Secondary Changes of Rocks in Zhamanshin Meteorite Crater (Kazakhstan)

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Abstract. Magnetic properties, structure, and phase composition of samples of ferruginous rocks from the Zhamanshin meteorite crater have been investigated. X-ray phase analysis, microscopy and magnetometry have revealed that studied rocks can be considered as a fine-grained polymictic sandstone which undergone significant alteration. All samples appear highly ferruginous, with cement of goethite with small particles of the matrix. Detrital grains are quartz, feldspar, rarely mica, as well as monazite, ilmenite, zircon, and cassiterite in accessory quantities. Inclusions of glass, probably of impact origin, with low silica, high alumina, and high iron content have also been encountered. A characteristic feature of goethite is the presence of Mn and a pronounced zonal structure manifesting itself in an increased Al content. Intergrowths and druses of authigenic magnetite are found in voids and cracks; magnetite however appears completely by iron (hydr)oxides. These observations generally agree with the paleogeographic data, and suggest that the crater and its vicinity experienced significant changes of the redox regime in the post-impact time.

1. Introduction

Study of impact structures (called astroblemes particularly in terrestrial context[1]) is of interest both with respect to their origin as well as from a more general geological point of view to elucidate the role of impact processes in the structural, morphological and material transformation of the outer shells of the Earth. This paper discusses the rocks from the basement and filling complex which are units typical of astroblemes’ geological structure [2] from the Zhamanshin impact crater, subjected to secondary changes. These data would help to infer the redox conditions in the crater which in turn are an essential building block to develop a model of changes in the mineral associations characteristic for impactogenic complex rocks. This study is focused on rocks that have been strongly iron-enriched occurring commonly through the area of Zhamanshin astrobleme.

A small set of samples collected during the geological and geophysical expedition of St. Petersburg State University in 2018 was investigated. These samples are peculiar in both their location within the astrobleme and in their textural characteristics. They are small, often elongated formations of bizarre shape, up to 4 cm in size along the long axis, of a dark brown color, somewhat resembling by their shape the tektite-like irghizites found elsewhere in the crater. Their surface is uneven but appears
dynamically smoothed (figure 1). These samples were found in the southeastern sector of the crater, about 1 km beyond the outer rim. It should be noted that in this part of the astrobleme, ordinary Zhamanshin impactites (irghizites and zhamanshinites) are extremely rare and only sporadically found. However, the studied samples had a typical look of an irghizite placer – a clearly bounded field of very small size (on the order of several meters) located on a clay clearing among the terrain overgrown with steppe vegetation.

Figure 1. An example of studied ferruginous forms (left) as compared to a typical irghizite form (right).

To study the mineral composition of the samples, optical microscopy, X-ray phase analysis, scanning electron microscopy in combination with electron probe microanalysis have been used. Magnetic properties have been characterized by measuring temperature dependences of initial magnetic susceptibility, room-temperature hysteresis loops, isothermal remanence acquisition, and backfield demagnetization curves, and, for the only suitable sample, also a FORC diagram.

2. Research results

2.1. X-ray diffraction phase analysis
Qualitative and quantitative phase analysis (identification of various crystalline phases and determination of their relative concentrations) has been performed using an automatic D2 Phaser powder diffractometer (Bruker, Germany), X-ray radiation – CoKα1+2, wavelengths $\lambda_{\text{CoKα1}} = 1.78900 \ \text{Å}$ and $\lambda_{\text{CoKα2}} = 1.79283 \ \text{Å}$, tube operation mode 30 kV / 10 mA, position-sensitive detector, reflection geometry, Bregg-Brentano focusing scheme, sample rotation speed of 20 revolutions per minute, $T = 25 \ ^\circ\text{C}$, air atmosphere. Phase identification was performed using the PowderDiffractionFile powder diffraction database (PDF-2, edition 2011). The composition of rocks is presented in weight %. According to the full-profile analysis by the Rietveld method, all the samples are dominated by goethite, present in the amount of 81-83 weight %, and additionally contain on average 13 weight % of quartz, 3-4 weight % of plagioclase, and < 2 weight % of microcline.

2.2. SEM and electron probe analysis
Micromineralogical studies by SEM have been carried out using a TM 3000 tabletop scanning electron microscope-microanalyzer (HITACHI, Japan) and a Quanta 200 3D electron scanning microscope (FEI, Netherlands) with the Pegasus 4000 analytical complex (EDAX, USA) in the reflected and secondary electrons mode. Electron probe microanalysis has been performed using an energy dispersive diffractometer attached to the latter microscope under high vacuum conditions at an accelerating voltage of 20 kV (Resource Center "Microscopy and Microanalysis" of the Scientific Park of St. Petersburg State University). Polished sections for SEM study have been prepared by pressing the samples into a resin with a semi-automatic press StruersCitoPress and a vacuum filling system.
StruersCitoVac with subsequent processing on a StruersTegraPol grinding and polishing machine (Resource Center of Nanotechnology of St. Petersburg State University Science Park).

Optical observations have shown that the samples are built primarily of a fine-grained and very iron-rich sandstone. SEM study has further established its polymictic nature (figure 2a). Detrital grains are represented by quartz, feldspar, individual mica grains, and accessory monazite, ilmenite, zircon, and cassiterite. Inclusions of glass, probably of impact origin, with low silica, high alumina, and high iron content have been encountered (figure 2b). Inclusions of plant residues also occur (figure 2c). The structure is detrital psammitic, fine-grained, grains angular with fracture cracks filled with cement. The texture is massive. The cement is authigenic, represented by goethite in which the clay particles of the matrix are observed. Peculiar features of goethite are the presence of about 1 wt. % Mn and pronounced zonal structure with up to 3 wt. % Al. In voids and cracks intergrowths and druses of octahedral habit crystals, up to 50 microns in size are found (figure 2d). The faces of the crystals are complicated by microrelief. In terms of chemical composition and morphology, these can be considered as authigenic magnetite subsequently replaced from the surface or completely by secondary minerals.

![Figure 2. SEM images: (a) polymictic sandstone; (b) glass inclusion; (c) an example of zonation in goethite; (d) intergrowths of octahedral habit crystals in voids and cracks.](image)

2.3. Magnetic properties

Magnetic properties studied included temperature dependences of initial magnetic susceptibility, and room-temperature hysteresis loops, isothermal remanence acquisition, and backfield demagnetization curves. Susceptibility vs temperature curves were measured between -192°C and 700°C using a susceptibility bridge MFK1-FA (AGICO), low- and high-temperature capacity being provided with a CS-L cryostat and a CS-4 furnace, respectively. Sample was first cooled to liquid nitrogen temperature, and a susceptibility curve during warming to room temperature was traced. Then the susceptibility was measured on heating and cooling the sample from room temperature to 700°C and back, in air. Finally, a second low-temperature susceptibility curve has been measured. Curie temperatures have been determined as a derivative of the respective susceptibility curves. Curves measured at low temperatures were primarily employed to trace mineralogical alteration induced by heating.
Hysteresis loops have been measured in a maximum field of 1.9 T using a Princeton Measurements Corporation 3900 vibrating sample magnetometer at the Institute of Physics of the Earth, RAS (Moscow). The same instrument was used to trace isothermal magnetization curves and backfield demagnetization curves. For the only sample in our collection, showing a non-negligible hysteresis, 118 First Order Reversal Curves (FORC) separated by a 5 mT field increment were also measured. The respective FORC distribution has been computed using the VARIFORC v.2.03 software [3].

Susceptibility versus temperature curves are shown in figure 3. At room temperature susceptibility is very low, of the order of $300 \times 10^{-9}$ m³/kg, as expected of a sample containing goethite as a major magnetic mineral. Néel temperature of goethite (120 °C in stoichiometric material [4]) is however not seen in susceptibility versus temperature curves. This is consistent with previous observation that Néel temperature is only clearly seen in well crystallized goethite samples [5]. Around 300°C, a small drop in susceptibility is observed which could be related to a dehydration of the goethite phase. When heated above 500°C, it further transforms into a strongly magnetic mineral, which, as suggested by the shape of the low-temperature curve measured after heating, is likely a slightly non-stoichiometric magnetite.

**Figure 3.** Example of a temperature dependence of magnetic susceptibility measured between −192 °C and 700 °C. Heating is shown by solid lines, cooling by dashed. Inset shows a close-up of heating curve.

Magnetization versus magnetic field curves for selected samples are shown in figure 4a. Most samples show nearly linear magnetization curves, with very small hysteresis and remanence. This is typical for goethite-bearing samples [6]. Remanence acquisition and backfield demagnetization curves (figure 4b) further reveal two types of behavior: nearly linear remanence growth in fields above 0.1 T up to 1.9 T and likely beyond (samples Ibr 2-16 and Ibr 2-54), and a relatively fast remanence acquisition between 0.1 and 0.7 T followed by a slower growth above 0.7 T (samples Ibr 2-02 and Ibr 2-23). This observation can be interpreted as an evidence for the presence of two different populations of goethite in the two latter samples. Remanence increase below 0.1 T is not typical for goethite and would therefore signify the presence of a very minor magnetically soft phase. If this is magnetite, its concentration should be roughly three orders of magnitude lower than that of goethite. It is then no surprise that magnetite is not observed by X-ray diffraction and only its pseudomorphs are seen microscopically.

**Figure 4.** Central parts of hysteresis loops (a) and IRM acquisition and backfield demagnetization curves for four representative samples.
Sample Ibr 2-29 is the only one showing a significant hysteresis due to goethite-like phase (figure 5a). After removing the linear contribution due to antiferromagnetism, the remaining loop shows extremely high $M_r/M_s$ ratio of 0.76. At the same time, coercivity (227 mT) does not seem particularly high for goethite. One has however to bear in mind that maximum field of 1.9 T available to us is not nearly sufficient to saturate goethite, and therefore the respective hysteresis loop must be considered as minor. Another interesting feature of this sample is that its coercivity spectrum is fairly narrow, concentrating largely between 120 and 260 mT, as attested by both remanence acquisition curve (figure 5a) and FORC diagram (figure 5b).

![Figure 5](image_url)

**Figure 5.** Central part of hysteresis loop (as measured, and with linear term removed) and IRM acquisition and backfield demagnetization curves (a) and FORC diagram (b) for sample Ibr 02-29. FORC distribution has been calculated using variable smoothing algorithm [3] with smoothing factor SF = 4 and $\lambda = 0.07$.

### 3. Discussion and conclusions

Zhamanshin is one of the youngest known astroblemes its age being however rather loosely constrained between 0.7–1.0 million years [7]. Zhamanshin depression is located about 35 km south-west of the town Irgiz in the southern part of the Turgai Plateau. The plateau is a clayey semi-desert having a flattened relief, complicated by table mountains 50-100 m high and gentle hollows. It is bound between the Southern Urals and Mugodzhary in the west and the Kazakh Uplands in the east. Along its axis, the plateau is crossed from north to south by Turgai hollow. The latter corresponds to a larger structure of Turgai trough connecting the West Siberian plate with the Turan lowlands in Kazakhstan. It is an erosion-tectonic hollow which can be traced in relief from the lower reaches of the Tavda River in the north to the Northern Aral region in the south.

In the paleogeography of the Aral Sea basin, two marine stages of a vastly different duration can be identified separated by a long continental break [8]. The first stage corresponds to rather long-lived Akchagyl and Absheron transgressions of the Caspian Sea which at their maxima reached Aral depression forming extensive, strongly desalinated sea bays. This stage terminated around 1 My ago with Turkan regression [8]. The second short marine stage corresponds to the last Aral Sea that existed during the entire Holocene prior to man-made changes of late 20th century. The sea body has formed in mid-Holocene, when Amu Darya changed its flow breaking from the south to the Aral depression. At this stage, the Northern Aral region was likely covered a system of water bodies of various hydrochemical composition, periodically drying up and turning into salt marshes. Climate regulated the river runoffs and, most importantly, the amount of evaporation from the sea surface determining the rhythm of sea level fluctuations [9].

The modern topography of Zhamanshin area is almost exclusively denudational, accumulative formations being confined to the hollows of the ancient runoff [10]. The only large permanent watercourse is Irgiz River; in the dry periods, it disintegrates into a number of separate water bodies. Irgiz follows an ancient valley, and historically must have experienced periods of greater flow as evidenced by a wide flood plain with a series of small erosion terraces.
Zhamanshin impact structure could have been formed at the site of a relatively large catchment basin developed on an extended topographic high area [11]. Within the structure, small hills are common with the slopes covered with fragments of Paleozoic rocks, whereas the depressions between them are filled by brecciated Mezo-Cenozoic rocks. The bottom of Zhamanshin structure is composed of eolian and lake sediments deposited in a lake that existed in the crater during its initial period. Currently, within the bottom these sediments are gradually eroded, erosion probably being the most intense immediately after the impact event [11].

Within the crater itself and in the nearby area, highly ferruginous rocks of red and brown color are abundant, represented by Paleozoic schists and Paleogene deposits. They are commonly found as fragments of various size, from the first cm to 0.5 m in diameter, sometimes slightly rounded. In some cases, pseudomorphs by organic residues can be suggested. Others, studied in this work, are a conglomerate (gravelite, sandstone) of the ferricrete type cemented by iron hydroxides. Their unusual forms can be explained in two ways: (i) formation of filling pseudomorphs occurring when a body (mineral) dissolves, with the bulk of the substance dissolving and the remaining void being filled with another mineral or rock inheriting the primary form, and (ii) wavy surfaces were formed via sediment accumulation in the form of lenticular layers, produced by rippling currents or waves. Subsequently, in the coastal conditions, sediment was destroyed and rounded, finally taking bizarre "irghizite-like" forms.

Presence of glass in most studied samples may indicate the post-impact origin of these rocks some of which could be altered impactites. Formation of magnetite in the hollows of consolidated sandstone, which took place at the early stage of alteration, and the presence of pyrite is consistent with the paleogeography data and indicates a change in the redox regimes in the crater area at this time. According to magnetic data, however, magnetite is only found in trace amounts in otherwise goethite-dominated samples, and therefore must have undergone the total replacement by iron hydroxides.

4. References
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