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A Meteorite Ablation Debris

Testing and Analysis

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Abstract

In this research report, 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.

Further to this, carbon content of a specimen of the meteorite debris has 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.

1. Introduction to Meteorites

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 [1]. 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: 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 [2]. Chondrites account for 90% of all meteorite falls. Iron meteorites may contain up to 90-95 wt% iron with other 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 [2]. 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 traveling through earth’s atmosphere. Suspected chondrites that are recovered through area surveying need testing 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.

2. Background Information

For some time locals have reported presence of a peculiar and strange looking variety of stones on a location called Pind (33°09'47"N and 73°34'09"E) approximately half a kilometer northeast of village Lehri (33°09'09"N and 73°33'35"E) in district Jhelum, Pakistan. 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 (some 30-40 years ago) but presently the land is not worked on and abandoned agricultural fields with their raised boundaries fill the landscape.

Figure 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 (DigitalGlobe/Google Earth).

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.

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

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 100 m across and 250 m in length, 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 colored layer indicative of rusting attributable to weathering effects.

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 or WD-XRF and energy dispersive XRF or ED-XRF. WD-XRF uses an analyzer crystal and offers optimal measurement conditions, very high sensitivity and low detection limits which makes it more suitable for use in research as compared to its counterpart ED-XRF which does not use an analyzer 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 [3].

4. Testing and Analysis using Combined XRD-XRF Analysis

From its unusual appearance, surface characteristics, weight to size ratio and the debris/by product (of some natural or man made phenomenon) manner in which this suspected stone variety is scattered over a limited area, 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. Elemental composition (wt%) determined from XRF spectrometry is included in Table 1.

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

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[1]	0.0015

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. 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. Magmas usually contain oxygen fugacities that are extremely oxidizing. Presence of wüstite will become very difficult to explain in terms of volcanic activity [4]. Also volcanic magnetite tends to contain TiO_2 in the range of nearly 4-30 wt% (being titano-magnetite in nature) where as the relatively low abundance of TiO_2 (0.848 wt%) detected in the tested sample helps to rule out a volcanic origin [4].

The possibility of being industrial waste is also considered. According to local history, in past no industry associated setups (mines, storage dumps and factories) of any kind have existed on or near the said location. Also no archeological remains of any furnaces or blacksmith activity (on a commercial

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[1] Determined through chemical testing at National Physical and Standards Laboratory

or industrial scale) exist in the vicinity of the location. So it is logical to assume that these sample stones were not deposited or transferred here as a result of industrial or human activity. Thus an industrial origin remains unlikely.

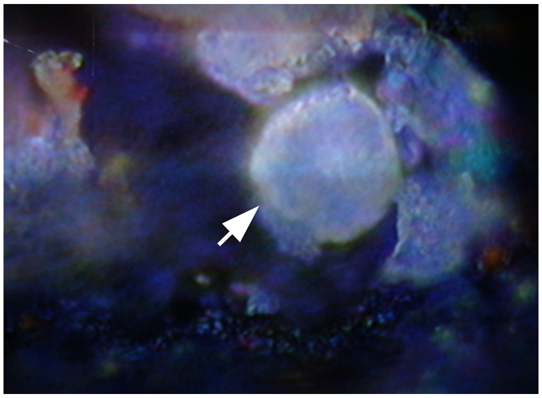

Figure 4. Metallic phase (white) observed at 100× magnification on a polished surface of the tested sample stone. Note almost round in shape single grain of metal phase with relatively well-defined boundary in the center of the photomicrograph section.

The mineralogical and elemental composition of the tested sample stone is more consistent with an extraterrestrial origin [5]-[7]. 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) points towards an extraterrestrial origin by ablation of a low Ni parent meteoroid body [5], [7].

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 sulphur. As discussed in 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.

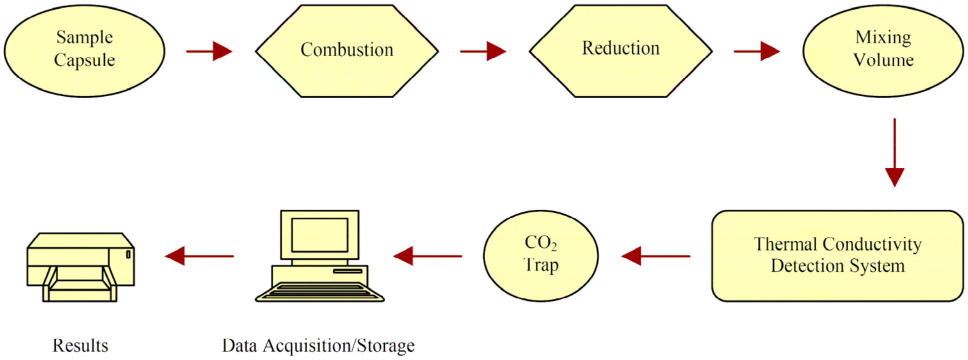

Figure 5. A generalized description of automated combustion analysis process.

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 sulphur can be measured (as sulphur dioxide) using different combustion and reduction reagents. The test results are stored on a computer for further statistical analysis using specialized software. Generally this process has a range of detecting carbon from 100 ppm to 100 wt% abundance value. Also this process has been found very successful for determining total carbon content of chondrites.

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 analyzed to gather information about the initial formation process and following environmental changes to the carbonaceous matter [8].

In carbon rich chondrites, carbonaceous matter has been identified as graphite, amorphous, kerogen-like, in some cases diamond, and mostly as a structurally unclear insoluble high molecular organic compound [8]-[10]. In iron and stony-iron meteorites, carbon is found as graphite or less ordered graphitic matter [8]-[10]. 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 [11].

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. Further more 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 in [12] 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 seems on entry into 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.

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 analyzed 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 in [13]. This carbon value and the elemental composition determined through XRF analysis supports 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 body on its entry into earth’s atmosphere and its subsequent explosive disintegration into small meteorites.

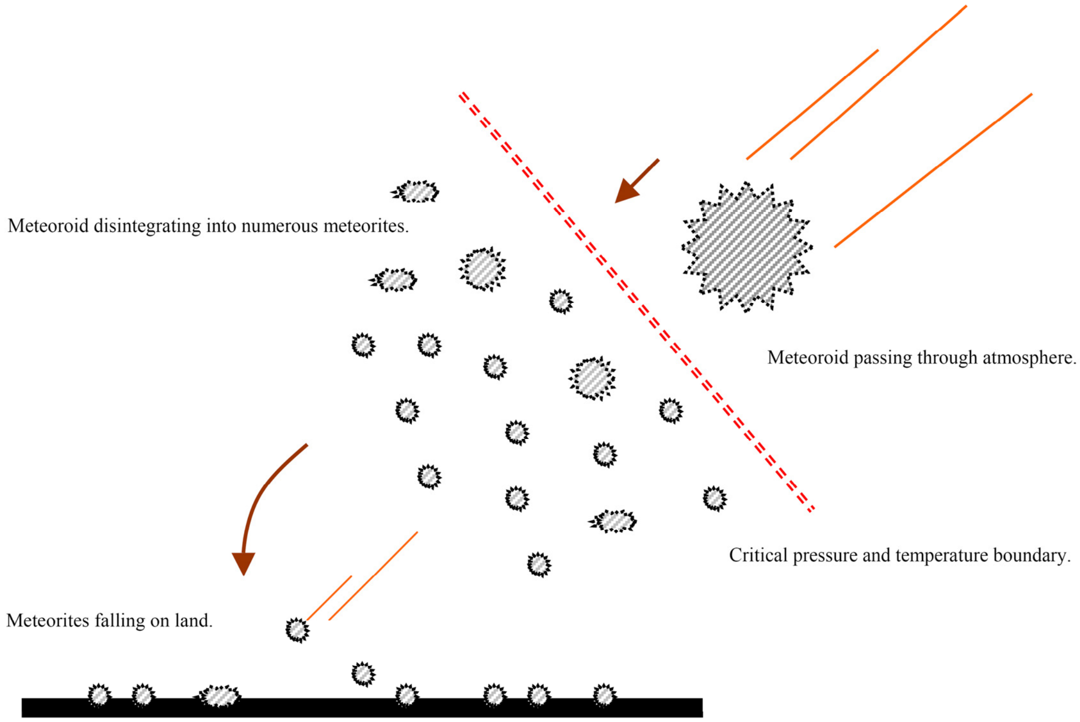

Figure 6. A schematic representation of explosive disintegration of the parent meteoroid body into meteorite debris.

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 with in the orbits of Mars and Jupiter (the so called asteroid belt).

7. Conclusion

The villagers have for many years known the existence of this unusual stone variety on the particular location. But they did not know what it was as in past no scientific analysis had been carried out. This research project for the first time reports findings of a systematic study to determine the nature of this suspected stone variety. The testing and analysis of collected samples from the location (included in section 4) points 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 (may be 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 neighboring 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.

Acknowledgments

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The initial hypothesis about the nature and origin of this meteorite ablation debris was developed while I was teaching a materials science and engineering course to mechatronics engineering students in spring of 2008.

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