SCIENTIFIC REPORTS

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# Jadeite in Chelyabinsk meteorite and the nature of an impact event on its parent body

Shin Ozawa[1], Masaaki Miyahara[1,2], Eiji Ohtani[1,3], Olga N. Koroleva[4], Yoshinori Ito[1], Konstantin D. Litasov[3,5] & Nikolay P. Pokhilenko[3]

[1]Department of Earth Science, Graduate School of Science, Tohoku University, Sendai 980-8578, Japan, [2]Department of Earth and Planetary Systems Science, Graduate School of Science, Hiroshima University, Higashi-Hiroshima 739-8526, Japan, [3]V. S. Sobolev Institute of Geology and Mineralogy, SB RAS, Novosibirsk, 630090, Russia, [4]Institute of Mineralogy, UB RAS, Miass, 456317, Russia, [5]Novosibirsk State University, Novosibirsk, 630090, Russia.

SUBJECT AREAS:
ASTEROIDS, COMETS AND KUIPER BELT
METEORITICS

Received
8 January 2014

Accepted
2 May 2014

Published
22 May 2014

Correspondence and requests for materials should be addressed to S.O. (shin.ozawa@m.tohoku.ac.jp)

**The Chelyabinsk asteroid impact is the second largest asteroid airburst in our recorded history. To prepare for a potential threat from asteroid impacts, it is important to understand the nature and formational history of Near-Earth Objects (NEOs) like Chelyabinsk asteroid. In orbital evolution of an asteroid, collision with other asteroids is a key process. Here, we show the existence of a high-pressure mineral jadeite in shock-melt veins of Chelyabinsk meteorite. Based on the mineral assemblage and calculated solidification time of the shock-melt veins, the equilibrium shock pressure and its duration were estimated to be at least 3–12 GPa and longer than 70 ms, respectively. This suggests that an impactor larger than 0.15–0.19 km in diameter collided with the Chelyabinsk parent body at a speed of at least 0.4–1.5 km/s. This impact might have separated the Chelyabinsk asteroid from its parent body and delivered it to the Earth.**

The Chelyabinsk asteroid airburst suddenly occurred on February 15, 2013. A 17–20 m asteroid entered the Earth's atmosphere and exploded about 30 km above the south of the Chelyabinsk city, Russia[1–3]. The shock waves generated by the explosions damaged many buildings and injured more than 1000 people in the area[1–3]. It reminded us that we are always subject to risks of asteroid impacts. Asteroids or comets with orbits approaching to the Earth are called as Near-Earth Objects (NEOs)[4]. They have been moved from their original orbits to the Earth-crossing orbits by gravitational forces, Yarkovsky effects, or collisions with other bodies[5]. Collisional history of the parent body of Chelyabinsk asteroid is important for clarifying evolution processes of NEOs.

Chelyabinsk meteorite is a unique sample: it is fragments of an NEO actually hit the Earth and its trajectory was well-recorded. Previous studies on Chelyabinsk meteorite reported that it is an LL5 ordinary chondrite with significant portions of shock-melt veins[1,3,6]. Shock-melt veins are formed by localized melting of materials during an impact due to concentration of stress, compaction of pores, or frictional heating. In shock-melt veins, both high-pressure and high-temperature conditions can be achieved simultaneously under shock, where constituent minerals can transform to their high-pressure polymorphs. Mineralogy of shock-melt veins in a meteorite reflects P–T–t (Pressure–Temperature–time) conditions during an impact[7–11]. In case of Chelyabinsk meteorite, detailed mineralogy of the shock-melt veins has not been clarified, and any high-pressure minerals have not been reported.

In this study, we carefully examined several fragments of Chelyabinsk meteorite containing shock-melt veins in order to clarify the magnitude of the impact event occurred on its parent asteroid. We found a clear evidence for an intense impact event: the existence of a high-pressure mineral jadeite in Chelyabinsk meteorite.

## Results

The polished sections of Chelyabinsk meteorite studied here consist of host-rock and pervasive shock-melt veins. The host-rock shows a typical equilibrated chondrite texture (Fig. 1a). Major constituents of the host-rock are olivine ($Fo_{71}Fa_{29}$), enstatite ($En_{74}Fs_{24}Wo_{2}$), diopside ($En_{46}Fs_{9}Wo_{45}$), albitic feldspar ($Ab_{84}An_{11}Or_{5}$), Fe-Ni metal and troilite (Supplementary Table S1). Accessory minerals are chromite, ilmenite and Cl-apatite. Outlines of chondrules can be barely recognized and matrix is well recrystallized. Chemical compositions of olivine and pyroxene are almost homogeneous and in the range of LL chondrites[12]. Feldspar has a grain size up to several tens

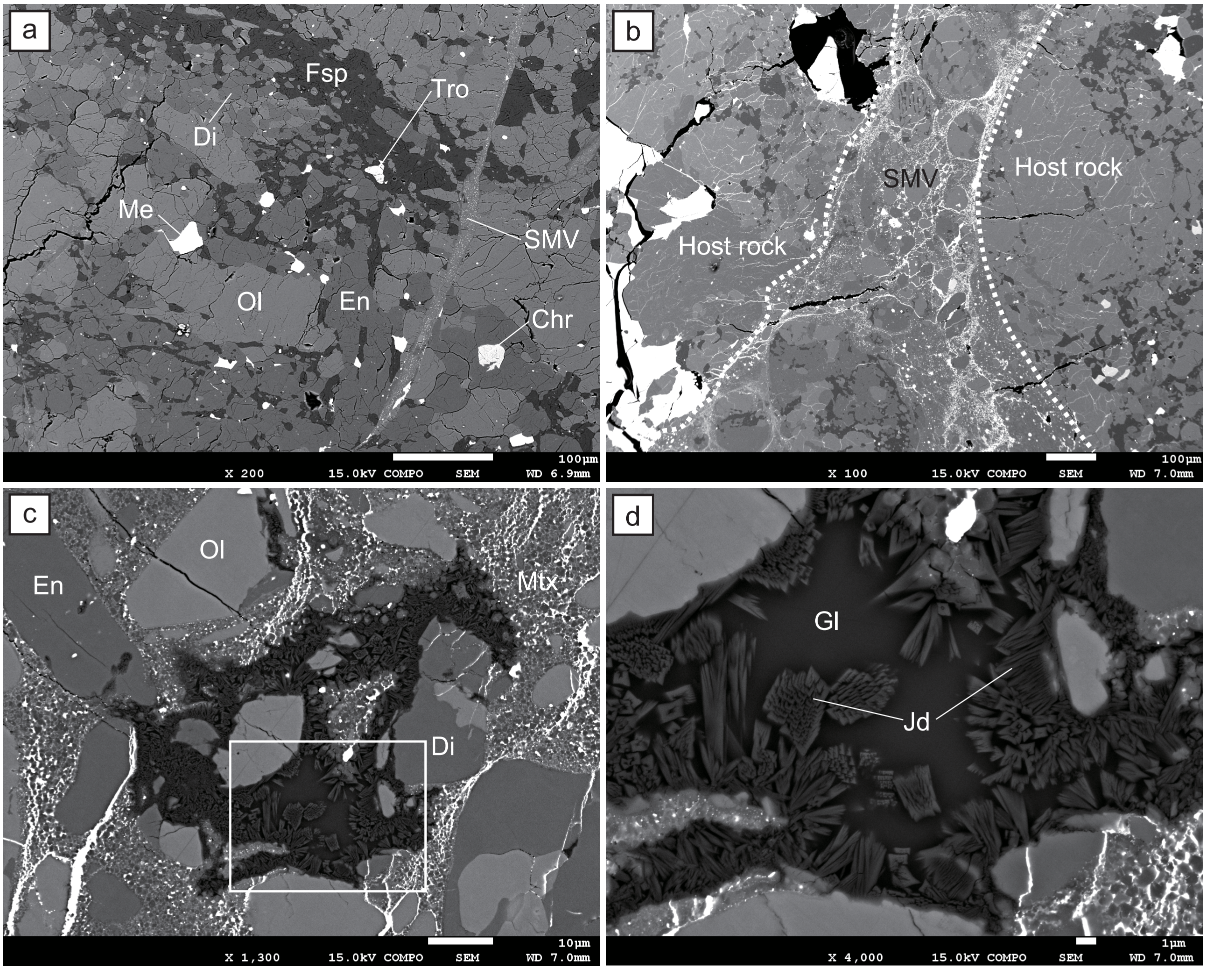

**Figure 1** | **Back-scattered electron images of Chelyabinsk meteorite samples.** (a) The host-rock showing an equilibrated chondrite texture. (b) A shock-melt vein cutting through the host-rock. The two white dotted lines represent the boundaries between them. (c) Coarse-grained fragments and fine-grained matrix in a shock-melt vein. (d) Enlarged view of the area shown by the white rectangular in (c). Needle-like and skeletal-rhombic crystals of jadeite occur with feldspathic glass. Ol = olivine, En = enstatite, Di = diopside, Fsp = albitic feldspar, Me = Fe–Ni metal, Tro = troilite, Chr = chromite, SMV = shock-melt vein, Mtx = matrix of shock-melt vein, Jd = jadeite, Gl = feldspathic glass.

of microns in diameter. Many shock-induced irregular fractures are observed in olivine, pyroxene, and feldspar. Planar fractures are also present in olivine and pyroxene. Feldspar is partly amorphous. These features suggest that this meteorite is an LL5 ordinary chondrite with the shock stage of S4 (moderately shocked) as reported by previous studies[1,3,6,12–14].

Pervasive shock-melt veins cut through the host-rock irregularly. Their width ranges from a few tens of microns to ~1 mm. The shock-melt veins consist of two lithologies: coarse-grained fragments entrained in the veins and fine-grained matrix (Figs. 1b and 1c). The coarse-grained fragments are mineralogically and chemically identical to the host-rock material. Some coarse-grained fragments have rounded shape indicating marginal melting.

Olivine and pyroxene in the coarse-grained fragments have fewer fractures compared to those in the host-rock, suggesting thermal healing of fractures. Some of them also show recrystallization textures probably formed by heating from the shock-melt vein matrix. To date, any high-pressure polymorphs of olivine or pyroxene have not been identified from the coarse-grained fragments.

Albitic feldspar in coarse-grained fragments has turned to be partially or totally amorphous. They are considered to be formed by either pressure-induced solid-state amorphization or quenching of thermally molten albitic feldspar. In some totally amorphized albitic feldspar, we identified needle-like, or skeletal-rhombic crystals of jadeite with a typical grain size of 1–3 µm. (Figs. 1c and 1d). Raman spectroscopic analyses of the crystals showed characteristic Raman peaks of jadeite at 379, 438, 528, ~583, 700, 989 and 1039 cm$^{-1}$ (Fig. 2; ref. 15). The needle-like jadeite appears to have nucleated along interfaces between the original albitic feldspar and other minerals or shock melt vein matrix. Whereas, the skeletal-rhombic jadeite is isolated from other minerals and surrounded by feldspathic glass. Bulk chemical composition of the jadeite-bearing grains is given in Supplementary Table S1. It is similar to that of albitic feldspar in the host-rock, but slightly enriched in K components (~0.9 wt% $K_2O$ in albitic feldspar in the host-rock, whereas ~1.6 wt% $K_2O$ in the jadeite-bearing grains). In addition, within each jadeite-bearing grain, jadeite-bearing parts ($Ab_{81}An_{12}Or_7$) is relatively enriched in Na and depleted in K components compared with coexisting jadeite-free feldspathic glass parts ($Ab_{72}An_{11}Or_{17}$) (Supplementary Table S1). The feldspathic glass parts have relatively non-stoichiometric composition compared with albitic feldspar in the host-rock.

Fine-grained matrix of the shock-melt veins consist of olivine, pyroxene, Fe-Ni metal and troilite with a typical grain size of 1–2 µm. Olivine and pyroxene are idiomorphic and some grains show compositional zoning. Fe-Ni metal and troilite occur as droplets, schlierens, or interstitial materials between the two silicates. These features indicate that the fine-grained matrix of the shock-melt veins crystallized from a melt of the bulk host-rock material.

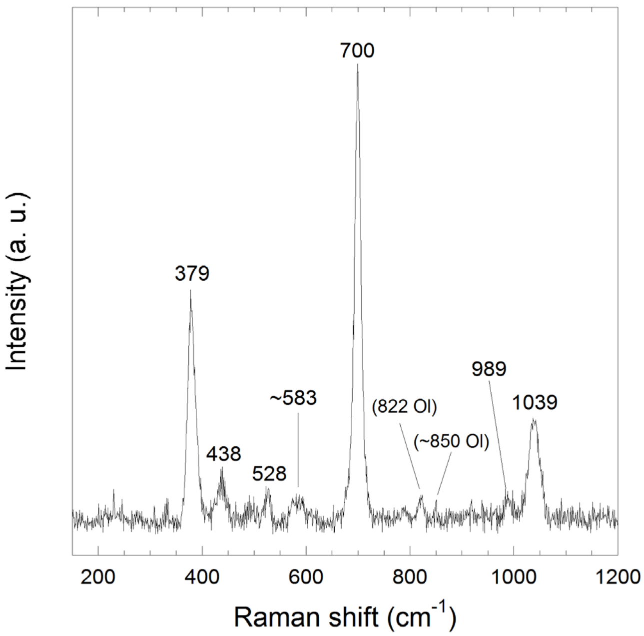

**Figure 2** | **Raman spectrum of jadeite.** Weak signals from neighboring olivine (Ol) are also present. a. u. = arbitrary unit.

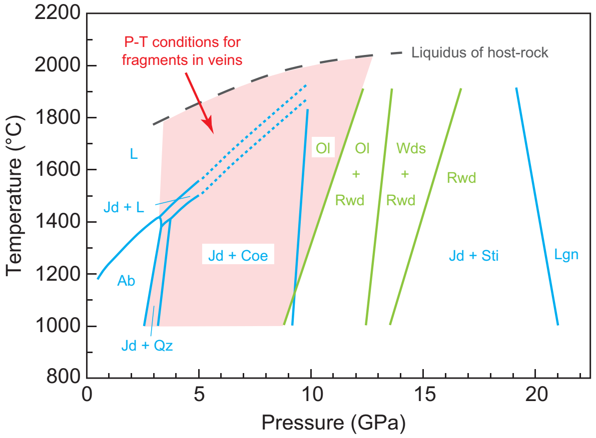

**Figure 3** | **Pressure-temperature phase diagram of albite and olivine.** The blue lines represent phase boundaries for albite[16–22], whereas the green lines represent those for olivine ($Fo_{71}$) (ref. 31). A possible liquidus curve of the host-rock (LL chondrite) is also shown by the gray dashed line[33,34]. The hatched area in red color indicates the estimated pressure-temperature conditions for coarse-grained fragments in the shock-melt veins during the impact. Ab = albite, Jd = jadeite, Coe = coesite, Sti = stishovite, Lgn = lingunite ($NaAlSi_3O_8$ with a hollandite structure), L = Albite liquid, Ol = olivine, Rwd = ringwoodite, Wds = wadsleyite.

## Discussion

High-pressure and high-temperature experiments on albitic feldspar have shown that albite dissociates into coesite + silica phases (quartz, coesite and stishovite) under high-pressure and -temperature conditions (Fig. 3 and Refs. 16–22). Impact-induced formation of jadeite from feldspar has been reported in shocked terrestrial rocks and meteorites[23–29]. Previously reported jadeite has granular or stringer-like morphologies, and no significant compositional difference exists between albitic feldspar in host-rock and jadeite-bearing grains in shock-melt veins[28,29]. Detailed transmission electron microscope (TEM) observations on natural and synthetic jadeite formed from feldspar indicated that the previously studied natural jadeite was formed from crystalline or amorphized albitic feldspar through a solid-state reaction[29]. On the other hand, jadeite in Chelyabinsk meteorite has needle-like or skeletal-rhombic morphologies, which suggest rapid crystallization of jadeite. The compositional difference between albitic feldspar in host-rock and the bulk jadeite-bearing grains in the shock-melt veins suggests that the original albitic feldspar entrained in the shock-melt veins experienced melting, in which elemental migration of K occurred (Supplementary Table S1). The compositional difference between jadeite-bearing parts and coexisting jadeite-free feldspathic glass parts also suggests long-distance atomic diffusion of Na and K during jadeite formation. Such elemental migrations seem to be difficult in solid-state reaction during the short duration of an impact. These features suggest that jadeite in Chelyabinsk meteorite was formed by rapid crystallization from molten albitic feldspar.

In the solid-state feldspar dissociation reaction or slow crystallization of albitic melt, some silica phases (quartz, coesite or stishovite) should coexist with jadeite. However, any silica phases were not identified with jadeite in Chelyabinsk meteorite. The same thing has also been reported for other impact-induced jadeite in terrestrial rocks and meteorites[23–29]. The crystallization kinetics of jadeite and silica phases from amorphized albitic feldspar was studied by Kubo *et al.*[30]. Their results suggest that nucleation of silica phases is considerably delayed compared with that of jadeite. The absence of silica phases in jadeite-bearing grains can be due to short duration of high-pressure and -temperature conditions during an impact event.

Figure 3 shows a pressure-temperature phase diagram of albite and olivine ($Fo_{71}$) (Refs. 16–22, 31). Albite dissociates into jadeite + quartz at about 3 GPa and the silica phase changes to coesite or stishovite with increasing pressure. Above 19 GPa, lingunite ($NaAlSi_3O_8$ with a hollandite structure) or an assemblage of $NaAlSiO_4$ with a calcium ferrite structure + stishovite can be formed. Thus, jadeite can be stable at 3–19 GPa as a liquidus or subsolidus phase. Olivine ($Fo_{71}Fa_{29}$) transforms to its high-pressure polymorphs (ringwoodite or wadsleyite) from 9–12 GPa[31]. Enstatite ($En_{75}Fs_{25}Wo_0$) transforms to majorite at 17 GPa and 1800°C[32]. In this study, we identified jadeite in the shock-melt veins of Chelyabinsk meteorite, whereas any high-pressure polymorphs of olivine or pyroxene have not been identified so far. It suggests that the equilibrium shock pressure of the jadeite-forming impact was at least 3–12 GPa.

The shock-melt vein matrix is considered to have crystallized from a melt with the bulk Chelyabinsk meteorite composition. Thus, temperature of the shock-melt vein matrix would have been higher than the liquidus temperature of bulk LL chondrite. The liquidus temperature of bulk LL chondrite can be estimated as intermediate between those of Allende carbonaceous chondrite and KLB1 peridotite[33,34]. When we assume the pressure condition to be 3–12 GPa, a liquidus temperature of LL chondrite can be estimated to be 1700–2000°C (Fig. 3). Therefore, pressure-temperature conditions of the shock-melt vein matrix are estimated to be 3–12 GPa and over 1700–2000°C. For coarse-grained fragments, which are not completely molten, the conditions would be 3–12 GPa and below 1700–2000°C (Fig. 3).

Shock-melt veins cools down and solidifies by conduction of heat to surrounding relatively cool host-rock. Cooling and solidification of a melt vein starts from the interface between host-rock and veins, and finishes at the center of the veins. If jadeite exists at the center of a shock-melt vein, it may indicate that the shock-melt vein completely solidified under pressure condition of 3–12 GPa. The maximum width of shock-melt veins which contain jadeite at the center is about 1 mm. When we assume temperature of the host-rock and shock-melt vein during the shock compression as 100°C and 2000°C respectively, the solidification time of the shock-melt vein is calculated to be ~70 ms based on the cooling speed analysis of shock-melt veins by Langenhorst and Poirier[7,35] (Details of the calculations are provided in Supplementary information). When the vein completely solidifies, the temperature within the vein is still high (>1100°C). If pressure release occurs at this time, jadeite might vitrify or back-transform to low-pressure phases due to the ambient pressure and high-temperature conditions. Thus, the shock pressure duration could be longer than 70 ms.

Using the Rankine-Hugoniot's relations, we can calculate the size and impact velocity of the impactor which caused the jadeite-forming impact[8,36,37]. The estimated shock pressure of 3–12 GPa and its duration of $>$70 ms correspond to a scenario that an impactor larger than 0.15–0.19 km collided with a parent body of Chelyabinsk meteorite with a relative speed of 0.4–1.5 km/s (Details of the calculations are provided in Supplementary information). The impact velocity seems to be consistent with those of impacts in the main asteroid belt[38]. Popova et al. suggested that the Chelyabinsk parent body experienced a significant thermal and/or collision event 4,452 ± 21 Ma ago based on the U–Pb radiometric dating of apatite[3]. On the other hand, Galimov *et al.* suggested that Chelyabinsk meteorite records an impact event at 290 Ma ago based on Sm–Nd isotopic systematics of whole rock samples[6]. The impact event which formed the pervasive shock-melt veins and jadeite was probably the last intense impact event recorded in Chelyabinsk meteorite. If there were subsequent thermal or more intense impact processes, jadeite could not have survived. Thus, the impact event studied here might have occurred at or after 290 Ma ago, and the Chelyabinsk asteroid probably separated from its parent body at this event. Dynamical lifetimes of asteroids placed on the orbital resonances of the main asteroid belt were estimated to be less than 10 Ma[39]. The Chelyabinsk asteroid blasted off from its parent body could have moved into an orbital resonance at $<$10 Ma ago, and then been delivered into an Earth-crossing orbit.

## Methods

We selected several fragments of Chelyabinsk meteorite containing shock-melt veins. They were embedded in epoxy and cut at the center. The cut surface was polished with diamond abrasive and isopropyl alcohol. The polished samples were carbon-coated and observed with scanning electron microscopes (Hitachi S-3400N and JEOL JSM-7001F). Accelerating voltage and probe current were 15 kV and 1.4 nA, respectively. Chemical compositions of the constituent phases were determined with an energy-dispersive X-ray spectrometer attached to the SEM, JEOL JSM-7001F. Phase identification of materials was conducted with a micro-Raman spectrometer (JASCO NRS-5100). Wavelength and power of the laser were 532 nm and 6.5 mW, respectively. The laser beam was focused to ~1 μm in diameter on the sample through an attached ×100 objective lens. Raman signals from the sample were collected for 60–240 seconds and accumulated twice for each spectrum. Raman shift was calibrated with the strong peak of silicon standard at 520 ± 0.5 $\mathrm{cm}^{-1}$.

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## Acknowledgments

We appreciate technical assistance from M. Abe in sample preparation and M. Nemoto in micro-Raman spectroscopic measurements. We would like to thank Dr. Zhidong Xie (Nanjing University) for his careful review and constructive comments for this paper. This study was supported by a grant-in-aid for Scientific Research (No. 22000002) by MEXT and by the Ministry of education and science of Russian Federation, project 14.B25.31.0032 to E.O.

## Author contributions

S.O., M.M., E.O., K.D.L., O.N.K. and N.P.P. designed this research. S.O., M.M., E.O., O.N.K. and Y.I. curated the meteorite samples. S.O., M.M. and E.O. observed and analyzed the samples. S.O., M.M. and E.O. wrote the manuscript.

## Additional information

**Supplementary information** accompanies this paper at http://www.nature.com/scientificreports

**Competing financial interests:** The authors declare no competing financial interests.

**How to cite this article:** Ozawa, S. *et al*. Jadeite in Chelyabinsk meteorite and the nature of an impact event on its parent body. *Sci. Rep.* **4**, 5033; DOI:10.1038/srep05033 (2014).