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CONFERENCE
SERIES

Čermák7

7th International Meeting on Heat Flow and the Thermal Structure of the Lithosphere

20-22 June 2022, Potsdam, Germany

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EDITORIAL

Dear Colleagues,

Potsdam welcomes you to the **7th International Meeting on Heat Flow and the Thermal Structure of the Lithosphere**. The **Čermák7** meeting remembers the successful tradition of the former Czech “castle meetings”, which were organized by the Geophysical Institute of the Czech Academy of Sciences in the years from 1982 to 2006. In honor of the chairman of those meetings, Vladimír Čermák, the name Čermák is adopted now for the conference series and the meetings ahead, organized under the auspices of the IHFC.
The Potsdam Čermák7 meeting is organized both as a conference and a workshop. It provides a unique opportunity for researchers, students and industry experts to show and discuss recent results and developments in heat-flow determination and interpretation, experimental petrophysics, geothermal exploration and lithosphere studies. Based on your scientific contributions an appealing program with 3 special talks, 26 oral presentations and 21 poster presentations reflecting the diversity of our heat-flow community. Surrounded by forests and lakes and rich in historical castles and cultural attractions, we are looking forward to an exciting Čermák7 meeting with many fruitful discussions!

The Local Organization Committee

Sven Fuchs   Ben Norden   Angela Spalek

GFZ German Research Centre for Geosciences, Germany

It is nice to realize, that the heritage of the castle meetings was not fully forgotten.
I very much appreciate the initiative of several fellow workers of the GFZ German Research Centre for Geosciences at Potsdam, who are ready to revitalize the idea. To keep the tradition to assemble a team of about 50 to 100 ardent participants eager to present their results, increase or diversify their knowledge, by spending couple days in a pleasant housing premise together with their colleagues from other part of the world. What a wonderful motivation. I was deeply touched by the GFZ appeal to provide my name to acknowledge my sometime activities by paginate the proposed June 2022 **7th International Meeting on Heat Flow and the Thermal Structure of the Lithosphere** by seven, to internationally recognize the continuation. It is a real honor for me.

Vladimír Čermák

Czech Academy of Sciences, Czech Republic

		Conference		Workshop	
Time	**Sunday (June 19)**	**Monday (20 June)**	**Tuesday (21 June)**	**Wednesday (22 June)**	**Thursday (23 June)**
08:30		Opening	E1–E4 Session 2		
09:00		Čermák talk		Workshop Session 1	
09:30		A Session 1			Telegrafenberg Tour (optional)
10:00		Coffee Break	Coffee Break		
10:30		B1–B4 Session 1	Bus transfer	Coffee Break	
11:00	Arrival		Boat tour (optional)	Workshop Session 2	
11:30					Departure
12:00		Lunch Break			
00:30			Bus transfer	Lunch Break	
01:00	Sightseeing Potsdam (optional)	C1–C4 Session 2	Lunch Break		
01:30				Workshop Wrap up	
02:00		Coffee Break	F1–F5 Session 3		
02:30		D1–D3 Session 2			
03:00	Registration opens		Coffee Break	Coffee Break	
03:30		Poster Attendance Time		Workshop Final Results	
04:00			G1–G5 Session 3		
04:30					
05:00					
05:30		Bus transfer			
06:00	Welcome reception and Icebreaker Party 6-… pm	Evening lecture		Transfer / Closing lecture	
06:30		Conference Dinner Barberini Museum 6-10 pm		Final Dinner 6-9 pm	
07:00			IHFC business meeting 7-9 pm		
07:30					
08:00					

Monday, 20 June 2022

Session 1 - Chair: Ilmo T. Kukkonen

08:30	**Opening Organization Committee**
	Sven Fuchs, Chair Local Organization Committee
08:35	**Welcome Speech GFZ**
	Susanne Buiter, Scientific Executive Director GFZ - German Research Centre for Geosciences
08:40	**Welcome Speech IUGG**
	Alexander Rudloff, Secretary General of IUGG - International Union of Geodesy and Geophysics
08:45	**Welcome & Honorary Speech IHFC**
	Massimo Verdoya, Chair of the IHFC - International Heat Flow Commission
09:00	**Čermák talk**
	Vladimír Čermák, Czech Academy of Sciences
09:30	**Thermal conductivity of Triassic evaporites and its influences on the rheology of an active extensional area: the Northern Apennines**
	Cristina Pauselli
09:50	**Coffee Break**
10:20	**Thermal conductivity at elevated temperatures for the sedimentary and metamorphic rocks from the Western Himalaya, India**
	S Eswara Rao
10:40	**Determination of thermal conductivity of clastic sediments using geophysical well logs and its application for heat flow density determination in Hungary**
	Laszlo Lenkey
11:00	**Repeated temperature logs of 2 km deep borehole Litoměřice, Czechia**
	Jan Šafanda
11:20	**Thermal observations from deep boreholes in northwestern Europe: Increase of conductive heat flow with depth and long-term palaeoclimatic effect**
	Niels Balling
11:40	**Lunch Break**

Monday, 20 June 2022

Session 2 - Chair: Ladislaus Rybach

12:40	**Heat flow of the Norwegian continental shelf**
	Christophe Pascal
13:00	**Low heat flow from the Mesoarchean Singhbhum Craton and its comparison with the adjacent Singhbhum Shear Zone**
	Labani Ray
13:20	**New advances in heat flow measurement in China**
	Yibo Wang
13:40	**Updated and improved continental conductive surface heat flow database from Mexico**
	Orlando Miguel Espinoza Ojeda
14:00	**Coffee Break**
14:30	**Heat Flow Map of the Czech Republic**
	Petr Dědeček
14:50	**A geothermal heat flow model for Africa based on Random Forest Regression**
	Magued Al-aghbary
15:10	**Present-Day Surface Heat Flow Prediction Using Geophysical Proxies**
	Jeffrey Nunn
15:30	**Poster Attendance Time**
16:30	**Break**
17:30	**Bus transfer from hotel Seminaris**
18:00 - 22:00	**Evening lecture & Conference Dinner at Museum Barberini**
	Talk: The Surface Heat Flow of Mars - Report about an attempt to measure it directly with the InSight mission - and to constrain it from seismic data and modeling
	Tillman Spohn

Tuesday, 21 June 2022

Session 2 - Chair: Niels Balling

08:40 am **Heat flow exploration in and around the Gulf of California Rift: Past, Present and Future. Results from in depth exploration in South Pescadero Basin**
Raquel Negrete-Aranda

09:00 **AuScope 'Heat Flow Program' to upgrade Australia's heat flow infrastructure**
Graeme Beardsmore

09:20 **Geotherms and Thermal Parameters from the Curie Depth Constrained Spectral De-fractal Method: Examples from Africa, Australia, and North America**
Dhananjay Ravat

09:40 **The temperature of continental mantle lithosphere as seen by a petrologist: An example from Cameroon Volcanic Line in West Africa**
Jacek Puziewicz

10:00 **Coffee Break**

10:30 **Bus transfer from hotel Seminaris**

11:00 **Boat tour**

12:30 **Bus transfer to hotel Seminaris**

13:00 **Lunch Break**

Session 3 - Chair: Graeme Beardsmore

14:00 **Continental lithospheric heat flow, temperature field and thickness – Examples and comments**
Ladislaus Rybach

14:20 **A 3.85 Ga record of Heat Production and Its Geodynamic Response**
Derrick Hasterok

14:40 **On Antarctic Geothermal Heat Flow**
Mareen Lösing

15:00 **Tectonic inheritance, thermal field and rheological configuration of the lithosphere - lessons learnt from 3D models and open questions**
Mauro Cacace

15:20 **The thermal regime and hydraulic properties of crystalline rocks at 6 km depth: Results of geothermal studies and hydraulic stimulation in the St1 Deep Heat project, Espoo, Finland**
Ilmo T. Kukkonen

15:40 **Coffee Break**

Session 3 - Chair: Andrea Foerster

16:10 **Heat and Fluids in the Earth's Crust – on the Back of an Envelope**
David Chapman

16:30 **Heterogeneities of the lithospheric thermal structure and rheology control Cenozoic intracontinental deformation in southeast China**
Shaowen Liu

16:50 **Water-Loaded Depth and Heat Flow Pattern of the Eastern Mediterranean Sea**
Massimo Verdoya

17:10 **A Regional Heat Flow Low in the South Formentera Basin (Western Mediterranean): a Hydrothermal Circulation Combined with Brine Reflux?**
Jeffrey Poort

17:30 **The global heat flow database - status, progress and future projects**
Sven Fuchs

17:50 **Conference Closing**
Massimo Verdoya, Sven Fuchs

From 18:00 **Buffet dinner**

19:00-21:00 **IHFC Business meeting**

Monday, 20 June - Tuesday, 21 June 2022
POSTER PRESENTATION

P01 **Two Decades of Geothermal Climate Change Observatory, Prague-Sporilov**

Vladimír Čermák

P02 **Heat flow distribution of southern South America and its connection with the geotectonic setting**

Rodolfo Christiansen

P03 **Thermal structure of the Apennine– Tyrrhenian basin system (central Italy)**

Gianluca Gola

P04 **The Importance of Thermal Conductivity for Optimized Geothermal Analysis and Development**

Arya Hakimian

P05 **Apollo Lunar Heat Flow Paradox**

Shaopeng Huang

P06 **GeoLaB - a geothermal underground laboratory for basic research**

Thomas Kohl

P07 **Geothermal regime of the Kuqa foreland basin, northwestern China**

Shaowen Liu

P08 **Combining magnetic and gravity data to infer the crustal architecture and heat flow in Wilkes Land, Antarctica**

Mareen Lösing

P09 **Heat flow and thermal regime in the Guaymas Basin, Gulf of California: Estimates of conductive and advective heat transport**

Florian Neumann

P10 **Quality assessment of German heat-flow data: A contribution to a revised Global Heat Flow Database**

Ben Norden, Andrea Förster, Sven Fuchs

P11 **A thermo-physical subsidence model for paleo-bathymetry reconstruction in extensional basins: quantifying the effect of lateral heat transfer**

Alberto Pastorutti

Monday, 20 June - Tuesday, 21 June 2022

POSTER PRESENTATION

P12 **Marine geothermal heat flow research at the University of Bremen and MARUM – Center for Envi ronmental Sciences**

Aline Ploetz

P13 **Mozambique Channel heat flow: new data and predicted heat flow map**

Jeffrey Poort

P14 **Heat flow estimates in the Northern Mozambique Channel**

Frédérique Rolandone

P15 **Geothermal atlas of the Sudetes and their foreland: an interdisciplinary project for recognizing the geothermal potential in SW Poland**

Piotr Słomski

P16 **Mapping the Thermal Structure of Southern Africa From Curie Depth Estimates Based on Wavelet Analysis of Magnetic Data With Uncertainties**

Mohamed Sobh

P17 **Lithospheric thermal structure from thermal data collection in and around Japan**

AkikoTanaka

P18 **Mantle thermal conditions of the Zagros collision zone and surroundings**

Magdala Tesauro

P19 **On the thermal and seismotectonic environment of the Finnish part of the Wiborg rapakivi batholith**

Toni Veikkolainen

P20 **Testing the Lithospheric Implication of four different Geothermal Heat Flow models for Greenland**

Agnes Wansing

P21 **Do temperature predictions of the crust need to consider pressure and temperature-dependent rock thermal conductivity?**

Andrea Förster, Hans-Jürgen Förster, Ben Norden, Sven Fuchs

P22 **Heat flow measurements in Slovenia and convective share in the borehole thermograms**

Dušan Rajver

Wednesday, 21 June 2022
CERMAK7 WORKSHOP
AGENDA

Goal: Agreement on (1) the basic workflow of the quality scheme and on (2) the specific scoring characteristics separately for probe sensing (marine) and borehole/mine (continental) data.

Block 1 **Starter (09:00 – 10:30)**

- General introduction to the quality scheme procedure
- Specific introduction to the methodological evaluation of marine probe data
- Specific introduction to the methodological evaluation of borehole/mine data

Coffee Break

Block 2 **Break Out (11:00 – 12:30)**

- Break out session (60 min) for group work on borehole/mine for probe sensing data. Clarification of open questions, finding solutions
- Presentation and discussion of group output, agreeing on the best solution

Lunch Break

Block 3 **Test, test, test (13:30 – 15:00)**

- Live test of the quality scheme on real data sets in small groups (group work) – identifying obstacles
- Presentation and discussion of group output, find solutions to obstacles

Coffee Break

Block 4 **Finalizing + Writing (15:30 – 17:00)**

Paper organization – Organizing the writing process efficiently

18:00 - 21:00 **Closing lecture & Final Dinner**

Talk: Climate change and heat flow: Last decades to measure heat flow in shallow holes

Ilmo T. Kukkonen

NOTES

Thermal conductivity of Triassic evaporites and its influences on the rheology of an active extensional area: the Northern Apennines

Cristina Pauselli (1), Gianluca Gola (2), Giorgio Ranalli (3), Paolo Mancinelli (4), Fabio Trippetta (5), Paolo Ballirano (5), Massimo Verdoya (6)

(1) Università di Perugia, Italy; (2) National Research Council of Italy, Italy; (3) Carleton University, Canada; (4) Università degli Studi "G. D'Annunzio", Italy; (5) Università Sapienza di Roma, Italy; (6) University of Genoa, Italy

The thermal properties of evaporitic rocks are of fundamental importance for several investigations spanning from the thermal regime of the crust, hydrocarbons-oriented investigations, and tectonic studies. We estimate the thermal conductivity of evaporitic rocks with a two-pronged method. First, an exhaustive review of the literature allows the determination of the conductivity for the main evaporitic minerals and of their variation with temperature. Secondly, in order to assess the effects of compositional variability, we select six samples of Triassic evaporites from the Apennines (from both outcrops and boreholes) and measure their mineralogical composition and thermal conductivity. We have chosen the northern Apennines because there are clear pieces of evidence about the role of evaporites in seismogenesis where the 1997–1998, 2012, and 2016–2017 seismic sequences were characterized by clusters of aftershocks that have likely involved mainly the Triassic evaporites. Laboratory measurements and field analyses, conducted on both borehole and outcrop samples, together with numerical modeling confirm that evaporites represent a key lithology in terms of both sealing properties and earthquake triggering.The results obtained in this work can be summarized in the following points: (i) A review of the literature encompassing works published in the last 80 yr has allowed us to retrieve average values of thermal conductivity for the main evaporite rocks-forming minerals at ambient conditions: anhydrite, 5.39 W/(mK) (± 0.13), dolomite, 4.91 W/(mK) (± 0.11) and gypsum, 1.64 W/(mK) (± 0.24). (ii) The relationships describing the thermal conductivity behaviour as a function of temperature in evaporite rocks and minerals were revised on the basis of a world while review of a wide data set. (iii) New thermal-conductivity values were obtained from samples of Triassic Evaporites of Italian peninsula, coming from outcrops and boreholes. The mineral composition is a major factor controlling the thermal conductivity: the samples with the largest thermal conductivity were mainly composed of anhydrite and dolomite, whereas the lowest values occurred in samples exhibiting a high content of gypsum. A positive correlation between thermal conductivity and density was observed. (iv) The agreement between the measured thermal conductivity and the values predicted from the mineral composition through the adopted mixing models justifies the use of mixing models when experimental determinations are not available. (v) The presence of thick, high thermal conductivity anhydrite/dolomite formations at depth, can produce a strong lateral variation of surface heat flow, with an increase of temperature gradient in the shallower layers and a decrease of the temperature gradient within the evaporite layers. This could have important implications both for the exploitation of low enthalpy geothermal resources and for the seismogenic role of evaporite formations. This last theme will be discussed taking into account the case of the northern Apennines.

Presenter: Cristina Pauselli (cristina.pauselli@unipg.it)

Thermal conductivity at elevated temperatures for the sedimentary and metamorphic rocks from the Western Himalaya, India

S. Eswara Rao, Labani Ray, Tavheed Khan
CSIR-National Geophysical Research Institute, India

Thermal conductivity of rocks and its variation with temperature are important parameters for determining lithospheric thermal structure, thermal evolution of sedimentary basins, geothermal resources, geo-engineering, and seismogenesis. Thermal data are not available for the Western Himalayan rocks which are primarily composed sedimentary and metamorphic rocks of Proterozoic to Eocene in age. These rocks are formed by the tectonic activities during the collision of the Indian and Asian plates. We measured the thermal conductivity of sedimentary and metamorphic rocks of the Western Himalaya using a steady-state divided bar method on 20 samples ranging from room temperature (25 °C) to 300 °C. Studied samples are sandstone, limestone, phyllite, and schist. Petrography and geochemistry were used to characterise the samples. Quartz, feldspar, mica, and chlorite are the most common minerals of the sandstone. The majority of the grains are subangular to subrounded. The limestone is primarily composed of calcite, with a trace of silica. Schist is primarily composed of quartz, feldspar, mica in the form of muscovite and biotite, amphibole, and chlorite. The study reveals that thermal conductivity decreases with an increase of temperature and the drop in thermal conductivity with temperature are higher for sandstone & limestone (30–32%) and lesser for phyllite and schist (20–25%). The average temperature coefficient of thermal conductivity b value is highest for limestone and sandstone (1.7 *10-3 1/K), intermediate for phyllite (1.2 *10-3 1/K), and lowest for schist (0.92 *10-3 1/K). The differences in thermal conductivity at ambient and higher temperatures for each rock variety are well correlated with the compositional change from Arkose to greywacke. This is the first systematic study of thermal properties for Western Himalayan rocks, and it will be useful for thermal modeling and seismogenic studies of this region.

Presenter: S. Eswara Rao (eswar5063@gmail.com)

Determination of thermal conductivity of clastic sediments using geophysical well logs and its application for heat-flow density determination in Hungary

Laszlo Lenkey, János Mihályka, Petra Paróczi
Eötvös Loránd University, Hungary

During harmonization of geothermal data in the framework of the TransEnergy project we observed that temperature is the same in the Hungarian and Slovenian sides of the border, but the heat flow density is higher in Slovenia. A plausible resolution of this contradiction is that in Slovenia higher thermal-conductivity values were used in calculating the heat flow density. This observation highlights the need for determining the thermal conductivities in a coherent way. In case of clastic sediments geophysical well logging data offer solution for this problem. We used natural gamma ray, resistivity, bulk density, neutron porosity and acoustic logs in order to determine the volumetric fractions of coarse grained sediments ('sand'), fine grained sediments ('clay') and water (porosity). Assigning proper thermal conductivities for these components we calculated the thermal conductivity of sediments by mixing laws. The thermal conductivity of shales and sandstones was calculated by harmonic mean and the lower Hashin-Shtrikman bound, respectively. We determined the thermal conductivity of sand and clay used in the mixing laws by matching calculated and measured thermal conductivities. In this matching process 236 thermal conductivity data measured in laboratory by DLS technique were used. Major part of these core samples preserved their original pore water by waxing. We recalculated the heat flow density in seven boreholes in Hungary using the thermal conductivities determined from the well logs. The method results in better quality heat-flow-density values, because the calculated thermal conductivities approach better the measured thermal conductivities than those thermal conductivities, which are based on the extension of the measured values to certain lithological units. As the Neogene and Quaternary sediments in the Pannonian Basin were deposited in the same sedimentary cycle, and as the method was calibrated with the thermal conductivities of these sediments, it offers the extension of the method outside Hungary in the whole Pannonian Basin.

Presenter: Laszlo Lenkey (laszlo.lenkey@ttk.elte.hu)

Repeated temperature logs of 2 km deep borehole Litoměřice, Czechia

Jan Šafanda, Petr Dědeček, Vladimír Čermák, Tomáš Uxa
Czech Academy of Sciences, Czech Republic

Temperature in 2 km deep borehole Litoměřice, drilled in 2007, was repeatedly logged down to 1700 m in the period 2007–2020. We were able to monitor a return of the temperature to the near equilibrium temperature-depth profile undisturbed by drilling. A detailed knowledge of temperature gradient together with thermal conductivity, diffusivity and heat production measurements on the drill-core samples of mica schist that occurs below 900 m depth enabled us to analyse the heat flow vertical variations in the lithologically homogeneous depth section 900–1,700 m. We came to the conclusion that temperature-depth profile in this section contains a robust climate signal of the last glacial cycle. The reconstructed ground surface temperature history used as a surface forcing function in a numerical solution of the transient heat conduction equation provided an estimate of the climatic heat flow disturbances also in the upper 900 m of the well. According to it, the heat-flow reduction close to the surface amounts to 25 mW/m^2 and at 500 m depth to 22 mW/m^2. The T-z profile contains also signal of the recent warming manifested by a negative temperature gradient close to the surface and a temperature minimum at a depth of about 40 m. The minimum has been migrating downward at a rate of 1.5–2 m per year in the period 2015–2020. The temperature log from June 2020 also confirmed our assumption on the origin of a temperature anomaly observed in previous temperature logs in the section 1600–1700 m of perforated inner steel tubing. After the tubing removal in the fall 2019, the anomaly disappeared.

Presenter: Jan Šafanda (jsa@ig.cas.cz)

Thermal observations from deep boreholes in northwestern Europe: Increase of conductive heat flow with depth and long-term palaeoclimatic effect

Niels Balling
Aarhus University, Denmark

Terrestrial heat-flow data constitute a highly valuable observational source of information for understanding structure and dynamics of the lithosphere and the underlying upper mantle. Thus, observed surface heat flow forms the principal surface boundary constraint for modelling and interpreting the thermal structure of the deep subsurface. The measurement of terrestrial heat flow, as based on Fourier´s law of heat conduction, is in principle straightforward. However, a number of factors may affect the near surface temperature gradients and the resulting local value of heat flow such as climatic temperature variations, erosion, sedimentation, topographic variations, groundwater flow and conductivity contrasts. The extent to which such perturbations are present is best evaluated, if observations from a great depth range are available. This is the case from observations from a number of shallow and deep boreholes in northwestern Europe. We present and analyze heat-flow data from the Danish Basin (depth range up to 3,000 m) and the Baltic Shield (depth range up to 5,000 m). From the Danish Basin, high quality observations from a number of boreholes show a characteristic increase of heat flow with depth from around 35–40 mW/m² at depths of 100–400 m to 70–75 mW/m² at depths greater than 2,000 m (Balling, 2013, Møller et al., 2019, Fuchs et al., 2020). From the deep Gravberg borehole in central Sweden, detailed information on the thermal structure in terms of temperature gradients, thermal conductivity, heat production and heat flow is available to a depth of 5,000 m (Balling, 2013). We measure a modest increase of heat flow with depth. However, when accounted for a relatively high radiogenic heat production from the granitic rocks, observed near surface heat flow is found to be 15–18 mW/m² below the predicted steady-state equilibrium value of about 66 mW/m². During the latest ice ages, the study area of northern Europe experienced low temperatures, and major parts were covered by ice sheets for long periods. For both areas, we observe an overall conductive regime, and we interpret the perturbed heat-flow depth profiles as due mainly to a long-term palaeoclimatic transient effect. Preliminary modelling provides consistency with observations for models with late glacial temperatures about 10 °C (central Sweden) to 15 °C (Danish Basin) below the post-glacial level. Combines with other observations, such as those of Kukkonen and Joeleht (2003), we find present-day shallow heat flow in northern Europe be significantly affected by long-term palaeoclimatic surface temperature variations and should not be applied (uncorrected) for deep thermal modelling.

Presenter: Niels Balling (niels.balling@geo.au.dk)

Heat flow of the Norwegian continental shelf

Christophe Pascal
Ruhr University Bochum, Germany

We present new heat-flow determinations on 63 exploration drillholes of the Norwegian continental shelf. The analyses are based on DST temperatures and lithological descriptions of drill cuttings. The results suggest median heat flows of 64 mW/m², 65 mW/m² and 72 mW/m² for the North Sea, the Mid Norway Margin and the SW Barents Shelf respectively. The heat-flow data from the Mid Norway Margin show gradual decrease towards the deep Møre and Vøring basins. This latter effect is attributed to reduced heat input from crustal sources due to attenuation of the basement below these two basins.

Presenter: Christophe Pascal (christophe.pascal@rub.de)

Low heat flow from the Mesoarchean Singhbhum Craton and its comparison with the adjacent Singhbhum Shear Zone

Labani Ray, Nishu Chopra, Eswara Rao Sidagam
CSIR-National Geophysical Research Institute, India

The Singhbhum Craton is one of the oldest (3.53 Ga) cratons in the Indian Shield that is exposed over an area of ~40,000 km². The core of the craton constitutes voluminous Paleoarchaean granitoids surrounded by highly-rich mineralized belts. Major rock formations in the core of the craton are the Older Metamorphic Group, Older Metamorphic Tonalite Gneiss, and three phases of the Singhbhum Granite. North of the craton is bounded by a mineralized shear zone known as Singhbhum Shear Zone, which is roughly east-west trending 200 km long and up to 25 km wide arcuate belt of folded supracrustal rocks that divides the Singhbhum Craton and North Singhbhum Mobile Belt. Heat flow plays an important role to estimate lithospheric temperature distribution, which is an essential parameter to understand the evolution and stabilization of the craton. Heat flow has been determined from the Singhbhum Craton using 7 deep boreholes with a depth range between 200 and 400 m. The data constitute the first heat-flow determinations from the core of the Singhbhum Craton. The study reports evidence of abnormally low heat flow (27–34 mW/m², average: 30 ± 3 mW/m²) in the Singhbhum Craton compared to the generally observed heat flow from the other cratons of the Indian Shield, i.e., Bundelkhand Craton (32–41 mW/m², average: 37 ± 8 mW/m²), Dharwar Craton (25–50 mW/m², average: 36 ± 8 mW/m²) and Bastar Craton (51–64 mW/m², average: 56 ± 6 mW/m²). Thermal conductivity and heat production are measured on about 200 samples covering major rock formations of the craton. Thermal conductivity shows intra and inter variations between the studied formations and an increasing trend from north to south. Heat production shows very low values compared to the granitic rocks observed in the other cratons of the Indian Shield. But thermal gradient does not show any particular trend. Also, heat flow in the Singhbhum Craton is half of that reported from the Singhbhum Shear Zone (59 to 63 mW/m²; average: 61 ± 2 mW/m²). The abrupt variations in heat flow from the Singhbhum Craton to Singhbhum Shear Zone will have important geodynamic implications

Presenter: Labani Ray (labani.ngri@gmail.com)

New advances in heat-flow measurement in China

Yibo Wang (1), Shengbiao Hu (1), Sven Fuchs (2)

(1) Chinese Academy of Sciences, China; (2) Helmholtz Centre Potsdam - GFZ German Research Centre for Geosciences, Germany

This study reviews the process of compiling heat-flow data in continental China, examining 1230 previously published heat-flow data one by one, updating newly published data in recent years, and gaining some new insights. The compilation work mainly includes (1) correction of 174 references and 145 location information; (2) elimination of 63 duplicate compiled data; (3) addition of 195 heat-flow data published in recent years. Based on the above data, the following new advances were obtained in this study: (1) for different depth levels of basins, the favorable areas for geothermal resource exploration are not the same, and the uplift area is not necessarily a favorable area for geothermal resources; (2) the volcanic activity area (Wudalianchi Mountain and Changbai Mountain) in northeast China does not coincide with the high heat flow background area, and the high heat flow area is mainly concentrated in the interior of Songliao Basin where the volcanic activity is weak; (3) the Ordos Block is seismologically confirmed to be a stable, unbroken craton block, yet reflects a similar relatively high heat flow background to that of east China; (4) the background heat flow in the Gonghe Basin (Northeastern Tibet Plateau) is high, and deep magma chamber may be an important cause of thermal anomalies; (5) the heat flow in the Qinghai-Tibet Plateau is high in the south and low in the north on the whole, and the high surface heat flow shows a spread consistent with the North-South Rifting System; (6) the high heat flow results in the northern Hainan indicate that it is likely to be influenced by deep thermal anomaly control (mantle plume?); (7) Based on the latest compilation of oceanic heat flow in the northern part of the South China Sea, the thermal-rheological structure of the crust along the continental margin from north to south has been studied, and the results show that the rheological structure gradually transitions from a ‘jelly sandwich’ model to a ‘Christmas tree’ model.

Presenter: Yibo Wang (ybwang@mail.iggcas.ac.cn)

Updated and improved continental conductive surface heat-flow database from Mexico

Orlando Miguel Espinoza Ojeda (1), Rosa Maria Prol-Ledesma (2), Jesús Arturo Muñiz-Jaúregui (2)
(1) Universidad Michoacana de San Nicolás de Hidalgo, México; (2) Universidad Nacional Autónoma de México, México

It is well known that conductive heat flow is a very important parameter used to explain directly/indirectly several geological, geophysical and geochemical processes in Earth´s interior. In addition, it is one of the main input parameters for reliable estimations of the geothermal resources related with Geothermal and Petroleum Systems. This may be possible principally, since heat flow is used to describe the subsurface temperature profiles, the heat transport mechanisms and allowing to establish the heat storage reserves. Since 2014, the collection for data to estimate new continental conductive heat-flow values in Mexico have been an exhaustive scientific task. As a result, data for almost 4,500 sites have been compiled, mostly from geothermal and petroleum deep boreholes. In this context, approximately 4,000 sites have been analyzed and evaluated to estimate new heat-flow values. Additionally, approximately 700 heat-flow values were compiled and published between 1974 and 2018. Therefore, this continuous updating of the Mexican continental heat-flow database, will allow defining areas with thermal anomalies and to classify sites of low, medium and high enthalpy, resulting in a better knowledge of the Mexican geothermal resources. Finally, the obtained data will help interested entities, private and public, in collaboration with academic institutions, to improve the geothermal exploration techniques for the discovery of new geothermal systems. Presently, all efforts have focused on the five high enthalpy geothermal fields under exploitation; however, new low and medium enthalpy may be discovered. Additionally, the scientific community interested in Earth science studies will benefit from this information.

Presenter: Orlando Miguel Espinoza Ojeda (omespinozaoj@conacyt.mx)

Heat flow map of the Czech Republic

Petr Dědeček (1), Jan Šafanda (1), Tomáš Uxa (1), Vladimír Čermák (1), Jan Holeček (2)
(1) Czech Academy of Sciences, Czech Republic; (2) Czech Geological Survey, Czech Republic

The contribution summarizes the results of a three-year joint project of the Institute of Geophysics and the Czech Geological Survey which aimed at revising and supplementing the heat-flow map of Czechia and constructing subsurface temperature maps up to a depth of 5 km. More than three hundred temperature logs found in the archives of the Czech Geological Survey and data from several newly drilled boreholes, mostly in the West Bohemia, have been processed. About two-thirds of the records had to be excluded mainly due to borehole convection, insufficient shut-in time or low quality of industrial logs. Topographic corrections were applied to the remaining wells where necessary, and the thermal conductivity of the rocks encountered by wells was estimated either by measurements on drill-core samples or by values found for the individual rock types in literature. This made it possible to compile a revised map of heat flow of Czechia. Subsequently, this map was used for construction of temperature maps at depths of 400, 1,000, 2,000, 3,000 and 5,000 m. The maps take into account the geological structure of Czechia and thermal properties of rocks typical for the individual geological units and allowed to delineate areas suitable for utilization of deep geothermal energy.

Presenter: Petr Dědeček (pd@ig.cas.cz)

A geothermal heat flow model for Africa based on random forest regression

Magued Al-Aghbary, Mohamed Sobh, Christian Gerhards
TU Bergakademie Freiberg, Germany

Direct Geothermal Heat Flow (GHF) measurements in Africa are sparse and unevenly distributed. To overcome the challenge of modelling GHF from such measurements, this study implements a hybrid model of Random Forest regression and krigging with external drift. In order to do so, we trained the model with global as well as regional data sets. Therefore, the quality and reliability of the geo-observables are assessed before the algorithm is trained. After tuning the algorithm's hyperparameters, the trained model relates the GHF to various geophysical and geological geo-observables, e.g., Moho depth, Curie depth, gravity/magnetic anomalies, and seismic wave velocities. Finally, the krigging with external drift is used in a post-processing step to include spatial dependencies. As a result, the predicted GHF map of Africa shows good performance indicators and is consistent with existing GHF maps of Africa. Apart from representing the GHF of the Africa in its entirety, this model indicates GHF anomalies and could help in GHF exploration.

Presenter: Magued Al-Aghbary (Magued.Wahab@doktorand.tu-freiberg.de)

Present-day surface heat-flow prediction using geophysical proxies

Jeffrey A. Nunn, Robert S. Pawlowski, E. Johnson
Chevron Technical Center, U.S.A.

Geoscientific understanding and economic assessment in petroleum exploration depends on the utilization of reliable heat-flow measurements and predictions. Heat-flow predictions are essential for hydrocarbon thermal-maturity modeling, seal and reservoir-quality prediction, geodynamic modeling, thermo-tectonic and crustal architecture studies, magnetic modeling, and alternative energy resources. An analytical challenge/deficiency arises in areas with sparse measured heat flows, resulting in higher uncertainties. We use multiple geological and geophysical proxy data sets to estimate present-day surface heat flow in regions devoid of heat-flow measurements such as central Africa and much of South America. Our approach can easily be adapted to support global scale heat-flow estimation using a 'big data' approach that leverages several widely available proxy data sets. Heat-flow estimation on oceanic-type crust and continental-type crust is addressed separately because of key differences in active thermal processes. For oceanic-type crust, we build upon the well-established relationship between present-day sea floor heat flow and age of oceanic crust. However, instead of the standard inverse power-law relationship, we use a polynomial function to model sea floor heat flow as a function of ocean-crust age which more accurately represents younger oceanic crust (<50 Ma) where hydrothermal circulation substantially modifies conductive cooling. For continental-type crust, we use multiple proxy data sets: crystalline crust thickness, thermo-tectonic age, lithospheric thickness, and lithosphere shear wave velocity to constrain present day surface heat flow. The 1D relationship between each proxy data set and present-day surface heat flow is empirically derived and final present-day surface heat flow is determined using a combination of the estimated heat-flow components to derive the best prediction of heat flow at the surface. These predictions can then be combined with actual surface heat-flow measurements to characterize the thermal regime. We have also explored using the Curie Depth as a temperature boundary condition. If the Curie depth is known from external or proprietary sources (e.g., magnetics), it can be used as the basis for a prediction of present-day surface heat flow assuming 1D steady-state heat conduction and estimates of the average thermal conductivity and radiogenic heat production of overlying crustal and sedimentary rocks. We demonstrate the utility of our methods using examples from western Africa that result in a more thermo-tectonically plausible present-day surface heat flow map and good agreement with direct measurements of surface heat flow.

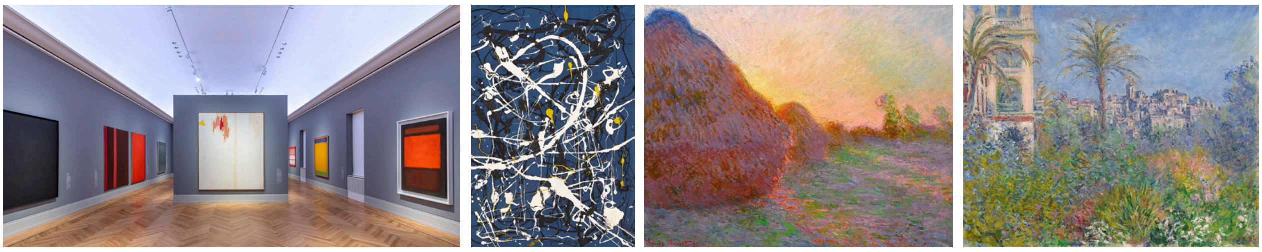
Presenter: Jeffrey Nunn (Jeffrey.Nunn@chevron.com)

CONFERENCE DINNER
Monday, 20 June 2022, 18:00 - 22:00

MUSEUM BARBERINI
POTSDAM

Enjoy the conference dinner at an extraordinary place, discover the artists and their work during a personal guided tour. The Museum Barberini is one of the most popular museums in Germany with international exhibitions and an extraordinary collection of Impressionist paintings.

17:30	Bus transfer from hotel Seminaris to Museum Barberini
18:15	Evening lecture **The Surface Heat Flow of Mars - Report about an attempt to measure it directly with the InSight mission - and to constrain it from seismic data and modeling** (Tillman Spohn)
19:00	Guided tour through the current exhibition "The Shape of Freedom" and the Hasso Plattner Collection with focus on French Impressionism
20:00	Conference Dinner
22:00	Bus transfer from Museum Barberini to hotel Seminaris



The Shape of Freedom. International Abstraction after 1945
June 4 — September 25, 2022

The exhibition examines the creative interplay between Abstract Expressionism and Art Informel in transatlantic exchange and dialogue, from the mid-1940s to the end of the Cold War.

Following World War II, painting went in completely new directions. A new generation of artists turned their backs on the styles of the interwar period: Instead of figurative representation or geometric abstraction, painters in the orbit of Abstract Expressionism in the US and Art Informel in Western Europe pursued a radically impulsive approach to form, color, and material. As an expression of individual freedom, the spontaneous painterly gesture gained symbolic significance. Large-scale color-field paintings created a meditative space for ruminating the fundamental questions of human existence.

Online Live Tours & Talks in English

For interested art lovers from outside the town, the Museum Barberini offers virtual tours in English. In a live zoom conference, art historians will guide you through the galleries and show the works, giving you the opportunity to see both the gallery rooms in total as well as single works. During the zoom conference, participants can ask questions or simply listen – and enjoy the collection almost as if you were in the museum.

Thu, 30. June, 6:30 PM / Thu, 1. Sep, 6:30 PM / Thu, 22. Sep, 6:30 PM

More on https://www.museum-barberini.de/en/

Heat-flow exploration in and around the Gulf of California Rift: Past, present and future. Results from in-depth exploration in South Pescadero Basin

Raquel Negrete-Aranda (1), Florian Neumann (2*), Robert Harris (3), Juan Contreras (2), Ronald M. Spelz-Madero (4), Robert Zierenberg (5), Dave W. Caress (6), Jennifer Paduan (6)

(1) Centro de Investigación Científica y Educación Superior de Ensenada, Mexico; (2) CICESE, Mexico; (3) Oregon State University, U.S.A.; (4) Autonomous University of Baja California, Mexico; (5) University of California, U.S.A.; (6) Monterey Bay Aquarium, U.S.A

The Gulf of California has been considered as a natural laboratory to study sedimentary basin development due to its unique stage as an active young rift characterized by an array of normal and strike-slip faults that connect a series of pull-apart sedimentary basins. Our knowledge about the distribution of heat flow in the Gulf of California has been steadily growing during the last 8 years. Thanks to an international collaborative effort we keep expanding the heat-flow database in this area, specially in three key basins: Wagner basin in the North, Guaymas Basin in the central Gulf and Southern Pescadero basin in the near the gulf mouth. Our goal is to obtain a regional picture of the Gulf's thermal state and understand the expression of highly-localized hydrothermal systems that have been recently studied and discovered that exchange copious amounts of heat and solutes from the deep Earth's interior to the ocean. This time, I will be presenting the results of the an in depth exploration and heat-flow survey in the Southern Pescadero Basin as an example of the type and resources involved in executing a successful heat-flow survey and implications in our understanding of how hydrothermal systems work in this particular tectonic setting and the colonization of thermophile species unique to this setting.

Presenter: Raquel Negrete-Aranda (rnegrete@cicese.mx)

AuScope 'Heat Flow Program' to upgrade Australia's heat-flow infrastructure

Graeme Beardsmore (1), Tim Rawling (2)
(1) University of Melbourne, Australia; (2) AuScope Ltd., Australia

The measurement and delivery of heat-flow data has historically been uncoordinated and disjointed in Australia. State and federal agencies have operated sporadic, short term measurement programs independently of academic and industry-led programs. Specialised field and laboratory equipment is dispersed, obsolete and/or duplicated around the country. Notwithstanding some individual efforts, there has been no centralised national program to coordinate heat flow research or data delivery. To address these shortcomings, a consortium of six universities, two federal research organisations, and a state geological agency, led by the University of Melbourne, recommended AuScope Ltd to invest in upgrading Australia's heat-flow capabilities. AuScope is a coordinating body for the Australian earth science research community, funded by the Australian Government through the National Collaborative Research Infrastructure Strategy (NCRIS). The 'Heat Flow Program' was subsequently included as a fundamental component of the 'Downward Looking Telescope' infrastructure framework in AuScope's 'Five-Year Investment Plan', with a notional AU$ 3–7 million budget. Aiming to launch by 2024 (dependent on continuing NCRIS support for AuScope), the Heat Flow Program will deliver state-of-the-art infrastructure to measure crustal heat flow, temperature and rock thermal properties. The program will cultivate a collaborative Australian heat-flow research community, with international linkages, operating a coordinated, findable and accessible network of heat-flow instrumentation and facilities. It will bring new sensors, tools and testing sites online, open new research avenues, and provide human resources to investigate low emission energy systems, groundwater resources, glaciology, marine systems, mineral exploration under cover, geohazard risk, climate change, geotechnical engineering, ore genesis, global tectonics, and other fields of research.

Specific components of the Heat Flow Program include:

1. The 'Heat Needle', an innovative shallow heat-flow probe for onshore measurements;
2. Active 'Distributed Temperature Sensors' (A-DTS)—powered fibre optic systems for in situ borehole heat flow measurements;
3. An 'Aquifer Thermal Energy Storage' (ATES) test site, including research boreholes;
4. A marine heat-flow measurement system for Australian research vessels;
5. Petrophysical equipment for measuring rock properties in the laboratory and field;
6. Digital facilities for compiling and delivering national heat-flow data.

Through its 'Opportunity Fund', AuScope already supported the University of Melbourne to install DTS and A-DTS fibre optic cables in research bores around Australia between 2020 and mid-2022; and the University of Tasmania to build a system for Australia's national marine research vessel, the RV Investigator, and the Australian Antarctic Division's icebreaker, the RSV Nuyina, to measure heat flow in ocean-floor sediments as part of sediment coring programs from 2022.

Presenter: Graeme Beardsmore (g.beardsmore@unimelb.edu.au)

Geotherms and thermal parameters from the Curie depth constrained spectral de-fractal method: Examples from Africa, Australia, and North America

Dhananjay Ravat
University of Kentucky, U.S.A.

We recently developed a new method of constraining geotherms deep in the crust in which we incorporate the magnetic Curie depth and temperature as an ‘a posteriori’ condition into the solution of 1-D heat-flow equation to anchor geotherms at the Curie depth. The Curie depth is derived carefully from the spectral De-fractal Method where the fractal parameter of the magnetic field is also derived. The Curie depth constraint allows determination of an additional parameter: the ratio of radiogenic heat production (A) to thermal conductivity (K). When K can be estimated from geologic knowledge or measurements, bulk A can be calculated. When the constraint is applied to one-dimensional steady state heat-flow equations with exponentially decreasing radiogenic heat production, one can use the surface observed and computed values of As to validate the method. We crosschecked observed values of As and K against the ratio As/K derived from the method in New Hampshire, Wyoming, and Colorado. Excluding high heat-flow locations in these regions as anomalous, the difference between the observed and computed As in all these cases is less than 6–7%. There are also regions where both the derived parameters (As and K) are not within the acceptable range for the given reduced heat-flow; these are generally the regions of complex active tectonics or anomalously high or low heat-flow values where the steady-state assumption is not valid. In the mid-oceanic ridge scenario of the Red Sea, the Curie depth corresponds to the Moho and reasonable values of K yield low values of A consistent with the expectation from mafic oceanic crust. We have applied the method to constrain the heat-flow and thermal properties in Africa, Australia, and North America. There are many areas of the world where high quality aeromagnetic data are available and, therefore, our method will be useful in constraining lithospheric geotherms and thermal parameters where the steady-state assumption is valid in a regional sense. One could also use the method of constraining geotherms to deep crustal temperature proxies from other geophysical parameters (e.g., seismology).

Presenter: Dhananjay Ravat (dhananjay.ravat@uky.edu)

The temperature of continental mantle lithosphere as seen by a petrologist: An example from Cameroon Volcanic Line in West Africa

Jacek Puziewicz
University of Wroclaw, Poland

The petrological information on temperatures in mantle lithosphere comes from mineral equilibria in peridotites xenoliths. The trustful P and T data can be recovered from garnet-bearing peridotite xenoliths, which occur in cratonic areas, and the geotherms based on the resulting P-T data are available for the deeper mantle parts of cratonic lithosphere. The xenoliths coming from the mantle lithosphere in Phanerozoic and Neoproterozoic continental areas contain no garnet, which makes impossible to estimate pressures. Nevertheless, if these xenoliths are sampled by volcanic activity, they offer an insight into the temperatures of the mantle lithosphere. In this abstract I will show an example of temperature estimates from peridotite xenoliths occurring in a recent (< 1 Ma) lavas of the Oku Volcanic Group, which is a part of the Cameroon Volcanic Line in West Africa. The lithosphere underlying Cameroon Volcanic Line was formed during Neoproterozoic collision of the Sahara and Congo cratons. The temperatures were calculated for two sets of xenoliths from Befang cinder cone (Tedonkenfack et al., 2021) and Wum maar (new data); all the studied peridotites belong to the mantle spinel facies. The equilibria between ortho- and clinopyroxene were studied. Two geothermometers were used: (1) the classical one of Brey and Köhler (1990), based on major element exchange, and (2) the one of Liang et al. (2013), based on rare earth elements (REE) exchange. The diffusion speed of major elements are one to two orders of magnitude greater than those of REE. The analytical data were collected with uttermost care, and after the samples exhibiting disequilibria between pyroxenes were eliminated, the studied set of xenoliths comprised 27 samples (12 from Befang and 15 from Wum). The calculated TBK and TREE differ by < 25 °C in 23 samples. The single sample of websterite which originated by deposition from recent lavas yields TBK = 936 °C, and TREE = 1098 °C, demonstrating different record of post-magmatic cooling. The perfect match between TBK and TREE in other samples shows that at the moment of entrainment into erupting lava they were in thermal equilibrium and that the temperatures of lithospheric mantle were not affected by Cenozoic volcanism. The unpublished results of me and my coworkers show that in many areas (e. g. some parts of the mantle lithosphere underlying Variscan orogen of Europe) TBK and TREE differ significantly (30–100 °C). On the other hand, the example presented in this study shows that careful geothermometric study can reveal fragments of thermally equilibrated mantle lithosphere even in the areas of active volcanism. Funding and acknowledgements. This study was funded by National Science Centre, Poland, project NCN 2021/41/B/ST10/00900. I am grateful to Magda Matusiak-Małek for comments which helped to improve the final version of the text.

Presenter: Jacek Puziewicz (jacek.puziewicz@uwr.edu.pl)

Continental lithospheric heat flow, temperature field and thickness – Examples and comments

Ladislaus Rybach
Eidgenössische Technische Hochschule Zürich, Switzerland

Geothermal conditions and processes are fundamental in issues related to the structure and dynamics of the continental lithosphere. Structures and properties are more complex in the continental than in the oceanic lithosphere. Here the continental lithosphere is addressed. The only direct geothermal observable at or near the surface is terrestrial heat flow. The temperature field in the lithosphere can be calculated by numerical modelling. This needs reliable input parameters, characterizing the rock constituents, especially about thermal conductivities (incl. its temperature dependence) and about radioactive heat production. The latter can be inferred from seismic vp velocities. Besides modelling, there are other means to obtain information about the temperature field: Xenolith p/T data, seismic tomography. Lithospheric thickness depends on the thermal conditions at depth: The base of the lithosphere is customarily located at the intersection of the local geotherm with some solidus curve or a mantle adiabat. Seismic tomography can also shed light on the topography of the lithosphere/ asthenosphere boundary. Examples will be shown from W. USA, Scandinavia, Central Alps, and Massif Central/France. In conclusion, the approaches are becoming increasingly sophisticated. In particular, the still growing computer capacity allows for the handling of more and more complex situations, processes, and structures. High-tech numerical modelling is not the problem, rather the input data. Constant emphasis must therefore be put on the extension of reliable databases, both in terms of surface observables like heat flow and of petrophysical properties like thermal conductivity and radioactive heat production.

Presenter: Ladislaus Rybach (rybach@ig.erdw.ethz.ch)

A 3.85 Ga record of heat production and its geodynamic response

Derrick Hasterok (1), Martin Hand (1), Matthew Gard (2), Renee Tamblyn (3), Jacqueline Halpin (4)

(1) University of Adelaide, Australia; (2) Geoscience Australia, Australia; (3) University of Bern, Austria; (4) University of Tasmania, Australia

Radiogenic heat production is perhaps the largest contributor to uncertainties when extrapolating the surface thermal regime to greater depths. Despite its reputation as a notoriously difficult to predict quantity, there are several geodynamic processes that may lead to systematic variations in heat production in igneous rocks. In this presentation, we discuss the influence of some of these processes including fractionation in volcanic arc settings, thermal stability in the early Earth, and the impact of supercontinents. Within volcanic arc settings, the concentration of heat producing elements is controlled by height of the crustal column as are many trace elements. Three arcs, Banda, Calabrian and Aeolian, are clear outliers, which is likely due to the subduction of continental crust and/or thick packages of continental sediments. A similar pattern to volcanic arcs is observed in the continental crust through time, which may be recording the growth of continental crustal thickness, with low heat production in Archean terranes and increasing to approximately 2 Ga. At 2 Ga, heat production rapidly increases before remaining relatively stable until the present day. An alternative hypothesis for the gradual increase in heat production in the Archean suggests heat production is limited by crustal stability. If heat production exceeds a stability threshold then the crust will likely be reworked or remelted, resetting high temperature geochronometers. The crust becomes stable once heat production decays below the threshold. Evidence for such a threshold is inferred from the near constant 'original' heat production of terranes—accounting for decay since formation. Knowledge of these controls and/or variations on heat production will help produce more accurate geotherms for the continental crust and can improve regional prospectively for many trace elements.

Presenter: Derrick Hasterok (derrick.hasterok@adelaide.edu.au)

On Antarctic geothermal heat flow

Mareen Lösing (1), Tobias Stål (2), Alex Burton-Johnson (3), Jörg Ebbing (1), Ricarda Dziadek (4), Fausto Ferraccioli (5), Andrew Lloyd (6), Anya Reading (2), Carlos Martin (3), Jacqueline Halpin (2), Pippa L. Whitehouse (7), Yasmina Martos (8), Adam Mart

(1) Kiel University, Germany; (2) University of Tasmania, Australia; (3) British Antarctic Survey, United Kingdom; (4) MARUM, University of Bremen, Germany; (5) Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Italy; (6) Lamont-Doherty Earth Laboratory, U.S.A.

Geothermal heat flow (GHF) in polar regions plays a crucial role in understanding ice-bedrock coupling and predictions of sea-level rise. Direct measurements of the thermal gradient and inferred geothermal heat flow are sparse and localized to few accessible areas in Antarctica but are essential for ground-truthing of indirect models. These models are based on a variety of different methods, such as inverse modeling of glaciological properties, Curie point depth analysis from magnetic data, forward modeling, or empirical comparison of seismic data in a regional or continental magnitude. Recent models include multiple sources of information within similarity analyses and machine learning approaches. Up to now, the caveat remaining is the resolution of continent-wide GHF models, that reaches at most 20 km due to the available data sets and small-scale spatial variability that cannot be captured. Thermal parameters, such as heat production and thermal conductivity, substantially control the magnitude and spatial distribution of GHF. Thus, improving our knowledge about subglacial geology, as well as, studies on the influence on ice sheet models is required. This way, areas vulnerable to small-scale GHF variability can be detected and prioritized for future investigations and additional probing. In 2021, a geothermal heat-flow subcommittee was formed under the new INStabilities & Thresholds in ANTarctica (INSTANT) scientific research programme. The aim is to increase interdisciplinary communication on the urgent topic of Antarctica's contribution to past and future sea-level changes. At this stage, we focus on including broad expertise from the direct measurement community, glaciologists, and ice sheet modelers and introduce the subcommittee's goals and Antarctic-specific problems to the global heat-flow community.

Presenter: Mareen Lösing (mareen.loesing@ifg.uni-kiel.de)

Tectonic inheritance, thermal field and rheological configuration of the lithosphere - lessons learnt from 3D models and open questions

Mauro Cacace (1), Magdalena Scheck-Wenderoth (1,2), Judith Bott (1), Denis Anikiev (1), Ajay Kumar (1), Constanza Rodriguez Piceda (1), Naiara Fernandez Terrones (1)

(1) Helmholtz Centre Potsdam - GFZ German Research Centre for Geosciences, Germany; (2) RWTH Aachen University, Germany

Sedimentary basins are complex geo-reactors in which sediments accumulate over geological time, under varying loading conditions dictated by tectonic forces and variations in the thermo-mechanical configuration of the lithosphere on which they develop. They play a strategic role as 'living archives' of past tectonic movements, whilst also hosting a large proportion of the world's mineral and hydrocarbon deposits, and offering unique opportunities in the development of renewable resources. The investigation of a basin as a potential geothermal resource requires an in-depth and integrated consideration of the geological and tectonic controls on the heat flow as well as on the thermal, stress and hydraulic regimes at a regional scale. Such investigations are important to underpin large-scale exploration programs reducing the adverse effects on the environment. However, the superposed effects of these regimes have not yet been systematically investigated based on 'real world' settings by linking the scale of the whole lithosphere to the scale of the engineered reservoir. In this contribution, we review the results from previous and ongoing projects aimed at developing data-constrained 3D lithospheric-scale thermo-mechanical models across a range of tectonic settings. We showcase how a detailed 3D description of the lithology, related physical rock properties and their structure can be used to better assess both the internal thermal and rheological configuration of the lithosphere. Accordingly, this leads to consequences relevant for both geodynamic processes (mechanical strength of the lithospheric layers) and for utilization of geothermal resources (deep temperature distribution, depth to the brittle-ductile transition and associated seismic features).

Presenter: Mauro Cacace (cacace@gfz-potsdam.de)

The thermal regime and hydraulic properties of crystalline rocks at 6 km depth: Results of geothermal studies and hydraulic stimulation in the St1 Deep Heat project, Espoo, Finland

Ilmo T. Kukkonen (1), Pekka J. Heikkinen (1), Matti Sinisaari (2), Jussi Rytkönen (1), Aino Karjalainen (1), Jochem Kueck (2)

(1) University of Helsinki, Finland; (2) Helmholtz Centre Potsdam - GFZ German Research Centre for Geosciences, Germany

The company St1 Oy started a deep geothermal energy project in 2015 in Espoo, Finland. The project is a pilot to explore the technical and economic feasibility of geothermal district heating from the crystalline rock of Finland. With its two 6.2–6.4 km measured-length (MD) wells in Espoo, Finland, it is the world's deepest current Engineered Geothermal Systems project. The aim is to construct an EGS heat exchanger (doublet) at the depth of 6 km for district heating in crystalline rock with ca. 100°C formation temperature. The drill site is located in Espoo, southern Finland, about 10 km west of downtown Helsinki. The bedrock comprises Precambrian granitoids and migmatitic gneiss, overlain by a thin veneer of Quaternary sediments. The company drilled three wells in the project. OTN1 is a pilot hole, a 2-km deep completely cored diamond drill hole with 76 mm diameter. OTN2 and OTN3 are deep deviated wells drilled with rotary and percussion drilling. Their diameters range from 1,000 mm at surface to 216 mm at bottom. OTN3 was completed in 2018 at the MD of 6.4 km (6.1 km vertical) and OTN2 in 2020 at 6.2 km MD (5.8 km vertical), respectively. The distance between the lower ends of the deep wells is about 400 m. An extensive set of geophysical and geological loggings and studies have been carried out in the three wells, including stress field measurements, thermal, acoustic, radiometric, resistivity image logs and a VSP survey. Hydraulic stimulations were carried out in OTN3 in 2018 and OTN2 in 2020. Stimulation aimed at improving hydraulic conductivity at depth and demonstrating the pumping capacity of the wells and formation. The stimulation experiment in OTN3 was made by pumping fresh water into five packer-isolated sections at 5.8–6.4 km, with a total pumped volume of 18,160 m^3. During stimulation, wellhead pressures, flow rates and induced seismicity were continuously monitored and recorded. More than 61,000 micro-earthquakes were recorded in the experiment. Controlling the pumping rates, pressures and seismicity in almost real-time allowed injecting a considerable volume of fluid into the formation without exceeding the earthquake maximum magnitude limit of m^2. 1 set by the local authorities. Hydraulic conductivity of the deep wells were studied using the stimulation pressure and flow rate data, which indicated the hydraulic conductivity to be dependent on applied pressure. In other words, the fractured rock responded elastically, and only little permanent increase in conductivity was achieved. Geothermal data were collected from OTN1 and OTN3. In OTN1, a representative equilibrium temperature log obtained about 6 months after end of drilling along with 400 thermal conductivity/diffusivity measurements of the core provided a reliable basis for deep temperature predictions. Deep temperature data in OTN3 comprises several wireline temperature logs obtained at different phases of drilling operations. Most of these cover only parts of the complete well depth range and they are affected by various drilling disturbances. Nevertheless, the data is considered representative of the formation temperature within ten degrees. In the presentation, we present an overview of the geothermal and hydraulic properties of the OTN wells.

Presenter: Ilmo T. Kukkonen (ilmo.kukkonen@helsinki.fi)

Heat and fluids in the Earth's crust – on the back of an envelope

David Chapman
University of Utah, U.S.A.

The study of heat flow and fluid circulation in the Earth's crust over the past 50 years has revealed important features of the energetics of the planet–much of which can be elegantly revealed by 'back of the envelope' calculations. This paper focusses on four of those calculations. (1) A thermal model attached to sea floor spreading predicts heat flow (q=500/ (age)1/2 in mW/m^2), ocean bathymetry (d= 2.7+ 1/3 (age)1/2 in km), and lithosphere thickness (l= 11 (age)1/2 in km) where sea floor age is in My. That is, the heat loss, elevation, and lithosphere thickness for 70% of the Earth's surface in three tidy equations. (2) In the world's oceans, a systematic deficit of about 50 mW/m^2 between measured heat flow and heat flow predicted from sea floor spreading exists in sea floor younger than ~55 My. Ascribing this deficit to sea water circulating though the permeable upper oceanic crust and producing the heat-flow deficit by mining the heat, results in a prediction of the magnitude of this sea water circulation: the entire ocean depth circulates through the permeable crust every million years. (3) The most dramatic sea water circulation through the crust is evident in black smokers on ocean ridges. An estimate of the thermal power of a black smoker suggests about 20 MW, equivalent to a small power plant. The magnitude of this heat loss means that black smokers have a limited lifetime. (4) Integrated heat loss rate over the surface of the Earth is 44 TW. Back of the envelope estimates show that this thermal power dominates the energetics of many other Earth processes: mountain building (0.4 TW), volcanism (0.2 TW), seismic energy release (0.02 TW), and metamorphism (0.02 TW). Such an inventory leads to the concept of the Earth as a heat engine with heat flow driving tectonics. Two other numbers put Earth energetics into context. Human energy consumption is now 15 TW, exceeding the power of many Earth processes, and solar energy intercepted at the Earth's surface is 170,000 TW. Thus energetics at the Earth's surface is still dominated by solar flux meaning that solar energy remains the energy of the future for humans.

Presenter: David Chapman (chap65@gmail.com)

Heterogeneities of the lithospheric thermal structure and rheology control Cenozoic intracontinental deformation in southeast China

Peng Yang, Shaowen Liu
Nanjing University, China

It still remains open how the rheology of the lithosphere influences the intracontinental deformation. We estimate the lithospheric temperature and integrated strength of southeast China, constrained by independent observations. The results demonstrate remarkable heterogeneities of thermal structure and rheology of the lithosphere. The majority of the area is of high mantle heat flow and temperature, thin lithosphere, except for the western Yangtze Craton where a cold and rigid mantle exists. The lithosphere thins southeastward from 200 km in the craton interior to 70 km in the South China Sea. Both rheologically 'jelly sandwich' and 'crème brûlée' models are observed, depending on the geothermal conditions. The seismicity in SE China is restricted to the 600 °C isotherm, weak lithosphere areas, and strength transition zones. The flat-slab subduction of the Paleo-Pacific Ocean and far-field effects of the Indo-Asia collision modulate the thermal regime and rheology of the lithosphere in SE China.

Presenter: Shaowen Liu (shaowliu@nju.edu.cn)

Water-loaded depth and heat-flow pattern of the Eastern Mediterranean Sea

Massimo Verdoya, Elie El Jbeily, Paolo Chiozzi
University of Genoa, Italy

We analysed terrestrial heat flow in combination with data of bathymetry, sediment and crustal thickness, derived from both global models and high-resolution local measurements, to investigate the nature of the lithosphere of the Eastern Mediterranean Sea (EMS) basins. Corrections for sedimentation and climatic changes were applied to infer the purely conductive steady-state geothermal flow. Bathymetric data were processed by removing subsidence caused by sediment deposition to obtain the water-loaded seafloor depth (WLD), i.e., the deepening of the continental/oceanic basement that is not related to sediments load or other external phenomena, but that can result from the tectono-thermal evolution of the lithosphere. Porosity and density information of sediments were considered to remove the sediment-load effect. At shallow depth, porosity and density data were available from offshore drillings. These data were corrected for the increase in volume (elastic rebound) due to the removal of the sediment overburden pressure. For the deeper sediment layers, density was inferred by converting seismic velocity data. Empirical relations describing the bulk-density variation as a function of depth were obtained for each main sedimentary basin, and sediment-load correction curves were generated and used to infer WLD. In the basins of likely oceanic nature, an additional crustal correction was applied to account for the isostatic replacement of a crustal thickness that differs from a reference crustal thickness with an equivalent water load. The water-loaded seafloor depths and the thermal data were then compared to reference models of continental stretching and ocean plate cooling. This allowed us to investigate the nature of the lithosphere and to understand seabed features that may not simply derive from cooling but may be accounted for by mantle dynamics. Such an analysis was carried out only in the sectors of the EMS characterised by free-air gravity anomalies of large wavelength, i.e., away from zones of subduction, flexural moats and seamounts in which WLD is very likely unrelated to lithosphere stretching and cooling. The results argued that the Levantine Basin (the easternmost part of the EMS) is floored by a continental crust that stretched by a factor of 2.5. Since the Levantine Basin should have reached thermal equilibrium, the surface heat flow does not show any enhancement caused by lithosphere extension. In the Ionian Basin (western sector of the EMS) and the Herodotus Basin (eastern part of EMS), WLD of 6 km and 7.2 km, respectively, are in favour of a very old lithosphere of oceanic type. By adopting the oceanic plate cooling model as a reference, the residual bathymetry, i.e., the difference between the bathymetry predicted by the model and the estimated WLD, is negative, namely -0.4 km in the Ionian Basin and -1.6 km in the Herodotus Basin. This is consistent with the free-air gravity anomaly data and could be evidence of a cold and thick lithosphere sinking in the asthenosphere. The average residual heat flow of the Ionian and Herodotus basins is smaller by 12–17 mW/m^2 to the reference value of the plate model. This again supports the lithosphere to be anomalously colder than a typical, old oceanic lithosphere. The half-space cooling model is in better agreement with the heat-flow data, but the residual bathymetry is positive by about 1.5 km and thus inconsistent with the free air gravity pattern.

Presenter: Massimo Verdoya (verdoya@dipteris.unige.it)

A regional heat-flow low in the South Formentera Basin (Western Mediterranean): A hydrothermal circulation combined with brine reflux?

Jeffrey Poort (1), Massimo Bellucci (2), Damien Do Couto (1), Simon Blondel (3), Frédérique Rolandone (1), Team WESTMEDFLUX

(1) Sorbonne Université, France; (2) IUEM and Ifremer, France; (3) OGS and University of Trieste, Italy

During three oceanographic cruises between 2015 and 2018 (MedSalt, WestMedFlux, WestMedFlux-2), a total of around 200 new heat-flow data were collected in the Western Mediterranean aligned along regional profiles that show an important heat-flow variability on the basin-scale, but also locally on the margins. Here we will focus on the heat-flow anomalies observed on the South Balearic margin, and more specifically on the South Formentera basin. This marginal basin is bordered by the Emile Baudot Escarpment and several seamounts that make the transition to the abyssal plain. We identified a large zone within this basin that is characterized by a low heat flow, up to a minimum of 0 mW/m^2. Locally, a high heat flow (>150 mW/m^2) was measured at the top and at the foot of the escarpment. How to explain the basin-scale reduction of heat flow on this margin? During the Messenian Crisis 6 Ma ago the sea level of the Western Mediterranean dropped by 1.5 km for about 600 thousand years. This will have put the South Formentera basin to sea surface level and allowed a topographic-driven fluid flow of meteoric water (cf. Poort & Polyanksy, 2002). After the reflooding of the Mediterranean at 5.3 Ma such a system would have ceased. However, the deposit of Messenian evaporitic layers in the marginal basins and karst development gave the perfect condition to start a brine reflux flow system similar to the Bahama carbonate platform (Whitaker & Smart, 1990). Residual brines generated by seawater evaporation can induce a density driven flow, infiltrate to depth of several km and migrate laterally over >100 km (Jones et al., 2004). Rock dredged on the seamounts that's rims the basin proofed to be of original basaltic composition and seismic reflection data revealed that the basement under the basin is largely composed of volcanic material of pre- and post Messenian age. This intense basaltic volcanism and the structural heterogeneities of the Emile Baudot transform fault may have offered an additional hydrothermal driving force and the necessary conduits to sustain for long time the regional fluid circulation in the South Balearic margin. We propose that the co-existence of low and high heat-flow anomalies in the South Formentera basin is the result of a heat redistribution by a regional fluid circulation system in the sediments and basement of this volcanic transform margin. The fluid circulation could be driven by a combination of a brine reflux that started in the Messenian time and a hydrothermal system thanks to the volcanic nature of the basement.

Presenter: Jeffrey Poort (jeffrey.poort@sorbonne-universite.fr)

The Global Heat Flow Database – status and future developments

Sven Fuchs (1), The Global Heat Flow Database Working Group (2)

(1) Helmholtz Centre Potsdam - GFZ German Research Centre for Geosciences, Germany; (2) 91 scientists from 36 countries

The Global Heat Flow Database (GHFDB) is fostered and maintained by the International Heat Flow Commission (IHFC) for nearly 60 years now. From the very beginning, periodic revisions of the GHFDB were carried out to update the heat-flow database entries and the underlying scientific methods according to the state of science and database technology at the time. The digitization and evolution of technological concepts over the past decades and the increasing scientific demand for quality-assured and authenticated data cumulated in the start of a fundamental database revision in 2021. Here, we present the community-driven efforts to unravel the associated challenges of the revision process. We also provide an overview on the status of the ongoing work based on a global collaboration of heat-flow scientists. The database revision so far included (i) the collaborative development of a new database structure that substitutes the former database structure from 1976, (ii) the transformation of data to this new structure, (iii) the start of the Global Heat Flow Data Assessment Project to scrutinize and reassess legacy heat-flow data according to the new structure. This ongoing process is currently driven by over 90 geoscientists worldwide, and we welcome further researchers willing to contribute to this undertaking. Finally, we present (iv) results from the 2022 GHFDB update including first revision results and we introduce (v) a new project on the development of a global heat-flow research data infrastructure.

Presenter: Sven Fuchs (fuchs@gfz-potsdam.de)

NOTES

Two decades of geothermal climate change observatory, Prague-Sporilov

Vladimír Čermák, Jan Šafanda, Petr Dědeček, Milan Krešl
Czech Academy of Sciences, Czech Republic

We have analyzed a sizeable number of repeated temperature logs until depth of 150 m and calculated corresponding GTHs (ground temperature histories). Logging was accompanied by monitored series of air temperature, near surface temperatures and shallow subsurface temperatures under various land cover types (bare clayey soil, sand, short cut grass and asphalt) on the ground of the Institute of Geophysics in Prague during last two decades. Part of results obtained in 2003–2013 was actually published earlier and now is completed with additional 2016–2021 data set. Of interest is a continuous robust climate warming which with only small annual variations equals to 0.06 K/year, slightly decreasing at present time. The ground skin temperature is generally warmer than the surface air temperature, even when the temperature over different covers differed significantly. Special attendance was paid to assessing the offset values, which dramatically varied on daily as well as on annual scales by up to 30+ K; however, on a long time scale the offset value well characterized the environment, asphalt 4 K, sand 1.6 K, soil 1.4 K and grass 0 to 0.2 K. The calculated GTHs confirmed the observed pronounced climate change following the relatively stable conditions in 1920–1970. The 20-year-long observation interval enabled directly compare monitoring data with climate modelling. The results of confronting various building material and surface cover types clearly has its practical application in large town greenery planning.

Presenter: Vladimír Čermák (cermak@ig.cas.cz)

POSTER PRESENTATION
P2

Heat-flow distribution of southern South America and its connection with the geotectonic setting

Rodolfo Christiansen (1), Guido Gianni (2), Carlos Ballivian (2), Hector Garcia (2), Stefan Wohnlich (1)
(1) Ruhr University Bochum, Germany; (2) CONICET, Argentina

The surface heat flow of southern South America is presented based on an updated database containing 1113 locations. The new heat-flow map of the southern portion of the continent (south of 16° 30'S latitude) shows a strong spatial correlation with geothermal zones and with the most up-to-date lithospheric thickness maps. High heat-flow zones associated with a thick radiogenic crust, volcanic activity, and a hot asthenospheric wedge can be observed in the Central Andes. The Pampean flat-slab region, shows low heat-flow areas coinciding mostly with the horizontal projection of the Juan Fernández aseismic ridge and not with a wide region as previously thought. Furthermore, a close relationship between the subduction of the ridges at different angles and a cold upper-plate lithosphere is suggested. Besides active regions of arc magmatism and a thin lithosphere, a hot upper-plate upwelling beneath the Patagonian Platform would be contributing to the high heat flow in the area. The foreland region exhibits zones of low heat flow coinciding with a thick cratonic lithosphere, and local high heat flow in suture zones possibly triggered by ancient delamination beneath these regions.

Presenter: Rodolfo Christiansen (rodo_christiansen@hotmail.com)

POSTER PRESENTATION
P3

Thermal structure of the Apennine–Tyrrhenian basin system (central Italy)

Gianluca Gola (1), Stefano Bellani (1), Paolo Chiozzi (2), Massimo Verdoya (2)
(1) CNR National Research Council of Italy, Italy; (2) University of Genoa, Italy

We present an up-to-date review of the existing terrestrial heat-flow data measured along the Apennine–Tyrrhenian basin system in central Italy and surrounding seas. The data collection included more than one thousand site-specific heat-flow determinations obtained by means of the interval or the boot-strapping methods. The choice of method depended both on the lithostratigraphic complexity of the explored successions as well as the number of available temperature data. Furthermore, laboratory thermal conductivity measurements on more than two hundred core samples together with the application of correction procedures accounting for pressure and temperature effects allowed the calculation of reliable heat-flow values and their lateral and vertical variability. The observed site-specific heat-flow values were finally corrected for the Holocene paleoclimate changes (the last 12,000 years on a 1000-year time-step) and topographic effects. Although the thermally anomalous on-land sectors of Southern Tuscany and Northern Latium are characterized by a detectable hydrothermal circulation, the analysis and correction of the heat-flow data for advective heat transport phenomena, allowed to estimate the conductive component of the terrestrial heat-flow enabling the extrapolation at large depth of crustal temperature profiles. The results are discussed and interpreted in the framework of the actual tectonic models and the complex evolution of magmatism and volcanism along the Tyrrhenian margins of peninsular Italy from Miocene to the Present.

Presenter: Gianluca Gola (g.gola@igg.cnr.it)

POSTER PRESENTATION
P4

The importance of thermal conductivity for optimized geothermal analysis and development

Arya Hakimian
C-Therm Technologies, Canada

Energy demands continue to rise worldwide because of increasing development and population. Electricity generation currently accounts for a significant amount of greenhouse gas emissions. Furthermore, fossil fuel-based power generation results in significant additional negative effects, in the forms of air pollution and resulting chronic health impacts in regions surrounding power generation stations. For this reason, a key priority in the mitigation of anthropogenic global warming is the global transition of energy economies from fossil fuel-based power to renewable and non-emitting power sources. One such alternative is the utilization of geothermal energy. Geothermal energy refers to producing renewable energy from underground heat, and it is described by the U.S. Department of Energy as a 'vital, clean energy resource' and that it 'supplies renewable power around the clock and emits little or no greenhouse gases.' To be economically viable, sufficient heat must be available at shallow subsurface depths to minimize the expensive drilling and pumping costs associated with geothermal production. In regions that are not tectonically or volcanically active, any geothermal potential lies in (1) decay heat from radiogenic intrusive rocks, or in (2) elevated heat flow through moderate-temperature sedimentary basins coupled with low thermal conductivity rocks acting as insulators in the basin fill. As such, the thermal properties of rocks and soils are extremely important for the design of these renewable energy systems and requires estimation or direct measurement in the relevant depth intervals. Geological mapping is a crucial aspect to the development of these technologies and has been an area of extensive research for many groups around the globe. For example, in England geological mapping started over two centuries ago and since then there has been extensive onshore exploration for minerals, coal, oil, gas and other geothermal resources. When looking at the research and data in this application space, thermal conductivity presents itself as a key component for this type of analysis, which can be crucial for future developments in this field. C-Therm's MTPS, TPS, and TLS methods are three transient-based options for characterizing the thermal performance of geological samples of varying formats ranging from bulk solids to unconsolidated aggregates. Transient solutions also greatly benefit from the ability to be easily setup under varying environmental conditions that allow for more representative testing conditions (i.e., temperature, saturation, and pressure). In this presentation, we will highlight the application of the three methods toward the thermal testing of geological materials relevant to geothermal energy. Basic examples will be presented for each method as well as more novel applications such as the incorporation of high-pressure configurations.

Presenter: Arya Hakimian (Arya.Hakimian@ctherm.com)

POSTER PRESENTATION
P5

Apollo Lunar heat-flow paradox

Shaopeng Huang
Shenzhen University, China

Heat flow density (or heat flow in short) is a fundamental parameter in planetary sciences. While there are about 75,000 heat-flow measurements on the Earth (Fuchs et al., 2021), up to date the two Apollo measurements on the Moon are the sole measured heat-flow values from a planetary body other than the Earth (Langseth and Keihm, 1977). Moreover, there have been controversies surrounding these two lunar heat-flow measurements. Heat flow is determined as the product of subsurface temperature gradient and the thermal conductivity of the medium in which the temperature gradient is measured. For the Apollo Lunar Heat Flow Experiment (AHFE), two boreholes were drilled by astronauts into the lunar regolith at each of the landing sites of Hadley Rille Apollo 15 and Taurus Littrow Apollo 17. Each borehole received an array of thermometers designed for measuring subsurface temperatures and thermal conductivity. The AHFE began from July 1971 to January 1977 at the Apollo 15 site, and from December 1972 to September 1977 at the Apollo 17 site. Temperatures and thermal conductivities from the surface down to the depths of about 1.5 m and 2.4 m of the regolith at the Apollo 15 and 17 sites, respectively, were continuously monitored over the entire duration of the AHFE. However, it is an unanswered question why the PI of the AHFE decided only to analyze the data up to December 1974 rather than the entire records. Based on short-term in situ measurements, a 33 mW/m^2 for the Hadley Rille site (Langseth et al., 1972) and a 28 mW/m^2 for the Taurus Littrow site (Langseth et al., 1973) were initially determined. The values were later revised to 21 for Hadley Rille and 14 mW/m^2 for Taurus Littrow (Langseth et al., 1976). The 36–50% downward revision in the heat-flow estimates were primarily due to the thermal conductivities estimated by the analysis of long-term subsurface temperature time series being significantly lower than the initial in situ heating measurements. The mean of the two measured lunar heat-flow values is less than a quarter of the global terrestrial heat flow (Lucazeau, 2019). However because of the mall size of the Moon, if the value is of global representative, it would imply a bulk Uranium concentration of 46 ppb, which is about twice of the Earth mantle (Rasmussen and Warren, 1985) and several times of chondrite meteorites (Arden, 1977). From a geochemical perspective, Warren and Rasmussen (1987) believe that a regional representative lunar heat flow must be about 12 mW/m^2 (Warren and Rasmussen, 1987). There are other studies (e.g., [Laneuville et al., 2014; Siegler et al., 2020]) demanding a downward correction to the Apollo measured heat-flow measurements. To reconcile the difference between the observed and theoretically predicted lunar heat flow, Saito et al. (Saito et al., 2007) restored the lost Apollo 17 subsurface temperature time series from December 1974 to September 1997 and come up with a heat-flow estimate of 3.7 mW/m^2, because the restored portions of the temperature time series at depths shows a much smaller thermal gradient than does the earlier portions that Langseth and his colleagues had analyzed. Nagihara et al. (2018) further show that the decreasing thermal gradients are evident in the long-term records from both Apollo 15 and 17 sites. All of the time series from various depths show continuous warming over the entire duration of the AHFE. However the simultaneous warming was more pronounced at shallower than at greater depths, leading to a decreasing trend in the thermal gradient.

Presenter: Shaopeng Huang (shaopeng@szu.edu.cn)

Poster presentation

POSTER PRESENTATION
P6

GeoLaB – A geothermal underground laboratory for basic research

Thomas Kohl
Karlsruhe Institute of Technology, Germany

In order to develop the geothermal potential in an environmentally sound and economical way, new scientifically based strategies are urgently needed. For this purpose, a new underground research laboratory GeoLaB (Geothermal Laboratory in the Crystalline Basement) at the edge of the Rhine Graben is proposed as a Helmholtz large-scale infrastructure project. Although GeoLaB is aimed at geothermal energy applications, it will be an international platform that will allow basic research in crystalline analogues to be carried out at field scale. The laboratory will be equipped with state-of-the-art digital, sensing, and logging devices, allowing it to be used for a variety of topics relevant to modern heat flow studies. Among other things, the influence of scale effects, ionizing radiation, geochemical interactions, or heat transfer from fluids to the matrix at specific locations could be studied. Digital infrastructure would enable state-of-the-art monitoring and the establishment of digital twins to transmit long-term measurement series to any location worldwide. For sustainable use of geothermal energy, project goals include (1) efficient management of fracked reservoirs, (2) state-of-the-art multidisciplinary research with visualization concepts, and (3) transparent interaction with the public. The application and development of new tools for the analysis and monitoring of subsurface processes should lead to fundamental knowledge of great importance for a safe and ecologically sustainable use of geothermal energy. To this end, a tunnel up to 2 km long will be excavated to provide access to individual caverns where controlled experiments will be conducted and continuously monitored at greater depths. This will create a unique 4D benchmark data set with thermal, hydraulic, chemical and mechanical parameters. With this globally unique geothermal research infrastructure, GeoLaB connects cutting-edge research in the field of renewable energy with societal awareness. Thus, GeoLaB becomes a scientific benchmark for the development of new concepts to understand geothermal resources in deep-seated rocks.

Presenter: Thomas Kohl (thomas.kohl@kit.edu)

Geothermal regime of the Kuqa foreland basin, northwestern China

Guanzhong Feng, Wenjing Zhu, Shaowen Liu
Nanjing University, China

Geothermal regime of sedimentary basins plays a key role in understanding basin (de)formation process and assessing hydrocarbon and geothermal energy resources, and has attracted increasing attention from academia and industry. Here we investigated the geothermal regime of the Kuqa Foreland Basin (KFB), located between the northern Tarim Craton and southern Tianshan Mountain, northwestern China, with the formation temperature data and newly measured thermal properties. The geothermal gradient of the KFB is between 15 °C/km and 32 °C/km, with a mean of 22 ± 2.76 °C/km, and the heat flow ranges from 41 mW/m^2 to 56 mW/m^2, with an average of 49 ± 5.8 mW/m^2. Generally, the present-day geothermal pattern of the KFB is characterized by high in the north and low in the south, decreasing from the foredeep to the forebulge. We infer that this geothermal pattern is affected by the Cenozoic convergence between the Tarim Craton and Tianshan Mountain.

Presenter: Shaowen Liu (shaowliu@nju.edu.cn)

POSTER PRESENTATION
P8

Combining magnetic and gravity data to infer the crustal architecture and heat flow in Wilkes Land, Antarctica

Mareen Lösing (1), Max Moorkamp (2), Jörg Ebbing (1)
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The sparsity of direct Antarctic thermal gradient measurements requires an indirect estimation of geothermal heat flow (GHF) from geophysical data with assumptions about a simplified and undifferentiated lithosphere. This often results in weakly constrained and inconsistent models. From denser sampled continents, we know that thermal parameters and heat flow can exhibit large spatial variations depending on geology and tectonic history. We infer information about the crustal structure and possible geological features in Wilkes Land, East Antarctica, by jointly inverting for gravity and magnetic data. Both data sets are combined through a coupling method which increases the mutual information to get similar and statistically compatible inversion results. Data misfit and variation of information are minimized under the coupling constraint. The results show matching features of high magnitude density and susceptibility anomalies. Prominent structures along the edge of the Mawson craton and at the presumed Australo-Antarctic and Indo-Antarctic terrane boundary can be observed. Applying the same method to Australia, formerly connected to Wilkes Land, we can exploit the much better-known geology there and identify coherent structures along the adjacent margins. The inverted parameter relationship between susceptibility and density can be used as input for machine learning techniques to define a spatially variable heat production map, which in turn leads to improved heat-flow estimates. For this, we rely on existing petrophysical and geochemical databases to correlate and confine thermal parameters with our results.

Presenter: Mareen Lösing (mareen.loesing@ifg.uni-kiel.de)

Heat flow and thermal regime in the Guaymas Basin, Gulf of California: Estimates of conductive and advective heat transport

Florian Neumann (1*), Raquel Negrete-Aranda (1,2), Robert N. Harris (3), Juan Contreras (1), Christophe Galerne (4), Manet S. Pena-Salinas (5), Ronald M. Spelz (6), Daniel Lizarralde (6), Andreas Teske (7), Tobias Hoefig (8), and the Expedition 385 Scientists (*)

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Heat flow is estimated at eight sites drilled during Integrated Ocean Drilling Program (IODP) Expeditions 385 in the Guaymas Basin of the Gulf of California. The expedition was designed to understand the thermal regime of the basin and heat transfer mechanisms from sill intrusions into surrounding organic-rich sediment. Sediment corrections increase observed heat-flow values on average by 12% and range from 119 to 221 mW/m² in the basin. This is similar to other heat-flow values observed in the well sedimented basins of the north gulf, namely Tiburon, Delfin and Wagner basin, but about a factor of one-tenth of the heat flow observed in the Pescadero Basin in the South Gulf. By contrast, at Ringvent, the site of a young sill intrusion, heat flow is locally elevated, displaying values between 257 and 1,000 mW/m². Thermal analysis suggests that heat flow is distributed equally between conductive and advective heat transfer for plate ages older than 0.2 Ma. Drilling sites at Ringvent show this structure is an active, rapidly cooling intrusion with discharge velocities between 15–40 mm/yr, and the heat output suggests a sill intrusion ~240 m thick. This vigorous convective exchange of energy and fluids between the sill and sediments and the need of a recharge zone to sustain the observed flow at the Ringvent structure. Possible recharge may occur ~1 km from the ring structure through normal faults.

Presenter: Florian Neumann (fneu@gfz-potsdam.de)

POSTER PRESENTATION
P10

Quality assessment of German heat-flow data: A contribution to a revised Global Heat Flow Database

Ben Norden, Andrea Förster, Sven Fuchs
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We present a revision of the terrestrial heat-flow density (HFD) data of Germany. The data encompass about 600 entries acquired over a time span of more than 60 years. They differ in the documentation and availability of metadata. A multiple-step approach is applied to assess the data for quality: first, we scrutinized and updated the HFD values and evaluated them for completeness and reproducibility. Entries in the database with no basic data on how HFD was determined (such as temperature gradient, thermal conductivity, and metadata such as coordinates and depth interval) have been discarded (flagged as being not reliable) as they cannot be scientifically reproduced. Although this step is rigorous, it is necessary for setting up a scientific useful data pool following scientific criteria. As a consequence, the original German data set has been reduced by almost 80% down to 138 locations, which then were assessed in terms of methodological quality. In addition, HFD values are labeled for different governing effects, which are, for example, paleoclimate, heat refraction in the vicinity of salt structures, or local/regional fluid movements. The revised terrestrial heat flow on the German territory is on average 78 ± 7 mW/m², which is significantly higher than earlier estimates (65 mW/m²). The regional average heat flow (area-averaged) varies by 40%. Considering a representative radius of 10 km around each heat-flow location, the heat flow must be considered as unknown or highly uncertain for ca. 90% of the German onshore area. This raises the demand for new systematic heat-flow measurements on a national scale.

Presenter: Ben Norden (norden@gfz-potsdam.de)

POSTER PRESENTATION
P11

A thermo-physical subsidence model for paleo-bathymetry reconstruction in extensional basins: Quantifying the effect of lateral heat transfer

Alberto Pastorutti (1), Magdala Tesauro (1), Carla Braitenberg (1), Florence Colleoni (2), Laura De Santis (2), Martina Busetti (2)

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The reconstruction of past climatic conditions through simulation provides fundamental insights in how the future climate might evolve. In this context, reliable constraints on the evolution of past topographies and bathymetries play a central role. Direct observations of this evolution, such as those available from oceanic deep-drilling campaigns, cannot provide a complete picture: erosion, sedimentation, and the superposition of tectonic processes hinder reconstruction. The phenomena involved in the evolution of bathymetry include loading effects (e.g. due to sediments, water, ice), tectonic and thermal subsidence, and dynamic topography. Accounting these to reconstruct the evolution of bathymetry, in a procedure that involves iterative de-compacting and removal of overlying sediments, is called 'backtracking'. We focus on a methodological aspect of one of terms involved in backtracking analysis: thermal subsidence, the vertical contraction of the lithosphere due to cooling following extension. We build upon the prior results from the backtracking open source software PALEOSTRIP (Colleoni et al., 2021), which relies on an implementation of the 1-D thermal subsidence model by McKenzie (1978). Using the 1-D approximation for 2-D sections and 3-D volumes, while common, is likely to introduce an omission error, by neglecting horizontal heat advection. By extending the thermal subsidence model to 2-D-i.e. considering thermal advection in the direction normal to the extension axis-we aim at quantifying the omitted signal due to the 1-D approximation and its effect on the backstripping results. This amounts to a sensitivity analysis of backstripping with respect to the adopted thermal subsidence model. We implement a 2-D thermophysical model of the lithosphere that cools and thickens, following an instantaneous rifting event, using a particle-in-cell finite element approach (Underworld2, Mansour et. al 2020). This model is then integrated in the iterative backtracking procedure of PALEOSTRIP, substituting the 1-D thermal subsidence term. In the context of PNRA national Italian project 'Onset of Antarctic Ice Sheet Vulnerability to Oceanic conditions (ANTIPODE)', we test the difference in backtracking results using the 1-D and the updated thermal model. The benchmark target is the depth of the mid-Miocene unconformity across the Ross Sea area, using the ANTOSTRAT data atlas (Brancolini et al., 1995). In this region, located at the northwestern end of the West Antarctic Rift, extension occurred in two main episodes, a regional thinning associated with the breakup of New Zealand and Australia from Antarctica in the Cretaceous, and more focused extensional episodes during the Cenozoic, with the locus of extension moving sequentially from east to the west. In order to better simulate the thermal evolution of the study area, we plan, in the next stage, to modify the numerical code, by including the thermal effect due to a not-instantaneous rifting event.

Presenter: Alberto Pastorutti (apastorutti@units.it)

POSTER PRESENTATION
P12

Marine geothermal heat-flow research at the University of Bremen and MARUM – Center for Environmental Sciences

Aline Ploetz (1), Heinrich Villinger (2), Norbert Kaul (2), Karsten Gohl (3), Ricarda Dziadek (1)

(1) MARUM, University of Bremen, Germany; (2) University of Bremen, Germany; (3) Alfred-Wegener-Institute Helmholtz Centre for Polar and Marine Research, Germany

Marine heat flux observations provide fundamental constraints on physical, chemical and biological processes occurring near and below the seafloor. These observations are the crucial basis for estimating the subsurface temperature field and detecting advective heat transport processes. Processes that influence and are influenced by heat transport within seafloor sediments and basement rocks include:

- the thermal evolution of the oceanic crust and lithosphere;
- the geodynamics of plate boundaries and mantle convection;
- fluid circulation and associated impacts on water-rock interactions, seismicity, tectonics, and magmatism;
- occurrence and stability of gas hydrates;
- maturation of hydrocarbons at passive margins.

Understanding these processes involves the quantification of energy and fluid fluxes, requiring knowledge of the thermal state deduced from observations that include heat flux, sub-bottom temperature, and thermo-physical sediment properties. The Faculty of Geosciences and MARUM (University of Bremen) have a longstanding record of high-quality research in the field of marine heat flux studies. As one of the three active groups in Europe (Uni Bremen, GEOMAR–both Germany and Institut des Sciences de la Terre de Paris) in operating a marine Heat Flux Probe and one of the few world-wide we built an unique expertise and technical capability in subsurface characterization of thermal structures and processes in a marine environment. Our main objective is the presentation of methods, instrumentation, and recent and on-going projects to demonstrate the wide-range field of application. We present exemplary case studies from our field of expertise relating to subduction zones (seismogenic zones), gas hydrates, hydrothermal processes (Layer 2A, fault zones, fracture zones), and ridge related processes. Further on, economical projects like assessment and monitoring of thermal impact of buried off-shore power cables from wind farms on the environment come into focus.

Presenter: Aline Ploetz (aploetz@uni-bremen.de)

Mozambique Channel heat flow: New data and predicted heat-flow map

Bessière Eloïse (1), Poort Jeffrey (1), Tristan Cornu (2), Sylvie Leroy (1)
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The surface heat flow is crucial in many topics, like geothermal questioning, crustal structure, active and passive margin evolution, or Earth dynamics. However, the heat flow coverage on Earth is extremely heterogeneous and still very poor in many areas. This is also the case for the Mozambique Channel, where sporadic offshore heat flow dates mostly from the seventies or earlier. We will present 25 new marine-type heat-flow measurements acquired offshore in 2014 and 2015 during the MOZ cruises, completed with 4 new heat-flow values on-land derived from a reappraisal of old corrected well sites (PAMELA project). Heat flow is generally low to normal without strong variations, between 35 to 60 mW/m². One heat-flow value of nearly 100 mW/m² was obtained on the Angoche margin. As poor data coverage persists in large parts of the Mozambique Channel, we performed a heat-flow prediction mapping using the similarity method (Goutorbe et al., 2011; Lucazeau, 2019). Based on an extrapolation of old and new data guided by 14 geological and geophysical proxies, we obtain on a 0.1 x 0.1° grid an average heat flow and its uncertainty from the statistics of all values at grid points with similar proxies. We succeeded to obtain good predictability on 70% of pixels and an RMS error of <2.3 mW/m². The proxies selected for the prediction include a map of genetic crustal domains, sediment thickness, topography and bathymetry, crustal ages, Curie point depth, Free air anomaly, and distances to volcanoes, tectonic structures, and continent-ocean boundaries. The new Mozambique heat-flow map shows a predominantly low heat flow around 50 mW/m², which agrees with the Jurassic and Early Cretaceous age of the oceanic crust. Several heat-flow anomalies, both high and low, standoff to this background heat flow with two main orientations: N-S or NE-SW orientation. We will discuss these heat-flow trends in function of the structural and crustal elements that compose the Mozambique channel (fracture zones, volcanic activity, hyper-thinned continental or oceanic crust, etc.) and that were used as proxies in the heat-flow prediction.

Presenter: Poort Jeffrey (jeffrey.poort@sorbonne-universite.fr)

POSTER PRESENTATION
P14

Heat-flow estimates in the Northern Mozambique Channel

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In the Northern Mozambique Channel, between the East coast of Africa and the northern tip of Madagascar, the Comoros Islands form an archipelago of four volcanic islands. Their volcanic activity started during the Miocene after the Mesozoic opening of the Mozambique Channel. The recent outstanding observation of a submarine volcanic activity that has taken place since May 2018 to the east of Mayotte promoted numerous sea and land surveys. During the 2020–2021 SISMAORE cruise, we equipped a sediment corer with autonomous thermal sensors and we obtained four new heat-flow estimates. Heat flow in the Northern Mozambique Channel is poorly known, with only a few old measurements, indicating low values. Our new measurements provide values of 47, 45 and 42 mW/m^2 confirming that the regional heat flow in the Northern Mozambique Channel is low. These heat-flow values correspond to the lowest heat flow observed for a Jurassic oceanic lithosphere. Regarding the nature of the crust, two hypotheses are proposed that fit with the new heat-flow data. The first one is that off Mayotte the crust is mainly oceanic, with some heat production coming from felsic continental fragments in the crust or in the sediment deposits. The second one is that the crust is composed of a very thin continental layer overlain by effusive basalts and possibly underplated as the island of Mayotte. The heat flow is regionally low in the Northern Mozambique Channel and does not show a thermal signature that could be associated with a mantle plume. However, we measured one local and very high heat-flow value of 235 mW/m^2, east of the active volcano. This high value does not represent the regional heat flow, but is clearly the result of a local process. Several indications suggest that it can be linked with the circulation of hot fluids. The measurement is aligned with the new active volcano and located at the border of a topographic dome (30m-high and 10km-diameter) underlain by a magmatic sill. At the pinch out of the sill hot fluids appear to be driven vertically upwards to the surface. The source of the volcano is deep (>55 km depth), with shallower secondary reservoirs and with magma migration occurring through dykes intruding the lithosphere. The lava flows and seals by-pass systems imaged by multichannel seismic are reaching the surface, and could likely drive hot fluids.

Presenter: Frédérique Rolandone (frederique.rolandone@upmc.fr)

Geothermal atlas of the Sudetes and their foreland: An interdisciplinary project for recognizing the geothermal potential in SW Poland

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Polish Geological Institute, Poland

The geological structure of the Sudety Mountains and the Fore-Sudetic Block is dominated by crystalline rocks and poorly permeable, strongly lithified sedimentary units. As a result, the thermal waters of Lower Silesia are predominantly fissured waters and usually reside within deep fault zones and fracture corridors. The occurrences of thermal waters in several spa towns manifest the geothermal potential of the Sudetic region in SW Poland. There is a need for a regional synthesis of geothermal, petrophysical and geophysical data to provide comprehensive constraints on the geothermal state of the Sudetes. PGI-NRI has recently launched a project entitled 'Geothermal atlas of the Sudetes and their foreland' to improve our knowledge of the geothermal potential of SW Poland. The project takes a multidisciplinary approach and builds on multiple data sources such as geophysical logs from boreholes, surface geophysical data, hydrogeological information, and a large set (even up to 1000 samples) of newly obtained petrophysical laboratory measurements. The laboratory results will be used for the calculation and modelling of the thermal properties as well as the modelling of the thermal field in the studied region. We currently perform several types of petrophysical analyses on both surface outcrop and core samples to better characterize the rock properties in our region of interests that will be later used for thermal modelling. The porosity and density are measured by means of water immersion porosity technique (WIP). The amounts of K, U, Th, which is needed for radiogenic heat calculations, are obtained by gamma spectrometry method, utilizing a tailored pair of scintillation spectrometers that enable both laboratory and field measurements. The gamma spectrometry results are selectively confronted with bulk chemistry data as well as portable XRF analyses. The thermal conductivity of samples is analysed as a temperature function up to 190 °C using the FOX-50 instrument. The specific heat of the analysed samples is measured both in the FOX-50 instruments and by application of classical calorimetry. The obtained thermal parameters are joined with temperature data from boreholes for accurate estimation of the surface heat flow density in the region. The measurements are chiefly performed in a newly established laboratory at Lower Silesia branch of the PGI-NRI in Wrocław. The measurements are planned to be crosschecked and validate in outside laboratories, with application of complementary techniques. Additionally, a set of supplementary analysis is planned. The quantitative XRD studies will provide detailed information about the mineralogical composition of the analysed suite of samples. In addition, SEM BSE imaging is planned for a better control of the mineralogical composition and structure of the studied rocks. The region of the Sudety Mountains and the Fore-Sudetic Block is characterised by a great lithological diversity, and as a result we analyse both crystalline rocks such as granites and gneisses as well as sedimentary rock, including, for instances, various sandstones and mudstones. Therefore, the laboratory work can be quite challenging, and the methods need to be modified according to the different types of analysed rocks. In this presentation, we show our preliminary results from the Góry Sowie Massif (GSM), including gamma spectrometry, as well as porosity and density measurement and thermal conductivity data.

Presenter: Piotr Słomski (pslo@pgi.gov.pl)

POSTER PRESENTATION
P16

Mapping the thermal structure of Southern Africa from Curie depth estimates based on wavelet analysis of magnetic data with uncertainties

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Surface heat flow provides essential information on the thermal state and thickness of the lithosphere. Southern Africa is a mosaic of the best-preserved and exposed crustal blocks, assembled in the early late Archean and then modified by a series of major tectono-thermal events, both of Precambrian and Phanerozoic. Understanding the thermal and compositional structure of the southern African lithosphere provides crucial information for the actual causes, processes of lithospheric stability, and modification. Curie depth, interpreted as the depth of 580 °C, provides a valuable constraint on the thermal structure of the lithosphere. Due to the sparse distribution of surface heat-flow data, we examine the degree to which the thermal structure of the crust can be constrained from Curie depth estimates in southern Africa. We provide a Curie depth map for southern Africa (obtained from the inversion of magnetic anomaly data via power spectral methods and wavelet analysis) alongside a heat-flow map (based on the previous Curie depth estimates), both equipped with uncertainties via a Bayesian approach. Opposed to other cratonic regions, the observation of shallow Curie depths and low heat flow over the Kaapvaal Craton suggests a thermochemical reworking of the cratonic lithosphere in this region. Furthermore, a comparison with a model for the Moho depth reveals significant variations of the Curie depth, which may be located below or above the Moho in large regions. Both observations indicate that in certain regions magnetic anomaly-based Curie depth estimates may reflect a compositional rather than a temperature-controlled constraint.

Presenter: Mohamed Sobh (mohamed.sobh@geophysik.tu-freiberg.de)

POSTER PRESENTATION
P17

Lithospheric thermal structure from thermal data collection in and around Japan

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Heat-flow data contribute to the imaging of the lithospheric thermal structure, which greatly influences tectonic and geological processes and constrains the strength of the lithosphere, the modes of deformation, and the depth distribution of earthquakes. To provide a more reliable estimation of the lithospheric thermal structure, some complementary approaches are possible. One approach is to update and incorporate the existing thermal data. A new version of the database ‘Thermal Data Collection in and around Japan’, which contains continuously updated heat flow and geothermal gradient data and adds thermal conductivity data in and around Japan, has been released in March 2019 [https://www.gsj.jp/data/G01M/GSJ_MAP_TDCJ_2019.zip]. This provides an opportunity to revisit the thermal state of the lithosphere along with other geophysical/geochemical constraints. Another approach is based on the complementary interpretation of different geophysical data sets. One of the promising indicators is the cut-off depth of shallow seismicity. Several studies have been conducted to assess the inverse correlation between the cut-off depth and heat flow since it has been attributed primarily to the temperature. Another indicator is the depth of magnetic sources based on spectrum analysis of magnetic anomaly data. This analysis is still controversial, however, a good correlation between estimated depths of crustal magnetic sources and heat flow suggests that this depth may reflect the broad average temperature. We address the advantages and limitations of each data and method.

Presenter: Akiko Tanaka (akiko-tanaka@aist.go.jp)

POSTER PRESENTATION
P18

Mantle thermal conditions of the Zagros collision zone and surroundings

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Late Mesozoic convergence between the Arabian plate and Eurasia generated subduction the Neo-Tethys ocean beneath Central Iran and the onset of the closure of the oceanic domain occurred in the Late Cretaceous. The final closure of the Neo-Tethys ocean (~12 Ma) formed the Zagros collision zone composed of different parallel tectonic features from southwest to northeast: the Zagros Fold and Thrust Belt (ZFTB), the Sanandaj–Sirjan Metamorphic Zone (SSZ), and the Urumieh–Dokhtar Magmatic Assemblage (UDMA). The ZFTB is the young and seismically active zone of the Zagros Mountains and is separated from the SSZ by the Main Zagros Thrust (MZT), which is considered to be the suture zone between the Arabian and Iranian plates and assumed deeply rooted. The SSZ consists mainly of Precambrian metamorphic rocks and igneous rocks, whose formation is related to the subduction of the Neo-Tethyan slab. Currently, the convergence is accommodated across the Iranian Plateau and the surrounding mountain ranges, at a rate of 10–20 mm/yr, resulting in different styles of deformation in this active collision/subduction zone (e.g. Khorrami et al., 2019). Several models, based on the interpretation of seismic tomography and receiver function data, revealed high velocities beneath the Zagros in the upper mantle down to depths exceeding 200 km, implying a relatively thick lithospheric mantle. However, some studies, based on the lack of deep seismicity in the Zagros and absence/reduction of high-velocity anomalies below 200 km depth, support the hypothesis of the slab break-off and delamination of the lower part of Arabian lithosphere. In contrast, other studies reveal the slab continuity up to the depth of the transition zone. Furthermore, according to some authors, thick high-velocity lithosphere of Arabian Plate is extended beneath UDMA and southeastern Central Iran, while based on some others, thin lithosphere characterizes the UDMA and the SSZ. Therefore, up to now, it has not been reached a consensus on the maximum depth neither on the lateral extension of the subducting Arabian lithosphere. Other uncertainties are related to the dip and nature of the slab. In order to address these controversial issues, we analyze global and regional seismic tomography models and convert their absolute velocities in temperature, assuming the composition of a Phanerozoic mantle, taken from studies on xenolith samples. Indeed, the conversion in temperatures allows us to better identify the shapes of the upper mantle features. To this purpose, we use Perple_X (Conolly, 2005) that computes physical properties for a given mineralogical model, expressed by the main mantle oxides. In addition, we compare the results obtained with the seismicity distribution, as well as the depth of the Curie point (Li et al., 2019), and the effective elastic thickness obtained from isostatic analyses, in order to improve our understanding of the geodynamic setting of the area.

Presenter: Magdala Tesauro (mtesauro@units.it)

POSTER PRESENTATION
P19

On the thermal and seismotectonic environment of the Finnish part of the Wiborg rapakivi batholith

Toni Veikkolainen, Ilmo Kukkonen, Tuija Luhta, Timo Tiira
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Understanding the thermal evolution of the lithosphere is essential for studying the seismotectonic environment of the 1.65–1.62 Ga old Wiborg rapakivi batholith (WRB) in the southeastern Fennoscandian Shield. WRB is an exceptional formation with a 10 km thick and 150 km wide layer of porphyritic rapakivi granite with a small proportion of mafic rocks. Gravity and wide angle seismic data suggest a strongly gabbro-anorthositic composition in the middle crust. Direct heat-flow measurements from boreholes in WRB are scarce but the situation with heat production is remarkably better. Lithogeochemical data from 93 rock outcrop samples from the Finnish side of WRB, measured at the Geological Survey of Finland, provide an average heat production of 3.6 ± 1.2 μW/m³. This exceeds the Finnish average 1.4 ± 1.4 μW/m³ and also features sharp contrasts to the neighboring areas. WRB is partly located in Russia, and heat production data from the Russian side of the batholith are unavailable. The variation of heat production with depth greatly affects the shape of geotherms. In WRB an exponentially decreasing model is not appropriate due to the strong bimodal magmatism shown by the dominance of felsic rocks in the layer above mafic rocks. A layer cake model is better suitable because some layer boundaries are visible in seismic cross-sections, and different proportions of rock types with known heat-production values can be used to account for changes in mean heat production of a layer. In our layer cake model, we applied a decreasing thermal conductivity by temperature in one-dimensional thermal model where the layer thicknesses were estimated using data from three seismic refraction surveys that cross the WRB area: BALTIC, KOKKY, and SOFIC. In WRB reasonable value for surface temperature is 5 °C, based on the annual mean temperature, and 60 mW/m² for the crustal heat flow measured at a borehole in Loviisa. The depth of the upper crust down to 10 kilometres is obtained from the refraction data. WRB has the highest occurrence of natural earthquakes in southern Finland. Surface waves are usually visible in seismograms of the WRB earthquakes, confining hypocenters of these events to the uppermost 5 km of the crust. On the contrary, the average Fennoscandian seismic cutoff depth is 28 ± 4 km, based on assuming a brittle-ductile transition at 350 °C. In WRB earthquakes cease to exist at a much lower temperature due to the exceptionally low stress resistance of the upper crust dominated by rapakivi granites. In our models, the upper crust (0 to 10 km) has a 96.7% felsic and 3.3% mafic composition, leading to the heat production $H = 3.5$ μW/m³. In the middle crust (10 to 30 km), we have $H = 0.5$ μW/m³ and in the lower crust (30 to 41 km) $H = 0.3$ μW/m³, associated with the increasing content of mafic rocks. The Fennoscandian shield is almost entirely at the same erosion level. Therefore the Moho heat-flow values ranging 9 to 15 mW/m² determined from mantle xenoliths in the eastern Finland, can be applied to produce three geotherms with surface heat flow of 57 to 63 mW/m². The corresponding Moho temperature range is 370–510 °C. This emphasizes the sensitivity of geotherms on heat flow and the need for further crustal heat-flow measurements in the area.

Presenter: Toni Veikkolainen (toni.veikkolainen@helsinki.fi)

Poster presentation

POSTER PRESENTATION
P20

Testing the lithospheric implication of four different geothermal heat-flow models for Greenland

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The geothermal heat flow (GHF) in Greenland is an important boundary condition for the overlying ice sheet by controlling the amount of melt on the base of the ice. Since direct measurements of GHF are sparse one must rely on GHF models from geophysical models. Unfortunately, such GHF models vary largely among each other and are partly even contradicting. In this study, we explore the lithospheric implication of four different GHF models. We do this by testing the different GHF models with Bayesian analysis and forward modelling of the lithosphere. Our models are adjusted to the gravity field and topography and compared to shear wave velocities from a tomography model and crustal constraints from receiver function analysis. We find that particularly low (< 40 mW/m^2) and high (> 90 mW/m^2) GHF values are complicated to model without unusual low/high crustal heat production. From a lithospheric scale perspective, it is furthermore difficult to model high variance in SHF over short distances as seen e.g., around NGRIP in some models. Here, local effects may dominate the GHF estimates. In general, is necessary to model the GHF in Greenland from an integrative perspective including all available constraints and to include lateral variations in crustal configuration.

Presenter: Agnes Wansing (agnes.wansing@ifg.uni-kiel.de)

Do temperature predictions of the crust need to consider pressure and temperature-dependent rock thermal conductivity?

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Rock thermal conductivity (k) is an essential parameter for the determination of subsurface temperature by numerical models. In addition to other causes of uncertainty, experimental studies have proven a strong dependence of k on pressure (P) and temperature (T). Respective P-T correction relations for k not only differ in response to the measuring techniques, but also are a function of rock type. In general, a non-consideration of the P-T effect on k results in an underestimation of crustal T. Application of a subset of ca. 50 experimentally derived numerical P-T relations have shown that the underestimation of crustal T is lowest (and perhaps neglectable) for Archean/Proterozoic-consolidated terranes with a granitic upper crust and a granulitic lower crust and surface heat flow (qs) of 40–50 mW/m². On the contrary, in stabilized Phanerozoic terranes, in which the crust is composed of a variety of rock types and qs typically is >60 mW/m², T-difference at the crust-mantle boundary is substantial, maximizing to values of 130 K (for qs 60 mW/m²) resp. 240 K (for qs 80 mW/m²). Whether this range of T correction is trustworthy and not the result of unsuitable laboratory techniques applied, is a still unsolved question. A reduction of uncertainty basically requires systematic measurements of different rock types in a cross-validated approach, in which different analytical procedures are involved. The evaluation of the plethora of yet available P-T relations to k is of paramount importance not only for inferences on lithosphere T and thickness, but also for the depth realm of interest for the use of geothermal resources, in which the T prognosis is of economic impact. Here, the application of the P-T relations results in maximum temperature prognosis uncertainties of about 8 °C and 55 °C at 2 km depth and at 8 km depth, respectively. This effect positively correlates with the magnitude of the basal heat flow used in modeling.

Presenter: Andrea Förster (for@gfz-potsdam.de)

POSTER PRESENTATION
P22

Heat flow measurements in Slovenia and convective share in the borehole thermograms

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All available heat flow data for Slovenia are reviewed and updated. Data base consists now of 118 heat flow values, which were determined from a wide range of boreholes' depths, from as shallow as 100 m to 4048 m. Of them, 91 values were calculated by measuring the temperature gradient in each borehole and the thermal conductivity of rock samples from the same borehole. The remaining 29 heat flow values were calculated using the measured temperature gradient in each borehole and adopted thermal conductivities from nearby boreholes with the same or very similar lithology. The surface pattern of geothermal activity is presented with heat flow density (HFD) map, showing that heat flow values are mostly correlated with major geological features and units. For the Pannonian Basin geothermal anomaly in northeastern part of the country higher HFD values are characteristic due to thinner Earth's crust (90 to 210 mW/m2), while for the Dinarides and the Southern Alps quite low HFD values (20 to 50 mW/m2) are found owing to deep meteoric water circulation in predominantly karstic regions and the thicker crust there. In more central part, belonging to the Sava folds region with thick clastic and carbonate rock mixtures, mostly average values (45 to 80 mW/m2) are determined with some small exceptions. A generally negative correlation is found between heat-flow and crustal thickness. Maps presenting the formation temperatures at different depths are also available. An attempt is done in drawing another HFD map without the pronounced convection anomaly zones where water circulation disturbs the geothermal field. In the measured temperature-depth (T-z) profiles of some boreholes evident convection zones are detected, mostly due to hydrothermally active faults of the Mesozoic carbonate or Paleozoic metamorphic basement. From few other T-z profiles it may be concluded that such zones can be expected deeper below the boreholes' bottom. Determination of the convective component of HFD was attempted in two ways: (a) with a Peclet number analysis and (b) in a visual manner, that is in a way where a deeper geotherm is drawn so that the convective part is not considered, but only the conductive component down to a deeper section. Especially the latter method helped us to constrain the HFD values in conductive regime only, in northeastern part to 124 mW/m2, and in the Čatež geothermal field in the east (the eastern portion of the Krška kotlina sedimentary basin) to not more than 72 mW/m2. In view of the search for applicable sources of geothermal energy such maps are indispensible. Unfortunately, much of the country (northern, western, southern and some central parts) lacks more deep geothermal data to help us extract other (possibly hidden) convection zones.

Presenter: Dušan Rajver (dusan.rajver@geo-zs.si)

The surface heat flow of Mars – Report about an attempt to measure it directly with the InSight mission – and to constrain it from seismic data and modeling

Tilman Spohn
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On Nov 28, 2018 NASA/JPL landed a geophysical observatory – InSight – in Elysium Planitia, Mars. The mostly European payload includes a 6-component seismometer (3 VBB, 3 SPP), a magnetometer, an atmosphere sensor package, a geodesy sensor package and the Heat Flow and Physical Properties Package HP3. The latter was provided by a consortium led by the German Aerospace Center's (DLR) Institute of Planetary Research. It includes a radiometer to measure the surface brightness temperature and a small penetrator of 40 cm length and 2.7cm diameter, nicknamed the Mole. The latter was planned to drag a carbon fiber tether equipped with 14 platinum resistance temperature sensors to measure temperature differences with a 1-σ uncertainty of 6.5 mK to a depth of 5 m. The Mole is equipped with sensors to measure the thermal conductivity to 3.5%. The target depth was chosen to avoid the disturbance by the seasonal surface temperature variations. The heat-flow measurement was targeted to ± 5mW/m² (1). This would have been the first extraterrestrial heat-flow measurement after Apollo on the Moon. Thermal models using cosmochemical constraints predict an average heat flow of about 25 mW/m² (2). Inversion of seismic travel time data from InSight gave a mantle temperature profile (3) that is consistent with the estimate. The package was deployed in February 2019 and the mole began to dig to depth (4). Unfortunately, the penetration failed already at 31 cm depth. The root cause of the failure – as was determined through an extensive, almost two year recovery campaign – was a lack of hull friction in an unexpectedly thick cohesive duricrust (4,5). The Mole requires this friction to absorb recoil from its internal hammer mechanism. The mole penetrated further during the campaign aided by the lander's robotic arm and reached a final depth of 40 cm, 2 cm below the surface. It is now used as a thermal probe measuring the thermal conductivity of the porous Martian soil caused by atmosphere pressure variations over the seasons. The thermal conductivity data together with the penetration rate data and seismic recordings during the mole hammering have been used to derive a thermal-mechanical model of the top 40 cm of the soil (4). It is layered with an about 20 cm thick duricrust with a MPa penetration resistance underneath a thin layer of dust and sand. The duricrust overlies an about 10 cm layer of cohesionless sand (as was expected to be representative of the Martian soil when the Mole was designed (5) and a layer of sand/gravel about 5 times more resistant than the duricrust. The seismic data could not resolve the layering but found an average P-wave velocity of 114 m/s and a S-wave velocity of 60 m/s. The average density is 1211 kg/m³ determined from thermal conductivity and diffusivity measurements (assuming constant heat capacity). The thermal conductivity increases from 14 mW/m K to 34 mW/(mK) through the top 1cm sand/dust layer, keeps the latter value in the duricrust and the sand layer underneath and then increases to 64 mW/(mK) in the sand/gravel layer below.

Presenter: Tilman Spohn (tilman.spohn@issibern.ch)

Climate change and heat flow: Last decades to measure heat flow in shallow holes

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Past and present climatic changes modify the subsurface temperatures in continental areas. Although borehole temperatures are now accepted as one of the important archives of past climate variations, the future development of increasing surface temperatures predicts a difficult situation for the traditional geothermal research, i.e., determination of the geothermal gradient for crustal and lithospheric purposes. According to the climatic warming trends in the IPCC 2021 report, the global average temperature will be several degrees higher by 2100 than in the mid-20th century. Together with the earlier climatic changes during the past 2000 years, the IPCC trends imply that bedrock temperatures will be disturbed to depths of 200–250 m by the end of this century. Further, in northern mid and high latitudes the amplitude of the disturbance is expected to be bigger than the global average trends. In areas where the crustal heat flow is inherently low, e.g. Archaean and Proterozoic shields, and which were affected by strong climatic disturbances during the last glaciation are especially vulnerable in this respect. In such areas, the present shallow gradient is very low, and the future warming will remove most of the deep heat-flow signal in the uppermost few hundred meters. After a couple of hundreds of years, the deep heat-flow signal will be practically lost or seriously disturbed in the uppermost 300 m. Naturally there will be deep boreholes allowing the determination of the deep heat-flow signal, but deep holes are not generally available everywhere. Most of the heat-flow data in continents is based on measurements in shallow boreholes. For instance, about half of the European data in the IHFC database have been derived from wells with median depths smaller than 400 m. Paleoclimatic corrections can be applied on the measured data if the past climate on the borehole site is known, but corrections which may amount to several tens of per cent of the measured gradient value are problematic. Inversion studies have shown that the ground surface temperature histories can be quite variable and reflect not only paleoclimatic effects but also site dependent factors such as terrain type, vegetation and air-ground coupling. Although societies currently struggle for diminishing the climate warming rates, we who work with geothermal measurements and databases should prepare for the worst scenarios. It can be foreseen, that the present geothermal data sets compiled by International Heat Flow Commission will be invaluable in the future, and the preservation and continued availability of them is very important. It is urgent to measure borehole temperatures while they still show a deep heat-flow signal.

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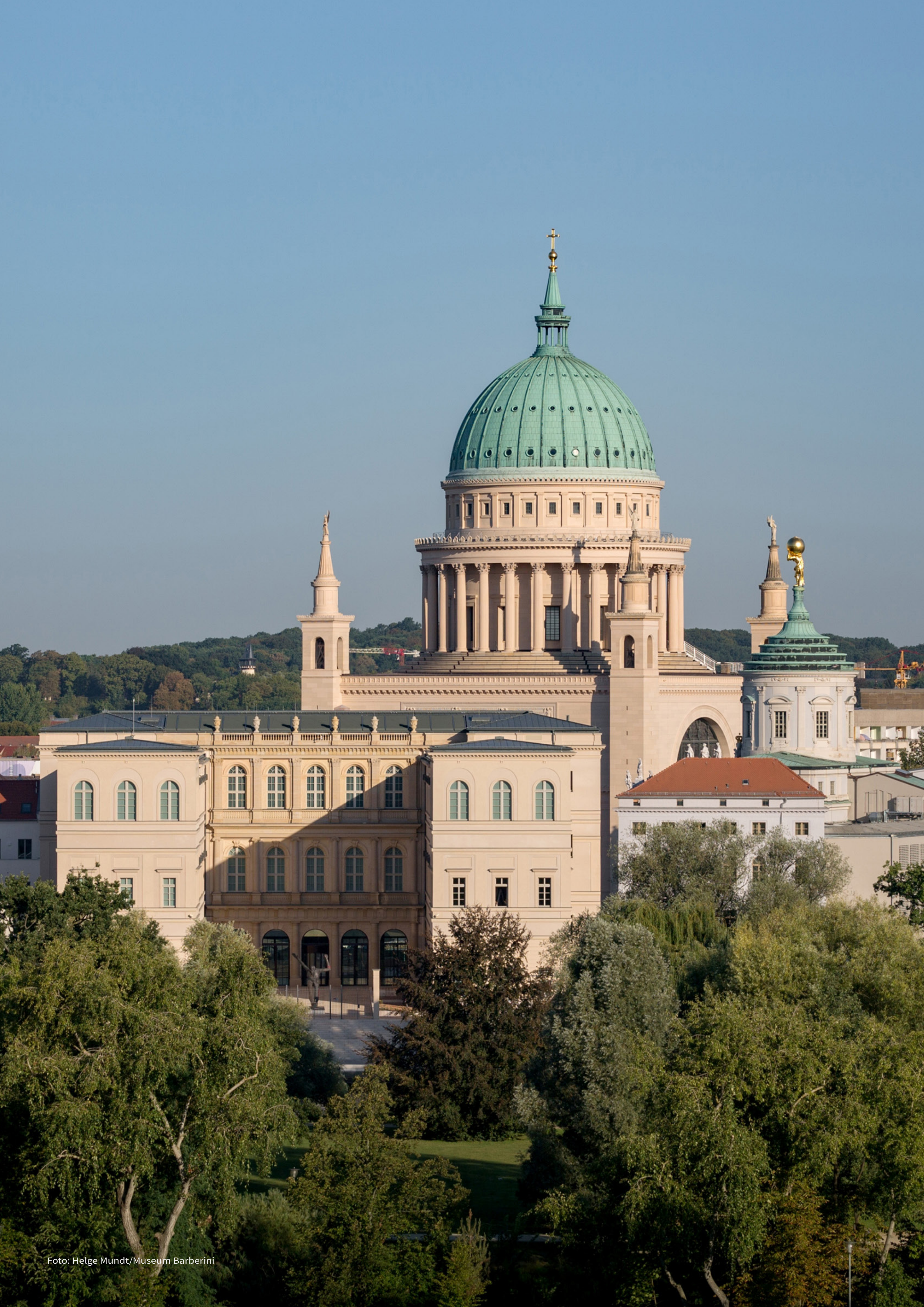

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