**Conference paper**

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# High pressure impacts on meteorites

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**Abstract:** In the invited article, we review observations on changes in meteorite texture relevant to the early stages of formation of the Solar System based on the experimental shock wave loading of the material at the laboratory. Investigation of the physical and structural properties of high-pressure impacts on meteorites is important for few reasons, such as: Protection of the Earth from the near-Earth objects (NEOs); Study of processes that cannot yet be achieved under laboratory conditions; Understanding of conditions for asteroid mining.

**Keywords:** formation; HTMC-XVI; meteorites; shock experiment; shock features; structure.

## Introduction

High shock pressures and high temperatures are an essential part of the matter evolution processes in the Solar System. Some pieces of evidence from different stages of meteoritic parent bodies formation could be observed in the chondritic material. Accretion of the presolar nebula followed by the high-temperature differentiation processes leads to the formation of the texture and structure of planetesimals and meteorite parent bodies. Numerous high-speed collisions and breaking up of small bodies in space yielded a wide variety of meteorite matter types. Trace of those high-pressure impacts can be observed in texture, mineralogy, and isotope composition of different types of meteorites. A meteoritic material keeps such evidence of collisions e.g. in iron and stony-iron meteorites: Neumann bands [1] or ε-phase [2], and traces of shear deformation [1]; in stony meteorites: brecciation, impact veins, silicates darkening [3, 4], ringwoodite and maskelynite formation, etc. [5]. High-speed collision with the atmosphere of the Earth leads to fragmentation, high-temperature ablation, decrease the mass of a meteorite body, and fusion crust formation. In some cases, plastic deformation features formed from the collision with the Earth surface can be found [6, 7].

A meteoritic bombardment of the Earth is essential and it still has value among the natural hazards. That is one of the important reasons to investigate meteoroids chemical composition and their physical properties. On the other hand, it is the unique opportunity to study the results of processes which could not yet be performed in the actual technological conditions.

Moreover, this information could be useful for asteroids destruction or asteroid-mining purposes. Consumption of the finite resources of Earth continues to increase, and this modern phenomenon places significant stress on the global economy, the ecosystem, and the future of societies on Earth. One proposal to address this scarcity is to exploit resources from near-Earth objects (NEOs), such as asteroids. It is believed that a substantial fraction of these NEOs contains platinum group metals, which are highly prized in the current market, and occur in greater relative abundance than on Earth. Iron, nickel, cobalt, methane, water, ammonia and other useful materials are present in many asteroids [8].

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High-pressure and high-temperature impacts on a meteoritic matter at the laboratory allow reproducing some of the stages of meteoritic material evolution. Modeling of fragmentation during fireball fall, brecciation, and heating under shock wave loading by high-speed collisions give information about material properties and probable consequences prediction (e.g. [9–14]).

## History of meteorites

Meteorites are valuable geologic specimens because they represent samples of the solar system bodies which are mostly of the inner solar system (Moons, Mars and asteroids). They are easier to obtain for the laboratory study than a teeny amount of matter delivered by the modern space missions. The oldest calcium–aluminum-rich inclusion at the carbonaceous chondrite specimen was estimated to form 4568.2 million years ago [15].

The Solar System formed from the cloud of interstellar dust and gas collapsed. Due to the interstellar cloud had been slowly spinning, the result was a nearly flat rotating disk of the solar nebula. The general part of the dust and gas in the disk moved to the center of the nebula to form protosun. Dust and gas remaining in the nebula were incorporated into primitive planetary material. Initially, nebular dust accreted to the small aggregates. In some regions of the solar nebula, these aggregates were melted by high-temperature events. Molten silicate and metal droplets cooled quickly in the nebula and formed chondrules. Following accretion of the chondrules at changing surrounding temperatures lead to the chondritic parent bodies, planetesimals formation.

The most primitive meteorite specimens are samples of complex, mixtures of nebular material. Often primitive meteorites contain traces of presolar grains [16]. While the small planetary bodies from which primitive meteorites come formed throughout a large portion of the inner solar system. Thus, meteoritic parent bodies produced in different regions of the solar nebula and affected by different thermal processing had slightly different chemical and structural properties. The three chemical groups of primitive chondrites representing these variations are the carbonaceous chondrites, enstatite chondrites, and unequilibrated ordinary chondrites.

When planetesimals continued to accrete into larger solar system bodies, the temperatures of these bodies began to increase significantly, in part from the energy deposited by impacts as they grew by accretion. Thick accumulation layer of material insulated the interiors of these bodies, preventing heat produced by naturally-occurring radioactivity from radiating into space. Also, planetesimals have been heated by interacting with a magnetic field from the Sun through the inner regions of the nebula.

Consequently, temperatures were able to rise high enough to metamorphose primitive chondritic material causing minerals to recrystallize and grow in size. Meteorite samples of these metamorphic rocks are equilibrated chondrites because the metamorphic process also homogenized the disparate chemical compositions of minerals in these bodies.

When the temperature in the planetesimals became high up to that primitive material was completely melted, the material produced from the igneous processes became nonchondritic. At the same time, due to increasing sizes of the planetesimals, substantial gravitational fields led to the displacement of the material: iron-rich metal separated from the silicate portions at the partially or wholly molten bodies to form dense iron-rich cores inside shells of silicate material. This process is similar to that responsible for the differentiation of the Earth. Pallasites are intimate mixtures of iron-rich metal and silicate crystals, and appear to represent regions where achondrite and iron meteorite magmas (core) were incompletely separated, such as the core-mantle boundaries of planetesimals. It should be noted that this is a simplistic explanation of the pallasites origin. Moreover, the origin of some iron meteorites is still controversial [17].

The meteorites of different types come from asteroids. They are mostly presented by fragments of parent planetesimals or mixtures of fragmented planetesimals, and much rarely – by fragments of differentiated planetary bodies. Thus, not only chondrites were found on the Earth but Lunar meteorites as well as Shergotty, Nakhla, and Chassigny, which are suspected to be ejected from the surface of Mars, were found in Antarctica.

Since different types of meteorites formed through a variety of processes on many different planetary bodies, they have substantially different physical and chemical properties [18]. At the same time, most meteoroids which approach the Earth could have experienced significant collisional processing since they formed at the Main Asteroid Belt. The main process of formation were impact disruption and excavation followed by consequent production of smaller bodies. The delivery of the material to the Earth-crossing orbit region was due to non-gravitational forces and planetary resonances [19].

In spite of complicated history, the meteoritic material remains traces of the processes experienced. Therefore, by studying meteorites, we can obtain details about the impact-induced shock metamorphism and other processes related to impacts.

## Shock features in meteorite material

Impact melt meteorites or impact melt breccias have formed from a material that was liquefied or partially liquefied from the extreme pressure and heat generated by a large meteorite or asteroid impact in space. Depending on the pressure it will affect these meteoroids in different ways. More lightly shocked meteorites may just display dark shock veins running through while the impact melts will display a melted and deformed matrix. High-pressure minerals in meteorites occur in and in the vicinity of shock-induced melt veins and melt pockets up to several mm in width and are thought to have formed by two possible mechanisms: the solid-state transformation of the host-rock minerals or heating up by the surrounding material.

Nature and origins of meteoritic breccias were precisely observed by Bischoff et al. [3]. Different types of breccia were specified, such as accretionary breccia, genomict breccia, regolith breccia, fragmental breccia, impact melt breccia, granulitic breccia, polymict/monomict/dimict breccias, as well as the components of the breccias. Brecciation mechanism was described and illustrated. All the meteorites with anomalous thermal histories probably formed as a result of major impacts into hot bodies <100 m.y. after the asteroids accreted. In each case, the impact debris reaccreted so that cooling rates at lower temperatures were much slower than those at 1000 °C. The regimes of collision-induced effects as a function of the approach velocity and the size of the colliding bodies were summarised. Minimum velocities for the onset of certain shock effects in meteorites (e.g. formation of impact melts and regolith breccias) were estimated from 1 to 5 km $s^{-1}$. Likewise, the authors showed that the following information can be derived from the breccia texture and structure: constraints on cratering events and catastrophic impacts on asteroids; relative abundance of different rock types among projectiles; speeds of the forming impacts; new rock types from both unsampled parent bodies and unsampled parts of known parent bodies, etc. [3].

From the study by Dodd and Jarosewich [20] of 33 of 52 type L4–L6 chondrites that they have examined in thin section contain closed bodies of crystal-laden glass or devitrified glass (melt pockets) that testify to in-situ melting. A close correlation between the distribution of melt pockets and shock intensity as inferred from the characteristics of olivine and plagioclase indicates that the pockets reflect shock melting. The appearance of pockets coincides with a sharp decrease of $^{40}Ar$ in L-group chondrites, suggesting that shock melting was responsible for the loss of argon and raising the possibility that this process redistributed other volatile elements as well. The use of three criteria for shock intensity – olivine and plagioclase characteristics, and the presence or absence of melt pockets – leads to a refined shock classification for equilibrated chondrites that is based entirely on petrographic observations.

Further studies of the shock features significantly improved shock classification of the meteoritic material [5]. Moreover, new results lead to a revision of the scale [21].

The current shock classification scheme of meteorites assigns shock levels of S1 (unshocked) to S6 (very strongly shocked) using shock effects in rock-forming minerals such as olivine and plagioclase. It should be mention that these shock P and T are estimated by comparing the observations from shock recovery experiments with the features seen within naturally shocked meteorites The S6 stage (55–90 GPa; 850–1750 °C) relies solely on localized effects in or near melt zones, the recrystallization of olivine and pervasive melting, or the presence of mafic high-pressure phases such as ringwoodite. However, high whole rock temperatures and the presence of high-pressure phases that are unstable at those temperatures and pressures of 0 GPa (e.g. ringwoodite) are two criteria that exclude each other. There is a difference between the P and T estimated from shock recovery experiments (S1–S6) and also the P and T estimated from high-pressure mineral assemblage within shock melt veins.

The high-pressure mineral assemblage within shock melt veins crystallizes under high temperature compared the bulk meteorite and also most probably during shock pressure release. An assemblage of high-pressure phase provides a minimum shock pressure during elevated pressure conditions to allow the formation of this phase, and a maximum temperature of the whole rock after decompression to allow the preservation of this phase. Rocks classified as S6 are characterized not by the presence but by the absence of those thermally unstable high-pressure phases. High-pressure phases in or attached to shock melt zones form mainly during shock pressure release. This is because shocked rocks (<60 GPa) experience a shock wave with a broad isobaric pressure plateau only during low velocity (<4.5 km/s) impacts, which rarely occur on small planetary bodies; e.g. the Moon and asteroids. The mineralogy of shock melt zones provides information on the shape and temporal duration of the shock wave but no information on the general maximum shock pressure in the whole rock [21]. The mineral assemblage within shock melt vein provide information about the P and T during crystallization of the phases and not always on the equilibrium peak P and T. Crystallization pressure and equilibrium shock pressure can be different depending upon the crystallization time and shock pulse duration [22].

Sharp and DeCerli [23] showed that interpretation of the observed microstructures of shocked meteorites can yield new insights on the impact history of meteorites. It is possible to present simple explanations of complicated phenomena, such as the quasichaotic nature of shock propagation in heterogeneous and/or porous materials. They also present examples illustrated how the principles of shock-wave and thermal physics may be used to interpret the history of naturally shocked materials and how the occurrences and formation mechanisms of high-pressure minerals in meteorites can be used to constrain shock pressures.

It was noted by Blackburn et al. [24], that even a working timeline for the history of ordinary chondrites includes chondrule formation as early as 0–2 Ma after our Solar System's earliest forming solids (CAIs), followed by rapid accretion into undifferentiated planetesimals that were heated internally by $^{26}$Al decay and cooled over a period of tens of millions of years. There remains conflict, however, between metallographic cooling rate (Ni-metal) and radioisotopic thermochronometric data over the sizes and lifetimes of the chondrite parent bodies, as well as the timing of impact-related disruptions. The importance of establishing the timing of parent body disruption is heightened by the use of meteorites as recorders of asteroid belt wide disruption events and their use to interpret Solar System dynamical models. It was an attempt to resolve these records by contributing the $^{207}$Pb–$^{206}$Pb data obtained on phosphates isolated from previously unstudied ordinary chondrites [24].

As far as the thermal evolution of a chondrite parent body caused sufficient processing of the surface material. Therefore, the simulation of the thermal evolution for a chondrite parent body such as either remains intact or is disrupted by impact prior to forming smaller unsorted "rubble piles" is possible with the data of the Pb-phosphate, Ni-metal and thermometry data.

The thermal model by Blackburn et al. [24] and previously published thermometry data limit accretion time to 2.05–2.25 Ma after CAIs. Measured Pb-phosphate data place minimum estimates on parent body diameters of ~260–280 km for both the L and H chondrite parent bodies. They also consistently show that petrologic Type 6 (highest thermal metamorphism) chondrites from both the H and L bodies have younger ages and, therefore, cooled more slowly than Type 5 (lesser metamorphism) chondrites. This is interpreted as evidence for Type 5 chondrite origination from shallower depths than Type 6 chondrites within initially concentrically zoned bodies. This contrasts metallographic cooling rate data that are inconsistent with such a simple onion shell scenario. One model that can reconcile these two data sets takes into account subtle differences in temperature to which each system responds. This working model requires that disruption occurs early enough such that the Ni-metal system can record the cooling rate associated with a rubble pile (<70 Ma), yet late enough that the Pb-phosphate system can record an onion shell structure (>30 Ma). For this 30–70 Ma timeline, re-accretion into smaller rubble piles will ensure that the originally deeply buried and hot Type 6 samples will always cool faster as a result of disruption, yielding nearly uniform ages that record the time of parent body disruption. This is consistent with the available Pb-phosphate data, where all but one Type 6 chondrite (H, n = 3; L, n = 4) yields a cooling age within a narrow 4505 ± 5 Ma timeframe. These data collectively imply that the H parent bodies were catastrophically disrupted at ~60 Ma [24], while the L chondrite parent asteroid breakup was at ~250 Ma [25]. In addition, combined Ni-metal and Pb-phosphate models confirm that a subset of Type 4 chondrites record early rapid cooling likely associated with erosional impacting of the H and L parent bodies on ~5 Ma timescales [24].

Chen and El Goresy [26] reported a detailed survey of maskelynite in the shocked L-chondrites Sixiangkou, Tenham, Peace River, Dar al Gani 355, the SNC meteorites Dar al Gani 476, Zagami, ALH84001 and Chassigny, and the eucrite Stannern. They presented unequivocal evidence that maskelynite in meteorites is not diaplectic plagioclase glass formed by solid-state transformation, but a dense quenched glass. The duration of the shock pulse in natural events can be several orders of magnitude longer than in shock experiments. Since kinetic effects are crucial factors in promoting phase transitions, vitrification and melting, experimentally induced solid-state vitrification of plagioclase produced in dynamic experiments is inadequate for calibration of peak shock pressures in maskelynite-bearing natural samples. Maskelynite, an important constituent of shocked meteorites, once thought to be diaplectic plagioclase glass formed by the shock-induced solid-state transformation. Mentioned systematic investigation of shocked L-chondrites and SNC meteorites indicates that maskelynite does not contain inherited fractures or cleavage, and shock-induced fractures. Chen and El Goresy [26] found no evidence for models calling for melting that initiated in PDFs and affected the whole crystals.

In the review article, Tomioka and Miyahara [27] aimed to summarize the findings on natural high-pressure minerals in shocked meteorites. They revealed that heavily shocked meteorites contain various types of high-pressure polymorphs of major minerals (olivine, pyroxene, feldspar, and quartz) and accessory minerals (chromite and Ca-phosphate). These high-pressure minerals are micron to submicron sized and occur within and in the vicinity of shock-induced melt veins and melt pockets in chondrites and lunar, howardite–eucrite–diogenite (HED), and Martian meteorites. Their occurrence suggests two types of formation mechanisms (1) solid-state high-pressure transformation of the host-rock minerals into monomineralic polycrystalline aggregates, and (2) crystallization of chondritic or monomineralic melts under high pressure. Based on experimentally determined phase relations, their formation pressures are limited to the pressure range up to ~25 GPa. Textural, crystallographic, and chemical characteristics of high-pressure minerals provide clues about the impact events of meteorite parent bodies, including their size and mutual collision velocities and about the mineralogy of deep planetary interiors.

The review by Tomioka and Miyahara [27] explains the different high-pressure phases of the main and accessory minerals in meteorites and their corresponding low-pressure mineral phases. High-pressure mineralogy in naturally shocked rocks studied by modern techniques was presented. The high-pressure polymorphs and transformation mechanisms of their formation were shown on the examples of meteorites of different types. Based on the advances in analytical techniques, including electron microscopies, X-ray diffractometories, and micro-Raman spectroscopy, many of the high-pressure minerals that previously were only known as synthetic minerals have been discovered in shocked meteorites [27].

Gillet et al. [28] presented a review of the static high-pressure and high-temperature experiments for different mineral system dominantly present in meteorites and the mineralogy of shocked meteorites. The high-pressure minerals in these rocks result either from solid-state reactions or from the crystallization of melts at high pressures. Comparisons of naturally shocked samples with samples processed in dynamic experiments must be made with extreme caution. The duration of the equilibrium shock pressure experienced by meteorites can vary over at least three orders of magnitude ($10^{-2}$ s to 10 s), and they lie within the lower range of the duration of static experiments conducted in diamond anvil cells or multianvil apparatus. The authors assumed that dynamic experiments up to 130 GPa have never produced any reconstructive solid-state phase transition or liquidus high-pressure minerals that offer a reliable calibration of the continuum of shock pressures and temperatures. The solid-state transformations observed in shocked meteorites are in many cases incomplete and provide only insights into the initial stages of high-pressure phase transitions, crystallization, and chemical interdiffusion. High-pressure minerals occur within shock melt veins formed during shock release phase and not during the equilibrium peak pressure. In contrast, the natural high-pressure species crystallized from silicate liquids at high pressures and temperatures provide more precise information on the pressures and temperatures reached during a shock event on the parental asteroid.

For example, recent discoveries of different high-pressure minerals were performed by Baziotis et al. [29]. The study was carried out on the L6 chondrite fall Château-Renard, based on co-located Raman spectroscopy, scanning electron microscopy (SEM) with energy-dispersive X-ray spectroscopy and electron backscatter diffraction, electron microprobe analysis, and transmission electron microscopy (TEM) with selected-area electron diffraction. They noted that a single polished section contained a network of melt veins from ~40 to ~200 μm wide, with no cross-cutting features requiring multiple vein generations. They found high-pressure minerals in veins greater than ~50 μm wide, including assemblages of (1) ringwoodite + wadsleyite; (2) ringwoodite + wadsleyite + majorite-pyropess; (3) ahrensite + wadsleyite; and (4) sodic pyroxene + ahrensite + wadsleyite + clinoenstatite. The absence of periclase +(retrogressed) bridgmanite or periclase + stishovite suggests an upper bound for the peak pressure of ~23–25 GPa, whereas the presence of ringwoodite and majorite suggest peak pressures in the range of 17–23 GPa. Furthermore, the co-occurrence of ringwoodite-ahrensite solutions with wadsleyite implies a modestly lower P range, 14–18 GPa (or less accounting for Fe-rich compositions), along with rate-controlled nucleation of the high-pressure polymorphs of olivine. On the other hand, using binary jadeite-diopside phase diagrams to estimate the pressure implied by the occurrence of omphacitic pyroxene suggests peak $P \leq 15.5$ GPa. The inconsistency of ≥1.5 GPa in these pressure estimates suggests that either spatial heterogeneity, temporal evolution, multiple impact events, or some combination of these are recorded by the various high-pressure mineral assemblages in the investigated section. In addition, the temperatures estimated for majorite growth (≥1800 °C) in the melt veins centers and wadsleyite formation (≤1500 °C) at the melt veins edges require a temperature gradient during high-pressure mineral growth. By the study, it was shown that it is possible to constrain on the impact record of this meteorite and the L-chondrites in general from the data. At the same time, different veins may be recording altogether different shock events [29].

From the other point of view, jadeite formation in shocked ordinary chondrites was interpreted by Miyahara et al. [30] in the following way. Albitic feldspar in shocked ordinary chondrites (Yamato 791384 L6 and Yamato 75100 H6) and albite recovered from static high-pressure and high-temperature synthetic experiments were investigated with a transmission electron microscope (TEM) subsequent to a conventional micro-Raman spectroscopy analysis to clarify albite dissociation reaction under high-pressure and high-temperature condition [30]. When jadeite forms from albite, $SiO_2$ phase as a residual phase of albite dissociation reaction should accompany jadeite from the stoichiometry. However, albitic feldspar in and adjacent to shock-melt veins of the shocked chondrites dissociates into jadeite + residual amorphous (or poorly-crystallized) material having varied chemical compositions between jadeite and $SiO_2$ phase. TEM observations of albitic feldspar in the shocked chondrites and albite recovered from the static high-pressure and high-temperature synthetic experiments show that jadeite crystallization is initiated by grain refinement of albite (or albitic feldspar). Nucleation occurs along grain-boundaries or at triple-junctions of the fine-grained albite crystal assemblage. Jadeite crystal starts to grow from the nucleus through grain-boundary diffusion. Considering the pressure condition recorded in the shock-melt veins of the shocked chondrites, stishovite is the most likely as a residual $SiO_2$ phase accompanying jadeite. High-pressure and high-temperature condition induced by a dynamic event is very short. Stishovite would hardly form through a dynamic event due to sluggish nucleation rate of stishovite compared with that of jadeite, thus leading to induce heterogeneous and incomplete albite dissociation reaction; albite dissociates into a jadeite + residual amorphous material.

Other high-pressure minerals formation processes were studied by Ozawa et al. [31]. They studied the high-pressure polymorphs of olivine, pyroxene, and plagioclase in or adjacent to shock melt veins in two L6 chondrites (Sahara 98222 and Yamato 74445). The aim of the study was to clarify the related transformation mechanisms and to estimate the pressure-temperature conditions of the shock events. Wadsleyite and jadeite were identified in Sahara 98222. Wadsleyite, ringwoodite, majorite, akimotoite, jadeite, and lingunite ($NaAlSi_3O_8$-hollandite) were identified in Yamato 74445. It was noted that wadsleyite nucleated along the grain boundaries and fractures of original olivine. The nucleation and growth of ringwoodite occurred along the grain boundaries of original olivine, and as intracrystalline ringwoodite lamellae within original olivine. The nucleation and growth of majorite took place along the grain boundaries or fractures in original enstatite. Jadeite-containing assemblages have complicated textures containing “particle-like,” “stringer-like,” and “polycrystalline-like” phases. Coexistence of lingunite and jadeite-containing assemblages shows a vein-like texture. These transformation mechanisms based on our textural observations and chemical composition analyses. The shock pressure and temperature conditions in the shock melt veins of these meteorites were also estimated based on the mineral assemblages in the shock melt veins and in comparison with static high-pressure experimental results [31].

Hu and Sharp [32] provided an investigation of the mechanisms, kinetics and identification criteria for post-shock annealing of high-pressure signatures. According to the study on Mbale L5/6 chondrite, the shock pulse must have been shorter than ~1 s to provide the high-temperature conditions for post-shock back-transformation of wadsleyite. Many highly shocked L chondrites, which have abundant high-pressure minerals, must have experienced relatively long shock durations combined with rapid cooling of shock-melt regions to preserve high-pressure phases. The most highly shocked samples, such as impact melt breccias, lack high-pressure phases because of post-shock back-transformations.

Rubin [33] in his study revealed that LL chondrite MIL 99301 has experienced successive episodes of thermal metamorphism, shock metamorphism and annealing. The first recognizable petrogenetic episode resulted in thermal metamorphism of the rock to petrologic type 6 (as indicated by homogeneous olivine compositions, significant textural recrystallization, and the presence of coarse grains of plagioclase, metallic Fe–Ni and troilite). The source of heat for this thermal episode is not identified. The rock also experienced shock metamorphism to shock stage S4 as indicated by extensive silicate darkening (caused by the dispersion within silicate grains of thin chromite melt veins and trails of metallic Fe–Ni and troilite blebs), polycrystalline troilite, myrmekitic plessite, a relatively high occurrence abundance (equal to $100 \times$ [(number of occurrences)/$mm^2$]) of metallic Cu (in 3.6), the presence of numerous chromite-plagioclase assemblages, and coarse grains of low-Ca clinopyroxene with polysynthetic twinning. The shock event responsible for these effects must have occurred after the epoch of thermal metamorphism to type-6 levels; otherwise, the polycrystallinity of the troilite would have disappeared and the low-Ca clinopyroxene would have transformed into orthopyroxene. Despite abundant evidence of strong shock, olivine and plagioclase in MIL 99301 exhibit sharp optical extinction, consistent with shock stage S1 and characteristic of an unshocked rock. This implies that an episode of post-shock annealing healed the damaged olivine and plagioclase crystal lattices and thereby changed undulose extinction into sharp extinction. The rock was probably annealed to metamorphic levels approximating petrologic type 4; more significant heating would have transformed the low-Ca clinopyroxene into orthopyroxene. It is not plausible that an episode of annealing occurring after the epoch of thermal metamorphism could have been caused by the decay of $^{26}Al$ because this isotope would have decayed away by that time. Impact heating is a more plausible source of post-metamorphic annealing of rocks in the vicinity of impact craters on low-density, high-porosity asteroids with rubble-pile structures [33].

The above study confirmed the assumption that secondary thermal processes can anneal traces of shock history of the chondritic material. The annealing effect was studied in detail by Xie and Sharp [34]. They studied the host-rock fragments entrained in a 580-μm-wide melt vein of the Tenham L6 chondrite using field-emission scanning electron microscopy (FESEM) and transmission electron microscopy (TEM) to better understand the solid-state transformation mechanisms and the shock conditions. The melt vein consists of a matrix of silicate plus metal-sulfide that crystallized from immiscible melts, and sub-rounded host-rock fragments that have been entrained in the melt and transformed to polycrystalline high-pressure silicates by solid-state transformation mechanisms. These high-pressure phases include ringwoodite, low-Ca majorite, clinoenstatite, hollandite-structured plagioclase, and Ca-rich majorite. The Ca-rich majorite occurs as a symplectic intergrowth with a Ca-poor amorphous silicate phase in a 200 μm-diameter chondrule in the vein. This intergrowth seems to be the result of a disproportionate breakdown of a Ca-rich clinopyroxene precursor into Ca-rich majorite and $(FeMg)SiO_3$ perovskite, which subsequently vitrified upon pressure release. The TEM observations suggest that most solid-state transformations in the Tenham are reconstructive.

The transformation of olivine to polycrystalline ringwoodite appears to involve incoherent intracrystalline nucleation and interface-controlled growth. Lamellae in partially transformed olivine are not continuous coherent lamellae, but rather lamellae of polycrystalline ringwoodite, which is inconsistent with a coherent lamellar transformation mechanism. Growth rate calculations based on published kinetic data suggest that the time required to grow 1 μm ringwoodite crystal is ~100 ms at 1600 K, suggesting that the minimum shock pulse duration of approximately 100 ms.

Thereby, some shock effects could have been as produced by the (several) impacts in space, as subsequently annealed to the lower shock stages of the host silica minerals.

## Shock experiments

Shock experiments on the meteoritic material allow scientists to understand the shock phenomena in extraterrestrial materials and planets. Shock-induced texture changes are observed in different types of meteorites and it helps to better evaluate physical and petrological properties of meteorites (and potential meteoroids).

The different shock recovery experiments were performed to date [35–41]. More detail observation of the experiments on shock metamorphism with the updated shock classification system was presented in the review by Stoffler et al. [42].

Shock experiments on macroscopic spherical samples of the L4 ordinary chondrite Saratov (natural shock stages S2–S3) were carried out by Bezaeva et al. [9] using explosively generated spherical shock waves with the pressure gradient and maximum peak pressures of 400 GPa while shock-induced temperatures were >800 °C (up to several thousand °C). The evolution of shock metamorphism within a radius of the spherical samples was investigated using optical and scanning electron microscopy, microprobe and magnetic analyses as well as Mossbauer spectroscopy and X-ray diffraction techniques. Petrographic analyses revealed a shock-induced formation of three different concentric petrographic zones within the shocked samples: zone of total melting, a zone of partial melting, and zone of solid-state shock features. Progressive pressure-induced oxidation of Fe-Ni metal, whose degree increased with increasing shock peak pressure was found. The amount of FeO within melted zone increased the factor of 1.4 with respect to its amount in the unshocked Saratov sample. This suggests that within the completely melted zone about 70 wt% of the initial metallic iron was oxidized, whereas magnetic analyses showed that about 10 wt% of it remained intact. This strongly supports the hypothesis that, in addition to oxidation, a migration of metallic iron from the central heavily shocked zone I toward less shocked peripheral zone took place as well (likely through shock veins where metallic droplets were observed). Magnetic analyses also showed a shock-induced transformation of tetrataenite to taenite within all shocked subsamples, resulting in magnetic softening of these subsamples (decrease in remanent coercivity).

These results have important implications for extraterrestrial paleomagnetism suggesting that due to natural impact processes, the buried crustal rocks of heavily cratered solid solar system bodies can have stronger remanent magnetism than the corresponding surface rocks.

Similar shock experiment was performed for the Tsarev L5 ordinary chondrite by Muftakhetdinova et al. [10]. Textural changes were noted: initial material in the outer part of the sample was changed with the completely melted material in the central part. The fact of the breccia texture of the original Tsarev chondritic material makes it possible to compare experimentally created textural shock features with original material as experimentally melted parts of the Tsarev meteorite with melted material of the initial breccia material.

As for the shock experiment with Chelyabinsk LL5 meteorite [11], the four visually different zones obtained from the spherical shock experiment on the light-colored lithology of Chelyabinsk LL5 were studied by optical and electron microscopy: shock melt, dark-colored, brighter-dark-colored and light-colored material. All shock stages were revealed in the experimentally shocked sample: from the S4 of the initial material up to the completely melted material. Kohout et al. [12] noted that at ~50 GPa peak pressure shock darkening of silicates is observed due to troilite melt penetrating silicate grains associated with a reduction in the intensity of silicate 1 and 2 μm absorptions. This process stops at higher pressures as partial melting of silicates along grain boundaries isolates troilite melt. Darkening occurs again upon the complete melting of the material. At the onset of silicate melting, shock darkening effects in ordinary chondrites cease and reappear again only upon complete melting.

Such an unusual effect of the shock was of high interest for numerical modeling. Moreau et al. [43] determined the shock-darkening pressure range in ordinary chondrites using the iSALE shock physics code. They simulated planar shock waves on a mesoscale in a sample layer at different nominal pressures. Iron and troilite grains were resolved in a porous olivine matrix in the sample layer. The post-shock temperatures (and the fractions of the tracers experiencing temperatures above the melting point) for each material were estimated after the passage of the shock wave and after the reflections of the shock at grain boundaries in the heterogeneous materials. The results showed that shock-darkening, associated with troilite melt and the onset of olivine melt, happened between 40 and 50 GPa with 52 GPa being the pressure at which all tracers in the troilite material reach the melting point. It was demonstrated that the difficulties of shock heating in iron and also the importance of porosity in chondrites. It was shown, that distribution of post-shock temperature depends on the amount and distribution of metal particles in the chondritic material. While in [44] was shown that the collapse of pores can generate local hotspots, where the shock pressure is amplified by up to a factor of four. Although this is a very localized effect, adjacent iron grains may undergo strong heating.

Further, in [45], it was shown, that iron melting only occurred in models presenting either strong shock wave concentration effects or effects of heating by pore crushing. They also concluded that specific dispositions of iron and troilite grains in mixtures allow for melting of iron and explained why it is possible to find a wide textural variety of melted and unmelted metal and iron sulfide grains in shock-darkened ordinary chondrites.

On the other hand, from the static high-pressure experiments, other features of the meteoritic material were revealed by Chandra et al. [46]. They provided high-pressure investigations using 57Fe Mössbauer spectroscopic and synchrotron X-ray diffraction techniques with diamond anvil cell on a meteorite fall at Nathdwara (India) H6 chondrite. Mössbauer spectroscopic measurements were performed with compression up to 10 GPa under hydrostatic conditions while XRD measurements were carried out up to 16 GPa in both hydrostatic and non-hydrostatic environments. Mössbauer studies demonstrated phase transitions for troilite and pyroxene at low pressures of 4.5 GPa and 6 GPa, respectively. They aimed to investigate the behavior of olivine which showed an unusual transformation of high spin $Fe^{2+}$ configuration at room pressure to low spin $Fe^{2+}$ phase at ~6 GPa. High-pressure XRD measurements supported the above findings. Further XRD studies indicated a reversible incomplete transformation of olivine to wadsleyite at 14.46 GPa under the hydrostatic condition and complete transformation into ringwoodite at 16.7 GPa under non-hydrostatic compression.

Summarizing mentioned above, the features of the meteoritic material formed at high-pressure impacts in space, as well as structural features revealed after the high-pressure laboratory experiments are intensively studying. The interest in the subject is due to the formation of the high-pressure phases under the unique conditions that could not yet be fully reproduced at the laboratories. On the other hand, these studies and modern analytical techniques allow obtaining the data which help to provide inside into formation processes of the meteoritic material in space.

## Conclusion

Impacts during the early stage of the formation of parent bodies of different types of meteorites resulted in a variety of shock features (e.g. shock melting, melt veins, fracturing and plastic deformation, high-pressure and temperature phase transformation). High-pressure and high-temperature impacts on the meteoritic and analogous matter at the laboratory allow estimating transforming conditions at some of the stages of meteoritic material evolution. It is important to study physical properties and textural changings of the meteoritic material because it allows solving at least several tasks:

– to study the results of processes which could not yet be performed in the actual technological conditions;
– to decipher the physical processes affecting the surface of the potentially hazardous asteroid;
– to get prepared for the asteroid mining tasks in the near future.

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