Editorial to “Heat Flow: Recent Advances”

Vladimir Cermak¹ · Shaopeng Huang^{2,3} · Dhananjay Ravat⁵ · Massimo Verdoya⁴

Published online: 28 December 2017

© Springer-Verlag GmbH Germany, part of Springer Nature 2017

Geothermics, one of the principal geophysical disciplines, is a science pertaining to the earth's interior heat. It focuses primarily on the investigations of the thermal structure of the earth, distribution of internal heat sources and heat transfer mechanisms through experimental and theoretical studies. Geothermics is relatively young and much of its advances have been achieved only over the last 80 years. Despite its youth, during this time, geothermal studies have broadened and expanded into further scientific domains, sometimes into obvious sub-disciplines such as radiometry and hydrology, and sometimes into surprisingly less apparent fields of interest such as paleoclimatology and global warming. Of special importance is the sub-discipline of applied geothermics addressing geothermal energy and its use in electric power generation and space heating.

During the 26th General Assembly of the International Union of Geodesy and Geophysics held in Prague, from 22 June to 2 July, 2015, Symposium S13 *Terrestrial Heat Flow* was organized. This Symposium addressed various aspects

of geothermics, namely heat flow data and their interpretation, heat flow and tectonics, subsurface temperature field, borehole temperature inversion, borehole climatology and applied geothermics. This session was the largest of its kind realized in the last several years and in 24 oral and 28 poster presentations well reflected the contemporary level of knowledge. Here we present twelve selected contributions providing a representative illustration. Several contributions of that session were already submitted to different journals, and therefore, are not included here.

Four papers in this volume address the interpretation of observed heat flow data in terms of crustal/lithosphere structure in a specific region or area. **Jacek Majorovicz** describes the geothermal activity of the Western Canadian foreland basin and addresses the problem of why its north-western part was characterized by relatively high heat flow of about 80 mWm^{-2} while the southeastern part evidenced only 50 mWm^{-2} , when the whole underlying Precambrian basement and 200 km thick lithosphere do not practically differ and no significant heat flow vs. radiogenic heat production statistical relationship was found. To explain the existing large heat flow contrast the author had to conclude that the high heat production layer of the upper crust must vary in thickness by as much as factor of 2 or that heat production measured at top of the Precambrian basement is not representative for deep rocks. The author speculates that the previous explanation that the heat in the basin is redistributed by the regional fluid flow systems driven from high hydraulic head bound from higher to lower elevations is inconsistent with the observed Darcy fluid velocities and/or basin geometry. Given the available facts, the author concludes that at the moment no definite explanation for the observed high heat flow is at hand, and high heat generation of the thicker than normal, 20 km, upper crust, remains the preferred explanation.

Tectonically, the continental margin of Brazil (CMB) is a passive continental margin where heat flow is not expected to be high. Surprisingly, **Valiya Hamza et al.** discover within the CMB a narrow belt where heat flow is, in general, higher than 70 mWm^{-2} , in contrast to lower than 60 mWm^{-2}

✉ Vladimir Cermak
cermak@ig.cas.cz

Shaopeng Huang
shaopeng@umich.edu; shaopeng@mail.xjtu.edu.cn

Dhananjay Ravat
dhananjay.ravat@uky.edu

Massimo Verdoya
verdoya@dipteris.unige.it

¹ Institute of Geophysics, Czech Academy of Sciences, Bocni II/1a, 14131 Prague-Sporilov, Czech Republic

² Institute of Global Environmental Change, Xi'an Jiaotong University, 99 Yanxiang Road, Xi'an 710054, China

³ Department of Earth and Environmental Sciences, University of Michigan, 1100 N University Avenue, Ann Arbor, MI 48109-1063, USA

⁴ Department of Earth and Environmental Sciences, University of Genoa, Viale Benedetto XV, 5, 16132 Genoa, Italy

⁵ Departments of Earth and Environmental Sciences and Physics and Astronomy, University of Kentucky, 40506 Lexington, Kentucky, USA

in the adjacent continental and oceanic regions. Hamza and colleagues suggest that this high heat flow anomaly is a surface manifestation of relatively shallow crustal magma intrusions to the depths of no more than 20 km and the elapse time of no more than 5 Ma. Their discovery was enabled by reanalyzing a large dataset of bottom hole temperature (BHT) measurements from both onshore and offshore oil wells. Efforts were made to correct the effects of drilling on the BHT and sea floor temperature variation on geothermal gradient calculation. This work is of importance to the interpretation of other geothermal belts along passive continental margins of North America, Africa, India and Australia.

Paolo Chiozzi and Massimo Verdoya investigate heat flow and residual bathymetry over the Mascarene hotspot swell and propose a thermal model to assess whether the heat flow and topography are accounted for by a temperature increase at the base of the lithosphere postulated in many hotspot models. Culling of the spurious data suggested that there is not any significant heat-flow anomaly over the swell and lithosphere reheating plays only a minor role in the present ~ 500 m magnitude residual bathymetric high. No appreciable variation was observed between on-land and marine heat-flow observations, thus advective redistribution of heat near the swell axis does not seem to occur. Estimates of buoyancy flux point to a decrease with time of material flux from the mantle and thus the major mechanism for the origin of the swell may be the dynamic support originated from upwelling of deep mantle.

Shaoven Liu and Lijuan He developed a geodynamical model for the Cenozoic back-arc extension of Bohai Bay Basin in eastern China and related the extension in the Bohai Bay Basin to the trench retreat of the subduction of the Pacific Plate. Using the 2D multi-episodic extension model of Liu et al. (2016) in their analysis of heat flow and subsidence data, they inferred the timing and locations of principal centers of rifting and stretching. They found an inverse relationship between variations of the inferred average strain rate and the speed of plate motion of the Pacific Plate. The authors conclude that the shifts of the centers of extension in the Bohai Bay Basin and the degree of associated stretching were caused by the decreased rate of subduction and the greater speeds of eastward trench retreat at approximately 40 and 20 Ma. Their results suggest that presently the trench is advancing (the highest Pacific Plate velocity of 105 mm year⁻¹ since Cretaceous) and the Bohai Bay Basin is in the weak shortening mode in response to it.

To reconstruct the thermal regime and contemporaneous magmatic activity of the Middle/Late Permian Emeishan large igneous province in southwestern China. **Chuanqing Zhu et al.** used vitrinite reflectance and apatite fission track data from a number of deep boreholes. Two heating patterns were proposed, namely heating of the overlying lithosphere by magmatic activity related to the mantle plume, or direct

heating of country rock by a stock of basalt. The estimated erosion thickness at the Middle/Late Permian unconformity was found to be of about 2 km, which could not meet the required steady-state heat conduction conditions in volcanic environment. However, erosion implies a pre-erosion doming process, which provides a significant evidence for a mantle plume. The reconstructed paleotemperature gradients, erosion thicknesses, and their variations are consistent with a mantle plume structure and corresponding igneous activity.

Two papers address geophysical studies in the Enhanced Geothermal Systems. The contribution presented by **Andrea Forster et al.** is a good example how elemental geophysical research may contribute to practical applications, in this case, for a potential deployment of geothermal heat in municipal heating system. To propose a successful geothermal project it is necessary to describe the exploitation strategy, among others to select the targeting depth for the required temperature. This study illustrates the uncertainties of the geothermal modeling in forecasting deep temperature field by evaluating all controlling factors, such as local geology, crustal structure, rock thermal properties, surface and deep heat flow. The zone of interest presents the Enhanced Geothermal System located in the Elbe Valley, Saxony, Germany, the broader municipal regions of the cities of Dresden and Meissen. The study delineates highest temperatures within the intermediate and mafic rocks forming the deepest portions of the underlying massif. Boreholes 3–4 km deep need to be drilled to reach the envisioned economically favorable temperatures of 120 °C.

Caitlin Hartig targeted sedimentary rocks of the Red River Formation, Williston Basin in North Dakota, USA, where the Enhanced Geothermal System can be developed in both crystalline rocks and sedimentary basins in formations with temperatures exceeding 140 °C. The spatial variations of the properties of the Red River Formation were analyzed to map the subsurface formation temperatures. The resulting maps include depth to the top of the formation, depth to the bottom of the formation, porosity, geothermal gradient, heat flow, and temperature. These results can be utilized directly to create a reservoir simulation model and to ascertain the thermal response of the reservoir to fracture stimulation.

The knowledge of the subsurface temperature field is central for understanding practically all geophysical processes. At constant surface conditions, the underground temperature is governed by the outflow of heat (heat flow) from the deeper interior. However, the surface temperature is not constant and any temperature variations slowly propagate downwards and appear superimposed on the background geotherm. Shallow earth's subsurface "remembers" what has happened on the surface in the past. Geothermics may thus have numerous interesting applications in, e.g., paleoclimatology, the fact which became crucial in present climate warming discussions. Two following contributions suitably

address this topic. **Dmitry Demezko et al.** continued the analysis of the temperature log of the 2363 m deep borehole in Alberta, Canada, and reconstructed its ground surface temperature history for the last 30,000 years. Two ways to adjust the timescale of geothermal reconstructions are discussed, namely the traditional method based on the a priori data on thermal diffusivity value, and the alternative one including the orbital tuning of the surface heat flux and the earth's insolation changes. The second approach provided better agreement between the reconstructions and evidence of the deglaciation chronology.

Jacek Majorowicz and Jan Safanda presented warming and cooling patterns based on paleoclimate inversion of almost one hundred borehole logs from Central Canada. The resulting climate history of the last 2–3 centuries indicated that the warming in the studied area was not uniform and that some smaller regions underwent insignificant cooling. Areas of larger cooling are located on the northeastern part, while areas of warming concentrated in the southeast. Land clearing is an unlikely factor for forcing these changes, and warming is partly due to global warming experienced in the nineteenth century.

In the extraction of geothermal energy from borehole heat exchangers, parameters such as subsurface thermal conductivity and borehole thermal resistance are necessary. **Massimo Verdoya and Paolo Chiozzi** in their second paper investigate modeling methods to estimate these parameters. The models generally used in analyzing temperature data recorded during in situ thermal tests normally assume conduction as the primary mechanism of heat transfer, but such an assumption is not valid at high Darcy velocities. To circumvent the problem, the authors used the moving line source model and found that the model is able to give reliable ground thermal conductivity, borehole thermal resistance, and Darcy velocity of the aquifer.

Precipitation represents one of the dominant factors affecting the moisture dynamics and thus the heat flow and

temperature of the upper soil layer. The convective heat transport from water infiltration reduces both soil temperature and the near surface temperature gradient. **Vladimir Cermak and Louise Bodri** examined the causal relationship between the ground-air temperature offset and the precipitation changes for monitored data series at shallow observatory polygon in Prague (Czech Republic) under four different land covers (bare soil, sand, short-cut grass and asphalt). The results of the Granger causality test did not reveal any evidence for precipitation to ground–air temperature offsets on the daily scale of aggregation except for the asphalt pavement. On the contrary, strong evidence was found on the hourly scale for all cover types except for sand. Obtained results provided valuable information on the delay-time of the ground surface temperature and surface air temperature caused by three rainfall events and confirmed the importance of using autoregressive models to understand the ground/air temperature relationship.

The organization of the meeting and the preparation of this issue were the project of the International Heat Flow Commission of the IASPEI. The editors are indebted to all heat flow colleagues who delivered their presentations and participated in lively discussions. Special thanks are due to those who helped by reviewing one or more of the submitted manuscripts. Their comments and suggestions were most helpful in producing this volume.

References

- Liu QY, He LJ, Huang F, Zhang LY (2016) Cenozoic lithospheric evolution of the Bohai Bay Basin, eastern North China Craton: constraint from tectono-thermal modeling. *J Asian Earth Sci* 115:368–382