Weathering and Strontium Contamination of Meteorites Recovered in the Sultanate of Oman

By Florian J. Zurfluh (above), Beda A. Hofmann, Edwin Gnos, Urs Eggenberger, Nicolas D. Greber and Igor M. Villa

Introduction

Meteorites are fascinating rocks from outer space. Their study in thin section lets us travel to foreign worlds. Actually, they provide a lot of essential information to understand the evolution of the early Solar System. However, because meteorites are formed under conditions very different from those prevailing on Earth today, they are chemically not stable and change during their residence in terrestrial environments. Meteorites can be collected after falls or searched systematically in regions where favorable conditions for accumulation and preservation occur. The three most important regions nowadays are Antarctica, the Saharan desert and Oman. The ways of meteorite accumulation, methods of recovery and collection, and the resulting availability for science is different for these three sources. A report of the Antarctic meteorite search by ANSMET was presented in an earlier issue of this magazine (Righter et al., 2011). In this article we would like to present our approach to search for meteorites and some observations of terrestrial alteration we have made on meteorites we have collected in Oman. Some of these signatures are similar to other recovery areas while others are unique.

The Omani-Swiss meteorite search and research project

Before 2000, only a few meteorites were known from Oman. This changed dramatically with the Meteoritic Bulletin 84 in 2000 (Grossman, 2000) where 39 meteorites from Oman were described. More than 30 years ago the Institute of Geology at the University of Bern established partnership with the Sultanate of Oman. Due to this long-term collaboration with Oman, two of us (BAH and EG) initiated the Omani-Swiss meteorite search and research project with the help of Tjerk Peters (1936-2009), former professor of mineralogy, University of Bern. Ali Al-Kathiri was the first Omani PhD-student at the University of Bern and the Natural History Museum of Bern. Since 2001 ten field campaigns were conducted which resulted in approximately 5500 meteorite finds belonging to ~690 meteorite falls (Hofmann et al., 2011).

A careful planning of the fieldwork is fundamental. Suitable surfaces for meteorite recovery are selected using satellite images available from Google Earth and other sources. Based on our experience from former campaigns, we have learned to interpret the satellite images to plan our routes along the most suitable surfaces. During the campaigns 2009 and 2010 we mainly followed routes from the coast towards the interior of the country. The idea behind this was to find meteorites at various distances from the sea to study its influence on the weathering. Search for meteorites is performed visually by car or by foot. For security reasons we search with at least two cars. To obtain quantitative information for the meteorite find density we systematically search by foot numerous quadrangles of one quarter of a square kilometer each. Such a foot search takes about ~2 hours when 4-6 persons are involved and it is conducted in the morning hours. We perform our field campaigns in winter (between January and March) in view of the fact that the temperatures are relatively pleasant (typical daytime temperatures 25-30°C).

When a meteorite is found the finders give signs to the other searchers and all members of the search group meet at the find location. Usually, searches are performed in sight distance but often one is very concentrated and the eyes are fixed to the ground with the consequence that one looses the beckons from the other team when they have found a meteorite. Our procedure of meteorite collection is standardized according to the following routine: record the coordinates by GPS (Fig. 1a), take photographs with a label containing the field number and a scale bar (Fig 1b), esti-

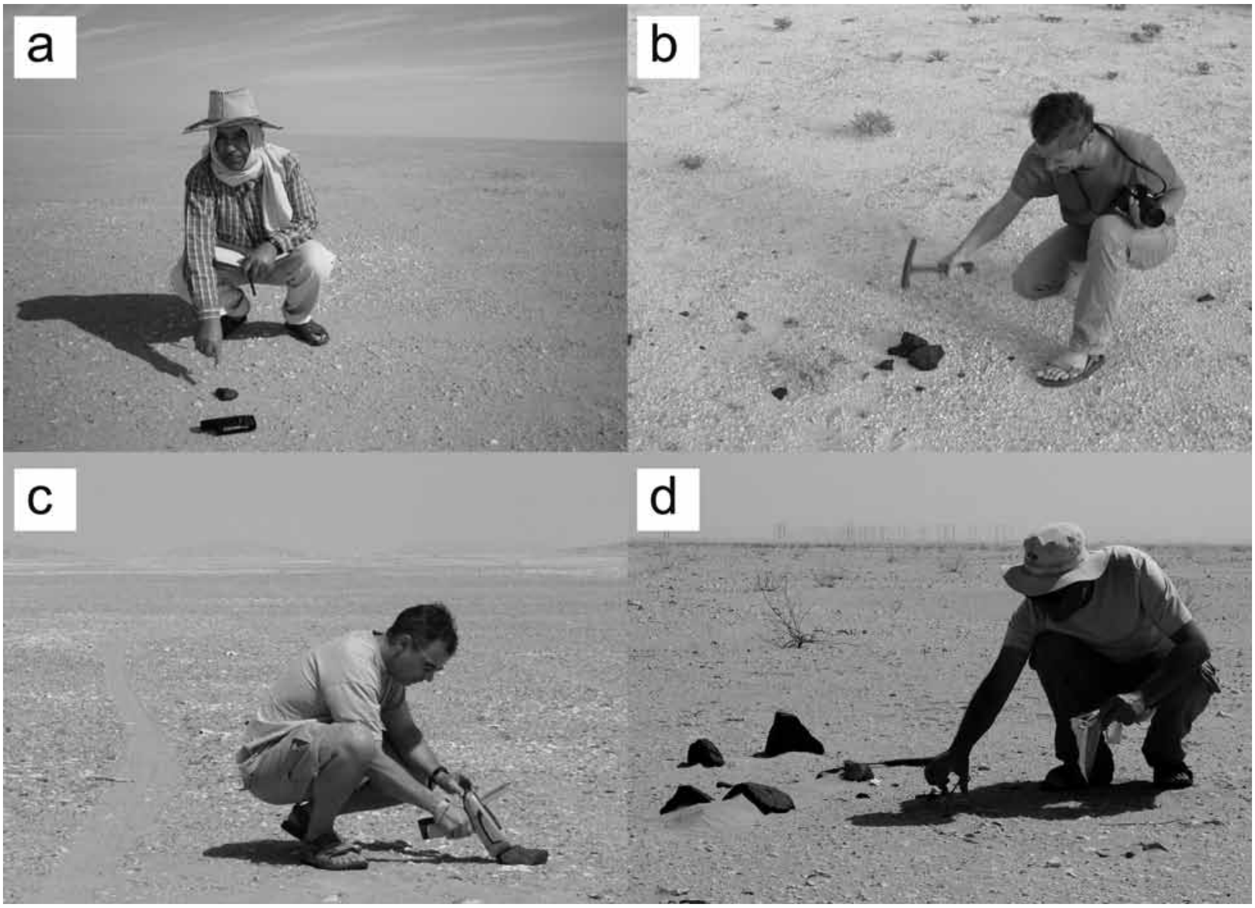

Figure 1. Work that has to be done during meteorite recovery: a) Mohammed Al-Batashi points to a newly found meteorite in the flat desert of Oman. The GPS (device visible in front of the meteorite) coordinates are recorded and noted into the field book (photo courtesy of Silvio R. Lorenzetti). b) Don't be afraid, this picture is a fake! This meteorite was already fragmented due to weathering. A look inside a rock for identification is best done using a hammer. However, meteorites are too valuable and therefore we use non-destructive methods for meteorite identification, as it is visible e.g. in Fig. 1c. Anyhow, Edwin Gnos will take a serious picture of the meteorite with a label for identification and a compass for orientation to document the find situation. c) Urs Eggenberger performs a HHXRF measurement on a dark rock in the desert. We were able to identify this rock as a meteorite and could even determine its class using elemental ratios and bulk concentrations. Based on the Sr and Ba content we can also estimate, how long the rock lay there. d) To avoid contamination samples are collected without touching and wrapped in polypropylene bags. Beda Hofmann collects here samples with tweezers for microbial studies. The meteorite visible here is 1002-153 (not named yet), a 28.79 kg L6 S5 W4.0 chondrite (paired with 1002-157, Fig. 3b) weathered into 917 fragments.

mate the degree of burial, perform analyses for identification (magnetic susceptibility or HHXRF measurement, Fig 1c), collect all fragments without touching (Fig. 1d), weight all, or at least the largest fragments, note the number of fragments and the total weight. In some cases we also measure distance and direction (with a compass) of the fragments with respect to the largest fragment. All data are recorded in field books and recently also on a tablet computer. Samples are then wrapped in polypropylene bags, labeled several times and stored in metal boxes for transport. For small to medium sized samples the large bags help to build up a kind of soft shield around the samples to avoid further fragmentation or damage during transport. For selected meteorites we additionally collect soil samples beneath and near the meteorite. The recording of the coordinates is essential for studies on find density and to answer questions of pairing, i.e. the identification of samples belonging to the same fall event. In hot deserts, meteorites usually are found on the place where they have fallen. This allows us to reconstruct meteorite strewn fields (Gnos et al., 2009).

When the meteorites have reached the Natural History Museum Bern, we unpack them without touching, clean them with pressurized air and count the number of fragments and take the accurate weight. Based on an agreement, the samples are on loan for study while remaining property of the Sultanate of Oman. After a macroscopic description of weathering features such as wind ablation and salt efflorescence, a sample is cut off using isopropanol as coolant, and thin sections for classification are prepared. The main masses are stored in a rock archive in the basement of the Natural History Museum Bern at constant temperature and relative humidity of 40% maximum. The degree of shock (Stöffler et al., 1991), weathering grade (Wlotzka, 1993, with modifications) and the petrologic type (Van Schmus and Wood, 1967) of the chondrites are determined for each individual find by the use of optical microscopy in reflected and transmitted light. Those investigations have to be performed by at least two persons for verification. Afterwards, the composition of the minerals is analyzed with the electron microprobe and X-ray diffraction to assign

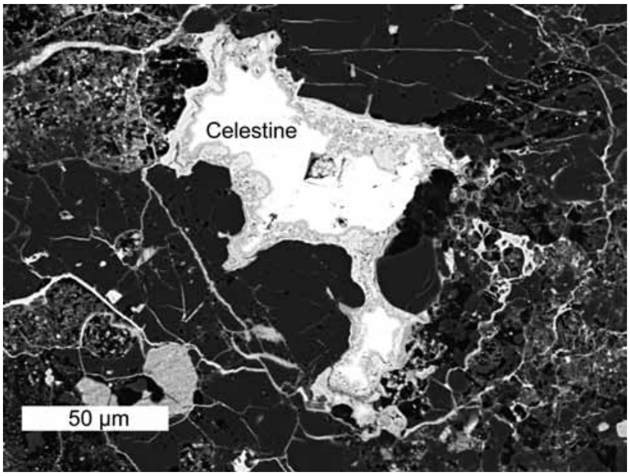

Figure 2. Backscatter electron (BSE) image of a large terrestrial celestine (SrSO4) crystal occupying a (former) pore space in a H5 S2 W4.5 chondrite. The dark minerals are the silicates olivine and pyroxene, the bright veins are iron hydroxides produced by weathering.

the group (Brearley and Jones, 1998). Most of the meteorites are ordinary chondrites belonging to the H or L groups. After classification, the pairing of meteorites is resolved by direct comparison of meteorites which have a similar classifications and close geographical provenance. The whole procedure of classification and check for pairing is very time consuming and non-trivial, but it is necessary for a proper statistic evaluation of the find population.

Weathering

When we find meteorites in Oman, they usually lack a black fusion crust, the typical characteristics of meteorites, and are strongly weathered, i.e. they have a rusty color and/or are sometimes broken up into several fragments. Which processes are responsible for the damage of meteorites? Air, water and salts from soil are the enemies of meteorites and are the main agents to decompose the primary constituents of the extraterrestrial rocks. Even though the climate in Oman is relatively hot and dry, the daily temperatures vary over several tens of degrees and water is present more one would

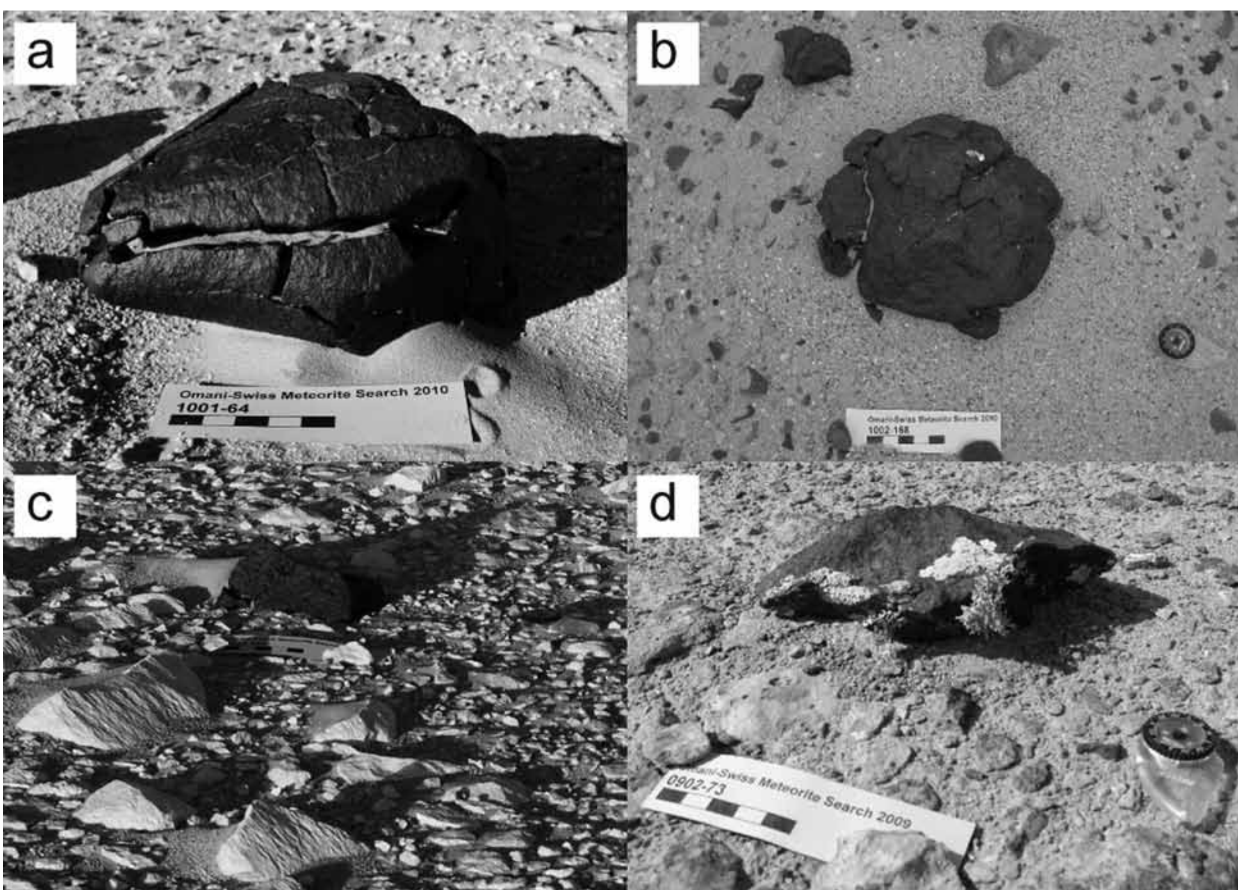

Figure 3. The change of meteorites during their stay in the hot desert: a) Due to the replacement of iron-nickel metal by Fe-oxides and Fe-hydroxides, which need more space, meteorites can swell and fragment. Salt weathering and input of sand into the cracks enhance fragmentation, as it is visible on the "crocodile" meteorite 1001-064 (name pending), a H6 S1 W3.0. Since H chondrites have high metal contents they have an increased tendency to fragment during weathering. b) Effects of weathering and contamination are visible on meteorite 1002-168 (name pending), a H5 S3 W3.6 chondrite. Sand, cemented by Fe-hydroxides sticks to the meteorite surface. The whitish spot on the meteorite is guano. c) Wind ablation can modify the surface of the meteorites. Meteorite 1002-157 (name pending), L6 S5 W3.3, was shaped into a ventifact over thousands of years similar to the surrounding stones. d) The main fragment of Al Huqf 070, L3.7-3.9 S3 W4.0, at the find site. This highly weathered chondrite is fragmented into several pieces, some of them completely covered by lichen.

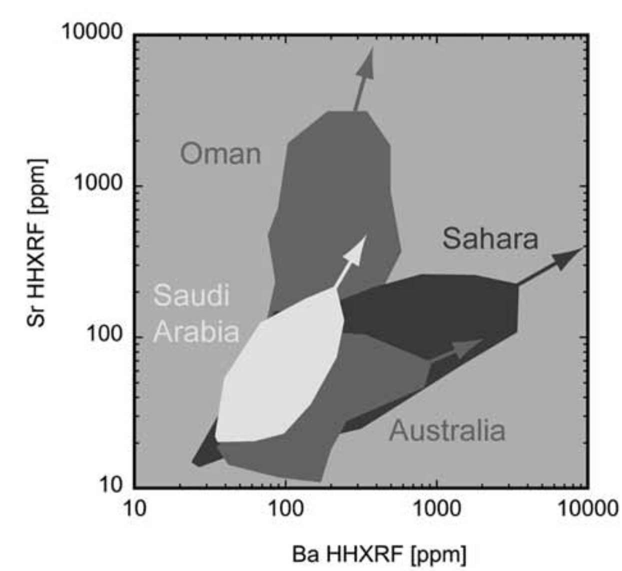

Figure 4. Logarithmic plot of Sr versus Ba obtained by HHXRF measurements of ordinary chondrites from various classical recovery areas. Note that meteorites from Sahara and Australia tend to preferentially accumulate Ba whereas Arabian meteorites (Oman and Saudi Arabia) are Sr-dominated.

expect. Winds from SE bring humidity from the Arabian Sea inland with the result of fog and dew on the rocks. Today, rain is rare but occurs normally at least once per year (inland desert <15 mm). In ordinary chondrites metallic (nickel-) iron grains usually are affected first, followed by the iron sulfide troilite. Both minerals are replaced by a mixture of iron oxides and iron hydroxides ("rust"), which causes the brown-reddish staining of the meteorites. These newly formed minerals need more space than the original minerals and form a network of veins (Fig. 2) and cracks can evolve. Frequent winds transport sand and salts into the cracks, which enhance weathering (Fig. 3a). These processes eventually cause fragmentation of meteorites at advanced stages of weathering (Fig. 3a and b). Another important enemy of meteorites is sandblasting. Sand grains transported by the wind impact on the surface of the rocks and chip small fragments. In extreme cases, ventifacts are formed (Fig. 3c). Close to the coast, humidity is highest and the rocks, including meteorites, are covered by lichen. Consequently, the recognition of these meteorites is very difficult (Fig. 3d). In addition, the soil surfaces in these areas are mostly made up of larger rocks and cherts commonly covered with black desert varnish, rendering meteorite recognition even more difficult. Biology is also involved in the decomposition of meteorites. Lichen, mosses, fungi and bacteria can inhabit meteorites and use their constituents as nutrients and source of energy. Also higher forms of live are a source of contamination of meteorites as we found bird excrements on several meteorites (Fig. 3b).

Strontium in hot desert meteorites

With this background in weathering of meteorites, we will now look at the strontium contamination in ordinary chondrites found in Oman. To quantify the amount of contamination we measured a large number of meteorites using a handheld X-ray fluorescence (HHXRF) device (Zurfluh et al., 2011). This instrument, resembling a taser we know from science fiction movies (Fig. 1c), allows us to perform a lot of nondestructive chemical analyses of our samples within short time. We observed strontium accumulations up to 200 times the value of an unweathered ordinary chondrite which lies between 9 and 11 ppm (Wasson and Kallemeyn, 1988). We measured up to 2200 ppm! Even in the core of meteorites the concentrations reached up to 888 ppm. It is clear that the Sr derived from outside. But from where? To solve this question we performed 87Sr/86Sr isotopic analyses of three meteorites found at different distances to the sea. In addition, corresponding soil samples were analyzed. The results showed the local soil as source of the strontium. The 87Sr/86Sr ratio of the three soil samples is different but always similar to the corresponding meteorite. For this reason we can exclude sea spray, which also contents Sr, to be an important source of contamination of meteorites in Oman. Moreover, the contamination with Sr increases terrestrial residence time in the meteorite. Strontium links to sulfur, to produce the strontium sulfate mineral celestine (Fig. 2), a mineral with a low solubility in water. This fact allows an accumulation of terrestrial Sr in the meteorite over time.

Beside meteorites from Oman, we have also measured meteorites from Saudi Arabia, Sahara and Australia. Interestingly, meteorites found on the Arabian Peninsula have the tendency to preferentially accumulate strontium whereas the Saharan and Australian meteorites have a stronger barium signal (Fig. 4). It is likely possible to estimate the terrestrial residence time of the meteorites based on Sr and Ba uptake and degree of weathering. But it has to be calibrated for each collection individually since the rate of uptake varies with geographical provenance.

Although a high percentage of the meteorites from Oman are badly weathered, all of them are worth to be studied, as these features contain important and interesting information. Beside the fascinating stories they can tell from their journey through time and space, it is also worth and necessary to listen to their terrestrial anecdotes.

Acknowledgments

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