-requisite for advancing novel approaches to societal challenges facing the Earth system.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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