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NORTHWEST AFRICA 6486: RECORD OF LARGE IMPACT EVENTS AND FLUID ALTERATION ON THE L-CHONDRITE ASTEROID

C. A. Lorenz¹
E. V. Korochantseva¹,
M. A. Ivanova¹
J. Hopp²,
I. A. Franchi³,
M. Humayun⁴,
M. O. Anosova¹
S. N. Teplyakova¹
M. Trieloff²

¹Vernadsky Institute RAS, Kosygin St. 19, 119991, Moscow, Russia, c-lorenz@yandex.ru
²Institut für Geowissenschaften, Klaus-Tschira-Labor für Kosmochemie, Universität Heidelberg, Im Neuenheimer Feld 234-236, 69120 Heidelberg, Germany
³Planetary & Space Sciences, School of Physical Sciences, Open University, Milton Keynes, MK7 6AA, UK, ian.franchi@open.ac.uk
⁴National High Magnetic Field Laboratory and Department of Earth, Ocean & Atmospheric Science, Florida State University, Tallahassee, 1800 E. Paul Dirac Drive, FL 32310, USA; humayun@magnet.fsu.edu

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Abstract

We report results of petrological, geochemical, and geochronological investigations of the unusual K-rich L-chondrite melt rock Northwest Africa 6486 (NWA 6486). The rock has slightly fractionated siderophile elements and a mostly unfractionated L-chondrite pattern of lithophile elements with the exceptions of enrichments in K and Rb and chondritic Sr abundance similar to the K-rich inclusions found in the ordinary chondrites and indicating a fractionation of alkaline elements through the vapor. We suggest that NWA 6486 and related K-rich chondritic inclusions were formed in situ on the OC parent bodies and that K and Rb enrichment of these rock most probably is a result
of the selective impact evaporation of volatile alkali elements followed by the reaction of a vapor with shock melt. NWA 6486 recorded a breakup event of the L-chondrite parent asteroid at 470 Ma during which it was formed. We observe in NWA 6486 unusual veins, depleted in K, Na, Ca, and Al relative to the host rock. We suggest that NWA 6486 was affected by aqueous fluids that produced alteration zones depleted in a feldspar component on the walls of opened fractures. The melt veins could be formed during a subsequent impact event by \textit{in situ} melting of the fracture walls or due to decomposition of an injected supercritical aqueous-silicate fluid. The aqueous alteration and the second impact event had no detectable effect on Ar and oxygen isotopic systems. Cosmic-ray exposure ages indicate that NWA 6486 was ejected from its parent asteroid \textasciitilde3-4 Ma ago.

\section*{INTRODUCTION}

\textbf{L-chondrites represent one of the main groups of chondrites.} L-chondrite melt rocks make up only 0.1\% of L-chondrites (Meteoritical Bulletin 2021). Most probably, they represent fragments of impact melt dikes or sheets and generally are similar to the melts occurring in shock-melted chondrites (Fujiwara and Nakamura 1993; Mittlefehldt and Lindstrom 2001; Metzler et al. 2011; Hutson et al. 2013; Herd et al. 2013; Kuehner et al. 2017; Vaci et al. 2020) and in ordinary chondrites as igneous-textured, unfractionated inclusions (Ruzicka et al. 1998, 2000; Corrigan and Lunning 2013; Armstrong and Ruzicka 2015; Ruzicka et al. 2019). However, some L-chondrite melt rocks and igneous-textured inclusions also have features of chemical fractionation (Migdisova et al. 1992, 1994; Ruzicka et al. 2000; Goodrich and Kring 2016). L-chondrite melt rocks typically have fine- to medium-grained porphyritic or poikilitic textures, as well as chemical compositions of silicates and bulk oxygen isotopic compositions similar to those of L chondrites. Some L-chondrite melt rocks are shocked (Mittlefehldt and Lindstrom 2001; Vaci et al. 2020), indicating their formation during different shock events of the parent body history.

\textbf{L chondrites most frequently show disturbed radiometric clocks.} The $^{39}$Ar-$^{40}$Ar chronometer of L-chondritic meteorites indicates a single asteroid breakup event at 470 $\pm$ 6 Ma (e. g., Korochantseva et al. 2007; Weirich et al. 2012, Vaci et al. 2020). Radioisotopic dating techniques such as Rb-Sr and U-Pb are more refractory and commonly show older ages than the K-Ar system. However, they also record the time of a catastrophic event (Nakamura et al. 1990; Fujiwara and Nakamura 1992; Yin et al. 2014; Li and Hsu 2018; Wu and Hsu 2019). The agreement of ages,
determined by various radioisotopic dating methods with different resetting behavior of their chronological clocks during secondary events, indicates that the impact event dated at 470 Ma ago on the L-chondrite parent body was of very large scale. However, some L chondrites record old impact events (Ar-Ar ages >4.3 Ga; Bogard 2011), e.g., a very ancient age of 4.461 ± 0.008 Ga was determined by Ar-Ar dating for L-melt rock PAT 91501 (Benedix et al. 2008). Therefore, chondritic melt rocks should record important information about the impact and thermal history of the L-chondrite parent body and geochronology of the impact events.

NWA 6486 is a melt rock related to L chondrites (Meteoritical Bulletin 2021). It was found in an unknown part of the Northwest Africa region. It is a small pebble-like stone of 4.5 g weight, lacking fusion crust. The stone became an object of interest due to its high potassium content unusual for chondrites (Lorenz et al. 2018; Korochantseva et al. 2018a). The purpose of this paper is identification and dating of the processes on the L-chondrite asteroid based on petrological, geochemical, and ⁴⁰Ar/³⁹Ar dating investigations of NWA 6486, and its comparison with other shock-melted L-chondrite meteorites and achondritic inclusions from L chondrites.

SAMPLES AND METHODS

A thick polished section of NWA 6486 provided by the meteorite collection of the Russian Academy of Sciences was investigated by optical (Leica DRMX optical microscope) and scanning electron microscopy using the Smithsonian Institution FEI NOVA NanoSEM 600 field emission scanning electron microscope, which is equipped with a Thermo Electron energy dispersive X-ray spectrometer. High resolution backscattered electron (BSE) images were obtained for several studied areas. The SEM was operated at 15kV, with a beam current of 2–3 nA.

Chemical compositions of olivine, pyroxene, chromite, Fe,Ni metal and troilite were determined via wavelength-dispersive analysis with JEOL JXA-8900R, JEOL 8530F Hyperprobe (Smithsonian Institution), and Cameca SX-100 (Vernadsky Institute) electron microprobes operated at 15 kV accelerating voltage, 20 nA beam current, and peak counting times of 20 seconds for major elements and 40 seconds for minor elements. Altered areas, minerals of melt veins and pockets, mesostasis, and phosphates were analyzed by wavelength-dispersive analysis with the JEOL JXA-8900R and JEOL 8530+ Hyperprobe (Smithsonian Institution) using a broad beam (up to 5 µm) at 15 kV accelerating voltage, 15 nA beam current, and peak counting times of 20 seconds for major
elements and 40 seconds for minor elements. Natural and synthetic crystalline minerals were used both as calibration standards and as unknowns that were analyzed at the beginning and the end of each run to check analytical accuracy and instrument drift. Matrix corrections were applied using ZAF (for the JEOL JXA-8900R), Phi-Rho-Z (for JEOL JXA 8530+ Hyperprobe), and PAP (for the Cameca SX-100) software routines. Detection limits in silicates were ~0.02 wt. % each for SiO₂, TiO₂, Al₂O₃, Cr₂O₃, FeO, MnO, MgO, CaO, and Ni; and ~0.05 wt. % each for K₂O, and Na₂O.

Laser ablation ICP-MS analyses of the metal phases were performed with a New Wave UP193FX excimer laser system coupled to an Electro Scientific Industries Thermo Element XR™ at the Plasma Analytical Facility, Florida State University (Humayun et al. 2007; Humayun 2012). Spot analyses were performed with either a 25 µm beam spot ablated for 5 seconds or with a 50 µm beam spot ablated for 10 seconds, both at 20 Hz repetition rate, with 2 GW/cm² fluence. Standardization of the measurements is identical to that previously described involving NIST 1263a steel, North Chile (IIAB), and Hoba (IVB) (Campbell et al. 2002; Humayun 2012). The precision obtained on the spot measurements is better than 5% for most elements, except for P, S, and Cr (due to heterogeneous distribution) and Re (15-25%, due to lower count rates).

Trace element concentrations in the silicate phases were determined by LA-ICP-MS (Laser NewWave UP-213) combined with a high-resolution mass-spectrometer ThermoElement-XR (Vernadsky Institute) at 4 Hz repetition rate, 40 µm beam spot. The standard samples of synthetic glasses NIST-610 and NIST-612 and natural glass ML3B were used for measurement calibrations (MPH GeoRem Database, Jochum et al. 2009; Pearce et al. 1997). Precision of the standard measurements is ~10-20%. The data were compiled using the Glitter software (Van Achterbergh et al. 2001). The bulk microelement composition in NWA 6486 was calculated from the mineral compositions determined and their modal abundances. Mineral modal abundances were determined using digital microscopic images of the NWA 6486 polished section and image processing software for selecting and counting areas of similar colors for main phases and by visual microscopic measurement and count for minor and accessory phases. High–resolution ⁴⁰Ar–³⁹Ar analysis of the NWA 6486 whole rock sample (0.0354 g) followed standard procedures given by Jessberger et al. (1980) and Trieloff et al. (1994, 2003). After cleaning with ethanol, the sample was wrapped in high-purity (99.999%) Al foil and placed into an evacuated quartz ampoule bracketed by age monitor NL 25 hornblende (2.657±0.004 Ga; Schaeffer and Schaeffer 1977; Schwarz and Trieloff 2007). In addition, one CaF₂ monitor was added to the ampoule. The ampoule was irradiated for 96 hours at the
Portuguese Research Reactor (RPI) located at the Nuclear and Technologic Institute (ITN), Sacavém, Portugal, with Cd-shielding to suppress the thermal and epithermal neutron flux, in particular the $^{37}\text{Cl}(n,\gamma\beta)^{38}\text{Ar}$ reaction. Because of technical reasons the irradiation process was not continuous but split into several time intervals over two weeks. The respective J-value was $(4.83\pm0.04) \times 10^{-3}$.

Correction factor for interfering neutron reaction derived from the monitor analyses was $(^{38}\text{Ar}/^{39}\text{Ar})_K = (1.36 \pm 0.20) \times 10^{-2}$. $(^{40}\text{Ar}/^{39}\text{Ar})_K = (1.23 \pm 0.24) \times 10^{-2}$ was taken from Brereton (1970). Due to the significant time gap between irradiation and measurement, most of the $^{37}\text{Ar}$ had decayed and was below detection limit. For interference corrections we thus had to set $(^{36}\text{Ar}/^{37}\text{Ar})_{Ca}$, $(^{39}\text{Ar}/^{37}\text{Ar})_{Ca}$, and $(^{40}\text{Ar}/^{37}\text{Ar})_{Ca}$ factors to zero. Argon analyses were performed at the University of Heidelberg using an in-house modified VARIAN MAT CH5 mass spectrometer. The sample was stepwise heated to temperatures from 400 °C to 1700 °C (24 steps) using an induction-heated furnace with $^{40}\text{Ar}$ blank values of 36×$10^{-10}$ cc STP at 800°C and 72×$10^{-10}$ cc STP at 1500 °C (10 min heating duration). While low temperature blanks are usually dominated by the line blank, high temperature extractions significantly depend on furnace temperature. A series of blanks (20, 800, 1100, 1500, and 1700 °C) was measured before analyzing this sample to obtain a calibration curve and correct individual extractions at different temperatures. The additional blank subtraction in 760-800 °C extractions was applied to account for the Al-foil contribution (based on $^{38}\text{Ar}/^{36}\text{Ar}$ ratio and $^{38}\text{Ar}$ release pattern). This subtracted blank comprises about 30-40% $^{40}\text{Ar}$. Note that absolute temperatures may deviate by several tens of °C, however, temperature differences during stepwise heating are quite reliable. During and after heating the sample gas was in contact with two hot (400 °C) and one cold Zr-Al-getter. During each day, sample and blank measurements were bracketed by analyses of calibration gas with the composition of air. Although Lee et al. (2006) provided an update of atmospheric argon isotopic composition, we used the Steiger and Jäger (1977) convention ($^{40}\text{Ar}/^{36}\text{Ar} = 295.5\pm0.5$) for reasons of consistency (see also below) to correct for instrumental mass fractionation and to calculate absolute argon concentrations.

The ages were calculated using the decay constants given by Steiger and Jäger (1977). Since the revision of these decay constants is in progress (Renne et al. 2010, 2011; Schwarz et al. 2011), we used the old decay parameters until a general consensus for new convention values is achieved. $(^{40}\text{Ar}/^{36}\text{Ar})_{\text{trapped}}$ ratios and apparent ages presented in the text and in all figures were calculated using values for cosmogenic production ratios of $(^{36}\text{Ar}/^{38}\text{Ar})_{\cos}=0.65 \pm 0.2$ (Eugster et al. 1991) and $(^{40}\text{Ar}/^{38}\text{Ar})_{\cos}=0.2 \pm 0.1$ (Lämmerzahl and Zähringer 1966), and planetary argon with $^{36}\text{Ar}/^{38}\text{Ar}$ ratio
of $5.35 \pm 0.05$ which agrees within uncertainty with the value of $5.34 \pm 0.02$ given by Ott (2002). The significance of all reported uncertainties is $1\sigma$.

A separate split of the meteorite weighing ~ 50 mg was used to measure bulk oxygen isotopic composition at the Open University. The sample was crushed in an agate mortar and pestle. Oxygen isotopic compositions were determined in replicate on ~2 mg aliquots of the partly homogenized sample by laser fluorination. The samples were heated with a CO$_2$ laser (10.6 µm) in the presence of excess BrF$_5$, the gas purified over hot KBr and cryogenic traps and then analyzed on a Thermo MAT 253 mass spectrometer. Analytical precision was ~ $\pm 0.052\%$ and $\pm 0.093\%$ (2$\sigma$) for $\delta^{17}$O and $\delta^{18}$O respectively, providing a precision of ~ $\pm 0.017\%$ (2$\sigma$) for $\Delta^{17}$O (Greenwood et al. 2015).

RESULTS

Petrography and Mineral Chemistry

NWA 6486 is a medium-grained rock of porphyritic texture. The rock consists of subhedral and anhedral olivine (300-500 µm) and minor pyroxene grains (Fig. 1b) set in a groundmass of devitrified glass and fine-grained pyroxene (Fig. 1c). The modal mineral composition of NWA 6486 is (vol.%): olivine 57.3; glass 29.6; pyroxene 8.6; troilite 2.23; metal 1.32; Ca phosphates 0.03; chromite <<1%. Olivine demonstrates undulatory and mosaic extinction. The olivine grains are fractured; the fractures terminate at the grain margins (Fig. 1a). Olivine (Fo$_{77}$, Fe/Mn=44, Table 1) has no zoning. In some areas olivine margins are corroded by glass. Glass veinlets, several microns in width, crosscut the olivine grains. Some of the glass veinlets are associated with metal or troilite veins, terminating at the contacts of olivine with the groundmass (Fig. 1c). The finest reaction rims were occasionally observed at the contact of some large olivine grains and the matrix as a discontinuous corona of clinopyroxene with sub-micron chromite symplectites (Fig. 1d). Occasionally, anhedral grains of low-Ca pyroxene (En$_{73-74}$Wo$_{1-1.8}$, Fe/Mn=31-34) are associated with olivine (Table 1). The minor tabular- to skeletal crystals, 200-400 µm in size, are CaO-poor pyroxene (En$_{71}$Wo$_{2.4}$, Fe/Mn=27.8) with rims of pigeonite (En$_{46.4}$Wo$_{16.5}$) (Fig. 1b, Table 1).

Locally, large (up to 600 µm) olivine grains form dense clusters in the main mass of the meteorite. The clusters differ in texture from the main mass of the meteorite and comprise anhedral olivine grains with minor (~15 vol.%) interstitial groundmass with exceptionally fine (5-10 µm) pyroxene phenocrysts. The olivine grains contain minor tabular chromite inclusions and angular
metal and troilite grains 50-100 µm in size. The composition of the olivine is the same as that in the main mass of the meteorite.

The NWA 6486 olivine is poor in incompatible elements in comparison with CI chondrites composition (Table 4, Fig. 6b). The olivine REE pattern is characterized by typical prevalence of HREE over LREE. All elements have concentrations in the range 0.1-1xCI and unusual Eu and Dy depletions. Olivine has an extreme Ba enrichment (16xCI) and it is depleted in Sr (0.88xCI) (Fig. 6c).

Pyroxene of the groundmass is mostly elongated skeletal crystals of augite (En<sub>60</sub>Wo<sub>18</sub>) of 10-300 µm length and 5-15 µm width (Fig. 1c, d). Chromite usually occurs as fine (5-20 µm), irregular grains or needles and elongated skeletal crystals up to 50 µm in size, but rarely as large as 100 µm within the groundmass (Table 1). Rare, larger chromite grains typically associated with troilite occur as angular inclusions in the groundmass and within the large olivine grains. The chromite-troilite inclusions often are surrounded by low-Ca pyroxene. Calcium phosphates are represented as merrillite and Cl-apatite (Table 1). Grains of Cl-apatite (Cl ~5.5 wt.%) are rarely located in the groundmass of the rock. Anhedral grains of merrillite, 100 µm in size, mostly occur along the margins of metal-troilite aggregates and in several melt pockets. The merrillite contains up to 3.7 wt.% MgO and 2.9 wt.% Na<sub>2</sub>O.

The bulk chemical composition of the groundmass glass obtained by EPMA broad beam analyses (Table 2) shows that glass between pyroxene grains contains (wt.%) 3.6 CaO, 3.0 K<sub>2</sub>O, 4.2 Na<sub>2</sub>O, and 0.5 P<sub>2</sub>O<sub>5</sub>. Sub-micron opaque inclusions are quite irregularly distributed in the groundmass which comprises areas enriched and depleted in opaque minerals. Reflected light colors of the inclusions indicate possible occurrence of metallic Fe and sulfide. Bulk analyses of the groundmass in different areas obtained by defocused beam EPMA analysis, show S and Ni contents 0.43±0.30 wt % and below detection limit, respectively (Table 1) indicating that the inclusions are composed of Fe sulfide and probably Ni-free, Fe metal.

The groundmass of NWA 6486 is enriched in Al (3.4xL), Ca (4.1xL), Ti (3.4xL), and poor in Mg (0.5xL) and Fe (0.2xL) in comparison with the average L chondrite composition, and it is extremely enriched in K (22xL) in contrast to Na (2.5xL) (Table 1, Fig. 6b). The groundmass contains ~3.5xCI abundances of lithophile trace elements with a flat REE pattern (CI-norm. La/Lu=0.98) and negative Eu anomaly (Eu/Eu*=0.6) (Table 4, Fig. 6c). The groundmass is highly enriched in Rb (30xCI) correlated with K, and Ba (12xCI) in a contrast to Sr (2xCI). Merrillite in the
groundmass is Sr- and Y-rich. It is also enriched in REEs (Fig. 6c) with a CI-normalized ratio of La/Lu=2.63.

The irregularly-shaped metal-troilite assemblages in NWA 6486 are 0.5 - 3 mm in size. They occupy a small area of the meteorite section and seem to be co-oriented. The assemblages have a globular-like or irregular texture with elliptic or irregular metal grains, 350±100 µm in size, enclosed in the troilite matrix (Fig. 2a) and contain 48 vol% metal. Troilite in the groundmass is represented by large, irregular, polycrystalline grains.

Iron-nickel metal is mostly the low-Ni phase with local areas of fine-grained, patchy- or micro-plessitic texture of the low-Ni phase and taenite (Fig. 2b, c). High resolution back scattered images (Fig. 2d) and chemical profiles along Fe,Ni metal grains show that Fe,Ni metal is represented by three phases (wt.% of Ni) – low-Ni phase (7.01±0.23, Ni/Co = 7.7), medium-Ni phase (28.9±2.01) taenite and high-Ni taenite (44.8±1.97) (Table 3). The low-Ni phase is homogeneous in composition while taenite is zoned from 34.4 to 24.3 wt.% Ni toward the contacts with the low-Ni phase and troilite. The high-Ni taenite has no detectable zoning at the contacts with the medium-Ni taenite and the low-Ni phase at 1 µm-step profiles. All phases have P and Si contents below detection limit. The highest observed Ni concentrations (47.1 wt.%, Table 3) together with BSE SEM observations indicate that grain boundaries could be outlined by tetrataenite rims of sub-micron width. A single metal object 300 µm in size differs from the larger metal-troilite aggregates because it is surrounded by a pyroxene rim (En$_{78}$Wo$_{0.8}$ Fe/Mn = 33 at.), 30 µm in width, with angular inclusions of troilite (Fig. 2d). The object contains some troilite and Ca phosphate inside the rim at the contact with metal. The rim of the object has a well defined contact with the host material but has no contacts with a closely located glass vein. The large metal-troilite aggregates are surrounded by a halo of coarse-grained idiomorphic olivine grains with minor Ca phosphate and glass. Olivine crystals (Fo$_{76}$) in the halo are less fractured and significantly more idiomorphic in comparison to those in the rock groundmass but they have similar chemical compositions.

Terrestrial weathering products occur mainly as thin veinlets of FeNi hydroxide; rare microscopic veinlets of Ca carbonate were found in the olivine grains located near the meteorite surface.

**Melt Pockets and Glass Veins**
The NWA 6486 meteorite contains rare shock melt veins (5-15 µm width and up to 250 µm in length) and small pockets (up to ~50 µm in size) comprised of aluminosilicate melt matrix (SiO$_2$ 58.5 wt%; Al$_2$O$_3$ 6.24 wt%, Table 2) with metal-troilite globules (Fig. 3a). The matrix contains fragments of olivine (Fo$_{75.6}$; Fe/Mn = 46.5), pyroxene (En$_{74.5}$Wo$_{1.1}$; Fe/Mn = 36.1) and rare merrillite, apatite, chromite inclusions and troilite globules; metal is rare. No zoning was observed at the contact of the pockets with the host meteorite. These melt pockets will be designated as Type 1 melt pockets.

The section of NWA 6486 is crossed by centimeter-long silicate melt veins of 10-20 µm in width (Fig. 4a) connected with relatively large (100-1000 µm in size) melt pockets designated as Type 2 melt pockets (Fig. 4b). The Type 2 melt pockets (Fig. 4c, d) have complicated textures and widely varying chemical compositions. Each Type 2 melt pocket is typically composed of several olivine grains surrounded by microcrystalline material (matrix). Rarely, fragments of the meteorite groundmass occur in the Type 2 melt pockets. The large olivine grains in the Type 2 melt pockets are heterogeneous in composition. Cores of the olivine grains typically are composed of densely-packed, micron-sized crisscrossed olivine veinlets with a composition corresponding to Fo$_{89}$±2.7 (Table 2) and a submicron interstitial phase which appears lighter in BSE image. Some cores are comprised of massive olivine (Fo$_{89}$). The stoichiometry of the olivine is not ideal (Mg + Fe = 1.96 per 4 O afu.) probably due to phase polycrystallinity. The magnesian cores are rimmed by olivine Fo$_{66}$±3.51 (Fe/Mn=338±163, Table 2). Some of the olivine grains are extremely Mn-poor (Fe/Mn up to 650 at.). The smaller grains have only small veinlet-textured magnesian cores or comprise only the ferroan olivine. At the contact with the magnesian core, the rim is less ferrous (Fo$_{70}$, Fe/Mn = 263). The ferrous and magnesian olivines at the contacts form veinlet-like intergrowths (Fig. 4c, d).

The olivine grains are decorated by micron-sized olivine crystals distributed along the grain boundaries with the matrix of the melt pockets. The matrix (Mg# 67.7±4.13; Fe/Mn = 172±57, Table 2) has a heterogeneous, fine-grained to cryptocrystalline texture and contains inclusions of olivine (Fo 66.3±3.51; Fe/Mn = 338±163, Fig. 5a, b) of several microns in size (Fig. 5c). The matrix has notable concentrations of Cr$_2$O$_3$ (1.2±0.7 wt%, Fig. 5a) and minor Ni, Ca, Al, and S (Table 2). The matrix surrounding the large, rimmed olivine inclusions is microcrystalline (material A, Mg# 70-73, Fe/Mn= 75-90, Fig. 5c, d). At the section surface the matrix resembles an aggregate of elongated grains with some empty spaces between them (Fig. 5e). Toward the margins of the pockets, material A has sharp contacts with the microcrystalline matrix without voids (material B) (Mg# 73-75,
Fe/Mn= 90-120, Fig. 5c, d) which gradually changes to the essentially fine-grained (Fig. 5d) or cryptocrystalline material C (Mg# 63-70, Fe/Mn=64-178) containing inclusions of olivine. The matrix in the Type 2 melt pockets occasionally contains tiny inclusions of Ca phosphate and chromite.

Olivine of the host meteorite (Table 2) has discontinuous zoning of 15-25 µm width toward the contacts with the Type 2 melt pockets (Fig. 4c). The MgO content in olivine gradually increases from 38 to 49 wt.% (up to Fo$_{90.5}$) and the Fe/Mn ratio simultaneously decreases from 44 to 23 (at.). The inner part of the magnesian zone in the host olivine resembles a network of very thin veinlets of high-Mg olivine which are similar to that observed in the magnesian olivine inclusions within the melt pockets. Occasionally, the veinlets of ferrous olivine propagate from the Type 2 melt pockets into the host olivine grains through the magnesian rim of the host olivine grains (Fig. 4c).

The veins connecting the Type 2 melt pockets have a linear morphology and cross the host meteorite at angles ~90°, rarely 45° without shear. The modal abundance of the veins and Type 2 melt pockets in NWA 6486 is 0.8 vol.%. The veins have no gas vesicles, and they are free of mineral fragments and metal-sulfide globules. The veins are composed of cryptocrystalline material, similar to the matrix of the pockets of Type 2 by texture. The main components of the melt are SiO$_2$, FeO, and MgO (Table 2). The melt in the veins has a different Fe/Mn ratio at the contact with the NWA 6486 groundmass (72±8 at.) and olivine (105±17 at., Table 2). The micron-sized high-Mg rims occur in the host olivine grains at the contacts with the melt veins (Table 2).

Type 3 melt pockets (Fig. 3b-d) are found on the contacts of metal-troilite aggregates with the surrounding main mass of the meteorite and as isolated objects in the main mass comprising cryptocrystalline aggregates of olivine (Fo 48.4 - 63.1; Fe/Mn = 194-254) and minor interstitial melt with a high abundance of metal and sulfide globules. The olivine analyses have variable abundances of Cr$_2$O$_3$ 2.0-5.0 wt.%; Ni 3.2-8.5 wt.% and Al$_2$O$_3$ 0.9-1.1 wt.% due to the beam overlap with tiny, randomly distributed inclusions of chromite, Fe-Ni metal, and glass. The pockets contain inclusions of olivine Fo$_{58.4}$ (Fe/Mn = 244 at.), Fo$_{77.7}$ (Fe/Mn = 46.8 at.) and Fo$_{83.3}$. The olivine inclusions of the last two compositions have thin veinlet-like inclusions of more magnesian and more ferrous olivine, respectively (Fig. 3b). The inclusions of magnesian olivine have thin FeO-rich rims. The inclusions of aluminosilicate melt (SiO$_2$ 61.7 wt.%; Al$_2$O$_3$ 8.8 wt.%) are connected with the meteorite groundmass (Fig. 3b). The olivine grains of the host meteorite surrounding the melt pockets have irregular, discontinuous zoning at the contact with the melt. Veins of ferrous olivine-like material
beginning in the melt propagate through the host olivine crossing the magnesium zoning (Fig. 3b). Type 3 melt pockets associated with large metal-silicate aggregates typically contains inclusions of Ca phosphate (Fig. 3d).

**Bulk Chemical, Argon and Oxygen Isotopic Compositions of NWA 6486**

The trace element composition of olivine, groundmass, phosphates, FeNi-metal, melt pockets, and veins determined by LA-ICP-MS, bulk trace element composition of the NWA 6486 silicate portion calculated by recombination of modal mineral abundances and bulk macro-element composition of NWA 6486 acquired by XRF are presented in Table 4 and illustrated in Figures 6a-c. Detailed data comprising concentrations of Ar isotopes and apparent ages for each temperature extraction are given in Table 5. In NWA 6486, the major Ar release occurs below 1000 °C (Fig. 7a). The age spectrum with a standard correction for trapped primordial argon with \( ^{40}\text{Ar}/^{36}\text{Ar} = 1\pm1 \) is irregular (Fig. 7b). The three-isotope diagram \( ^{40}\text{Ar}/^{36}\text{Ar}_{\text{trapped}} \) vs. \( ^{39}\text{Ar}/^{36}\text{Ar}_{\text{trapped}} \) indicates the presence of excess Ar (Fig. 7c). The K concentration determined by Ar-Ar dating is 0.52 wt.% (error: 5%). The isochron for the temperature extractions at 560-1100 °C reveals trapped Ar with \( ^{40}\text{Ar}/^{36}\text{Ar}_{\text{trapped}} \) ratio of 522 ± 59 (Fig. 7c).

Oxygen isotopic composition of acid-washed samples (\( \delta^{17}\text{O} = 3.49 \pm 0.13\%_o, \delta^{18}\text{O} = 4.59 \pm 0.22\%_o, \Delta^{17}\text{O} = 1.103 \pm 0.020\%_o \)) is shown on Figure 7d.

**DISCUSSION**

**Petrology, Geochemistry and Genesis of NWA 6486**

NWA 6486 has a fine-grained porphyritic texture indicating crystallization from a melt. The compositions of olivine and pyroxene, its Fe/Mn atomic ratio (Ol 45.4-47.3; Px 28-34) (Table 1); Co content in kamacite (0.86±0.2 wt.%) (Table 3), and oxygen isotopic composition (Fig. 7d.) correspond to the range of L chondrites (Rubin 1990; Goodrich and Delaney 2000; Afiattalab and Wasson 1980; Brearley and Jones 1998; Greenwood et al. 2016 and references therein).

The NWA 6486 metal and troilite contents (3.26 and 3.31 wt.%) are less than those in L chondrites (8.39±0.95 and 6.12±1.33 wt.%, respectively; McSween et al. 1991; Dunn et al. 2010), indicating segregation of these phases from the source chondrite melt of the NWA 6486. Metal and
troilite depletion was observed as a specific feature of some melt rocks related to L chondrites (e.g. Fujiwara and Nakamura 1993; Harvey 1993; Benedix et al. 2008; Kuehner et al. 2017; Vaci et al. 2020) and as a feature of the larger melt rock inclusions in ordinary chondrites (Ruzicka et al. 1998, 2000; Armstrong and Ruzicka 2013, 2015; Ruzicka et al. 2019).

The composition of the metallic nodules from the metal-troilite aggregates of NWA 6486 is different from the L-chondrite metal (Kong and Ebihara 1997) by depletion of highly refractory siderophile elements (W, Re, Os, Ir, HRS), in moderately refractory Ni, Co, Pd, and the highly volatile siderophile elements Au, As, Sb, Cu, Ge, and Sn with exception for Mo and Ga (Fig. 6a). The NWA 6486 metal composition is depleted in Re, Os, and Ir similarly to the large metal nodules in the ordinary chondrites (Widom et al. 1986; Rubin 1995, 1999) but shows depletion in W, Ni, Co, and in volatile siderophiles and enrichment in Ga. Enrichment in Mo in the NWA 6486 nodules could be attributed to the abundance of troilite in the metal nodules. The solid metal/liquid silicate distribution coefficient (Dsmlis) of W at ordinary chondrite fO2 (~12 at 1300°C, -1 IW, McSween and Labotka 1993) is 19.4 (Schmitt et al. 1989). It is high enough that a large part of W should be distributed in a metal phase during melting of the NWA 6486 precursor similar to Ga (Dsmlis Ga=12.7, Schmitt et al. 1989) which has a high concentration in the NWA 6486 metal and could have been reduced from silicates. Thus, the notable W depletion in NWA 6486 metal in contrast to the OC metal nodules could not be a result of oxidation of W and its loss as volatile WO2 during impact melting. Based on this observation, we conclude that the NWA 6486 metal composition corresponds to fractionation of siderophile elements in the liquid metal but not to selective vaporization/condensation processes (e.g. Rubin 1999). Instead, the pattern of HRS depletion with a smooth depression between W and Ru shows that the metal is a product of partial melting of the chondrite metal that was depleted in HRS with distribution coefficients solid/liquid >>1 (Os, Ir) and less depleted in less compatible elements (Chabot et al. 2003, 2007). In this case, the depleted abundances of HRS (Fig. 6a) and the chondritic Os/Ir ratio in the metal of NWA 6486 show that the metal is most likely a product of small-scale melting rather than large-scale fractionation of the L-chondritic source. Significant Ni depletion in the NWA 6486 metal (Fig. 6a) in comparison to the L-chondrite metal cannot be explained by dilution of the metal phase by Fe reduction from silicates during precursor melting since the silicate compositions of NWA 6486 are in the L-chondrite range. As explanation, we propose that the Ni depletion could be a result of the metal phase dilution by the metallic Fe remaining after the high-temperature decomposition of troilite and evaporation of S
during the precursor melting. This mechanism seems to be consistent with near surface conditions of NWA 6486 formation.

Thus, the siderophile element composition of the NWA 6486 metal nodules corresponds to the composition of the metal liquid after partial melting of the L-chondrite metal, distribution of some W and Ga from silicates to the metal, and partial evaporative loss of S. The resulting S-bearing metal liquid could be segregated as a small pool.

It was not possible to obtain the elemental composition of Type 1 and 3 melt pockets and melt veins due to their small sizes. The bulk composition of the Type 2 melt pockets matrix acquired by the EPMA and LA-ICP-MS (Tables 2 and 4) indicate depletion in Ca (0.28xL), Al (0.38xL), Na (0.07xL), and K (0.5xL) relative to the bulk NWA 6486 and the groundmass composition. It is also depleted in Rb (6.6xCl) and Sr (1.1xCl) and less depleted in Ba (12xCl) relative to the groundmass (Table 4, Fig. 6c). Concentrations of REE in the Type 2 melt pockets are lower than those of NWA 6486 and L-chondrite bulk and could be reproduced by a mixture of olivine and minor groundmass (Fig. 6c).

Bulk composition of NWA 6486 (Table 4) is different from L chondrites in its extreme enrichment in K (8.2xL), Ca (1.56xL), Al (1.26xL) and Ti (1.43xL) and depletion in P (0.36xL) and Cr (0.21xL) (Fig. 6b). Iron, S, and Ni are also depleted due to depletion of the meteorite in Fe,Nimetal and troilite. Concentrations of Si, Na, Mg, and Mn are L-chondritic (Fig. 6b). The REE pattern of NWA 6486 is flat with a shallow Eu depletion mostly similar to that of L chondrites (Fig 6c). Other trace element compositions of NWA 6486 are mostly similar to L chondrites with the exception of already mentioned Ba and U enrichments, extreme Rb enrichment (10xCl), and depletion in Sr, Y, and Pb (Fig. 6c).

Barium and Sr abundances of the groundmass and olivine are similar to those in the least weathered inner parts of desert meteorites from Northwest Africa (Stelzner et al. 1999) (Fig. 7e). The concentration of Sr in NWA 6486 is L-chondritic (Fig. 6c). Thus, the enrichment in Ba observed in the olivine and groundmass, may be attributed to terrestrial contamination of NWA 6486. Olivine is poor in K (<200 ppm) and Rb (0.53 ppm, Table 4) in contrast to K and Rb-rich groundmass (2.11 wt% and 67.8 ppm, respectively, Tables 1, 4). Therefore, the unusual K and Rb enrichment of the meteorite is not a result of terrestrial weathering. All analyzed phases of NWA 6486 have increased CI-normalized U/Th ratios relative to L chondrites (groundmass 1.4; merrillite 3.4; Olivine 5.9) and they are richer in U and poorer in Th relative to CI chondrites, with the exception of apatite and
Type 2 melt pockets (Fig. 6c). Increased relative abundances of U (2.3 and 4.9xCI, respectively) could also mark terrestrial weathering. Typical REE indicators of terrestrial contamination are La and Ce. Concentrations of these elements are not too high relative to those of other REEs (Fig. 6c). Thus, the lithophile trace element distribution in NWA 6486 and occurrence of secondary Fe,Ni hydroxides and rare Ca carbonates both suggest a moderate weathering degree of the meteorite.

**Crystallization and Postcrystallization Histories of NWA 6486**

We could not determine a cooling rate during crystallization of NWA 6486 due to the absence of sufficient indicators. NWA 6486 is relatively fine-grained in comparison to the other L-chondritic melt rock PAT 91501 (Mittlefehldt and Lindstrom 2001; Benedix et al. 2008) which is depleted in metal and troilite like NWA 6486. The rock texture of NWA 6486 indicates that relatively slow growth of subhedral olivine crystals changed to quick crystallization of the groundmass.

The metal phase of NWA 6486, according to classification by Buchwald (1975), corresponds to net plessite, containing isolated taenite islands within a continuous network of a low-Ni metal phase. Goldstein and Michael (2006) have proposed that in meteoritic iron with total Ni abundance of ~9 wt.%, the Fe,Ni metal should experience sub-solidus conversion by the following sequence: \( \gamma \rightarrow \alpha_{2} + \gamma \rightarrow \alpha + \gamma \). According to these authors, the net-plessite texture of the NWA 6486 metal could be formed by martensitic conversion which starts at \( T \leq 350^\circ\text{C} \). It is possibly that the most Ni-rich plessite areas contain thin layers of tetrataenite which starts to grow at \( T \leq 350^\circ\text{C} \) (Yang et al. 1996). If this scenario is correct, the subsolidus cooling of NWA 6486 was relatively slow, at least below 500°C to form tetrataenite, taenite and low-Ni phase.

**Other K-Bearing Rocks Related to Ordinary Chondrites and Nature of K-enrichment in NWA 6486.**

Among ordinary chondrites several meteorites contain large melt masses or inclusions sharing some characteristics of NWA 6486. The K-rich, L-chondrite melt rock (Northwest Africa 2981, NWA 2981) is similar in texture and composition, and probably is paired to NWA 6486 (Meteoritical Bulletin 2021. NWA 2981 consists of mostly small (<0.5 mm) euhedral to subhedral olivine crystals (Fa_{22.6}; FeO/MnO = 46) set in the groundmass of glass (in wt%: SiO₂ 67; Al₂O₃ 10.2; CaO 5.7; Na₂O 2.17; K₂O 2.13; MgO 5.9; FeO 3.0) and skeletal crystals of Ca-pyroxene with
scattered mm-sized Fe,Ni-troilite inclusions. The glass composition of NWA 2981 is almost similar to that of NWA 6486 (Fig 8a), the differences between the two compositions could be attributed to small addition of Ca-pyroxene into analysis of the glass of NWA 2981. NWA 6486 could be similar to the melted lithologies of three L-chondrite breccias, containing large volumes of melt, NWA 5964, NWA 6454 and NWA 6580 (Meteoritical Bulletin 2021).

Potassium enrichment relative to chondritic levels with near chondritic or depleted Na abundances (Na/K<8, wt.) is a feature of some igneous-textured inclusions in ordinary chondrites which have mostly microporphyritic textures and are poor in Fe,Ni metal and troilite (Kempe and Müller 1969; Fodor et al. 1974; Ikeda and Takeda 1979; Wlotzka et al. 1983; Rubin 1985; Wlotzka et al. 1992; Ruzicka et al. 1998, 2000; Yokoyama et al. 2013; Armstrong and Ruzicka 2015, Ruzicka et al. 2019). The REE patterns of those inclusions are near chondritic (Wlotzka et al., 1983; Ruzicka et al. 1998, 2000; Armstrong and Ruzicka 2015, Ruzicka et al. 2019) (Fig. 8a). The K-rich inclusions are enriched in Rb, Cs, and Ba (Wlotzka et al. 1983, 1992; Yokoyama et al. 2013). Similarly, NWA 6486 has a microporphyritic texture, depleted in Fe,Ni metal and troilite and has unfractionated REEs abundances (Fig. 6b). Similar to other K-rich inclusions, NWA 6486 is enriched in K and Rb (Fig. 6b, c) and it only differs slightly in K/Na and K+Na from the K-rich fragments from the H-chondrite Acfer 111 (Wlotzka et al. 1992) and groups together with clasts in LL chondrites Bhola (Fodor et al. 1974; Wlotzka et al. 1983, clast B1), Krähenberg (Wlotzka et al. 1983, clast K1) and Vishnupur (Ruzicka et al. 1998, clast Vi2) (Fig. 8b). The large, igneous olivine-rich inclusion of porphyritic texture found in LL3 chondrite ALHA 76004 (Olsen et al. 1978) contains K-poor glass coexisting with K-rich glass close to the glass composition in NWA 6486 and NWA 2981 (Fig. 8a). The glasses of NWA 6486, 2981, and ALHA 76004 are also in the range of K/Al and Na/Al ratios of micron-sized K-rich glass inclusions observed in olivine grains of the L-chondrite melt rock PAT91501 (Mittlefehldt and Lindstrom, 2001) and in the Shaw chondrite (Taylor et al., 1979); however the glasses in PAT 91501 and Shaw are very rich in SiO₂ and possibly differ in genesis from the K-rich NWA 6486 groundmass.

Several chemically different groups of porphyritic inclusions in chondrites have been established and several mechanisms were proposed for their genesis (Ruzicka et al. 2000 and refs. therein). NWA 6486 has Na/Al (at.) ratio of 0.5 and groups by this ratio together with some other K-rich inclusions (Fig. 8c) to an “unfractionated+K” inclusions cluster with Na/Al at. ratio 0.35 - 0.85 established by Ruzicka et al. (2019) which have chemical compositions unfractionated by selective
evaporation/condensation and interpreted as impact melted chondrite materials enriched in K. NWA 6486 is enriched in K and Rb relative to Sr that correspond to the distribution of these elements in K-rich inclusions in ordinary chondrites. This distribution has been interpreted as a result of fractionation of volatile K and Rb, and refractory Sr due to selective evaporation/condensation of the volatiles (Wlotzka et al. 1983, 1992; Yokoyama et al. 2013, 2017).

The origin of the K-rich inclusions in ordinary chondrites remains unclear. The L chondrite-related melt rocks NWA 6486 and NWA 2981, together with two large microporphyritic inclusions from NWA 869 (L3-6) and Meteorite Hills (MET) 00489 (L3.6) (Ruzicka et al. 2019) fill the gap between the more common H- and LL -related K-rich chondritic inclusions. All these objects have mostly similar textures. The analyzed objects show compositional trends of their Na, K, and Rb distributions indicating that a common mechanism of alkali element enrichment occurred on the ordinary chondrite parent bodies or in their accretional reservoirs. The relatively large size of NWA 6486 that is comparable in size to the K-rich meteorites and inclusions in NWA 869 and MET 00489 mentioned above (Ruzicka et al. 2019) indicates that their formation processes were able to generate significant masses of K-rich melts.

The possible mechanisms of enrichment of chondrite materials in K and Rb, based on the distribution of alkaline and rare earth elements were discussed in detail by Wlotzka et al. (1983, 1992) and Yokoyama et al. (2013) who argued against igneous fractionation and liquid immiscibility. Wlotzka et al. (1993) also noted that selective evaporation/condensation of Na and K in impact events is not the appropriate mechanism because it may result in erratic and variable enrichment of volatile elements. Wlotzka et al. (1983, 1992) have noted that the K-rich objects are enriched in Rb, Cs but depleted in other volatile elements (Cu, Ga, Zn) relatively CI composition. These elements should also enter in the vapor phase but are depleted in the K-rich objects relative to CI chondrites. Following to that, Wlotzka et al. (1983, 1992) proposed an alternative mechanism of alkali elements enrichment. These authors proposed K-Na exchange between the vapor phase and cold feldspar leading to replacement of Na by K in the feldspar observed in the experiments of Orville (1963) and Fournier (1979). According to the model (Wlotzka et al. 1983), heating of the chondrite material generated a Na-K bearing vapor. Exchange of the vapor with feldspar in the cold chondrite material by K, Rb, and Cs resulted in enrichment of the feldspar phase in these elements. Further impact melting of this material would form the K-rich melt rocks. This process increases the K/Na ratio in the resulting rocks but would not alter the initial sum of K+Na (at.) corresponding to
the abundance of the feldspar phase in the rock. Wlotzka et al. (1983) argued for the plausibility of this mechanism based on the constant Na+K (at.) throughout the compositions of all feldspar phases in each chondrite and their K-rich inclusions.

However, Yokoyama et al. (2013) noted that K-rich objects in the Yamato 74442 LL chondrite contain glass rather than feldspar and could not be preferentially enriched in K and Rb through the reaction of feldspar with the vapor. Among the K-rich rocks, the bulk Na abundance decreases with increasing K (Fig. 8c), but K+Na/Al (at.) simultaneously increases relative to the corresponding H, L, and LL materials (Fig. 8d) which could not occur in the case of K/Na exchange between feldspar and the vapor proposed by Wlotzka et al. (1983). The observed negative trend of Na vs. K+Na/Al ratio (Fig. 8d) can be acquired by addition of K-rich material to the chondrite material. Ruzicka et al. (2019) showed that unfractionated K-rich inclusions have high Na/MgCI and K/MgCI ratios at roughly chondritic Al/MgCI due to their high K and Na contents.

Thermal metamorphism appears isochemical with respect to K (Kallemeyn et al. 1989) similar to major rock-forming elements (McSween et al. 1988). Potassium and Rb abundances are constant with increasing petrologic type for L chondrites, while Cs decreases (Kallemeyn et al. 1989, Schaefer and Fegley 2010). This element distribution does not correspond to that of the chondritic K-rich inclusions and therefore it is unlikely that K-Rb-Cs bearing vapor was generated due to internal heating of the chondritic parent body. Based on the isotopic compositions of K, Rb, Ca, and Sr, Yokoyama et al. (2013, 2017) suggested that K-rich objects in the Yamato 74442 LL chondrite are exogenous and could have formed by two-component mixing of K-rich nebular and K-poor LL-chondritic material on the parent body, followed by impact melting, vaporization, and re-condensation of the mixture providing additional fractionation of Rb and Sr (Yokoyama et al. 2013). These authors noted that the aforementioned processes could produce isotopic fractionation. However, similar to the K-rich fragment in the LL chondrite, Krähenberg (Humayun and Clayton 1995), the K-rich fragments could avoid this process, probably due to incomplete evaporation and condensation or a high potassium partial pressure (Yokoyama et al. 2013).

The re-condensation of the K-rich impact vapor without dilution by K-poor chondritic material, and formation of macroscopic condensate particles appear to require a large volume of the K-rich target material and impact vapor, meaning a large impact event. This is probably inconsistent with factors excluding the isotopic fractionation mentioned above. The K/Ca and Rb/Sr isotopic data of Yokoyama et al. (2017) suggest that K-rich materials were formed on the LL-chondrite parent
body at least twice (in different events and/or from different sources). However, the K-rich nebular materials needed for the mixing model are rare. Only accessory inclusions of K-rich phases (K-Na feldspar, orthoclase, roedderite or merrihueite) have been observed in ordinary chondrites (Wlotzka et al. 1992; Krot and Wasson 1994; Wood and Holmberg 1994; Bischoff et al. 1993). We note that the bulk silicate composition of NWA 6486 resembles that of a Type IA (porphyritic olivine) chondrule found in Parnallee LL3.5 (McCoy et al. 1991) and a megachondrule from Carraweena L3 (Ruzicka et al. 1998) (Fig. 8a). However, these minerals and chondrules have never been observed as macroscopic aggregates which could be mixed with the chondritic material and provide the observed concentrations of K and Rb in the resulting mixture. The absence of appropriate K-rich nebular condensates among meteorite samples probably weakens the assumption of Yokoyama et al. (2013).

A possible alternative model could be selective impact evaporation/condensation. Experiments on hypervelocity impacts indicated that selective evaporation results in an increase of K$_2$O/Na$_2$O ratio in the condensed material by a factor of two for basalt targets and is in agreement with the results of experimental evaporation of mafic rocks (Gerasimov et al. 1998 and refs. therein). Rubidium is also enriched in the vapor phase as indicated by its presence in impact experiments on a granite target (Yakovlev and Ljul 1991). Enrichment in K (~1.6xL) in the shock melts at the contact with host material was found in several chondrites by Kunz et al. (1997). Potassium (up to 3xL) and Rb enrichment were also noted in impact melts in the Chico L6 chondrite (Norman and Mittlefehldt 2002). Potassium-rich melts in four shocked chondrites were reported by Ruzicka et al. (2019). These cases indicate a redistribution of moderately volatile elements during impact melting events and can probably be explained by exchange between alkaline-rich vapor and the impact melt (Ruzicka et al. 2019). Other phenomenon that could increase the concentration of K in the target rock is selective condensation of K observed in nature as K-rich impactites and reproduced in experiments by Yakovlev et al. (1981, 1985 and refs therein). The experiment on condensation of a basaltic vapor in vacuum (Yakovlev et al. 1985) showed that the K/Na ratio in the condensates grows significantly with increasing temperature of the condensation surface from 25 to 700°C. This phenomenon was explained by the efficient recombination of K on the trap surface during disequilibrium condensation in the absence of oxygen. If long-lived traps like large-scale crushing zones could exist below the parent body surface and be protected from dilution by K-poor chondritic regolith, it could accumulate the alkali-rich condensates and melts from several impact events. In
this case, K concentration and K/Na ratio could reach the values of K-rich inclusions and the bulk NWA 6486 (K/Na = 10xL). Impact melting of the traps material could generate K-rich melts.

Thus, despite the absence of Rb-Sr and K-Ca isotopic data available for NWA 6486, based on the natural and experimental observations noted above, we suggest that an impact origin in situ on the OC parent body of NWA 6486 and related K-rich inclusions in ordinary chondrites is more plausible than the hypothesis of Yokoyama et al. (2017) that invokes a K-rich exogenous nebular-condensate impactor. The K and Rb enrichment of these rocks most probably is a result of the selective evaporation of volatile alkaline elements followed by the reaction of the vapor with shock melt filling fractures in the impact crater basement.

**Shock metamorphism**

NWA 6486 has shock metamorphic features similar to several chondrite melt rocks and the melt rock inclusions in ordinary chondrites (Corrigan and Lunning 2013; Vaci et al. 2020). This indicates that after formation, the impact melt rock sampled by NWA 6486 remained on the parent body and suffered subsequent impact (-s). Thus, the melt rock should be formed by specific conditions to avoid ejection from the parent body into space during the rock-forming impact event. The melt could be stored as veins injected into the impact crater basement (e. g. Yolcubal and Sack 1997). Type 1 melt pockets are intermediate in composition (Table 1) between the groundmass glass and the bulk meteorite (Table 4), similar to those in other chondrites (e. g. Ruzicka et al. 2000) and contain metal-troilite globules representing a typical feldspar-rich, low temperature shock melt (Dodd and Jarosewich 1979). These pockets and the optical features of olivine indicate that the average shock pressure was between 15-20 and 30-35 GPa (Stöffler et al. 1991).

The Type 2 melt pockets are much larger, much more abundant, and have a different texture and composition than the Type 1 and 3 melt pockets. The texture of the Type 2 melt pockets is similar to those observed in shocked chondrites and shocked chondritic melt rocks (Feng et al. 2011; Acosta-Maeda et al. 2013; Pitarello et al. 2015; Wu and Hsu 2019; Vaci et al. 2020). The heterogeneous texture and composition of the olivine inclusions in the melt and the olivine grains of the host meteorite are similar to those cited above and are related to transformation of olivine to its high-pressure polymorphs. Variations of Mg# and Fe/Mn ratio in zoned olivine inclusions in the Type 2 melt pockets (low Fe/Mn in Mg-rich olivine and high Fe/Mn in Fe-rich olivine, Table 2), relative to the host olivine (Table 1), are similar to high-pressure olivine modifications in shocked
chondrites (Acosta-Maeda et al. 2013; Wu and Hsu 2019) and could be the result of Fe-Mg inter-diffusion during high-pressure olivine transformation. The matrix of the Type 2 melt pockets is poorer in Na, K, Al, Ca, and Ti, richer in Fe relative to the associated melt veins and has the same Cr content (Table 2, Fig. 6b). The small olivine inclusions in the matrix have similar Mg# to the matrix (Fig 5a, d), which could be an indicator of crystallization of olivine from the same melt as the pocket matrix but, in contrast, also have a higher Fe/Mn ratio. The Type 2 melt pockets and the connecting veins most probably were formed together during the same event. The linear morphology, absence of metal and sulfide globules, shearing structures, and signs of melting of the wall-forming phases distinguish the melt veins in NWA 6486 from the shock melt pockets and veins in highly-shocked chondrites (e.g. Pitarello et al. 2015) and in experimentally shocked rock samples (Kenkmann et al. 2000; Heider and Kenkmann 2003). Local shock melting in meteorites is a result of shock pressure peaks followed by post-shock temperature peaks due to adiabatic decompression. Several mechanisms of shock melt vein formation are known (Kenkmann et al. 2000; Heider and Kenkmann 2003 and refs. therein). The texture of the melt veins in NWA 6486 argues against frictional melting and more likely corresponds to melting due to shock closure of the fractures (Heider and Kenkmann 2003). The bulk composition of the final melt veins must correspond to the host rock in cases where the fracture cuts one lithology. However, all analyses of the NWA 6486 veins similar to those of Type 2 melt pocket matrix show depletions in Al, Na, and K and enrichment in Fe in comparison to the groundmass, the Type 1 melt pockets, and bulk compositions of NWA 6486 and average L chondrites (Table 2, Fig. 6b). This indicates that the veins and the Type 2 melt pockets are not a result of simple in situ shock melting and were formed in a complex process discussed in the section below.

The Type 3 melt pockets are similar to the Type 2 except for the abundance of the metal and troilite globules, the higher abundance of ferrous olivine, and the lower abundance of glass. Type 3 pocket compositions indicate that they could be formed by mixing of local in situ shock melt and vein melt; however, no interconnections of the Type 3 melt pockets and veins were observed. The simplest interpretation is that all types of melt pockets are traces of one common impact event, but the Type 1 pockets were formed in a local isolated environment while the Type 2 melt pockets, connecting veins, and the Type 3 pockets are the result of some mobilization of the impact melt products.
Origin of the Veins Connecting the Type 2 Melt Pockets.

Compositions of the melt veins and the Type 2 melt pockets in NWA 6486 are contrast with composition of the Type 1 melt pockets, which represent a feldspar-rich, low-temperature melt (Fig. 6b). Simultaneous depletion of the veins and the Type 2 pockets in volatile Na and K and refractory Al, Ca, and Ti in comparison with the NWA 6486 bulk composition could not be a result of selective evaporation. The K/(K+Na) ratios (at.) in the veins and the Type 2 pockets (0.26-0.32) are less than the groundmass composition (0.37) and higher than L chondrites (0.06, Wasson and Kallemeyn 1988). This could indicate that the source of the melt most probably was the NWA 6486-like material.

The average Fe content in metal- and troilite-free veins and Type 2 pockets (17 wt.%, calculated from FeO, Table 2) is higher than that in the bulk silicate portion of NWA 6486 (15.5 wt.%, Table 4; Fig. 6b). If the source of the vein material was NWA 6486 or similar material as proposed above, almost complete oxidation of metal and Fe sulfide is required to provide the FeO content in the vein material. The veins and the Type 2 melt pockets have notable S contents (Table 2) that, together with the absence of troilite globules in the veins and Type 2 melt pockets in contrast to the Type 1 melt pockets, could be evidence of oxidized sulfide as a source of FeO enrichment. However, the vein material is Ni-poor, similar to the groundmass glass (Tables 1, 2), and its Fe/Ni ratio (30-100) is too high in comparison with the L-chondrite Fe/Ni ratio (17.6, Wasson and Kallemeyn 1988). It could indicate that the source of the vein material was depleted in Fe,Ni metal and enriched in FeS in comparison to NWA 6486 or that Ni was removed as NiO during the vein formation. The veins could not be depleted in Ni due to terrestrial weathering because Fe-oxyhydroxides were not observed. Wide variation of the Ni content in the Type 2 melt pockets from below the detection limit to 0.89 wt.% (average = 0.3 wt%) (Table 2) may be explained by shock melting of occasional inclusions of Fe,Ni metal in the groundmass of NWA 6486.

Chemical differences between NWA 6486 and its veins resemble that of so-called bleached chondrules (BC) observed in ordinary chondrites, which were possibly formed by dissolution and removal of the feldspathic mesostasis by a water-bearing fluid (Kurat 1969; Michel-Levi 1976; Skinner et al. 1989; Grossman et al. 2000; Lewis et al. 2017). Aqueous alteration in unequilibrated chondrites modified chondrules by removal of chemical components (mostly Na, K, Al, Ca, Sr, and Si) and by introduction of new components (H$_2$O, halogens, Fe, Ni, and possibly Rb) (Grossman et al. 2000). Aqueous alteration in ordinary chondrites of all petrologic types has been proposed based
on calcite and smectite occurrence (Nagahara 1984; Hutchison et al. 1987; Alexander et al. 1989), presence of saponite and carbide-magnetite aggregates (Krot et al. 1997), halite (Zolensky et al. 1999; Rubin et al. 2002), correlated chemical and oxygen-isotopic changes in feldspar (Dyl et al. 2012; Bischoff et al. 2013), and occurrence of amphiboles and FeO-rich olivine (Dobrica and Brearley 2014). Based on these observations the chondrites were reacted with water at temperatures from ~100-200°C (aqueous alteration) up to 800°C (fluid-rock interaction) (Brearley and Krot 2013).

Similar to the BCs in unequilibrated chondrites, the NWA 6486 veins and the Type 2 melt pockets show enrichment in Fe and depletions in Na, K, Al, and Ca in comparison to the bulk meteorite and average L-chondrite compositions. Similar to BCs, the NWA 6486 vein material contains only 0.5x the normative feldspar abundance in the source rock. In contrast to the BCs, the melt veins and Type 2 melt pockets have high analytical totals and high normative chromite (up to 2.9 wt.%). Hypothesizing of the aqueous alteration as formation process of the veins, an absence of $\text{H}_2\text{O}$ in the veins should indicate a high temperature for their formation. Depletion of the melt pockets in U in comparison to the NWA 6486 bulk and groundmass composition (Fig. 6c) could be a result of its dissolution and removal, possibly as $\text{UO}_2^{2+}$ from the altered fracture walls by a fluid.

The compositional differences between the melt veins and the NWA 6486 host could be explained by (1) in situ chemical alteration of the vein precursor material or (2) by injection of the material from a distant source and its deposition in the fractures. Secondary alteration of the feldspar-rich groundmass and olivine in the NWA 6486 material at the contact with the veins was not observed. Therefore, in the case (1), an interaction of rock with the water-bearing fluid was a high temperature process or signs of the interaction were removed by later processes. The Type 2 melt pockets are obviously connected with veins and filled by a vein-like material, forming the matrix surrounding the olivine grains (Fig. 4). This must mean that the Type 2 melt pockets were formed by filling the cavities containing fragments of olivine, by shock vein material. Based on that the following three scenarios of the vein formation could be suggested: (1) reaction of the rock with an aqueous fluid moving through the fractures resulted in alteration of only the wall material and the following in situ shock melting of the fracture walls erased possible mineralogical footprints of this aqueous alteration; (2) the NWA 6486-like material was changed in earlier episode of aqueous alteration and then was shock melted and injected into the unaltered NWA 6486 host rock; or (3) the
NWA 6486-like material was shock melted and reacted with water vapor, the reaction products were injected in the fractures and partly deposited as the veins and the Type 2 melt pocket matrix.

In case (1), the impact event on the L-chondrite parent body (1 in Table 6) could have produced a number of L-chondrite melt rocks including NWA 6486 (2 in Table 6). This or later impact events initiated hydrothermal activity on the parent body. The aqueous fluid infiltrated through the largest open fractures in NWA 6486 and reacted with the walls while most of the rock was unaffected (3A in Table 6). The fluid dissolved the groundmass, removed Na, K, and Al, oxidized Fe,Ni metal and troilite and removed Fe Ni and some trace elements like U and further deposited FeO that was mobilized from the surrounding rock. The veins observed in NWA 6486 could also have low Ni contents similar to that of the meteorite groundmass because they do not intersect large metal-troilite aggregates. A later impact event (4A in Table 6) resulted in complete in situ melting of the altered walls of the fractures and formation of the veins and the Type 2 pockets.

In case (2), water-bearing fluid-rock interaction resulted in depletion of NWA 6486-like material in Na, K, Ca, and Al and oxidation of metal and sulfide (3B in Table 6) and resulted in formation of a reservoir of bleached rock. The fluid reservoir should be isolated from the dry NWA 6456 formation region; e.g. it could be an older hydrothermally altered xenolith that was combined with NWA 6456 rock due to reassembly of the parent body. Then the altered rock was shock melted in a subsequent impact event and the melt was injected into NWA 6486 through the fractures, forming the melt veins. Local shock melting and mixing of shocked olivine fragments with injected melt formed the melt pockets (4B in table 6).

In case (3) the melt vein formation could be described as a sequence of the following processes. On stage (i) a shock melting of NWA 6486 at P>75 GPa (Stöffler et al. 1991) had occurred during the impact of an icy projectile (3C in Table 6). The melt could be generated near the impact crater floor, or in situ in the rock. Based on the suggested limited distribution of NWA 6486-like rocks on the L-chondrite parent body and the small thickness of the melt veins, the melt most likely should be formed in situ because it implies only short distance transport of the melt into the fractures in the NWA 6486 host. Then, (ii) the shock melt was mixed with water vapor and injected into the fractures of the host rock (4C in Table 6) and, while the impact product moved through the fractures, the pressure decreased and the mixture of silicate melt and water vapor was converted to a supercritical water-silicate fluid, effectively dissolving the rock-forming elements of the melt (e.g. Manning 2004) (stage iii). Because the Si and Fe are less soluble in aqueous fluids than other rock-
forming elements (Manning 2004), a further pressure drop resulted in deposition of Si-Fe-rich melt in the fractures of NWA 6486 (stage iv). At places, injected melt was mixed with in situ shock melts and shocked mineral grains. Thus, the melt veins and pockets were formed while the K, Na, and Al-bearing fluid moved away from NWA 6486 through the fractures. In this scheme, the fluid did not dissolve the groundmass of NWA 6486 because the fluid was saturated with a feldspathic component. Simultaneous enrichment of the melt veins and pockets in Cr$_2$O$_3$ indicate some process of concentration of Cr and homogenization of its distribution in the melt in comparison to that of the NWA 6486 mesostasis. This could not be a result of in situ shock melting. Trivalent chromium is insoluble in aqueous fluids under low P-T conditions; however, high-pressure experiments showed the mobilization of Cr$^{3+}$ at P = 0.5-1 GPa and T = 500-700°C (Watenphul et al. 2014), which could support a hypothesis of super-critical fluid alteration during the melt vein formation. It is possible that aqueous alteration in case (1) was produced by a high-pressure, water-bearing fluid as well. The possible disadvantage of this model could be that a large volume of water is needed for fluid formation; for example, in the Ab-H$_2$O system, a supercritical fluid exists below ~1.6-2 GPa and above 650°C (Manning 2004), and needs more than 20 wt.% H$_2$O (Manning 2004). Speculatively, a scenario like case (3) could be realized in shock processes on water-rich bodies like Ceres or Mars.

Thus, Case (1) seems to be most plausible because a) this scenario is consistent with observed textures and compositions of the melt veins and the host rock; and b) this scenario is a combination of mostly local, in situ processes which can be realized in less specific conditions than other scenarios. The sources of water could be unequilibrated water-bearing L-chondrite xenoliths survived the parent body evolution. Case (2) requires relatively a large volume of aqueously-altered material to generate impact melt of specific composition without any mixing with surrounding target rock (-s) that is unlikely. Case (3) could be plausible also because it could be realized in one impact event.

**Oxygen Isotopic Composition**

NWA 6486 has the L-chondrite oxygen isotopic composition. Comparison of NWA 6486 with K-rich inclusions in other L chondrites indicates its proximity to the inclusion 869-I1 in NWA 869 (L3.6) but different from the inclusion MET-I2 in MET 00489 which is out of the L-chondrite field of oxygen isotopic composition (Fig. 8d). These two inclusions have Na/K weight ratios of 0.87 and 1.43, respectively (1.1 in NWA 6486). The K-rich inclusion DIM-I1 from Dimmitt (H3.7) is out of
the H chondrite oxygen isotopic composition range. These differences could be evidence that the K enrichment is connected with some common process rather than specific to the source. We suggest that secondary alteration for NWA 6486 was likely involved in the formation processes of the melt vein precursor material, and these processes did not shift the bulk oxygen isotopic composition from the L-chondrite field. This could indicate several possibilities: (i) all the components evolved in the melt vein formation were in isotopic equilibrium and originated from interiors of the L-chondrite parent body, similar to other cases of aqueous alteration found in ordinary chondrites; (ii) if the melt vein or vein protolith involved an exogenous water source, such as a $^{16}$O-poor icy impactor (e.g. Clayton 2003), the resulting melt did not have the L-chondritic oxygen isotopic composition. The oxygen diffusion rate increases with increasing $P_{H_2O}$ and $T$, thus there should be some oxygen isotopic shift at the contact of the L-chondrite host and the melt depleted in $^{16}$O. However, because of the short duration of vein formation (Dyl et al. 2012), the change of oxygen isotopic composition of the host rock due to diffusion would occur at micrometer scale and could not be affect the bulk oxygen isotopic analysis. Finally, it is also possible that two chips of NWA 6486 used for the analyses did not contain any melt veins because of their limited distribution in the meteorite.

$^{40}$Ar/$^{39}$Ar Dating of NWA 6486

The identified trapped Ar composition with ($^{40}$Ar/$^{36}$Ar)$_{\text{trapped}}$ ratio of 522 ± 59 (Fig. 7c) likely represents extraterrestrial gas with some contribution of atmospheric contamination typical of meteorites, especially those found in deserts (Korochantseva et al. 2005; Trieloff et al. 2018). Trapped argon of extraterrestrial origin with isotopic composition distinct from primordial/solar/terrestrial was previously identified in L chondrites and other types of asteroidal meteorites (e.g., Korochantseva et al. 2007; Weirich et al. 2012; Hopp et al. 2014; Trieloff et al. 2018) and its origin is ascribed to thermal processes related to primary metamorphism or impact events. This derives from mobilization of preexisting components (e.g., solar $^{36}$Ar and radiogenic $^{40}$Ar) accumulated before impact events, fractionation, and redistribution from neighboring rocks (gases released from deeper hot rocks are trapped by rocks at shallower depth, in voids/fractures which have been immediately isolated) or within the rock (Trieloff et al. 2018; Korochantseva et al. 2017, 2018b, 2020, 2021). The latter is possible if mobilized gases are not immediately lost from the system (buried rocks) and are partially trapped in voids/defects upon further cooling of material
and/or in gas inclusions of crystallizing melt. This interpretation is in agreement with the model of the K-enrichment of NWA 6486 (see above).

Correction for the identified trapped argon composition results in a plateau age of 453 ± 8 Ma (1σ; ~87% 39Ar release; Fig. 7b). The value of the trapped argon composition and respectively corrected age depend on the selection of isochron data points. For example, if the 1100 °C extraction is excluded, the temperature extractions 560-1070 °C yield (40Ar/36Ar)_{trap} =488±69 and a plateau age of 477 ± 10 Ma (1σ; ~83% 39Ar release). Both age values for NWA 6486 completely agree (within 2σ) with the time of the large scale event on the L-chondrite parent body - 470 Ma ago (e. g., Korochantseva et al. 2007; Weirich et al. 2012) (Fig. 7b). Later, the aqueous alteration and shock metamorphism resulting in the formation of tiny melt veins and pockets did not affect the K-Ar system of NWA 6486. It is notable that Ar/Ar age of aqueously altered R chondrites does not differ from the age of other R chondrites (Righter et al., 2016). It is difficult to reset the K-Ar system of impact melts and intensely shocked material that are highly retentive for argon and resistant to subsequent impact events (e.g., Trieloff et al. 2018). Evidently, the secondary shock event was not powerful or long-lasting enough to affect the K-Ar system of NWA 6486.

The total amount of cosmogenic 38Ar is 14.2*10^{-10} cm^3 STP/g (~34% of 38Ar_{total}). The size of the pre-atmospheric body and the shielding depth of our sample are currently unknown. NWA 6486 is a small, single stone (4.5 g) and we have found only NWA 2981, weighing 19 g, as a possible paired meteorite based on petrological similarities (Meteoritical Bulletin database 2021). Therefore, we suggest that the size of the meteoroid from which NWA 6486 was derived was relatively small. The cosmic ray exposure (CRE) age calculated using the model of Leya and Masarik (2009) for a pre-atmospheric body with a radius up to 100 cm is 3-4 Ma. This is in the CRE age range of L chondrites (Wieler 2002), although the latter predominantly show a longer exposure history. The short CRE age assumes a simple exposure of this impact melt sample, corresponding to a short transition time from the L-chondrite parent body to the Earth.

**Timing of Secondary Alteration of NWA 6486**

Grossman et al. (2000) provided evidence for pre-metamorphic aqueous activity on the ordinary chondrite asteroids. Dobrica and Brearley (2014) have concluded that aqueous alteration in Tieschitz (H/L 3.6) is related to metamorphism that occurred during the first few million years of evolution of the H parent body. Zolensky et al. (1999 a, b) and Rubin et al. (2002) indicated that
water was present after metamorphism, but prior to final lithification and may either be indigenous fluids from elsewhere in the H-chondrite asteroid or fluids introduced by late-stage impacts of icy bodies. A model describing the effect of an aqueous fluid on metamorphosed material, according to Grossman (2000), should include the fragmentation of the parent body, mixing of dehydrated material of petrological types 4 and 5 and hydrated material of type 3, and subsequent thermal metamorphism. Fries et al. (2011) have argued that water-bearing halite crystals in Zag and Monahans (Zolensky et al. 1999; Rubin et al. 2002) are exogenous and was ejected from the water-rich body like Enceladus or Ceres and softly accreted on the chondrite asteroid. Dyl et al. (2012) and Bischoff et al. (2013) have reported evidence for short-lived water–rock reactions in the metamorphosed ordinary chondrite breccia Villalbeto de la Peña (L6) and concluded that such the reaction could be explained via late-stage episodic release of an aqueous phase from the chondrite asteroid interior, implying that ordinary chondrites accreted wet. Alternatively, impacts with H$_2$O-bearing planetesimal(s) could explain short pulses of water–rock reaction because they would potentially provide high temperatures and transient volatile phase (Dyl et al. 2012).

In a case of NWA 6486, the formation of unusual veins should have occurred later than the 470 Ma event. If the veins are the result of fluid-rock interaction, it seems plausible that the hydrothermal activity episode on the L-chondrite parent body was a result of heating of water-bearing unequilibrated material and NWA 6486 host rock after the re-assembly of disrupted parent body, or was initiated by a collision with one of the ice-bearing bodies of the main asteroid belt (e.g. Campins et al. 2010; Rivkin and Emery 2010; Agarwal et al. 2017).

CONCLUSIONS

Based on mineralogy, petrography, trace element geochemistry, and isotope compositions of oxygen and argon of NWA 6486, we showed that the meteorite is a L-chondrite – related impact melt rock, possibly paired to NWA 2981. The rock has undergone a small-scale fractionation of siderophile elements; it is unusually enriched in K and Rb along with the mostly unfractionated pattern of other lithophile elements. NWA 6486 shares similarities with other K-rich inclusions from ordinary chondrites. A relative distribution of K, Rb, and Sr in NWA 6486 and K-rich inclusions show a fractionation of these elements due to selective evaporation. Based on the natural and experimental observations we suggest that an impact origin, in situ, on the OC parent body of NWA 6486 and related K-rich inclusions in ordinary chondrites is more plausible. Observed negative
trends of Na vs. K+Na/Al ratio, and high Na/Mg\textsubscript{CI} and K/Mg\textsubscript{CI} ratios at roughly chondritic Al/Mg\textsubscript{CI} ratios indicate that K enrichment in these rocks is a result of addition of K concentration rather than K-Na exchange between the vapor and cold feldspar target proposed by Wlotzka et al. (1983). The K, Rb and Cs enrichment of these rocks most probably is a result of selective impact evaporation of volatile alkali elements followed by the reaction of the vapor with shock melt filling the fractures in the impact crater basement.

NWA 6486 likely recorded at least two recent impact events on the L-chondrite parent body, and formed in the first impact event. The $^{40}\text{Ar}-^{39}\text{Ar}$ age of this event is in agreement with the ages of most L chondrites indicating an asteroid breakup event at 470 Ma. The trapped argon of asteroidal origin in NWA6486 is also likely related to this event that led to release, mobilization, and redistribution of accumulated gases on the L-chondrite asteroid. After formation, NWA 6486 experienced other shock event that formed the melt pockets and unusual veins depleted in Na, K, Ca, and Al in comparison to the host rock composition. This event possibly took place on a large fragment of the L-chondrite body or on an asteroid that re-accreted from its fragments. The melt was probably formed by \textit{in situ} shock melting of the rock around the fractures previously affected by water-bearing fluid. These processes have not had a detectable effect on the bulk argon and oxygen isotopic compositions of NWA 6486. Further, NWA 6486 was affected by the latest shock event and was ejected to the space. The delivery time of NWA 6486 from the parent body asteroid to the Earth calculated from its exposure age determined by the total amount of $^{38}\text{Ar}_{\text{cos}}$, is $\sim$3-4 Ma.

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Tables

Table 1. Compositions of main and minor phases in the NWA 6486.

Table 2. Compositions of the phases in melt veins and pockets in the NWA 6486.

Table 3. Chemical composition of troilite and Fe,Ni-metal in NWA 6486.

Table 4. Trace element composition (LA-ICP-MS) of Fe,Ni metal and silicate phases, calculated bulk abundances of macro- and trace elements in a silicate portion of NWA 6486.

Table 5. Concentrations of Ar isotopes (in ccm STP/g) and apparent ages (in Ma) for each temperature extraction of NWA 6486 whole rock (35.4 mg).

Table 6. Possible mechanisms of the melt vein formation in NWA 6486.
Figures captions

Fig. 1. BSE image of the NWA 6486 texture: a) subhedral and anhedral olivine grains. The grains are fractured; the fractures are terminated on the grains margins; b) pyroxene grain in the groundmass; c) the groundmass is composed of devitrified glass and pyroxene with minor chromite and troilite; d) chromite skeletal crystal in the groundmass; an inset shows a finest discontinuous reaction rim on the contact of olivine and groundmass composed of clinopyroxene with the sub-micron chromite symplectites. Ol – olivine; Px – pyroxene; Cpx – clinopyroxene; Gm – groundmass; Chr – chromite; Rim – reaction rim.

Fig. 2. Texture of metal and troilite aggregates in NWA 6486: a) large metal-troilite aggregate; b) the patchy and net-plessite texture of the FeNi metal; Figs. 2a, b are reflected light images; c) isolated Fe,Ni metal object surrounded by pyroxene rim with troilite inclusions; d) patchy FeNi aggregate composed of kamacite, taenite and high-Ni phase, possibly tetrataenite; Figs. 2c, d are BSE images. Mt – metal; LNi – low-Ni phase; Tn – taenite; NTn – high Ni taenite; Tr – troilite.

Fig. 3. Textures of shock melt pockets in NWA 6486: a) the veinlet-like Type 1 melt pocket comprised by Na-Al- bearing silicate glass and metal-troilite globules; largest troilite globule contains the glass globules; b) Type 3 melt pocket comprises the inclusions of olivine different in composition and inclusion of the meteorite groundmass with interstitial FeO-rich matrix with metal and sulfide globules; c) Type 3 melt pocket of in the troilite grain; the melted area unusually terminates on the troilite grain margins, the FeO rich matrix contains fine mineral inclusions and troilite globules; d) the melt pocket of Type 3 on the contact of silicate main mass with metal-troilite aggregate contains inclusions of Ca-phosphate; Figs. a-c – BSE, d – reflected light image. Gl – glass, Mx – melt pocket matrix, Ph – phosphate.

Fig. 4. a) Melt vein in the NWA 6486 host; note a groundmass inclusion in the vein (right side); b) the Type 2 melt pockets; c) the Type 2 melt pocket contains the inclusions of olivine with Mg-rich cores and Fe-rich rims and inclusions of Fe-rich olivine surrounded by crypto- to microcrystalline matrix (MX); the host olivine has discontinuous high-Mg zoning on the contacts with the matrix; d) the olivine with a large Mg-rich core has veinlet-like internal texture and surrounded by Fe-rich
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Fig. 5. Composition of the matrix (solid circles) and its olivine inclusions (open circles) of the Type 2 melt pockets: a) Fo (Mg# for matrix) vs. Fe/Mn (at.); b) Fo (Mg# for matrix) vs. Cr2O3 (wt.%); c) texture variations of the matrix in the Type 2 melt pockets: A - material with empty interstitial voids between the crystals; B - microcrystalline and C - essentially fine-grained materials; d) the Mg# and Fe/Mn profiles from the inner large inclusion of olivine through the matrix to the contact with the host olivine.

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<td>σ (13)</td>
<td>σ (2)</td>
<td>σ (18)</td>
<td>σ (3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiO₂</td>
<td>38.4 ±0.58</td>
<td>54.2 ±0.94</td>
<td>53.9 ±2.43</td>
<td>67.7 ±0.90</td>
<td>61.0 ±1.44</td>
<td>0.12 ±0.19</td>
<td>0.12 ±0.03</td>
<td>0.28 ±0.82</td>
<td>0.38 ±0.40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.02 ±0.02</td>
<td>0.11 ±0.04</td>
<td>0.06 ±0.14</td>
<td>0.48 ±0.04</td>
<td>0.35 ±0.06</td>
<td>1.63 ±0.60</td>
<td>0.87 ±0.04</td>
<td>0.02 ±0.02</td>
<td></td>
<td>b.d.</td>
<td></td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>0.05 ±0.06</td>
<td>0.90 ±0.70</td>
<td>0.80 ±3.08</td>
<td>13.3 ±0.40</td>
<td>7.76 ±0.23</td>
<td>4.84 ±0.70</td>
<td>3.69 ±0.04</td>
<td>0.03 ±0.10</td>
<td>0.05 ±0.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cr₂O₃</td>
<td>0.03 ±0.02</td>
<td>0.76 ±0.93</td>
<td>1.07 ±1.33</td>
<td>0.27 ±0.11</td>
<td>0.30 ±0.08</td>
<td>59.9 ±0.95</td>
<td>62.5 ±1.57</td>
<td>0.07 ±0.21</td>
<td>0.03 ±0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FeO</td>
<td>21.2 ±0.67</td>
<td>14.8 ±1.07</td>
<td>17.3 ±21.7</td>
<td>12.4 ±3.43</td>
<td>2.94 ±0.40</td>
<td>5.65 ±0.76</td>
<td>29.8 ±0.64</td>
<td>25.2 ±0.62</td>
<td>0.85 ±0.52</td>
<td>1.97 ±1.47</td>
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</tr>
<tr>
<td>MnO</td>
<td>0.48 ±0.06</td>
<td>0.48 ±0.05</td>
<td>0.62 ±0.87</td>
<td>0.52 ±0.06</td>
<td>0.08 ±0.02</td>
<td>0.25 ±0.03</td>
<td>0.77 ±0.11</td>
<td>0.75 ±0.02</td>
<td>0.03 ±0.02</td>
<td>0.03 ±0.04</td>
<td></td>
</tr>
<tr>
<td>MgO</td>
<td>39.7 ±0.80</td>
<td>27.0 ±1.77</td>
<td>25.5 ±15.2</td>
<td>18.6 ±3.47</td>
<td>11.5 ±1.01</td>
<td>2.23 ±0.15</td>
<td>6.54 ±0.14</td>
<td>3.66 ±0.36</td>
<td>0.17 ±0.15</td>
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</tr>
<tr>
<td>CaO</td>
<td>0.05 ±0.05</td>
<td>0.63 ±0.31</td>
<td>1.22 ±7.50</td>
<td>7.77 ±5.90</td>
<td>3.65 ±0.53</td>
<td>7.49 ±1.37</td>
<td>0.03 ±0.04</td>
<td>0.04 ±0.01</td>
<td>46.3 ±0.97</td>
<td>50.8 ±0.89</td>
<td></td>
</tr>
<tr>
<td>Ni</td>
<td>n.d.</td>
<td>n.d.</td>
<td>b.d.</td>
<td>0.04 ±0.03</td>
<td>b.d.</td>
<td>b.d.</td>
<td>b.d.</td>
<td>b.d.</td>
<td>0.05 ±0.05</td>
<td>0.06 ±0.06</td>
<td></td>
</tr>
<tr>
<td>Na₂O</td>
<td>b.d.</td>
<td>0.21 ±0.22</td>
<td>0.09 ±0.42</td>
<td>0.49 ±0.39</td>
<td>4.19 ±0.18</td>
<td>2.45 ±0.18</td>
<td>b.d.</td>
<td>b.d.</td>
<td>2.78 ±0.24</td>
<td>0.57 ±0.04</td>
<td></td>
</tr>
<tr>
<td>K₂O</td>
<td>b.d.</td>
<td>0.16 ±0.14</td>
<td>b.d.</td>
<td>0.35 ±0.27</td>
<td>3.03 ±0.12</td>
<td>2.13 ±0.17</td>
<td>b.d.</td>
<td>b.d.</td>
<td>0.05 ±0.01</td>
<td>b.d.</td>
<td></td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.05 ±0.05</td>
<td>b.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>0.47 ±0.05</td>
<td>0.26 ±0.07</td>
<td>b.d.</td>
<td>b.d.</td>
<td>46.4 ±1.16</td>
<td>40.5 ±1.28</td>
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</tr>
<tr>
<td>S</td>
<td>b.d.</td>
<td>b.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>0.24 ±0.14</td>
<td>0.43 ±0.30</td>
<td>b.d.</td>
<td>b.d.</td>
<td>0.16 ±0.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cl</td>
<td>b.d.</td>
<td>b.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>0.04 ±0.01</td>
<td>0.02 ±0.01</td>
<td>b.d.</td>
<td>b.d.</td>
<td>5.16 ±0.28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>99.9 ±0.99</td>
<td>99.3 ±0.5</td>
<td>100.5 ±98.4</td>
<td>99.4 ±99.4</td>
<td>99.8 ±99.6</td>
<td>99.4 ±99.7</td>
<td>100.5 ±100.5</td>
<td>99.9 ±99.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fo (mol%)</td>
<td>77.0 ±0.82</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>En (mol%)</td>
<td>74.9 ±2.54</td>
<td>70.7 ±46.4</td>
<td>59.7 ±20.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wo (mol%)</td>
<td>1.26 ±0.64</td>
<td>2.4 ±16.5</td>
<td>18.0 ±15.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe/Mn (at.)</td>
<td>44.0 ±4.91</td>
<td>30.6 ±3.38</td>
<td>27.5 ±24.5</td>
<td>23.4 ±23.4</td>
<td>6.53 ±39.8</td>
<td>7.21 ±22.1</td>
<td>4.76 ±22.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sigma and parentheses are standard deviation and a number of analyses, respectively;
1 - host olivine; 2 - host pyroxene associated with olivine; 3, 4 - large pyroxene phenocryst core and rim; 5 - fine pyroxene fenocrysts in the groundmass; 6 - glass in the groundmass (defocused beam); 7 - groundmass bulk (defocused beam); 8 - chromite in the groundmass; 9 - chromite in the shock melt pocket; 10 - merrillite; 11 - apatite.
Table 2. Compositions of the phases in melt veins and pockets in the NWA 6486.

<table>
<thead>
<tr>
<th></th>
<th>All in wt%</th>
<th>σ (6)</th>
<th>σ (4)</th>
<th>σ (36)</th>
<th>σ (16)</th>
<th>σ (5)</th>
<th>σ (11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>58.7</td>
<td>41.4</td>
<td>0.86</td>
<td>41.9</td>
<td>1.05</td>
<td>39.3</td>
<td>2.19</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.33</td>
<td>0.14</td>
<td>0.04</td>
<td>0.07</td>
<td>0.04</td>
<td>0.07</td>
<td>0.03</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>6.26</td>
<td>1.86</td>
<td>0.38</td>
<td>1.96</td>
<td>0.42</td>
<td>0.95</td>
<td>0.54</td>
</tr>
<tr>
<td>Cr₂O₃</td>
<td>0.48</td>
<td>1.31</td>
<td>0.06</td>
<td>1.22</td>
<td>0.06</td>
<td>1.22</td>
<td>0.73</td>
</tr>
<tr>
<td>FeO</td>
<td>6.89</td>
<td>21.9</td>
<td>1.15</td>
<td>18.8</td>
<td>0.80</td>
<td>26.2</td>
<td>3.51</td>
</tr>
<tr>
<td>MnO</td>
<td>0.36</td>
<td>0.20</td>
<td>0.04</td>
<td>0.26</td>
<td>0.02</td>
<td>0.17</td>
<td>0.06</td>
</tr>
<tr>
<td>MgO</td>
<td>14.5</td>
<td>30.9</td>
<td>1.97</td>
<td>32.9</td>
<td>1.72</td>
<td>30.7</td>
<td>2.3</td>
</tr>
<tr>
<td>CaO</td>
<td>8.87</td>
<td>1.11</td>
<td>0.14</td>
<td>1.10</td>
<td>0.35</td>
<td>0.52</td>
<td>0.33</td>
</tr>
<tr>
<td>Ni</td>
<td>b.d.</td>
<td>0.03</td>
<td>0.02</td>
<td>0.04</td>
<td>0.06</td>
<td>0.25</td>
<td>0.71</td>
</tr>
<tr>
<td>Na₂O</td>
<td>1.97</td>
<td>0.30</td>
<td>0.15</td>
<td>0.34</td>
<td>0.18</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.99</td>
<td>0.18</td>
<td>0.07</td>
<td>0.24</td>
<td>0.13</td>
<td>0.08</td>
<td>0.07</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.28</td>
<td>0.11</td>
<td>0.01</td>
<td>0.10</td>
<td>0.00</td>
<td>0.16</td>
<td>0.11</td>
</tr>
<tr>
<td>S</td>
<td>0.24</td>
<td>0.37</td>
<td>0.24</td>
<td>0.61</td>
<td>0.42</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>Cl</td>
<td>0.02</td>
<td>0.03</td>
<td>0.03</td>
<td>b.d.</td>
<td>b.d.</td>
<td>b.d.</td>
<td>b.d.</td>
</tr>
<tr>
<td>Total</td>
<td>99.9</td>
<td>99.8</td>
<td>99.5</td>
<td>99.9</td>
<td>99.8</td>
<td>100.3</td>
<td>99.5</td>
</tr>
<tr>
<td>Fo* (mol%)</td>
<td></td>
<td>67.7</td>
<td>4.13</td>
<td>89.0</td>
<td>2.7</td>
<td>90.5</td>
<td>0.17</td>
</tr>
<tr>
<td>Fe/Mn (at.)</td>
<td></td>
<td>105</td>
<td>17</td>
<td>72</td>
<td>8</td>
<td>172</td>
<td>57</td>
</tr>
</tbody>
</table>

Sigma and parentheses are standard deviation and a number of analyses, respectively;
1 - glass of shock melt pocket of Type 1; 2 - melt vein in olivine; 3 - melt vein in groundmass; 4 - 7 - phases in the melt pockets of type 2; 4 - matrix; 5 - magnesian olivine; 6 - magnesian rim of the host olivine on the contact with the melt; 7 - ferroan olivine. 1-4 are defocused beam analyses.

*For other phases Mg# [100xMg/(Fe+Mg)]
Table 3. Chemical composition of troilite and Fe,Ni-metal in NWA 6486.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>σ (40)</td>
<td>σ (36)</td>
<td>σ (4)</td>
<td>σ (33)</td>
<td>σ (4)</td>
<td>σ (33)</td>
</tr>
<tr>
<td>Fe</td>
<td>92.0</td>
<td>0.48</td>
<td>90.5</td>
<td>69.7</td>
<td>51.5</td>
<td>53.3</td>
</tr>
<tr>
<td>Ni</td>
<td>7.01</td>
<td>0.23</td>
<td>6.31</td>
<td>28.9</td>
<td>2.01</td>
<td>47.1</td>
</tr>
<tr>
<td>Co</td>
<td>0.91</td>
<td>0.12</td>
<td>0.48</td>
<td>0.34</td>
<td>0.04</td>
<td>0.15</td>
</tr>
<tr>
<td>S</td>
<td>b.d.</td>
<td>–</td>
<td>b.d.</td>
<td>–</td>
<td>0.00</td>
<td>b.d.</td>
</tr>
<tr>
<td>Mn</td>
<td>b.d.</td>
<td>–</td>
<td>b.d.</td>
<td>b.d.</td>
<td>–</td>
<td>0.00</td>
</tr>
<tr>
<td>Cr</td>
<td>b.d.</td>
<td>–</td>
<td>b.d.</td>
<td>b.d.</td>
<td>–</td>
<td>0.00</td>
</tr>
<tr>
<td>Total</td>
<td>99.9</td>
<td>97.3</td>
<td>99.0</td>
<td>98.7</td>
<td>98.3</td>
<td>99.0</td>
</tr>
</tbody>
</table>

1 - kamacite in the metal-troilite aggregates; 2 - kamacite, fine grain in the groundmass; 3 - medium-Ni taenite; 4 - taenite with highest Ni; 5 - high-Ni taenite, average; 6 - troilite in the metal-troilite aggregates.
Table 4. Trace element composition (LA-ICP-MS) of Fe,Ni metal and silicate phases, calculated bulk abundances of macro- and trace elements in a silicate portion of NWA 6486.

<table>
<thead>
<tr>
<th>Element</th>
<th>Olivine σ (N) ppm</th>
<th>Groundmass bulk</th>
<th>Phosphate σ (5)</th>
<th>Melt in melt pocket of Type 2</th>
<th>Bulk silicate portion σ (N)</th>
<th>Bulk NWA 6486σ (19)</th>
<th>ppm Fe,Ni metal σ (19)</th>
<th>wt% Silicate portion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rb</td>
<td>0,53</td>
<td>67,8</td>
<td>5,57</td>
<td>0,72</td>
<td>6,7</td>
<td>1,98 (5)</td>
<td>24,2</td>
<td>1,2</td>
</tr>
<tr>
<td>Sr</td>
<td>2,71 0,38 (5)</td>
<td>15,8</td>
<td>1,25</td>
<td>53,2</td>
<td>8,05</td>
<td>1,83 (8)</td>
<td>7,49</td>
<td>0,28</td>
</tr>
<tr>
<td>Y</td>
<td>0,07 0,004(2)</td>
<td>5,07</td>
<td>0,62</td>
<td>45,0</td>
<td>0,69</td>
<td>0,57 (4)</td>
<td>1,97</td>
<td>0,12</td>
</tr>
<tr>
<td>Zr</td>
<td>1,89 0,38 (2)</td>
<td>13,4</td>
<td>3,32</td>
<td>b.d.</td>
<td>5,23</td>
<td>1,35 (4)</td>
<td>5,94</td>
<td>0,60</td>
</tr>
<tr>
<td>Nb</td>
<td>b.d.</td>
<td>0,94</td>
<td>0,09</td>
<td>b.d.</td>
<td>0,53</td>
<td>0,17 (8)</td>
<td>0,33</td>
<td>0,02</td>
</tr>
<tr>
<td>Ba</td>
<td>47,9 18,3 (5)</td>
<td>27,5</td>
<td>15,0</td>
<td>3,85</td>
<td>28,4</td>
<td>9,44 (5)</td>
<td>40,6</td>
<td>5,4</td>
</tr>
<tr>
<td>La</td>
<td>0,02 0,001 (2)</td>
<td>0,87</td>
<td>0,10</td>
<td>20,6</td>
<td>0,17</td>
<td>0,6 (6)</td>
<td>0,39</td>
<td>0,02</td>
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<tr>
<td>Ce</td>
<td>0,07</td>
<td>2,13</td>
<td>0,21</td>
<td>51,2</td>
<td>0,38</td>
<td>0,13 (6)</td>
<td>0,96</td>
<td>0,04</td>
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<tr>
<td>Pr</td>
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<td>0,31</td>
<td>0,03</td>
<td>6,32</td>
<td>0,04</td>
<td>0,01 (7)</td>
<td>0,14</td>
<td>0,01</td>
</tr>
<tr>
<td>Nd</td>
<td>0,10</td>
<td>1,72</td>
<td>0,23</td>
<td>25,8</td>
<td>0,29</td>
<td>0,05 (6)</td>
<td>0,75</td>
<td>0,04</td>
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<tr>
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<td>0,47</td>
<td>0,10</td>
<td>13,1</td>
<td>0,19</td>
<td>0,06 (3)</td>
<td>0,23</td>
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<tr>
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<td>0,13</td>
<td>0,04</td>
<td>5,11</td>
<td>0,07</td>
<td>0,02 (4)</td>
<td>0,08</td>
<td>0,01</td>
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<tr>
<td>Gd</td>
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<td>5,17</td>
<td>0,22</td>
<td>0,07 (3)</td>
<td>0,30</td>
<td>0,03</td>
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<tr>
<td>Dy</td>
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<td>0,17</td>
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<td>0,04 (6)</td>
<td>0,34</td>
<td>0,03</td>
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<tr>
<td>Er</td>
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<td>0,59</td>
<td>0,14</td>
<td>6,00</td>
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<td>0,28</td>
<td>0,03</td>
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<tr>
<td>Tm</td>
<td>0,09 0,03 (4)</td>
<td>0,55</td>
<td>0,11</td>
<td>12,5</td>
<td>0,11</td>
<td>0,03 (6)</td>
<td>0,29</td>
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</tr>
<tr>
<td>Dy</td>
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<td>0,08</td>
<td>0,02</td>
<td>0,82</td>
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<td>0,003</td>
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<tr>
<td>Hf</td>
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<td>b.d.</td>
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<td>0,01 (5)</td>
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<td>0,01</td>
</tr>
<tr>
<td>Ta</td>
<td>0,04 0,02 (3)</td>
<td>b.d.</td>
<td>0,04</td>
<td>0,03</td>
<td>0,04</td>
<td>0,01 (3)</td>
<td>0,01</td>
<td>0,003</td>
</tr>
<tr>
<td>Pb</td>
<td>b.d.</td>
<td>0,26</td>
<td>(1)</td>
<td>b.d.</td>
<td>0,40</td>
<td>(1)</td>
<td>0,09</td>
<td>0,003</td>
</tr>
<tr>
<td>Th</td>
<td>0,003 0,001 (4)</td>
<td>0,10</td>
<td>0,01</td>
<td>0,01</td>
<td>0,03</td>
<td>0,01 (7)</td>
<td>0,04</td>
<td>0,002</td>
</tr>
<tr>
<td>U</td>
<td>0,020 0,01 (5)</td>
<td>0,04</td>
<td>0,01</td>
<td>0,09</td>
<td>0,03</td>
<td>0,01 (7)</td>
<td>0,03</td>
<td>0,003</td>
</tr>
</tbody>
</table>

Rb, Sr, Y, Zr, Nb, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Dy, Er, Tm, Dy, Hf, Ta, Pb, Th, U.
The elements are in the order of atomic weight with exception of those in Fe,Ni and bulk macro elements data ordered by volatility; \(^1\)the grain on the contact with melt pocket of type 2; \(^2\)the calculated average microelement composition of the silicate component of the NWA 6486 based on LA determination of microelement compositions and mineral modes; \(^3\)an error of calculation of average composition of silicate component; \(^4\)calculated silicate portion based on EPMA and mineral modes.
Table 5. Concentrations of Ar isotopes (in ccm STP/g) and apparent ages (in Ma) for each temperature extraction of NWA 6486 whole rock (35.4 mg).

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>$^{36}$Ar×10^{-11}</th>
<th>$^{38}$Ar×10^{-11}</th>
<th>$^{39}$Ar×10^{-11}</th>
<th>$^{40}$Ar×10^{-9}</th>
<th>$^{40}$Ar-$^{39}$Ar age</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>27±2</td>
<td>6±1</td>
<td>3.6±0.5</td>
<td>85±5</td>
<td>4521±200</td>
</tr>
<tr>
<td>500</td>
<td>61±2</td>
<td>13±1</td>
<td>104±3</td>
<td>259±6</td>
<td>1423±21</td>
</tr>
<tr>
<td>560</td>
<td>24±2</td>
<td>5±1</td>
<td>206±7</td>
<td>247±6</td>
<td>821±15</td>
</tr>
<tr>
<td>600</td>
<td>25±2</td>
<td>5±2</td>
<td>769±14</td>
<td>635±10</td>
<td>605±5</td>
</tr>
<tr>
<td>650</td>
<td>34±2</td>
<td>5±2</td>
<td>943±16</td>
<td>728±11</td>
<td>572±4</td>
</tr>
<tr>
<td>680</td>
<td>29±1</td>
<td>6±2</td>
<td>725±14</td>
<td>568±9</td>
<td>579±4</td>
</tr>
<tr>
<td>700</td>
<td>22±1</td>
<td>5±1</td>
<td>498±10</td>
<td>401±7</td>
<td>592±5</td>
</tr>
<tr>
<td>720</td>
<td>26±1</td>
<td>6±1</td>
<td>524±11</td>
<td>435±8</td>
<td>607±5</td>
</tr>
<tr>
<td>760</td>
<td>30±8</td>
<td>6±3</td>
<td>1022±50</td>
<td>790±30</td>
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<tr>
<td>800</td>
<td>52±2</td>
<td>12±3</td>
<td>1262±24</td>
<td>1039±18</td>
<td>604±4</td>
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<tr>
<td>850</td>
<td>144±3</td>
<td>30±3</td>
<td>1550±24</td>
<td>1673±25</td>
<td>756±3</td>
</tr>
<tr>
<td>880</td>
<td>139±4</td>
<td>31±3</td>
<td>1281±36</td>
<td>1566±44</td>
<td>836±3</td>
</tr>
<tr>
<td>920</td>
<td>174±5</td>
<td>38±4</td>
<td>1509±42</td>
<td>1801±50</td>
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</tr>
<tr>
<td>950</td>
<td>169±5</td>
<td>37±3</td>
<td>1361±39</td>
<td>1588±44</td>
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<tr>
<td>970</td>
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<td>27±2</td>
<td>1027±30</td>
<td>1242±35</td>
<td>829±5</td>
</tr>
<tr>
<td>1000</td>
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<td>22±2</td>
<td>773±23</td>
<td>984±28</td>
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<tr>
<td>1040</td>
<td>57±2</td>
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<td>628±7</td>
<td>738±5</td>
<td>811±5</td>
</tr>
<tr>
<td>1070</td>
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<td>588±8</td>
<td>515±5</td>
<td>636±5</td>
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<tr>
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<td>28±2</td>
<td>15±2</td>
<td>753±11</td>
<td>515±5</td>
<td>515±5</td>
</tr>
<tr>
<td>1140</td>
<td>16±1</td>
<td>14±2</td>
<td>651±13</td>
<td>335±5</td>
<td>400±5</td>
</tr>
<tr>
<td>1170</td>
<td>16±1</td>
<td>14±1</td>
<td>461±15</td>
<td>206±5</td>
<td>352±7</td>
</tr>
<tr>
<td>1220</td>
<td>21±1</td>
<td>15±1</td>
<td>310±14</td>
<td>149±5</td>
<td>376±11</td>
</tr>
<tr>
<td>1450</td>
<td>130±3</td>
<td>43±1</td>
<td>420±8</td>
<td>509±7</td>
<td>829±10</td>
</tr>
<tr>
<td>1700</td>
<td>130±7</td>
<td>40±3</td>
<td>308±23</td>
<td>486±25</td>
<td>1020±41</td>
</tr>
<tr>
<td>Total</td>
<td>1613±16</td>
<td>423±10</td>
<td>17677±119</td>
<td>17495±108</td>
<td>704±5</td>
</tr>
</tbody>
</table>

The amounts of short-lived $^{37}$Ar in temperature fractions are poorly constrained because the sample was measured in significant time after irradiation and they are not presented here. The apparent ages are calculated by applying a small nominal correction of primordial trapped argon from $^{40}$Ar, assuming $^{40}$Ar/$^{36}$Ar=1±1 in each temperature extraction. All uncertainties are 1σ.
**Table 6. Possible mechanisms of the melt vein formation in NWA 6486.**

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
</table>
| 1 | 1. L-chondrite precursor of NWA 6486 enriched in K.             | 2. Impact event I (470 Ma); probably catastrophic breakup of L chondrite parent body; Formation of NWA 6486 and similar rocks as the impact melts with variable metal and sulfide contents, injected into the crater floor fractures. | 3A. Aqueous alteration of NWA 6486
3B. Aqueous alteration of NWA 6486-like rock.  
3C. Impact event II; Icy projectile strikes the target contained NWA 6486; evaporation of the projectile and impact melting of the target were followed by an injection of vapor-melt mixture through the fractures in to the host rock. |
| 2 | 3A. Aqueous alteration of NWA 6486                             | 3B. Aqueous alteration of NWA 6486-like rock.                    | 3C. Decreasing of the pressure of vapor-melt mixture and formation of super-critical fluid; further pressure drop and precipitation of the FeO-SiO2-MgO melt as veins; exhausting of the remained K Na Ca Al-bearing fluid through the fractures. |
| 3 | 4A. Impact event; *in situ* shock melting of altered material around the fractures. | 4B. Impact event II on the complex target of NWA 6486 and altered NWA 6486-like mixture and formation of super-critical fluid; Impact melting of the altered rock and further pressure drop and precipitation of the injection of the melt into the fractures in the FeO-SiO2-MgO melt as veins; exhaustion of NWA 6486; formation of the veins and melt pockets. |