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Understanding the coupled evolution of orogens, sedimentary basins and their fluid-rock interactions

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ABSTRACT

Studying orogens-basins interaction requires a multi-scale approach that combines multi-methodological field studies with basin-wide observations and integration with the dynamics of the lithosphere, the evolution of sedimentary sequences, kinematics of neighbouring mountain chains and fluid-rock interaction processes. This special issue developed out of the Sedimentary Basins Workshop (Task Force VI) of the International Lithosphere Program that took place at IFP Energies Nouvelles, France, in November 2021. It comprises 14 contributions that focus on the interactions between deep and shallow tectonic and sedimentary dynamics with fluid-flow and fluid rock interaction processes. Findings are based on field observations and associated laboratory methodologies, together with numerical modelling, that allow analysis across varied temporal and spatial scales for some of the world's best available analogues. These analogues include the orogenic systems of the Pannonian - Carpathians - Alps - Dinarides, the Pyrenees, the Mediterranean region, the Precaspian Basin and the Tibetan Plateau amongst other areas. The associated multi-scale processes that are addressed are of major societal importance, in terms of geohazards (e.g., earthquakes), geo-resources (e.g., geothermal energy, groundwater) and environmental / climatic changes (e.g., dynamic topography). Investigation of these processes in such natural laboratories and through the various applied multi-disciplinary approaches improves our understanding of the dynamic evolution of sedimentary basins and guides the future sustainable exploitation of geo-resources in the context of climate change mitigation. Throughout this special issue, fluids and their interaction with host-rocks are highlighted because most of the future usages of the subsurface will involve injecting fluids and gases underground (e.g., geothermal energy, hydrogen, or CO_2 storage), and the dynamics and impacts of these applications still need to be properly understood.

1. Introduction

Studying the interacting processes in orogens and sedimentary basins requires a multi-scale approach that combines various methodological field studies with basin-wide observations and integration with the evolution of the underlying lithosphere derived by geophysics (Fig. 1; Matenco et al., 2022). Such studies also require an integration between the evolution of sedimentary sequences, coeval kinematics of neighbouring mountain chains and their associated multi-scale fluid-rock interaction processes (Bernard et al., 2019). Current studies suggest the existence of large-scale zones of interaction between individual orogens and genetically associated sedimentary basins, where coeval forcing factors in erosion, transport and deposition control both the formation and exhumation of mountain chains and the architecture of deposition in sedimentary basins (Matenco and Haq, 2020; van Unen et al., 2019).

Understanding such complex interactions worldwide means bringing together multi-disciplinary field-oriented studies to basin-orogen scale observations and process-oriented modelling (Cloetingh et al., 2015; Vilasi et al., 2009). It also requires understanding of complex sediment transport systems and associated fluid content, fluid flow and fluid-rock interactions that span over multiple orogens and sedimentary basins (Fig. 2; Nader, 2016; Roure et al., 2005). Besides, the investigation of these interactions between orogen-scale and sedimentary basin-scale processes requires study areas where individual components are well known to derive the mechanics of their interaction. Thereafter, the coupled processes deriving lithospheric and multi-scale tectonics with sedimentary basins architecture and fluid-rock interactions can be better understood. All processes described in this Special Issue have global

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relevance, while case studies are variable from several European, African, and Asian regions, from the great Mediterranean area (including Carpathians) to North Africa, the Precaspian Basin, and Tibetan Plateau systems (Fig. 3). These areas offer excellent natural laboratories to study processes across multiple sedimentary basins and orogenic systems situated in the spatial proximity required for interaction (Table 1). They allow the extrapolation of processes to understand many other similar systems worldwide.

2. Coupled processes of orogens, basins and fluid rock interactions

The major processes operating in orogens, sedimentary basins and associated fluid-rock interactions are presented in three inter-related groups: deep and near surface processes, multi-scale tectonics and sedimentary basins processes, and fluid-flow and fluid-rock interaction processes as summarised below:

2.1. Deep and near surface processes

Coupling deep and near-surface processes is a one of the key directions of research in solid Earth sciences, where studies vary from long-term (deep-time) dynamic topography (mantle-driven) to lithospheric-scale processes impacting the recent and local scale geomorphological evolution of topography (Ruszkiczay-Rüdiger et al., 2020). For instance, volcanic geoforms found in the central Pannonian Basin of Europe, which are geomorphological surfaces typically observed in eroded basaltic volcanoes worldwide, have been used to constrain lithospheric uplift (Fodor et al., 2005). Other examples include the seismic attenuation (i.e., attenuation of waves produced by earthquakes in the deep Earth) that has been applied globally to constrain crustal rheology (the generic response of rocks to deformation) in process-oriented numerical modelling (Natale Castillo et al., 2022). Continental indentation (collision of continental fragments) is a process globally observed to be often associated with a transition to slab-retreat (subduction that migrates in a foreland direction) that has significant impact on sedimentary and geomorphological processes, which are usually observed at different temporal scales (deep-time to recent). The response of sedimentary basins and river drainage pattern evolution in such tectonic settings has been analysed for instance in the Dinarides – Hellenides transition, where process-oriented inferences are extracted (Gemignani et al., 2022). The lithospheric thermal distribution is driven by the inherited tectonic history and its understanding is gradually becoming more important due to its impact into the quantification and distribution of the near-surface potential for geothermal resources as well as the usage of the subsurface within the framework of energy transition and climate change.

2.2. Multi-scale tectonics and sedimentary basins processes

The far-field transmission of deformation from orogens to sedimentary basins and its impact on the evolution of topography and natural hazards such as seismicity is a well-known geological process well documented in places such as such as the Alps, the Carpathians or the Himalayas (Matenco et al., 2022b). These processes are less understood for deeper time settings, and they are also less understood in slab-retreat, back-arc extension and indentation settings, where orogenic exhumation and basin evolution are quantified, such as for instance in the external Dinarides; (Stojadinovic et al., 2012). The evolution of topography and the relationship with the post-collisional sediment sourcing and sedimentary basin erosion due to depositional shifts (changing the sedimentation from one basin to an adjacent one) are analysed by using optimal case studies such as the Ebro Basin (Spain) and its connection with the Western Mediterranean evolution (Pellen et al., 2019). The link between the far-field continental collision transmission of deformation and the present-day earthquakes, seismogenic potential and observed geodetic deformation is derived by using a new process-oriented analysis of the otherwise well-known and optimal case of the northern Iran region (Rashidi and Derakhshani, 2022). Complex continental collision tectonic settings are observed worldwide to be associated with back-arc collapse (formation of sedimentary basins in the back of the orogen by local extension) and transformant (i.e. strike-slip) subduction margins, such as in the Mediterranean or SE Asia. One process less understood is the relationship between collision, the formation of foreland fold and thrust belts and subsequent subduction transformant margins including STEPs (subduction-transform-edge-propagator (Govers and Wortel, 2005), where a migration of slab detachment takes place along the strike of an orogen. This process is best studied along the north African margin in the Mediterranean (Roure et al., 2012), providing generic overview, while focussing on the Tunisian Tell and the High Atlas (Morocco).

2.3. Fluid-flow and fluid-rock interaction processes

The subsurface of the Earth is where reactive fluids enriched with numerous dissolved components or gasses circulate at various scales (from crustal to sedimentary basins and aquifer/reservoir scales; Fig. 2). These fluids flow in an open system, changing their own composition as well as the surrounding host rocks by active interactions through mineral dissolution, precipitation, or mineral replacement processes at

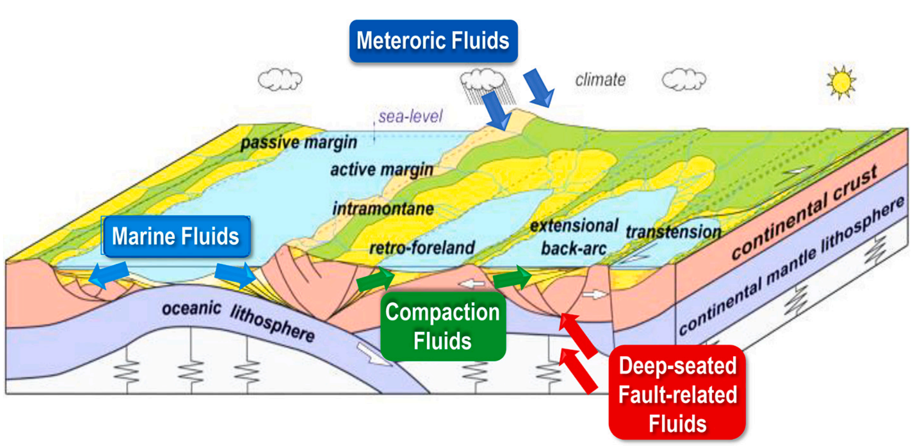

Fig. 1. Schematic illustrations of the coupled multi-scale evolution of orogens, sedimentary basins as well as their underlying lithosphere and fluid-flow, fluid-rock interactions (after Matenco et al., 2022). Four different types of fluids are indicated involving specific fluid-rock interaction processes as follows: Marine Fluids, Meteoric Fluids, Compactional Fluids, and Deep-seated Fault-related Fluids.

geological timescale (rock diagenesis) and their equivalent at societal-relevant timescale in the exploitation of sustainable subsurface geo-resources (e.g., geothermal) and subsurface storage (CCS, energy). Given the multi-scale and open nature of the exchange systems, fluid circulation and fluid-rock interaction have been challenging to quantify and are ones of the least known processes in solid Earth research, particularly in crossing the scales of observation. One way to tackle this problem would be to apply a crustal to reservoirs approach, combining observational, analytical and experimental methodologies, with geophysical and numerical modelling. Recent contributions with a crustal-scale approach have provided new methodologies in linking the fluid content with scattering and absorption features derived by geophysical attenuation tomography and linking the enigmatic world-wide observed lower crustal seismicity (i.e. earthquakes) with crustal fluids and thermo-mechanical structure (Borleanu et al., 2019; Lavecchia et al., 2022). At a shallower scale, coupling between deformation, thermal evolution and diagenetic effects in sedimentary basins and collisional orogen (i.e. a mountain chain) by using the relevant examples of the Mediterranean basins (e.g., the Dinarides and Albanides) has brought further understanding to the distribution of geo-resources in such complex geologic terrains (Hawie et al., 2015; van Unen et al., 2019; Vilasi et al., 2009). Diagenetic processes in carbonates with particular focus on dolomitization (process of calcite mineral replacement by dolomite) are still subject to a broad range of analyses and evolving methodologies, in a series of contributions in relevant case studies and a new process-oriented methodology of quantification of the mass transfer between calcite and dolomite (Gasparrini et al., 2023).

3. Summary of special issue contents

In the remainder of this paper, we summarise the findings of the 14 contributions to our special issue entitled *Understanding the coupled evolution of orogens, sedimentary basins and their fluid-rock interactions*, and discuss those new papers in a wider context (Fig. 3, Table 1).

3.1. Papers addressing coupled deep and near-surface processes

One of the major international initiatives to investigate the effects of deep and near surface processes, specifically in terms of dynamic topography, is TOPO-EUROPE (Cloetingh and Willett, 2013). The societal impact of topography evolution is fundamental due to its association with various geohazards, environmental and climate change impacts. In order to understand the Earth System, the processes behind residual effects of the ice ages on crustal movement, tectonic uplift/subsidence, development of river systems, natural climate and environmental changes, as well as man-made anthropogenic impacts need to be understood. Cloetingh et al. (2023, this VSI) discusses the perspectives on climate and energy societal challenges and provides an update of the TOPO-EUROPE initiative in studying societal relevant processes.

Sedimentary basins in collisional settings form as a result of shortening, lithospheric folding, back-arc extension, or mantle convection. Imaging their interior structure can improve safe exploration and production of geo-resources involving fluid injection in seismogenic areas. Seismic attenuation is a new methodology to study such processes, as it is highly sensitive to fluid saturation and fluid-rock interaction and may constrain small changes in the subsurface. Borleanu et al. (2023, this VSI) employ a frequency-dependent attenuation tomography method to study seismic properties, applied to the Carpathian Orogen and the surrounding basins, with a focus on decoupling effects from scattering and absorption. This objective is achieved by determining S-wave peak delay times and late-time coda quality factors based on first-order Tikhonov inversion and analytical sensitivity kernels. Based on their analysis of 366 small to moderate crustal local earthquakes ($0.7 < ML < 5.8$), recorded by the permanent and temporary stations operated by the Romanian Seismic Network between 2008 and 2021, the relative importance between scattering and absorption was found to be frequency-dependent and highly locally heterogenous. This further indicates the presence of isolated fluid-rock domains that scatter but also decrease wave amplitude (Fig. 4). Seismic attenuation is also commonly used to understand the properties of upper mantle and lithosphere rocks and link these properties with the geodynamic and thermal evolutions. Rheological properties of crustal rocks depend on various parameters, such as grain size, composition, or hydrous conditions. These parameters determine the deformation mode in response to the tectonic stress. The brittle-ductile transition (BDT) marks the maximum depth of the intraplate earthquakes and the one of fluids circulation in porous media in the crust. The same fundamental mechanisms that define the rock rheology impact the attenuation of seismic wave propagation. Therefore, seismic attenuation can be used to understand the brittle-ductile transition depth. Natale Castillo et al. (2022, this VSI) applied a numerical modelling procedure to test the possibility of using the seismic attenuation to characterize the viscous rocks deformation and the brittle-ductile transition depth. Seismic arrivals can be inverted for both the seismic velocity and the attenuation (quality factor, Q). Based on this inversion the functional form of the attenuation can be related to the rheology of the crust and hence the depth of the brittle-ductile transition. This provides a potentially novel method to map crustal structures and to constrain crustal mechanical properties. The effects of crustal fluids and thermo-mechanical structures on the observed seismicity in several regions around the globe, which are characterized by a seismically active lower crust and stress release by ductile flow are still not well known. An optimal place to study this process is the Gargano

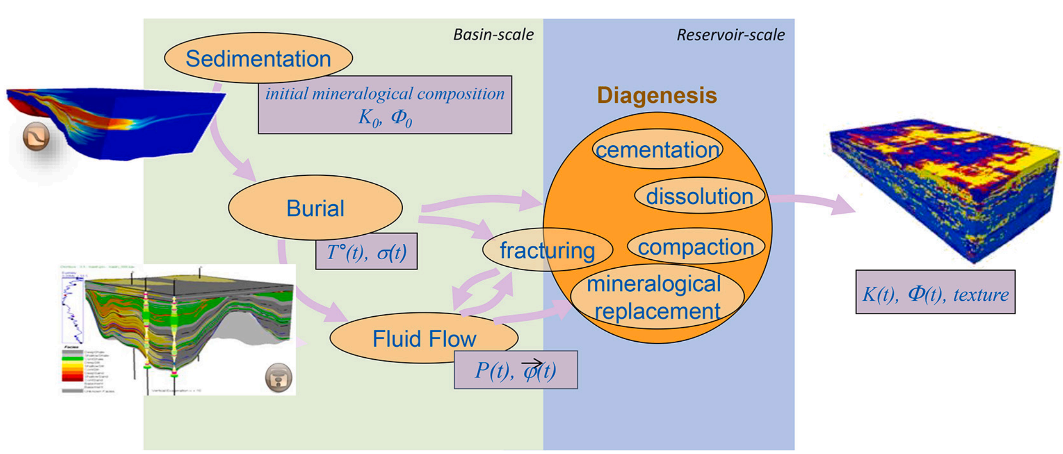

Fig. 2. Schematic diagram illustrating how sedimentary basins and reservoirs/aquifers need to be considered as integrated systems (rocks and fluids). Multi-scale, inter-related sedimentary, tectonic, and diagenetic factors result in the complexity and heterogeneity of the subsurface environment (after Nader, 2016).

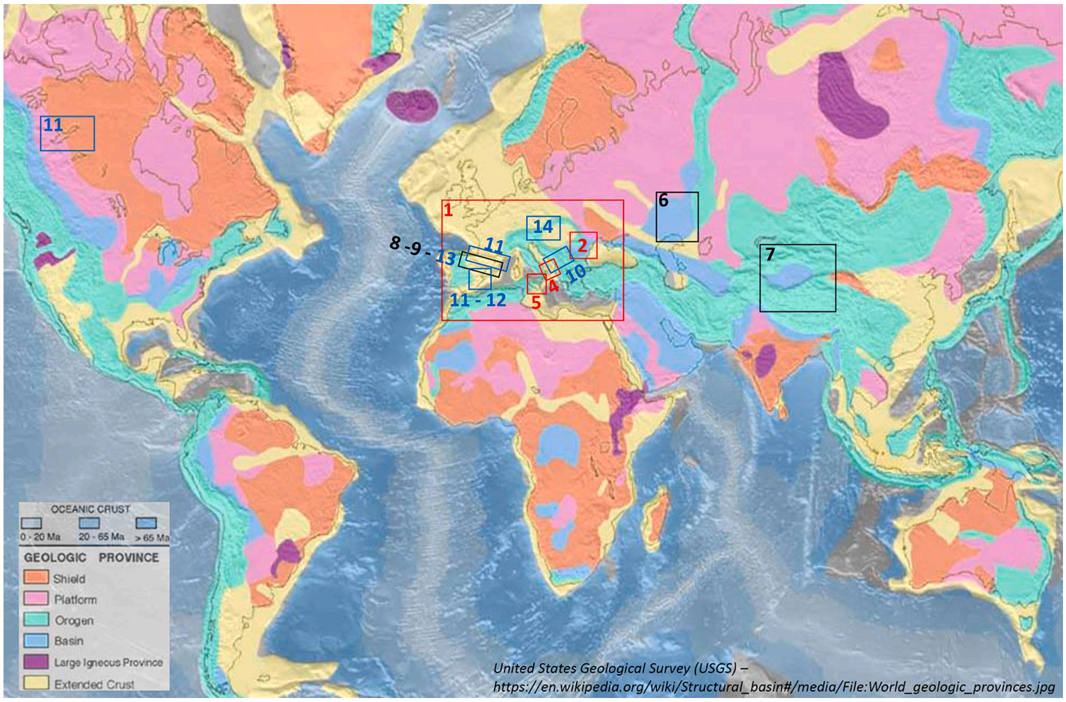

Fig. 3. Map of the world geologic provinces (USGS) showing the study sites/areas covered by this special Issue, organized by specific themes: Coupled deep and near-surface processes (red); Coupled multi-scale tectonics and sedimentary basins processes (black); and Coupled sediments, fluid and fluid-rock interactions (blue). Numbers refer to the following articles in the special Issue: 1) Cloetingh et al. (2023); 2) Borleanu et al. (2023); 3) Natale Castillo et al. (2022); 4) Lavecchia et al. (2022); 5) Floridia et al. (2022); 6) Novčić and Toljić (2023); 7) Wang et al. (2023); 8) Rat et al. (2022); 9) Cofrade et al. (2023); 10) (Nader et al., 2023); 11) Centrella et al. (2023); 12) Marin et al. (2023); 13) Ramirez-Perez et al. (2023); 14) Ben Mahrez et al. (2023). See Table 1 for further details. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Summary of study area, themes, applications and methodologies in this special issue entitled *Understanding the coupled evolution of orogens, sedimentary basins and their fluid-rock interactions*.

No.	Study area	Theme	Applications	Methodologies	References
1	Europe		Geohazards	TOPO-EUROPE, dynamic topography	Cloetingh et al. (2023)
2	Carpathian orogen (Romania)		Earthquakes	Seismic attenuation, tomography	Borleanu et al. (2023)
3	N.A.	Coupled deep and near-surface processes	Earthquakes	Seismic attenuation, modelling	Natale Castillo et al. (2022)
4	Gargano (Italy)		Earthquakes	thermo-rheological modelling	Lavecchia et al. (2022)
5	Sicily (Italy)		Geothermal Energy	3D lithospheric,thermal modelling	Floridia et al. (2022)
6	Precaspian Basin (Kazakhstan)		Geo-resources, conceptual models	3D seismic interpretation, kinematic analyses	Novčić and Toljić (2023)
7	Tibetan plateau (China)	Coupled multi-scale tectonics and sedimentary basins processes	Provenance, tectonics	Detrital Zircon U—Pb Dating, Geochemistry	Wang et al. (2023)
8	Pyrenees, Basque-Cantabrian Basin (Spain)		Concepts of basin incision, infill, and exhumation	U-Th-Sm/He dating on apatite in sandstones, thermal modelling	Rat et al. (2022)
9	Les Avellanes diapir, Pyrenean FTB (Spain)		Salt *syn*-kinematic evolution	Fieldwork based structural, stratigraphic, and petrographic data	Cofrade et al. (2023)
10	Dinarides (Montenegro)		Geo-resources	Field structural analysis and integrated kinematic/thermal model	Nader et al. (2023)
11	Pyrenees (France), Pine Point (Canada), Maestrat (Spain)		Diagenesis, paleo-fluid chemistry	EPMA and LA-ICP-MS analyses, mass balance, partition coefficients	Centrella et al. (2023)
12	Montmell-Vallès Fault, Catalan Coastal Ranges	Multi-scale characterization of coupling between sediments, fluid and fluid-rock interactions	Structural inheritance	Synthesis, structural styles, fluid-rock interactions	Marin et al. (2023)
13	Oliana anticline, Pyrenees		Geothermal energy, CCS	Stratigraphy, fracturing, petrological, petrophysical and thermal analyses	Ramirez-Perez et al. (2023)
14	Eastern Pannonian Basin (Hungary)		Groundwater	Seismic data and well-log interpretations, cluster analysis	Ben Mahrez et al. (2023)

Promontory (GP, southern Italy), close to the Gargano-Dubrovnik lineament, a seismogenic zone separating the central and southern Adriatic basins where a recently installed seismic network has recorded an intense seismic activity in the lower crust at depths between 20 and 30 km. Lavecchia et al. (2022, this VSI) analysed the possible mechanisms that control the distribution of seismicity in order to identify the factors

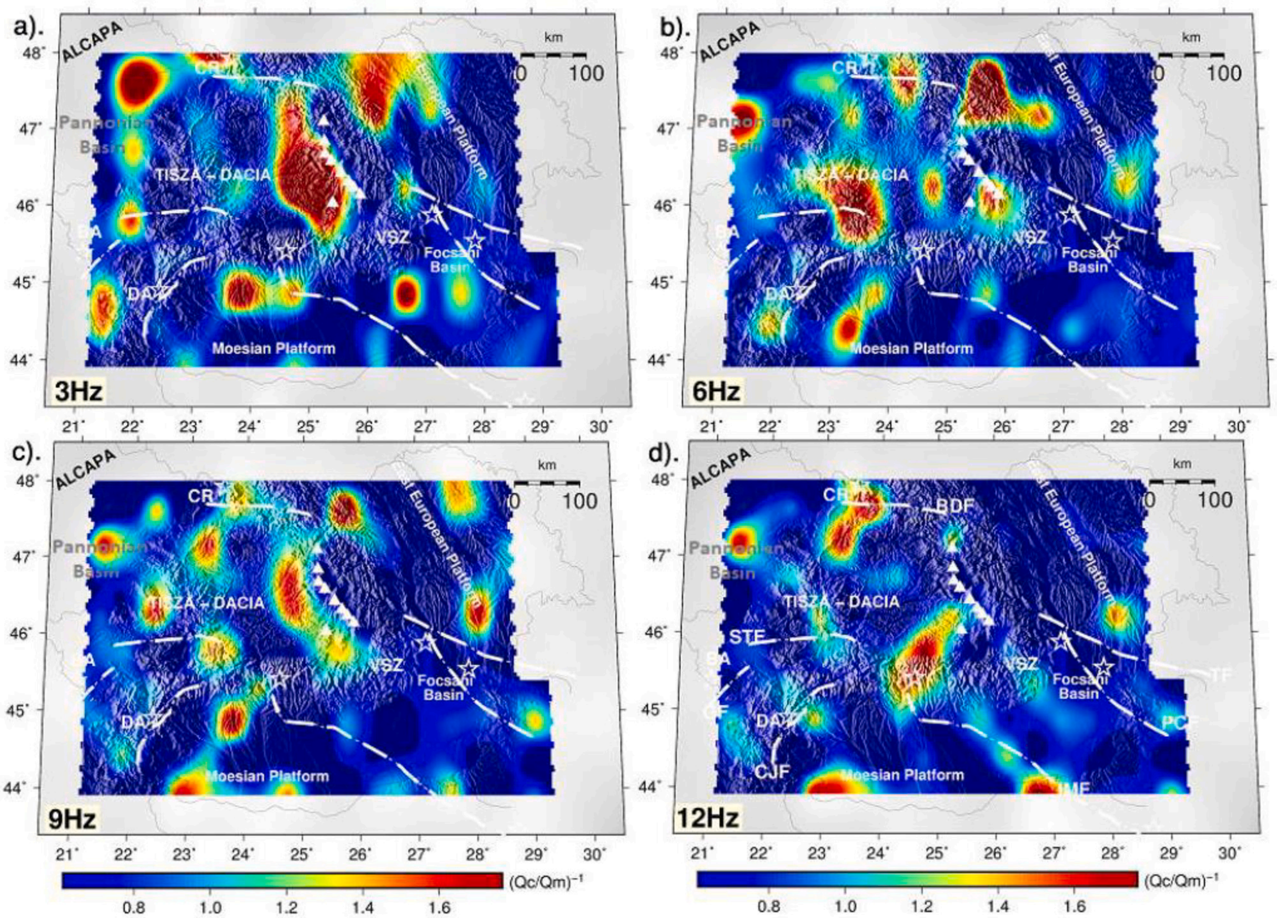

Fig. 4. Results of frequency-dependent attenuation tomography (a method to study seismic properties) applied on the Carpathian Orogen and the surrounding basins, with a focus on decoupling effects from scattering and absorption (from Borleanu et al., 2023, this VSI). The figure shows (Qc/Qm)-1 (absorption) maps for frequency ranges of 3 Hz (a), 6 Hz (b), 9 Hz (c), and 12 Hz (d). Red and blue colors are areas of high absorption and low-absorption, respectively. White triangles indicate the volcanic structures. The abbreviations are as follows: BA-Banat region, BDF-Bogdan and Dragoș Vodă Faults, CJF-Cerna-Jiu Fault, CPO: Capidava–Ovidiu Fault, CR-Crișana-Maramureș region, DA-Danubian region, GF-Gataia Fault, IMF: Intramoesian Fault, PCF-Peceneaga Camena Fault, SFG: Sfântul Gheorghe Fault, STF-South Transilvania Fault, TF-Trotuș Fault, VSZ-Vrancea seismic region. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

that make the lower crust seismically active by building a thermo-rheological model of a layered continental crust, calibrated on geometrical, lithological and thermal constraints (Fig. 5). The numerical simulations demonstrate that the presence of water in the upper crystalline basement and sedimentary cover provides a plausible explanation for the distribution of the seismicity which is probably affected by the composition of the crystalline basement.

The quantification of the near-surface geothermal potential relies on the assessment of the thermal and mechanical configuration of the deeper lithosphere. Such investigation requires the proper understanding of the geological and tectonic forcing on the regional thermal, stress and hydraulic regimes and their feedback mechanisms. This approach is more relevant in complex and active tectonic settings, such as in the case of the interplay between collision, along strike changes in the subduction zone and the formation of back-arc extensional basins, which is observed in many geodynamic settings worldwide. Sicily in the Central-Western Mediterranean provides an optimal case study due to its unexplored geothermal potential hosted within a complex geodynamic framework driven by the Africa-Eurasia collision. Floridia et al. (2022, this VSI) have reconstructed the present-day lithospheric state of Sicily to quantify its shallow and intermediate depth thermal regime. The resulting geological model was used to derive the present-day conductive thermal field as a whole and for individual tectonic or geological units, as well as considering different boundary conditions. The thermal

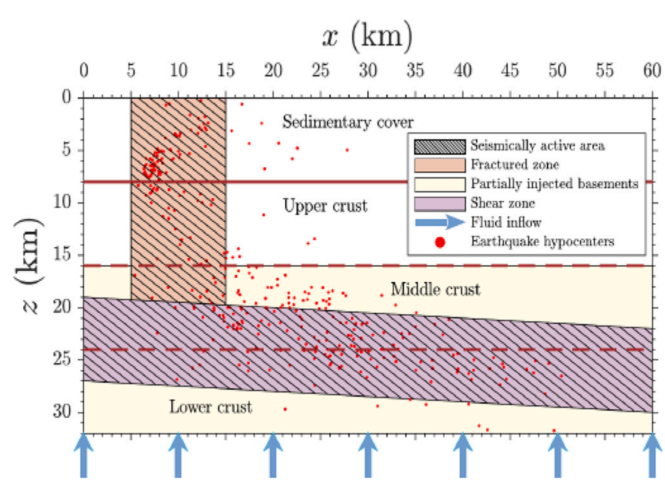

Fig. 5. A schematic section of the Gargano Promontory (GP, southern Italy), inferred from a thermo-rheological model of a layered continental crust, taking into account a multiphase crustal lithology, the presence of fluids in the crystalline basement, lateral variations of geotherm and stress field. Hatched areas indicate the envelope of the depth distribution of seismicity (from Lavecchia et al., 2022, this VSI).

field at depths of <10 km is demonstrated to be largely controlled by the variability of sedimentary thickness in the foreland and the orogen, while deeper temperatures are primarily controlled by the distribution of the heat transferred from the deeper mantle and the upper to lower crustal configuration. This novel approach provides new perspectives for the exploration of geothermal energy resources in Sicily and provides constraints to better understand the thermo-mechanical structure of complex collisional settings.

3.2. Papers addressing coupled multi-scale tectonics and sedimentary basins processes

The evolution of intraplate sedimentary basins located in the vicinity of an active convergent plate boundary is often controlled by the collisional dynamics of the adjacent orogen. The transfer of compression from the orogen to the platform's interior results in the formation of complex structural geometry and kinematics that often reactivate older crustal faults, focus far field stresses, and control the evolution of associated sedimentary basins. One place where such intricate processes can be optimally understood is the Precaspian Basin, situated at the SE periphery of the East European Craton and bordered to the east by the Uralian orogen. The Precaspian Basin and its northern margin experienced long-term extension and subsidence interrupted by several short-lived shortening episodes. To understand the impact and role of pre-existing basement structures on the geometry and kinematics of the subsequent deformation, Novčić and Toljić (2023, this VSI) analysed subsurface data from the northern margin of the Precaspian Basin by the means of 3D seismic data interpretation correlated with wells and structural modelling. This approach allowed them to provide new insights into the kinematic effects of a Late Devonian contraction event in this region. The observed distribution of deformation (arcuate pattern of faults, trending from WSW-ENE to NW-SE) indicate that it was driven by a NE-SW oriented contraction and transpression, where faults show the characteristics of a restraining bend area. The study area is interpreted to be part of a regional transcurrent fault system developed on the northern periphery of the Precaspian Basin. An intra-lithospheric stress localisation transmitted by the Paleouralian subduction zone would have resulted in the reactivation of pre-existing basement structures, and the propagation of faults localized short-term exhumation of the northern margin of the Precaspian Basin. Generated by the collision of Magnitogorsk volcanic arc with East European Craton, far-field stress transfer produced a zone of oblique deformation featuring several linearly distributed dislocated restraining bends and thrust ridges composing a transpressional range domain (Fig. 6). These data and interpretation demonstrate that the northern margin of the Precaspian Basin is an excellent natural setting to investigate and better understand mechanisms of far-field strain localisation and reactivation of deformational structures in stable platform areas.

The sedimentary record potentially preserves the impacts of surface processes that are controlled by the interactions of tectonic evolution

Fig. 6. A schematic model showing the kinematic relation between the continent-arc collision in the present-day South Urals and the intracratonic transpressional range along the northern margin of the Precaspian Basin (Novčić and Toljić, 2023, this VSI), producing a series of spatially dislocated restraining bends and thrust ridges.

and climate changes. The detrital content of sediments preserved in basins may provide constraints on the nature of source rocks (i.e., provenance), dynamics of sediment transport, as well as tectonic and climatic evolutions. The complex interaction between orogenic belts and nearby sedimentary basins and the role of plate collision in the basin-mountain coupling process can be inferred from provenance analyses of preserved sediments. Wang et al. (2023, this VSI) investigate the provenance of the Cenozoic sediments filling the Qaidam Basin (Tibetan Plateau, China) by combining petrology, major elements, trace elements, REE, and Zircon U—Pb dating analyses. They provide new insight about the collision of the Indian and Asian plates and the resulting Himalayan Mountains. The preserved sediments can also be recycled through erosion, transport and re-deposition during the complex, interrelated evolution of tectonics and depositional basins. Paleogeographic reconstructions that are based on stratigraphic and lithofacies analyses in northern Iberia indicate continental/fluvial and shallow-marine siliciclastic depositional environments, that were recycled during the subsequent Pyrenean orogenic phase in the Ebro foreland basin, and eventually transferred to the Mediterranean realm during post-orogenic incision of the Ebro Basin. Hence, the Ebro Basin is believed to be a typical place to understand generic processes related to gateways and sedimentary basins connectivity. It closed by 36 Ma, while its reconnection to the Mediterranean Sea initiated between 7.5 and 12 Ma leading to the erosion of 500 m to nearly 2000 m thick sedimentary deposits. The distribution of erosion and the precise timing of incision are not constrained at basin scale. Rat et al. (2022, this VSI) used thermochronological analysis of Cenozoic sediments exposed in adjacent thrust belts (Pyrenees, Basque-Cantabrian basin, Cameron basin) and drilled cores from the centre of the Ebro Basin, to estimate the age and amount of incision. The results showed that erosion increased around 10 Ma and affected mostly the basin edges (compared to the centre of the basin) (Fig. 7). Rat et al. (2022, this VSI) demonstrate that a regional-scale uplift, driven by deep seated processes, took place in the larger area of the Western Mediterranean, where the landscape responded to a complex tectonic re-organisation that ultimately closed the oceanic gateways and triggered the Messinian Salinity Crisis of the Mediterranean region.

The understanding of salt sheets movements and deformation is crucial for predicting caprock integrity and subsurface geometries. This can be achieved by investigated the associated *syn*-kinematic deposits. Cofrade et al. (2023, this VSI) explore the influence of the origin, advance and emplacement of an allochthonous salt body in continental settings on the local sedimentation in terms of facies distribution, sediment provenance and stratigraphic relationships, based on a representative field analogue (Les Avellanes diapir, frontal part of the South-Central Pyrenean fold and-thrust belt, Spain). This diapir is made up of Triassic evaporites, shales and carbonates, and it is bordered by a structurally controlled sub-basin featuring mixed clastic-evaporitic sequences of early Oligocene age. Based on sedimentary, stratigraphic and petrological data, the events and processes recorded by the diapir evolution, and the adjacent sedimentary sequences were unravelled (Fig. 8). A prograding alluvial to colluvial system is associated with the piercing of the salt. The dissolution of the salt resulted in the formation of a caprock with stacks of stringers of intra-salt carbonates and dolerites layers. The ongoing uplifting caused the incision of the local drainage network, marked as a paleo-relief in the stratigraphic sequence, filled by *syn*-kinematic breccias derived by the erosion, transport, and sedimentation of the caprock. The headward erosion reached the salt underneath the caprock, triggering the lateral extrusion that was favoured by the local topography, overriding the syn-kinematic breccia deposit.

3.3. Papers addressing multi-scale characterization of coupling between sediments, fluid and fluid-rock interactions

The fact that fluid flow and fluid-rock interactions have been demonstrated to be coupled with the deformation processes in major

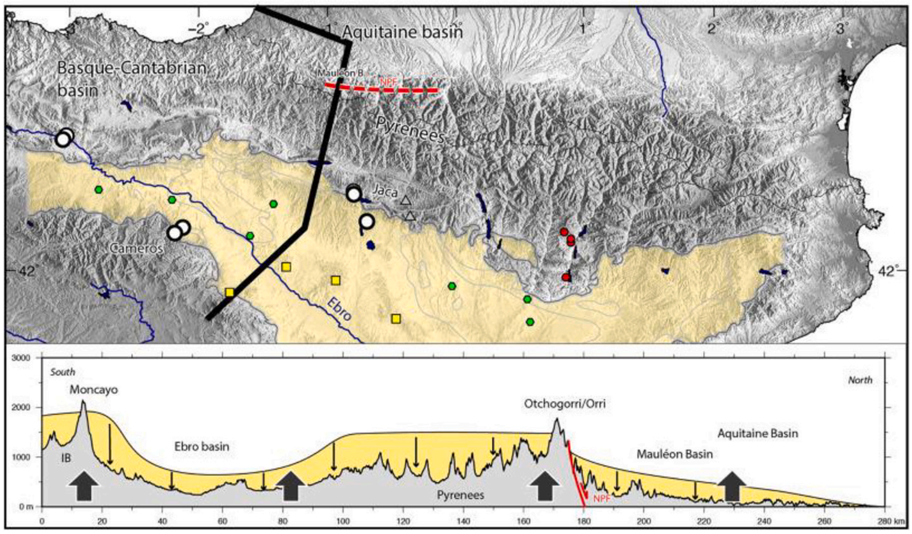

Fig. 7. The age and amount of incision of the Ebro Basin (Spain) estimated through thermochronological analysis of Cenozoic sediments exposed in adjacent thrust belts (from Rat et al., 2022, this VSI). This figure shows a reconstruction of pre-incision (pre-10 Ma) sediment infill along a N-S profile stretching from the Iberian Range to the Aquitaine Basin. Yellow surface indicates the sediment infill and large black arrows the 10 Ma-plate-scale uplift. The arrows directed downwards represent the erosion since 12–6 Ma between the reconstructed paleo-topography and present-day topography in grey. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

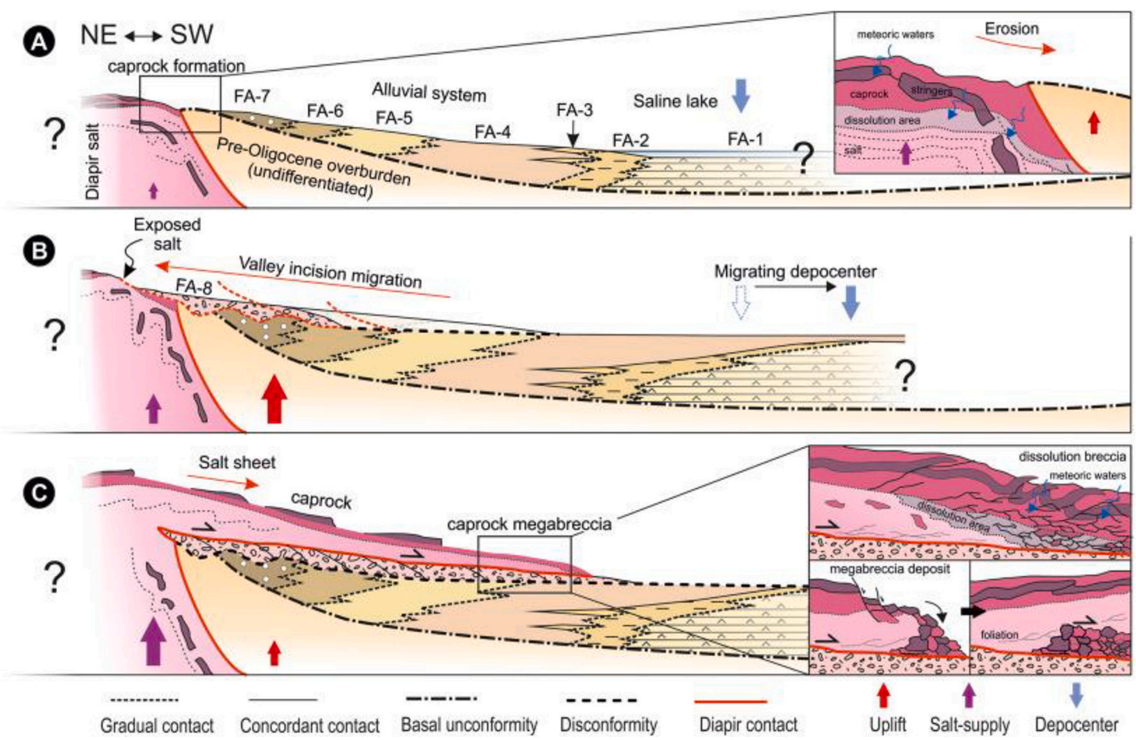

Fig. 8. Conceptual model illustrating the processes controlling the sedimentary evolution and salt sheet emplacement in the Os de Balaguer sub-basin (Les Avellanes diapir), in the frontal part of the South-Central Pyrenean fold and-thrust belt, Spain (from Cofrade et al., 2023, this VSI). FA-1 to FA-8 represent the interpreted sedimentary facies associations distributed between the salt diapir and the saline lake (depocenter).

worldwide fold and thrust belts (Roure et al., 2005), implies numerical modelling of such processes should also be coupled in order to better quantify their inter-related effects. Coupled kinematic and thermal modelling was applied to one regional, key geological section in the SE External Dinarides, in order to quantify the differences in shortening and slip-rates, exhumation and subsidence rates, thermal history and maturity of potential source rocks, as well as erosion and sedimentation rates, and to ultimately infer the conditions favourable for subsurface geo-resources (Nader et al., 2023, this VSI). Correlating the available kinematics in a multi-stage restoration of the investigated section shows that the Eocene – Oligocene phase of contraction retains the largest amount of ~85 km shortening accumulated in the external-most parts of the Dinarides that took places in a typical fore-ward breaking sequence of deformation, associated with the formation of a foredeep-wedge in the Adriatic basin. The key additional process that changed the normal orogenic geometry and rock burial evolution was the onset of the out-of-sequence oblique transpressional to thrusting deformation starting with 9 Ma that cumulated 65 Km, associated with the Adriatic indentation. Restoration and kinematic modelling had direct effects on the coupled heat transfer simulations – even at localized scales. For example, upon the Cretaceous - Eocene thrusting the calculated geothermal gradient was significantly lower in the Budva zone, when compared with the nearby South Adriatic Basin and the High-Karst unit (Fig. 9). After the Miocene extension the geothermal gradient increased northwards, demonstrating higher thermal effects, an effect that still can be seen in the present-day thermal distribution (Fig. 9). The coupled modelling results infer a considerable hydrocarbon potential for the South Adriatic basin and Dalmatian unit and a viable geothermal energy potential for the Dalmatian and High-Karst units.

Diagenesis involves chemical reactions between fluids and host rocks under specific physico-chemical conditions, resulting in dissolution, mineral cementation and mineral replacement (such as dolomitization), as well as evolving fluids that incorporate dissolved chemical species. The original and evolving fluids are rarely preserved in the rock record. Centrella et al. (2023, this VSI) provided a new approach to quantify the amount and chemical composition of the diagenetic fluids based on natural and synthetic (laboratory-formed) dolomites (Fig. 10). Fluid composition in equilibrium with dolomite for major and trace elements was achieved based on EPMA and LA-ICP-MS data using a mass balance approach. The method consists of an analytical quantification of the mass transfer between the original calcite and the newly formed dolomite, determining those elements moving in and out of the system. This approach was applied on variably dolomitized Jurassic limestones of the Layens anticline in the Pyrenees (France), the Middle Devonian Presqu'ile barrier in Pine Point (Canada), and the Cretaceous limestones of the Benicassim area of the Maestrat Basin (Spain). By using the results obtained from mass balance calculation, the amount of fluid required to dolomitize a fixed amount of limestone can be obtained for different fluid source (brine and seawater). Estimation of the partition coefficients for all trace elements for investigated case studies were also determined and compared.

Tectonic evolution is believed to be to a large extent influenced by structural inheritance, implying fault reactivation processes. Some of the key controlling factors for fault reactivation include the host-rocks, fluid flow and diagenesis, as well as mechanical properties and the fault nature. Marin et al. (2023, this VSI) investigate the fluid-rock interaction control on fault reactivation along the Montmell-Vallès Fault System in the central Catalan Coastal Ranges. There, two periods of Cenozoic tectonic inversion affected a previously well-developed Mesozoic extensional basin system. Fault reactivation, which appears to be influenced by the mechanical properties of the inherited fault zones, shows differences along strike from NE to SW and appears decoupled from surface to depth due to its kinked-planar geometry and the change of fault dip angle with depth. The deeper and less dipping planes of the major faults are reactivated in the entire zone, whereas the upper and highly dipping parts of the faults only show local reactivations. Observations indicate that the fault dip, the mechanical properties of the resulting fault rocks (gouge versus cemented breccias), as well as lithologies (granites and siliciclastic metasediments versus carbonate rocks) and mineral precipitation and cementation product of fluid circulation significantly control the fault reactivation.

Ramirez-Perez et al. (2023, this VISI) applied field investigations (sedimentology/stratigraphy and structural geology), as well as petrophysical and petrothermal analyses on a potential outcrop analogue of subsurface geothermal reservoirs (the Oliana anticline in the Southern Pyrenees). Five lithofacies were distinguished including conglomerates, hybrid arenites, lithic arenites, carbonates and evaporites. Petrophysical measurements indicate dispersed values of bulk density, connected porosity, permeability, and velocity of compressional acoustic waves. Diagenetic processes (e.g., dissolution, cementation) and fracturing, coupled with petrological features such as mineral composition, matrix content and grain size, appear to be the most critical controlling factors for rock porosity. Connected porosity values were associated with bulk density, compressional wave velocity and permeability data. Thermal conductivity measures confirmed a compositional control on the thermal properties of rocks. At the scale of the studied anticline, thermal characterization reveals a low conductive area that matches the carbonate and evaporite succession of the anticline core and a highly conductive zone associated with the detrital succession of the fold limbs.

Predicting subsurface fluid flow dynamics is essential for geothermal energy production, but also and foremost for groundwater exploitation. Hydrostratigraphic classification which relate to defining rock bodies with characteristic hydraulic conductivity that is also influenced by the subsurface lithological heterogeneity and connectivity, has been applied by Ben Mahrez et al. (2023, this VSI) on the uppermost 1800 m thick late Neogene to Quaternary basin-fill succession in the eastern part of the Pannonian Basin. Five combined 3D seismic volumes with seven key horizons and 30 well logs, allowed for RMS amplitude mapping as well as lithology determination based on GR and SP wireline logs. Hence, seismic geomorphological features and depositional architectures were deduced. The applied workflow allowed the identification of sand bodies, deltaic lobes, complex channel belts, simple fluvial channels (aquifers), and muddy flood plain (aquitards). Based on vertical sand distribution patterns, the former single aquifer unit was further subdivided in three major stratiform and some corridor-like minor hydrostratigraphic units. The applied workflow, that is adapted from the oil-and-gas industry, resulted in the characterization of units of varying sand content and deduced hydraulic conductivity, building a spatially complex facies-based model of hydrostratigraphy at the basin scale.

4. Conclusions

Based on a broad range of case studies and multi-disciplinary approaches, this review illustrates that deep and shallow (surface) Earth systems, tectonic and sedimentary basins, as well as fluid-flow and fluid rock processes are inter-related. Understanding such mechanisms and their impacts on the evolution of orogens, basins and geo-resources needs an integrative, often coupled, multi-scale (temporal and spatial) and inter-disciplinary approach. Throughout this special issue, these mechanisms are studied through relevant field observations associated to experimental investigations and numerical modelling. Therefore, we promote the use of natural laboratories, where the results of specific analogue processes can be distinguished, identified, and quantified, to develop and confirm process-oriented hypotheses.

The interplay between deep and shallow Earth processes is inherently expressed by dynamic topography evolution which has been highlighted by TOPO-EUROPE in recent decades, providing insights for predicting geohazard, environmental and climate change impacts (Cloetingh et al., 2023, this VSI). Earthquakes are one of the major deep Earth processes affecting societies. Seismic attenuation is commonly used to estimate the maximum depths of both intraplate earthquakes and fluids circulation in the crust. This is illustrated by a novel frequency-dependent attenuation tomography method that is sensitive to fluid saturation was applied on the Carpathian Orogen and the surrounding basins (Borleanu et al., 2023, this VSI). Furthermore, the Gargano Promontory (southern Italy), was used to infer the effects of crustal fluids and thermo-mechanical structures on observed seismicity by means of numerical modelling (Lavecchia et al., 2022, VSI). The thermal and mechanical configurations of the deeper lithosphere constrain, as well, the near-surface geothermal potential, especially in complex and active tectonic settings, such as Sicily (Floridia et al., 2022, this VSI).

Coupled tectonic and sedimentary basins processes are well observed in collisional orogens such as the Precaspian Basin and the adjacent Uralian orogen, where the transfer of compression from the orogen to the platform's interior can be examined (Novčić and Toljić, 2023, this VSI). Paleogeographic reconstructions demonstrate that the fluvial and shallow-marine siliciclastic deposits have been recycled during the

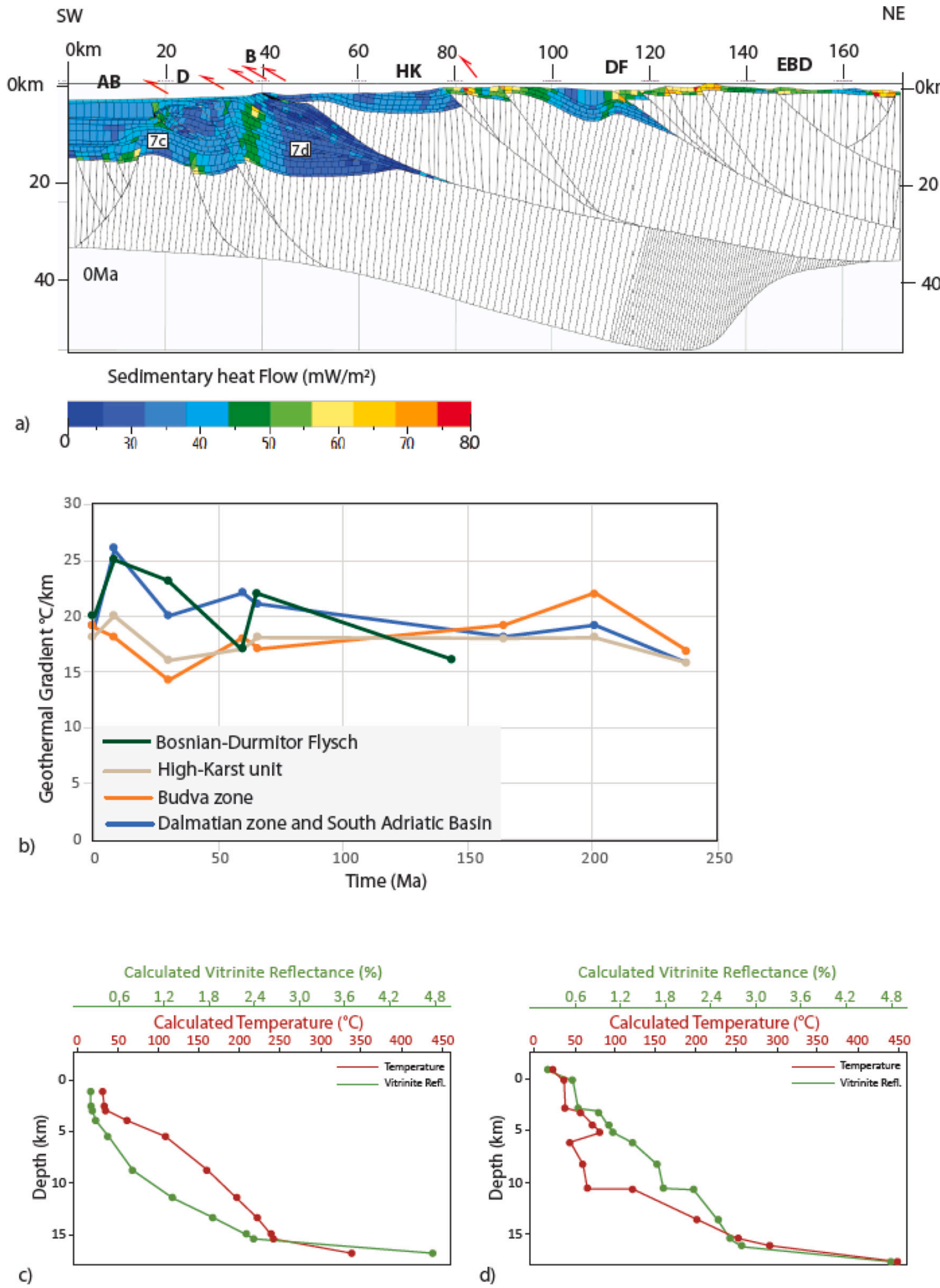

Fig. 9. Results of coupled kinematic and thermal model of the Dinarides section by Nader et al. (2023, this VSI): a) Basal heat flow distribution across the sedimentary cover of the present-day, reflecting the constant basal input heat flow value of 40 mW/m^2. This corresponds with the present-day surface heat flow values; b) Diagram demonstrating the variable geothermal gradients across the Dinarides through space and time, which were extracted from the thermal model; c, d) Temperature (°C) and vitrinite reflectance (%) depth-evolution plots extracted from the thermal model, from two subsurface locations. The abbreviations are as follows: AB-South Adriatic Basin, D-Dalmatian unit, B-Budva, HK-High Karst unit, DF-Durmitor Flysch, EBD-East Bosnian Durmitor unit.

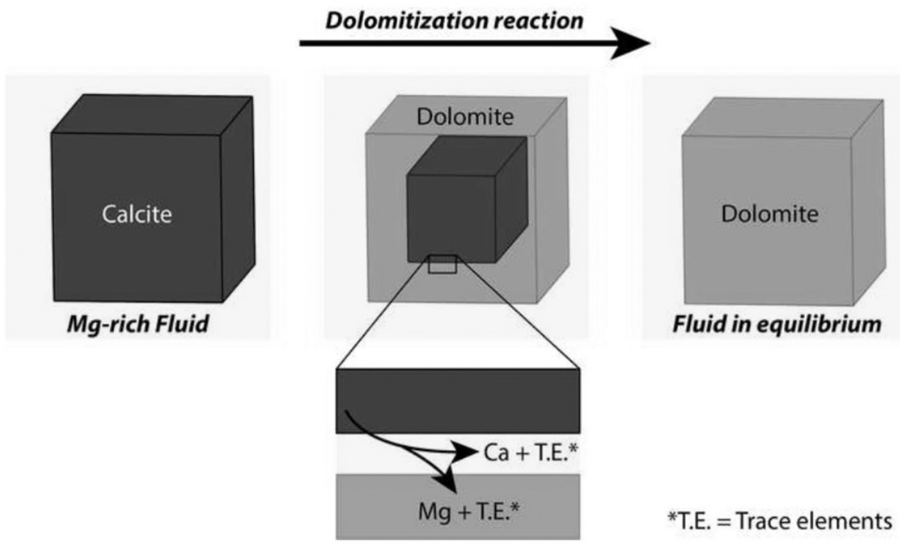

Fig. 10. Schematic illustration of the replacement process of calcite by dolomite which was quantified on several natural and synthetic samples by Centrella et al. (2023, this VSI).

Pyrenean orogenic phase in the Ebro foreland basin before transfer to the Mediterranean realm, illustrating how the interactions of tectonic and climatic evolutions control surface processes (Rat et al., 2022, this VSI). Furthermore, the provenance of the Cenozoic sediments filling the Qaidam Basin (Tibetan Plateau, China) provided new insights on the collision of the Indian and Asian plates (Wang et al., 2023, this VSI). On another scale, the lateral movement of salt sheet fronts was recorded by adjacent *syn*-kinematic sedimentation in Les Avellanes diapir, South-Central Pyrenean fold and-thrust belt (Cofrade et al., 2023, this VSI).

The interactions between fluids, host rocks, and fluid circulations can be observed at multiple scales and lead to broad range of implications. Predicting subsurface fluid flow dynamics by means of hydrostratigraphic classification, that is essential for groundwater exploitation, was demonstrated on the Neogene-Quaternary succession of the eastern part of Pannonian basin (Ben Mahrez et al., 2023, this VSI). Coupled kinematic and thermal modelling applied to a basin-scale geological section in the SE external Dinarides – typical of contractional orogens, resulted in highlighting the presence of potential hydrocarbon and geothermal geo-resources (Nader et al., 2023, this VSI). Sedimentological, stratigraphic, structural, petrophysical and petrothermal analyses were applied on the Oliana anticline (Southern Pyrenees) to characterize an outcrop analogue of geothermal reservoirs (Ramirez-Perez et al., 2023, this VIS). More locally, the controls of fluid-rock interactions on fault reactivation were highlighted on the Montmell-Vallès Fault System, central Catalan Coastal Ranges (Marin et al., 2023, this VSI). Mass balance calculations were applied to quantify the amount and chemical composition of the diagenetic fluids related to natural and synthetic dolomites at the reservoir-scale (Centrella et al., 2023, this VSI).

Declaration of Competing Interest

The authors declare no competing interests.

Data availability

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

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