International Heat Flow Commission (IHFC) Quadriennium Report 2007 - 2011

The IHFC and its working Groups (WG) report the following activities for the period January 2007 - June 2011:

- **WG on borehole temperature data base :**

Borehole temperature comprises an independent archive of information on climate change which is complementary to the meteorological and other climate proxy records. With support from the NSF, NOAA, and the international geothermal community, a global database of borehole temperatures has been established for the specific purpose of climate change. This database is accessible to the scientific community at the University of Michigan (http://www.geo.lsa.umich.edu/~climate) and the World Data Center-A/NOAA Paleoclimatology Program (http://www.ncdc.noaa.gov/paleo/borehole/) websites. The database currently consists of about 1000 borehole sites in North America, South America, Europe, Africa, Asia, and Australia (Figure 1).

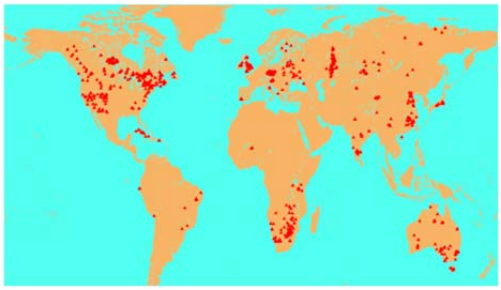

Figure 1. Locations of the borehole sites of the global database of borehole temperatures for paleoclimate reconstruction.

In their recent paper published in the Geophysical Research Letters, Shaopeng Huang and Henry Pollack of the University of Michigan and Po-Yu Shen of the University of Western Ontario [Huang et al., 2008] present a suite of 20,000 year reconstructions that integrate the geothermal information preserved in this a global database and in the other IHFC database – the global heat flow. These reconstructions show the warming from the last glacial maximum, the occurrence of a mid-Holocene warm episode, a Medieval Warm Period (MWP), a Little Ice Age (LIA), and the rapid warming of the 20th century. The reconstructions show the temperatures of the mid-Holocene warm episode some 1–2 K above the reference level, the maximum of the MWP at or slightly below the reference level, the minimum of the LIA about 1 K below the reference level, and end-of-20th century temperatures about 0.5 K above the reference level.

From a global perspective, climate reconstruction based on the existing data in the global database of borehole temperatures indicates a temperature increase over the past five centuries of about 1 K, half of which has occurred in the 20th century alone. The magnitude of ground surface warming over the past five centuries is greater in the northern hemisphere than in the southern hemisphere. The five-century cumulative change is over 1.0 K in the northern hemisphere and 0.7 K in the southern hemisphere. The 20th century temperature change is 0.6 K in the northern hemisphere versus 0.4 K in the southern hemisphere. These estimates of 20th century warming are consistent with the instrumental record of surface warming determined from meteorological stations. When the recent climate change is placed in the context of longer-term trends, the 20th century stands out as the warmest century of the past five, a result consistent with many proxy-based climate

reconstructions. The significance of the results derived from this database is highlighted in the report of the 4th Assessment Report of the International Panel on Climate Change (IPCC, 2007). Over the period of Jan 2007- May 2011, the ISI Web of Science recorded 66 citations of this global database of borehole temperatures for climate reconstruction.

References

The group is still involved in running several of the "borehole climate" observatories run all over the world.

In Europe e.g., Caravelinha in Portugal; Malence in Slovenia; Praha–Sporilov in the Czech Republic.

Selected publications include:

Bodri, L., Cermak, V., 2007. *Borehole Climatology*. Elsevier, Amsterdam.

Huang, S.P. and Liu, J.Q., 2010. Geothermal energy stuck between a rock and a hot place. *Nature*, 463: 293, doi:10.1038/463293d.

Huang, S. P., Pollack, H. N., Shen, P.-Y., 2008. A late Quaternary climate reconstruction based on borehole heat flux data, borehole temperature data, and the instrumental record, Geophysical Research Letters, 35, L13703, doi:10.1029/2008GL034187.

Huang S.P., Taniguchi M, Yamano M, C.-H. Wang, 2009. Detecting Urbanization Effects on Surface and Subsurface Thermal Environment – A Case Study of Osaka. *Science of the Total Environment*, 10.1016/j.scitotenv.2008.1004.1019, 407: 3142-3152.

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, S. Solomon, et al. (Eds), Cambridge University Press, Cambridge.

National Research Council, 2006. Surface Temperature Reconstructions for the Last 2,000 Years, National Academies Press, Washington, DC.

Šafanda, J., Rajver, D., Correia, A., Dedecek, P.2007. Repeated temperature logs from Czech, Slovenian and Portuguese borehole climate observatories. Climat. Past, 3, 453-462.

The thermal regime is still very little explored in the South American continent (see Figure 1). Recent advances were reported by commission members in:

Alfaro, C., Alvarado, I., Quintero, W., Hamza,V. M., Vargas, C., Briceño, L.A., 2009. Preliminary Geothermal Gradient Map of Colombia (in Spanish), Proc.12th Colombian Geológical Congress, Paípa, Boyacá, Colombia, 7-11 September, 2009.

Gutierrez, M. V., Hamza, V. M., 2009, Thermal Field of the crust in the Bahia Sul sedimentary basin and adjacent region: Results of evaluation based on corrected data for the continental margin (in Portuguese), Proc. 11th International Congress of the Brazilian Geophysical Society held in Salvador, Brazil, August 24-28, 2009.

- **WG on Paleoclimate:**

Several commission members participated in the international conference “The Polish climate in the European Context: An historical overview” organized by Prof. Rajmund Przybylak from University Torun in Poland in October 2007:

Čermák, V., Dedecek, P., Šafanda, J., Kresl, M., 2010. Climate warming: evidence stored in shallow subsurface. In: Przybylak, R.; Majorowicz, J.; Brázdil, R.; Kejna, M. (Eds.), The Polish Climate in the European Context: An Historical Overview, Springer, Dordrecht.

Majorowicz, J., 2010. The Climate of Europe in Recent Centuries in the Context of the Climate of Mid to High Latitude Northern Hemisphere from Borehole Temperature Logs. In: Przybylak, R.; Majorowicz, J.; Brázdil, R.; Kejna, M. (Eds.) The Polish Climate in the European Context: An Historical Overview, 2010, DOI 978-90-481-3167-9_4, Springer, Dordrecht.

Mottaghy, D., Majorowicz, J., Rath, V., 2010. Ground Surface Temperature Histories Reconstructed from Boreholes in Poland: Implications for Spatial Variability. In: Przybylak, R.; Majorowicz, J.; Brázdil, R.; Kejna, M.(Eds.) The Polish Climate in the European Context: An Historical Overview, 2010, DOI 978-90-481-3167-9_17, Springer, Dordrecht.

Przybylak, R., Majorowicz, J., Brázdil, R., Kejan, M. (Eds.), 2010. The Polish Climate in the European Context: An Historical Overview, XVIII + 535 p., Springer, Dordrecht.

Šafanda, J., Majorowicz, J., 2010. Geophysical Data. In: Przybylak, R.; Majorowicz, J.; Brázdil, R.; Kejna, M. (Eds.) The Polish Climate in the European Context: An Historical Overview, Springer, Dordrecht.

More selected papers concerned with paleo-temperature reconstruction are:

Diochon, A. L. Kellman, Beltrami, H., 2009. Looking deeper: an investigation of soil carbon losses following harvesting from a managed northeastern red spruce (Picea rubens Sarg.) forest chronosequence, Forest Ecology and Management, 257, 2, 413-420, doi:10.1016/j.foreco.2008.09.015.

Gonzalez-Rouco, J. F., Beltrami, H., Zorita, E., Stevens, M. B., 2009. Borehole climatology: a discussion based on contributions from climate modeling, Climate of the Past, 5, 97-127, 2009.

Hamza, V.M., Alfaro, C., Alvarado, I., Quintero, W., López, J., Monsalve, M.L., Pulgarín, B., Madrid, C., 2009. Surface Temperature Variations of the Last Two Centuries in Bogotá, Colombia., Proceedings of the 12th Colombian Geológical Congress, Paípa, Boyacá, Colombia, 7-11 September, 2009.

Huang, S. P., Pollack, H. N. Shen, P.-Y., 2008. A late Quaternary climate reconstruction based on borehole heat flux data, borehole temperature data, and the instrumental record, Geophysical Research Letters, 35, L13703, doi:10.1029/2008GL034187.

MacDougall, A.H., Beltrami, H., Gonzalez-Rouco, J.F., Stevens, M.B. Bourlon E., 2010. Comparison of observed and General Circulation Model derived continental sub- surface heat flux in the Northern Hemisphere, J. Geophys. Res., doi:10.1029/2009JD013170.

Smerdon, J.E., Beltrami, H., Creelman, C., Stevens, M.B., 2009. Characterizing land-surface processes: A quantitative analysis using air-ground thermal orbits, J. Geophys. Res., 114, D15102, doi:10.1029/2009JD011768.

Commission members Jacek Majorowicz and Jan Šafanda delivered lectures on the borehole climate contribution to the climate past studies during the workshop „History of the Arctic climate in the 19th century and the beginning of the 20th century based on early instrumental data (ACEIP)“ organized by Prof. Rajmund Przybylak from University Torun in Poland in July 2008.

Volker Rath, Jesus Fidel Gonzalez Rouco and commission member Jan Šafanda convened the session CL35 „Subsurface temperature signals of climate change, processes involved, and importance to climate modelling“ during the EGU 2008 General Assembly in Vienna.

Several commission members were involved in geothermal research of impact structures Chicxulub, Chesapeake Bay drilled within the International Continental Scientific Drilling Programme, the result of which were presented e.g., :

Heidinger, P., Wilhelm, H., Popov, Yu., Šafanda, J., Burkhardt, H., Mayr, S., 2007. Preliminary results of geothermal investigations in the borehole Eyreville-B, Chesapeake Peninsula, Geological Society of America, Denver, October 2007.

Heidinger, P., Wilhelm, H., Popov, Yu., Šafanda, J., Burkhardt, H., Mayr, S., 2009. First results of geothermal investigations, Chesapeake Bay impact structure, Eyreville core holes. Geological Society of America Special Papers 2009, 458, p. 931-940, doi:10.1130/2009.2458(39).

Čermák, V., Bodri, L., Šafanda, J., 2009. Tidal modulation of temperature oscillations monitored in borehole Yaxcopoil-1 (Yucatán, Mexico). Earth and Planetary Science Letters, 282, 131–139.

Čermák, V., Šafanda, J., Bodri, L., 2010. Thermal instability of the fluid column in a borehole, application to the Yaxcopoil hole (Mexico). International Journal of Earth Sciences, 2010, Vo.99, N.6, 1437-1451.

Šafanda, J., Heidinger, P., Wilhelm, H., Čermák, V., 2007. Post-drilling destabilization of temperature profile in borehole Yaxcopoil-1, Mexico. Hydrogeology Journal, 2, 423-428, doi: 10.1007/s10040-006-0082-8.

Šafanda, J., Wilhelm, H., Heidinger, P., Čermák, V., 2009. Interpretation and mathematical modeling of temporal changes of temperature observed in borehole Yaxcopoil-1 within the Chicxulub impact structure, Mexico. Journal of Hydrology, 372, 9-16, doi:10.1016/j.jhydrol.2009.03.023.

A strong geothermal aspect was present also in another drilling project supported by the International Continental Scientific Drilling Programme – the Outokumpu borehole

Kukkonen, I.T., Rath, V., Kivekäs, L., Šafanda, J., ., Čermák, V., 2011. Geothermal Studies of the Outokumpu Deep Drill Hole, Geological Survey of Finland, Special Paper 51, 181-198, 2011.

Kukkonen, I.T., Rath, V., Kivekäs, L., Šafanda, J., ., Čermák, V., (in review): Geothermal Studies of the Outokumpu Deep Drill Hole, Finland: Vertical variation in heat flow and palaeoclimatic implications, Phys. Earth Planet. Interior.

A great number of papers and posters were presented at several international meetings in the past year. A list would be too extensive for this purpose.

- **WG on Outreach:**

Speaker Massimo Verdoya is awaiting the final response for a funding request for a new cooperation project between Italy and Morocco which hopefully would restart our activities in northern Africa. The project is focused on the geothermal (low enthalpy) potential of some regional aquifers in the north Atlas zone and might involve also colleagues from Tunisia.

V.M. Hamza and C. Alfaroheld a 5-day short course INGEOMINAS, Bogotá, Colombia, September, 2009 on **Geothermics in Hydrocarbon Exploration**,

Following the objectives of this working group, a big effort was put in trying to stimulate the interest on geothermal research with special reference to people operating in African countries. The working group has especially promoted the participation of African scientists in the geothermal symposium and workshop at the 2009 IASPEI General Assembly in Cape Town. A list of potential contributors has been compiled and a number of scientist, not only familiar with general geothermics but also involved in the renewable energies field, was contacted.

Besides this dissemination activity, research and training activities was performed within the framework of national and trans-national research programs which involved several countries, such as Morocco, Tunisia, Algeria, Portugal, France and Italy. Research topics spanned from geothermal studies of general interest (heat flow, lithospheric structure and

geodynamics) to applied topics, such as geothermal potential assessment, hydrogeothermics, and the role of heat and mass flow in petrogenesis and oil accumulation. The following issues were dealt with in detail: (i) Geothermal potential of Morocco; (ii) Thermal structure of the Iberia-Africa plate; (iii) Hydro-geothermal characters of the Moroccan Atlas; (iv) thermal modeling of the Liassic geothermal aquifer of western Morocco; (v) Processing of oil well temperature data, thermal regime and Petroleum Occurrence in the Essaouira Basin.

The research results were presented at 12 international conferences (among the others The World Geothermal Congress, Bali, 2010 and the IAH Congress on Groundwater Quality Sustainability, Krakow, 2010). A number of scientists and PhD students of several institutions took part in these projects (Universities of Oujda, Rabat and Marrakech, Morocco; University of Évora, Portugal; Institut de Physique du Globe, Paris; University of Genoa, Italy; Center of Renewable Energies of Algeria). Concerning the training activity one Phd student was supported by the working group to attend a training periods and courses on exploration of geothermal energy in Kenya and in Iceland.

- **WG on Heat Flow Data Base:**

Intensive discussions on a new digital format and background data bank have converged. The heat flow data base will be integrated into the Pangaea data base (http://www.awi.de/index.php?id=3086&L=1) maintained at the Alfred-Wegener Institute for Polar and Marine Sciences at Bremerhaven, Germany. Once completed, this will greatly enhance the utility of the heat flow data base as it can be combined with other geographical and geoscientific data maintained at Pangaea. A great number of new data, mainly from hydrocarbon industry but also from academia will be added, once the migration has been completed which is expected by fall of 2011.

- **WG on Thermal Properties**

International collaboration in metrological testing instruments for thermal property measurement was organized with participation of RWTH Aachen University (Germany), Schlumberger Moscow Research Center, and Russian State Geological Prospecting University, Moscow State University. The testing was organized (1) to compare quality of specific heat capacity measurements performed with different instruments, (2) to improve the rock thermal property measurement technique, (3) to obtain reliable thermal property references which are necessary in both basic and applied geothermics.

Four new instruments were developed for high precision measurements of the thermal properties of non-consolidated and consolidated rocks and fluids at laboratory and formation conditions. Jointly with the equipment developed in 1995 - 2006, the new instruments provide essential improvement of the measurement quality to solve basic and applied geothermal problems. As total the combination of the instruments developed in 1990 - 2010 creates a unique experimental base for studying thermal rock properties and for experimental geothermal research as whole.

The advanced experimental geothermal base developed was applied to provide representative data on formation thermal properties and specific heat flow within the following international ICDP projects:

- study of the Chixculub impact structure (Mexico) jointly with Technical University Berlin, Karlsruhe University (Germany), Institute of Geohysics of Prague (Czech Republic) and National Center of USA Geological Survey, with participation of Profs. H. Burkhardt, H. Wilhelm, Drs. S. Mayr, V. Čermák, J. Šafanda, G. Gohn, W. Horton;
- study of the Chesapeake impact structure (USA) jointly with Technical University Berlin, Karlsrue University (Germany) and National Center of USA Geological Survey, with participation of Profs. H. Burkhardt, H. Wilhelm, Drs. S. Mayr, G. Gohn, W. Horton;
- joint analysis of geothermal and petrophysical data of four impact structures: Puchezh-Katunki (Russia), Ries (Germany), Chixculub (Mexico) and Chesapeake (USA) collected in the projects mentioned above with participation of Profs. H. Burkhardt, H. Wilhelm, Drs. S. Mayr, G. Gohn, W. Horton;
- geothermal study of a gas-hydrate field in the Nankai trough jointly with the SKK Center (Schlumberger, Japan);
- geothermal study of gas-hydrates in the Mallik research well (Canada) jointly with the SKK Center (Schlumberger, Japan);
- petrothermal study of rocks encountered in the deep Krafla well in Iceland drilled within the IDDP program.

Six articles were published in international journals and 12 reports in international conferences were delivered reporting the results from these projects.

The International geothermal conference "The Earth's Thermal Field and Related Research Methods" was organized in May 2008 in Moscow. 59 researchers from 6 countries and from 36 Universities and Research Centers participated with more than 60 presentations.

The special volume of geothermal articles was published in Russian with participation of 106 researchers as the papers authors (Ed. Prof. Yu. Popov).

More than 30 presentations with description of recent evolution in thermal petrophysics and experimental basic and applied geothermics were given in International conferences and as lectures in Universities and Research Centers in Russia, Indonesia, Germany, USA, Austria, Canada.

- **WG on Applied Geothermics:**

The aim of this WG is to share the experience and know-how of the IHFC with practitioners interested to develop geothermal energy. There is an obvious lack of awareness by many developers of many theoretical facts and practical results developed over decades by the geothermal community represented in the IHFC. This WG attempts to bridge this gap opening up, at the same time, the dynamic new field of renewable energy to the IHFC, a topic of high societal relevance.

One of the major projects performed during this reporting period was performed by the MeProRisk consortium formed by German universities in Aachen, Berlin and Kiel and two commercial companies. In this project, an improved methodology was developed for exploring, developing and operating geothermal reservoirs. The main achievements are: (i) an improved detection of fractures and faults based on an analysis of reflectivity performed on 3D-seismics; (ii) the development of an iterative procedure comprising both prognostic (forward) simulation of 3D flow and heat transport for predicting temperature and flow rate

and inverse parameter estimation of hydraulic and thermal reservoir properties, both with specified uncertainty. The iteration of this process is performed as long as the uncertainties are unacceptably large. They are reduced by introducing new data obtained from new experiments (boreholes, geophysics); decisions on the location and depth of new exploration boreholes are based on the mathematical methodology of optimal experimental design (oed), adapted to this purpose. Some of these theoretical developments were already tested successfully in commercial projects. In a second phase to be started in the fall of 2011, the methodology will be further refined and applied to three large commercial and academic projects for producing geothermal heat and power in Italy and Australia.

The advanced experimental geothermal base developed in the framework of the WG on Thermal Properties was also applied to infer representative formation thermal property data and to study formation and reservoir thermal regimes within the following projects performed jointly with the Russian of super-deep drilling company “Nedra”, with special emphasis on temperature, temperature gradient, rock thermal properties and heat flow density for the following boreholes:

- Yen-Yakhinskaya super-deep well drilled in the West Siberia;
- Kurgano-Uspenskaya deep well drilled in the West Siberia;
- Onezhskaya well drilled in the European part of Russia;
- Voronezhskaya well drilled in the European part of Russia.

These boreholes were drilled to solve both basic and applied problems connected with the (1) structure and evolution of the crust and (2) exploration of ore deposits and oil-gas fields.

Detailed experimental studies of reservoir and formation thermal properties and temperature regimes were performed to provide design and optimization of the enhanced oil recovery methods in following heavy oil fields: Yarega, Uiglikuti, Suzunskoye, Messoykha, Russkoye (all – Russia). Similar investigations were performed for few heavy oil fields in Canada and gas shale fields in the US. The investigations were performed within the collaboration with Schlumberger, Lukoil, Rosneft, TNK-BP, Gazprom-Neft, Conaco-Philips, Shell oil-gas companies. Similar geothermal and petrothermal research were performed at the first time in the practice of geothermics.

In all projects mentioned above the detailed data extend essentially the database on the rock thermal properties, temperature, temperature gradient, and heat flow density within the Earth's crust.

Geothermal and petrothermal research was also performed jointly with the company RusGydro to study feasibility of a 50 MW geothermal power station in Kamchatka (Russia).

Finally, a big focus of activity was organizing the symposium "Heat Flow, Tectonics, and Geothermal Energy" for 2011 IUGG General Assembly in Melbourne, comprising 23 oral and 12 poster presentations.

Some Publications of working group members are (by no means a complete list!):

Alexandrino, C.H., Hamza, V.M., 2009. A new method to estimate the crustal and lithosphere thickness using elevation, geoid anomaly and heat flow., Proc. 11th International Congress of the Brazilian Geophysical Society held in Salvador, Brazil, August 24-28, 2009.

Cardoso, R.R., Hamza, V.M., 2009, A Source of Error in McKenzie Model of Lithospheric Extension and its Implications for Petroleum Play in Sedimentary Basins. Proc. 11th International Congress of the Brazilian Geophysical Society held in Salvador, Brazil, August 24-28, 2009.

Clauser, C., 2009. Heat Transport Processes in the Earth's Crust, Surveys in Geophysics, 30, p. 163-191

Gessner, K., Kühn, M., Rath, V., Kosack, C., Blumenthal, M., Clauser, C., 2009. Coupled Process Models as a Tool for Analysing Hydrothermal Systems, Surveys in Geophysics, 30, 133-162.

Gomes, A.J.L., Hamza, V.M., 2009, Geothermal gradients and heat flow in the Paraná basin (in Portuguese), Proc.11th International Congress of the Brazilian Geophysical Society held in Salvador, Brazil, August 24-28, 2009.

Huang, S.P. and Liu, J.Q., 2010. Geothermal energy stuck between a rock and a hot place. Nature, 463: 293, doi:10.1038/463293d.

Kolditz, O., Blöcher, G. M., Clauser, C., Diersch, H.-J., Kohl, T., Kühn, M., McDermott, C. I., Wang, W., Watanabe, N., Zimmermann, G., Bruel, D., 2010. Geothermal Energy Systems, In: E. Huenges (ed), *Geothermal Energy Systems*, Wiley, Weinheim, pp. 245-301.

Rühaak, W., Rath, V., Clauser, C., 2010. Detecting thermal anomalies within the Molasse Basin, Hydrogeology Journal, 18(8), 1897-1915.

Vieira, F., Hamza, V.M., 2009, Thermal structure of the crust in northeast Brazil (in Portuguese), Proc. 11th International Congress of the Brazilian Geophysical Society held in Salvador, Brazil, August 24-28, 2009.

Vogt, C., Mottaghy, D., Wolf, A., Rath, V., Pechnig, R., Clauser, C., 2010. Reducing Temperature Uncertainties by Stochastic Geothermal Reservoir Modeling, Geophysical Journal International, 181, 321-333.

- **General activities**

Commission members published the following monographs and contributed the following chapters to the *Encyclopedia of Solid Earth Sciences* published by Springer and the *Treatise on Geophysics* published By Elsevier:

Bodri, L., Cermak, V., 2007. *Borehole Climatology*. Elsevier, Amsterdam.

Chapman, D. S., Hasterok, D. 2011. Thermal Isostasy In: H. Gupta (Ed), *Encyclopedia of Solid Earth Sciences*,*2nd ed.,*Springer, Dordrecht.

Clauser, C., 2011. Thermal Storage and Transport Properties of Rocks, I: Heat Capacity and Latent Heat. In: H. Gupta (Ed), *Encyclopedia of Solid Earth Sciences*,*2nd ed.,*Springer, Dordrecht.

Clauser, C., 2011. Thermal Storage and Transport Properties of Rocks, II: Thermal Conductivity and Diffusivity. In: H. Gupta (Ed), *Encyclopedia of Solid Earth Sciences*,*2nd ed.,*Springer, Dordrecht.

Clauser, C., 2011. Radiogenic Heat Production of Rocks. In: H. Gupta (Ed), *Encyclopedia of Solid Earth Sciences*,*2nd ed.,*Springer, Dordrecht.

Jaupart, C., Labrosse, S., Mareschal, J.-C., 2007. Temperatures, Heat and Energy in the Mantle of the Earth, In: D. Bercovici (Ed), *Treatise on Geophysics,* vol. 7Elsevier, Amsterdam, pp. 253-303.

Jaupart, C., Mareschal, J.-C., 2007. Heat Flow and Thermal Structure of the Lithosphere, In: D. Bercovici (Ed), *Treatise on Geophysics,* vol. 7Elsevier, Amsterdam, pp. 217-251.

Mareschal, J.-C., Jaupart, C., 2011. Energy budget of the Earth. In: H. Gupta (Ed), *Encyclopedia of Solid Earth Sciences*,*2nd ed.,*Springer, Dordrecht.

Aachen, 23 June, 2011

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(Chair, International heat Flow Commission)