GEOLOŠKI ANALI BALKANSKOGA POLUOSTRVA

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https://doi.org/10.2298/GABP240116003S
Short Communication
Кратко саопштење

Geodynamics of basins above subducted slabs: an integrated modelling study of tectonics, sedimentation, and magmatism in the Timok Magmatic Complex

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Abstract. Volcano-sedimentary basins located in the orogenic hinterland area overlying subducted slabs are observed worldwide to be driven by the switching tectonic regimes induced by the changing mechanics of the slab. Despite many qualitative studies, the quantitative link between the subducted slab's mechanics and the overlying basins' evolution is less understood. Among the many examples observed worldwide, the Timok Magmatic Complex (TMC) in Serbia represents an optimal natural laboratory due to the complex tectonic setting during the various stages of the Middle Jurassic–Paleogene evolution of the subduction system. The TMC is a segment of the larger Late Cretaceous Apuseni-Banat-Timok-Srednogorie (ABTS) magmatic belt, formed in response to the evolution of the subducted Mesozoic Neotethys oceanic slab beneath the Carpatho-Balkanides of south-eastern Europe. The TMC basin, with the associated intrusive and extrusive magmatics and volcano-sedimentary deposits, represents an excellent area for a process-oriented study on the interplay between tectonics, sedimentation, and magmatism in the basins above evolving subducted slabs. Within the scope of the newly funded TMCmod project, coupled field and laboratory kinematic and petrological investigations will be focused on creating a conceptual definition of the TMC geodynamic evolution, by combining near-surface observations with the known evolution of the subduction system. This definition will be subsequently validated through analogue modelling and integrated into a coherent geodynamic model of tectonic switching in basins driven by the evolution of subducted slabs. The new model of the TMC basin's geodynamic evolution will quantitatively advance the strategy of prospecting and exploration of world-class porphyry copper-gold deposits, which have been actively exploited in this region for more than a century. Furthermore, reconstructed regional kinematic evolution will improve seismic hazard assessment during industrial and societal infrastructure planning and construction.

Key words
Timok Magmatic Complex, Neotethys subduction, basin geodynamics, analogue modelling.

Апстракт. Еволуција вулканогено-седиментних басена у залеђу орогених појасева, који се налазе изнад субдукционих зона, контролисана је променама у регионалним тектонским режимима, до којих долази услед

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измена у механизмима субдукције. У бројним постојећим квалитативним студијама, још увек није на квантитативан начин документована веза између механизама субдукције и еволуције басена изнад субдукционих зона. Међу бројним примерима широм света, Тимочки магматски комплекс (ТМК) у Србији представља оптималну природну лабораторију за проучавање претходно наведених феномена, услед сложене, вишефазне тектонске еволуције овог средњојурског до палеогеног субдукционог система. ТМК представља део већег горњокредног Апусени-Банат-Тимок-Средњегорје (АБТС) магматског појаса, који је настао током субдукције океанске литосфере мезозојског Неотетиса под Карпато-балканиде југоисточне Европе. ТМК, са припадајућим вулканогено-седиментним стенским формацијама, представља веома подесну област за проучавање интеракције тектонике, седиментације и магматизма у басенима изнад активних субдукционих зона. У циљу реализације недавно започетог пројекта TMCmod, нова теренска и лабораторијска кинематска и петролошка истраживања биће спроведена да би се формирао концептуални модел геодинамичке еволуције ТМК. Овај концептуални модел ће, затим, бити проверен методама физичког аналогног моделовања, да би исходишно био интегрисан у први целовити геодинамички модел, који објашњава како субдукција контролише тектонску еволуцију асоцираних басена. Нови модел геодинамичке еволуције басена ТМК омогућиће квантитативна побољшања у будућој стратегији истраживања и експлоатације порфирских лежишта бакра и злата, која се на овом простору експлоатишу дуже од једног века. Поред тога, реконструисана регионална кинематска еволуција унапредиће оцену сеизмичког хазарда током планирања и градње индустријске и друштвене инфраструктуре.

Кључне речи:
Тимочки магматски комплекс, субдукција Неотетиса, геодинамика басена, аналогно моделовање.

Concept and objectives

The along-arc variability in the geodynamic evolution of orogens is often related to the kinematics of the subducted slab and the variable obliquity of the subduction direction. These processes affect the structural control of the back-arc basin formation and deformation and its interplay with associated sedimentation and subduction-related magmatism (e.g., Gallhofer et al., 2015; Menant et al., 2018). The Cretaceous convergence between Europe- and Adria-derived continental units led to the subduction and closure of the intervening Neotethys Ocean (Schmid et al., 2008, 2020; van Hinsbergen et al., 2020). As a result of the Neotethys subduction, an elongated belt composed of magmatic rocks with a calc-alkaline character was emplaced on the European continental margin (i.e., the Apuseni-Banat-Timok-Srednogorie (ABTS) magmatic belt, e.g., von Quadt et al., 2005), situated in the Carpatho-Balkanides orogen of south-eastern Europe. The kinematics of the back-arc deformation along the ABTS belt is variable and less constrained, where the proposed models vary from extension to transtensional pull-apart basin opening for different back-arc segments (Drew, 2006; Chamberfort & Moritz, 2006; Gallhofer et al., 2015; Knaak et al., 2016). The subsequent latest Cretaceous–Paleogene Adria-Europe continental collision (Ustaszewski et al., 2010; Stojadinović et al., 2022), followed by complex post-orogenic deformations, facilitated the bending and clockwise rotation of the upper European continental plate that deformed the entire Carpatho-Balkanides into a complex orocline (Krstekanić et al., 2020, 2022).

The Timok Magmatic Complex (TMC) in Serbia represents one of the successive segments of the Late Cretaceous Apuseni–Banat–Timok–Srednogorie (ABTS) magmatic belt (Fig. 1), where a system

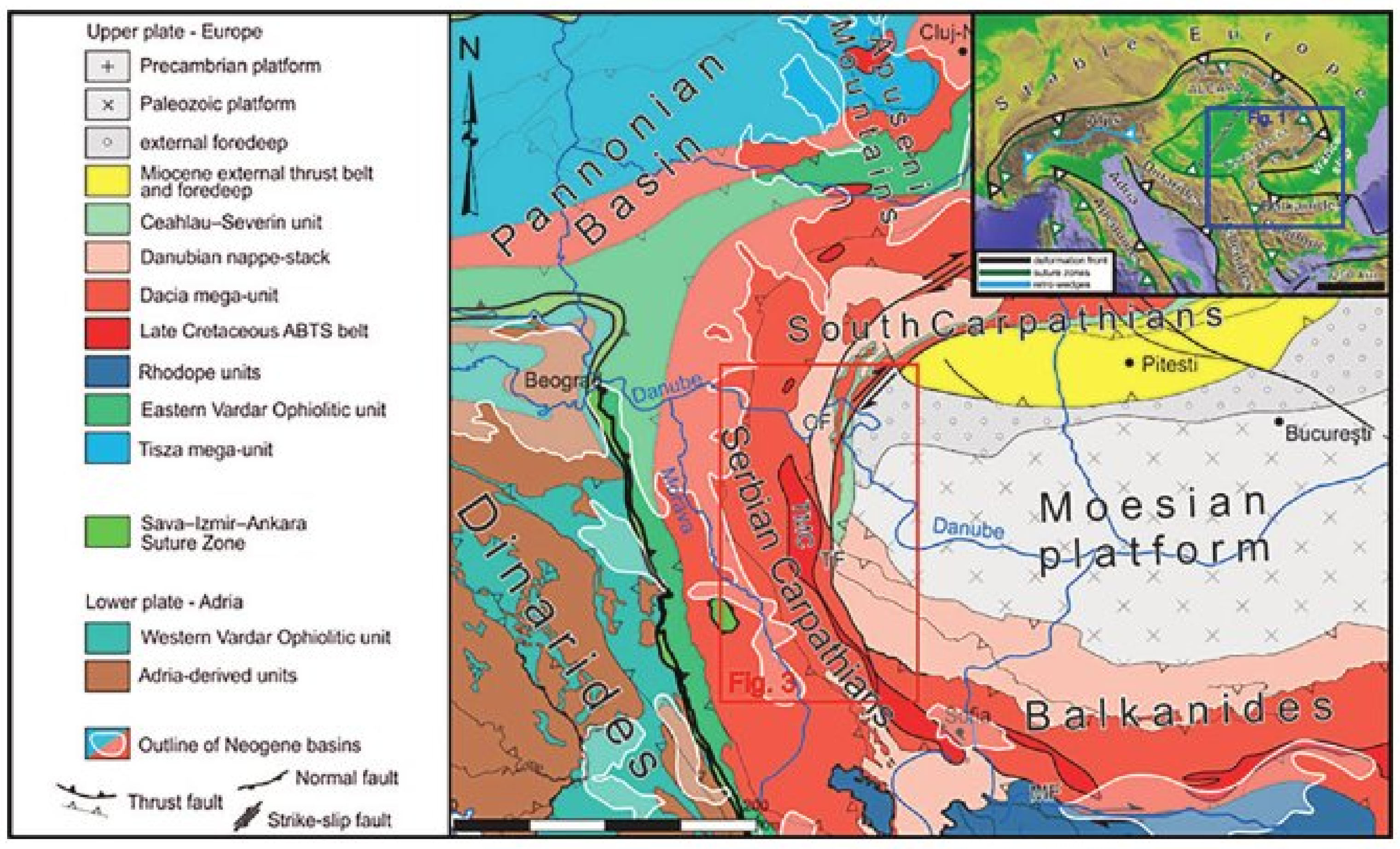

Fig. 1. Tectonic map of the Carpatho–Balkanides and surrounding area with the main tectonic units (modified after SCHMID *et al., 2020). Thick black lines delineate the suture zone between Europe- and Adria-derived units. TMC– Timok Magmatic Complex;* ***MF)*** *Maritza Fault;* ***CF)*** *Cerna Fault;* ***TF)*** *Timok Fault. The red rectangle indicates the location of Figure 3. Inset: Digital elevation model of Alps-Carpathians-Dinarides orogenic system of south-eastern Europe with the first order tectonic features. The blue rectangle indicates the location of the main figure.*

of intrusive and extrusive magmatic products was interlayered with sediments in a complex volcano-sedimentary basin. Due to its location overlying the subducted Neotethys slab, the evolution of the basin was controlled by the changing slab kinematics. This includes its changes from flat advancing to steep retreating during subduction and collision, controlling the tectonic inversion moments and localization of deformation and magmatism in the fore-arc and back-arc system (Fig. 2; GALLHOFER et al., 2015; TOLJIĆ et al., 2018, 2020).

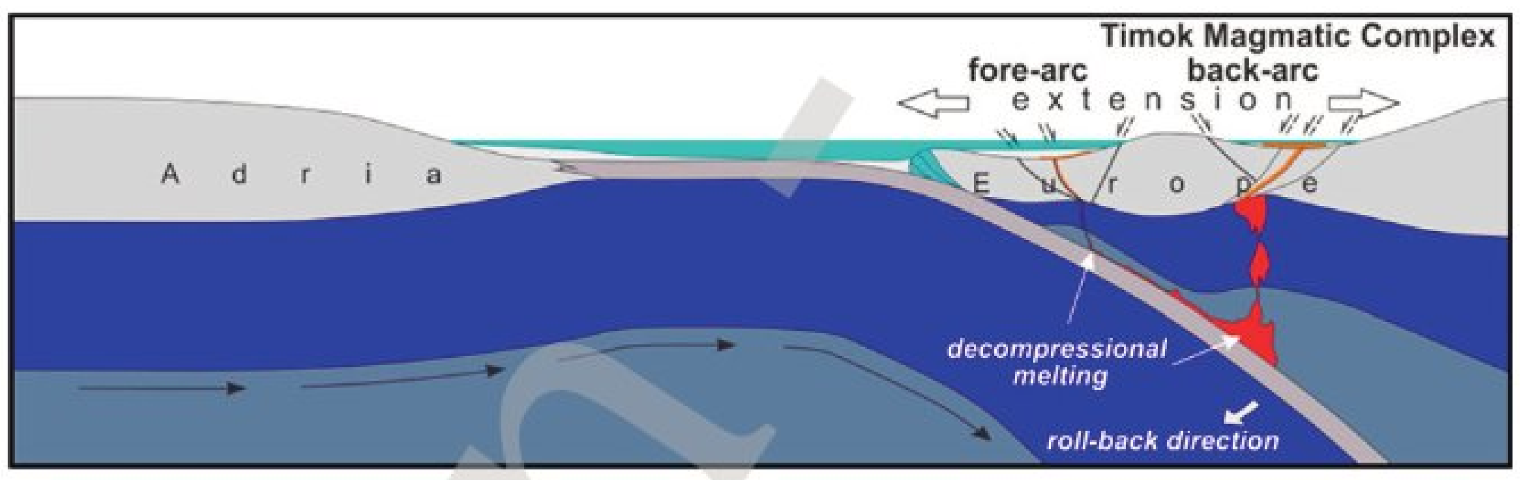

Fig. 2. Conceptual sketch of the Cretaceous Neotethys fore-arc to back-arc subduction system (modified after TOLJIĆ *et al., 2018).*

The aforementioned observations define the volcano-sedimentary basin hosting the TMC as an excellent natural laboratory for a process-oriented study on the interplay between tectonics, sedimentation, and magmatism in basins above evolving subducted slabs. This multi-disciplinary geoscientific study will be realized within the framework of the research project: GEODYNAMICS OF BASINS ABOVE SUBDUCTED SLABS: an integrated modelling study of tectonics, sedimentation, and magmatism in the Timok Magmatic Complex – TMCmod. The main objective of the TMCmod project is to increase understanding of the interplay between tectonics, sedimentation, and magmatism in continental back-arc basins located above subducting systems with variable kinematics and to develop a first quantitative model coupling the Timok Magmatic Complex (TMC) basin with its Neotethys subduction driver.

Methodological approach

The TMCmod project will be realized through a process-oriented multi-disciplinary geoscientific study, focused on the structural control of TMC basin evolution and its associated magmatic and sedimentary processes. The full capacities of the Laboratory for low-temperature thermochronology, Laboratory for petrology of magmatic and metamorphic rocks, Laboratory for Paleontology and Historical Geology, and Centre for Remote Sensing and GIS of the Faculty of Mining and Geology, University of Belgrade (FMGUB), will be utilized to conduct this study. Coupled field and laboratory kinematic analyses will be performed to constrain the kinematics and age of activity along major fault zones (Fig. 3), which controlled the opening and subsequent inversion of the TMC sedimentary basin and, therefore, affected its sediment deposition, magmatism, and associated ore-formation processes. Furthermore, kinematic investigations will be combined with detailed sedimentological analyses and the new high-resolution petrological, geochronological and thermochronological dating of key magmatic and sedimentary rock sequences.

A wide range of geological data will be collected and generated during the implementation of the TMCmod project. This includes structural, petrological, and sedimentological data collected during field

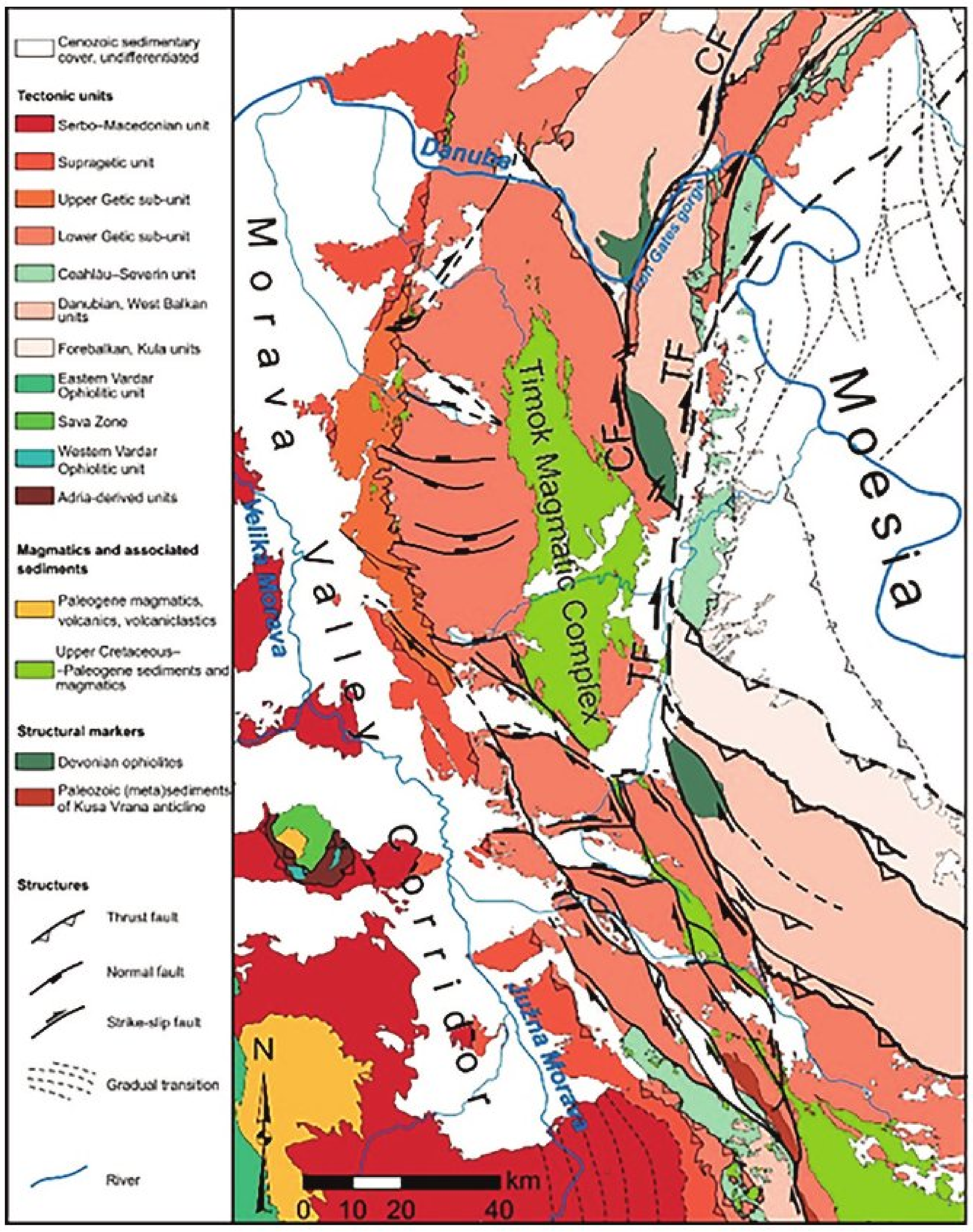

Fig. 3. Tectonic map of the Timok Magmatic Complex basin and the surrounding Carpatho-Balkanides orogen (modified after Krstekanić *et al., 2022).* ***CF)*** *Cerna Fault,* ***TF)*** *Timok Fault.*

campaigns and the data obtained by various laboratory analyses including petrological, sedimentological, syn-kinematic mineral dating, radiometric dating and fission-track analyses (Fig. 4). Outcrop-scale data collected directly in the field will include: field kinematic data of all significant deformational structures, including their geometries, and mapping data with geological columns of key sedimentological sequences. Data from laboratory analyses will be obtained by: petrological and sedimentological thin-section analyses; syn-kinematic minerals dating to determine the time of (re)activation of major deformational structures; geochronological dating to define absolute ages of magmatic emplacement at crucial sites; trace elements mineral analysis and geochemical whole rock data; detrital thermochronology dating for sedimentary provenance analyses. Analyses and integration of collected data will be conducted by using specialised software such as TectonicsFP, WinTensor, HeFTy, Binomfit, etc (Brandon, 2002; Delvaux & Sperner, 2003; Ketcham, 2005; Ortner et al., 2002). During the project implementation, an internal GIS database with collected and generated geological data will be developed and accessible online.

The observational and analytical inferences will be validated by physical analogue modelling, which represents a powerful experimental tool to investigate the interplay between processes in geodynamic settings characterized by variable tectonic regimes, strain rates, magmatic input, and sedimentation rates (Fig. 4). The analogue modelling will test the effects of strain rate, magmatic intrusion, and sedimentation rate on the overall evolution of an extensional/transtensional basin. The upper crustal- to basin-scale models will be built and experiments conducted in an external tectonic modelling laboratory (TecLab) at the Faculty of Geosciences, Utrecht University. The state-of-the-art equipment (i.e., high-resolution digital cameras, CT scanner, etc.) will be used to monitor the model evolution, while the deformation of the models will be analysed using particle image velocimetry techniques. Integrated data on the kinematics of deformational structures; time, volumes, and depths of magmatic rocks emplacement; as well as the rates of basin deposition will be used as input data during analogue modelling. Furthermore, the analogue modelling procedures will also yield novel data, which will be analysed using strain analysis software such as PIVlab and StrainMap (Thielicke & Stamhuis, 2014; Broerse et al, 2021) in the final phases of project implementation.

Expected outcome

The novelty of the TMCmod project lies in its multi-disciplinary approach that, for the first time in Serbia, combines modern field and laboratory analyses of tectonic structures, absolute ages of rocks and deformation, basin infill provenance analysis, reconstruction of depositional systems, and analogue modelling of the segment of the upper plate back-arc system where the TMC is developed. The results of the kinematic study will enable a better understanding of the mechanisms and timing of TMC back-arc

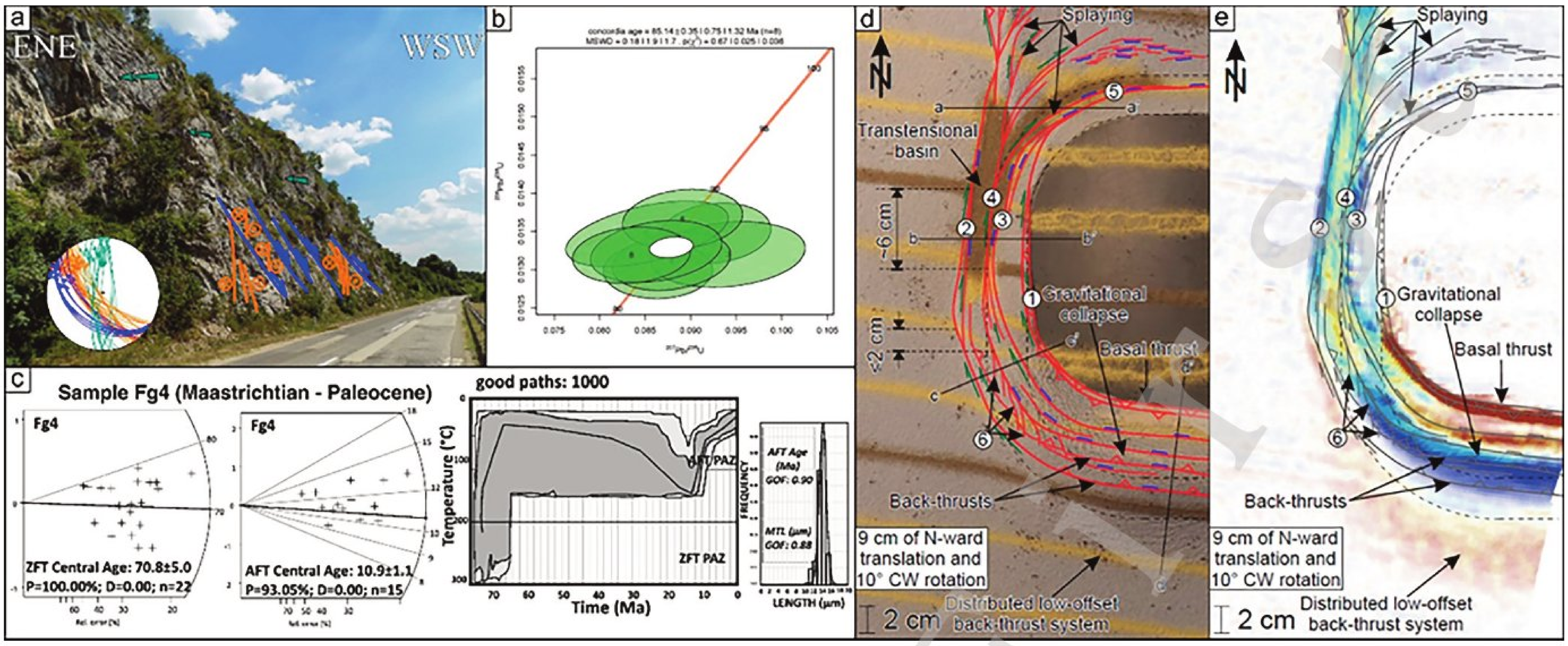

Fig. 4. *Multi-disciplinary approach:* ***a)*** *Field structural analysis (Krstekanić et al., 2022);* ***b)*** *U/Pb absolute dating (Banješević et al., 2019, Velojić et al., 2020, 2023);* ***c)*** *– Provenance study using detrital thermochronology (Stojadinović et al., 2017);* ***d, e)*** *Analogue modelling of complex fault systems (Krstekanić et al., 2021).*

basin opening and its subsequent moments of inversion. The obtained petrological results will provide new constraints on the age, volumes, and depths of shallow sub-volcanic intrusions emplacement in the TMC basin and define genetic links of magmatism and associated ore-formation processes. In addition, we will determine the provenance and deposition rates of Cretaceous sedimentation in the TMC basin and reconstruct its depositional systems. The new analogue geodynamic model of the TMC basin and its correlation with other segments of the ABTS belt improve the overall understanding of the interplay between tectonics, magmatism, and sedimentation in the back-arc settings. The new inferences can be used in various geodynamic realms where similar controlling mechanisms on basin(s) evolution can be recognized (Fig. 5). The well-documented geodynamic model of the TMC basin will be very useful for planning and realization of all future geological studies and mining of mineral resources in this area. The TMC represents an important mining province, where world-class porphyry copper-gold deposits (e.g., Jelenković et al., 2016; Banješević et al., 2019; Velojić et al., 2020, 2023) are actively exploited for more than a century. Since large segments of these deposits were highly deformed, the reconstruction of deformational evolution of the TMC that will be conducted in this project has a high potential impact on the prospecting and exploration of the aforementioned mineral resources. The TMC represents a region with a moderate level of recent seismic activity. Constraints on kinematics and time of activity of major regional faults will facilitate the detection of their seismo-tectonically active segments. That,

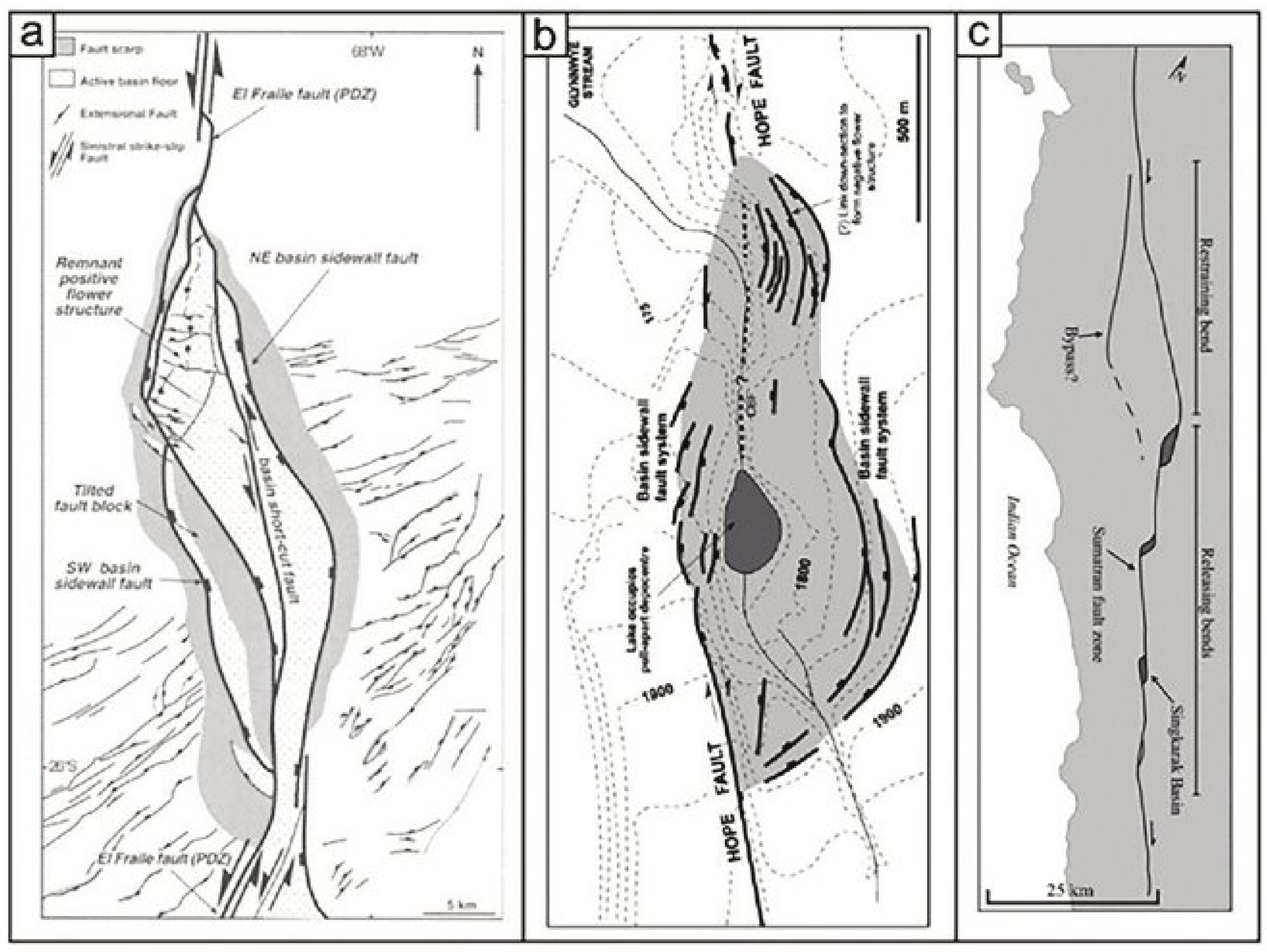

Fig. 5. *Worldwide examples of basins with similar geometry as the TMC.* ***a)*** *Salina del Fraile basin above the Andean subduction zone (Reijs & McClay, 2003).* ***b)*** *Glynn Wye depression, New Zealand (modified after Dooley & Schreurs, 2012).* ***c)*** *Various pull-apart sigmoidal basins along the Sumatran fault zone in the back-arc region of the Sunda subduction zone (Mann, 2007).*

again, will improve natural hazard assessment during the planning and construction of industrial and private objects.

Summary

A process-oriented multi-disciplinary geoscientific study will be realized in the basin hosting the Timok Magmatic Complex (TMC), within the scope of the TMCmod project. The project activities will consist of field investigations and sampling, followed by various laboratory investigations, which will include analyses of tectonic structures, and geochronological, petrological, and sedimentological analyses. The results of all preceding activities will be used to create the integral conceptual model of the geodynamic evolution of the TMC basin (Fig. 6). The conceptual model will be subsequently validated by a series of analogue modelling experiments. Process-wise, the main project feedback will be a better understanding of the interplay between tectonics, sedimentation, and magmatism in back-arc basins, while for the case study of the TMC, the novel, well-documented integrated model of its geodynamical evolution in the context of the larger ABTS belt will be developed.

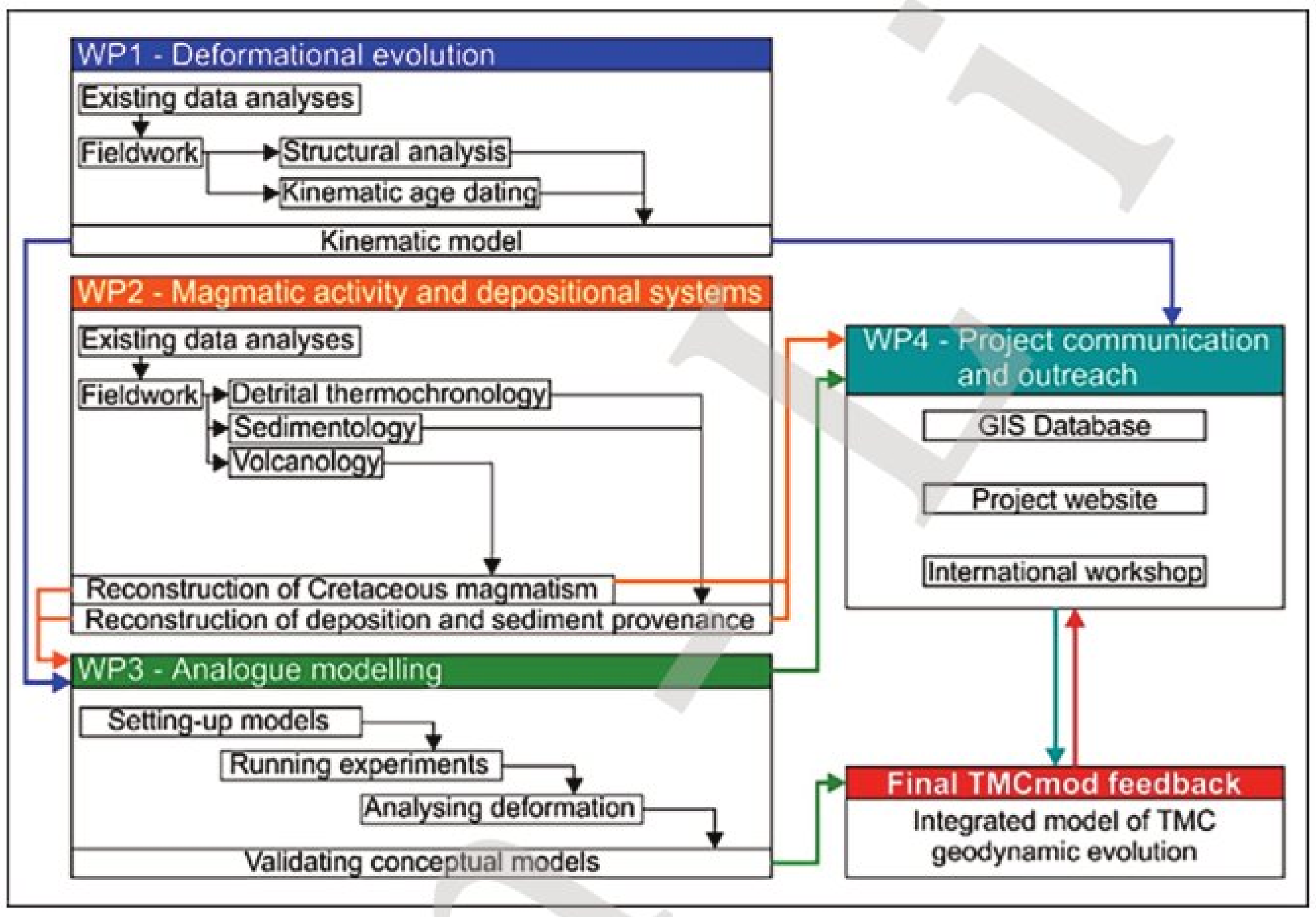

Fig. 6. *TMCmod project implementation scheme.*

Acknowledgements

This research was supported by the Science Fund of the Republic of Serbia, GRANT No TF C1389-YF, GEODYNAMICS OF BASINS ABOVE SUBDUCTED SLABS: an integrated modelling study of tectonics, sedimentation, and magmatism in the Timok Magmatic Complex – TMCmod (PROJECT No 7461). Editor-in-chief Nevenka Djerić is acknowledged for guidance during the manuscript submission. Hazim Hrvatović and an anonymous reviewer are acknowledged for reviewing the original version of the manuscript. Liviu Matenco and Dejan Radivojević are gratefully acknowledged for their help during the preparation of the project proposal.

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Резиме

Геодинамика басена изнад субдукционих зона: интегрална моделска студија о тектоници, седиментацији и магматизму у оквиру Тимочког магматског комплекса

Мултидисциплинарна студија из домена геонаука биће реализована у басену Тимочког магматског комплекса (ТМК), у оквиру пројекта TMCmod. Пројектне активности састојаће се од теренских истраживања и узорковања, која ће бити праћена и лабораторијским истраживањима, укључујући анализе тектонских структура, као и геохронолошке, петролошке и седиментолошке анализе. Резултати свих претходно наведених активности биће укључени у целовити концептуални модел геодинамичке еволуције басена Тимочког магматског комплекса (ТМК). Овај концептуални модел ће, затим, бити проверен кроз серију експерименталних аналогних модела. У контексту геодинамичких процеса, главни научни допринос пројекта биће боље разумевање интеракције тектонике, седиментације и магматизма у басенима лоцираним изнад активних субдукционих зона. Такође, биће развијен нови, целовити квантитативни модел геодинамичке еволуције басена ТМК.

Manuscript received January 16, 2024
Revised manuscript accepted February 26, 2024