Kombinierte Interpretation petrophysikalischer Eigenschaften von Impaktiten und Postimpaktiten

-

Combined interpretation of petrophysical properties of impactites and postimpactites

Dem Fachbereich Geowissenschaften der Freien Universität Berlin
vorgelegte Habilitationsschrift

von

Dr. rer. nat. Dipl.-Phys. Sibylle I. Mayr

Foreword

The written post-doctoral thesis herewith submitted consists of a monograph and five publications in peer-reviewed journals, together with a conference contribution. The monograph is an evaluative summary of my share of the published research results.
The work is based on the following publications (my share is estimated at ** %):

1. Popov, Y., Romushkevich, R., Bayuk, I., Korobkov, D., Mayr, S., Burkhardt, H., and Wilhelm, H. (2004). *Physical Properties of Rocks from the Upper Part of the Yaxcopoil-1 Drillhole (Chicxulub Crater)*. Meteoritics & Planetary Science 39, 799-812. (ca. 20%)

2. Mayr, S., Burkhardt, H., Popov, Y., and Wittmann, A. (2007). *Estimation of hydraulic permeability considering the micro morphology of rocks of the borehole YAXCOPOIL-1 (Impact crater Chicxulub, Mexico)*. Int J Earth Sci (Geol Rundsch), 97, 385-399. (ca. 75%)

3. Mayr, S. I., Wittmann, A., Burkhardt, H., Popov, Y., Romushkevich, R., Bayuk, I., Heidinger, P., and Wilhelm, H. (2008). *Integrated Interpretation of Physical Properties of Rocks of the Borehole YAXCOPOIL-1 (Chicxulub impact structure)*. J. Geophys. Res., v. 113, 21 p. B07201. (ca. 75%)

4. Mayr, S., Burkhardt, H., Popov, Y., Romushkevich, R., Miklashevskiy, D., Gorobtsov, D., Heidinger, P., and Wilhelm, H. (2009). *Physical rock properties of the Eyreville core, Chesapeake Bay impact structure*. in GSA Special Paper 458, 137-163. (ca. 75%)

5. Popov, Y., Mayr, S.*, Romushkevich, R., Burkhardt, H., and Wilhelm, H. (2014). *Petrophysical Properties of Impactites taken from four Meteroritic Impact Structures*. Meteoritics & Planetary Science 49 896-920. (*corresponding Author) - (ca. 50%)

6. Mayr, S. and Popov, Y. (2015). *Petrophysical characteristics of impactites*. In Bridging the Gap III: Impact Cratering in Nature, Experiments, and Modeling; Abstract no. 1017, pages 1-2. (Konferenzbeitrag, ca. 98%)

Further publications on this subject with my participation:

1. Wilhelm, H., Popov, Y., Burkhardt, H., Šafanda, J., Cermák, V., Heidinger, P., Korobkov, D., Romushkevich, R., and Mayr, S. (2005). *Heterogeneity effects in thermal borehole measurements*. J. Geophys. Eng. 2 No 4, 357-363.

2. Heidinger, P., Wilhelm, H., Popov, Y., Šafanda, J., Burkhardt, H., and Mayr, S. (2009). *First results of geothermal investigations, Chesapeake Bay impact structure, Eyreville boreholes*. in GSA Special Paper 458, 931-940.

3. Popov, Y., Romushkevich, R., Korobkov, D., Mayr, S., Bayuk, I., Burkhardt, H., and Wilhelm, H. (2011). *Thermal properties of rocks of the borehole Yaxcopoil-1 (Impact Crater Chicxulub, Mexico)*. Geophysical Journal International, 184, 729-745.

The nine publications are attached as a CD for an appraisal of the work.

Summary

Many of the 188 meteorite impact craters known on the Earth to date were discovered in the course of oil exploration. Several of these craters are associated with mass extinction, for example the Chicxulub impact structure (Yucatan, Mexico); others result in hydraulic anomalies, for instance the Chesapeake impact structure (Virginia, USA). Besides geophysical field measurements, deep boreholes are used to investigate these structures.

The aim of the work presented in this post-doctoral thesis was on the one hand the preparation and provision of information for modelling (e.g. temperature field, hydraulic measurements, seismic measurements, etc.) and on the other a comparative interpretation of the physical properties of the rocks which were changed or came into being due to impact (impactites). The planning and performance of the extensive supplementary petrophysical measurements on rocks from the boreholes Yaxcopoil-1 (Chicxulub impact structure) and Eyreville (Chesapeake impact structure) and the interpretation of the data from different perspectives in interdisciplinary collaboration with scientists and researchers from the fields of geothermics, impact research, geology and mineralogy were a major component of the work. The samples investigated comprise both post-impactites and allochthonous impact breccia (suevites and lithic breccia) and impact melt rocks as well as the autochthonous or parautochthonous shocked and displaced target rocks.

The basis of my work was measurements on half cylinders, taken at short intervals from continuous drill cores. These measurements on the densely sampled cores were performed by the Popov group and comprise for mechanically stable samples the connective porosity (ratio of pore volume to total volume) and the density of the vacuum-dry and fully saturated rock and, resulting therefrom, also the density of the solid portion of the rock and the thermal properties of the dry or saturated rock. An initial grouping of the data was made on the basis of the geological information provided by the core field geologist.
I supplemented this database to include the different, mostly nondestructive petrophysical measurements. Where possible, representative samples were chosen from the half cylinders already investigated. Measurements of the P and S wave velocities v_p and v_s were as far as possible carried out under the same conditions (dry and fully saturated, direction of measurement with regard to layering, no or only low axial pressure), but also in some cases depending on saturation and pressure (Mayr et al., 2008, Mayr et al., 2009). The data sets are extended to include measurements of permeability, internal surface, electrical properties, NMR relaxation times, pore radius distribution by means of mercury injection measurements and further optical analyses (in particular Mayr et al., 2007, Mayr et al., 2008).
For the Yaxcopoil-1 borehole (Chicxulub) an important focus was the estimation of the permeability from the internal surface, the electrical properties, the porosity, the NMR relaxation times and the pore radius distribution. This also included an assessment of the internal surface with a view to

the different rock types (Mayr et al., 2007). For the Yaxcopoil-1 borehole, quasi-continuous logs of the P wave velocities and electrical conductivity were obtained from the supplementary measurements and the measurements at the densely sampled cores. The different effects of the structure and texture (e.g. porosity, grain contacts, microfossils) and mineralogy on the physical properties were taken into consideration (Mayr et al., 2008).
For the Eyreville borehole (Chesapeake) porosity and densities were determined as a supplement to the available database for mechanically unstable samples (poorly consolidated claystones and sandstones from the upper section of the borehole). In contrast to the Yaxcopoil-1 borehole, not only were representative samples selected to measure the P and S wave velocities, but measurements were taken at as many samples as possible. The lack of stability of the half cylinders was a very restricting factor, for which reason it was only possible to take measurements at all samples for granites. The saturation and pressure dependence of the velocities were also determined for these (Mayr et al., 2009).

Investigations of the different rock types (calcites, dolomites, anhydrites as well as suevites, lithic breccia and lower suevites) from the Yaxcopoil-1 borehole (Chicxulub) showed that all physical properties correlate naturally with porosity. Due to the different properties of the rock-forming minerals, the two petrophysical parameters density and thermal conductivity allow a distinction to be made between predominantly calcarenite, dolomite and anhydrite types. For more highly porous rocks ($\phi > 15\%$) the influence of structure and texture is more marked with thermal conductivity (particularly in the case of the suevites and lithic breccia). On the other hand, with the elastic velocities it is not possible to make a grouping with regard to mineralogy, and the influence of texture and structure is predominant (microcracks). Due to the above-mentioned factors different correlations were used to calculate quasi-continuous v_p logs from the densely measured data. The interpretation of the elastic properties, in particular the saturation-dependent v_p and v_s measurements, is, with regard to microcrack density, in agreement with the interpretation with respect to the orientation of megablocks.
For the electrical properties, the same relationship can be used for all rock types, whereas a distinction must be drawn between different rock types in the case of the internal surface: the Tertiary limestones, the suevites and the lithic breccia of the uppermost five units (without the lower suevites), the lower suevites, the Cretaceous anydrites and the dolomites. For the suevites and lithic breccia there are additional influences due to hydrothermal waters after the impact. Accordingly, different permeability estimation models were used for the different groups. The Tertiary limestone samples are characterized by high porosities ($< \phi <$) and relatively low permeabilities between 10^{-14} m^2 and 10^{-19} m^2. The estimated values for the suevites and lithic breccia (without lower suevites) between $^{-18}$ m^2 and 10^{-15} m^2 are of the same magnitude as those of the post-impact limestones (type 1). On the other hand, very low permeabilities between 10^{-15} m^2 and 10^{-23} m^2 are estimated for the low-porosity lower suevites, Cretaceous anhydrites and dolomites. For the suevites and lithic breccia (without lower suevites) and in the post-impact limestones there is the possibility of a convective contribution to heat transport (Mayr et al., 2007).

In the case of the rocks from the Eyreville borehole (Chesapeake) the extensive measurements showed that the parameters density and thermal conductivity do not permit a clear grouping, whereas the different elastic properties of, in particular, limestone and quartz are clearly shown in the velocities (post-impactites and the Exmore breccia). Along with these differences is the influence of texture and structure, also with the granites, shales and pegmatites (target rocks) together with the suevites and lithic breccia. It was not possible to calculate logs from correlations to supplement the measured data due to the different influences. The saturation and pressure-dependent measurements of v_p at all granite samples enable a zoning of the granite megablocks.

In both boreholes, the analyses of the saturation and pressure-dependent P and S wave velocities confirm the additional influence of microcracks in the rock. In other words, this type of measurement provides further information on the interpretation of the data with regard to, for example, the impact-induced destruction of the rocks. The internal surface of both boreholes also shows differences, due above all to differences in the clay content. The result of the analysis of the temperature measurements in both boreholes was that these - due to clear differences in thermal conductivity - can react very sensitively to changes in lithology. Both the internal surface and temperature measurements in the borehole can therefore be used as additional parameters to determine geological boundaries.

After the physical properties of post-impactites and impactites of the two investigated craters had been considered in Mayr et al., (2007), Mayr et al. (2008) and Mayr et al. (2009), the peculiarities of the physical properties of the impactites were compared with results from similar previous work at two further impact craters. In Popov et al. (2014) a distinction is first made between impact breccia (including the impact melt rocks) and the shocked and displaced target rocks. In Mayr and Popov (2015) a distinction is also drawn within the first group between the impact breccia (suevites and lithic breccia) and the impact melt rocks.
The work confirms that the physical properties reflect the influence of meteorite impact and can be used to distinguish between the different lithologies and to investigate the effects of meteorite impact on the affected rocks. Porosity most influences the physical characteristics of impactites (and also post-impactites). Porosity is here understood to mean both the porosity which can be quantified by means of laboratory measurements and the form of the pores (e.g. cracks, closed pore space).
In the impact breccia an increase in porosity caused by the impact is observed, whereas the impact melt rocks are evidently lower-porous rocks. The petrophysical properties can thus serve as both an indicator and a delineator, e.g. between the impact breccia and the impact melt rocks. However, the influence of the mineralogy of the target rocks on the impact breccia (suevites and lithic breccia) and of the impact melt rocks is also significant.
The physical properties of the target rocks are influenced by three factors: 1) lithology (i.e. mineralogy) 2) the geological processes before the impact and 3) effects caused by the impact itself (shock metamorphism). The physical properties of the target rocks correlate with the degree of shock metamorphism, mainly due to the impact-induced porosity increase. Moreover, a decrease in seismic velocities in the target rocks is observed due to the higher number of microcracks, less due to a porosity increase. The physical properties are thus a help for the interpretation of the

properties of the target rocks with regard to shock metamorphism or the origin and the orientation of megablocks. Due to their evolutionary history, the impactites in a crater are in general heterogeneously distributed. The observed degree of destruction depends on the scale (field, borehole, sample); this also applies to the investigated physical properties (Mayr et al., 2008; Mayr et al., 2009; Popov et al., 2014; Mayr and Popov, 2015).

For the interpretation of the physical properties of impactites two factors were of key importance. The first was the interdisciplinary cooperation between petrophysicists, theoretical geophysicists, geologists and mineralogists. Secondly, the good database made it possible not only to consider individual samples (sample scale), but also to record impact-induced changes in petrophysical properties in other scales (borehole and field scale).

The results presented in this post-doctoral thesis not only support the petrophysical and lithological characterization of the impact structures Chicxulub and Chesapeake but also yield further insights into the petrophysical properties of a broad variety of rocks, ranging from carbonate rocks over clays to plutonic rocks. Especially they contribute to a better understanding of physical properties of impactites and by this to the interpretability of field, borehole and laboratory data found in the vicinity of impact structures.

Inhaltsverzeichnis