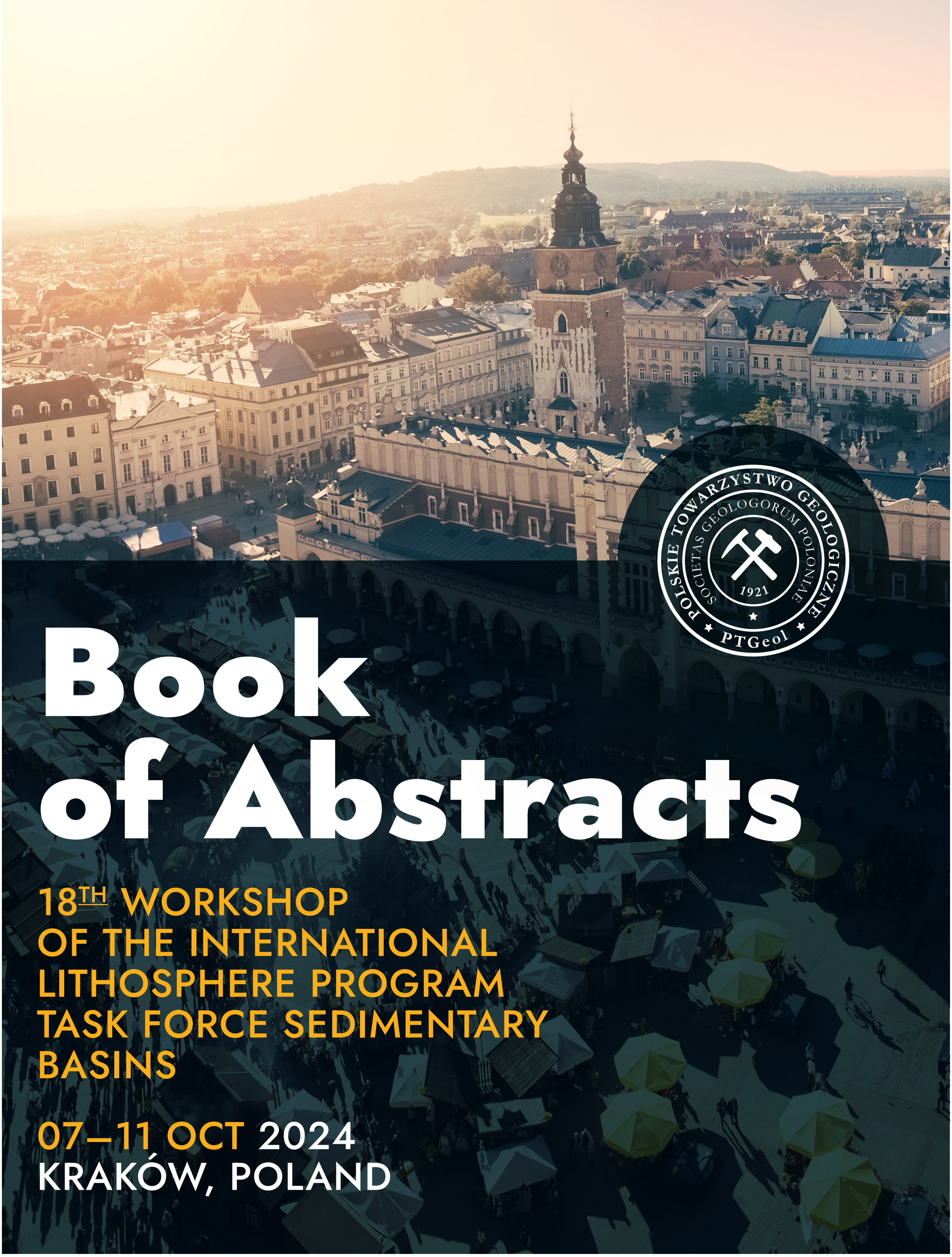

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Book of Abstracts

18TH WORKSHOP OF THE INTERNATIONAL LITHOSPHERE PROGRAM TASK FORCE SEDIMENTARY BASINS

07–11 OCT 2024
KRAKÓW, POLAND

ING PAN
JAGIELLONIAN UNIVERSITY IN KRAKÓW
INTERNATIONAL LITHOSPHERE PROGRAM
Institute of Geophysics Polish Academy of Sciences

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Organizers:

Polish Geological Society

In co-operation with:

Institute of Geological Sciences, Polish Academy of Sciences

Institute of Geological Sciences, Jagiellonian University

Polish Geological Institute – National Research Institute

International Lithosphere Program

Institute of Geophysics, Polish Academy of Sciences

Editorial co-ordination:
Piotr Krzywiec
Editing:
Ewa Dąbrowska-Jędrusik, Monika Masiak
Graphic Design:
Łukasz Borkowski, Monika Cyrklewicz
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Introduction

It is my great pleasure to welcome all potential participants to the 18th workshop of the International Lithosphere Program – Task Force VI on Sedimentary Basins.

General aim of this Task Force for almost two decades has been focused on fostering knowledge-sharing and collaboration among the attendees, with the ultimate goal of advancing our understanding of sedimentary basins and their role in the broader geologic context.

Apart from fundamental questions related to formation, evolution and demise of sedimentary basins more applied aspects such as energy, underground storage, geohazards have been also of great interest to both the organizers and participants.

18th edition of this workshop held in Kraków, Poland, will not be different. It is our ambition to cover broad spectrum of studies, both fundamental and applied, and present leading-edge results in these disciplines, and therefore we invite presentations on various topics related to applications of geological, geophysical, geochemical and other techniques to resolve both fundamental scientific questions regarding structure and evolution of sedimentary basins as well as societal challenges such as natural hazards, energy transition, and environmental issues.

Two days of oral and poster presentations will be combined with two very interesting field trips during which both surface and subsurface data will be used to present very complex and challenging structure and evolution of S Poland located above one of the key regional geological boundaries, the Teisseyre-Tornquist Zone.

Prof. Piotr Krzywiec

CHAIRMAN OF THE ORGANIZING COMMITTEE

Organizing Committee (including Field Trips):

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Dr Aleksandra Stachowska, Institute of Geological Sciences, Polish Academy of Sciences, Warsaw, Poland

Scientific Committee:

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Dr Hamid M. Nick, Technical University of Denmark – Danish Offshore Technology Centre, Lyngby, Denmark

Dr Paweł Poprawa, AGH University of Mining & Metallurgy, Kraków, Poland

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Prof. Andrea Moscariello, University of Geneva, Geneva, Switzerland

Dr Brandon Lutz, U.S. Geological Survey, Denver, CO, USA

Prof. Fanwei Meng, China University of Mining and Technology, Xuzhou, China

DAY 1, OCTOBER 8

09:00–09:10	Opening remarks (Piotr Krzywiec*)
09:10–09:25	Welcome talk (Mariusz Kędzierski*)
09:25–09:45	Dynamics of sedimentary basins and introduction to ILP Task Force VI (Liviu C. Matenco*, Piotr Krzywiec, Fadi-Henri Nader)

MAGMATIC ACTIVITY WITHIN SEDIMENTARY BASINS
(chair: P. Poprawa, S. Poppe)

9:45–10:05	Sill stacking in subseafloor unconsolidated sediments and control on sustained hydrothermal systems: evidence from IODP drilling in the Guaymas Basin, Gulf of California (Christophe Galerne*, Alban Cheviet, Wolf-Achim Kahl, Christin Wiggers, Wolfgang Bach, Florian Neumann, Martine Buatier, Tobias W. Höfig, Daniel Lizarralde, Andreas Teske, Manet Peña-Salinas, Jens Karstens, Christoph Böttner, Christian Berndt, Ivano W. Aiello, Kathleen M. Marsaglia, Swanne Gontharet, Henning Kuhnert, Joann Stock, Raquel Negrete-Aranda, Junli Zhang, Achim Kopf) **KEYNOTE**
10:05–10:25	The Neuquén basin, Argentina - A world-class case study illustrating magma-rock interactions in hydrocarbon-bearing sedimentary basins (Olivier Galland*, Juan B. Spacapan, Octavio Palma, Ezequiel Lombardo, Ole Rabbel, Dougal Jerram)
10:25–10:45	Impact of the petit-spot volcanism on the sedimentary cover in the Japan Trench area from high-resolution seismic imaging (Andrzej Górszczyk*, Yousef Amirzadeh)
10:45–11:05	Mississippian igneous flare-up at the SW slope of the East European Craton and its interaction with the Baltic and Lublin–Lviv basin (Paweł Poprawa*, Ewa Krzemińska, Piotr Krzywiec, Krzysztof Nejbert, Stanisław Mazur, Łukasz Słonka, Ewa Słaby, Maciej Tomaszczyk, Leszek Krzemiński)
11:05–11:25	Iceland plume and its magmatic manifestations: LIP-Dornröschen in the North Atlantic (Sierd Cloetingh*, Alexander Koptev) **KEYNOTE**
11:25–11:45	Evolution of a maar-diatreme volcano within a sedimentary basin characterized by combined aquifer system (Mátyás Hencz*, Károly Németh, Tamás Spránitz, Tamás Biró, Dávid Karátson, Márta Berkesi)
11:45–12:05	Emplacement mechanisms of thick magma sheets in layered sedimentary basins: the post-caldera trachyandesite intrusions of the Intra-Sudetic Synclinorium, Poland (Sam Poppe*, Marek Awdankiewicz, Michael S. Petronis, Michael Heap, Claire Harnett, Stanislau Shytsik, Madison Allcorn, Alexandra Morand, Daniel Mège)

12:05–12:50: LUNCH

12:50–13:20: POSTER SESSION

FOLD-AND-THRUST BELTS AND FORELAND BASINS
(chair: M. Rowan, Ł. Słonka)

13:20–13:40	Broken Foreland Basins in the Andes and North American Cordillera (Brian K. Horton*) **KEYNOTE**
13:40–14:00	Evolution of tectonic successions controlling in- versus out-of- sequence, thin- versus thick- skinned deformation in external thrust belts and their foredeeps (Liviu C. Matenco*)
14:00–14:20	Tectono-stratigraphic evolution of the Eastern Mediterranean and Arabian Gulf region. Implications for hydrocarbon potential (Mohammed Alsaleh*, Al Fraser)
14:20–14:40	Geodynamic controls on Late Paleozoic flexural extension in the Arkoma Basin, USA (Brandon Lutz*, Mark Hudson, Tyson Smith, Marieke Dechesne, Leland Spangler)
14:40–15:00	A lithospheric transect from the Ligurian Sea to the Po Basin (Northern Italy): the dismembered and active Oligocene-to-recent foreland basin system based on an updated crustal and upper mantle gravity and geophysical model (Tamara Yegorova, Andrea Artoni*, Luigi Torelli, Anna Murovskaya, Aasiya Qadir, Nicolò Chizzini, Fabrizio Storti)

15:00–15:20: COFFEE BREAK / POSTERS

15:20–15:40	Salty sandwich; role of multiple-salt layers within the stratigraphic column of a fold-thrust belts (Hemin Koyi*) **KEYNOTE**
15:40–16:00	Basement nappe stacking and orogen-parallel extension in the North Dobrogea orogen (Andreea Marza-Ene*, Anneke Royakkers, Liviu C. Matenco, Hannah Pomella, Vlad Victor Ene, Bernhard Fugenschuh, Ioan Munteanu)
16:00–16:20	Deformation dynamics of the retro-wedge foreland: Seismic interpretation and numerical modeling study of the Llanos Basin, Colombia (Michal Nemčok*, Stephen A. Hermeston, Andreas Henk, Andres Mora, Camilo Higuera, Mauricio Parra, Samuel Rybar, Lucia Ledvenyiova)
16:20–16:40	Post hoc ergo propter hoc? On the origin of fluid emanations in the East Carpathians, Romania (Alexandru Szakács*, István János Kovács, Csaba Szabó, Márta Berkesi, Thomas Pieter Lange, Ágnes Gál, Ákos Kővágó, Orsolya Gelencsér, Sándor Gyila)

16:40–17:00 GENERAL DISCUSSION

17:00–20:00: ICEBREAKER

DAY 2, OCTOBER 9

GEOTHERMAL STATE AND EVOLUTION OF SEDIMENTARY BASINS
(chair: S. Mazur, L. Fodor)

08:00–08:20	The deep thermal field in plate tectonics (Magdalena Scheck-Wenderoth*, Judith Bott, Mauro Cacace, Denis Anikiev, Ajay Kumar) **KEYNOTE**
08:20–08:40	Deep and shallow geothermal energy resources in the Netherlands (Fred Beekman*, Liviu C. Matenco, Jan-Diederik van Wees)
08:40–09:00	The structural framework of the Southwestern Swiss Plateau termination: the impact on fluid-flow pathways and implications for geothermal exploration (Andrea Moscariello*, Ovie Eruteya, Fiammetta Mondino)
09:00–09:20	Geothermal vs hydrocarbon exploration in sedimentary basins: a de-risking workflow applied to the Swiss Plateau (Silvia Omodeo-Salé, Yasin Makhloufi, Ovie Emmanuel Eruteya, Andrea Moscariello*)

09:20–09:40: COFFEE BREAK / POSTERS

TECTONICS OF SEDIMENTARY BASINS
(chair: B. Horton, M. Nemčok)

09:40–10:00	Cenozoic inversion and bathymetry of the Black Sea: insights from the Ukrainian sector (Sergiy Stovba*, Randell Stephenson, Stanisław Mazur, Petro Fenota, Dmytro Vengrovych, Andrii Tyshchenko) **KEYNOTE**
10:00–10:20	Inversion Tectonics in the Southern Baltic Sea: Insights from Deep Seismic Profiles (Stanisław Mazur*, Sergiy Stovba, Małgorzata Ponikowska, Michał Malinowski, Piotr Krzywiec, Yuriy Maystrenko, Christian Hübscher)
10:20–10:40	Basement under cover; deformation of sedimentary layers above an oblique basement fault (Hemin Koyi*)
10:40–11:00	New constrains on the neotectonic deformation pattern of the Pannonian Basin: Are the fault pattern, the kinematic and stress data in agreement? (László Fodor*, Kristóf Porkoláb, Eszter Békési, Barbara Czecze, Gábor Csillag, Dániel Kalmár, Márta Kiszely, Szilvia Kövér, Bálint Süle, Anna Świerczewska, Antek Tokarski, Zoltán Wéber)
11:00–11:20	New flexural model of inversion tectonics (Piotr Krzywiec*)
11:20–11:40	From mid-Jurassic extension to obduction-related mélange formation: sedimentary records from a displaced segment of the Adriatic passive margin (NE Hungary) (Szilvia Kövér*, János Haas, Nevenka Djerić, Ottilia Szives, Péter Ozsvárt, László Fodor)
11:40–12:00	Copper hosting basins at the edge of cratons – The Yeneena Basin in Western Australia as a case study (Weronika Gorczyk*, Ian Tyler, Fariba Kohanpour)

12:00–12:45: LUNCH

DIAGENESIS AND FLUIDS IN SEDIMENTARY BASINS
(chair: A. Wysocka, M. Scheck-Wenderoth)

12:45–13:05	Intensive diagenesis and reservoir-quality modifications in shallow-buried syn-tectonic ramp limestones (Upper Cretaceous), United Arab Emirates (Mohammad Alsuwaidi*, Howri Mansurbeg, Daniel Morad, Mohammed Y. Ali, Sadoon Morad) **KEYNOTE**

13:05–13:25	Conceptualizing fluid-rock interaction diagenetic models in tectonic settings (Fadi H. Nader*, Liviu C. Matenco, Bilal U. Haq)
13:25–13:45	Shallow methane accumulations on the Romanian continental shelf of the Black Sea (Gabriel Ion*, Constantin Lazăr, Vlad Apotrosoaiei, Adrian Popa)
13:45–14:05	Understanding injected CO2 flow and trapping mechanisms with basin modelling principles (Mateusz Zaręba*, Geovani Christopher Kaeng)

14:05–14:25: COFFEE BREAK / POSTERS

EVOLUTION OF SEDIMENTARY COVER
(chair: A. Moscariello, W. Gorczyk)

14:25–14:45	Evolution of the Carboniferous sedimentary fill of the Lublin Basin (SE Poland) in the light of sequence stratigraphy and its impact on the prospects for energy resources, bauxites and CO2 storage (Maria I. Waksmundzka*) **KEYNOTE**
14:45–15:05	Internal structure of Upper Jurassic subsurface carbonate buildups in SE Poland - an insight from seismic forward modelling supported by outcrop analogues (Łukasz Słonka*, Marcin Krajewski, Piotr Krzywiec)
15:05–15:25	Yen Bai Basin (Red River Fault Zone, northern Vietnam) as an example of the tectono-sedimentary play (Anna Wysocka*, Stanisław Mazur, Piotr Krzywiec, Anna Filipek, Phan Dong Pha, Nguyen Quoc Cuong, Do Van Thang, Nguyen Van Kieu, Daniel Zaszewski)
15:25–15:45	Exotic provenance of the Middle Carboniferous sandstones of the Donets Basin according to the results of the U-Pb zircon dating (Leonid Shumlyanskyy*, Vladyslav Shumlyanskyy)
15:45–16:05	From Eocene Greenhouse to Oligocene Icehouse: the marine record of the Paratethys (Eastern Carpathians and Transylvanian Basin, Romania) (Mihaela Melinte-Dobrinescu*, Relu-Dumitru Roban, Alina Magdaş, Gabriela Cristea)
16:05–16:25	Upper Cretaceous syn-inversion depositional systems in the southeastern East European Craton, NE Poland (Aleksandra Stachowska*, Piotr Krzywiec)

16:25–16:45: COFFEE BREAK / POSTERS

EVAPORITIC BASINS AND SALT TECTONICS
(chair: Ł. Grzybowski, A. Stachowska)

16:45–17:05	The complicating role of salt in rift-related sedimentary basins (Mark G. Rowan*) **KEYNOTE**
17:05–17:25	Geological exploration of salt structures for solution mining and underground storage in Poland – techniques used and current challenges (Łukasz Grzybowski*, Mariusz Chromik)
17:25–17:45	How to search for signs of life in Martian Evaporites: Evidence of fluid inclusions in the polygonal structures of evaporites similar to Mars in the Qaidam Basin (Fanwei Meng*, Anatoliy R. Galamay)
17:45–18:05	Internal deformation of salt diapirs: A case study from the Altaussee Salt Mine (Marta Adamuszek*, Marcin Olkowicz, Marcin Dabrowski, Mariusz Fiałkiewicz, Bartłomiej Grochmal, Thomas Leitner, Oscar Fernandez)

18:05–18.30: GENERAL DISCUSSION & CONCLUDING REMARKS

20:00–23:00: GALA DINNER

POSTERS

Provenance of the Black Flysch and Ceahlău thrust sheets of the Eastern Carpathians (Constantin Lazăr*, Relu-Dumitru Roban, Mihai Ducea, Andrei-Rareş Stoian)
Northern Apennine buried structures observed from analyses of geophysical data to evaluate their geothermal potential (Magdala Tesauro*, Valentina Cortassa, Gianluca Gola, Thomas Nanni, Marina Facci, Antonio Galgaro, Adele Manzella)
Integrated geological modelling for assessing geothermal potential in the Romagna and Ferrara Folds (Valentina Cortassa*, Magdala Tesauro, Gianluca Gola, Thomas Nanni, Marina Facci, Antonio Galgaro, Adele Manzella)
Link between magmatic intrusions and the previous rift system, inferences from New Zealand passive margin (Cristina Mărioara Călugărean*, Ioan Munteanu)
Miocene Carpathian foreland basin in SE Poland and W Ukraine – its unusual structure and depositional infill formed due to extensional reactivation of inherited Mesozoic faults (Piotr Krzywiec*)
Defining the kinematic of scale-folds: Inferences from an East Carpathians Nappe (Valentin Nistor*, Liviu C. Matenco, Ioan Munteanu)
Unraveling fluid flow and fluid-rock interactions during the Dinarides collisional orogenesis: integrated structural fracture analysis and petrographic and geochemical characterization (Maja Maleš*, Fadi Henri Nader, Liviu C. Matenco, Uroš Stojadinović, Nemanja Krstekanić, Renaud Divies, Nikola Ranđelović)
Theoretical insight into a kinematic model of fault-bend folding (Szymon Mol*)
Jurassic-Lower Cretaceous sedimentological evolution and tectonostratigraphy of the southern distal passive margin of the Alpine Atlantic in the Serbian part of the Carpatho-Balkanides (Nevenka Djerić*, Renata Jach, Špela Goričan, Daniela Reháková, Alfred Uchman, Hans-Jürgen Gawlick, Ján Schlögl, Uroš Stojadinović)
Structural geometry and evolution of salt diapirs and related fault system around the Tonb-Bozor Island, SE Persian Gulf: Potential diapiric basin for future CO2 storage (Mehrsa Haji Khani*, Mahdi Najafi)
The latest Famennian to early Mississippian tectonic deformations and uplift at the distal foreland of the Variscan orogen (Lublin-Lviv Basin; SW East European Craton) driven by transpression and thermal doming (Paweł Poprawa*, Maciej Tomaszczyk)
Influence of anhydrite interlayers on the structural stability of salt caverns (Michał Słotwiński*, Marta Adamuszek, Dąbrowski Marcin)
Geotouristic relevance of Romanian mineral and rock type localities (Ágnes Gál*, Alexandru Szakács, Corina Ionescu, Marinel Kovacs)
Overpressure Prediction Challenges in Deepwater Fold-Thrust Belt of the Sundaland Continental Margin, Southeast Asia (Mateusz Zareba*, Geovani Christopher Kaeng)
Deep-seated, faults-driven geothermal resources in the Himalaya-Karakoram Orogenic belt, Northern Pakistan (Mumtaz Muhammad Shah*, Muhammad Anees)
New insight into structure of the East European Craton in Poland based on analysis of potential field data and regional deep seismic reflection profiles (Mateusz Mikołajczak*, Stanisław Mazur, Piotr Krzywiec)
Syn-depositional thrusting within the NW Qaidam Basin, Tibet Plateau, China – insight from 3D seismic data (Mateusz Łasiewicki*, Piotr Krzywiec, Fanwei Meng, Wenhang Liu, Stanisław Mazur)

Multistage selective diagenesis increasing poro-perm properties of Anisian sponge-microbial-coral patch reefs and adjacent facies in the Muschelkalk of Upper Silesia, southern Poland (Iga Ryczkowska*)
The role of hydrocarbon generation and expulsion in joint system formation by natural hydraulic fracturing mechanism: case of shales in the Lower Paleozoic Baltic Basin (Poland) (Marek Jarosiński*, Kinga Bobek, Paweł Poprawa)
The Integrated Prediction Error Filter Analysis algorithm in the reservoir parameters estimation in thinly-bedded Miocene formations from well logs and laboratory tests (Sebastian Waszkiewicz*, Paulina Krakowska-Madejska, Jadwiga Jarzyna, Paul van der Vegt)

INTERNAL DEFORMATION OF SALT DIAPIRS: A CASE STUDY FROM THE ALTAUSSEE SALT MINE

Marta Adamuszek[1]

[1]Computational Geology Laboratory, Polish Geological Institute – National Research Institute, Wrocław, Poland

Co-authors: Marcin Olkowicz[2], Marcin Dąbrowski[1], Mariusz Fiałkiewicz[1], Bartłomiej Grochmal[1], Thomas Leitner[2] and Oscar Fernandez[3]

[2]Salinen AG, Altaussee Austria; [3]Department of Geology, University of Vienna, Vienna, Austria

Our study was conducted within the Altaussee salt mine, located in the Northern Calcareous Alps, Austria, where extensive deformation of the Permian to Triassic evaporitic succession has led to the formation of a highly complex tectonic mélange. The salt-bearing strata are particularly notable for their abundance of brecciated fragments, composed of anhydrite, polyhalite, sandstone, and limestone, with fragment sizes reaching up to several meters in diameter. The halite content in these deposits varies significantly, ranging from 30% to 65%. The most striking features are the structures that have developed around or in close proximity to the brecciated clasts, which are found either as isolated fragments or in clusters. The alternating thin red and greyish layers in the halite-rich matrix significantly enhance the visibility of these structures, allowing for a detailed study of their intricate and complex morphology.

Our investigation focuses on well-exposed structures in the salt cavern ceiling, which covers approximately 4000 square meters. By employing a customized photogrammetric technique, advanced image post-processing, and lidar data as a reference, we produced a highly detailed orthophoto map of 1,000 square meters of the cavern ceiling with a resolution of 1 mm/pixel. Within the cavern, we documented numerous closed contour patterns. The closed contours rarely exhibit regular elliptic shape, instead, they often display complex patterns, such as curves wrapping around adjacent clasts, folded eye shapes, or tie-shapes resulting from eye-shaped contours being squeezed between neighboring clasts. Using 2D and 3D numerical modelling, we tested various scenarios of the origin of these structures.

Choose program group: Stress, strain and fluids in sedimentary basins

Email: marta.adamuszek@pgi.gov.pl

TECTONO-STRATIGRAPHIC EVOLUTION OF THE EASTERN MEDITERRANEAN AND ARABIAN GULF REGION. IMPLICATIONS FOR HYDROCARBON POTENTIAL

Mohammed Alsaleh

Saudi Aramco, Dhahran, Saudi Arabia

Co-authors: Al Fraser
Imperial College, London, UK

One of the world's promising regions in hydrocarbon exploration that is largely underexplored is the Eastern Mediterranean basin. It covers a significant area including several sub basins of Levant, Nile and Herodotus. It has a thick sedimentary cover which has undergone several stages of extension, thermal subsidence and compression. While most of exploration efforts to date have concentrated on Tertiary shallow strata, the deeper age strata may actually be much more prospective as is the case within Middle Eastern lands which opens a question of possible similar carbonate reservoirs given the combined history of the two regions of neo-Tethys opening. Examining combined regional and local multiple surveys of 2-D seismic lines gives a basin-wide overview of structural, stratigraphic and petroleum elements. Proven source rocks and hydrocarbon bearing reservoirs despite the scarcity of deep wells indicates a potentially prospective petroleum system within Jurassic and Cretaceous plays. Large extended chains of isolated carbonate buildups similar to today's Bahamas reefs are interpreted within the basin similar to the recent large gas field Zohr discovery in Egypt's offshore water. The study suggests even larger carbonates exist within deeper Mesozoic strata. Several other types of plays are suggested as possible traps for hydrocarbons of stratigraphic and structural nature. The Eastern Mediterranean basin is encouraging for hydrocarbon exploration despite the scarcity of data and drilling wells which can potentially supply surrounding countries with oil & gas in the long term.

Email: mohammed.saleh.5@aramco.com

INTENSIVE DIAGENESIS AND RESERVOIR–QUALITY MODIFICATIONS IN SHALLOW-BURIED SYN-TECTONIC RAMP LIMESTONES (UPPER CRETACEOUS), UNITED ARAB EMIRATES

Mohammad Alsuwaidi[1]

[1]Department of Earth Science, Khalifa University, Abu Dhabi, United Arab Emirates

Co-authors: Howri Mansurbeg[2], Daniel Morad[3], Mohammed Y. Ali[1] and Sadoon Morad[4]

[2]General Directorate of Scientific Research Center, Salahaddin University-Erbil, Erbil, The Kurdistan Region, Iraq; [3]Petrographica, Uppsala, Sweden; [4]Department of Petroleum Engineering, Knowledge University, Erbil, Kurdistan Region, Iraq

This study utilizes petrographic, geochemical and fluid-inclusion microthermometric analyses to delineatethe conditions controlling the distribution of diagenetic alterations and associated reservoir-quality evolution of shallow-buried (around 1.3 km) syn-tectonic, foreland-basin ramp limestones, Upper Cretaceous of the United Arab Emirates. The diagenetic alterations are linked to porewater evolution during tectonic evolution of the basin, as well as to the depositional facies and sequence stratigraphy. Diagenetic processes have led to either preservation, deterioration, or improvement of reservoir quality of the limestones. Deterioration ensued mostly from calcite cementation by hot basinal/hydrothermal brines and from mechanical compaction of ductile peloids formed by micritization of allochems. Micritization, notably prevalent in the transgressive lagoon and upper ramp slope packstones, as well as in the regressive shoal grainstones below marine-flooding surfaces, led to the development of abundant microporosity. Porosity was preserved in the grainstones by partial calcite cementation (rims, as well as scattered equant crystals and syntaxial overgrowths), which supported the framework against mechanical compaction. Dissolution of aragonitic allochems and subsequent cementation by equant calcite was notably prevalent in regressive (including LSW) shoal grainstones. These processes occurred during repeated episodes of subaerial exposure and meteoric-water incursion as a consequence of active syn-tectonic deposition of the formation. Calcite cementationoccurred dominantly by hot basinal/hydrothermal brines with temperatures of approximately 60–135°C and a salinity of 16–22 wt.% NaCl eq. migrating to shallow depths along deep sub-vertical faults. Although not-systematic, porosity and permeability are larger in limestones in the oil than in the water zones, indicating that oil emplacement retarded diagenesis.

Email: mohammad.alsuwaidi@ku.ac.ae

DEEP AND SHALLOW GEOTHERMAL ENERGY RESOURCES IN THE NETHERLANDS

Fred Beekman[1]

Department of Earth Sciences, Utrecht University, Utrecht, The Netherlands

Co-authors: Liviu C. Matenco[1] and Jan-Diederik van Wees[1,2]

[2]TNO/Dutch Geological Survey, Utrecht, The Netherlands

Geothermal energy has been exploited in the Netherlands since 2007. Most geothermal wells have been developed by private companies for heating greenhouses. The first public well for district heating became operational in The Hague only two years ago. A second public well, which will also be used for research purposes, was drilled in Delft less than a year ago. The geothermal wells are located in Mesozoic rift basins and produce direct heat from aquifers of Triassic or Rotliegend sandstone at depths between about 2,000 and 3,000 m. Temperatures range from 60 to 90°C, in line with the average Dutch geothermal gradient of 31°C/km derived from borehole temperature data from several hundred wells.

The amount of energy produced by a geothermal well depends not only on technical factors such as well diameter and pumping pressure, but also on local geological parameters such as depth, thickness and permeability of the aquifer. Using a digital 3D geological model of the Netherlands, TNO/DGS calculated the geothermal potential of different aquifers. The results show not only large differences in geothermal potential between aquifers, but also vertical and lateral heterogeneity within aquifers caused by differences in depositional environment, facies and burial history. A more detailed characterisation of the internal stratigraphy of aquifers is therefore important to optimise the location of new geothermal wells.

Of increasing importance are shallow Tertiary sandstone aquifers, which are being considered at various locations in the Netherlands for seasonal storage of excess heat produced by industry and/or of excess electricity produced by solar and wind. A national research programme is currently investigating the storage of excess industrial heat in the Early Pliocene Maassluis Formation, which consists mainly of fine- to medium-grained sand, in the greater Rotterdam port area. A more detailed characterisation of the aquifer is obtained through reinterpretation of seismic and well data, measurements of porosity and permeability of core samples and regional stratigraphic forward modelling studies.

A pilot project was launched this summer to demonstrate the feasibility of storing excess electricity generated by a solar panel field in shallow aquifers under the Utrecht University campus. A higher-resolution subsurface model will be obtained by integrating seismic data and new stratigraphic studies with existing shallow subsurface data.

Email: fred.beekman@uu.nl

LINK BETWEEN MAGMATIC INTRUSIONS AND THE PREVIOUS RIFT SYSTEM, INFERENCES FROM NEW ZEALAND PASSIVE MARGIN

Cristina Mărioara Călugărean[1]

[1]Institute of Geodynamics Sabba S. Ştefănescu, Romanian Academy; [2]Faculty of Geology and Geophysics, University of Bucharest, Romania

Co-authors: Ioan Munteanu[2, 1]

The aim of this study is to define the architecture of the New Zeeland continental margin (Great South Basin study area) resulted from tectonic inversion of a previous magma poor rift system. The New Zeeland continental margin is a good place to study the factors controlling the localization of subduction magmatism intruding the previous extensional domain. The study benefits from the recent acquired high resolution 3D seismic data, that gives the possibility of mapping the intrusive bodies as well as the deep structure of the rift system following the new establish concept of a rift evolution, based on the Iberia–Newfoundland case study. The New Zealand microcontinent has a long tectonic history which start with the Jurassic–Cretaceous intracontinental extension processes which led ultimately to the continental break-up and formation of expansion ridge in Late Cretaceous. The oceanic expansion continues throughout the Cenozoic times while the New Zealand become passive margin domain with subsidence driven by thermal coaling of a previous extended continental lithosphere. The passive margin sediments are intruded by magmatic material along the inherited rift structure conduits. Present tectonic architecture is governed by the subduction of Tasman Basin under Zealandia continent along Alpine Fault in the last 20Ma. We have identified and mapped several magmatic bodies like sills, dykes, laccolith and even volcanic structures, that, in some cases, are crossing the entire sedimentary stive reaching the seafloor, while many others are trapped at different stratigraphic levels. The deep rift architecture is defined by some characteristic tectonic structures like H-block, continental ribbons and demi-grabens. These blocks are bounded by poly-phase structural elements, either stretching, exhumation or thinning faults. Crustal thinning was accommodated along the detachment resulting in lower crust migration and uplift of continental upper lithospheric mantle. This architecture suggest that this area correspond with the necking and transition domains of a magma-poor rift system. The source of the magmatic material might be related with active subduction process, while their migration and localization along continental crust is facilitated by the inherited extensional faults.

Email: m.cristinacalugarean@gmail.com

ICELAND PLUME AND ITS MAGMATIC MANIFESTATIONS: LIP-DORNRÖSCHEN IN THE NORTH ATLANTIC

Sierd Cloetingh

Department of Earth Sciences, Utrecht University, Utrecht, The Netherlands

Co-authors: Alexander Koptev

GFZ German Research Centre for Geosciences, Potsdam, Germany

Plume-lithosphere interactions are key in the coupling of deep Earth and surface processes, impacting deformation and evolution of sedimentary basins and continental topography at different spatial scales (Cloetingh et al., 2022, 2023). The North Atlantic region is a prime example of the interaction between plate tectonic movements and thermal instabilities in the Earth's mantle. The opening of the Labrador Sea/Baffin Bay and the North Atlantic, the widespread volcanism and the localized uplift of the topography in Greenland and the North Atlantic are traditionally attributed to the thermal effect of the Iceland mantle plume. However, several prominent features of the region – the temporal synchrony of magmatism and break-up events, the symmetrical configuration of the Greenland–Iceland–Faroe Ridge, and the diachronous domal uplift of the North Atlantic rifted margins – have inspired alternative, "non-plume" views. According to these, the North Atlantic Igneous Province (NAIP) and Iceland magmatism originate from plate tectonic processes sourced in the shallow upper mantle, at odds with the unequivocal presence of deep-seated low-velocity seismic anomalies beneath Iceland and the isotopic signatures of plume-derived melts in Cenozoic magmatic units.

We resolve apparent contradictions in the observations and reconstructions and reconcile end-member concepts of the Late Mesozoic–Cenozoic evolution of the North Atlantic realm. We show that simultaneous Paleocene (~62–58 Ma) magmatism in Western Greenland/Baffin Island and the British Isles, which together form the NAIP, is driven by two processes accidently coinciding in time: 1) the propagation of the Labrador Sea/Baffin Bay spreading axis has overlapped with the ~100–80 Ma dated segment of the Iceland hotspot track near the West Greenland margin, while 2) the actual tail of the Iceland plume has reached the eastern continental margin of Greenland, allowing a horizontal flow of hot plume material along corridors of relatively thinned lithosphere towards Southern Scandinavia and Scotland/Ireland. In this framework, the subsequent formation of the symmetrical Greenland–Iceland–Faroe Ridge can be coherently explained by the continuous supply of hot plume material through an established channel between Eastern Greenland and the British Isles. In contrast to the Scotland/Ireland region, the South Norway continental lithosphere remains too thick to enable localized uplift of the topography and melting immediately after plume lobe emplacement at ~60 Ma. Therefore, the development of topographic domes in Southern Scandinavia only started ~30 Myr later in the Oligocene as a consequence of increasing ridge-push compression that built up during the opening of the Norwegian–Greenland Sea.

The evolution of the North Atlantic region shows that a thermal anomaly that has been hidden below a thick lithosphere for tens of Myr without signs of excessive magmatism can be re-initialized (or "re-awakened") by the lateral propagation of spreading ridges or by the tapping of its source beneath thinner segments of the overlying lithosphere due to horizontal plate movements. We dub this type of Large Igneous Province (LIP) as LIP-Dornröschen (LIP-Sleeping Beauty) (Koptev et al., 2021; Koptev and Cloetingh, 2024). We hypothesise that the term LIP-Dornröschen may be applicable to a broad family of LIPs, including Precambrian and oceanic LIPs. This means that the interpretation of the timing of LIP formation from the perspective of mantle dynamics should be treated with caution, as there may be delays between the timing of upwelling in the mantle and detectable magmatic manifestations at or near the Earth's surface.

Email: s.a.p.l.cloetingh@uu.nl

INTEGRATED GEOLOGICAL MODELLING FOR ASSESSING GEOTHERMAL POTENTIAL IN THE ROMAGNA AND FERRARA FOLDS

Valentina Cortassa [1]

[1] Dipartimento di Matematica, Informatica e Geoscienze, Università di Trieste, Trieste, Italy

Co-authors: Magdala Tesauro [1,2], Gianluca Gola [3], Thomas Nanni [3], Marina Facci [4], Antonio Galgaro [4] and Adele Manzella [3]

[2] Department of Earth Sciences, Utrecht University, Utrecht, The Netherlands; [3] Istituto di Geoscienze e Georisorse, CNR, Pisa, Italy; [4] Dipartimento di Geoscienze, Università di Padova, Padova, Italy

Geothermal energy is recognised as a sustainable and environmentally friendly solution for power generation and district heating/cooling. It provides continuous availability year-round and day-long, with considerable potential for development worldwide. However, the exploitation of deep geothermal reservoirs requires thorough and detailed reservoir characterisation.

The InGEO project ("Innovation in GEOthermal resources and reserves potential assessment for the decarbonisation of power/thermal sectors") aims to develop an innovative exploration workflow that integrates geological/geophysical data and other direct and indirect information, in order to characterise the reservoir rocks and the overlying sedimentary cover. InGEO is a PRIN 2022 PNRR Project and has received funding from the European Union, Next Generation EU.

Our target area includes the Romagna and Ferrara folds, where a thermal anomaly has been identified and attributed to thermal convection in deep-seated Mesozoic carbonate units. The Romagna and Ferrara folds represent the outer deformation front of the Northern Apennines thrust and fold belt, buried beneath the Plio–Pleistocene terrigenous deposits of the Po plain. The Ferrara folds consist of a Mesozoic carbonate sequence that was strongly deformed during Neogene and Quaternary tectonics, while the Romagna folds consist of Tertiary clastic formations overlying Mesozoic limestones.

We collect, digitise and analyse data from over 200 seismic surveys from the VIDEPI database, 250 deep (>1500 m) boreholes (CNR database) and 160 borehole logs (sonic and lithological logs). We use this database, to construct a 3D geological model, needed to evaluate the geothermal potential of the reservoir. The model is based on the identification of main lithological unconformities, through the interpretation of seismic reflection lines constrained by well-stratigraphic data. The obtained results will be further complemented by those derived from thermophysical experiments carried out on samples representative of each main geological unit.

This geological model will contribute to the development of an open-source web-based GIS tool and will serve as the main input for the calculation of the geothermal potential of the area, thus improving the business planning for the exploitation of deep geothermal resources in Italy.

Email: valentina.cortassa@units.it

JURASSIC-LOWER CRETACEOUS SEDIMENTOLOGICAL EVOLUTION AND TECTONOSTRATIGRAPHY OF THE SOUTHERN DISTAL PASSIVE MARGIN OF THE ALPINE ATLANTIC IN THE SERBIAN PART OF THE CARPATHO-BALKANIDES

Nevenka Djerić [1]

[1]Faculty of Mining and Geology, University of Belgrade, Belgrade, Serbia

Co-authors: Renata Jach[2], Špela Goričan[3], Daniela Reháková[4], Alfred Uchman[2], Hans-Jürgen Gawlick[5], Ján Schlögl[4] and Uroš Stojadinović[1]

[2]Institute of Geological Sciences, Jagiellonian University, Kraków, Poland; [3]Paleontološki Inštitut Ivana Rakovca ZRC SAZU, Ljubljana, Slovenia; [4]Department of Geology and Palaeontology, Faculty of Natural Sciences, Comenius University, Bratislava, Slovakia; [5]Department for Applied Geosciences and Geophysics, Energy Geosciences, Montanuniversität Leoben, Leoben, Austria

The Jurassic to Early Cretaceous depositional history of the Carpatho-Balkanides reflects the graben (Early Jurassic) to passive continental margin (Middle Jurassic to Late Cretaceous) evolution of the Alpine Atlantic. As there is still no consensus about the Jurassic–Cretaceous palaeogeographic position of the Carpatho-Balkanides on the northern edge of the Moesian unit (Europe or wider Adria) a detailed knowledge of the passive continental margin depositional history is crucial to solving such open questions. Whereas the Early Jurassic graben infilling (Gresten Facies in a wider sense) is palaeogeographically only diagnostic to decide if units derive from the western or eastern Alpine Atlantic, the Middle Jurassic to Upper Cretaceous sedimentary successions differ in their overall lithology, sedimentological evolution, microfacies and geochemical characteristics on both the northern and southern margins of this oceanic domain but have only been studied in an overall manner up to now. Modern biostratigraphic age dating, sedimentological or geochemical studies are missing.

Jurassic–Lower Cretaceous deposits along the valley of the Danube River in Serbia have been studied. The new biostratigraphic and microfacies results from the Middle–Upper Jurassic sedimentary rocks of the three successions are complemented by the obtained geochemical data. Detailed biostratigraphic analyses of radiolarians, calpionellids, dinoflagellates, and ammonites shed light on the paleoenvironmental and paleogeographic changes of the open marine environments in the Serbian part of the Carpatho-Balkanides, during Middle Jurassic–Early Cretaceous times. These successions indicate a typical horst-and-graben topography, well known from other domains of the Alpine Atlantic, formed during the continental break-up around the Early/Middle Jurassic boundary. Sedimentary successions deposited in deeper basins or in a horst position can be distinguished. The topographic difference was apparently diminished by the Early Cretaceous, when Maiolica type limestone above radiolarites and above condensed Rosso-Ammonitico-type limestone became ubiquitous. This depositional history resembles sedimentary successions from the northern units of the Eastern Alps or Western Carpathians. The successions studied are also closely similar to those of the Southern Alps, but the underlying rocks are different. The pre-Toarcian deposits in the study area are quartz sandstones and conglomerates (Gresten facies), whereas the coeval deposits of the Southern Alps are platform to deeper-water carbonates.

Email: nevenka.djeric@rgf.bg.ac.rs

NEW CONSTRAINS ON THE NEOTECTONIC DEFORMATION PATTERN OF THE PANNONIAN BASIN: ARE THE FAULT PATTERN, THE KINEMATIC AND STRESS DATA IN AGREEMENT?

László Fodor[1]

[1]HUN-REN Institute of Earth Physics and Space Science, Sopron, Hungary; [2]Department of Geology, Institute of Geography and Earth Sciences, Eötvös University, Budapest, Hungary

Co-authors: Kristóf Porkoláb[1], Eszter Békési[1], Barbara Czecze[1], Gábor Csillag[3], Dániel Kalmár[1], Márta Kiszely[1], Szilvia Kövér[1,2], Bálint Süle[1], Anna Swierczewska[4], Antek Tokarski[5] and Zoltán Wéber[1]

[3]HUN-REN Research Centre for Astronomy and Earth Sciences, Budapest, Hungary; [4]AGH University, Kraków, Poland, [5]Institute of Geological Sciences, Polish Academy of Sciences, Kraków, Poland

Neotectonic deformation of the Pannonian basin is marked by the inversion of the former extensional to transtensional basin formation process. Several normal faults were reactivated as reverse faults while a basin-wide change in stress regime has been documented toward compressional or transpressional regime. Despite this generally accepted features, new data may show some discrepancies in this simple picture, and few regions will be presented in this context.

One characteristics of the present-day stress field – mostly known from earthquake focal mechanism and borehole break-out data – is the curved σ1 trajectories from the closely N–S to closely E–W direction from the south-western to the eastern part of the basin. This changing direction is in contrast with the linearity of supposedly active strike-slip faults of NE-SW orientation, shown to be present in the entire basin. Seismic data show that these relatively linear strike-slip faults were originated during the post-rift phase, after ~ 9 Ma, or potentially even earlier, and they are supposed to be active during the neotectonic phase started around 6 Ma or few million years later. Sinistral kinematics of these faults are derived from the presence of en echelon secondary fractures.

However, below the Great Hungarian Plane, stress field data derived from new earthquake focal mechanisms would induce dextral or normal-dextral kinematics on the supposedly sinistral faults, in agreement with other stress data and even with strain rate data calculated from GPS. Near the Lake Balaton, the well-documented NE-striking sinistral fault kinematics disagree with ENE–WSW oriented compression (from focal mechanism). Further to the NE, in the Vértes Hills, the discrepancies are between the fault directions, their kinematics, and stress inferred from earthquakes. Namely, focal mechanisms would suggest NE–SW directed compression, while part of the active faults are parallel to σ1 and have normal kinematics. The other active structure, the Mór Fault is subperpendicular to σ1, but to remain active this fault should have changed its long-lasting normal kinematics to reverse one which has not documented yet.

These discrepancies could have several reasons, like improper kinematic observations on the surface, a recent (<1 Ma) change in the stress field, when the short time span was not enough to develop important new faults corresponding to new stress field, slightly different deformation characters at the seismogenic depth than on the surface, transient character of recent (0–50 y) deformation pattern, difference in deformation mechanism at depth and in near-surface.

Email: fodor.laszlo@epss.hun-ren.hu

GEOTOURISTIC RELEVANCE OF ROMANIAN MINERAL AND ROCK TYPE LOCALITIES

Ágnes Gál [1]

[1]Department of Geology, Babeş-Bolyai University, Napoca, Romania

Co-authors: Alexandru Szakács[2], Corina Ionescu[3] and Marinel Kovacs[4]

[2]Institute of Geodynamics, Romanian Academy, Bucharest, Romania; [3]Electron Microscopy Center, Babeş-Bolyai University, Napoca, Romania; [4]Technical University of Cluj-Napoca, North University Centre of Baia Mare, Napoca, Romania

According to the IMA Commission on New Minerals, Nomenclature and Classification, 6062 minerals are currently known worldwide [July 2024 (https://cnmnc.units.it/)], out of which 39 are first described in today's Romania. Due to the high geological diversity of Romanian territorry, considerate is important to combine the 'geological diversity' and the 'geotourism', the latter involving mineral and rock-type localities. The type localities can be listed in three major regions: i) Oaş-Gutâi, ii) Apuseni Mts. and iii) Banat Region and include16 type localities where new minerals and one new chemical element have been described for the first time. The type locality of a common rock, dacite, can be also added to the list of Romanian first discoveries. A plagioclase-phyric volcanic rock, it was firstly described by the Austrian geologists Hauer and Stache (1863) at Poieni/Kissebes in the northern Apuseni Mts.

The richest mineral type localities are Săcărâmb/Nagyág in the southern Apuseni Mts. (with 8 new minerals discovered here), Baia Sprie/Felsőbánya in the Baia Mare region (6 new minerals) and Băița Bihor/Rézbánya in the Northern Apuseni Mts. (6 new minerals). The chemical element tellurium and two new mineral species (native tellurium and tellurite) make the once flourishing but nowadays abandoned Fața Băii/Facebánya mining spot worldwide famous.

The touristic, scientific and educational value and significance of the type localities regarded as "geosites" and "geodiversity sites" are discussed. In order to stress the scientific and patrimonial value of the Romanian mineral and rock type localities in terms of scientific, educational and touristic values, they were classified and hierarchically ordered, Baia Sprie, Săcărâmb and Măgura Uroiului being the highest ranked. From the geoconservation and geotouristic perspective, site protection and valuation strategies at local and/or regional scales are envisaged. A roughly NS-oriented touristic route connecting the most of mineral and rock type localities, as well as three ex-situ geosites (mineralogical museums) is proposed.

Email: agnes.gal@ubbcluj.ro

SILL STACKING IN SUBSEAFLOOR UNCONSOLIDATED SEDIMENTS AND CONTROL ON SUSTAINED HYDROTHERMAL SYSTEMS: EVIDENCE FROM IODP DRILLING IN THE GUAYMAS BASIN, GULF OF CALIFORNIA

Christophe Galerne [1,2]

[1]MARUM Center for Marine Environmental Sciences, University of Bremen, Bremen, Germany; [2]FB5 Geosciences, University of Bremen, Bremen, Germany

Co-authors: Alban Cheviet[2,3], Wolf-Achim Kahl[4], Christin Wiggers[2], Wolfgang Bach[1,2], Florian Neumann[5], Martine Buatier[3], Tobias W. Höfig[6,7], Daniel Lizarralde[8], Andreas Teske[9], Manet Peña-Salinas[10], Jens Karstens[11], Christoph Böttner[12], Christian Berndt[11], Ivano W. Aiello[13], Kathleen M. Marsaglia[14], Swanne Gontharet[15], Henning Kuhnert[1], Joann Stock[16], Raquel Negrete-Aranda[17], Junli Zhang[1] and Achim Kopf[1]

[3]Laboratoire Chrono-Environment, UMR 6249, Université Franche-Comté, Besançon, France; [4]MAPEX – Center for Materials and Processes, University of Bremen, Bremen, Germany; [5]GFZ, German Research Centre for Geosciences, Section 4.8 Geoenergy, Potsdam, Germany; [6]International Ocean Discovery Program, Texas A&M University, College Station,TX, USA; [7]Coastal, Marine, and Polar Research, Research Center Jülich, Rostock, Germany; [8]Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA, USA; [9]Department of Earth, Marine and Environmental Sciences, University of North Carolina at Chapel Hill, NC, USA; [10]Department of Coastal Oceanography, UABC, Zona Playitas, Ensenada, Mexico; [11]GEOMAR | Helmholtz-Zentrum für Ozeanforschung Kiel, Kiel, Germany; [12]Department of Geoscience, Aarhus University, Aarhus, Denmark; [13]Moss Landing Marine Laboratories, San Jose State University, Moss Landing, CA, USA; [14]Department of Geological Sciences, California State University, Northridge, CA, USA; [15]LOCEAN, UMR 7159, Sorbonne Université/CNRS/IRD/MNHN, Paris, France; [16]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA, USA; [17]Department of Geology, CICESE, Ensenada, Mexico

Magma emplacement in the top unconsolidated sediments of rift basins is poorly constrained in terms of mechanics and associated hydrothermal activity. Our study compares two shallow sills from the Guaymas Basin (Gulf of California) using core data and analyses from IODP Expedition 385, and high-resolution 2D seismic data. We show that magma stalling in the top uncemented sediment layer is controlled by the transition from siliceous claystone to uncemented silica-rich sediment, promoting flat sill formation. Space is created through a combination of viscous indentation, magma-sediment mingling and fluidization processes. In low magma input regions, sills form above the opal-A/CT diagenetic barrier, while high magma input leads to upward stacking of sills, forming funnel-shaped intrusions near the seafloor. Our petrophysical, petrographic, and textural analyses show that magma-sediment mingling creates significant porosity (up to 20%) through thermal cracking of the assimilated sediment. Stable isotope data of carbonate precipitates indicate formation temperatures of 70−90°C, consistent with the current background geothermal gradient at 250−325 m depth. The unconsolidated, water-rich host sediments produce little thermogenic gas through contact metamorphism, but deep diagenetically formed gas bypasses the low-permeability top sediments via hydrothermal fluids flowing

through the magma plumbing system. This hydrothermal system provides a steady supply of hydrocarbons at temperatures amendable for microbial life, acting as a major microbial incubator. Similar hydrothermal systems are expected to be abundant in magma-rich young rift basins and play a key role in sustaining subseafloor ecosystems. Finally, our study allows to refine recent discoveries that indicate large fraction of the thermogenic gases mobilized during contact metamorphism process remain trapped in the lower contact aureoles or in the sills. We show here that this process is confirmed in the deeper studied sill, thereby improving our understanding of natural carbon sequestration process associated with magmatic intrusions.

Email: cgalerne@uni-bremen.de

THE NEUQUÉN BASIN, ARGENTINA – A WORLD-CLASS CASE STUDY ILLUSTRATING MAGMA-ROCK INTERACTIONS IN HYDROCARBON-BEARING SEDIMENTARY BASINS

Olivier Galland[1]

[1]Njord Centre, Department of Geosciences, University of Oslo, Norway

Co-authors: Juan B. Spacapan[2], Octavio Palma[3], Ezequiel Lombardo[4], Ole Rabbel[1] and Dougal Jerram[1,5]

[2]YPF, Argentina, [3]Universidad Nacional de La Plata, Argentine; [4]Chevron Argentina/Universidad de Buenos Aires, Argentina; [5]DougalEarth, UK

The Neuquén Basin, Argentina, has been one of the most productive hydrocarbon basins in South America. In addition, the Neuquén Basin hosts massive Cenozoic volcanism. The combination of substantial subsurface data, generated by oil industry, and outstanding outcrops make the Neuquén Basin a fantastic playground to study magma-rock interactions. This contribution summarizes research in the Neuquén Basin implemented during the last decade, through demonstrative case studies that illustrate different aspects of magma-rock interactions and their implications for the evolution of sedimentary basins.

The Neuquén Basin hosts the peculiar Río Grande Valley (RGV) oil fields. The reservoir rocks are fractured andesite to basalt sills preferentially emplaced in the main source rock formations of the basin (Spacapan et al., 2020, doi: 10.1016/j.marpetgeo.2019.08.038). Integrated studies from borehole data and geological field observations and sampling in nearby field analogues demonstrate that hydrocarbons produced in the RGV fields resulted from the local maturation of the source rock due to cooling intrusions, the regional burial being insufficient to trigger maturation of the organic matter (Spacapan et al., 2018, doi: 10.1016/j.marpetgeo.2018.01.018; Palma et al., 2024, doi: 10.1144/SP547-2023-119). Thus, the RGV oil fields have been generated by volcanism, and subsequently hosted within the igneous rocks.

Hydrocarbons produced from one of the largest oil fields of the basin, the El Trapial field, are trapped in a gentle subcircular dome structure of ~20 km diameter. The center of the dome coincides with the center of the eroded, Lower Miocene Cerro Bayo de la Sierra Negra volcanic complex. The integration of field mapping and the analysis of substantial subsurface data demonstrates that this dome resulted from the emplacement of the plumbing system of the volcanic complex in the form of numerous sills and thin laccoliths (Lombardo et al., 2024, doi: 10.1144/SP547-2023-98). The structural trap is thus of volcanic origin, not tectonic.

The northern Neuquén Basin hosts an Upper Miocene andesitic plug, Cerro Alquitrán, from which large amounts of bitumen naturally seep out. Field mapping demonstrates that fracturing and brecciation within the intrusion, associated with its emplacement, consist of high-permeability corridors that locally affect regional subsurface fluid migration (Galland et al., 2023, doi: 10.1111/bre.12782). Thus, the permeability properties of igneous intrusions are essential for predicting fluid migrations in volcanic basins.

All in all, our contribution (1) documents various effects of magma-rock interactions in sedimentary basins, and (2) highlights the great scientific value of the Neuquén Basin as a world-class case study for unravelling processes of magma-rock interactions in sedimentary basins.

Email: olivier.galland@geo.uio.no

COPPER HOSTING BASINS AT THE EDGE OF CRATONS – THE YENEENA BASIN IN WESTERN AUSTRALIA AS A CASE STUDY

Weronika Gorczyk

School of Earth Sciences/Centre for Exploration Targeting, University of Western Australia, Perth, Australia

Co-authors: Ian Tyler and Fariba Kohanpour

CSIRO, Canberra, Australia

The Yeneena Basin – a Neoproterozoic basin formed at the eastern margin of the Pilbara Craton in Western Australia – is a significant example of a mineral-rich (mainly Cu, Au and U) basin. To obtain a better understanding of how to target prospective West Australian basins, a holistic multi-disciplinary system workflow approach was applied. Novel combinations of analytical and numerical techniques were applied to drill core information and geophysical, geochronological, and spectral data sets to allow revision of interpretations of the development history and metal potential of the highly prospective Yeneena Basin. With this holistic approach we were able to link lithospheric-scale architecture and associated mineral systems, with the development of basins and sub-basins, as well as reactivation of major tectonic boundaries during inversion of the basin.

The Neoproterozoic Yeneena Basin is located in the northwest Paterson Orogen of Western Australia and hosts numerous significant sediment-hosted mineral deposits including Nifty Cu, Telfer Au–Cu, Winu Cu–Au, and Kintyre U. However, limited exposure of stratigraphic units within the basin has resulted in significant knowledge gaps about their correlations, depositional history, source of detritus and potential links to regional tectono-magmatic events. We present an extensive U–Pb geochronology dataset of samples across the Yeneena and northwest Officer Basins to define and compare the detrital zircon age spectrum of individual formations, along with facies analyses, carbon and Lu/Hf isotope studies, supported by a reinterpreted geological map and stratigraphic sequence of the Yeneena Basin and adjacent northwest Officer Basin.

Email: weronika.gorczyk@uwa.edu.au

IMPACT OF THE PETIT-SPOT VOLCANISM ON THE SEDIMENTARY COVER IN THE JAPAN TRENCH AREA FROM HIGH-RESOLUTION SEISMIC IMAGING

Andrzej Górszczyk

Institute of Geophysics, Polish Academy of Sciences, Kraków, Poland

Co-authors: Yousef Amirzadeh

Institute of Geophysics, Polish Academy of Sciences, Kraków, Poland

Petit-spot volcanoes, recently discovered volcanic structures, have significantly enriched our understanding of intraplate volcanism, particularly occurring in response to plate flexure during subduction. Discovery of these volcanoes in the vicinity of the Japan Trench marked a milestone showcasing the profound impact of tectonic processes on the intraplate volcanism and alternation of the sedimentary cover at the forefront of subduction zones. One of the key question marks surrounding the petit-spot volcanoes is the extraction and ascent of melts to the seabed that would require development of lithospheric-scale fractures. As for now, no physical model has been devised to validate this hypothesis. The complexities involved in understanding the intricate genesis of petit-spot volcanism underline the need for its further investigation with innovative approaches.

In 2017 Japan Agency for Marine-Earth Science and Technology (JAMSTEC) carried out an active seismic survey to investigate the geological setting impacted by petit-spot volcanism in the trench outer-rise region of the Japan Trench. During the survey 40 ocean-bottom seismometers (OBS) were deployed at 2 km intervals along an 80-km long 2D receiver profile, coupled with the firing of air-gun shots at 100 m intervals along an extensive 100-km shooting profile. The resulting dataset holds the potential for constructing a high-resolution velocity model with full-waveform inversion (FWI) for in-depth analysis of sedimentary cover and deeper structures.

In this work we use first arrival traveltime tomography and time-domain acoustic FWI to reconstruct P-wave velocity model at the wavelet resolution. We push the inversion up to 8 Hz, which allows us to delineate sharp velocity contrasts within the sedimentary cover over incoming plate and within the subducting crust that are likely related to the petit-spot volcanism phenomenon occurring in this region. The resulting velocity model promises to contribute to our comprehension of intraplate volcanism, offering a perspective on the broadening of our understanding the underlying processes causing intraplate volcanism and the alternation of related sedimentary basins.

Email: agorszczyk@igf.edu.pl

GEOLOGICAL EXPLORATION OF SALT STRUCTURES FOR SOLUTION MINING AND UNDERGROUND STORAGE IN POLAND – TECHNIQUES USED AND CURRENT CHALLENGES

Łukasz Grzybowski

Institute of Geology UAM, Adam Mickiewicz University in Poznań, Poland

Co-authors: Mariusz Chromik[2]

The Research and Development Centre for Mining of Chemical Raw Materials "CHEMKOP", Kraków, Poland

Poland has favorable geological conditions for constructing caverns in salt structures for their subsequent use as volumes for storing liquid and gaseous fuels as well as energy, e.g., in the form of hydrogen. Particularly important geological objects considered as the sites for the location of storage caverns are salt diapirs of the Zechstein Supergroup, occurring in a narrow zone within the Polish Lowlands in the Cuiavian and Western Pomerania regions. Some of them are already utilized as solution mining and storage facilities (e.g., Mogilno and Góra diapirs), and some are currently considered as potential locations for the construction of storage capacities (e.g., Damasławek, Lubień Kujawski, and Goleniów).

Assessment of the storage potential of a given salt structure or the perspectives for the construction of consecutive caverns on an already exploited structure is based on the result of geological exploration works. These works are carried out using various geological and geophysical methods, which can be classified into two groups that lead to (a) determining the geometry of the salt body and the nature of contact with the surrounding rocks and (b) assessment of the internal geology within the diapir, including the spatial relationship between rocks with different petrophysical properties. The former is necessary to determine the limits of the exploitation, i.e., to set the boundary safety pillar. The second group of methods allows for the appropriate design of the cavern leaching process in order to optimally exploit resources and/or to obtain the desired cavern shape.

This paper presents the techniques currently used in Poland for the geological exploration of salt diapirs, with a particular discussion on the usefulness of the results of seismic and borehole GPR surveys. Examples of the use of these methods in Poland are indicated, and their advantages and limitations in relation to the demands of the solution mining projects are discussed.

Email: lukasz.grzybowski@amu.edu.pl

EVOLUTION OF A MAAR-DIATREME VOLCANO WITHIN A SEDIMENTARY BASIN CHARACTERIZED BY COMBINED AQUIFER SYSTEM

Mátyás Hencz[1]

[1]MTA EPSS Fluids By Depth Momentum Research Group, HUN-REN Institute of Earth Physics and Space Science, Sopron, Hungary

Co-authors: Károly Németh[2], Tamás Spránitz[1], Tamás Biró[3], Dávid Karátson[3] and Márta Berkesi[1]

[2]Saudi Geological Survey, Jeddah, Saudi Arabia; [3]Department of Physical Geography, Institute of Geography and Earth Sciences, ELTE Eötvös Loránd University, Budapest, Hungary

The study of monogenetic volcanic fields provides critical insights into the complex interactions between magmatic processes, local geological settings, and paleogeography. This research focuses on the volcanic evolution of Szent György Hill, located within the monogenetic, phreatomagmatic Miocene–Pleistocene Bakony–Balaton Highland Volcanic Field (BBHVF) in the Pannonian Basin, Central Europe. Szent György Hill, one of the buttes within this field, exhibits a deeply-eroded monogenetic volcanic edifice, where the pyroclastic sequence can be investigated in several outcrops. Detailed field mapping and stratigraphic framework development at Szent György Hill have revealed a complex sequence of pyroclastic deposits. Image analysis of cut pyroclastic rock surfaces (after stratigraphically-controlled sampling) was employed to quantify the relative abundance of different juvenile and lithic components within these pyroclastic samples. The analysis focused on distinguishing between components resulted by phreatomagmatic (sideromelane volcanic glass) and magmatic-dominated (tachylite volcanic glass, basaltic clasts) eruption processes. The results of this analysis suggest a temporal shift in eruption style at Szent György Hill. The initial phreatomagmatism is evidenced by the higher proportion of sideromelane glass in the lower stratigraphic units, which were driven by the interaction of rising magma with external water sources from pre-volcanic aquifers, which are associated with the siliciclastic sedimentary rock- and carbonate-dominated substrate underlying the region. The spatially and temporally changing water supply is likely to have played a crucial role in the evolving eruption dynamics. The underlying siliciclastic sedimentary rocks and carbonate formations provided a complex aquifer system, influencing the amount and timing of water interaction with the ascending magma. The results highlight the polycyclic nature of Szent György Hill volcano. The findings suggest that even within a monogenetic volcanic field, individual volcanic centers can exhibit diverse eruption scenarios, underscoring the importance of considering both external conditions and internal magmatic processes when assessing eruption dynamics. In particular, the role of combined aquifer systems in influencing eruption style and evolution is emphasized, highlighting the need for a multidisciplinary approach to understanding the complexities of monogenetic volcanism.

Email: hencz.matyas@epss.hun-ren.hu

BROKEN FORELAND BASINS IN THE ANDES AND NORTH AMERICAN CORDILLERA

Brian K. Horton

University of Texas at Austin, Austin, TX, USA

A broken foreland basin is defined as a region of sediment accommodation that forms in an intraplate continental setting inboard of a retroarc or collisional orogenic belt. The basin is compartmentalized (partitioned or fragmented) by positive topographic features produced by discrete basement-involved contractional structures. Accommodation is regulated by flexural loading and fault-block tilting with subordinate dynamic subsidence and sediment infilling (ponding) within internally drained areas.

Discrimination of broken and unbroken (continuous) foreland basin conditions enables time-space reconstructions of deformation patterns responsible for growth of integrated topography in thin-skinned fold-thrust belts and isolated topographic highs in distal foreland regions. Such reconstructions require delineation of the position and long-term advance (relative to the trench or suture) of (1) the orogenic topographic front (marked by frontal thrust-belt structures) and (2) the foreland deformation front (defined by isolated basement block uplifts). The dissimilar sedimentary histories of broken versus unbroken foreland basins are manifest in contrasting sediment accumulation histories, time-stratigraphic patterns, depositional environments, sediment routing, and provenance.

Examples from the modern Andes and the Cretaceous-Paleogene Laramide province of North America show a clear spatial correlation between flat slab subduction and zones of distributed intraplate shortening with broken foreland conditions. However, deformation advance toward the plate interior is sensitive not only to geodynamic configuration but also inherited structural/stratigraphic geometries and mechanical processes related to crustal/lithospheric strengthening and weakening. Although important, flat slab subduction is neither necessary nor sufficient to uniquely explain all examples of inboard deformation advance within continental plate interiors.

Finally, it is proposed that most broken foreland basins can be ascribed to a combination of: (1) underlying conditions in the form of tectonic inheritance, including precursor structural, stratigraphic, thermal, and rheological heterogeneities and anisotropies; and (2) mechanical triggers, such as increased stress, enhanced horizontal stress transmission, and/or variable crustal strengthening or weakening.

Email: horton@jsg.utexas.edu

SHALLOW METHANE ACCUMULATIONS ON THE ROMANIAN CONTINENTAL SHELF OF THE BLACK SEA

Gabriel Ion[1]

[1]National Institute of Marine Geology and Geo-ecology, Bucharest, Romania

Co-authors: Constantin Lazăr, Vlad Apotrosoaiei and Adrian Popa

[2]Doctoral School of Geology, University of Bucharest, Bucharest, Romania

During Quaternary, successive sea level variations affected the present NW continental shelf of the Black Sea (the widest one in this basin) and potentially enabled the formation of deltas that subsequently were buried by newer or reworked sediments. In general the sea level variations are controlled by the climatic changes, subsidence and tectonics. At this level tectonics and the corresponding time frame, we think is more related to the post-glacial rebounding phenomena that affected the lithosphere after the successive glaciations that took place in Quaternary times.

Previous works showed there are methane accumulations in Pliocene sediments and we discovered some typical gas accumulations in Quaternary sediments.

These young sedimentary deposits organized as fluvial and delta bodies are not or very little deformed in comparison with the old counterparts; these sedimentary deposits could serve as valuable information for a better understanding of deltaic bodies and associated methane accumulations in general, even for much more older structures.

In our researches we mainly employed very high resolution seismics (chirp sub-bottom profiling and seismics with a sparker source) and we discovered typical fluvial and deltaic sedimentary bodies developed on several vertical horizons that have to be correlated with the regressive and transgressive tracts corresponding to the sea level variations. The Quaternary sea level variations produced successive sedimentary depositions characterized by specific seismo-acoustic facies.

Interesting seismic facies indicating gas accumulations (most probable biogenic methane) have been discovered. These accumulations are related to the vertical gas migration from deeper sediments, where the gas has been produced via microbiological degradation of the organic matter.

Further researches are needed in order to better quantify the sedimentary bodies that hosted the organic matter that has been decomposed and produced methane that migrated and accumulated in shallower sedimentary structures. The semi-regional geometry of the paleo-deltas has to be better mapped and interpreted in the local geological and paleo-geographic context.

Email: gion@geoecomar.ro

THE ROLE OF HYDROCARBON GENERATION AND EXPULSION IN JOINT SYSTEM FORMATION BY NATURAL HYDRAULIC FRACTURING MECHANISM: CASE OF SHALES IN THE LOWER PALEOZOIC BALTIC BASIN (POLAND)

Marek Jarosiński[1]

[1]Polish Geological Institute – Nationat Research Institute, Warsaw, Poland; [2]Academy of Mining and Metallurgy, Kraków, Poland

Co-authors: Kinga Bobek[1] and Paweł Poprawa[2]

[2]Academy of Mining and Metallurgy, Kraków, Poland

Our integrated tectonic and geomechanical study of the Lower Paleozoic shale succession in the Baltic Basin, targeted some fracture formation mechanisms that have not been quantitatively considered in the basin modelling studies. Namely, the factors controlling the fracture stratigraphy, stress components in basin exhumation and the effects of hydrocarbon decompression during expulsion on the natural hydraulic fracture growth.

Structural profiling of cores and scanner images from eight exploration boreholes has revealed the main three natural fracturing episodes, which are stratified on a basin scale. We interpreted fracture formation using the subsidence and hydrocarbon generation models which integrated with geotectonic context allowed us to identify a unique period of the latest Carboniferous when peak gas production and maximum overpressure met the stress direction and regime changes required for the formation of the study fracture system. We evaluated the components of pore overpressure (compaction and gas generation) and the factors controlling stress changes due to exhumation (lithostatic unloading, thermal and pore pressure relaxation) and collisional compressive stress release. We concluded that in the Pomeranian shales, stress relaxation due to exhumation dominated the "purely tectonic" factor of stress changes triggering fracturing.

In this thick shale sequence, we also studied the volumetric effects of decompression following natural hydraulic fracturing during hydrocarbon expulsion. Decompression is caused by the upward propagation of natural hydraulic fractures where the fracturing gradient pressure decreases. We determined of the maximum vertical extent of expulsion-related natural fractures, which appeared to be proportional to the thermal maturity of the source rock. Fracture height and the amount of generated gas and condensate+oil were incorporated into a geomechanical model of each borehole, which compares the theoretical capacity of natural hydraulic fractures with the volumetric effects of hydrocarbon decompression. For the shales studied we demonstrate that the decompression effect can play a dominant role in the upward propagation of natural fractures when the fractures are several hundred meters tall. In the case of more bounty shale reservoirs, hydrocarbon decompression can create a self-driving mechanism that forces the natural hydraulic fractures to reach the paleo-surface.

Email: marek.jarosinski@pgi.gov.pl

STRUCTURAL GEOMETRY AND EVOLUTION OF SALT DIAPIRS AND RELATED FAULT SYSTEM AROUND THE TONB-BOZOR ISLAND, SE PERSIAN GULF: POTENTIAL DIAPIRIC BASIN FOR FUTURE CO_2 STORAGE

Mehrsa Haji Khani

Department of Earth Sciences, Institute for Advanced Studies in Basic Sciences (IASBS), Zanjan, Iran

Co-authors: Mahdi Najafi

Geosciences Barcelona, Geo3Bcn-CSIC, Barcelona, Spain

This paper investigates the geometry and evolution of the Oligocene and lower Miocene Fars salt diapers, Precambrian Hormoz salt diapers, and adjacent minibasins in the southeast Persian Gulf. Utilizing 2D offshore seismic lines, integrated with well data, we conducted detailed interpretations to construct NE-trending geological cross-sections south of the Tunb-Bozorg Island. Subsequent stepwise restoration, guided by thickness patterns of syn-kinematic sediments, local unconformities, growth strata, and halokinetic sequences, unveiled the growth history of salt massifs, turtle anticlines, and salt horns featuring normal fault systems at their crests. The identified stages for diapiric growth include; 1) The pre-kinematic stage, coinciding with the deposition of the Gachsaran Formation in the Lower and Middle Miocene; 2) the Growth of salt pillows, concurrent with the basal deposition of the Guri Member at the Middle and Late Miocene boundary; 3) Passive and rapid diapir growth, synchronous with the Guri Member deposition in the Late Miocene; and 4) The post-diapirism stage and basins associated with salt incompressibility, corresponding to the deposition of the Upper Mishan and Aghajari formations during the Late Miocene and Pliocene times. One of the roles of salt tectonics in energy transfer could be the storage of CO_2 in the porous environment around the salt and some depleted oil and gas fields. Effectively exploiting these resources requires a deeper understanding of the composition, geometry, and evolution of salt structures and sediments around the reservoir, which can be strongly influenced by salt tectonic processes that change rapidly over time and space and influence migration paths and trap development. The SE Persian Gulf's complex salt diapiric system may work as a future CO_2 storage basin in the Middle East.

Email: mehr.7522@gmail.com

FROM MID-JURASSIC EXTENSION TO OBDUCTION-RELATED MÉLANGE FORMATION: SEDIMENTARY RECORDS FROM A DISPLACED SEGMENT OF THE ADRIATIC PASSIVE MARGIN (NE HUNGARY)

Szilvia Kövér[1,2]

[1] HUN-REN, Institute of Earth Physics and Space Science, Sopron, Hungary; [2] ELTE Eötvös Loránd University, Institute of Geography and Earth Sciences, Department of Geology, Budapest, Hungary

Co-authors: János Haas[2], Nevenka Djerić[3], Ottilia Szives[4], Péter Ozsvárt[5] and László Fodor[1,2]

[3] University of Belgrade, Faculty of Mining and Geology, Belgrade, Serbia; [4] Department of Collections, Geological Survey, Supervisory Authority for Regulatory Affairs, Budapest, Hungary; [5] HUN-REN-MTM-ELTE, Research Group for Paleontology, Budapest, Hungary

The two most interesting moments in the life-cycle of oceanic margins are the end of rifting and break-up, thus the first moment of becoming a passive margin, and the transformation into an active margin due to the closure of the ocean. This latter crucial event is the target of our investigation regarding the Adriatic passive margin facing the Neotethys Ocean during the Middle Triassic–Middle-(Late?) Jurassic interval. The reconstruction of this complex history is difficult at straight subduction zones and even more challenging at curved ones or at the termination/transfer zones of oceanic systems. This is the case with suture zones in the northernmost part of the Dinarides and its displaced segment, the Bükk nappe system. Up to now, there are two main competing models concerning the way of obduction and lower plate imbrication in the Dinarides–Albanides–Hellenides. One suggests, that the Western Vardar Ophiolite nappe juxtaposed the Adriatic margin during the Late Jurassic to earliest Cretaceous (Berriasian) with W- to NW-vergency, which predates the nappe-stacking of the Adriatic passive margin (Schmid et al., 2008, 2020; Djerić et al., 2012; Cvetković et al., 2016; Porkoláb et al., 2019). The other suggests synchronous ophiolite obduction and passive margin imbrication in the Bajocian–Bathonian interval, then propagation of the deformation both in the upper plate (internal thrusting within the ophiolite nappe), and in the lower plate during the late Bathonian–Oxfordian (Gawlick and Missoni, 2019 and references therein).

Micropaleontological, sedimentological and structural investigation of more than thirty boreholes resulted in the detailed characterisation and 3D depositional model of the Recsk Succession. The sedimentation in its Bajocian–early Callovian extensional half-grabens was characterised by pelagic limestones then dark shales with sandstone intercalations. Mass-flow deposits both from the footwalls of graben-bounding normal faults and from the Adriatic-Dinaric Carbonate Platform were frequent. The lack of contractional structures or ophiolite-derived material in the gravity mass flow exclude their attribution to any mélange units related directly or indirectly to the Neotethyan subduction front. In the overlying Tarna Olistostrome sedimentation lasted at least till the Tithonian, indicated by new nannofossil findings. This is the oldest possible age for the overthrusting of the ophiolite nappe over this segment of the Adriatic passive margin. This suggests that the change from extension to shortening occurred between the Callovain and the Tithonian at the investigated northernmost termination of the Neotethys system.

Email: koversz@gmail.com

BASEMENT UNDER COVER; DEFORMATION OF SEDIMENTARY LAYERS ABOVE AN OBLIQUE BASEMENT FAULT

Hemin Koyi

Hans Ramberg Tectonic Laboratory, Uppsala University, Uppsala, Sweden

Based on seismic data, a series of systematic scaled analogue models are used to simulate the impact of an oblique basement fault on deformation in the sedimentary cover. Models consisted of a set of layers of loose sand on two basal plates whose contact simulated a basement fault. Depositional history was simulated in the model by producing both pre-kinematic and syn-kinematic deposition, and an erosion phase in between. Deformation of the model was achieved by moving one of the basement plates in a way that it initiated an oblique slip along the basement fault. This oblique movement induced both a strike-slip and dip-slip (shortening) components in the cover sand layers. This kinematic evolution resulted in formation of an open anticline (box fold) in the cover units along the strike of the fault. Serial sections of the model shows that the box fold change symmetry along strike. The results of these models are used to outline the dynamic evolution of Shah anticline in the UAE, which was previously interpreted to have formed above a basement pop-up structure. Theresults presented here emphasize that significance of small amount of dip-slip along an oblique basement fault in deformation of cover units.

Email: Hemin.Koyi@geo.uu.se

SALTY SANDWICH; ROLE OF MULTIPLE-SALT LAYERS WITHIN THE STRATIGRAPHIC COLUMN OF A FOLD-THRUST BELTS

Hemin Koyi

Hans Ramberg Tectonic Laboratory, Uppsala University, Uppsala, Sweden

Deformed sedimentary successions in many fold-thrust belts (e.g. Zagros fold-thrust belt, Spanish Pyrenees, Appenines) include mechanically weak layers of salt not only at their base but at different stratigraphic levels. Kinematics and dynamics of deformation in such fold-thrust belts are not only influenced by the mechanical behaviour of the basal décollement, but also by the weaker units embedded within the stratigraphic succession. Seismic data and results of scaled models, containing multiple weak horizons of viscous layers acting at detachement, are used here to argue for variation in deformation style, intensity and extent in different parts of a fold-thrust belt [e.g., the Zagros fold-thrust belt (ZFTB)]. The results show that during shortening, deformation along a basal detachment steps up into a shallower detachment above which the deformation front propagates further and faster than at deeper levels. As a result, deformed shallow, and younger sediments are placed above deeper, older undeformed sediments. This deformation scenario suits reported field observations from the Zagros FTB, where upper Miocene and younger sediments, located above Gachsaran evaporites in the belt, show folds with Zagros trend (NW–SE) whereas deeper older units are unaffected by the Zagros orogeny and show the old Arabian trend (N–S) that formed before the Zagros orogeny. Decoupling between pre- and post-Gachsaran units by the Gachsaran evaporites results in disharmonic folding between the two units where geometry, size and age of the structures differ and will be addressed in this talk. Such decoupling does not only play a significant role in the mode and mechanics of deformation in a fold-thrust belt, it may also have significant impact on hydrocarbon exploration in oil-rich fold-thrust belts.

Email: Hemin.Koyi@geo.uu.se

MIOCENE CARPATHIAN FORELAND BASIN IN SE POLAND AND W UKRAINE – ITS UNUSUAL STRUCTURE AND DEPOSITIONAL INFILL FORMED DUE TO EXTENSIONAL REACTIVATION OF INHERITED MESOZOIC FAULTS

Piotr Krzywiec

Institute of Geological Sciences, Polish Academy of Sciences, Warsaw, Poland

Foreland basins form due to subduction of the continental foreland (lower) plate beneath the foreland fold-and-thrust wedge that progressively propagates towards its foreland. Tectonic subsidence within the foreland basins is a function of topographic load exerted by orogenic wedge, of subsurface loads operating at depth within the subduction zone, of load exerted by sedimentary infill of foreland basin, and of mechanical properties of the foreland (lower) plate. Numerous flexural modelling studies illustrated how combination of various parameters could result in formation of deep water underfilled or shallow water overfilled foreland basins. Mechanical properties of the lower plate are determined by its effective elastic thickness and its lateral variations, from low values of thinned continental crust to high values of thick cratonic crust. Flexural models are based on one important assumption – that lower plate behaves as continuous elastic or viscoelastic plate (beam). There is however one departure from this assumption – flexural extension of the lower plates that occurs due to its bending that, eventually, leads to formation of a system of normal faults i.e. to brittle rather than to elastic deformation. In many cases this normal faulting is rather minor and distributed over wide zones, so in regional context it does not diminish applicability of flexural modelling for studies of foreland basins. This could however quite drastically change if the lower plate contains deeply rooted regional faults zones, inherited from previous phases of tectonic evolution of a given area, that could get reactivated during plate flexure.

Miocene (Badenian–Sarmatian) Carpathian foreland basin developed in front of the Carpathians. Its most northern, external part in S Poland and W Ukraine is characterized by presence of extensive evaporitic horizon that served as a detachment for syn-depositional frontal thrusts developed in the Miocene foreland basin infill in central part of the Polish Carpathian foreland basin. These frontal thrusts are absent in more eastern segment, in SE Poland and W Ukraine that developed above the Teisseyre-Tornquist Zone located between the East European Craton and the West European Platform. In this area, large scale normal faults of total offset in order of 1–2 km, that cut Miocene foreland basin infill, underlaying Meso-Paleozoic sedimentary cover and crystalline basement, are present. Their formation could be attributed to the Miocene reactivation of faults, previously responsible for (1) Mesozoic extension and localized subsidence of the so-called Mid-Polish Trough, i.e. axial part of extensive Permian-Mesozoic epicontinental basin, and (2) its Late Cretaceous inversion, uplift and erosion. Some strike-slip movements along those faults could be also observed during latest, Sarmatian stages of evolution of the Carpathian foreland basin.

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Email: piotr.krzywiec@twarda.pan.pl

NEW FLEXURAL MODEL OF INVERSION TECTONICS

Piotr Krzywiec

Institute of Geological Sciences, Polish Academy of Sciences, Warsaw, Poland

Inversion tectonics has been intensely studied since the early 1980s, when concept of inversion of sedimentary basin was formulated by Bally (1983). He proposed relatively simple model of a tectonic half-graben bounded by deeply rooted normal listric fault, subsequently reactivated due to regional compression as reverse fault. This model, used with some minor modifications by numerous authors until today, explains however inversion of relatively small individual grabens, not large sedimentary basins. In all those previous models, one important element hasn't been widely considered – flexural subsidence of flanks of inverted basins. Only recently, a model for Subhercynian Cretaceous Basin in Germany, formed due to uplift of basement block in Late Cretaceous, was proposed that illustrates some of the aspects of foreland flexure during regional inversion tectonics (Hindle and Kley, 2021). Flexural behavior of flanks of inverted basin implies specific thickness and facies distribution of syn-inversion strata, similar to foreland basin depositional system, with regional thickening of inversion-related succession towards the inversion axis, and presence of coarse-grained deposits in vicinity of basement blocks uplifted due to inversion.

The Permian-Mesozoic Polish Basin, that was fully inverted in Late Cretaceous, provides excellent example of such flexural inverted basin. It was characterized by most subsiding axial part, the Mid-Polish Trough, which, due to inversion, was transferred into the Mid-Polish Anticlinorium (MPA) that could be traced from vicinity of Bornholm (SW Baltic Sea) towards SE Poland and W Ukraine, where it plunges beneath the Carpathians. Part of the Upper Cretaceous syn-inversion succession is characterized by regional thickening towards the MPA that could be attributed to the inversion-related flexural subsidence. Upper Cretaceous progradational wedges, localized thickness reductions and unconformities developed along the edges of crustal blocks uplifted during inversion. Proposed model, based on high-quality seismic data calibrated by deep wells, provides comprehensive explanation of upper crustal configuration and regional depositional architecture formed due to inversion tectonics. This model could be applied to other inverted intracontinental sedimentary basins in Europe and elsewhere.

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Email: piotr.krzywiec@twarda.pan.pl

PROVENANCE OF THE BLACK FLYSCH AND CEAHLĂU THRUST SHEETS OF THE EASTERN CARPATHIANS

Constantin Lazăr[1,2]

[1] The National Institute for Research and Development on Marine Geology and Geo-ecology – GeoEcoMar, Romania; [2] Doctoral School of Geology, University of Bucharest, Bucharest, Romania

Co-authors: Relu-Dumitru Roban[3], Mihai Ducea[3,4] and Andrei-Rareş Stoian[1]

[3] Faculty of Geology and Geophysics, University of Bucharest, Bucharest, Romania; [4] Department of Geosciences, University of Arizona, Tucson, AZ, USA

In the northern part of the Eastern Carpathians (Romania), the Maramureş region reveals several tectonic units that include remnants of the Mesozoic Ceahlău – Severin Ocean. Among these units is the 'Black Flysch', which features a mafic complex that developed during the Middle to Late Jurassic interval. In the studied area, the 'Black Flysch' Nappe also contains younger deposits such as deep-water carbonates and siliciclastics. In the same area Ceahlău Nappe also occurs, enclosing mainly turbidites. Both above-mentioned tectonic units are included in the Outer Dacide Nappe system.

The mafic complex occurring in the 'Black Flysch' Nappe consists of basalts akin to ocean island basalts. These are different from the enriched and normal mid-ocean ridge basalt blocks incorporated in the Upper Jurassic–Lower Cretaceous sediments of the Ceahlău Nappe towards the east (in regard to the ones comprised in the 'Black Flysch' Nappe). This fact suggests variable expansion rates along the Ceahlau–Severin rift system.

The U-Pb age distribution spectra of the detrital zircons picked from the samples belonging to the 'Black Flysch' and Ceahlău units show similarities for the 180–3,000 Ma interval. Significant peaks have been obtained for the following ages (in order of magnitude): ~460 Ma, 580–620 Ma, ~320 Ma, 180–200 Ma, and 950–1,100 Ma. In the 'Black Flysch' unit, Ordovician ages (~460 Ma) dominate, indicating a main provenance from of the Bucovinian Nappe basement. By contrast, in the Ceahlău unit the Late Neoproterozoic peak (~600 Ma) holds greater significance and has a counterpart both in the sediments of the Eastern European Platform and in the paragneisses of the Bucovinian Nappe. When looking at the small percentage of inherited ages that exceed 1 Ga, we can rule the Eastern European Craton as an insignificant source area.

Email: lazar.constantin@geoecomar.ro

GEODYNAMIC CONTROLS ON LATE PALEOZOIC FLEXURAL EXTENSION IN THE ARKOMA BASIN, USA

Brandon Lutz

Appalachian State University, Boone, NC, USA

Co-authors: Mark Hudson, Tyson Smith, Marieke Dechesne and Leland Spangler

U.S. Geological Survey, Denver, Colorado, USA

The Arkoma Basin formed on the southern margin of Laurentia during the Late Paleozoic assembly of Pangea. It is a pro-foreland basin with remarkably thick (≤6.5 km) Pennsylvanian foredeep strata. Foredeep subsidence was accommodated in part by normal faulting of continental crust along the edge of Laurentia as an attached oceanic plate subducted southward. Here, we use basin-scale 3D modeling and 2D flexural kinematic modeling to reveal the patterns and style of growth faulting across the basin through time, and therefore inform the underlying dynamics of basin development.

We demonstrate that growth faulting was diachronous, migrating from SE to NW at a rate of ~20 ± 5 km/m.y. over greater than 10 m.y. Diachronous flexural extension may be explained by diachronous suturing along the margin due to oblique collision along pre-existing margin salients and recesses, and/or inherent variations in lithospheric strength.

The 3D model demonstrates a regular and repeated pattern of fault segmentation wherein ~E–W trending down-to-the-S normal faults are segmented by basement-inherited NE-trending oblique normal faults. At intersection with NE-trending faults, vertical separation along E–W normal faults decreases by hundreds of meters, tips out, and/or is transferred to other isolated fault strands. The high-resolution 3D model reveals the structure of multiple relay ramps formed at these intersections. The fault segmentation patterns are visible at the scale of nearly the entire basin and closely mimic those depicted in seminal studies conducted at the outcrop scale with supporting kinematic data. This study demonstrates that flexural extension, a process by which organic-rich shelfal rocks are deeply buried by turbidites and black shales (in this setting), was heavily influenced by pre-existing lithospheric structure, and that it can be used to provide a detailed record of tectonic process affecting continental margins.

Email: lutzbm2@appstate.edu

Syn-depositional thrusting within the NW Qaidam Basin, Tibet Plateau, China – insight from 3D seismic data

Mateusz Łasiewicki[1]

[1]Institute of Geological Sciences, Polish Academy of Sciences, Warsaw, Poland

Co-authors: Piotr Krzywiec[1], Fanwei Meng[2], Wenhang Liu[1] and Stanisław Mazur[3]

[2]School of Resources and Earth Sciences, China University of Mining and Technology, Xuzhou, China; [3]Institute of Geological Sciences, Polish Academy of Sciences, Kraków, Poland

Cenozoic closure of the Tethys Ocean in central Asia was associated with formation of an extensive zone of tectonic compressional deformations reaching the N margin of the Tibetan Plateau and beyond. One of the northernmost zones of compressional deformations is known from the NW part of the Qaidam Basin, located above the Tibetan Plateau in W China, where important influence on formation of these structures of the regional strike-slip Altyn Tagh fault could be also observed.

High-quality 3D seismic data acquired above the Jandingshan, Heiliangzi i Janbei anticlines in the NW Qaidam Basin illustrated that in this part of the Qaidam Basin three types of structures could be observed: (1) thick-skinned fully-coupled thrusts and associated folds that embrace both pre-Cenozoic (Cretaceous and older) substratum / basement as well as Cenozoic (Paleogene–Neogene and Quaternary shallow water to terrestrial sedimentary succession of the Qaidam Basin, including Eocene evaporites, (2) thick-skinned compressional / transpressional structures developed beneath the Eocene evaporites, and (3) thin-skinned folds and associated thrusts and backthrusts fully decoupled along the Eocene evaporites.

Shallow growth strata precisely imaged by seismic data indicate young, mid-Miocene to recent thrusting, uplift, and localized erosion. Detailed analysis of growth strata packages developed above and in vicinity of three main structural elements, i.e. provided insight regarding lateral variations of initiation and later growth of Jandingshan, Heiliangzi and Janbei anticlines.

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Email: lasiewicki1996@gmail.com

UNRAVELING FLUID FLOW AND FLUID-ROCK INTERACTIONS DURING THE DINARIDES COLLISIONAL OROGENESIS: INTEGRATED STRUCTURAL FRACTURE ANALYSIS AND PETROGRAPHIC AND GEOCHEMICAL CHARACTERIZATION

Maja Maleš[1, 2, 3, 4]

[1]IFP Energies Nouvelles, Rueil-Malmaison, France; [2]Faculty of Geosciences, Utrecht University, Utrecht, The Netherlands; [3]Faculty of Mining and Geology, University of Belgrade, Belgrade, Serbia

Co-authors: Fadi Henri Nader[1,2], Liviu C. Matenco[2], Uroš Stojadinović[3], Nemanja Krstekanić[2,3], Renaud Divies[1] and Nikola Ranđelović[2,3]

Understanding fluid flow and fluid-rock interactions in the subsurface is crucial for the sustainable exploitation of geological resources, such as geothermal energy, hydrogen production, and potential CO_2 storage. The NW–SE trending and SW-vergent Dinarides mountain chain, a complex collisional orogen in southeastern Europe, is a perfect place to investigate the evolution of fluid-flow and fluid-rock interactions, whereby field observations could be integrated with laboratory analyses and numerical modelling. Our research focuses on unravelling the fluid-flow and fluid-rock interactions that occurred during the deformation of the Dinarides orogen. A field campaign across five different tectonic units in the External Dinarides orogen in Montenegro (Dalmatian, Budva, High Karst, Pre Karst and East Bosnian-Durmitor units) involved detailed structural analyses of fractures, cemented fault gouges, fault slickensides, tension gashes and folding cleavages. About 40 sites have been investigated, yielding 60 structural measurements. A total of 46 representative samples were collected for petrographic analyses (including conventional optical microscopic techniques and cathodoluminescence), geochemical analyses (stable oxygen and carbon isotopes), Rock-Eval, fission track dating and fluid inclusions analyses. Field investigations allowed us to associate the sampled veins (and fracture-filled cements) to the known Dinarides tectonic events based on their structural context and orientations, i.e., NE–SW Late Cretaceous–Eocene contraction, NE–SW Oligocene contraction, and bimodal NE–SW/NW–SE Miocene extension. The preliminary petrographic analysis of 39 thin-sections allowed us to distinguish various vein-filling sparry and equant calcite cements, often displaying crystal twinning. Dolomite cements are less common in fractures, whereas some pervasive host-rock dolomitization has been observed. Cathodoluminescence patterns are mostly dull, occasionally bright, suggesting a predominantly burial environment during vein-filling and cementation, with some transitions between meteoric and burial conditions. Stable oxygen and carbon isotopic values of 50 sampled matrix and vein-filling will provide further information on the original chemical signatures of the related fluids and the temperature conditions during precipitation. By achieving such a quantitative petrographic and geochemical characterization of the structurally timed fracture-filling across the Dinarides, our findings enhance the understanding of fluid flow and fluid-rock interactions in such collisional orogens and can be applied to similar settings elsewhere.

Email: maja.males@rgf.bg.ac.rs

BASEMENT NAPPE STACKING AND OROGEN-PARALLEL EXTENSION IN THE NORTH DOBROGEA OROGEN

Andreea Marza-Ene[1,2]

[1] Doctoral School of Geology, Faculty of Geology and Geophysics, University of Bucharest, Bucharest, Romania; [2] Department of Earth Sciences, Utrecht University, Utrecht, The Netherlands

Co-authors: Anneke Royakkers[2], Liviu C. Matenco[1,2], Hannah Pomella[3], Vlad Victor Ene[4,5], Bernhard Fugenschuh[3] and Ioan Munteanu[4,5]

[3] Faculty of Geology and Atmospheric Sciences, University of Innsbruck, Innsbruck, Austria; [4] Faculty of Geology and Geophysics, University of Bucharest, Bucharest, Romania; [5] Institute of Geodynamics "Sabba S. Ştefănescu", Romanian Academy, Bucharest, Romania

Orogenic extension has been demonstrated in various geodynamic settings to create lower crustal domes with a variable syn- and/or post-thickening structure, from typical core complexes to orogen parallel domes. The orogen parallel domes formed during the final stages of continental collision at high geothermal gradients are rather difficult to constrain due to the juxtaposition of crustal thickening, mantle lithospheric removal, and syn- to post-kinematic magmatism. One optimal situation to study such an orogen parallel extensional dome is observed in the North Dobrogea orogen of Eastern Europe. Here, we observe a marked contrast of metamorphism in the most internal Macin unit that is high-grade (upper amphibolitic metamorphic facies) in the centre of this unit and low-grade (anki- to greenschist metamorphic facies) over its flanks. We use field and microstructural kinematic observations to characterize the main structures associated with nappe stack burial and extensional exhumation. The results demonstrate two main stages of deformation, a first one associated with burial of a mafic protolith up to amphibolitic conditions that took place by top-to-NE nappe stacking, and a second deformation characterized by extensional exhumation, top-to-SE shearing, and retrograde metamorphism. This second deformation created an orogen-parallel extensional dome with a significant tectonic omission across a major detachment. The exhumation in the footwall of the detachment started in high temperature conditions, demonstrated by pervasive migmatization and emplacement of syn-kinematic plutons. The extension and the associated formation of the metamorphic dome is likely coeval with the Early–Middle Triassic rifting magmatism that generated the emplacement of alkaline plutons in the Macin unit and mafic volcanics in the neighbouring Niculitel unit. These results demonstrate the need to reinterpret the structure of the Macin unit to include a typical ophiolitic suture zone overlaid by forearc sediments, metamorphosed in greenschist to upper amphibolitic facies and thrusted by an upper continental plate. Furthermore, when combined with the few similar observations described worldwide, these results demonstrate that orogen-parallel extensional domes can also develop at high temperatures during or after the late stage of continental collision.

Email: andreea.marza@s.unibuc.ro

EVOLUTION OF TECTONIC SUCCESSIONS CONTROLLING IN- VERSUS OUT-OF-SEQUENCE, THIN- VERSUS THICK-SKINNED DEFORMATION IN EXTERNAL THRUST BELTS AND THEIR FOREDEEPS

Liviu C. Matenco

Department of Earth Sciences, University of Utrecht, Utrecht, The Netherlands

Observations in sedimentary basins affected by significant amount of deformation shows that the fault-induced depositional space, at various spatial and temporal scales, is closely linked to the basin kinematics. The sediment infill reflects the history of deepening and shoaling facies controlled by the activation and changes in the fault's offset rates. Simply stated, this translates as shifting sedimentary facies towards the basin center or towards the source area in response to increasing or decreasing depositional space, creating tectonic successions, controlled by the balance between the rates of creation of depositional space and sediment supply associated with significant changes in the evolution of sedimentary facies. This concept applies also to external thrust belts and their foredeeps at a wide range of spatial and temporal scales where the type of tectonic succession controls the coeval kinematics and the spatial distribution of thrusted geometries. When combined with the rheology of sediments and the mechanics of subduction, these patterns control the kinematics of thrusting and the balance between in- and out-of-sequence thrusting and the one between the development of thin- versus thick- skinned thrust belts, particularly in the final stages of continental collision. This interplay is illustrated by a number of key examples in the Mediterranean orogenic system, with particular focus to the Dinarides and Carpathians orogens. While the transition from thin to thick-skinned is controlled by the thickness of tectonic successions, mechanics of shortening and rheological distribution, the interplay between in- and out-of-sequence has a multi-stage control depending on the stage of collision, distribution and thickness of tectonic successions, as well as the evolution of the subducted slab during and after collision.

Email: l.c.matenco@uu.nl

INVERSION TECTONICS IN THE SOUTHERN BALTIC SEA: INSIGHTS FROM DEEP SEISMIC PROFILES

Stanisław Mazur[1]

[1]Institute of Geological Sciences, Polish Academy of Sciences, Kraków, Poland

Co-authors: Sergiy Stovba[1,2], Małgorzata Ponikowska[1], Michał Malinowski[3,4], Piotr Krzywiec[1], Yuriy Maystrenko[5] and Christian Hübscher[6]

[2]S.I. Subbotin Institute of Geophysics, National Academy of Sciences of Ukraine, Kyiv, Ukraine; [3]Institute of Geophysics, Polish Academy of Sciences, Warsaw, Poland; [4]Geological Survey of Finland, Espoo, Finland; [5]Geological Survey of Norway (NGU), Trondheim, Norway; [6]Institute of Geophysics, University of Hamburg, Hamburg, Germany

We reinterpreted the DEKORP-BASIN'96 offshore seismic profiles PQ-002 and PQ-004-005, which run ENE-WSW across the southern Baltic Sea as well as the BGR16-212 (Baltec) profile located off the Polish coast. These profiles traverse the transition zone between the East European Craton (EEC) in the northeast and the Palaeozoic Platform in the southwest, intersecting the Teisseyre-Tornquist Zone (TTZ) and Sorgenfrei-Tornquist Zone (STZ) near Bornholm Island. The STZ is typically seen as an intra-cratonic structure within the EEC, while the TTZ is considered the edge of the Precambrian craton. Both zones exhibit significant compressional deformations linked to the Alpine inversion of the Permian–Mesozoic basins during the Cretaceous-Paleogene transition. Our study aimed to elucidate the structure of this transition zone and determine if it varies north and south of Bornholm. We also sought to document the Late Cretaceous-Paleocene deformations and their relationship to the STZ, TTZ, and the marginal zone of the EEC.

The results demonstrate that the southern Baltic Sea is underlain by a thick crust of the East European Craton with a Moho depth in the range of 38–42 km. The overall crustal architecture is shaped by three phases of localized stretching in the early Paleozoic, Devonian-Carboniferous, and Permian-Mesozoic. The most spectacular feature of the southern Baltic Sea is a zone of thick-skinned compressional deformation produced by Late Cretaceous–early Paleogene inversion, including a system of thrusts and back thrusts penetrating the entire crust in an 80–90 km wide inversion zone. ENE-vergent thrusts are traced from the top of the Cretaceous down to the Moho and they are accompanied by back thrusts of opposite vergence, also reaching the Moho. Inversion tectonics resulted in the uplift of a block of cratonic crust as a pop-up structure, bounded by thrusts and back thrusts, and the displacement of the Moho within the STZ and TTZ. The similar mechanism of intra-cratonic inversion was recognized for the Donbas Foldbelt in eastern Ukraine, and it may be characteristic of rigid cratons, where deformation is localized in a few preexisting zones of weakness.

Email: ndmazur@cyf-kr.edu.pl

FROM EOCENE GREENHOUSE TO OLIGOCENE ICEHOUSE: THE MARINE RECORD OF THE PARATETHYS (EASTERN CARPATHIANS AND TRANSYLVANIAN BASIN, ROMANIA)

Mihaela Melinte-Dobrinescu [1]

[1] National Institute for Marine Geology and Geo-ecology, Bucharest, Romania

Co-authors: Relu-Dumitru Roban, Alina Magdaş and Gabriela Cristea

Faculty of Geology and Geophysics, University of Bucharest, Bucharest, Romania; National Institute for Isotopic and Molecular Technologies, Cluj-Napoca, Romania

Within the Eocene–Oligocene boundary interval, a global climate deterioration took place, mirrored in the transition from the Eocene Greenhouse to the Oligocene Icehouse. These modifications are associated with major environmental changes (i.e., Cramer et al., 2011; Miller et al., 2020), such as deep-ocean and surface-ocean cooling, ice-sheet growth, and sea-level drop. The Oligocene thus represents a pivotal shift from a tropical to a modern, cooler world, marked in the sedimentary record and biotic turnover.

Various causes of these changes were assumed (Prothero et al., 2003), such as decline in carbon dioxide, tectonics of those times, i.e., India collision to Asian coastline, separation of Antarctica from Australia, and the realignment of Pacific mid-ocean ridge. Concurrently, the Tethyan Ocean split into the Mediterranean and Paratethyan seas.

For investigating the changes spanning the Eocene–Oligocene boundary interval at the onset of the Paratethys, sections from the Eastern Carpathians and Transylvanian Basin were studied. In the Eastern Carpathians, the transition from Eocene turbidites to Lower Oligocene anoxic hemipelagites (comprising brownish marls, clays, and cherts) is accompanied by fluctuations in Total Organic Carbon (TOC) and CaCO3 content, along with shifts of δ13C and δ18O isotope values. Another studied area is placed in the NW Transylvania, where the Eocene carbonate platform was replaced by a hemipelagic anoxic sedimentation in the Lower Oligocene. A similar pattern of δ13C and δ18O isotope fluctuation with the one identified in the Eastern Carpathians was observed. The stable isotope record of the studied Paratethyan successions show a similar trend with the global one, but some regional differences were observed. Probably, the isolation of the Paratethys and the influence of the Alpine orogeny overprinted the global signals.

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Email: melinte@geoecomar.ro

HOW TO SEARCH FOR SIGNS OF LIFE IN MARTIAN EVAPORITES: EVIDENCE OF FLUID INCLUSIONS IN THE POLYGONAL STRUCTURES OF EVAPORITES SIMILAR TO MARS IN THE QAIDAM BASIN

Fanwei Meng

China University of Mining and Technology, Xuzhou, China

Co-authors: Anatoliy R. Galamay[2]

Institute of Geology and Geochemistry of Combustible Minerals, National Academy of Sciences of Ukraine, Lviv, Ukraine

Based on its geological time scale, Mars is divided into the Noachian era (4 billion to 3.7 billion years ago), Hesperian era (3.7–3 billion years ago), the Amazonian era (3 billion years ago to present). A large amount of geological data supports that there was a rich hydrosphere on Mars during the Noachian period, with a scale equivalent to 100–1500 m global equivalent layer (GEL) (Di Achille and Hynek, 2010). This relatively large volume of liquid water on the surface of Mars gradually disappeared over 3 billion years ago (Scheller et al., 2021), with the escape of water vapor and gradual increase in salinity, ending with the formation of evaporites (Knauth, 2005; Murchie et al., 2009).

Polygonal surface structures are a common surface phenomenon of evaporative halite crust in the Qaidam Basin, and this obvious sedimentary structure has also been found on Mars (Zheng et al., 2013; Anglés and Li, 2017; Xiao et al., 2017). On Earth, the polygonal structure in the salt crust is explained as the growth of salt crystals in the salt and mud layers beneath the dry lake surface during the arid stage of the salt lake sedimentary cycle, resulting in the salt crust splitting into polygons (Christiansen, 1963). Large polygonal structures in salt crusts typically appear on the outer edge of dry salt lakes, while smaller polygonal structures typically appear inside dry salt lakes. The large polygonal structure at the foot of the southern wing of the Dalangtan hill ranges in length from 20 to 150 meters on each side, while the polygonal structure at the bottom of large volcanic craters on Mars has an average size of 120 meters (El Maary et al., 2010), and its characteristics and size are similar to those of the Dalangtan dry salt lake. In the Qaidam Basin's Xitai Salt Lake, there are also polygonal evaporite structures formed in modern times. This study discovered captured microbial signatures from fluid inclusions in the halite crystals (Meng et al., 2015), located in the central part of the polygonal evaporite structures. Therefore, the polygonal evaporite structures on the surface of Mars are priority exploration areas for preserving ancient signs of life.

Email: fwmeng@isl.ac.cn

NEW INSIGHT INTO STRUCTURE OF THE EAST EUROPEAN CRATON IN POLAND BASED ON ANALYSIS OF POTENTIAL FIELD DATA AND REGIONAL DEEP SEISMIC REFLECTION PROFILES

Mateusz Mikołajczak[1]

[1] Institure of Geological Sciences, Polish Academy of Science, Kraków, Poland

Co-authors: Stanisław Mazur[1], Piotr Krzywiec[2]

[2] Institure of Geological Sciences, Polish Academy of Science, Warsaw, Poland

The East European Craton (EEC) is an important geological area in Europe, consisting of three principal tectonic units that merged during the Paleoproterozoic (approx. 1.8 Ga): Volgo-Uralia in the east, Sarmatia in the south, and Fennoscandia in the northwest. The boundaries of Sarmatia and Fennoscandia extend into Poland, where they are concealed beneath Ediacaran and Phanerozoic sediment layers. Therefore, the precise location of the Fennoscandia-Sarmatia suture can be determined only through borehole and geophysical data. The latter have become essential in Poland, particularly since the sedimentary cover on the southwestern slope of the EEC often exceeds the depths that boreholes can reach. While there is general acceptance of the NE-SW direction of the suture between Fennoscandia and Sarmatia, its exact position remains unclear and has been the subject of various interpretations over time.

The seismic profile EUROBRIDGE'97 indicated that the Minsk Fault might serve as a possible suture between Fennoscandia and Sarmatia, with the Hanna Fault in Poland potentially continuing this feature. However, recent research suggests that the suture might be located further north, within the Grodno–Bialystok deformation zone located between Fennoscandia and the Belarussian-Podlasie Granulite Belt.

This study aims to elucidate the geometry and position of the collisional suture between Fennoscandia and Sarmatia by employing potential field data and high-resolution seismic reflection profiles. We examine PolandSPAN™ data from eastern Poland, which is oriented perpendicular to the expected location of the Fennoscandia-Sarmatia suture, specifically looking at profiles PL1-1000 and PL1-1100. A qualitative analysis of the gravimetric and magnetic data has enabled us to identify the locations of significant crustal discontinuities and lithological changes that correspond with the well-documented NE-SW metamorphic belts. Additionally, a quantitative evaluation of the potential field data, supplemented by the seismic reflection profiles, has allowed us to create two-dimensional geological models that are perpendicular to the suture's path. These models have uncovered a portion of the lower crust with increased density, as well as rock formations in the middle and upper crust that display both elevated density and magnetic susceptibility, potentially indicating the presence of mafic and ultramafic rocks. Our results support recent interpretations concerning the location of the Fennoscandia-Sarmatia suture and provide insights into its deep structure, including possible remnants of a former oceanic crust.

Email: ndmikola@cyf-kr.edu.pl

THEORETICAL INSIGHT INTO A KINEMATIC MODEL OF FAULT-BEND FOLDING

Szymon Mol

Institute of Geological Sciences, Jagiellonian University, Kraków, Poland; Computational Geology Laboratory, Polish Geological Institute – National Research Institute, Wrocław, Poland

Fault-bend folds are an example of fault-related folds. It means that their formation is associated with faults both in space and in time. Fault-related folds can be studied using kinematic models which describe only movement and geometry of rocks, but do not include any physical description of deformation in terms of stress and strain fields nor physical properties of rocks such as viscosity, elastic stiffness, etc.

Suppe (1983) proposed a two-dimensional kinematic model of folding by change in dip of a fault. The model predicts the interlimb angle in the chevron fold above a step in a fault from given data: main fault dip and the angle of change in fault dip. This result allows to reconstruct the whole geometry of the fold. The model is based on 3 assumptions: (i) area conservation (corresponding to rock mass conservation under plane strain), (ii) bed length conservation, (iii) bisection of the interlimb angle by axial surface (Suppe, 1983).

The poster presents a rigorous argument that the bisection of the interlimb angle follows from area and bed length conservation. So, it can be removed from the model assumptions and be treated as a property of the model. Moreover, finite strain distribution is obtained using this set of assumptions.

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Email: szymon.mol@student.uj.edu.pl

THE STRUCTURAL FRAMEWORK OF THE SOUTHWESTERN SWISS PLATEAU TERMINATION: THE IMPACT ON FLUID-FLOW PATHWAYS AND IMPLICATIONS FOR GEOTHERMAL EXPLORATION

Andrea Moscariello[1]

[1] Geo-Energy Group, Department of Earth Sciences, University of Geneva, Geneva, Switzerland

Co-authors: Ovie Eruteya and Fiammetta Mondino

[2] Geneva Earth Resources, Geneva, Switzerland

The Swiss Alpine foreland is described as generally moderately deformed plateau where the shortening related to the Alpine compression is accommodated mostly by fault surfaces sliding of the thick Mesozoic series over the Triassic evaporites. These observations led to the thin-skin theory which for many scientists is a mantra as considered the only logical model to explain the current structural deformation of the Jura mountains and neighbouring Swiss Plateau. In addition to this a series of long NW–SE deep regional strike slip faults succession were mapped supposedly compartmentalizing of the entire sedimentary. The role of these deeply rooted faults has been challenged by the recent examination of reprocessed and newly acquired 2D and 3D seismic in the Geneva Basin highlighting a variety of deformation affecting in different shape, scale and style the entire sedimentary succession. In summary:

- The study area shows a different style of deformation when comparing the northern and SW sectors. The former is dominated by E–W oriented lineaments while the latter by NE–SW lineaments including low angle thrusts.
- A newly identified system of conjugate regional lineaments oriented respectively E12N and E16S has been described in the centre of the basin. The main one (E12N) called the Rhone fault as it follows the path of the homonymous river, has a right-lateral kinematic overall displaying a transpressional character. This regional system might be responsible for the decoupling of the northern from the SW sector and their different styles as described before.
- The occurrence of a high degree of deformation at small scale (100s of meters in length) distributed within the Mesozoic succession is observed. These deformations consist of low-angle thrusts which root generally in shale and marly intervals.
- Thrust anticlines formed in the low-angle hanging wall have also been observed accounting for an ongoing deformation affecting the centre of the basin.
- The importance of Triassic salt displacement and dissolution in influencing the deformation style of the overburden sequence has been identified indicating the role that salt tectonics have played at early stage of burial of Triassic strata.
- Compressional deformation is observed affecting the ancient normal faults bordering the Permo-Carboniferous throughs which have been inverted most likely in Alpine time.

In this structurally complex tectonic framework, distribution of fault and dense fracture network associated with the different type of deformations described above are controlled by the geomechanical properties of lithological units. These structural features can play a key role in controlling the subsurface circulation of both hydrocarbon and geothermal fluids: the accurate description of their geometry, extension architecture and intersections will be key to predict fluid-flow behavior and identify possible targets for geothermal exploration wells.

Email: andrea.moscariello@uninge.ch

CONCEPTUALIZING FLUID-ROCK INTERACTION DIAGENETIC MODELS IN TECTONIC SETTINGS

Fadi H. Nader[1]

[1] IFP Energies nouvelles, Rueil-Malmaison, France; [2] Utrecht University, Utrecht, The Netherlands

Co-authors: Liviu C. Matenco[2,3] and Bilal U. Haq[2,4,5]

[3] Doctoral School of Geology, University of Bucharest, Bucharest, Romania; [4] Sorbonne University, Paris, France; [5] Smithsonian Institution, Washington DC, USA

Diagenesis entails a sub-metamorphic group of processes that change the composition and texture of sedimentary depositional rocks. Based on observations of diagenesis in various sedimentary systems and tectonic settings, we propose a new conceptual diagenetic model to better understand the relationship between multi-scale tectonic and the ensuing diagenetic processes. We demonstrate the applicability of our conceptual model in various tectonic and depositional systems with worldwide examples. Four distinct diagenetic fluid types are considered (i.e., basinal fluids, compactional fluids, meteoric fluids, and fault-associated fluids). Related, time-independent, diagenetic facies and their extent in the subsurface are defined as diagenetic facies tracts. They include the modified rock affected by a singular diagenetic fluid or process. The proposed diagenetic facies tracts are the basinal diagenetic facies tract, compactional diagenetic facies tract, meteoric diagenetic facies tract and fault-associated diagenetic facies tract. Their subsurface extent is controlled by the tectonic evolution, and we demonstrate that quantification and prediction is possible using a previously defined tectonic successions model. Each diagenetic facies tract is associated with a set of diagenetic processes and resulting products, that ultimately impact the pore space of the host rock and its flow properties. The combinations of several diagenetic tracts (into diagenetic facies tracts complexes) show that the optimal situation for enhanced flow is the one that combines meteoric diagenetic facies tracts with fracture-associated diagenetic facies tracts, where karst dissolution together with fracturing are common. Contrastingly, quiescent tectonic settings with a typical burial history result in excessive cementation and therefore reduced flow. These attributes are critical for the large-scale screening and quantification of subsurface geo-resources, conventional and particularly important for the sustainable ones (e.g., geothermal energy) and geological storage (e.g., CO_2 or energy) that are associated with enhanced fluid-rock interaction processes.

Email: fadi-henri.nader@ifpen.fr

DEFORMATION DYNAMICS OF THE RETRO-WEDGE FORELAND: SEISMIC INTERPRETATION AND NUMERICAL MODELING STUDY OF THE LLANOS BASIN, COLOMBIA

Michal Nemčok[1]

[1] Faculty of Mining and Geology, VŠB-Technical University of Ostrava, Slovakia; [2] RM Geology, Bratislava, Slovakia

Co-authors: Stephen A. Hermeston[3], Andreas Henk[4], Andres Mora[5], Camilo Higuera[6], Mauricio Parra[7], Samuel Rybár[1,8] and Lucia Ledvényiová[1]

[3] Louisville, Colorado, USA; [4] Institut für Angewandte Geowissenschaften, Technische Universität Darmstadt, Darmstadt, Germany; [5] Ecopetrol Óleo e Gás do BrasilPraia de Botafogo, Rio de Janeiro, Brazil; [6] Ecopetrol, Bogota, Colombia; [7] Institute of Geosciences, University of São Paulo, São Paulo, Brazil; [8] Dep. of Geology and Paleontology, Comenius University, Bratislava, Slovakia

Using the combination of reflection seismic interpretation with numerical modeling, this paper studies the deformation dynamics of the lower plate, overridden by the retro-wedge in the case of an advancing subduction zone. The Llanos foreland basin serves as the natural laboratory.

The modeling indicates that the orogen-parallel rift-related crustal thinning zone located in the lower plate results in its narrow flexure mode. Its lack results in a broad flexure mode.

The reflection seismic interpretation identifies five elongated clusters of flexure-driven normal-faults, centered on the forebulge axis. For five different stratigraphies of their syn-tectonic strata, they are located foreland-ward of thickness maxima of the coeval foreland basin fill. They are planar, steep and die out with depth without being detached. Both fault clusters and thickness maxima are characterized by the SW-to-NE migration in time. Those sub-sets of normal faults, which are adjacent to retro-wedge, underwent inversion to reverse faults, in a short time after the normal fault development, representing just several million years.

The modeling demonstrates that the inversion requires a stress regime with sub-horizontal $\sigma 1$ stress affecting the foreland crust located between the forebulge and retro-wedge. This regime does not occur when the foreland plate is loaded only by the vertical load of the retro-wedge. It requires both the vertical retro-wedge and horizontal loads affecting the lower plate.

The modeling also indicates that both aforementioned loading scenarios result in the development of forebulge axis-centered clusters of flexure-driven normal faults.

Email: rmgeology@rmgeology.sk

DEFINING THE KINEMATIC OF SCALE-FOLDS: INFERENCES FROM AN EAST CARPATHIANS NAPPE

Valentin Nistor[1,2,3,4]

[1] Department of Earth Sciences, Utrecht University, Utrecht, The Netherlands; [2] Doctoral School of Geology, Faculty of Geology and Geophysics, University of Bucharest, Bucharest, Romania; [3] Institute of Geodynamics Sabba S. Ştefănescu, Romanian Academy, Bucharest, Romania; [4] Geological Institute of Romania, Bucharest, Romania

Co-authors: Liviu C. Matenco[1,2] and Ioan Munteanu[2,3]

The study aims to define a genetic mechanism for the formation of high-angle recumbent folds and reverse faults in sediments characterized by contrasting rheological alternances. Although observed in many situations worldwide, a quantitative analysis of this deformation type is still needed. One optimal place to study this type of deformation is the Marginal Folds Nappe of Romania, where alternating sedimentary rheologies and associated deformation are well exposed in the deep-water to slope turbidites and more shallow deposits of the Bistrița half-window in the East Carpathians. We have combined new field kinematic observations with existing depth information to define the deformation history and analyze its relationship with the rheological distribution and mechanical stratification. Our kinematic analysis demonstrate that the specific type of deformation is indeed closely controlled by the rheological stratification. The deformation started with the formation of low-angle décollements and continued with the gradual formation of regional recumbent folds by gradual thinning along their flanks and thickening in hinges, accommodated by omission and duplication shears, as well as hinge-collapse, parasitic and outcrop-scale recumbent folds. Folding developed gradually with thrusting taking place along their overturned flanks and late-stage out-of-sequence fore- and back-thrusts, the result being a dominant sub-vertical position of observed strata. The high-degree of deformation was induced by the overthrusting of the more internal Tarcău Nappe. Particularly interesting is the high-angle geometry of densely packed reverse faults that formed gradually during the intense folding, which suggests multiple Miocene stages of deformation. These finding demonstrate a new kinematic and structural genetic type of deformation that can be used for predicting the depth geometry of reservoirs by the subsurface georesources exploration.

Email: valentin.nistor@s.unibuc.ro

GEOTHERMAL VS HYDROCARBON EXPLORATION IN SEDIMENTARY BASINS: A DE-RISKING WORKFLOW APPLIED TO THE SWISS PLATEAU

Silvia Omodeo-Salé, Yasin Makhloufi, Ovie Emmanuel Eruteya and Andrea Moscariello

Geo-Energy Group, Department of Earth Sciences, University of Geneva, Geneva, Switzerland

The Swiss Plateau (Switzerland) is characterized by a widespread occurrence of hydrocarbon seepages which are evidence of a complex active petroleum system characterized by multiple plays. Geothermal wells drilled over the last 20 years have also encountered both oil and gas (e.g. Schlattingen-1; St Gallen GT-1; etc.), which in some occasions have had negative short- and long term social perception and economic impact on the geothermal projects at local and national scale. Therefore, in order to assess the risk associated with the presence of oil and/or gas in areas of the Swiss Plateau with potential for geothermal energy exploration, it is critical to first evaluate the hydrocarbon potential of the basin. To achieve this goal, we adopted a robust workflow involving petroleum system modelling (PSM) and Common Risk Segment (CRS) maps. The PSM allows the re-construction of the thermal maturity of the potential source rocks, the timing of the hydrocarbon generation and expulsion, and to delineating the areas in the basin where migration and accumulations could occur. 2D PSM modelling was applied to five regional transects, representative of the stratigraphic and structural geometry of the basin throughout its extension.

The results obtained by the petroleum system modelling were used to produce Common Risk Segment (CRS) maps, which define the risk of hydrocarbon occurrence in an area. CRS maps evaluate and quantify the petroleum potential of an area and the risk of encountering hydrocarbon accumulations within a given geothermal play. The risk evaluation was calculated considering the following variables: presence and maturity of a source rock; presence and quality of a reservoir; presence and integrity of a seal; presence of a trap presence and the petroleum accumulation and saturation.

Several uncertainties in the final result must be considered, mostly related to the poor data availability and the consequent several assumptions and data extrapolations. However, we acknowledge that the final maps produced by the workflow proposed herein can be an essential basis for assessing the risk of encountering hydrocarbons, when drilling for geothermal exploration and production in the Swiss Plateau, which could be also applied elsewhere.

Email: silvia.omodeosale@unige.ch

EMPLACEMENT MECHANISMS OF THICK MAGMA SHEETS IN LAYERED SEDIMENTARY BASINS: THE POST-CALDERA TRACHYANDESITE INTRUSIONS OF THE INTRA-SUDETIC SYNCLINORIUM, POLAND

Sam Poppe[1]

[1] Centrum Badań Kosmicznych Polskiej Akademii Nauk (CBK PAN), Warsaw, Poland

Co-authors: Marek Awdankiewicz[2], Michael S. Petronis[3], Michael Heap[4], Claire Harnett[5], Stanislau Shytsik[2], Madison Allcorn[3], Alexandra Morand[6] and Daniel Mège[1]

[2] Institute of Geological Sciences, University of Wrocław, Wrocław, Poland; [3] Environmental Geology, Natural Resources Management Department, New Mexico Highlands University, Las Vegas, New Mexico, USA; [4] Institut Terre et Environnement de Strasbourg, Université de Strasbourg, Strasbourg, France; [5] UCD School of Earth Sciences, UCD University College Dublin, Dublin, Ireland; [6] School of Earth Sciences, University of Bristol, Bristol, UK

The emplacement of intermediate-composition magma as sills and laccoliths deforms the shallow crust of rocky planetary bodies. Monitored cases are rare on Earth, however, and only final surface deformation patterns are observed from orbit around e.g., the Moon or Mars. Studying exposed intrusive systems on Earth can be useful to understand magma emplacement mechanisms, especially in structurally complex, layered sedimentary basins. We have investigated trachyandesite intrusions in Permo-Carboniferous sandstones, shales, and rhyolitic tuffs of the Intra-Sudetic Synclinorium. The intrusions are exposed in commercial quarries at Gardzień, Tłumaczów, Świerki, and Głuszyca in Lower-Silesia, Poland. We have documented the geometries of exposed magma-host rock contacts in the field and in virtual outcrops produced from drone-based imagery, the mineralogy of host rocks, and the anisotropy of magnetic susceptibility (AMS) and paleomagnetism of the trachyandesites. The exposed floors and ceilings of the intrusive bodies reveal single, massif bodies in some places and stacked laccoliths and sills in other places. At the magma-host rock contacts, intrusive peperites and breccias attest to locally wet and poorly consolidated sediment conditions at emplacement. Shale near the contact has been sheared or intensively folded. Recrystallization and silicification without clear evidence of thermal metamorphism of the host sedimentary rocks near roof contacts testifies to secondary mineralization in a narrow contact aureole. AMS patterns along the intrusion floors suggest a general magma flow direction away from the adjacent Permian ignimbrite caldera, but local folding and faulting patterns along lateral and top contacts suggest complex flow in separate inflating magma lobes, corroborated by deformation features in the host rock. We have used laboratory-measured host rock uniaxial compressive and tensile strengths to calibrate the strength of a particle assemblage in a two-dimensional Discrete Element Method (2D DEM) model to simulate viscous magma emplacement in the Intra-Sudetic Permian sequence. Our simulations confirm that the emplacement mechanism and amount of fracturing in the host rocks strongly depend on the toughness and stiffness of the host rocks. Our results call for preserving access for geologists and students to these exceptional field sites to continue studying complex magma intrusion mechanisms in sedimentary basins, with global and planetary implications.

Email: sampoppe@cbk.waw.pl

MISSISSIPPIAN IGNEOUS FLARE-UP AT THE SW SLOPE OF THE EAST EUROPEAN CRATON AND ITS INTERACTION WITH THE BALTIC AND LUBLIN-LVIV BASINS

Paweł Poprawa[1]

[1] Faculty of Geology, Geophysics and Environmental Protection, AGH University of Krakow, Kraków, Poland

Co-authors: Ewa Krzemińska[2], Piotr Krzywiec[3], Krzysztof Nejbert[4], Stanisław Mazur[3], Łukasz Słonka[3], Ewa Słaby[3], Maciej Tomaszczyk[5] and Leszek Krzemiński[2]

[2] Polish Geological Institute – National Research Institute, Warsaw, Poland; [3] Institute of Geological Sciences, Polish Academy of Sciences, Warsaw, Poland; [4] Faculty of Geology, University of Warsaw, Warsaw, Poland; [5] PGNiG OGIE, PKN ORLEN S.A., Warsaw, Poland

Our study of boreholes, seismic survey, and magnetic data from the region between the Baltic Basin and the Lublin Basin indicates the existence of numerous buried intrusions and effusive complexes, most of them unnoticed so far, together with a few well-studied igneous massifs. They all are of alkaline character and developed in a time span of c. 350 to 338 Ma. Nonetheless, the main cluster of the TDM ages indicates that the extraction of parental magmas from its mantle source took place c. 1.25–0.85 Ga during the Grenville orogeny and the extension related to the break-up of the Rodinia/Pannotia supercontinent. In the central part of the Baltic Basin, deep seismic data reveal the presence of large sills, extending at least 160 km (N–S), emplaced in the crystalline basement at depths of 7–18 km (Pasłęk-Polik Deep Sills). In the Lublin Basin, the same data disclose deep sills in the sedimentary cover at a depth of c. 5.5–6.5 km, extending for c. 50 km (Minkowice-Pliszczyn Sills). Both coincide with shallower, sub-seismic scale lower Carboniferous intrusions. Conventional 2D seismic data allows us to demonstrate the presence of a sill system in the lower part of the Silurian section (extending c. 150 km N–S), located in the middle part of the offshore Baltic Basin (Gdańsk-Dalders Sills). All these igneous rocks occur in the coherent region and constitute a hitherto unrecognised Lublin-Baltic Mississippian Igneous Province (>120,000 km^2), which possibly extends to the western offshore Baltic Basin. Its denudation is evidenced by the Mississippian volcaniclastic formations of high thickness, developed in the adjacent basins. The igneous activity was triggered by thermal anomaly and/or mantle decompression caused by stress field reorganization, induced by the Variscan collision. Mississippian igneous activity affected palaeo-thermal regime of the pre-Carboniferous sedimentary successions of the Baltic Basin and the Lublin-Lviv Basin, locally leading to the development of anomalously high vertical gradients of thermal maturity. This induced a phase of oil and generation from the lower Paleozoic source rocks. Thermal anomalies led also to a porosity reduction of the Cambrian reservoir rock. Moreover, igneous activity determined the composition of natural gas dissolved in the brines within the sedimentary cover, locally causing a high content of nitrogen, hydrogen, helium, CO_2, and argon in total gas.

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Email: ppop.ecr@gmail.com

THE LATEST FAMENNIAN TO EARLY MISSISSIPPIAN TECTONIC DEFORMATIONS AND UPLIFT AT THE DISTAL FORELAND OF THE VARISCAN OROGEN (LUBLIN–LVIV BASIN; SW EAST EUROPEAN CRATON) DRIVEN BY TRANSPRESSION AND THERMAL DOMING

Paweł Poprawa

Faculty of Geology, Geophysics and Environmental Protection, AGH University of Krakow, Kraków, Poland

Co-authors: Maciej Tomaszczyk

PGNiG OGIE, PKN ORLEN S.A., Warsaw, Poland

Variscan orogeny in Europe impacted the development of the foreland plate, affecting subsidence and uplift histories and/or imposing tectonic deformations. An example of the Variscan distal foreland deformation is the early Mississippian major unconformity (referred to as the Bretonian) in the Lublin-Lviv Basin, located at the SW slope of the East European Craton. The unconformity divides the pre-Carboniferous rock complexes, being the subject to laterally differentiated uplift and erosion, from the post-tectonic sedimentary cover of the upper Visean to Westphalian age. The early Mississippian uplift separated the Lublin–Lviv Basin into several tectonic blocks, which differ in terms of stratigraphic extent of erosion cutting the sedimentary cover down to the different levels of the Devonian, the lower Paleozoic or the Precambrian basement. The estimated thickness of eroded sediments varies between individual blocks ranging from a few hundred to c. 2500 m at maximum. The early Mississippian uplift was associated with the development of a grid of faults, offsets of which usually range between a few hundred meters to c. 2000 m at maximum. Their structural style, revealed by seismic data, is mostly transpressive. This is additionally confirmed by an echelon pattern of some faults, which indicate a dextral strike-slip component. South and NE of the Lublin Synclinorium, the transpression-driven uplift was assisted by thermal doming, indicated by the oval shape of the zones with maximum thickness of eroded section, as well as by their coincidence with the location of Mississippian igneous intrusions and effusive rocks. An incipient latest Famennian phase of uplift and erosion is expressed by composition of sandstones and conglomerates of the Hulcze Formation (Lublin Synclinorium, SE Poland) and conglomerates and olistoliths of the Tumin Series (south of the Volodymyr Volynskyi Fault, W Ukraine), containing lithoclasts, pebbles and blocks of the local Ediacaran, lower Paleozoic and Devonian rocks. The SW part of the Lublin–Lviv Basin is distinguished as the Radom–Kraśnik Zone, previously considered devoid of Carboniferous. However, within this zone, seismic data locally also indicate the presence of angular unconformity between Devonian and Carboniferous. This is confirmed by legacy data of a few deep boreholes, revealing Carboniferous deposits resting on various stratigraphic units of the Devonian. Therefore, we postulate that the Mississippian tectonic deformation, uplift, and erosion affected also the Radom–Kraśnik Zone. The hiatus related to the Mississippian uplift and deformations covers time span of at least 15 My, i.e. (latest Famennian-?) Tournaisian to early Visean. It coincides in time with the major tectonic events within Variscan orogeny, such as the termination of convergence and continent-continent collision, as well as high-grade metamorphism. Having no other potential source of tectonic stress, the gid of transpressive faults and the uplift in the Lublin–Lviv Basin are interpreted here as the intraplate deformations imposed by the Variscan orogeny in its distal foreland.

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Email: ppop.ecr@gmail.com

THE COMPLICATING ROLE OF SALT IN RIFT-RELATED SEDIMENTARY BASINS

Mark G. Rowan

Rowan Consulting, Inc., Boulder, Colorado, USA

Many extensional basins contain salt, which may be classified as prerift, early synrift, late synrift, or postrift. Salt has unusual properties when compared to other sedimentary rocks – it is incompressible and it flows under applied stress – and thus complicates many aspects of basin analysis. In this broad overview, I summarize some of the effects of salt that might be underappreciated. First, it can be difficult to determine the timing of rifting when salt fills or partially fills graben: does the salt represent growth strata (synrift), did prerift salt flow into the space created during extension, or did postrift salt deposition fill in relict topographic relief? Second, accommodation for suprasalt strata may be generated either by ongoing rifting and the associated drop in the base salt and thinning of the salt, or by salt evacuation and flow into nearby diapirs. Third, basinward tilting of the basin margins due to thermal subsidence can be enhanced by proximal-to-distal salt flow and the consequent lateral shift in crustal load. Fourth, simple backstripping and calculations of loading subsidence due to sedimentation will be inaccurate if the suprasalt strata displace salt; instead, quantitative restorations that determine changing salt thickness through time are required. For example, movement of salt from a graben onto the rift shoulder counters the effects of flexural subsidence generated by graben fill. Finally, the emplacement of salt, whether autochthonous or allochthonous, perturbs normal sediment compaction due to its load and also its impermeability and thus potential impact on pore pressure. In summary, a proper understanding of salt and its evolution is a prerequisite for realistic analysis of basin formation during and after crustal extension in salt-bearing rift basins.

Email: mgrowan@frii.com

MULTISTAGE SELECTIVE DIAGENESIS INCREASING PORO-PERM PROPERTIES OF ANISIAN SPONGE-MICROBIAL-CORAL PATCH REEFS AND ADJACENT FACIES IN THE MUSCHELKALK OF UPPER SILESIA, SOUTHERN POLAND

Iga Ryczkowska

Institute of Geological Sciences, Jagiellonian University, Kraków, Poland

Carbonate rocks, particularly reefs and their surrounding facies, are important reservoirs for various resources. Their ability to store depends on their primary composition and diagenetic history.

This study reconstructs the influence of multistage selective diagenesis on the pore system evolution and porosity-permeability properties of the Anisian tropical reef system (Karchowice and Diplopora Beds) in the Muschelkalk of Upper Silesia, southern Poland, by combining field work, rock slab observations, standard and cathodoluminescence petrography, bulk and SIMS carbon and oxygen stable isotope analyses, porosity-permeability plug study, and computer image analysis of macroporosity (> 1 cm across).

The reef system comprises two levels of sponge-microbial-coral mounds, surrounded by various bioclastic, peloidal and micritic facies with Balanoglossites burrows. The strata have undergone a complex diagenetic evolution influenced by diverse fluids (marine, saline, meteoric) and diagenetic environments (shallow substratal, burial, telogenic). The key diagenetic processes include (in chronological order): 1) early-marine precipitation of isopachous fibrous rims; 2) early dissolution during exposure; 3) brine reflux dolomitization; 4) patchy silicification; 5) recrystallization; 6) burial calcite cementation by heated marine fluid; 7) deposition of vadose silt; 8) meteoric calcite cementation; 9) chemical compaction; 10) fracturing; and 11) final karstification, dedolomitization, iron oxide precipitation, and Liesegang ring formation due to meteoric water during Cenozoic telogenesis.

Numerous processes were selective and affected the same (more permeable) parts of the rocks. The strata display a wide range of porosity (0 to 39.7%) and permability (0,05 to 66,1 mD), with the highest values occurring in the reefs and burrowed facies. Late dissolution pores dominate and originated from selective removal of dolomitized micrite within burrows and between sponge-microbial automicrite as well as dolomite crystals, whereas primary and early pores are essentially occluded with calcite cements. The pores range in geometry and size, from sub-mm-scale dolomolds, through cm-scale vugs, caverns, and channels, to rare caves up to 2 m across.

This study demonstrates the transformation of the reef system from a tight to a porous formation, driven by multistage selective diagenesis and fluid flow, which amplified subtle permeability variations between different types of micrite.

Email: iga.ryczkowska@doctoral.uj.edu.pl

THE DEEP THERMAL FIELD IN PLATE TECTONICS

Magdalena Scheck-Wenderoth [1, 2]

[1] 1GFZ German Research Centre for Geosciences, Section 6.1, Potsdam, Germany; [2] Faculty of Georesources and Material Engineering, RWTH Aachen, Aachen, Germany

Co-authors: Judith Bott[1], Mauro Cacace, Denis Anikiev[1] and Ajay Kumar[1]

The Wilson Cycle creates specific lithospheric configurations characterized by a distinct geophysical configuration. With 3D data-integrated models we show how the upper few km of the Earth's crust have characteristic thermal fields depending on the setting and discuss the first-order controlling factors for these differences. We find that always the superposed effects of three main factors are relevant: (1) the distribution of different thermal conductivities, (2) the variable contributions of radiogenic heat in response to variations in crustal thickness and composition, and (3) the spatial variations in average geothermal gradient in response to the thermal lithosphere thickness. Depending on the setting, the configuration-dependent distribution of thermal properties leads to -specific 3D thermal fields that in turn control the local rheology and deformation. Rifts can be hot or cold depending on the rifting mode, the amount of stretching and the time since rift initiation. Accordingly, the "thermal anomaly" in the Upper Rhine Graben (Freymark et al., 2017) is almost unrelated to rifting whereas the thermal anomaly in the East African Rift System (Sippel et al., 2017) clearly relates to an impinging mantle plume. Passive margins can be hotter on their oceanic or their continental side depending on the age of the adjacent ocean (Gholamrezaie et al., 2018). Accordingly, the South Atlantic margins are colder oceanward as there an old oceanic lithosphere is present. In contrast in the North Atlantic the younger ocean and the superposed effects of the Iceland plume result in shallow temperatures increasing oceanward (Dacal et al., 2023). Orogens always have a hotter crust than their forelands as the topographic effect superposed with thickening of their radiogenic felsic crystalline crustal units lead to higher temperatures in the upper 20 km of the crust than at the same depth levels within the adjacent forelands. This hotter orogenic crust explains the lacking deep crustal seismicity in orogens as the Andes (Piceda et al., 2022) or the Alpine Himalayan Chain (Kumar et al., 2023). We present a comparative overview of these first-order differences and discuss the setting-specific consequences.

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Email: magdalena.scheck@gfz-potsdam.de

DEEP-SEATED, FAULTS-DRIVEN GEOTHERMAL RESOURCES IN THE HIMALAYA-KARAKORAM OROGENIC BELT, NORTHERN PAKISTAN

Mumtaz Muhammad Shah[1]

[1] Department of Earth Sciences, Quaid-i-Azam University, Islamabad, Pakistan

Co-authors: Muhammad Anees[2,3]

[2] Department of Structural Geology and Geothermics, Georg-August-Universität Göttingen, Göttingen, Germany; [3] Leibniz Institute for Applied Geophysics, Hannover, Germany

The northern Pakistan lies within the collision zone of the Indian and Asian plates encompassing the Himalaya, Kohistan, and Karakoram regions. These regions are part of the Himalayan Geothermal Belt, which extends across 3000 km along the Himalayas, with numerous hot springs resulting from high geothermal gradients. These gradients are driven by radiogenic heat production (RHP), deep exhumation, and the infiltration of meteoric water along faults.

To assess geothermal potential in these regions, we utilized satellite-based remote sensing, radiogenic heat production and thermal modelling. The Nanga Parbat Massif (NPM), central Karakoram, and eastern Karakoram emerge as promising geothermal targets with both hydrothermal and hot-dry rock systems. The Raikot Valley, Astore River, and Rupal-Tarishing areas of NPM contain radioelement-enriched hot rocks undergoing rapid exhumation, creating favorable conditions for geothermal activity. Active geothermal systems linked to the Raikot fault reveal signs of high heat flow and surface thermal anomalies, with estimated subsurface temperatures of ~100°C at 2–3 km depths. The Astore River cuts through high-RHP (~4.5 μWm^{-3}) gneisses, while the Raikot Valley features a steaming geyser at Tato, indicating shallow interaction with young granitic intrusions.

In the central Karakoram, the Hunza and Shigar valleys show moderate geothermal potential, supported by the presence of radiogenic granites (~4 μWm^{-3}) and hydrothermal alterations in country rocks. The Karakoram batholith, with a high lineament density and young granitic intrusions, exhibits elevated surface heat flow (~100 mWm^{-2}) and the potential for a hot-dry rock system with temperatures exceeding 100°C at depths of 2–3 km.

This study highlights the geothermal potential in the Raikot, Hunza, and Saltoro valleys, where high-temperature hot springs could support geothermal power production. Estimated subsurface temperatures range from 100–200°C at depths of ~2–3 km, sufficient to sustain geothermal power plants. Additionally, advanced geothermal technologies, such as closed-loop heat exchangers, could be implemented to enhance heat recovery while minimizing induced seismicity risks.

Email: mshah@qau.edu.pk

EXOTIC PROVENANCE OF THE MIDDLE CARBONIFEROUS SANDSTONES OF THE DONETS BASIN ACCORDING TO THE RESULTS OF THE U-PB ZIRCON DATING

Leonid Shumlyanskyy

Institute of Geological Sciences, Polish Academy of Sciences, Kraków, Poland

Co-authors: Vladyslav Shumlyanskyy

The Middle Carboniferous deposits of the Donets Basin (Donbas) contain over 100 coal seams and represent the main coal-productive horizon. The lower part of the C2 comprises argillaceous and sandy-argillaceous rocks that virtually contain no coal. These rocks crop out in the central Donbas, in the Naholny ridge. A sample of fine-grained sandstone was collected to define the provenance of the detrital material of the Dyakivska Group (C2dk) that crops out in the Hostry Buhor anticline. Zircons from this sample were analysed for U-Pb and Hf isotopes using the LA-ICP-MS. In total, 58 grains were dated, 37 of which yielded less than 15% discordant ages. The remaining 21 grains were omitted from further consideration.

According to the International stratigraphic chart, the age of the Dyakivska Group is ca. 320 Ma, while the youngest zircon in sandstone was dated at 326 ± 2 Ma, i.e. nearly identical to the presumed age of sedimentation. In total, 6 of 37 studied crystals yielded ages between 362 Ma and 326 Ma; all these reveal similar Hf isotope composition: εHfT = –7.3...-3.5. The largest group of 15 zircon grains varies in age from 454 to 631 Ma and has variable Hf isotope composition: εHfT from +11 to –12.9. This group includes two sub-groups derived from different sources: (1) juvenile zircons (age = 454–595 Ma, εHfT = +11...+3), and (2) zircons derived from crustal sources (age = 532–631 Ma, εHfT = –0.2...–12.9). Older grains are relatively rare: 4 crystals yielded ages between 740 to 1080 Ma, and 10 crystals were formed between 1900 and 3000 Ma. Most of these have negative εHfT values.

Lower Precambrian rock complexes of the Ukrainian shield (and Sarmatia in general) represent a minor source of the detrital material, and their share is close to 25%. The rest of the zircon crystals originate from younger sources located outside the Ukrainian Shield. At least three sources can be identified. One of them is juvenile whereas the rest two represent remobilized crustal rocks. We assume that these sources of the detrital material were located within the Crimea-North-Caucasus orogenic belt.

Email: lshumlyanskyy@yahoo.com

INTERNAL STRUCTURE OF UPPER JURASSIC SUBSURFACE CARBONATE BUILD-UPS IN SE POLAND – AN INSIGHT FROM SEISMIC FORWARD MODELLING SUPPORTED BY OUTCROP ANALOGUES

Łukasz Słonka [1]

[1] Institute of Geological Sciences, Polish Academy of Sciences, Warsaw, Poland

Co-authors: Marcin Krajewski[2] and Piotr Krzywiec[1]

[2] AGH University of Science and Technology, Krakow, Poland

The Upper Jurassic depositional system in south-eastern Poland developed within the northern margin of the Tethys shelf. Significant parts of the Oxfordian–Lower Kimmeridgian succession are exposed in the Krakow-Częstochowa Upland (KCU), including large carbonate build-ups, mostly forming heterogeneous complexes. The study area, located in the central Miechów Trough, remains one of the least known parts of the basin. This is mainly due to the lack of outcrops of Upper Jurassic rocks. Recently, the subsurface system of the Upper Jurassic carbonate build-ups has been interpreted from relatively dense coverage of 2D seismic data calibrated by deep wells. In this study, we present a verification of the internal structure of the studied carbonate build-ups by applying zero-offset theoretical wave field modelling and comparing the resulting synthetic data with field analogues from the adjacent KCU. The construction of each seismic-geological model was based on previously conducted seismic-stratigraphic interpretations. Key velocity and density data were derived from the two modern exploration wells that partially drilled the carbonate build-ups. In the modelling process, outcrop analogues were used to validate finer details, including internal geometries, lithology, and facies. This led to the identification of several seismic intervals, which correspond with the distinctive internal structure of the given organic complex. A comparison of the modelling results with the real seismic data revealed a high degree of agreement between the identified seismic intervals and the lithological intervals described in the outcrop analogues. The subsurface carbonate build-ups were found to correlate well with those documented in the KCU, thereby providing a more detailed regional insight into this part of the basin than has previously been possible. The reefal complexes comprise two principal levels of massive limestones, separated by thin to medium bedded pelitic limestones and marly limestones. The internal structure of the hybrid carbonate build-ups is markedly influenced by porosity, which frequently shapes the amplitude contrasts. The initial segments of the structures present a considerable challenge for accurate seismic interpretation, with the basement exhibiting partial influence from velocity pull-ups.

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Email: lukasz.slonka@twarda.pan.pl

INFLUENCE OF ANHYDRITE INTERLAYERS ON THE STRUCTURAL STABILITY OF SALT CAVERNS

Michał Słotwiński

Polish Geological Institute – National Research Institute, Computational Geology Laboratory, Wrocław, Poland

Co-authors: Marta Adamuszek and Marcin Dąbrowski

Polish Geological Institut – National Research Institute, Computational Geology Laboratory, Wrocław, Poland

The global shift towards net-zero carbon emissions, coupled with concerns about energy security, has driven increased use of renewables. Among these, wind and solar technologies have gained significant popularity. However, their intermittent nature, i.e. their power depends on transient atmospheric conditions and varies over time, introduces challenges for maintaining a consistent energy supply. This variability imposes a need for efficient energy storage solution that can capture the excess energy generated during high-power periods and release it during low-production times. One of the most promising technologies is the Power-to-Gas technology, which involves producing hydrogen through water electrolysis. The produced hydrogen then requires storage for later use, e.g. in underground caverns leached in rock salt deposits.

In Poland, suitable locations for underground storage are often found within bedded salt deposits. However, these deposits locally contain non-halite interlayers that can introduce several challenges: (1) their leaching rate differs significantly from that of halite, leading to irregular cavern geometry; (2) they can be more permeable than rock salt, potentially creating pathways for leakage, and (3) their mechanical properties (either stiff and brittle or fast-creeping) can impact cavern stability.

In this study, we numerically investigate the role for non-halite interlayers, such as anhydrite, on the mechanical stability of the salt cavern. The geometrical characteristics of our model is based on the observations from the salt deposit on Łeba Elevation in northern Poland. We conducted a range of numerical simulations using in-house built Finite Element Method codes in MATLAB. The cavern was simplified to a 2D half-section through application of axisymmetric geometry and appropriately modified constitutive equations. In the simulations we tested the role of (1) interlayer thickness, (2) its position within the salt bed, (3) cavern geometry, and (4) mechanical properties of rock salt and the interlayer, analysing the resulting stress, strain and velocity distributions around the cavern.

Email: mslot@pgi.gov.pl

UPPER CRETACEOUS SYN-INVERSION DEPOSITIONAL SYSTEMS IN THE SOUTHEASTERN EAST EUROPEAN CRATON, NE POLAND

Aleksandra Stachowska

Institute of Geological Sciences, Polish Academy of Sciences, Warsaw, Poland

Co-authors: Piotr Krzywiec

Institute of Geological Sciences, Polish Academy of Sciences, Warsaw, Poland

A comprehensive seismic-stratigraphic analysis of the Upper Cretaceous succession conducted in the SW marginal part of the East European Craton (EEC) in NE Poland allowed characterization of the Upper Cretaceous depositional systems significantly influenced by the inversion of the Polish Basin. In our study, we utilized 2D seismic profiles, including regional data from the PolandSPAN™ seismic survey. Geological and geophysical data from deep wells were used to calibration.

The Late Cretaceous–Palaeogene inversion of the Polish Basin caused substantial uplift in its central part, the Mid-Polish Trough, resulting in the formation of the Mid-Polish Anticlinorium. Seismic data from the NE flank of the Anticlinorium revealed that this uplift and the associated tectonic activity had a profound influence on depositional patterns in the study area, e.g. thickness changes, erosional incisions, clinoforms and numerous unconformities were observed. These seismic features were correlated with the activity of inversion structures, i.e. Koszalin–Chojnice Structure and the Nowe Miasto–Zawichost Fault Zone, which functioned both as morphological barriers and as alimentary areas for the Polish Basin. We suggest that contour currents flowed along these structures. Notably, our study describes a previously undocumented regional intra-Upper Cretaceous unconformity extending over 400 km. This unconformity separates the Upper Cretaceous succession into two units: a lower one with layer-cake geometry and an upper one with low-angle clinoforms pinches-out towards the SE.

The depositional architecture of the Upper Cretaceous, shaped by transverse and axial depositional systems, deviates from the traditional layer-cake model commonly used to describe sedimentary successions within the EEC. The evolution of this architecture is attributed to inversion tectonics as well as associated regional lithospheric buckling along the SW margin of the EEC. Additionally, modelling of the development of selected elements of the Upper Cretaceous depositional architecture revealed by the PolandSPAN™ data was performed, and preliminary results confirm their relationship with inversion tectonics.

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Email: aleksandra.stachowska@twarda.pan.pl

CENOZOIC INVERSION AND BATHYMETRY OF THE BLACK SEA: INSIGHTS FROM THE UKRAINIAN SECTOR

Sergiy Stovba

[1]Institute of Geological Sciences, Polish Academy of Science, [2]S.I. Subbotin Institute of Geophysics of NAS of Ukraine, Kyiv, Ukraine

Co-authors: Randel Stephenson[3], Stanisław Mazur[1], Petro Fenota[4], Dmytro Vengrovych[4] and Andrii Tyshchenko[5]

[3]School of Geosciences, University of Aberdeen, Aberdeen, UK; [4]JSC UkrGasVydobuvannya, Ukraine; [5]Taras Shevchenko National University of Kyiv, Kyiv, Ukraine

This study is based on the interpretation of an extensive set of seismic profiles and palaeogeographical reconstructions supported by other geological data. Many if not all of the rift-related faults in the study area were inverted since the middle Eocene, accompanied by folding of strata within syn-rift (half)grabens. Contraction in the middle Eocene formed a large folded landmass that occupied a wide area, including the northern part of the Western Black Sea Basin and most of the eastern Black Sea. The Eocene landmass was thereafter reduced by erosion due to basin subsidence and subsequent marine transgression until almost all the land was again submerged below sea level by the Early Miocene. Up to 5 km of the pre-late Eocene sediments were eroded. The second significant period of contraction occurred in the Sarmatian (Late Miocene) with folding/thrusting gradually ending by Pontian time. This S–N contraction made a decisive contribution to the generation and growth of thrusts with vertical offsets of 2–3 km and numerous anticlines with amplitudes of up to 2 km. An E–W broad landmass crossing the present shallow and deep-water parts of the BS and the entire Crimean Peninsula and its related crustal deformation was formed at this time. The crests of most folds were severely eroded and truncated prior to and during subsequent subsidence. The formation of lakes and islands during later marine transgression, as well as the internal architecture of sedimentary sequences near the shoreline of the landmass, suggest that until the end of the Pliocene the BS was a relatively shallow sea with water depths of a few hundred meters. The mechanical response to rapid basin subsidence in the Quaternary appears to have reactivated normal faulting of the previously inverted south-dipping rift faults along the southern coast of Crimea. The normal faulting in this area also caused local compressional stresses, which activated additional growth of some folds and thrusts up to the present time. It was only in the Pliocene that the accelerated subsidence began, leading to the formation of the deep-water BS seen at the present-day. An important implication of the results is that the widely-held assumption about the BS as a deep marine basin with water depths of 2000 m and more since Cretaceous rifting is unlikely.

Email: stovbasm@gmail.com

POST HOC ERGO PROPTER HOC? ON THE ORIGIN OF FLUID EMANATIONS IN THE EAST CARPATHIANS, ROMANIA

Alexandru Szakács[1, 2]

[1]Institute of Geodynamics, Romanian Academy, Bucharest, Romania; [2]Institute of Earth Physics and Space Sciences, HUN-REN, Sopron, Hungary

Co-authors: István János Kovács[2], Csaba Szabó[2,3], Márta Berkesi[2], Thomas Pieter Lange[2,3,5], Ágnes Gál4, Ákos Kővágó[2,3,6], Orsolya Gelencsér[3,5] and Sándor Gyila[7]

[3]Lithosphere Fluid Research Lab, Institute of Geography and Earth Sciences, Eötvös Loránd University, Budapest, Hungary; [4]Babeş-Bolyai University Cluj-Napoca, Napoca, Romania; [5]Doctoral School of Environmental Sciences, ELTE Eötvös Loránd University, Budapest, Hungary; [6]Doctoral School of Earth Sciences, Eötvös Loránd University, Budapest, Hungary; [7]Dr. Benedek Géza Rehabilitation Hospital, Covasna, Romania

Dry and wet carbon dioxide emanations occur in the East Carpathians within and nearby the Neogene-Quaternary volcanic range mostly around the youngest volcanic areas. Traditionally they are assigned to the so-called "post-volcanic activity". However, a close scrutiny of the distribution of these features shows that neither their location with respect volcanic areas, nor the age of volcanic activity do not show any significant correlation between the occurrence of the emanations and volcanism. For instance, CO_2-rich mineral water springs are known in the Oaş-Gutâi Mts. where volcanic activity finished ca. 8 My ago. In the "subvolcanic zone" where magma never reached the surface many mineral water springs are also found. CO_2 emergences are located far away from any past volcanic activity at Borsec, east of the Călimani Mts. where volcanism ceased ca. 6.8 My ago, or at Slănic Moldova on the eastern side of the East Carpathians were no volcanic activity occurred at all. Further clues against the "post-volcanic" origin of the gas emanations include conceptual considerations (the dissolved magmatic volatiles tend to be released earliest, and not preserved as late residual fluids within the volcanic plumbing system to feed "post-volcanic" manifestations) and analytical results (He isotopic compositions indicate mantle origin of at least part of the CO_2 emanations). The lack of direct space and time relationships between the fluid emanations and volcanism, as well as other evidences, call for alternative explanations and a paradigm shift. According to theoretical considerations and our new results a novel explanatory concept is emerging. Origin from decaying crustal magma storage can be excluded. Instead, the recent "pargasosphere hypothesis" provides a better conceptual interpretation framework: the subcrustal origin of CO_2 is explained by decarbonization at ca. 70 km depth prompted by the crystallization of partial melts in the cooling asthenosphere below. According to a case study of fluid emanations at Covasna town, with no volcanism in the close vicinity, the mantle component of the emanating gases can have multiple origins at subcrustal depths (slab dehydration, asthenosphere upwelling and the lithospheric mantle) whereas lithospheric-scale deformations enhance upward fluid flow into the crust where metamorphic reactions by decarbonization and devolatilization processes may contribute to further fluid generation. Although no magma storage processes are considered to explain surface fluid emanations in the vicinity of Neogene–Quaternary volcanic areas, indirect causal links between volcanism and deep-origin fluid fluxes cannot be excluded. We propose that volcanism-related tectonic processes created favorable channels as pathways for the fluid flow thus explaining the higher abundance of emanation spots in the close vicinity of the most recently active volcanic areas.

Email: szakacs@sapientia.ro

NORTHERN APENNINE BURIED STRUCTURES OBSERVED FROM ANALYSES OF GEOPHYSICAL DATA TO EVALUATE THEIR GEOTHERMAL POTENTIAL

Magdala Tesauro[1,2]

[1] Dipartimento di Matematica, Informatica e Geoscienze, Università degli Studi di Trieste, Trieste, Italy; [2] Department of Earth Science, University of Utrecht, Utrecht, The Netherlands

Co-authors: Cortassa Valentina[1], Gianluca Gola[3], Thomas Nanni[3], Marina Facci[4], Antonio Galgaro[4] and Adele Manzella[3]

[3] Consiglio Nazionale delle Ricerche, Institute of Geosciences and Earth Resources, Pisa, Italy; [4] Dipartimento di Geoscienze, Università degli Studi di Padova, Padova, Italy

The geothermal resources are distributed within the crust and thus the characterization of the shallow tectonic structures is crucial for planning exploration and exploitation of the geothermal reservoirs. In the InGEO PRIN 2022 PNRR project (Innovation in GEOthermal resources and reserves potential assessment for the decarbonisation of power/thermal sectors), which has received funding from European Union, Next Generation EU, we develop an innovative exploration workflow, integrating geological/geophysical data, organized to make available a sort of decision support system of geothermal projects.

We focus our study on the Northern Apennine buried structures, belonging to the Romagna and Ferrara Folds (RFF), which show a relatively low geothermal gradients, within the deep carbonate units (~14°C/km), and a significantly higher thermal gradient (~53°C/km) in the overlying impermeable cover. According to these evidences, fluid thermal convection occurrs in the deep-seated carbonate units of Mesozoic age, composing the local geothermal reservoir.

The shallow crust is investigated through a total of 535 deep exploratory wells (VIDEPI database: https://www.videpi.com/videpi/videpi.asp), with depths ranging from 0.5 up to 6.5 km below ground level. They provide essential information, concerning lithostratigraphy, temperatures measured during drilling stops, and geophysical logs, which are used to implement a geological model of the shallow structures in a companion study.

On the other hand, the results of several geophysical investigations, recently carried out in the Alps and Po plain, are used to identify the depth of the main crustal discontinuities, lateral variations of Bouguer anomalies, seismic velocities. The comparison between the Vp and Vs-depth distribution help identify both the main crustal layers and areas of crustal thickening. We observe a good correspondence between the low seismic velocities, characterizing the shallow crust of the RFF, and negative Bouguer anomalies. We also notice that the velocity in the shallow crust is consistent with that obtained from the linear regression between the P-wave sonic velocity and depth for the cemented sand. The Moho depth, reconstructed by estimating the depth of the iso-velocity contour of 4.1 km/s, increases towards the Apennines, from ~27 km to ~48 km, as the velocity in the sub-crustal lithosphere, which is low in the central part of the study area, likely due to a local asthenospheric upwelling.

Email: mtesauro@units.it

EVOLUTION OF THE CARBONIFEROUS SEDIMENTARY FILL OF THE LUBLIN BASIN (SE POLAND) IN THE LIGHT OF SEQUENCE STRATIGRAPHY AND ITS IMPACT ON THE PROSPECTS FOR ENERGY RESOURCES, BAUXITES AND CO_2 STORAGE

Maria I. Waksmundzka

Polish Geological Institute – National Research Institute, Warsaw, Poland

Based on lithofacies, cyclicity and sequence stratigraphy analysis, the depositional architecture within the Carboniferous sedimentary fill of the Lublin Basin, as well as palaeogeography was reconstructed. Elements of the depositional architecture have been characterized – sedimentary environments, i.e. shallow clay and carbonate shelf, delta, fluvial environments and hyperconcentrated flows. The lithofacies-stratigraphic succession is characterized by large variability, related with cyclic appearance of particular sedimentary environments, as well as the modifying influence of relative sea-level oscillations and local tectonics. These factor were decisive for the infilling of the accommodation space in the basin, as well as the mid- and post-Carboniferous erosion. The lowstand systems tracts are characterized by deposits of braided, meandering and anastomosing rivers, which flew in incised valleys, where hyperconcentrated flows also took place. The transgressive and highstand systems tracts are dominated by delta, as well as shallow clay and carbonate shelf facies. The thickness relationships of deposits representing various environments within the Tournaisian–Visean indicate a delta-marine depositional regime, and within the Serpukhovian–earliest Bashkirian – a delta regime. In the Bashkirian, the shallow shelf and delta environments were largely replaced by continental areas with fluvial sedimentation. The marine basin existed till the end of Westphalian A (middle Bashkirian), whereas in the late Bashkirian-Moscovian deposition took place solely in a continental–fluvial environment. Palaeothickness analysis indicates that beginning from the Tournaisian–Visean to the early Bashkirian, a depocentre developed close to the southern margin of the Lublin Basin; it gradually shifted to the SE of the basin. In the late Bashkirian–Moscovian following the reconstruction of the paralic basin into a continental basin, two new depocentres were formed in the NW and E of the basin. Deposition in the basin was ceased by tectonic inversion, which formed its present-day boundaries, as well as erosionally reduced the top of the Carboniferous succession. In the Lublin Basin, there are prospects for bauxites in the Tournaisian and Visean volcaniclastic rocks, as well as for the accumulation of hydrocarbons within the Bashkirian sandstones (sequences 9, 12, 16, 17) filling incised valleys. There were also three potential reservoir levels for CO_2 storage within the Serpukhovian (sequences 6, 7) and Bashkirian (sequence 11–15) sandstones formed in the same environments.

Email: maria.waksmundzka@pgi.gov.pl

THE INTEGRATED PREDICTION ERROR FILTER ANALYSIS ALGORITHM IN THE RESERVOIR PARAMETERS ESTIMATION IN THINLY-BEDDED MIOCENE FORMATIONS FROM WELL LOGS AND LABORATORY TESTS

Sebastian Waszkiewicz[1]

[1] AGH University of Kraków, Kraków, Poland

Co-authors: Paulina Krakowska-Madejska[1], Jadwiga Jarzyna[1], Paul van der Vegt[2]

[2] PanTerra Geoconsultants

The reservoir properties, as effective porosity and absolute permeability, of a geological deposits are key factors in analyzing the reservoir potential. Well logs are one of the highest resolution methods. Usually the measurement is carried out in the well every 10 centimeters. Unfortunately, even the relatively high resolution logging devices can sometimes be insufficient. The measurements deliver an averaged reading from the area of investigation, which varies depending on the type of physical field and type of probe. Beyond doubt, one of the ways to obtain better results is to use higher resolution and direct methods such as core laboratory measurements. Therefore, laboratory tests are broadly used to match standard interpretations made based on well logs. However, these methods also have limitations. Laboratory measurements provide only point information on the small core plug, representing the reservoir. Prediction of the continuous parameters only from the well logs or from laboratory tests, especially in heterogeneous rocks, is challenging. Hence, the special link was investigated, regarding the artificial neural networks supported by the advanced log analysis. The Integrated Prediction Error Filter Analysis algorithm (INPEFA), calculated for the intensity of the gamma ray GR, significantly improves the estimated porosity and permeability. Moreover, the INPEFA curves, used as an additional qualitative input, provided the continuous parameters for porosity and permeability more precisely in comparison to the neural network procedure without the INPEFA algorithm. The presented analyses demonstrated the potential of using neural networks in prediction of the continuous porosity and permeability curves based on well logs and laboratory results. Neural networks conducted on the well logs and INPEFA curves in a complex, heterogeneous, and thinly-bedded strata resulted in a significant improvement of the porosity and permeability resolution in the well profile.

Email: waszkiewicz@agh.edu.pl

YEN BAI BASIN (RED RIVER FAULT ZONE, NORTHERN VIETNAM) AS AN EXAMPLE OF THE TECTONO-SEDIMENTARY PLAY

Anna Wysocka[1]

[1] Institute of Geological Sciences, Polish Academy of Sciences, Warsaw, Poland

Co-authors: Stanisław Mazur[1], Piotr Krzywiec[1], Anna Filipek[1], Phan Dong Pha[2], Nguyen Quoc Cuong[3], Do Van Thang[4], Nguyen Van Kieu[5] and Daniel Zaszewski[4]

[2]Institute of Marine Geology and Geophysics, Vietnam Academy of Science and Technology, Hanoi, Vietnam; [3]Institute of Geological Sciences, Vietnam Academy of Science and Technology, Hanoi, Vietnam; [4]Faculty of Geology; University of Warsaw, Warsaw, Poland, [5]Vietnam Petroleum Institute, Petrovietnam, Vietnam

The Red River Fault Zone (RRFZ) is the most important of the strike-slip faults thought to guide lateral extrusion in SE Asia. The estimated left lateral displacement along the RRFZ from Eocene to Miocene is in the range of 200–700 km. Since the beginning of the Pliocene, the kinematics of the RRFZ have reversed to right-lateral, with the total lateral offset between 6 km and 60 km. Large displacements along those zone must have resulted in localised shear deformation and lateral extrusion of coherent crustal blocks towards the E and SE since the Eocene in response to the Himalayan collision and the indentation of the rigid Indian plate into Asia.

The Late Miocene reversal of fault kinematics was associated with regional inversion of elongated sedimentary basins, as evidenced by offshore and limited onshore seismic data. To fill the gap between offshore and onshore data, the detailed field work was carried out in the onshore Yen Bai Basin. The basin is directly bounded to the north by the main branch of the RRFZ, which separates the basin from the highly metamorphosed Con Voi Massif. Outcrops of lower Palaeozoic rocks form the southern boundary of the Yen Bai Basin. The basin is filled with Paleogene/Neogene clastic deposits. The central and SW parts of the basin are dominated by chaotic coarse-grained deposits with metre-sized olistoliths. Typically, the bodies of coarse-grained sedimentary breccias are parallel to the trace of the RRFZ. To the NE, thick coarse-clastic series of pebble-sized conglomerates with rare sand lenses occur. In the northernmost area, lacustrine series with turbidites predominate. They are characterised by heterolithic facies with graded bedding, convoluted bedding, synsedimentary folds, tool marks, abundant coquina beds and numerous floral fragments. All clastic series are strongly tectonised and cut by a series of outcrop-scale strike-slip and normal faults.

In our interpretation, the contrasting sedimentary facies of the Yen Bai Basin have been juxtaposed by syn- to post-depositional strike-slip movement along the RRFZ. Although the exposure is patchy, the location of fault splays cutting a sedimentary sequence can be traced using a combination of SRTM 3 and magnetic data. Reconstruction of strike-slip displacements along the fault splays allows the original depositional architecture of the Yen Bai Basin to be reconstructed.

Email: anna.wysocka@twarda.pan.pl

A LITHOSPHERIC TRANSECT FROM THE LIGURIAN SEA TO THE PO BASIN (NORTHERN ITALY): THE DISMEMBERED AND ACTIVE OLIGOCENE-TO-RECENT FORELAND BASIN SYSTEM BASED ON AN UPDATED CRUSTAL AND UPPER MANTLE GRAVITY AND GEOPHYSICAL MODEL

Tamara Yegorova[1,2] and Andrea Artoni[2]

[1] Institute of Geophysics of National Academy of Sciences of Ukraine, Kiev, Ukraine;
[2] Dipartimento di Scienze della Terra, University of Parma, Parma, Italy

Co-authors: Tamara Yegorova[1,2], Andrea Artoni[2], Luigi Torelli[2], Anna Murovskaya[1,2], Aasiya Qadir[1], Nicolò Chizzini[1] and Fabrizio Storti[1]

Along a 465 km long, SW-NE directed composite seismic reflection profile derived from published works, a new gravity model was constructed from the Ligurian Sea through the Northwestern portion of the Northern Apennines to the Po Basin as far as Verona province. This integrated profile crosses: 1) the extended alpine chain in the Ligurian sea; 2) the complex stack of embricated thrust sheets, which, from the lowest to the highest, are the metamorphic basement (Tuscan metamorphic unit), the Mesozoic carbonate rocks, the exhumed or buried Oligocene–Miocene (pre-late Messinian) NE-ward migrating foredeep depocenters, the Ligurian allochthonous nappes; 3) the late Messinian to recent foredeep of the Po Plain; 4) the foreland area of the Northern Apennines in the Verona area which coincides with the Southern Alps foothills and retrowedge of the Alps.

Gravity field along the transect varies strongly from high positive values of Bouguer anomalies (160 mGal) offshore to the low-amplitude gravity minima (–160 mGal) above the Po Basin. The structure of the sedimentary succession, basement, and the crystalline crust of the density model were constrained by offshore-onshore WARR (wide-angle reflection and refraction) and reflection seismic profiles. In addition, the European Moho compilation was used as well. We also constrained the upper mantle structure by the S-wave tomography model of Italy. Using the known velocity-density conversion functions for different velocity values and rock types, the velocity model of the crust was transferred into density one, from which the gravity effect was calculated by the GRAV3D software.

A stable solution of the modelling was obtained for an oceanic crustal segment, a continental crust, and a transition zone, which are varying as follows: from a thin (18 km) oceanic crust in the Ligurian Sea to ≤ 40 km-thick continental crust with a thick (up to 18 km) meta-sedimentary and sedimentary succession of the Po Basin. The ocean-continent transition zone, ~100-km wide and up to 25 km thick crust, includes most of the Northern Apennines' embricate stack that is thinned and dismembered here. However, a spectacular feature of the transition zone is an un-

derplated sub-Moho high-velocity/density body, which is ~7 km thick and deepens northeastward, below the Po Basin. We interpret this feature as a remnant of Alpine/European Plate subduction. Then, this transition zone is abruptly separated from the oceanic crust by a block, ~40 km wide, with subvertical flanks, marked by local magnetic anomaly, which we associate to exhumed HP/LT alpine metamorphic rocks. All these features are indicative of the complex nature of this transition zone, which was affected by various geodynamic processes during the long-lived history of the Europe and Africa plates convergence and the closure of the Ligurian Tethys ocean since the Late Cretaceous. These processes included the compressional deformation event of the crust (in Eocene times) during the closure of the Piedmont-Ligurian Ocean and the Apenninic subduction. Then, since middle Miocene (~20–15 Ma), rifting occurred in the area of the modern Ligurian Sea and the transition zone started to form; it led to formation of the modern Western Mediterranean Basin and southwards opening of the Tyrrhenian Sea under the influence of asthenospheric flows. The latters, in the offshore part of our transect, are recorded as low-velocity layers (from S-wave tomography) in the subcrustal portion, at a depth of about 30 km, and in the upper mantle. Corresponding zones of low density (up to 3.20–3.25 g/cm^3) are present in the upper mantle of our density model. The distribution of the high heat flow zones strictly corresponds to the subcrustal astenospheric heterogeneities confirming their recent origination. Similarly, the updated crustal and upper mantle model obtained for the Po Plain and Verona province suggests that the gravity, magnetic and heat flow anomalies fit well with a recent foredeep depocenter passing to its foreland area. Geological constraints, derived from Northern Apennines and Southern Alps foothills, suggest that this foredeep-foreland setting of the Po Basin started to be active since the latest Messinian.

Email: andrea.artoni@unipr.it

OVERPRESSURE PREDICTION CHALLENGES IN DEEPWATER FOLD-THRUST BELT OF THE SUNDALAND CONTINENTAL MARGIN, SOUTHEAST ASIA

Mateusz Zareba

Halliburton, Kraków, Poland

Co-authors: Geovani Christopher Kaeng

Geo Halliburton, Hague, The Netherlands

Overpressure presents major challenges in deepwater drilling in Southeast Asia. It effects primary well-design factors, such as the number of casing strings, mudweight used during drilling, and cementing programs, which are part of helping in minimizing potential subsurface hazard and non-productive time (NPT) as a result of kick, loss of circulation, and wellbore stability.

Southeast Asia's Sundaland geological region is the home of overpressurized sedimentary basins, mainly owing to the relatively young and active tectonic and rapid sedimentation in the basins. The study confirms that Sundaland continental margin deepwater environments have distinctive overpressure characteristics from those of shelf and onshore environments, which could be related to the compaction history, depositional facies, and structural styles of the region. They present some unique challenges in pore pressure prediction and well design. This environment, characterized by thick water columns, fine-grained sediment domination, and low-permeability systems, causes the overpressure to be shallow and continuous, running relatively parallel with effective stress. The presence of deepwater thrust-fold belts in major basins, as caused by gravity-driven and basement-driven shortening, also contributes to the region's characteristics. These compressional forces impact the compaction characteristic further and introduce common geopressure centroid phenomena, which in some cases have resulted in missed failure to reach drilling targets.

Email: Mateusz.Zareba@Halliburton.com

UNDERSTANDING INJECTED CO_2 FLOW AND TRAPPING MECHANISMS WITH BASIN MODELLING PRINCIPLES

Mateusz Zareba

Halliburton, Kraków, Poland

Co-authors: Geovani Christopher Kaeng

Geo Halliburton, Hague, The Netherlands

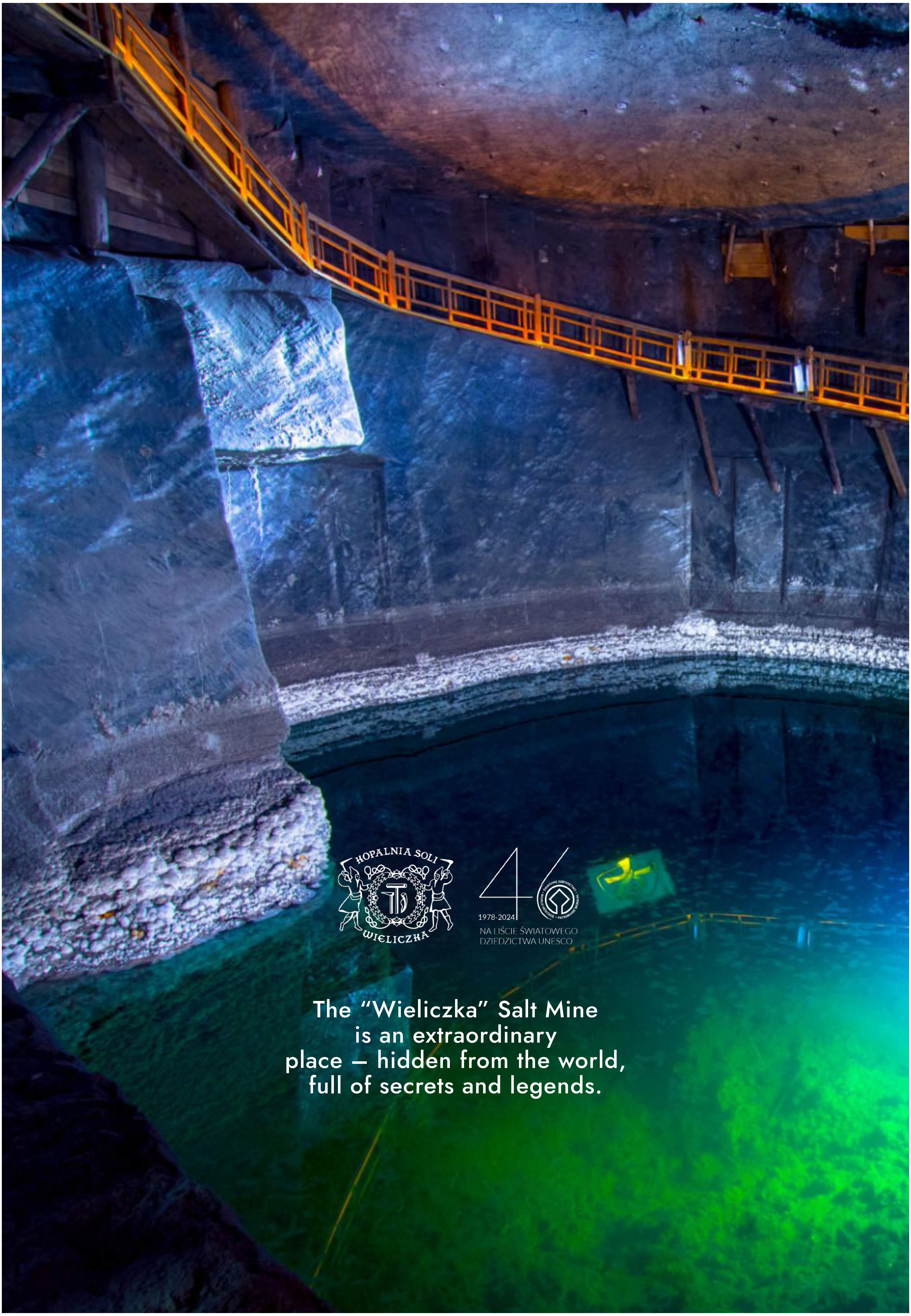
CO_2 migration and trapping in saline aquifers involves the injection of a non-wetting fluid that displaces the in-situ brine, a process that is often termed 'drainage' in reservoir flow dynamics. With respect to simulation, however, this process is more typical of regional basin modelling and percolating hydrocarbon migration. In this study, we applied the invasion percolation method commonly used in hydrocarbon migration modelling to the CO_2 injection operation at the Sleipner storage site.

We applied a CO_2 migration model that was simulated using a modified invasion percolation algorithm, based upon the Young-Laplace principle of fluid flow. This algorithm assumes that migration occurs in a state of capillary equilibrium in a flow regime dominated by buoyancy (driving) and capillary (restrictive) forces. Entrapment occurs when rock capillary threshold pressure exceeds fluid buoyancy pressure. Leaking occurs when fluid buoyancy pressure exceeds rock capillary threshold pressure. This is now widely understood to be an accurate description of basin-scale hydrocarbon migration and reservoir filling.

The geological and geophysical analysis of the Sleipner CO_2 plume anatomy, as observed from the seismic data, suggested that the distribution of CO_2 was strongly affected by the geological heterogeneity of the storage formation. In the simulation model, the geological heterogeneity was honored by taking the original resolution of the seismic volume as the base grid. The model was then run at an ultra-fast simulation time in a matter of seconds or minutes per realization, which allowed multiple scenarios to be performed for uncertainty analysis. It was then calibrated to the CO_2 plume distribution observed on seismic, and achieved a good match.

The study establishes that the physical principle of CO_2 flow dynamics follows the Young-Laplace flow physics. It is then argued that this method is most suitable for the regional site screening and characterization, as well as for site-specific injectivity and containment analysis in saline aquifers.

Email: Mateusz.Zareba@Halliburton.com


KOPALNIA SOLI
WIELICZKA
46
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