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IDENTIFICATION, TESTING, AND ANALYSIS OF A METEORITE DEBRIS FROM JHELUM, PAKISTAN

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Abstract

In this research paper, X-ray diffraction (XRD) and X-ray fluorescence (XRF) spectrometry have been used to determine the mineralogical and elemental composition of a stone sample recovered from a location near village Lehri in district Jhelum, Pakistan. The test data is compared with previous findings (as reported in literature and included in references) to identify this sample stone as part of a prehistoric meteorite ablation debris. Carbon content of a specimen of the meteorite debris has also been determined through combustion analysis. This carbon abundance has been compared with carbon wt% value of a certain type of meteorites to establish the origin and nature of the parent body of this particular meteorite debris.

Keywords: Meteorite debris, X-ray diffraction, XRF spectrometry, Combustion analysis, Carbon abundance.

1. Introduction

Meteorites are unique and valuable specimens of the diverse planetary material scattered throughout our solar system. The oldest meteorites were created as an outcome of the very first geological processes in the primitive, slowly evolving solar system somewhere around 4.5 billion years ago (Sears, 1978; McSween and Huss, 2010). As meteorites developed through variety of processes on planetesimals, they exhibit a marked difference in their structure and properties. Generally, three broad categories of meteorites are identified viz. chondrites or stony meteorites, iron meteorites and stony-iron meteorites. Chondrites are believed to have formed in the outer crust of planets or asteroids. They contain small grain like inclusions called chondrules that originated in the solar nebula and predate the formation of our planet. Chondrites in which trace of all chondrules has been removed due to igneous activity on the parent body are classified as achondrites (McSween, 2000; Smith et al., 2010). Chondrites account for 90% of all meteorite falls. Iron meteorites may contain up to 90-95 wt% iron with another major element being nickel. They contain two unique iron phases namely kamacite and taenite. Their crystal structure is always identified as a complex interlocking metallic mesh known as widmannstätten pattern. They constitute about 5% of all meteorite falls. Stony-iron meteorites are rare and are composed of nearly equal amounts of nickel-iron and silicate material. They are believed to have originated in the mantle or core of their parent bodies (McSween, 2000; Lauretta and McSween, 2006; McSween and Huss, 2010). They are further classified as pallasites and mesosiderites.

Generally, freshly fallen chondrites are easily identified as they always have a fusion crust around them produced due to melting of their outer layer caused by friction while travelling through the earth's atmosphere (Smith et al., 2010). Suspected chondrites that are recovered through area-surveying need testing in order to determine their chemical/elemental and mineral structure, which is then compared with known meteorite specimens for classification purposes. Iron and stony-iron meteorites are usually readily distinguished from rest of their surroundings due to presence of high metal content and their unique morphologies (Smith et al., 2010).

2. Background information

Locals reported presence of a peculiar and strange looking variety of stones on a location called Pind (33°09'47"N; 73°34'09"E), approximately half a kilometer northeast of

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village Lehri (33°09'09"N; 73°33'35"E) in district Jhelum, Pakistan (Figs. 1 & 2). Being part of Potohar plateau, the whole terrain is rugged, sub-mountainous, dry and arid in nature. This particular location (Pind) had been under cultivation since 30 to 40 years ago but presently, the land is not being worked on and abandoned agricultural fields with their raised boundaries fill the landscape.

The villagers also pointed out that this stone variety possesses magnetic properties. However, they were unable to provide any information regarding its origin or source. For analysis purposes, representative samples were collected from different sites on the location using magnetic prospecting. These sites lie within a narrow patch of land approximately 100m across and 250m long, extending from north to south on both sides of the road that leads from village Lehri to a nearby village Rawatra, further up in the northeast direction. All these samples are strongly magnetic and can be easily distinguished from the rest of the surrounding soil that consists of clay and rocks of ordinary appearance, commonly found in this part of Potohar plateau. The sample stones are irregular in shape with variable thickness (0.5 to 3 cm). They have rough and pitted surfaces containing depressions and shrinkage cracks. Most of them are black in color with metallic luster but a few are also covered with a dull bronze coloured layer indicative of rusting, attributable to weathering effects.

Fig. 1. An aerial view of the site identified by white dotted line. Image data: Elevation (1650 ft), Date (November 4, 2006), Eye Altitude (3148 ft), Source (Digital Globe/Google Earth).

Fig. 2. A specimen of the meteorite debris as found on the site.

3. Brief introduction to combined XRD-XRF analysis

X-ray fluorescence (XRF) spectrometry has become one of the most popular techniques for determining elemental composition of a variety of material types. An XRF spectrometer is used to determine the individual component wavelengths of the fluorescent emissions produced when any material sample is exposed to X-rays. Two variations of the technique in use are wavelength dispersive XRF (WD-XRF) and energy dispersive XRF (ED-XRF). WD-XRF uses an analyser crystal and offers optimal measurement conditions, very high sensitivity and low detection limits which make it more suitable for use in research as compared to its counterpart, ED-XRF, which does not use an analyser crystal and is considered a low cost alternative for routine applications. Though very handy for quantitative elemental analysis, XRF cannot be used to identify mineralogical (phase) composition of any given material sample. X-ray diffraction (XRD) is the technique of choice these days for determination of mineralogical make-up of a variety of materials, especially geological samples. The complimentary nature of XRD and XRF methods makes them invaluable for quantitative phase and elemental composition analyses (Loubser and Verryn, 2008).

Fig. 3. Meteorite debris specimen (scale: mm) tested using XRD and WD-XRF analyses.

4. Testing and analysis using combined XRD-XRF analysis

From its unusual appearance, surface characteristics, weight to size ratio and the debris/ released as a result of a natural or man-made phenomenon scattered over a limited area, the following three possible origins may be considered: volcanic, industrial and extraterrestrial.

To determine the elemental composition and mineralogy, combined XRD-XRF analysis was performed on a sample stone (dimensions: 4.1×2.9×1.4 cm), using the facilities at

Geoscience Advance Research Laboratories in Islamabad (Fig.3). Elemental composition (wt%) determined from XRF spectrometry is included in Table 1. XRD analysis detected wüstite ($Fe_{1-x}O$) and magnetite (Fe_3O_4) as predominant mineralogical phases in the outer crust of the tested sample stone.

Table 1. Elemental composition

Element	Abundance (wt%)
Si	3.93
Ti	0.508
Al	0.95
Fe	56.28
Mn	0.066
Mg	0.342
Ca	2.69
Na	0.114
K	0.146
P	0.228
V	0.07
Cr	0.324
Ni	0.00786
Sr	0.0093
Ba	0.367
W	0.024
Cl	0.046
Cu	0.0015

Presence of metallic phase in the interior structure of a polished face of the tested sample stone is illustrated using a section of a photomicrograph taken with reflected light at 100× magnification in Figure 4.

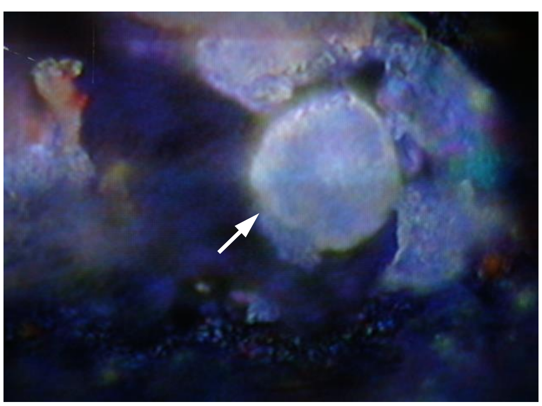

Fig. 4. Metallic phase (white) observed at 100× magnification on a polished surface of the tested sample stone. Note the almost-spherical shaped single grain of metal phase with relatively well-defined boundary in the center of the photomicrograph section.

Magmas usually contain oxygen fugacities that are extremely oxidising (Buddington and Lindsley, 1964). Hence theresence of wüstite is difficult to explain in terms of volcanic activity. Also, volcanic magnetite tends to contain TiO_2 in the range of nearly 4-30 wt% (being titano-magnetite in nature) whereas the relatively low abundance of TiO_2 (0.848 wt%) detected in the tested sample helps to rule out a volcanic origin (Buddington and Lindsley, 1964).

The possibility of the stone being industrial waste was also considered. However, according to local history, no industry associated setups (mines, storage dumps and factories) of any kind have existed on or near the said location. Furthermore, no archeological remains of any furnaces or blacksmith activity (on a commercial or industrial scale) exist in the vicinity of the location. Thus, it is logical to assume that these sample stones were not deposited or transferred as a result of industrial or human activity.

The mineralogical and elemental composition of the tested sample stone is more consistent with an extraterrestrial origin (Marvin, 1963; Blanchard, 1972; Blanchard and Davis, 1978). Increased relative abundance of Fe (Table 1), low abundance of cosmically abundant elements such as Mn, Cr and Ti (Table 1), presence of wüstite and low Ni content (Table 1) point towards an extraterrestrial origin by ablation of a low Ni parent meteoroid body (Blanchard, 1972; Blanchard and Davis, 1978).

5. Need for combustion analysis

Although X-ray fluorescence (XRF) spectrometry has become a fairly reliable method for elemental analysis in recent years, it can still miss on many lighter or trace elements like carbon and sulfur. As discussed in the next section, carbon abundance is significant for identifying the formation process and evolutionary stages that took place throughout the life span of a particular meteorite and its parent body. In this section, carbon content of the meteorite debris has been determined and this abundance has been compared with values reported in literature to identify the origin and nature of the meteorite.

The combustion analysis process for determining carbon content is completely automated and can be represented through the flow diagram appearing in Figure 5. A weighed material sample is enclosed in a capsule made of tin or aluminum and combusted in a furnace using pure oxygen. Combustion temperature may become as high as 1800°C, depending on the type of capsule used. The combustion products are treated with certain reagents to produce carbon dioxide and for clearing unwanted inclusions. Copper scrubbers are used to remove excess oxygen through reduction and a mixing arrangement ensures a homogeneous mixture with constant temperature and pressure. This mixture is passed through a series of thermal conductivity detectors that contain a CO_2 trap for measuring carbon. Similarly, sulfur can be measured (as sulfur dioxide) using different combustion and reduction reagents. The test results are stored on a computer for further statistical analysis using specialised software. Generally, this process has a range of detecting carbon from 100ppm to 100 wt% abundance value. This process succeeded in accurately determining total carbon content of chondrites.

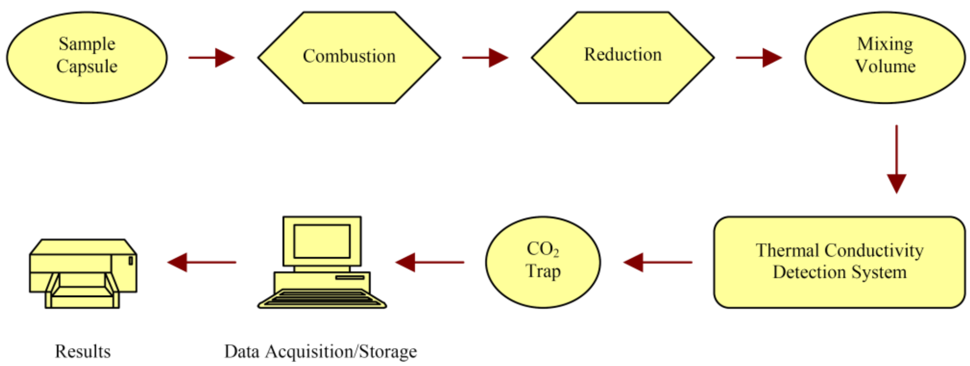

Fig. 5. A generalised description of automated combustion analysis process.

6. Analysis using carbon abundance

Carbon is one of the most important elements in nature. It can exist in many stable forms and the chemical structure of carbonaceous matter depends upon available environmental conditions. The abundance, composition and structure of carbon can be analysed to gather information about the initial formation process and following environmental changes to the carbonaceous matter (Murae et al., 1993).

In carbon rich chondrites, carbonaceous matter has been identified as graphite, amorphous, kerogen-like, diamond in some cases and mostly as a structurally unclear insoluble high molecular organic compound (Swart et al., 1983; Amari et al., 1990; Murae et al., 1993). In iron and stony-iron meteorites, carbon is found as graphite or less-ordered graphitic matter (Swart et al., 1983; Amari et al., 1990; Murae et al., 1993). It is interesting to note that regardless of morphology or structure of the carbonaceous material, the terrestrial and meteorite carbon tends to have the same isotopic composition (Libby, 1971).

In light of the above, it seems that carbon abundance can serve as a useful clue to identify the nature and origin of a particular meteorite. Furthermore, it can also be used to detect alterations in the structure of the original matter of the meteorite due to impacts or collisions, etc. In this regard, a very interesting study has been presented by Weller and Wegst (2009) where the initial carbon abundance in a chondrite detected using spectroscopic analysis was further explored through Fe-C Snoek peak analysis and it was determined that the chondrite's structure has been altered due to local heating effects in a collision.

For the meteorite debris under study, in XRD analysis, magnetite and wüstite have been detected as predominant iron phases. Presence of wüstite shows a reducing environment which may have existed either due to collision of the parent body with an other celestial object or due to high pressure and temperature caused by resistance offered from the atmosphere of earth. As the meteorite debris has been found lying over the site in form of small stones, it is likely that upon entry in the earth's atmosphere, the parent meteoroid succumbed to increasingly high pressure and temperature and, at a certain height, exploded into innumerable small pieces that came to rest on this particular site (Figure 6). This kind of behavior is typically observed with chondrites as they are more vulnerable to high pressure and temperature effects given their composition and structure.

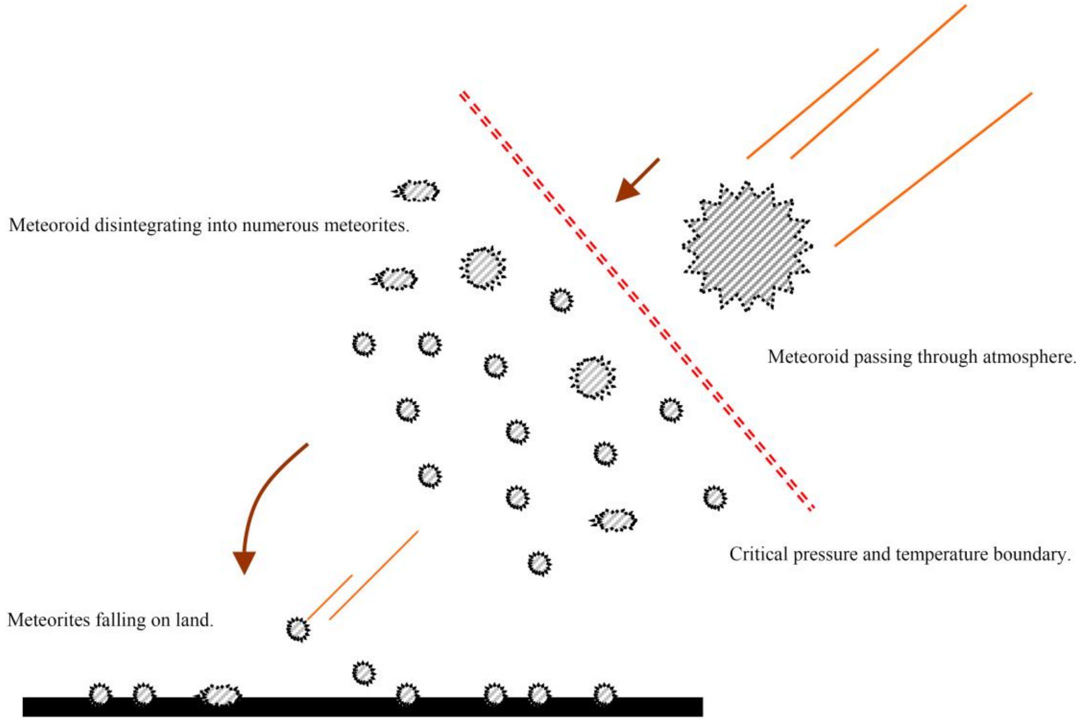

Fig. 6. A schematic representation of explosive disintegration of the parent meteoroid body into meteorite debris.

In order to determine the abundance of carbon and sulphur in the meteorite debris, a specimen was tested through combustion analysis using the facilities at Petroleum Geochemistry Laboratory of Hydrocarbon Development Institute of Pakistan in Islamabad. In combustion analysis of meteorites, carbon is released over three different heating ranges. Recent contaminants are detected below 500°C while weathering products (i.e. carbonates) decompose around 1000°C. The spallogenic components (from metals and silicates) are identified during melting. Heating up to 1000°C is used to determine the weathering age where as the melt is analysed to establish a terrestrial or residence age for the meteorite. The testing results are included in Table 2.

Table 2. Carbon and sulphur abundance

Element	Abundance (wt%)
C	**0.43**
S	**0.04**

The carbon abundance for this meteorite debris is in conformity with median carbon abundance value for enstatite chondrites (i.e. 0.4 wt%) as reported by Moore and Lewis (1965). This carbon value and the elemental composition determined through XRF analysis support the idea that the parent meteoroid body of this debris may have been an enstatite chondrite. Enstatite chondrites have a high iron content (up to 30 wt%) and contain a magnesium-silicon mineral enstatite ($Mg_2Si_2O_6$). The silicon and magnesium abundance values detected through XRF analysis are 3.93 wt% and 0.342 wt% respectively (Table 1). The increased relative abundance of iron (56.28 wt%) in the meteorite debris is attributed to ablation effects experienced by the parent meteoroid's body on its entry into earth's atmosphere and its subsequent explosive disintegration into small meteorites.

This meteoroid may be related to a primitive, undifferentiated parent body or an asteroid. Such asteroids represent the earliest rocky bodies that originated with in the solar system. Most of these asteroids float around the sun within the orbits of Mars and Jupiter, the so-called "asteroid belt".

7. Conclusion

This research project for the first time reports findings of a systematic study to determine the nature of the suspected stone variety. The testing and analysis of collected samples from the location (included in section 4) indicates that these sample stones can be positively identified as part of ablation debris of a parent meteoroid body (with low Ni content) that fell and crashed on or near this particular location, most possibly in prehistoric times.

On the basis of the analysis included in section 6, the meteorite debris is identified as enstatite chondrite in nature. The parent body of this meteorite debris may have originated from the asteroid belt. It may have been hurled (as a result of a collision with a neighbouring celestial object) into a trajectory that ultimately brought it into close proximity of earth and was finally pulled down by earth's gravity, causing it to crash on this particular site.

Due to technical limitations, attempts for radiocarbon analysis were not successful so a terrestrial age for the meteorite could not be established as of now. (Terrestrial age being the age or time elapsed since the meteorite landed on earth and started absorbing ^{14}C.) Further testing using thermo-luminescence (TL) analysis is proposed for this purpose.

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