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Research Article

Advances in the understanding of multi-scale and coupled evolution of orogens, sedimentary basins and the underlying lithosphere

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ABSTRACT

The integrated understanding of processes and mechanisms driving the coupled evolution of orogens and sedimentary basins and the underlying lithosphere-mantle system, requires a multi-scale temporal and spatial approach that crosses the traditional boundaries of disciplines and methodologies. While analysing the sedimentary infill we need to account for the characteristics and variations of the exhumation, evolving topography and external forcing in the source area, and the complexity of a transport system that is often characterized by a massive unidirectional sediment influx during moments of activity at tipping points or gateways. Such an influx can often span across multiple depocenters and sedimentary basins and is conditioned by an evolving structural geometry that can migrate in time, directly related to the evolving lithospheric structure in orogens that are influenced by their inherited rheology. Depocenters can be fed from multiple directions, while having an endemic or endorheic character during key evolutionary moments. The thermal structure and its variability in continental and oceanic domains conditions the rheology and subsequent structural evolution of the orogens, subduction zones and sedimentary basins, with significant consequences for understanding societally relevant issues. Quantifying basin deposition requires analysing the sediment transport network that can often span multiple interacting orogenic and sedimentary systems, where understanding the allogenic or autogenic nature of sedimentary processes can be significantly enhanced by knowing the inherited and evolving structural and tectonic parameters. Such sedimentary quantification is important for understanding the orogenic structure and the evolution of subduction systems, that include mechanisms such as cycles of burial-exhumation, formation of highly arcuate orogens and timings of nappe stacking events. Deriving processes in orogen - sedimentary basins systems also requires testing process-oriented hypotheses by focused studies in well-known natural laboratories, such as the examples from the Pannonian-Carpathians - Alps - Dinarides system and its analogues used by the numerous contributions in the special Global and Planetary Change issue entitled *Understanding the multi-scale and coupled evolution of orogens, sedimentary basins and their underlying lithosphere*, whose significance is explained in our review.

1. Introduction

The process-oriented integration of the evolution of a sedimentary basin infill and coeval kinematics of the neighbouring mountain chains is crucial to the understanding of feedback mechanisms between causal processes, such as subsidence and exhumation in extensional systems or thrust belts (e.g., Reiners and Brandon, 2006; von Hagke et al., 2014; Pomar and Haq, 2016; Bernard et al., 2019). Studying orogen - sedimentary basins interactions require a multi-scale approach that combines field studies with basin-wide observations and modelling, integrated with the evolution of the underlying lithosphere (e.g., Cloetingh and Haq, 2015; Gibson et al., 2015; Noda, 2016). Understanding such interactions is essential for quantifying the allogenic or autogenic forcing factors driving deposition and differential vertical movements

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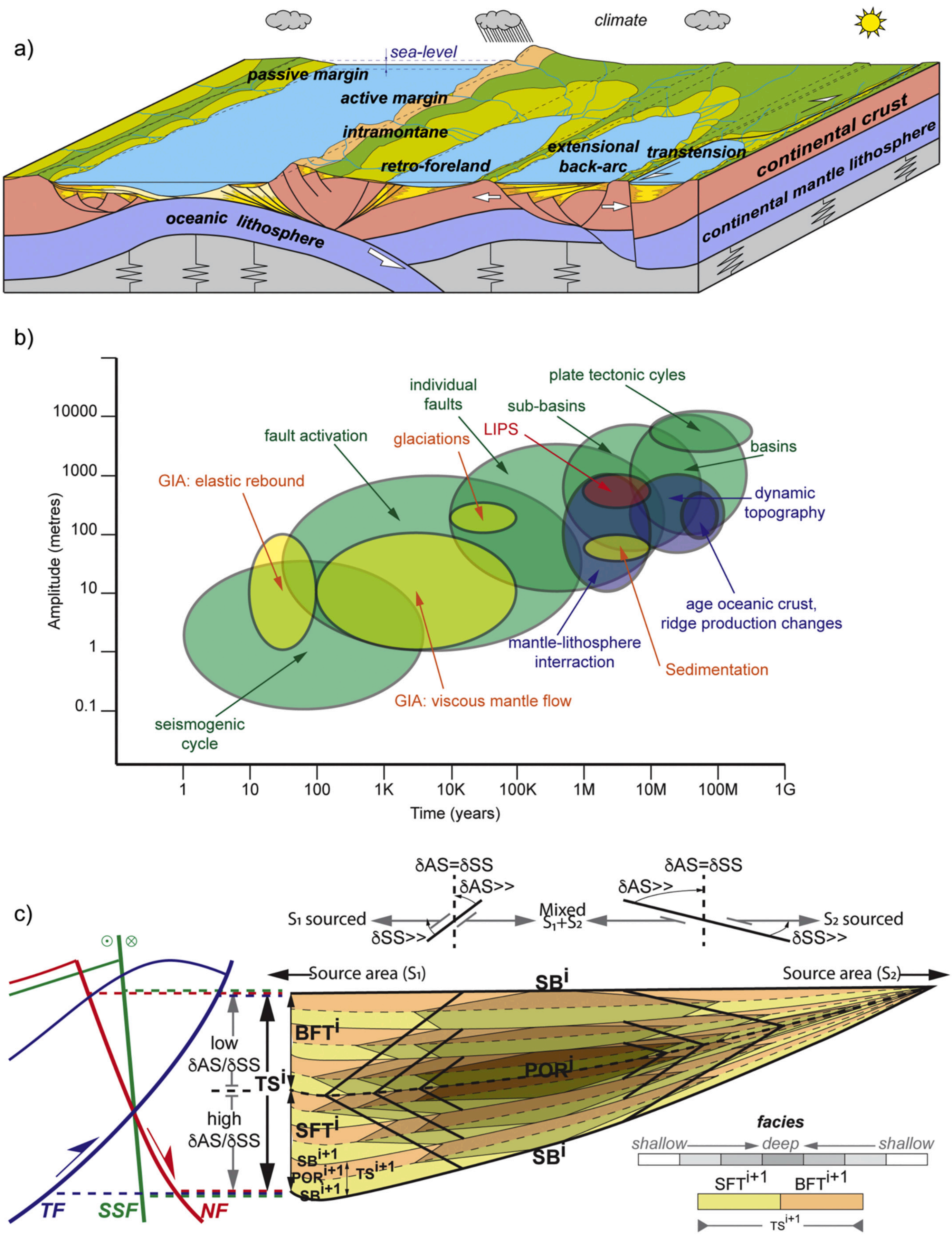

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Fig. 1. The coupled evolution of orogens, sedimentary basins and their underlying lithosphere in the multi-scale depositional concept of tectonic successions (after Matenco and Haq, 2020). a) Sketch block diagram showing various plate tectonic regimes, the development of the associated depositional space and depositional facies in various types of sedimentary basins. The depositional space appears triangular against active faults and can be sourced from multiple directions at various elevations. When tectonics is less important to other allogenic factors, such as eustatic fluctuations or climate, the sediment source tends to be unidirectional, as for example along passive continental margins; b) Temporal and spatial variability of the mechanisms that drive the creation and reduction of depositional space and sea-level variations (note the logarithmic scale of both axes). Mechanisms that have a direct tectonic component are depicted in green, large-scale mechanisms in blue, large igneous provinces (LIPS) in red, glaciations and sedimentation in yellow. LIPS - Large Igneous Provinces; GIA - Glacial Isostatic Adjustment; c) Conceptual definition of lower-order (i) and higher-order (i+1) tectonic successions (TS) in fault-bounded sedimentary basins, which are composed of a sourceward-shifting facies tract (SFT) and a basinward-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. The source areas may be located on its both sides, either proximal (S1), distal (S2), or along the strike of the fault bounded structure. Inclined thick and thin lines are contacts between different paleo-physiographic (bathymetry/elevation) facies units in the lower- and higher-order tectonic sequences, respectively. Lower and high order tectonic sequences (TS^{i} and TS^{i+1}) are defined at the scale of the entire depositional space in response to different orders of individual movements along the bounding fault(s). These successions are bounded by Succession Boundaries (SB) and contain a point of reversal (POR). The rate of creation of depositional space (δAS) is higher or lower than the rate of sediment supply (δSS) in SFT and BFT, respectively. For further details we refer to Matenco and Haq (2020).

(Fig. 1, Matenco and Haq, 2020). Coupled orogen - sedimentary basins studies also require a high-resolution quantification obtained from multiple methodologies that include sedimentology, structural geology, thermochronology and geophysical observations. The results can be further validated through numerical or analogue modelling (e.g., Armstrong, 2005; Sinclair et al., 2005; Willingshofer and Sokoutis, 2009; Morley, 2014; Cloetingh et al., 2015).

Current studies suggest the existence of large zones of interaction between individual orogens and genetically related sedimentary basins (e.g., Dvorkin et al., 1993; Capella et al., 2017; Jolivet et al., 2021). This finding leads to several outstanding questions about the kinematics of orogens that relate to the factors controlling the localization of intense deformation within the tectonic lower plate rather than the upper plate in mountain chains that result from continental collisions (Duretz and Gerya, 2013; Willingshofer et al., 2013; Mannu et al., 2017; Vogt et al., 2017; Andrić et al., 2018b). The interference between subduction zones located in proximity of each other may exert a major influence in the localization of deformation and in building tectonic topography, affecting the formation and evolution of intervening sedimentary basins and their infills (e.g., Cloetingh et al., 2005; Faccenna et al., 2021). Understanding such processes requires the analysis of complex sediment transport systems that may extend over multiple orogens and basins, which may be characterized by rapid delta build-ups at the sites of major discharges, and gateways that control the evolution and interaction between (semi-)enclosed basins (e.g., Karami et al., 2011; Matenco and Andriessen, 2013; Sztanó et al., 2013; Balázs et al., 2017b; Magyar et al., 2020). Such basins often function as endemic and endorheic systems with distinct and variable sea- or lake- levels, where dynamic sedimentation processes may accelerate during rapid basin filling events and require a multi-scale temporal analysis (e.g., Harzhauser and Mandic, 2008; Leever et al., 2011; Nichols, 2011).

Among the large variety of orogenic and sedimentary systems worldwide, the Mediterranean area (Fig. 2) offers a natural laboratory where processes across multiple sedimentary basins and orogenic systems and their interactions can be studied (e.g., van Hinsbergen et al., 2020 and references therein). A detailed knowledge of systems such as

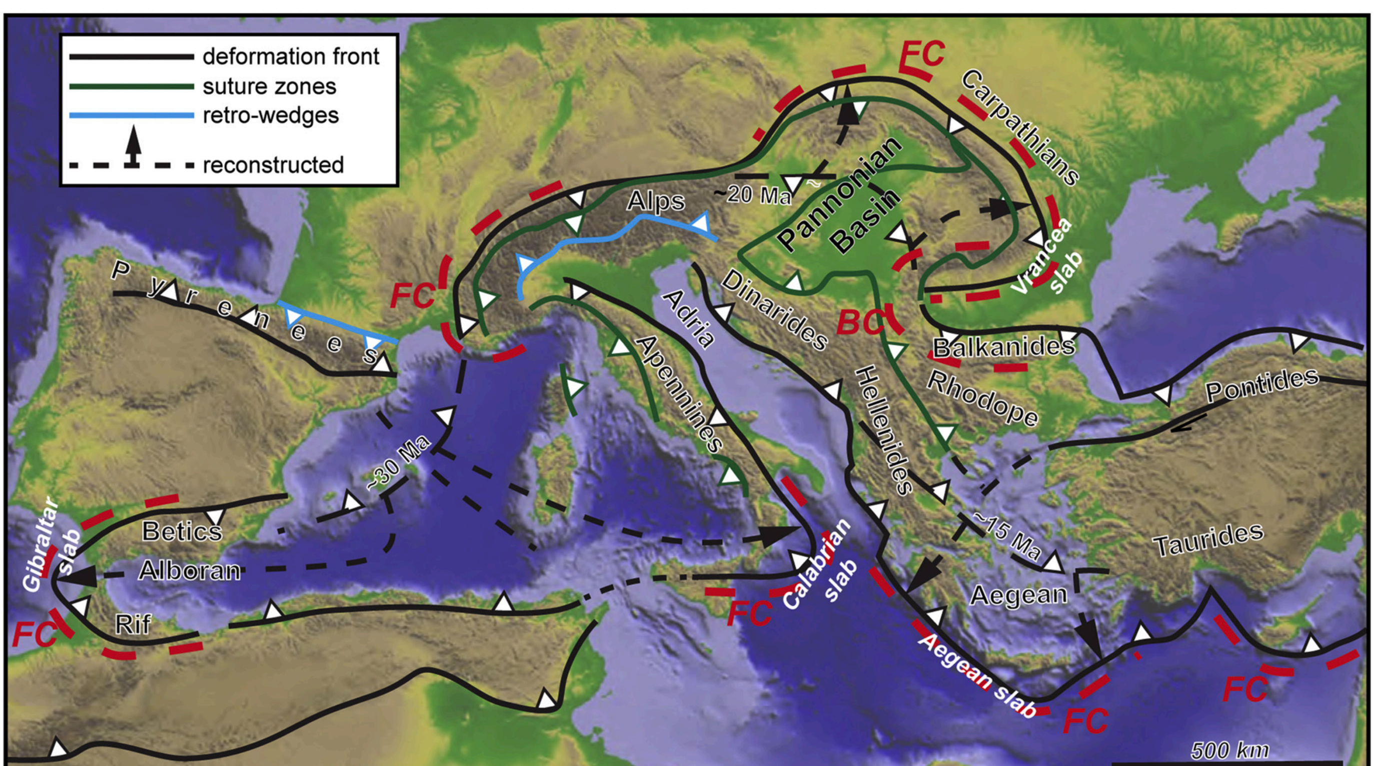

Fig. 2. The key elements of the Mediterranean Alpine-age orogens in terms of suture zones, retro-shears, orogenic fronts and their migration through time. Oroclines are indicated by dashed red lines: FC = foreland-convex orocline; BC - backarc-convex orocline (after Krstekanić et al., 2020, this VSI).

the Pannonian Basin or the Alps - Carpathians - Dinarides orogens and neighbouring areas (e.g., Horváth et al., 2015; El-Sharkawy et al., 2020; Schmid et al., 2020) allows the extrapolation of processes driving the deep Earth - surface coupling and associated sedimentation. These are important to understand many other analogue systems of orogen - sedimentary basins worldwide.

We analyse and integrate processes driving the coupled dynamic evolution of orogenic areas and subduction systems with the associated infilling of sedimentary basins. The integration first requires the definition of recent concepts in deep Earth to surface coupling, and then a multi-scale analysis linking the spatial and temporal scale of geodynamic evolution to societal-relevant issues, such as natural geohazards and geo-resources. We place our observations in the context of this multi-scale process-oriented analysis with an application centred to the Central Mediterranean system, where the Pannonian Basin recorded a complex interaction with multiple orogens, from the Alps and Carpathians to the Dinarides (Fig. 2). Several other orogenic, cratonic or sedimentary systems serve as worldwide analogues to the processes discussed and applied in the Central Mediterranean. These studies are part of a special issue of *Global and Planetary Change* entitled *Understanding the multi-scale and coupled evolution of orogens, sedimentary basins and their underlying lithosphere*, whose significance is explained in our review.

2. Interacting processes driving differential vertical motions and sediment transport/deposition

Numerous studies have demonstrated that multi-scale vertical movements and associated erosion control the evolution of sedimentary systems, modulated by climate and eurybathic variations (e.g., Matenco and Haq, 2020 and references therein). These studies have shown that sediment transport and depositional response takes place at a variety of spatial and temporal scales, resulting in sediment distribution in the entire topographic range of the Earth's surface (Fig. 1a), whether the response is modulated by the sea-level variations when connected with the open ocean, or by the balance between precipitation and evapotranspiration in endemic and/or endorheic situations, such as is the case of higher-altitude orogenic or intra-continental deposition (e.g., Nichols, 2011; Sztanó et al., 2013; Haq, 2014). Differential vertical and horizontal motions controlling the formation and evolution of accommodation space and sedimentary fluxes can be generated by a wide range of processes, from upper crustal faulting to long-term thermo-flexural effects that are usually grouped under the generic term of dynamic topography (e.g., Gurnis, 1993; Flament et al., 2013; Ballato et al., 2019), which may be derived either by tectonics (the tectonic topography of Braun, 2010), or by vertical stresses imposed on the base of the lithosphere by mantle convection (e.g., Faccenna and Becker, 2020). Dynamic topography can also affect sedimentary basins across timescales of up to 100 Myr and across continent length scales of 1000s of kilometres (Fig. 1b). This continent-scale dynamic topography has been quantified in terms of amplitudes and patterns (Fig. 1b, e.g., Steinberger et al., 2019) and may change with time at low rates based on changes in amplitude and continental positions (e.g., Conrad and Husson, 2009). For example, the continent-scale dynamic topography may be important for the Amazon Basin (Eakin et al., 2014; Dávila and Lithgow-Bertelloni, 2015), while the North America has large changes in long-wavelength dynamic topography that may have affected drainage basins and associated sediments (e.g., Liu, 2015; Liu et al., 2011; Wang et al., 2020).

The processes creating differential vertical and horizontal motions are controlled by numerous factors, such as, the balance between the rates of sediment flux and creation of accommodation space, the crustal and lithospheric rheology and the presence of inherited weakness zones, the thermal structure, glacial isostatic adjustment, or the rate of creating oceanic lithosphere, conditioned by climate and eustasy (e.g., Bercovici and Ricard, 2014; Cloetingh and Haq, 2015). The glacial isostatic adjustment (GIA) can take place over 10 yrs to 100 Kyrs time-scale (Fig. 2b), and leads to sediment redistribution and changes in sediment loading. For instance, the modelling of the loading effect of glacially induced sediment redistribution related to the Weichselian ice sheet in Fennoscandia and the Barents Sea suggested changes in eurybatic sea level of up to 2 m in the last 6000 years, resulting in present-day uplift rates reaching a few centimetres per year (Dalca et al., 2013; van der Wal and Ijpelaar, 2017). Such changes in sediment redistribution and loading can be important for local sea-level variability and exhumation of topography (the SIA - sediment isostatic adjustment of Kuchar et al., 2018), in the otherwise large wavelength isostatic effect in orogens by exhumation and erosion in their core and transporting the resulting sediments to the neighbouring basins (e.g., Champagnac et al., 2007 for the European Alps).

The depositional patterns observed in sedimentary basins demonstrate that the response to the various causal processes occurs over a wide range of spatial and temporal scales, creating sedimentary cyclicities from the 10 to 200 Myr and thicknesses from 3 to 11 km. These can be associated with large plate tectonic megacycles, sedimentary cycles in individual basins or sub-basins, the activation of faults systems or individual faults, and ultimately to the smaller-scale (cm to m) offsets of the seismogenic events that can occur in the short span of seconds (Fig. 1b).

No matter what scale is being studied, tectonically-driven sedimentation can be characterized as quasi-cyclic deposition that can be sourced from multiple directions, producing sediment bodies that can triangular in profile, with steep slopes that are prone to mass-wasting (Matenco and Haq, 2020). Sediments accumulate in wedge-shaped infill areas (Fig. 1c) that are often located too deep in the oceans, too high in the mountains or too far in the continental interiors to directly record the influence of shoreline and sea-level variations (Fig. 1a). While the modulation by climate and eurybathic variations is undeniable in many tectonically-driven sediment bodies, these specific characteristics make it less than meaningful to use a standard sequence-stratigraphic lexis that is more relevant to unidirectional sediment influx and a shoreline terminology, largely along relatively stable passive margins (e.g., Hardenbol et al., 1999; van Wagoner et al., 1990). Thus, the need for a more applicable concept in decoding tectonically-driven sedimentary patterns has been long recognized. Such a conceptual model ought to take advantage of a distinctive terminology to avoid confusion. One such conceptual approach is the identification of multi-scale tectonic successions, separated by succession boundaries and composed by sourceward- or basinward- shifting facies tracts (Fig. 1c, Matenco and Haq, 2020). The geometry, composition and thickness ratio between these facies tracts are controlled by the balance between the rate of accommodation-space creation and the rate of sediment supply. Such a conceptual approach is more effective in describing the evolution of tectonically-driven basin infill, particularly for periods of rapid differential vertical movements. Many studies have demonstrated that tectonics induce significant vertical and horizontal motions at all temporal scales (Fig. 1b). Nevertheless, during the more advanced stages of their evolution, sedimentary basins may acquire a more stable geometry with reduced tectonic influences. At that stage the well-known sequence stratigraphic approach with its numerous variations (e.g., Catuneanu, 2019 and references therein) may be used more effectively to describe the ensuing depositional patterns. In all situations, defining effective concepts to describe the observed sedimentary variability is fundamentally important for multi-scale facies prediction by process-oriented methodologies (e.g., Clevis et al., 2004; Hawie et al., 2015).

One prime natural laboratory where conceptual studies of coupled orogenic and sedimentary basins evolution can be applied is the Pannonian Basin of Central Europe (Fig. 3). This basin is a classical extensional back-arc system driven by a slab retreat of Mediterranean type, where previous studies have demonstrated the coupling between tectonic, climatic and surface processes in driving the evolution of its sedimentary architecture, strongly influenced by orogen-building

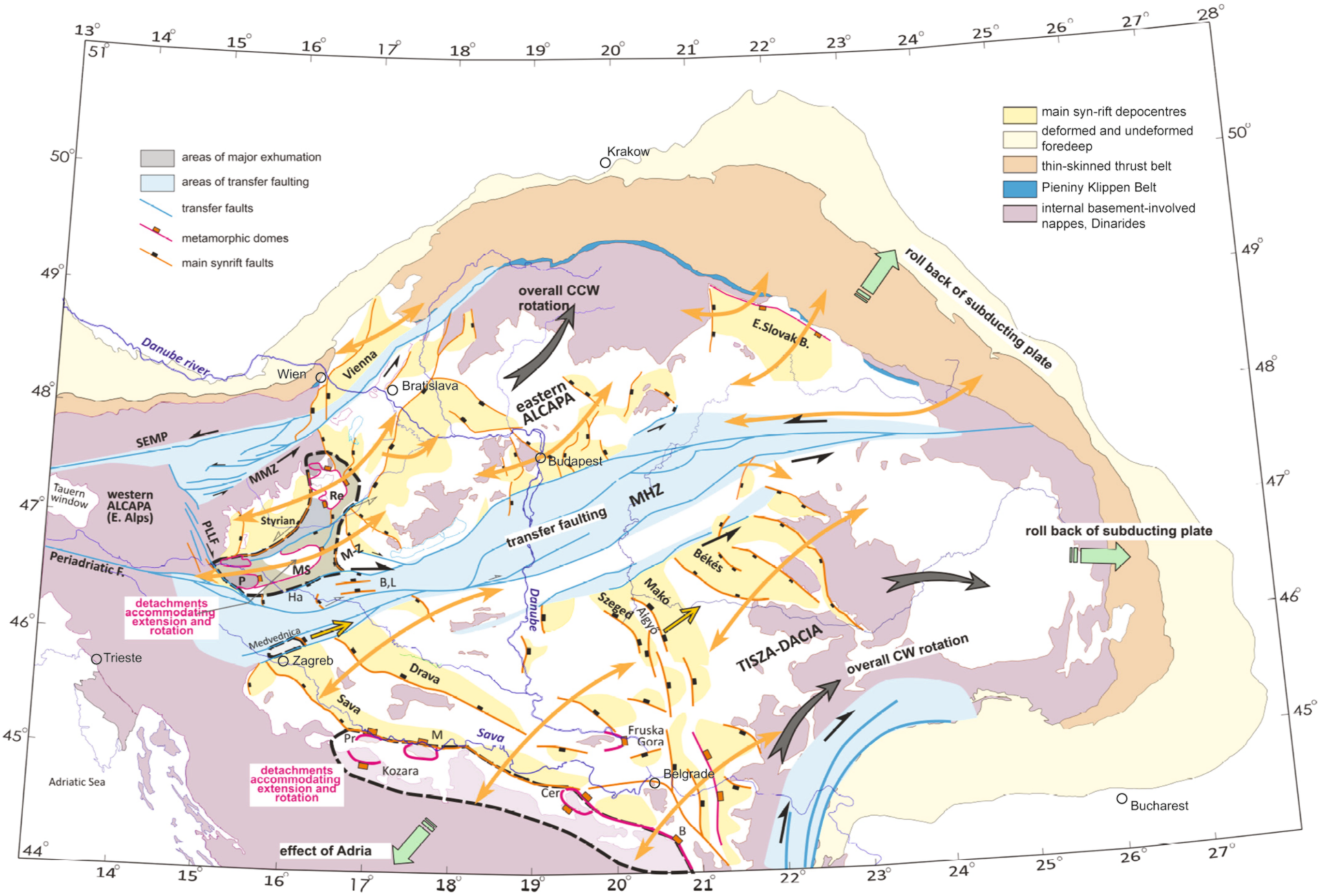

Fig. 3. The structure of the Pannonian Basin and its surrounding orogenic system with a model of evolution showing the geometry and timing of the major extensional structures, such as large normal faults or detachments (after Fodor et al., 2021, this VSI). B: Bukulja; B,L: Budafa, Lovászi grabens; Ha: Haloze; MS: Murska Sobota Ridge; M-Z: Mura-Zala Basin; M: Motajica; MMZ: Mur-Mürz-Zilina fault zone; P: Pohorje; PLLF: Pöls-Lavantal-Labot Fault; Pr: Prosara; Re: Rechnitz windows; SEMP: Salzachtal-Ennstal-Mariazell-Puchberg Fault; MHZ - Mid-Hungarian Shear Zone.

processes in the neighbouring mountain chains (e.g., Cloetingh et al., 2006; Horváth et al., 2006; Harzhauser et al., 2007; Kováč et al., 2017; Balázs et al., 2018b; Schmid et al., 2020, among others). These studies have also highlighted the importance of a coupled approach that bridges the different scales between high-resolution observations and regional to lithospheric-scale processes.

Recent observations and process-oriented modelling studies have demonstrated a strong coupling between the mechanisms of subduction and collision in the neighbouring mountain chains, such as the slab retreat of the Carpathians and Dinarides, and the subsequent indentation of the Adriatic micro-continent in the formation and evolution of the Pannonian Basin (e.g., Fodor et al., 2005; Fodor et al., 2008; Horváth et al., 2015; Matenco et al., 2016; Balázs et al., 2017a and references therein). These studies have shown that the coupling was associated with complex processes, such as extensional reactivation of inherited weakness zones, large-scale differential vertical axis rotations, rapid changes in the sedimentary transport driven by orogenic exhumation and diachronous infill across multiple sedimentary sub-basins systems. By integrating higher resolution tectonic system tracts or tectonic successions concepts combined with sequence stratigraphic approaches (e.g., Juhász et al., 2007; Csató et al., 2015; Balázs et al., 2016; Balázs et al., 2017b), previous studies have achieved new orogenic, lithospheric structure and basin evolution understandings for the entire Pannonian-Carpathians-Dinarides area, where the back-arc extension and the subsequent inversion migrated in space and time with deformation localised in rheologically weak zones, driven by the overall orogenic slab retreat and the Adriatic indentation. As an example, it is now apparent that the extension may have started during the Oligocene - early Miocene by reactivating the pre-existing oceanic Sava suture zone of the Dinarides along its entire strike, as previously inferred by observations and modelling studies in the SE part of the basin (e.g., Ustaszewski et al., 2010; Toljić et al., 2013; Erak et al., 2017; Stojadinovic et al., 2017). The extension along these structures was enhanced and migrated during 19–14 Ma period towards the central part of the Pannonian Basin (Balázs et al., 2017a) and towards the southern Dinarides, where an endemic lake system was eventually established (the Dinarides Lake System, Mandic et al., 2011; van Unen et al., 2019). Extension continued with significant offsets in areas that are presently closer to the Carpathians front, until ~8Ma when the overall subduction stopped and back-arc extension ceased (Matenco et al., 2016; Balázs et al., 2017a). In other words, the extension has migrated with time in the direction of roll-back, possibly accommodating the observed large scale opposite sense rotations of the two major intra-Carpathians units (ALCAPA and Tisza-Dacia, Fig. 3, Balla, 1984). The extension also accommodated the large-scale transfer of extensional deformation taking place at these units contact, reactivating a major transform fault connecting the opposite polarity subduction systems of the Alps and Dinarides (Fig. 3, Handy et al., 2015; Balázs et al., 2018b). Such a migration of extensional deformation in the direction of the slab roll-back associated with the activation of large inherited transform faults is a common process observed in several other Mediterranean back-arc systems (e.g., Jolivet et al., 2021 and references therein). Previous tectonic system tracts or tectonic successions studies have also demonstrated a close connection between sedimentation and evolution of individual sub-basins, connected during the later stages of extension and thermal subsidence, and the conditioning of a rapid asymmetric basin infill in a mostly SE-ward progradation direction between 10 and 4 Ma, roughly along the present-day trace of the Danube River (Fig. 3, Sztanó et al., 2005; Sztanó and Mészáros, 2006; Cserkész-Nagy et al., 2012; Magyar et al., 2013; Sztanó et al., 2013; Balázs et al., 2018a; Magyar et al., 2020). The detailed sedimentological, paleoenvironmental and paleogeographical evolution of this rapid progradation and its coupling to the tectonic-induced geometry and evolution still require significant further investigation.

The post- middle Miocene uplift of marginal mountain ranges and subsidence in some Pannonian Basin depocenters were for a long-time considered to be the expression of basin inversion taking place during the late-stage indentation of the Adriatic micro-continent, after the activity of the Carpathians subduction zone ceased in the middle Miocene. The differential vertical motions associated with the indentation were thought to be driven by lithospheric to crustal folding in a locked orogenic - sedimentary basins system (e.g., Horváth, 1995; Horváth and Cloetingh, 1996; Bada et al., 2007; Dombrádi et al., 2010). Recent studies have demonstrated that the basin inversion and indentation was a more gradual process that migrated with time over a much larger area than the Pannonian Basin. In the proximity of Adriatic indentor, the Miocene extension affected all external Dinarides orogenic areas and was followed by indentation effects starting at ~9Ma (van Unen et al., 2019 and references therein). The indentation is thought to have gradually migrated with time towards more northern areas in the internal Dinarides and the Pannonian Basin (e.g., Fodor et al., 2005; Ruszkiczay-Rüdiger et al., 2005; Toljić, 2005; Tomljenovic et al., 2008; Uhrin et al., 2009), reaching possibly as distant an area as the SE Carpathians with post-3 Ma deformations (Fig. 3, Matenco et al., 2007). However, a significant local variability is observed to be associated with large uncertainties in the timing and rates of vertical movements. All of these advances in the understanding the formation and evolution of the Pannonian Basin and surrounding mountain chains have set the stage of a new process-oriented framework for higher resolution studies to understand relevant processes and driving mechanisms, and quantifying relevant multi-scale effects in coupled orogens - sedimentary basins processes.

Studying processes in well-investigated systems of orogens - sedimentary basins systems is crucial to the understanding in other systems worldwide, such as frontier basins where the amount of observational data can be supplemented by process-oriented modelling and prediction. In the Eastern Mediterranean region (Fig. 4), the Levant Basin is a frontier geo-resources province that is an excellent example for understanding the interaction in orogenic-basins systems. This basin is situated at the meeting place between three major tectonic plates (Africa, Arabia and Eurasia), where the interaction can be studied in terms of mountain building, basin margin uplift, erosion and sediment supply to several depocenters. The multi-scale coupled mechanisms of tectonic uplift and basin infilling controlled the pathways for sediment transport and their depositional geometries. A series of recent studies extrapolating processes from better-known basins have demonstrated the multi-source character of the sedimentary infill in the Levant Basin (Fig. 4, Nader, 2014; Hawie et al., 2015; Hawie et al., 2018), including a multi-scale (in space and time) analysis of source to sink sediment transport by the means of stratigraphic forward modelling (Nader et al., 2018). Furthermore, to accurately model the complex infilling history of sedimentary basins in its full spatial and temporal dimensions, advanced seismic and field characterization techniques and novel interpretation methods must be first employed, which are compatible with the mechanisms of uplift, erosion and sediment transport. New approaches for tectono-stratigraphic interpretation by correlating outcrop with subsurface information are a first important step to discriminate the allogenic and autogenic controls, such as novel interpretations of the hierarchy of multiple-scale incision and infill cycles (e.g., Tőkés et al., 2021, this VSI). The prediction of the spatial distribution of time-constrained basin depositional events are also highly relevant for the understanding of paleo-climatic evolution (and related impacts), and for the understanding of the evolution of reservoirs relevant to the development of efficient and sustainable geo-resources for societal needs (Nader et al., 2018).

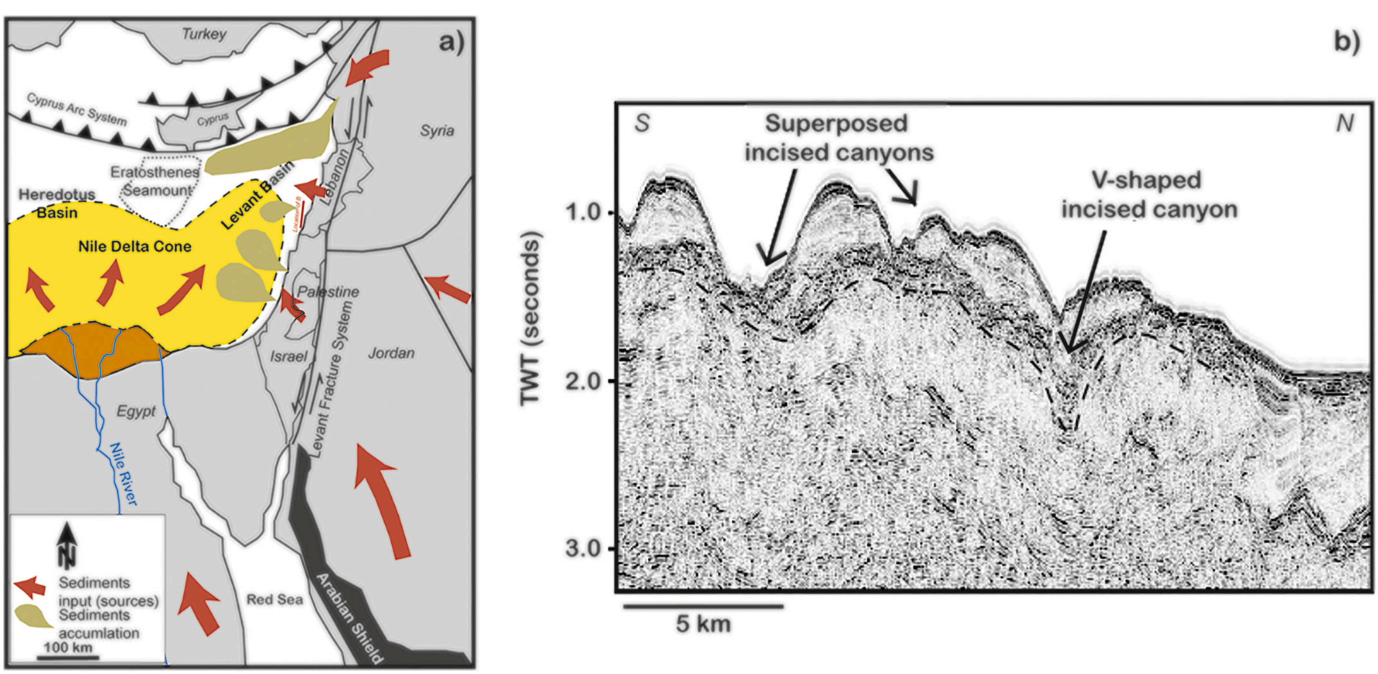

Fig. 4. Source to sink sediment routing in the Levant Basin of the Eastern Mediterranean (modified after Hawie et al., 2015). a) Simplified map showing map showing possible pathways for sediments from hinterland to basin; b) Example of seismic reflection profile featuring incised valleys providing the sediment pathways towards the main depocenters.

3. The coupling between orogens, sedimentary basins and the underlying crust and mantle in contributions to the special Global and Planetary Change issue

The general geochemical composition of the lithosphere and its association in terms of phase transitions and fluid content with deep geophysical anomalies is a key current topic in solid Earth dynamics, particularly relevant for the rheological, thermal and seismological character of the deep lithosphere and the lithosphere-asthenosphere boundary (e.g., Fischer et al., 2010; Rychert et al., 2020). The correlation between phase changes and the presence of mid-lithospheric discontinuities identified by geophysical studies is intriguing for understanding the evolution of the lower part of the lithosphere in the context of old cratonic versus recent orogenic areas (Selway et al., 2015; Kovács et al., 2017; Saha et al., 2021). These achievements have provided a new way of understanding the evolution of the lithosphere and have set the stage for a novel look at the global plate tectonics by the novel concept of the "pargasosphere" in the study of Kovács et al. (2021b, this VSI). The key petrological observation is that the pargasitic amphibole is stable at low fluid concentrations, which means that the solidus of the shallow upper mantle (<3 GPa) is usually the one of the pargasite dehydration at ~1100 °C, defining the lithosphere-asthenosphere boundary in continental and oceanic lithosphere younger than around 70 Ma (Fig. 5). In older continental lithosphere, the pargasite breaks down by releasing fluids, which may be responsible for the formation of mid-lithospheric discontinuities. This hypothesis is

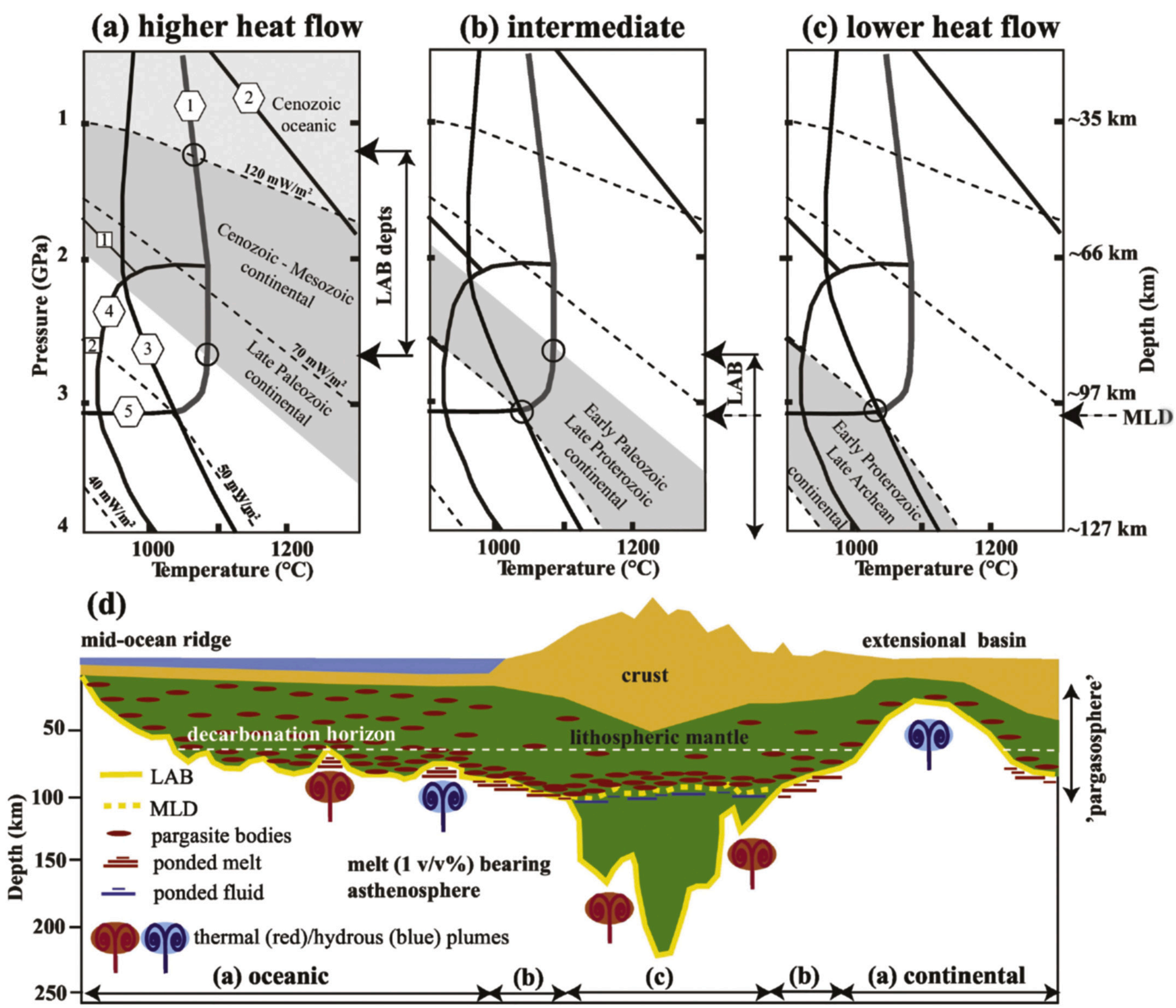

Fig. 5. Conceptual definition of the "pargasosphere" hypothesis (Kovács et al., 2021b, this VSI) where scenarios are considered for different tectonothermal ages of the lithosphere corresponding to a) young continental and oceanic lithosphere (heat flow >65 mW/m^2); b) old continental and oceanic lithosphere (heat flow 50–65 mW/m^2); c) old cratonic lithospheres (heat flow <~50 mW/m2). The solidus of the shallow upper mantle is the pargasite dehydration one shallower than 3 GPa and the water saturated solidus deeper than 3 GPa. Numbers in hexagons indicate the dehydration solidus of 1) pargasite; 2) dry solidus (bulk 'water' < 200 ppm); 3) water-saturated solidus (> 0.4 wt.%); 4) CO_2+H_2O bearing solidus; 5) sub-solidus pargasite dehydration curve. Numbers in squares indicate sub-solidus reactions 1) olivine (Ol) +clinopyroxene (Cpx) + CO2 → dolomite (Dol) + orthopyroxene (Opx); 2) Dol + orthopyroxene (Opx) → magnesite (Mag) + Cpx. (d) Schematic representation of the relationship between the lithosphere-astenosphere boundary and mid-lithospheric discontinuities in the different thermotectonic settings described above. Solid circles indicate the intersection of the geotherm and pargasite dehydration solidus. MLD - Mid-Lithospheric Discontinuity; LAB - Lithosphere - Asthenosphere Boundary. For further details see Kovács et al. (2021b, this VSI).

tested by modelling the variations of shear-wave velocities, temperatures and resistivity for various lithospheric columns and by observations in the SE Carpathian Vrancea zone of Europe (Fig. 2), providing an alternative phase-changes quantitative explanation for the genesis of intermediate-depth mantle seismicity presently observed. The hypothesis may be tested by a number of other alternative observations, such as gas emanations in locations situated at large distances from active volcanoes. The hypothesis has major implications for explaining the variability of a number of key geodynamic processes, such as delamination, intra-continental subduction or removal of cratonic roots.

The multi-scale (temporal and spatial) coupling between the deep Earth and surface processes requires understanding processes that are both presently active and were active in deep geological time. One typical example of a deep time process with a marked lack of representation in present-day plate tectonic configuration is the one of subduction initiation (e.g., Stern and Gerya, 2018; Beaussier et al., 2019). Understanding the factors controlling subduction initiation at passive continental margins or in intra-oceanic domain is one of the currently highest debated topics in plate tectonics, due to the complexity of localisation parameters, such as inherited rheology and structure, the age of oceanic lithosphere, the rate of convergence or lower crustal flow (e.g., Leroy et al., 2004; Nikolaeva et al., 2010; Zhong and Li, 2019). The strain localisation mechanisms for subduction initiation at passive continental margins are quantitatively analysed by the means of an advanced analogue and numerical modelling approach in the study of Auzemery et al. (2020, this VSI). The results demonstrate the importance of the original rheology of the ocean - continental passive margin transition and its subsequent thermo-mechanical impact in the mechanical behaviour during the evolution of subduction initiation. The combined modelling shows that there is a direct correlation between subduction initiation at passive continental margins and an intermediate thermo-tectonic age of the oceanic lithosphere in the order of 80Ma, favoured by a decoupled continental rheology and weakening mechanisms, such as low temperature plasticity or shear heating (Fig. 6). In

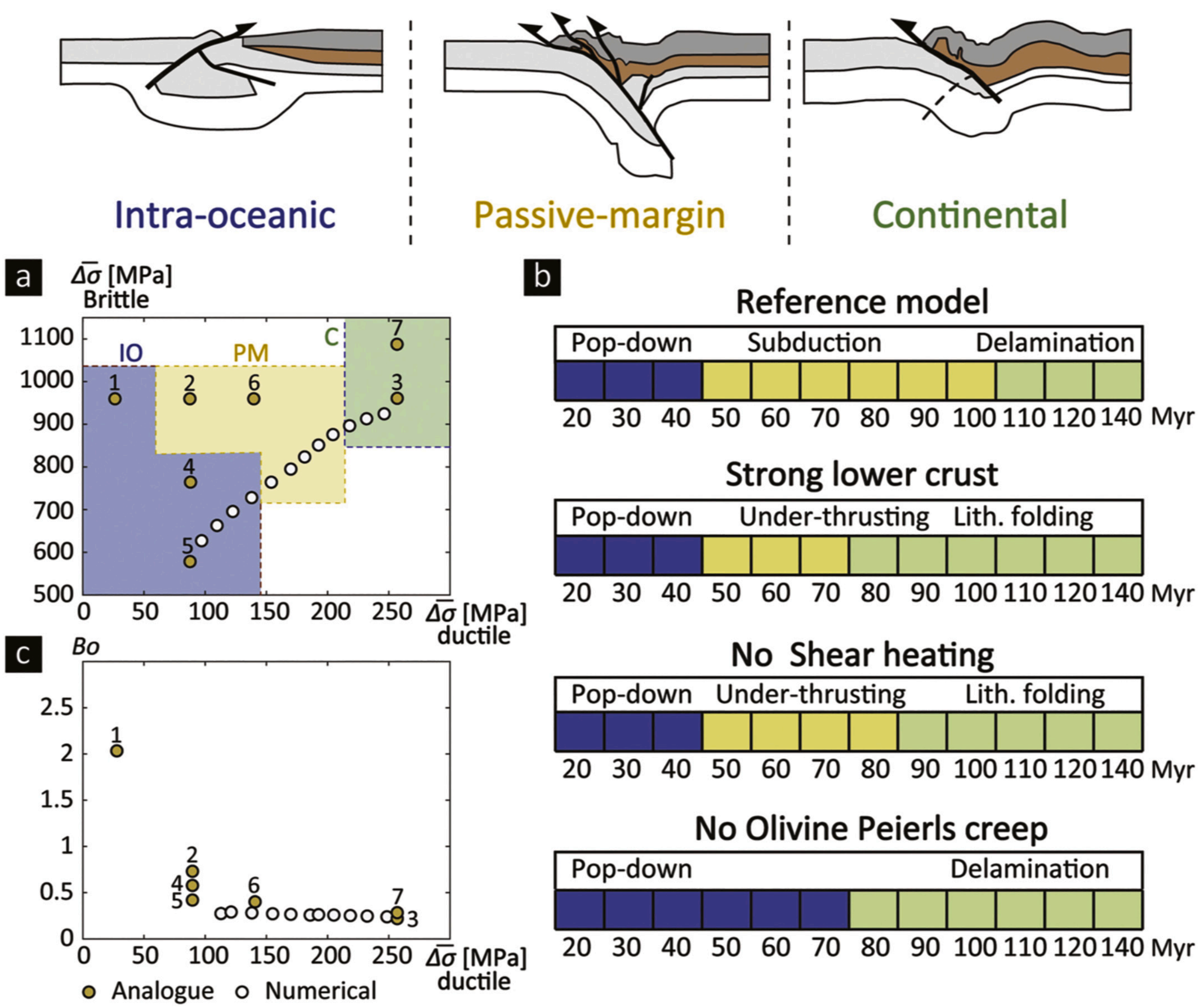

Fig. 6. Results from combined analogue and numerical modelling of subduction initiation (Auzemery et al., 2020, this VSI). The cartoons on the top are the styles of initiation in the intra-oceanic, passive margin transition and intra-continental domain. The colours of the text are used in the figures below. a) The influence of the relationship between the brittle and ductile strength on the type of subduction initiation. Dots are experiments, yellow analogue and white numerical (see details in Auzemery et al., 2020, this VSI); b) The relationship between the type of subduction initiation and the parametrical study in terms of the oceanic thermo-tectonic age, strength of the lower continental crust, shear heating and low temperature plasticity; c) The relationship between the buoyancy number (Bo, the ratio between the stress induced by the negatively buoyant oceanic lithosphere and its viscous strength) and the mean ductile strength.

contrast, subduction can be initiated in the oceanic domain at significantly lower thermo-tectonic ages. Theoretically, it can also be initiated in the continental lithosphere when mature, much older oceanic lithosphere is present, although it is difficult to demonstrate such a process with natural observations.

One other, less understood, plate tectonics process is the far-field interaction between different subduction zones associated with continental collision and tectonic complex situations, such as rapid slab-retreat, indentation or changes in subduction polarity. Many such situations are related to the evolution of small continental fragments either flanked by subduction zones, creating significant thickening and lateral escape against strike-slip faults, or located between retreating slabs and extensional back-arcs in highly arcuate orogens, influenced by rheological strength contrasts or the variability of the subduction mechanics (Molnar and Tapponnier, 1975; Davy and Cobbold, 1988; Regard et al., 2005). Nowhere is such an interplay between subduction zones more obvious than in the Mediterranean system of multiple orogens with often opposite polarities (e.g., Dinarides - Hellenides versus Alps, Fig. 2), indentation mechanics (e.g., Adria) and rapidly retreating slabs accommodating the movement of continental fragments by back-arc extension, formation of highly arcuate orogens and transfer faulting, all associated with a lateral interaction of the sub-lithospheric mantle flow (e.g., Faccenna et al., 2014; Handy et al., 2015; van Unen et al., 2019; van Hinsbergen et al., 2020; Jolivet et al., 2021). What is known about these processes in literature is combined with modelling in the study of Király et al. (2021, this VSI). This study shows that deformation transfers between subduction zones when they approach critical distances, being strongly influenced by the associated sub-lithospheric mantle toroidal or poloidal flows and slab dynamic effects, which alter the stress balance and changes the transfer of deformation. These processes are discussed in the framework of the Cenozoic evolution of the Mediterranean, which provides relevant examples of the activity of several subduction zones during the Africa-Europe convergence, while setting the stage for subduction inferences in analogues elsewhere in the world.

3.1. Understanding the evolution of orogenic systems and its impact to seismicity distribution

The relationship between the deep thermal structure, rheological strength, weakness zones and seismicity in one of the best known orogens worldwide, the European Alps (Fig. 2), is considered in the study of Spooner et al. (2020, this VSI) by creating a first 3D steady-state thermal model controlled by temperature measurements in wells and employing a heterogeneous compositional structure for the various tectonic domains. The results show that the shallow thermal field is controlled by topography and sediments blanketing effects. The deep thermal structure is controlled by the lithospheric thickness and a heterogeneous distribution of the crustal radiogenic heat production with higher values in the European lithosphere when compared with the Adriatic one, which implies a higher (ultra)mafic composition of the later. These observations agree with differences in seismicity clustering close to the brittle-ductile transition at higher temperatures in the larger Adriatic domain.

The relationship between an enigmatic deep structure and seismicity is also best illustrated in another classical European example, the one of the Romanian Carpathians (Fig. 2). Here, the major intermediate mantle (70–220 km) and crustal earthquakes defining the Vrancea seismogenic zone are associated with a laterally variable character of focal mechanisms and active deformation, as well as with a focused high-velocity mantle anomaly interpreted to represent the last stage of slab-detachment, possibly associated with significant petrological phase changes (Koulakov et al., 2010; Ismail-Zadeh et al., 2012; Petrescu et al., 2021; Kovács et al., 2021b, this VSI). The relationship between the Vrancea zone, the Carpathian tectonic evolution and the geometry of the underlying European craton together with the neighbouring Trans-European Suture Zone thrusted during continental collision is evaluated with a double-difference tomography approach of P- and S- wave velocities combined with a high-resolution analysis of crustal seismicity in study of Borleanu et al. (2021, this VSI). The study demonstrates a crustal transition at large depths from high velocities in the European craton to low(er) velocities in Paleozoic platforms beneath the core of the Carpathian Mountains, associated with a downward decrease in Vp/Vs ratio. In the parts of the platforms overlain by the Miocene volcanic chain, an increase in the Vp/Vs ratios infer the presence of fluids, mafic residue or partial melts. The newly relocated earthquake hypocentres in the area W-NW of the Vrancea seismogenic zone are vertically distributed in a velocity transition zone, which may indicate magmatic plumbing associated with the relatively recent formation of volcanic structures. To the north, where the volcanic structures are significantly older, the reduced seismicity clusters in the shallow 10 km beneath the volcanic chain, may be related to secondary systems of crustal faults.

Understanding the mechanics of subduction systems and its association with active seismicity requires understanding of the full 3D geometrical complexity of the tectonic lower plate, particularly when enhanced by the subduction of island-arcs or seamounts (Ishiyama et al., 2016; Sato et al., 2017). Such complexity is analysed in the case of the subducting Philippine Sea plate beneath the Suruga Through of the Japan active subduction system by the study of Matsubara et al. (2021, this VSI). In this natural case study, megathrust earthquakes occurred repeatedly at this plate boundary along the Nankai Trough. The key issue is related to the evolution of one major fracture zone (the Fujikawa-kako Fault Zone) in terms of partitioning the observed seismicity and localizing major events. Solving this issue requires an improved understanding of the subducting plate geometry and the deep prolongation of the major fracture zone. This improved definition has been achieved by integrating Vp and Vs seismic tomography with the observed micro-seismicity. The results demonstrate that the subduction zone is significantly shallower (6–10 km) than previously thought and clarifies the distribution between low velocity oceanic crust and high velocity oceanic mantle in the subduction zone.

The evolution and the mechanics of cycles in burial and exhumation of continental material in areas affected by significant syn-orogenic extension remains one of the least understood orogenic process, where various models of reactivating inherited nappe stacks or exhumation in subduction channels creating detachments or core-complexes exist (e.g., Brun and Faccenna, 2008; Liao et al., 2018). One novel scenario of distributed syn-orogenic extension in burial-exhumation cycles is analysed by Porkoláb et al. (2020, this VSI) in the case study of the Pelagonian unit of the Northern Sporades, belonging to the Aegean system of SE Europe. The study focuses on the influence of the inherited nappe stack rheology on the localization of crustal extension by the means of a structural and kinematic study combined with $^{40}Ar/^{39}Ar$ geochronological dating in the islands of Skiathos and Skopelos. The results demonstrate that the early Paleogene nappe stacking and burial in greenschists facies conditions was followed by opposite sense of shear extension and exhumation, distributed across a much larger zone by layer parallel shearing and reactivating nappe contacts with an opposite sense of shear (Fig. 7). This style of exhumation was influenced by the volumetric distribution of rheological contrasts, in particular weaker carbonate-rich layers, creating decoupling levels, which allowed the thinning and exhumation of significant parts of the nappe stack.

In contrast with the direct tectonic exhumation by back-arc extension, many studies have analysed the mechanics of erosional assisted contractional exhumation during the formation of mountain belts (Willett and Brandon, 2002; Brandon, 2004; Reiners and Brandon, 2006). This type of exhumation is controlled by numerous parameters, such as rheological inhomogeneities, the geometry of the subduction system or the orogenic magmatism (e.g., Gerya and Yuen, 2003; Duretz and Gerya, 2013; Andrić et al., 2018b). In this context, the mechanics of contractional exhumation in orogens affected by significant slab retreat that display one structural vergence (or single-vergent orogens) is much

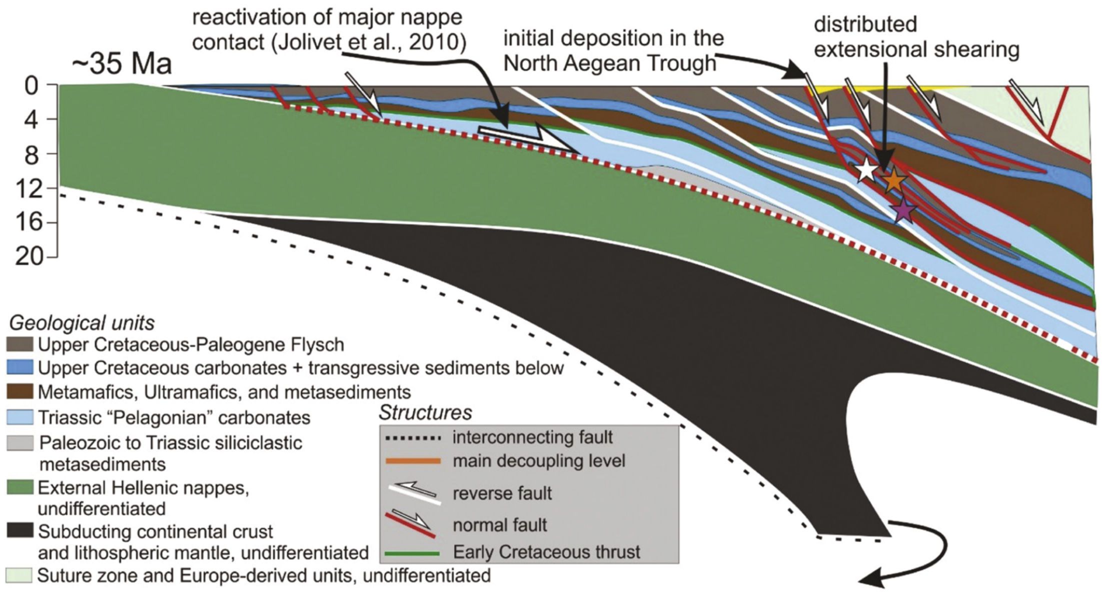

Fig. 7. Schematic evolutionary model for a burial-exhumation cycle applied to the Pelagonian unit of the Hellenides - Aegean system (after Porkoláb et al., 2020, this VSI). Both the initial top-SW nappe stacking and the subsequent top-NE extensional inversion are localized in the rheological weakness zones provided by the Upper Triassic and Upper Cretaceous carbonates. The localized shearing at stratigraphic contacts, the reactivation of top-SW marble mylonite shear zones and the reactivation of an Early Cretaceous nappe contact are highlighted by orange, white and purple stars, respectively.

less understood, also owing to the low amount of tectonic uplift observed in such orogens that is often at the resolution of thermochronological methods (e.g., Matenco et al., 2010; Merten et al., 2010). This type of exhumation is quantitatively analysed in the study of Necea et al. (2021, this VSI) by the means of a high-resolution low-temperature thermochronology transect across the SE Carpathian nappe stack and its foreland. This is an optimal natural case scenario of an active single-vergent orogen, where the nappe stack was significantly less affected back-arc extension, when compared with other Mediterranean orogens. The results demonstrate that the gradual accretion of sediments and crustal material was associated with an exhumation that migrated progressively towards the foreland of the orogen during the entire Cretaceous - Cainozoic nappe-stacking (Fig. 8). The initial exhumation pattern suggests a gradual building of an accretionary wedge during the oceanic subduction, which changed during the late Eocene, when enhanced exhumation took place over a larger area, interpreted to be an effect of the onset of collision in the SE Carpathians. Subsequently, the exhumation accelerated after locking the crustal subduction zone, interpreted as an effect of the continued contraction and differential vertical movements, driven by a mantle circuit characterized by the continuation of the Vrancea slab subsidence and asthenospheric upraise in its hinterland.

The processes associated with the formation of highly arcuate mountain chains, such as the ones often observed in the Mediterranean system, have been a subject of intense discussion, ideas varying from lateral changes in the geometry of plate boundaries, the lateral variability of slab retreat or slab-tearing mechanics, to processes associated with indentation of micro-plates (Hollingsworth et al., 2010; Pastor-Galán et al., 2012; Calignano et al., 2017). One of the best examples of oroclinal bending is the double 180° arcuated loop of the Carpathian Mountains (Fig. 2), which has a geometry characterized by a forearc-convex loop in the West, East and South Carpathians and another backarc convex orocline at the connection between the South and Serbian Carpathians with the Balkan Mountains. While the nature and evolution of the forearc-convex loop has been analysed by numerous studies, much less is known on the evolution of the backarc-convex one, which is a rather unique feature in the Mediterranean system. This feature is analysed in the study of Krstekanić et al. (2020, this VSI) by the means of a field kinematic and structural study in the critical area of the Serbian Carpathians. The results demonstrate that Cretaceous nappe stacking events were followed by an Oligocene - Miocene oroclinal bending associated with at least 40° of clockwise rotation of the South and Serbian Carpathians. The superposition between oroclinal bending, extension in the Dinarides and the formation of one of the largest strike-slip systems known in continental Europe (the 100 km dextral offset Cerna-Timok faults system), driven by the Carpathians slab pull, has created a complex pattern of deformation of coeval normal, strike-slip and reverse faults. These deformations were followed by a newly observed stage of late Miocene E-ward thrusting, driven by a transfer of deformation in the orocline during its formation around the rigid Moesian indenter. These results demonstrate the complexity of interacting geodynamic processes during the formation of oroclines at the transition between different subduction systems, such as observed in this study connecting the Carpathians with the Dinarides.

The nature of syn- to post- orogenic alkaline magmatism observed in numerous worldwide areas, such as in the Basins and Range province of North America or Western and Central Europe, is a debated issue given the numerous mechanisms proposed, which range from slab detachment, delamination, convective lithospheric thinning or evolution of mantle plumes (Hawkesworth et al., 1995; Wilson and Downes, 2006; Seghedi et al., 2011). This debate extends also to the larger Alpine - Pannonian area (e.g., Pécskay et al., 2006), where the study of Neubauer and Cao (2021, this VSI) analyses a previously underestimated idea on the link between post-orogenic inversion, indentation tectonics and alkaline magmatism emplacement. The study reports a migration of alkali-basaltic volcanic centres in the period of 11–1.7 Ma at the transition between the Eastern Alps and the Pannonian Basin. Three stages of alkaline magmatism are separated that are interpreted to have been associated with the evolution of a mantle upwelling underneath the ALCAPA mega-unit and with a thermally-induced lithospheric thinning, which migrated with time in an NNE-ward direction. The overall migration correlates with a gradual inversion of the Pannonian - Eastern Alps system driven by the motion of the Adriatic micro-continent.

The kinematics of the Adriatic micro-continent and its impact on the evolution of the surrounding orogens have been an intensively studied subject particularly in the Alps and Apennines mountains (e.g., Handy

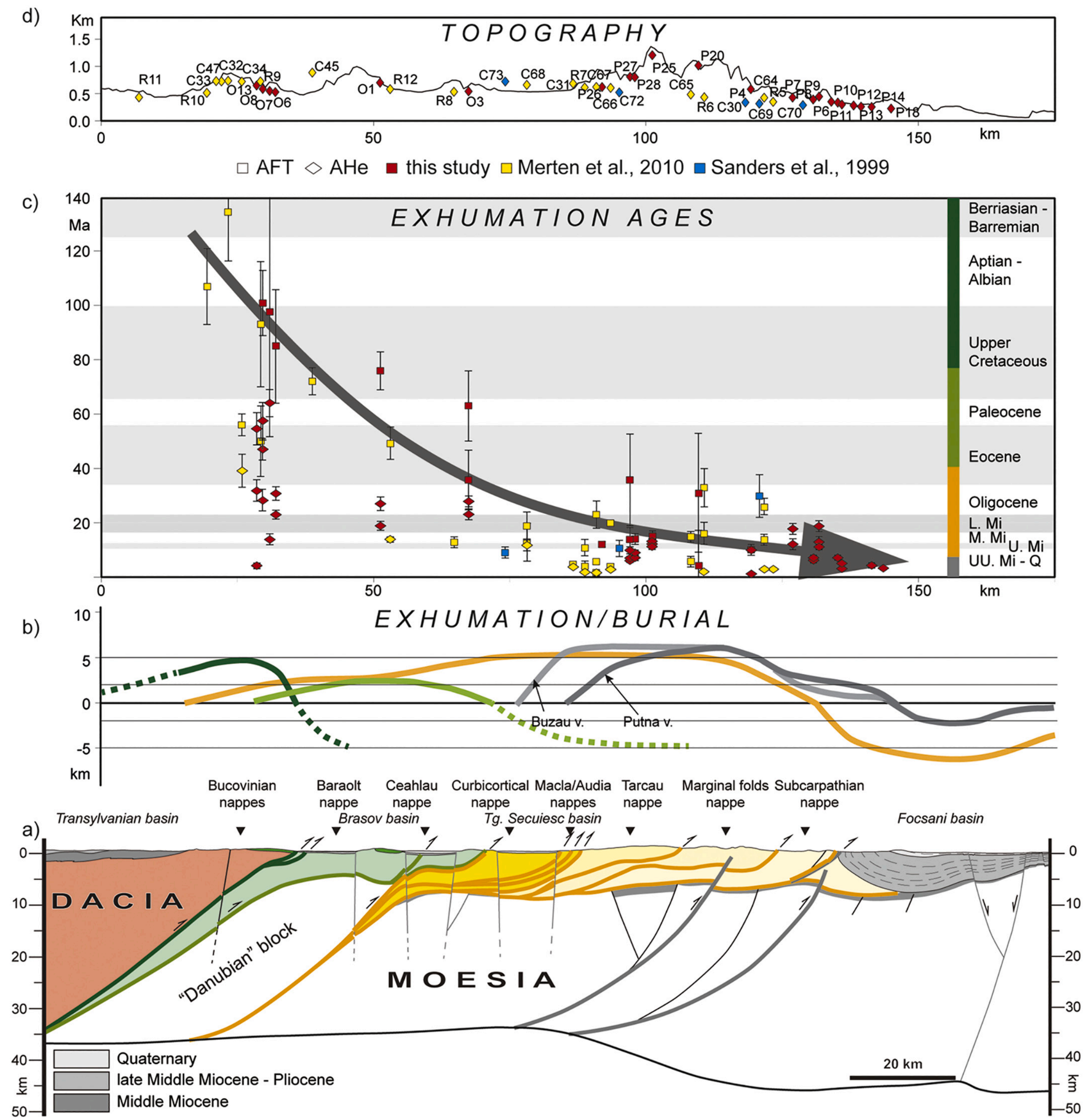

Fig. 8. Thermochronological transect in the SE Carpathians (simplified from Necea et al., 2021, this VSI); a) Crustal scale tectonic cross section along the SE Transylvanian Basin, SE Carpathians and their foreland including the Focșani Basin (see Fig. 2 for approximative location). Faults are coloured as a function of their activity following the four main time periods defined in Fig. 8c; b) The evolution of exhumation and subsidence across the nappes (Fig. 8a) for the four time periods defined in Fig. 8c. The latest Miocene - Quaternary exhumation is slightly different on the Buzău and Putna valleys and displayed with different shades of grey; c) Exhumation (apatite fission track - AFT and Apatite U-Th/He – AHe) ages plotted across the geological cross-section and with time. The four periods underlined are Late Jurassic - Cretaceous (until 78Ma), latest Cretaceous - middle Eocene, late Eocene - late Miocene (until 8 Ma) and latest Miocene – Holocene. L. Mi = lower Miocene, M. Mi = middle Miocene, U. Mi = upper Miocene, UU. Mi = uppermost Miocene, Q = Quaternary. Note the clear pattern of older ages in the western hinterland and gradually younger ages towards the eastern foreland; c) Sample code and location plotted against topography along the low-temperature thermochronological transect.

et al., 2010; Métois et al., 2015; Rosenberg et al., 2015; Király et al., 2018). By contrast, much less is known on the mechanics of nappe stacking versus the late-stage indentation in the Dinarides (Handy et al., 2019; van Unen et al., 2019). The mechanics of nappe stacking and lateral transfer faulting during late-stage collision in the NW segment of the Dinarides is analysed in the study of Balling et al. (2021, this VSI) by the means of reconstructing structural and kinematic transects combined with a flexural thin-sheet lithospheric modelling. The results infer significant strain partitioning across the Split-Karlovac Fault, a major dextral structure that crosses obliquely the Dinarides. To the NW, the transect across the Velebit Mountains is characterized by a triangle structure, while the SE transects shows a top S to SW nappe stack with significant out-of-sequence movements at the scale of the external Dinarides. A major increase of 80 km in the total amount of shortening is observed SE-wards across the Split-Karlovac structure. The flexural modelling demonstrates the compatibility of thrust-stacking sequence with the observed Eocene - Oligocene syn-kinematic deposition of coarse-clastics associated with the thrusting of the Velebit Mountains structure. These results demonstrate that segmentation during Paleogene nappe-stacking in the Dinarides played a more important role than hitherto assumed.

3.2. Sedimentary basins: from transport systems and dynamic sedimentation processes associated with subduction zones and rifting areas to the inherited rheology of cratonic systems

The sedimentary transport in major fluviatile networks characterized by gateways and temporary storage sinks shows often diachronous deposition of major periods of infill, associated with rapid evolution of deltaic systems, which are influenced by endemic/endorheic evolutions or major periods of sea-level variations (e.g., Garcia-Castellanos, 2006; Urgeles et al., 2011). One of the best worldwide examples characterized by endemic and endorheic evolution associated with sea or lake level variations across a system of multiple gateways is the complex sedimentary system developed along the present-day trace of the Danube River in Central and Eastern Europe (e.g., Matenco and Andriessen, 2013). This system was gradually filled across the Alpine foreland, the larger Pannonian area and the foreland of the Carpathians on the way to the present Danube Delta system and towards the main Black Sea sink (e.g., Munteanu et al., 2012; Magyar et al., 2013). The Neogene transport system in the lower Danube River network filled what is commonly known as the Dacian Basin located in the foreland of the South and SE Carpathians. This system and its connection with the Black Sea sedimentation is analysed in the study of Krézsek and Olariu (2021, this VSI) by the means of a subsurface analysis of reflection seismic data correlated by wells. The study demonstrate that the Dacian Basin started to evolve during middle Miocene times by coalescing several isolated depocenters inherited from and fed by erosion and re-deposition of the evolving external part of the Carpathians orogen. The fluvial network gradually evolved during ongoing subsidence into a major fluvial system located at roughly 100 km north of the present Danube position. As the subsidence continued, this fluvial network developed a major deltaic system that gradually evolved and filled the basin in an analogue precursor of the present-day Danube Delta, while the Danube migrated to its present southern position. When compared with worldwide major rivers (Fig. 9) that formed mostly within a simpler tectonic framework, the Danube represents an unusual system that filled and transited multiple basins by coalescing multiple small rivers in individual depocenters

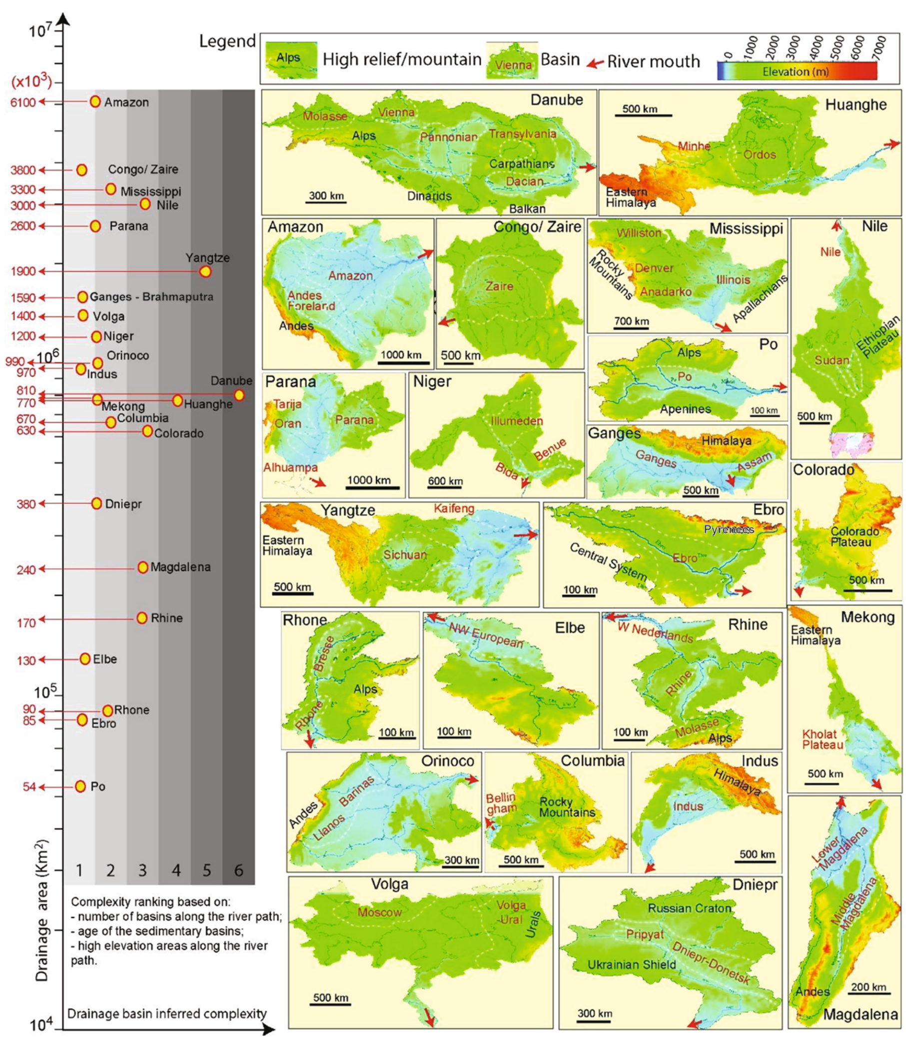

Fig. 9. Large worldwide rivers with the main structural elements and elevation of the river drainage areas (Krézsek and Olariu, 2021, this VSI). The complexity of the river drainage is ranked following the number of sub-basins crossed by the river path, age of these sub-basins and tectonic activity.

into a major system migrating in one direction eventually crossing the separating gateways.

The evolution of orogenic areas is associated with the development of individual sedimentary basin systems that are generally developed in different places as a function of the response to vertical movements in the evolving mountain chain (Fig. 1a, e.g., Cloetingh and Ziegler, 2007; Matenco and Haq, 2020). Such areas may dynamically evolve towards spatial juxtaposition in orogens associated with rapid slab retreat, where the migration of depocentres results in a dynamic interaction between backarc and forearc systems, as commonly observed in the complex dynamic evolution of the Mediterranean area in orogens such as the Betics-Rif, Hellenides-Aegean or the Apennines (e.g., Jolivet and Faccenna, 2000; Jolivet et al., 2021). One optimal place to study such an interaction between forearc and backarc systems are the sedimentary basins associated with the formation of the Calabrian arc in the area of Western Sicily, analysed in the paper of Milia et al. (2021, this VSI) by the means of interpreting a large seismic dataset correlated with well and dredge data, resulting in a Pliocene - Ealy Pleistocene evolutionary model. This study demonstrates the existence of two depositional areas associated with the evolution of the collisional chain in the Maghrebian thrust belt, one NE-SW oriented located south of the Egadi Islands, representing the continuation of the African foreland basin system, and another with E-W trend located north of these islands, where the extension associated with the evolution of the southern Tyrrhenian backarc system has migrated eastwards from early Pliocene to early Pleistocene. This overlapping sedimentary evolution was likely driven by the migration of the westward dipping slab, along-trench variations in subduction mechanics and slab detachment starting with Pliocene times.

The inherited deep crustal and mantle lithospheric structure has long been recognized to be a critical driver for the development of extensional rift systems in many sedimentary basins and passive margins worldwide, such as the Pannonian and Aegean Basins, the Piedmont-Liguria Ocean or the Atlantic margins (e.g., Ziegler and Cloetingh, 2004; Manatschal et al., 2015; Balázs et al., 2017a). The impact of the long-lasting extensional and orogenic processes at the Baltica margin in the formation of the Permo-Mesozoic Mid-Polish Trough and the Central European Basin System is analysed in the study of Mazur et al. (2021, this VSI). This is also a key area to understand the Cenozoic subduction process beneath the Carpathian orogen, while the inherited and contrasting lithospheric structures of the East European Craton and the area to the southwest played a decisive role as a backstop in the localisation and termination of subduction rollback process (Royden, 1993; Pharaoh et al., 2006). By combining an array of geophysical techniques that included deep reflection and refraction seismic profiles and gravity modelling, the study of Mazur et al. (2021, this VSI) analyses the Eadiacaran and early Permian rifting episodes. The results demonstrates that the Ediacaran rifting strongly influenced the localisation of the Palaeozoic and Permo-Mesozoic rifting in the inherited weak zone (necking zone at the southwestern margin of the East European Craton). This renewed rifting did not create well-recognisable large-offset crustal faults, the deformation being more distributed by uniform thinning in creating a crevice-type rift in the Mid-Polish Trough. The location of the pre-existing weakness zone associated with the change in lithosphere thickness may have localised the rifting and created a spatial shift in the emplacement of associated magmatism.

Previous studies have demonstrated that the evolution of cratonic areas and associated overlying sedimentary systems in platform-type of deposition is strongly conditioned by the inherited evolution and rheology that localises deformation in weak zones or at their transition to stronger areas (e.g., Cloetingh et al., 1995; Artemieva, 2003; François et al., 2013). The rheology and relationship with the tectonic inheritance in a heterogeneous cratonic area is studied in the contribution of Tesauro et al. (2020b, this VSI) by analysing the Australian continent, which shows generally younger ages eastwards in terms of the last significant thermo-tectonic deformation. Starting from a previous analysis of the temperature and compositional variations of the Australian upper mantle based on a joint interpretation of the seismic tomography and gravity data (Tesauro et al., 2020a), the study of Tesauro et al. (2020b, this VSI) achieves an integrated thermal crustal model, used further to derive the lithospheric strength characteristics and its variability across the entire continent. The results demonstrate that the highest strength values were obtained in the western Australian craton, as expected for this significantly older and colder lithospheric structure. Interesting is the observation that transitional zones between areas with significantly different strength localize the intra-plate seismicity. The lower strain values in cratonic areas influence the overall strength in an opposite fashion when compared with temperature effects. Furthermore, significant variations in crustal rheology in some sedimentary basins enhance the effect of temperature variations.

One of the best natural laboratories for investigating the processes that govern the long–term evolution of cratons and continental interiors is the less known Congo Basin overlying the Congo craton, amalgamated in the Late Paleozoic Gondwana orogenic system (e.g., Gray et al., 2008; Watts et al., 2018). The deep structure of this basin is analysed in a series of two studies. The first study of Delvaux et al. (2021, this VSI) reconstructed the stratigraphy and tectonic evolution in the central area of the Congo Basin by the means of interpretating a large array of seismic reflection profiles, correlated with refraction and well data. The study created a new seismo-stratigraphic and depositional framework, which incorporates a detailed geometry generally characterized by individual depocentres and separating highs that evolved throughout the history of the basin. The formation of this geometry was controlled by the inherited heterogeneity of the pre-Neoproterozoic basement and deep geodynamic processes during the evolution of Rodinia, Gondwana and Pangea amalgamation and breakup. Furthermore, depositional process in individual sub-basins were strongly controlled by climatic conditions and fluctuations during the drifting via the South Pole towards its present-day equatorial position. The second study of Maddaloni et al. (2021, this VSI) uses the previously obtained data and framework to analyse the aeromagnetic and gravity data in the central area of the Congo Basin by correlating two approaches, one data driven and another one with isostatic gravity modelling. The results match the geometrical transects illustrating a structure characterized by depocenters separated by structural highs and resolved a 7–18 km depth to basement structure in all sub-basin analysed. Interestingly, the analysis demonstrates the presence of high-density bodies at large depths in the southern part of the basin, interpreted to be inherited during the extensional evolution of the basin, conditioning its structure and evolution.

Understanding the structure and evolution of sedimentary basins is of crucial importance for a wide range of societal issues, long demonstrated for developing not only conventional geo-resources, but also for understanding the evolution of more sustainable geo-resources and storage, such as geothermal, carbon-capture or energy storage (e.g., Haszeldine, 2009; Cloetingh et al., 2010). In geothermal system, one important parameter to quantitatively forecast the technical and economic performance of reservoirs is temperature, where paleo-temperature corrections are a critical, but is less understood in how it influences distribution. An effective method for paleotemperature corrections in 3D thermal models in high-resolution datasets is developed in the study of Gies et al. (2021, this VSI) by using the natural case study of the Netherlands' subsurface, where a large 3D dataset of temperature in wells, structure and sedimentary distribution is publicly available. The analysis of this dataset demonstrates a thermal gradient of 20°/km for the shallow 400m, underlain by a 31°/km for the deeper 2–4 km structure. The study shows that understanding this significant difference can only be achieved by adding a paleo-surface temperature correction related to glaciation effects of the Weichselian glacial period, which is the missing link to understand the consistent overestimation of modelled temperatures in 74% locations for the top 2 km regularly distributed in the Netherlands' subsurface. These results demonstrate the importance of paleo-surface temperatures in predicting temperature models over large areas that are not significantly overprinted by other effects, such as groundwater flow. The updated models including paleotemperature corrections have major implications for assessing geothermal resource potential in shallow, few kilometres of deep reservoirs.

4. Advances in understanding one of the best-known sedimentary systems: the coupling between tectonics, sedimentation and lithospheric-scale processes in the Pannonian Basin: contributions to the special Global and Planetary Change issue

In backarc systems driven by slab retreat, the rheological inheritance of the stacked orogenic nappe structure is fundamental to the understanding of the subsequent activation of extensional shear zones and their migration through space and time (e.g., Brun and Faccenna, 2008; Balázs et al., 2017a; Porkoláb et al., 2020, this VSI). This inheritance and the impact on the Miocene evolution of the western Pannonian Basin (Fig. 3) is quantitatively analysed in the review of Fodor et al. (2021, this VSI) where new structural and thermochronological data, combined with seismic reflection profiles controlled by well information is also presented and the evolution is quantitatively tested by thermomechanical numerical modelling. The study demonstrates that the inherited Cretaceous nappe stack and suture zones played a critical role in conditioning the rifting geometry, formation of extensional detachments and their temporal evolution in the Pannonian Basin. The extension started at around 25–23 Ma and continued at higher rates between 19 and 15 Ma in the south-western part of the basin, where the mechanics of deformation was associated with footwall exhumation of the pre-existing Austroalpine nappes along large normal faults or extensional detachments exhuming deeply buried metamorphosed rocks. These structures generally reactivated major Cretaceous thrusts, exhuming a continental subduction channel in the (ultra) high pressure Pohorje Dome (Fig. 3). This dome experienced syn-kinematic magmatism, ductile stretching, westward tilting, and asymmetric exhumation along its eastern side, being associated with continental deposition in hanging-wall basins. The subsequent stage of extension took place with ~200 km shift to the E-NE at the western boundary of the Transdanubian Range, where new graben structures started with larger offsets around 15–14.5 Ma and continued at lower rates until ~8 Ma. Although there is still large observed local variability, conditioned by the reactivation of inherited weak zones, these results correlated with previous inferences in demonstrating a generalised migration of extension and associated depocentres in the direction of slab-roll back across the entire Pannonian Basin (see also Matenco and Radivojević, 2012; Balázs et al., 2017a).

4.1. High-resolution structural, sedimentological and paleo-environmental interpretation: from surface observations to forward modelling and reconstructions.

A detailed imaging of structural patterns in their near-surface expression is pre-requisite for understanding the upper crustal expression of recent and active tectonics and the relationship with inherited structures. This workflow is well illustrated in the study of Visnovitz et al. (2021, this VSI) performed in the area near the Lake Balaton, in the central part of the Pannonian Basin. The ultra-high resolution seismic dataset is combined with deep seismic profiles, borehole and surface structural data that is integrated with a morphotectonic and earthquake data analysis. The results show that the extension started in the late middle Miocene (~14–13 Ma), which is appreciably later (6–10 My) when compared with the southern Dinarides margin of the basin, but generally fits well with the overall migration of deformation across the entire Pannonian Basin. These extensional faults were transpressively reactivated by strike-slip faults associated with folding after 8 Ma during the basin inversion in a fault pattern that shows segmented geometries, stepovers and connecting splays. The distribution of seismicity demonstrates that these transpressive structures are still active at present.

The formation of coarse event beds in the rapid infill record of sedimentary basins is a process recognized worldwide to be driven by a combination of sedimentological and tectonic processes, such as out-sized coarse-grained events in prodeltas or distal marine lobe, slope collapse in rapid progradation settings, storm events or tsunamites in unstable sedimentary wedges (e.g., Kleverlaan, 1987; Young et al., 2000; Kane et al., 2017; Andrić et al., 2018a). While such event beds are a frequent occurrence in recent sedimentation where their genesis is clearer, their interpretation in the geological record is always challenging. An interesting situation of such an event bed composed of cobble to boulder gravels, interpreted as a tsunamite in the late Miocene sedimentation of the Pannonian Basin, is examined in the study of Sztanó et al. (2020, this VSI). None of the depositional features of this event bed are diagnostic for the genetic character, such as various degree of clast roundness, seaward dipping imbrication, bidirectional transport indicators, clast-supported fabric, large thickness of beds and lack of grading. However, the study offers a set of supplementary criteria composed of sedimentary facies, palaeobiological data and palaeogeographic reconstruction as a tool to discriminate the paleo-tsunamite origin. In terms of sedimentary facies, particularly diagnostic is the combination between matrix-supported fabric, a mixed clayey-sandy matrix in the clast-supported parts, preservation of articulated mollusc shells and the mixture of clasts and fossils from different proximal zones.

The process-based reconstruction of depositional environments and sedimentary cyclicity drivers often requires a discrimination between sedimentological autogenic processes and external, allogenic forcing factors of various types, from astronomical forcing to climate or tectonic processes, which is always challenging in turbidite systems (e.g., Posamentier and Allen, 1999; Postma et al., 2014; Matenco and Haq, 2020 and references therein). This challenge of differentiating the genetic drivers in turbidites is taken up by the study of Tőkés et al. (2021, this VSI) in a late Miocene turbidite-channel system from the southern Transylvanian Basin in the larger realm of the Pannonian depositional system. Five orders of hierarchy were identified where cycles of channel incision and turbidites infill reflect the variation in flow magnitudes of low to high-density turbidity currents and debris flows (Fig. 10). The study has defined a methodology of constructing incision-infill graphs that are calibrated by observations in the Transylvanian Basin and further tested by a comparison with the well-known known Permian deep-marine channel sequence from the Karoo Basin (South Africa). The study also infers a similar pattern of channel incision, lateral migration and aggradation across different hierarchical levels with a fractal behaviour, while cyclic flow changes in the magnitude of turbidity currents are inferred to be driven by sub-Milankovitch climate cycles that controlled sediment supply and the base level of Lake Pannon. A similar challenge in discriminating genetic drivers in turbidites is tackled in the study of Nyíri et al. (2021, this VSI) by considering the early post-rift sequence of a supra-detachment basin in the south-western part of the Pannonian Basin, which is characterized by the gradually decreasing extensional activity of a detachment fault cross-cut by transfer faults in its hanging wall. The study proposes a new model of turbidites and associated sand bodies distribution in basins bounded by low-angle normal faults or detachments (Fig. 11). When compared to basins controlled by high-angle normal faults, where turbidity currents are dominantly distributed along the axis of the basin defined by the normal faults, the gently dipping slope of the detachment or low-angle normal faults favours across strike transport and ponding of turbidites against the low-angle slopes of hanging-walls. The confined character of turbidity currents, associated with minor fault-related disturbances in gravity flows, results in the deposition of sandstone units with good reservoir characteristics across the entire direction of the turbiditic flow.

Studies of basin evolution that include tectonic and paleogeographic reconstructions rely on chronostratigraphic interpretations that are particularly challenging in endemic and/or endorheic basins such as the ones grouped in the Paratethys system or the Dinarides Lake System (e.g., Mandic et al., 2012; Palcu et al., 2021 and references therein). Based

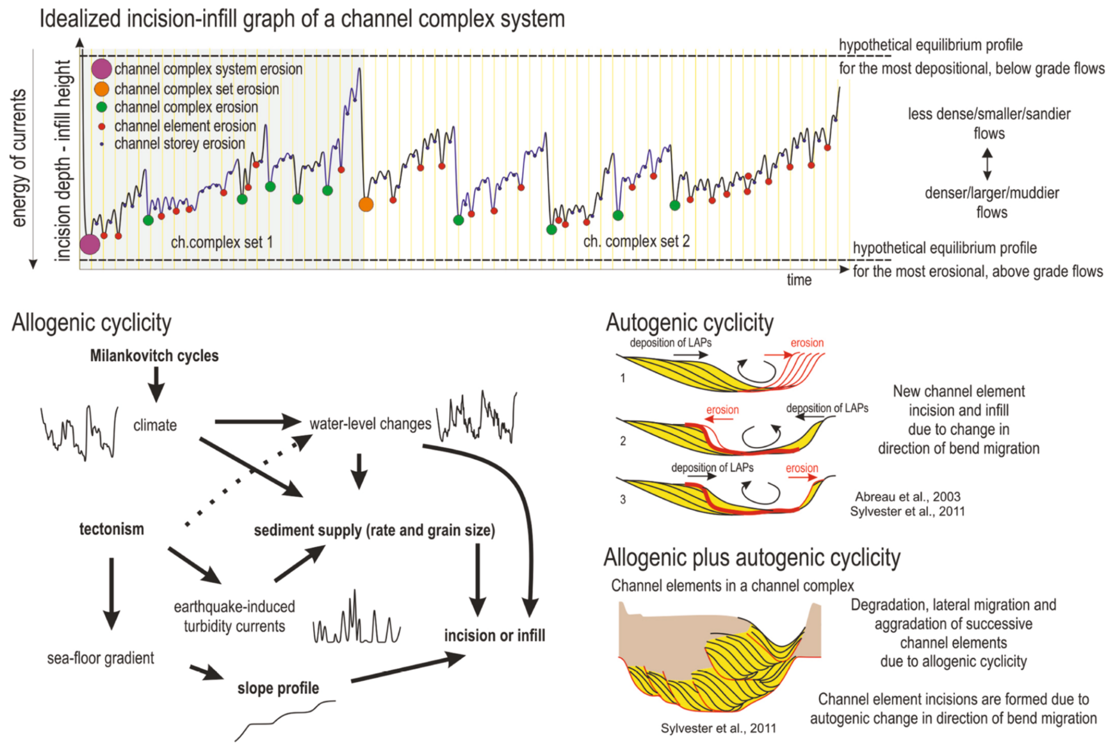

Fig. 10. Idealized incision-infill graph showing hierarchies from channel storeys to channel complex system and possible allogenic and autogenic controls on incision-infill cycles (Tőkés et al., 2021, this VSI). LAP = Lateral Accretion Package, ch. = channel.

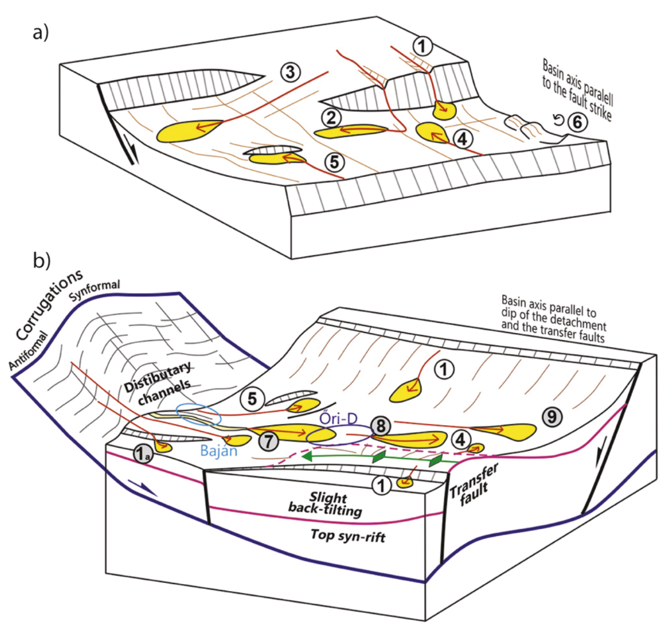

Fig. 11. Schematic illustration of sediment transport and sand fairways of different types of normal fault systems (after Nyíri et al., 2021, this VSI). a) high-angle normal fault systems, b) low-angle normal faults systems. 1 - footwall-derived sediment gravity, 2 - along-axis transport in high-energy currents, 3 - transport along relay ramps, 4 - hanging-wall transport, 5- deflection along smaller faults, 6 - slumping during hanging-wall rotation, 7 - gently linear slipping pathway along the detachment, 8 - lateral confinement along an internal anticline, 9- frontal confinement by back-tilting. Őri - D = Őri depocentre.

on previous works, the appraisal of Magyar (2021, this VSI) presents a compilation of the chronostratigraphic framework of the Late Miocene to Pliocene Lake Pannon that includes biochronology, magneto-stratigraphy, authigenic $^{10}Be/^{9}Be$ dating and the interpretation of a dense network of reflection seismic profiles and well data. The study highlights the importance of clinoform and clinothem geometries and the differences between lithostratigraphic and chronostratigraphic correlations. The results yield critical insights into the timing of the basin-filling processes in long-lived lakes or isolated marine basins, abundant in the Paratethyan region, including the Pannonian, Dacian, Black Sea and Caspian basins.

The coupling between the sedimentary basin architecture and evolution of neighbouring orogens requires a distinguishing tectonic from climatic forcing factors. Understanding the evolution of endemic and/or endhoreic systems, such as lacustrine environments in continental rift basins or orogenic areas, requires a specific approach where the multi-directional sourcing of sediments is not tied to the variability of a shoreline. The paper of Kovács et al. (2021a, this VSI) provides a quantitative evaluation of the evolution of endemic lacustrine sedimentary basins by the means of a 3D stratigraphic numerical forward modelling approach that considers the spatial and temporal variations of tectonic subsidence rates, climatically-induced lake-level variations and changes of water and sediment discharges during the post-rift evolution of the Pannonian Basin. This study is focused on modelling the main sedimentary transport routes and deposition patterns during the stages of post-rift subsidence and basin inversion. The new tectono-stratigraphic model together with the interpretation of seismic and well data from the southern part of the basin establishes a quantitative model for the observed shelf-edge trajectory and lake-level variations of Lake Pannon. These authors infer that the unconformities observed in the basin are the result of variable subsidence rates, lateral differences in sediment influx and autocyclic processes that are most effective at low sediment supply rates.

The advanced stage of research in the Pannonian Basin and its neighbouring orogens (e.g., Horváth et al., 2015; Schmid et al., 2020;

Magyar, 2021, this VSI) has resulted in the availability of high-resolution datasets describing the post-Paleogene sedimentary infill, exhumation of the source areas and quantitative analysis of the sediment transport system. This allows more detailed source to sink studies, such as the one of Arató et al. (2021, this VSI), which provides a quantitative inquiry of source regions and modern river sediments entering the Pannonian Basin from neighbouring orogenic areas, accomplished by a provenance study using low-temperature thermochronology (zircon and apatite fission-track), heavy mineral analysis and gravel petrography. The analysis enabled a quantitative differentiation between the Eastern Alps, Bohemian Massif, Western Carpathians, Eastern Carpathians and Southern Carpathians/Apuseni Mountains source regions. The results show that the zircon fission track methodology has a higher discrimination potential, while the recycled signature of the heavy mineral spectra can be differentiated in source areas by using the ultra-stable minerals and the areal extent of different sedimentary reservoirs. This approach has a high potential of systematic application at different depths and different chronostratigraphic units in the Pannonian Basin and extrapolated elsewhere, enabling a better characterization and reconstruction of temporal changes in source areas.

The advanced quantification of the Pannonian sedimentary infill and the hydrodynamic conditions associated with diachronous asymmetric extensional structures enable a novel analysis of the regional groundwater flow conditions with major implications on geothermal potential assessment. This novel analysis is presented in the study of Tóth et al. (2020, this VSI), which demonstrates that the asymmetry of structures is directly expressed in a similar asymmetry in the quantification of flow patterns and hydraulic head variations that significantly differ from earlier analytical approximations. This asymmetry has a critical role in discharge and accumulation patterns, thus controlling the location of sedimentary basin areas bearing the highest geothermal potential. These results will have a significant impact in the quantification of geothermal potential assessments of similar asymmetric sedimentary basins located elsewhere, which will need to consider local-scale anisotropy, conductive or less permeable fault geometries, the spatial variation of basal heat flux, which is linked to the asymmetric lithospheric and crustal thinning values, and the spatial variability of basement rocks and sediments with different thermal conductivities.

4.2. Syn-rift deformation, structural inheritance and basin formation

Previous studies have demonstrated a diachronous evolution of extensional structures and associated syn-kinematic sedimentation in the Pannonian Basin, associated with the formation of extensional detachments, low- and high-angle normal faults, transfer zones and transcurrent systems associated with a heterogeneous lithospheric and asthenospheric compositions (Hetényi et al., 2015; Balázs et al., 2018b; Fodor et al., 2021, this VSI and references therein). This overall structural system and the temporal evolution of deformation is reviewed and further detailed in the study of Šujan et al. (2021, this VSI) for the north-western part of the Pannonian Basin, in the Danube sub-basin and its subsidiary branches. The results demonstrate a four-stage evolutionary model where detailed stratigraphic, sedimentological, biostratigraphic and structural data suggest a migration in the location of a multi-stage subsidence from the basin margins to its centre driven by the overall asthenospheric uprise located beneath the Pannonian Basin. Extension ceased in the Danube Basin during the overall basin inversion after ~6.0 Ma, observed by the uplift of the basin margins and a transition of the fluvial system to central confinement.

Early deformation structures play an important role in understanding kinematic mechanisms in siliciclastic sediments. Previous work has recognized the importance of early structures, such as deformation bands, and by a non-destructive grain reorganization that continues with an increased proportion of grain fracturing or cataclasis (Aydin, 1978; Fossen et al., 2007; Beke et al., 2019). These studies have shown that such structures create strain hardening and widening of the deformation zone to metres-scale sizes, while deformation mechanism evolves as a function of burial diagenesis that change the rheology of clastic rocks. This mechanism is further investigated by the study of Beke et al. (2021, this VSI) in a detailed case study from the northern Pannonian Basin. They consider structural and diagenetic changes and their connection with fluid-flow, mainly by the combined oxygen and carbon isotopic records of structurally controlled calcite precipitation. The conductivity properties of distinct deformation structures and the related isotope data changed continuously during the basin evolution from early-stage single fault, then connected deformation bands, ending in the late-stage frictional faulting. As rift-related subsidence advances, the continuous infiltration of meteoric water, probably led by an increasing size of fluid cells, resulted in progressive cementation of development of small-scale brittle structures. These results further the understanding deformation bands by revealing a significant component of local fluid contribution in the formation of these structures, enhanced by the regional paleo- fluid flow system.

The role of inherited orogenic structures, such as nappe contacts and suture zones, in the creation and evolution of extensional basins and associated syn-kinematic deposition in the Pannonian Basin has been extensively discussed in previous studies (Tari et al., 1999; Balázs et al., 2017a; Plašienka, 2018; Schmid et al., 2020), although the reactivation of low-angle thrusts into normal faults at shallow crustal levels has remained a difficult to explain. This issue is explored in the study of Tari et al. (2021, this VSI) for the NW part of the Pannonian Basin and its connection with the Alps and Carpathians by the means of detailed crustal cross-sections analysis and their kinematic reconstructions. It demonstrates that Cretaceous nappe contacts were completely or partially reactivated by the Miocene extension in their depth prolongation when the direction of extension was favourably oriented, while in other cases these nappe contacts were crosscut by normal faults. The threshold for reactivation was around 20° difference in strike, as shown by the case of the Malé Karpaty horst. The study also emphasizes the difficulty to demonstrate an extensional reactivation of nappe contacts in subsurface studies, which can be resolved by structural studies that use additional well techniques, such as continuous coring or Formation Micro-Imaging (FMI).

4.3. The interplay between deep Earth and (near-)surface processes

Previous studies have inferred that extensional backarc systems, such as the Pannonian Basin, are inherently influenced by rheological variations and by the evolution of neighbouring orogens that change the deep crustal and mantle compositions by enrichment with subduction-related fluids and associated magmatism, while the strength and effective viscosity is linked to many other parameters, such as compositional layering, thermal properties, variations of strain rates, variable grain sizes or fluid-related mantle anisotropy (e.g, Downes and Vaselli, 1995; Burov and Yamato, 2008a; Burov et al., 2014). In this context, the analysis of magmatism combined with deep geophysical methods may provide critical constraints on the composition and rocks distribution in the deep crust and lithosphere (Kovács et al., 2021b, this VSI), as also demonstrated by two recent studies in the Pannonian Basin. In the first study of Liptai et al. (2021, this VSI) on the effect of water on the rheology of the lithospheric mantle beneath extensional basins considers water content of mantle xenoliths and its bearing to electrical resistivity in late Miocene to Pleistocene alkali basalts of the Pannonian Basin. It shows that marginal xenolith locations in the Carpathian-Pannonian region, associated with an inherited supra-subduction environment, are characterized by higher water content and thus have lower viscosity values than xenoliths from central locations having lower water content and thus higher viscosities. The exception to this is one central locality (Tihany), where the minimal decompression-induced water loss is explained by a greater depth associated with an older emplacement event. The higher water content of all marginal localities can be explained by the higher fluid-content being brought at mantle depths by the subduction in the neighbouring orogens, which indicate an inverse relationship between the water content and the distance from the subduction zone. The results highlight the relationship between high water content and low electrical resistivity, enabling a correlation between geochemical studies of mantle xenoliths and deep geophysical methods. This correlation is examined in the study of Patkó et al. (2021, this VSI) where the effect of metasomatism on the electrical resistivity of lithospheric mantle is derived by a joint xenoliths and magnetotelluric sounding for the Nógrád-Gömör Volcanic Field in the northern part of the Pannonian Basin. The results demonstrate a low resistivity anomaly at the same subcrustal depth where the metasomatized xenoliths were initially located, while small pockets of melted material may still be preserved at depth in this recent, 1.3–0.3 Ma old alkaline basaltic volcanic field. Furthermore, the intense melt upwelling in the central part

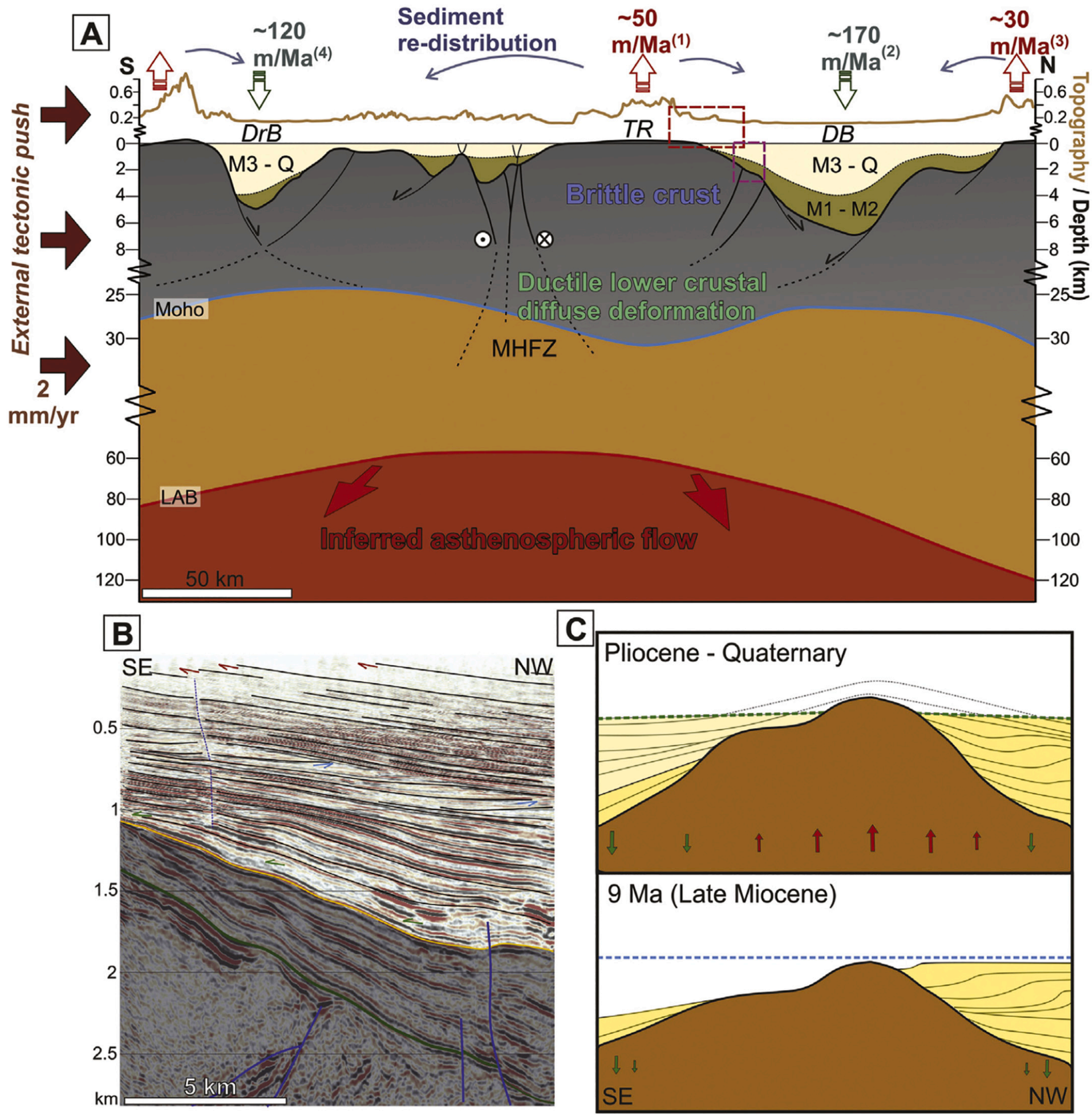

Fig. 12. Illustration of the mechanisms driving differential vertical motions in the Transdanubian Range segment of the Pannonian Basin (Ruszkiczay-Rüdiger et al., 2020, this VSI). (A) Simplified cross-section over the western Pannonian Basin with the main tectonic and surface processes that control the post- middle Miocene basin inversion. The mechanisms suggested are the northward push of the Adriatic continental micro-plate and associated gravitational stresses, inherited asthenospheric flow from the extension times and lower crustal flow. M1-M2: lower- to middle Miocene; M3-Q: late Miocene to Quaternary. DrB – Dráva Basin, TR – Transdanubian Range, DB – Danube Basin; (B) Seismic reflection profile showing dipping late Miocene strata towards the Danube Basin, and their truncation towards the Transdanubian Range (C) Evolutionary sketch of the Transdanubian Range evolution in post- middle Miocene times. Further explanations are available in Ruszkiczay-Rüdiger et al. (2020, this VSI).

of the field can be explained by deep deformation zones providing magma ascent pathways.

Given existing large uncertainties, the timing and rates of vertical movements in the Pannonian Basin during the post-middle Miocene Adriatic indentation and basin inversion still require further evaluation. The rate of vertical motions in the key area of the Transdanubian Range is studied by Ruszkiczay-Rüdiger et al. (2020, this VSI) by the means of incision rate calculations based on a structural study combined with dating of uplifted landforms such as river terraces. The study demonstrates a significant variability of uplift rates, larger in the axial and smaller in the marginal parts of the uplifting domain, ranging between 17 and 51 m/Ma. The analysis of associated brittle structures observed

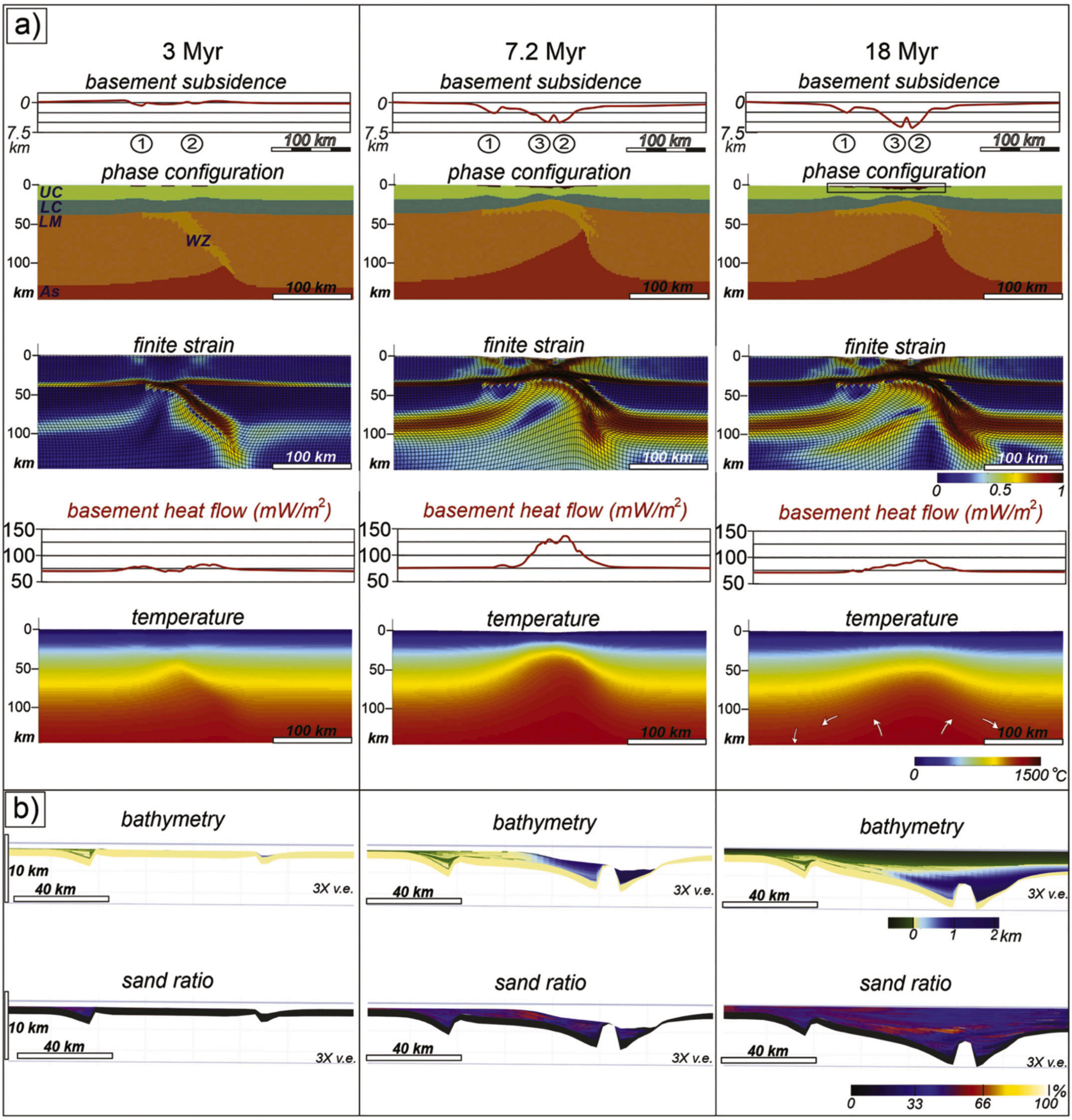

Fig. 13. Illustration of the stratigraphic-thermo-mechanical modelling approach coupling (a) thermo-mechanical and (b) stratigraphic modelling, applied to the evolution of the Pannonian Basin (Balázs et al., 2021, this VSI). The figure displays modelling results used as a reference for a further parametric study. This reference model simulates wet climatic condition (high erosion and sediment fluxes) and displays the evolution during 3 Myr of syn-rift, 7.2 Myr transition to post-rift and further 10.8 Myr post-rift. Numbers above the phase configuration results show the individual sub-basins. Depocenters are filled by sediments (red colour). UC – Upper crust, LC – Lower crust, LM – Lithospheric mantle, As – Asthenosphere, WZ – mantle weak zone. The basement subsidence pattern extracted from the thermo-mechanical experiment is used as input in the stratigraphic model.

in maps and along regional seismic profiles crossing the zones of differential vertical motions has shown only small-offset normal faults associated with folding that post-date the ~8.7 Ma deltaic sedimentation. The study concludes that the differential uplift of the Transdanubian Range during basin inversion is not controlled by upper crustal structures, but rather by a complex interplay of lithosphere-asthenosphere dynamics enhanced by surface processes (Fig. 12). The 100km wavelength, the gentle tilting angles and the low rates of uplift may justify mechanisms such as lower crustal and mantle flow towards uplifting areas.

The links and feedback mechanisms between tectonics, mantle dynamics and surface processes, in terms of erosion and sedimentation coupled to climatic variations, condition the evolution of orogens and associated sedimentary basins (Ueda et al., 2015; Ballato et al., 2019, among others). Understanding the interplay between these processes requires a process-oriented approach that handles the multi-scale coupling between high-resolution erosion and sediment redistribution, as well as deep crustal and mantle deformation. Also needed is better understanding of key processes, such as realistic rheological distributions, variable heat transport processes, or detailed sedimentation mechanics, including fluvial transport processes (Burov and Yamato, 2008b; Theissen and Rüpke, 2010; Balázs et al., 2017b). Along this line of reasoning, a novel modelling approach is presented by Balázs et al. (2021, this VSI) that aims to define a new stratigraphic-thermo-mechanical numerical modelling procedure applied to asymmetric extensional basins (Fig. 13). This approach combines thermo-mechanical and stratigraphic modelling methodologies and proposes a physics-based model for the migration of extensional deformation, syn- and post-rift surface differential vertical motions, and thermal evolution. The results are constrained by seismic, well and temperature data and infer a significant role of inherited lithospheric structures in the migration of deformation towards the centre of the Pannonian Basin. Erosion and sedimentation facilitate the localization of crustal thinning in deep half-graben geometries and contribute to lower crustal ductile shearing due to enhanced sediment loading. The coupled effects of effective lateral heat transport, sediment re-distribution and resulting basin flexure contribute to the post-extensional uplift of the basin margins and subsidence of its depocenters. The stratigraphic modelling results highlights the importance of tectonics-driven high subsidence rates that often supresses climatic signals.

5. Conclusions

This review demonstrates that an integrated understanding of processes and mechanisms driving the coupled evolution of orogens and sedimentary basins requires a multi-scale temporal and spatial analysis that crosses the traditional boundaries of disciplines, methodologies and singular approaches.

Analysing the sedimentary basin infill must account for the characteristics and variations of the exhumation, evolving topography and climate in the source area, the complexity of a transport system that is often characterized by massive unidirectional influxes during moments of activity at tipping points or gateways, spans across multiple depocenters and sedimentary basins, and is conditioned by an evolving structural geometry that often migrates with time in direct relationship with the evolving lithospheric structure in orogens and their inherited rheology. Depocenters can be fed from multiple source areas across different directions with sediments mixing on the basin floor, while having often an endemic or endorheic character controlled by the climate via the balance between precipitation and evapo-transpiration, rather than sea-level variations and connectivity with the marine realm. The thermal structure and its variability in continental and oceanic domains conditions the rheology and subsequent structural evolution of orogens, subduction zones and sedimentary basins. These factors have a direct impact on societally-relevant issues, such as natural hazards, i.e., in the distribution of active deformation zones and natural or induced seismicity, or in understanding the reservoirs in geothermal exploration. Awareness of the heterogeneity of lithospheric structure and rheology of cratons is important for understanding the processes that drive the subsequent formation of sedimentary basins and orogens during collision. Quantifying deposition in sink areas requires analysing the sediment transport network that often spans across multiple orogenic and sedimentary basins systems. Quantifying the allogenic or autogenic nature of sedimentological processes, such as event beds or turbidites, can be enhanced by knowing the inherited and evolving structural and tectonic parameters conditioning sediment fluxes and transport systems. Ultimately, understanding the impact of climatic, faunal or sea-level events can be achieved only by understanding the evolution of entire orogen-sedimentary basin system, where their impact is partitioned.

Quantifying sedimentary basins is also important for understanding the orogenic structure and the evolution of subduction systems, such as slab-related processes in terms of detachment or forearc-backarc interacting zones. It is also crucial for the orogenic mechanics, such as mechanisms of contractional-related exhumation, cycles of burial-exhumation and associated metamorphism, formation of highly arcuate orogens and the mechanisms and timing of nappe stacking events. Magmatism provides one of the very few sources of direct deep Earth observations and is particularly important for understanding the evolution of the deep mantle lithosphere in orogens and sedimentary basins and associated petrological phase changes when combined with geophysical methodologies.

Causal processes in orogen-sedimentary basins systems require testing process-oriented hypotheses by focused studies in natural laboratories where the various individual components of the systems are already well known, such as the Pannonian - Carpathians - Alps - Dinarides system, generating an understanding that may be applied elsewhere. Such an integrated understanding depends on our ability to cross observational areas and methodologies, from observational, analytical, experimental to process-oriented analogue and numerical modelling.

Declaration of Competing Interest

The authors declare no competing interests.

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