Carbon phases in stony meteorites I

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The investigation of the origin and formation of elemental carbon or carbon bearing mineral phases in extraterrestrial materials such as meteorites is of great importance for a deeper understanding of our solar system. Carbon phases, for example graphite or diamond, are abundant in space, they are known from planets, asteroids, comets or interplanetary dust particles (IDP). Apart from the formation and evolution of planets or smaller solar system bodies, extraterrestrial carbon phases offer important insights into processes in stars, in interstellar regions, and last but not least into the origin of life [1-3].
The existence and properties of various carbon phases and compounds in meteorites and other extraterrestrial materials has been investigated for many years. The main focus was on ureilites and certain carbonaceous chondrites [1], and priority was set on graphitic components and diamonds. The first more systematic study on “opaque phases in stony meteorites” which included graphite (C) and cohenite (Fe_3C) was published by Ramdohr in 1973 [4]. He found that graphite occurs in the matrices of about 10% of the investigated stony meteorites, in most cases in the highly reduced ones such as carbonaceous or enstatite chondrites. He further stated that diamond is absent in stony meteorites except ureilites, the latter also contain cohenite often together with schreibersite $(Fe,Ni)_3P$ [5 and refs.]. Other studies focused on the carbon distribution in the matrices of ordinary chondrites or on the graphite occurence in selected unequilibrated chondrites [6]. More recent investigations reported on the investigation and likely formation processes of diamond polymorphs, again mainly focusing on carbon rich meteorites [7,8]. Recently, (nano-micro) diamonds have been detected in melt veins / pockets of highly shocked meteorites such as Chelyabinsk [9].
Summarizing, with the exception of the early study of [4] the carbon-phase mineralogy has not really been investigated systematically in most meteorite types, there are many open questions. The presence of “modern” carbonaceous phases such as graphenes, fullerenes or nanotubes which can be exspected in a number of meteorite types has not been investigated in detail to our best knowledge. Reports show the finding of various fullerenes in carbonaceous chondrites such as Allende, Murchison and Tasgish Lake, and whereby fullerenes were found to represent important traps or carriers of extraterrestrial noble gases [10]. Nanotubes have not been detected in meteorites so far (at least we could not find any reference).

Therefore we have started a more systematic investigation on the carbon-phase mineralogy of a larger set of various stony meteorite types. Our main focus is not on shock veins or pockets but priority is on the carbon phase occurrence and distribution in the matrices. For this study we have selected the following recent falls and finds [11-16]: (a) Ordinary chondrites (equilibrated) Machtenstein H5 (find around 1956, classified 2014), Braunschweig L6 (fall 2013), Stubenberg LL6 (fall 2016), and for comparison the HED meteorite Saricicek (howardite fall 2015) as well as a large series of Almahata Sitta individuals [polymict ureilite, 15,16 and refs]. In our contribution we will present first results concerning the carbon phase mineralogy in these meteorites and will also focus on hypotheses concerning the possible formation processes of the meteoritic micro-nano diamonds [7,8,17]: (a) Chemical Vapor Deposition (CVD) and (b) shock metamorphism as optional in situ diamond producing processes, and (c) presolar diamonds of extrasolar origin (eg from supernovae explosions).

A very sophisticated technique is required for the investigation of carbon phases (including the “modern” ones) in a systematic and routinely performable manner, with sufficiently high data production rate but at the same with high precision and resolution. Our LASER Micro Raman Spectroscopy system is perfectly suited for identifying and discriminating (extra-) terrestrial mineralogy, we have optimized our measurement routine accordingly: (a) fully non-destructive (repeated experiments possible on one and the same spot under variable conditions), (b) investigations with high sensitivity and in parallel high resolution, optionally in 3 dimensions, (c) as a major advantage experiments on pristine material without any preparation or coating, (d) mineral polytypes (eg diamonds) can be well discriminated and (e) very short measurement time in order to keep likely alteration effects as low as ever possible during the Raman mappings. Variable LASER frequencies allow optimizing and fine-tuning the Raman system to specific sample and experiment requirements. High resolution scanning can produce very detailed distribution maps of selected mineral phases. Micro- or even nano-sized particles such as various diamond polytypes can be detected in this way [7,8]. Numerous studies demonstrate that LASER Micro Raman Spectroscopy is best suited for the detection and analysis of the “modern carbon phases” such as graphene, fullerene or nanotubes [10].

Within our Hayabusa sample analyses project we have successfully applied LASER Micro Raman Spectroscopy on several individual Itokawa particles of less than 100 µm in size [18].

AS we decided to investigate only naturally broken surfaces by Raman Spectroscopy, we can definitely exclude any preparation effects, or effects from materials introduced to our samples due to preparation (such as cutting or polishing materials).

The following overview summarizes the results obtained on the meteorites which we investigated within this study.
Abbreviations: O-C: ordinary chondrites; ACM: amorphous carbonaceous material, disordered graphite; G: graphite; D: diamond; C: cohenite;

1. Almahata Sitta	AS 39 Ureilite (coarse grained)	Fall	ACM, G, D, C (with schreibersite), graphene?
2. Machtenstein	O-C H 5	Find	ACM, G, D
3. Braunschweig	O-C L 6	Fall	ACM, G, D
4. Stubenberg	O-C LL 6	Fall	ACM, G, D, graphene?
5. Sariçiçek	HED, Howardite	Fall	ACM, G

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