The Kumtag Meteorite Strewn Field

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Abstract

The Kumtag meteorite strewn field was found in the Kumtag desert, 132 kilometers south of Hami city in the Xinjiang province, China. It is an ellipse of 2.5×7.9 km, with a long axis extending along the northeast-southwest direction. The largest individual meteorite of the strewn field weighs about 10 kg; the smallest individual has a mass of only 27 g. In total more than 100 individuals with a total mass of more than 180 kg were collected. The Kumtag meteoroid entered the atmosphere in the direction Northeast-Southwest. All meteorites collected in this strewn field are samples from the same unique meteorite shower. The Kumtag meteorite is an H5 ordinary chondrite with a shock stage S2, and a weathering grade W2. The cosmic ray exposure age of Kumtag is 6.7 ± 0.8 Ma, which is rather typical for H chondrites and which indicates that Kumtag was derived from the massive impact event on its parent body ~7 Ma ago. A significant He amount has been released during certain unknown process(es) before the Kumtag meteorite was ejected from its parent body.

Introduction

A meteorite is an extraterrestrial rock surviving its fall through the Earth atmosphere, which can provide crucial information about the early solar system but also about the dynamics of small bodies in the solar system. To date, meteorites found in Antarctica and hot deserts make up 55% and 45%, respectively, of all meteorites currently in our collections (Meteoritical Bulletin Database). Compared to the sometimes difficult meteorite search expeditions in Antarctica, more and more meteorite hunters prefer to search for meteorites in hot deserts due to the advantages of low costs, relatively low risks, and relatively comfortable working environments. To date, a large number of meteorites are found in many hot deserts worldwide. The regions include the Atacama (Muñoz et al. 2007; Gattacceca et al. 2011; Hutzler et al. 2016), Sahara (Bischoff and Geiger 1995; Schluter et al. 2002; Ouazaa et al. 2009), Southwestern United States (Zolensky et al. 1990; Rubin et al. 2000; Kring et al. 2001; Hutson et al. 2013), the Lut Desert in Iran (Pourkhorsandi et al. 2013, 2019), and the Xinjiang Province in China (Li et al. 2014, 2017; Zeng et al. 2018). Although large number meteorites from hot deserts have been studied over the years, there are only very few studies of meteorites from China.

The Kumtag meteorite strewn field is located east of the Kumtag sand levee, which is 132 kilometers from Hami city, Xinjiang, China. The strewn field is almost an ellipse, with its long axis extending from northeast to southwest. After its first discovery in 2008, more than 150 individual meteorites with a total mass of more than 180 kg have been collected during more than 20 successive meteorite searching campaigns. All individuals are named Kumtag in the Meteoritical Bulletin Database (MBD).

Here we present and discuss the physical geographic features and the geological background of the strewn field and we will mention the process of meteorite search. Furthermore, we will report the petrological characteristics and the cosmic ray exposure (CRE) ages of representative meteorites from this strewn field. In addition, we will give the gas retention age and the preatmospheric size.

Geographical Features And Geological Background Of The Strewn Field

The area of the meteorite strewn field is characterized by harsh natural conditions, including extreme droughts, a complex geomorphology, and diverse dune types, especially the unique feather dune. The elevation of the strewn field is between 1130 and 1190 meters above sea level (ASL), the average elevation is about 1170 meters ASL, and the change in altitude across the strewn field is about 20-60 meters. The area of the Kumtag meteorite strewn field is in the inland arid region, where the average annual temperature ranges from more than 40°C at the high end down to -30°C at the low end. The Kumtag desert is far away from the ocean—therefore only very little water vapor can reach the desert from the warm and wet air originating over the Pacific Ocean. From the other side, the Qinghai-Tibetan Plateau acts as a natural barrier, only a small part of the water vapor from Indian Ocean can cross the Hengduan Mountains. The area of Kumtag is extreme arid with an average annual precipitation of not more than 25 mm. The average annual evaporation is higher than 3000 mm and the relative humidity is between 35%-43% (Yang et al. 2012).

In this strewn-field area magmatic rocks are widely exposed (Fig. 1a); the most widely exposed rocks are gray-white and light-red granites formed in the Variscan period (Zhang et al. 2010). Other, intrusive rocks, in this field mostly consist of norite gabbro, grey-green gabbro, and quartz diorite, which were formed in the early Variscan period (prior the intrusion of granite) (Zhang et al. 2010). The surface rock is badly weathered and has been broken into sand and centimeter-sized rubble (Fig. 1b, c). The lower terrain is often covered with a thin layer of sands (Fig. 1d).

Meteorite distribution in the Strewn field

The first meteorite in this strewn field was accidentally found by one of coauthors (Peng Wang) in October 9, 2008, during his geological field work. A piece of a fractured black rock was collected on a granite pluton. After being broken with a geological hammer, silver white metal spots were observed on the fresh broken surface of this rock and it has therefore been identified as a possible meteorite. A piece of the meteorite with a mass of 969 g was donated to the Purple Mountain Observatory, Chinese Academy of Sciences in 2009. This piece was later named Kumtag (H5) by the Meteorite Nomenclature Committee. In the next eight years, about 130 meteorites have been collected by Peng Wang and his team of geologists in search campaigns either by foot or using cars. Among these meteorites, the GPS coordinates of 95 of them are known. In addition, for more than 40 kilograms the found coordinates are not known or have not been recorded because they have been collected by other meteorite hunters in this field.

According to the GPS coordinates, meteorites collected east of the Kumtag sand levee cover approximately an ellipse with dimensions 2.5×7.9 km, with a long axis extending from the northeast to the southwest (Fig. 2). In addition, meteorite sizes gradually increase along the long axis (northeast – southwest orientation). Meteorites collected near the northeast edge are usually less than 500 g in weight, while samples from the southwest edge are usually over 1 kg in mass. The largest individual (11.05 kg) was collected at the southwest border of this elliptical area. The study of the Jilin meteorite and other meteorite strewn fields demonstrate that the largest fragments have the longest flightpath, i.e., it indicates the upper end of the strewn field, and usually there is a size-sorting of fragments, i.e., the smallest fragment falls earliest (Joint investigation group of "Jilin meteorite shower". 1977; Simon et al. 2004; Gnos et al. 2009; Li et al. 2017; Zeng et al. 2018; Li et al. 2020). The location and the distribution of the fragments definitely suggests that (1) this collection area is a meteorite strewn field and (2) the entry direction of the Kumtag parent meteorite into the Earth atmosphere was from the northeast to the southwest (Fig. 2).

In addition, the Kumtag 049 meteorite found close to this strewn field is not part of this meteorite shower. Kumtag 049 is a L group meteorite (MBD) that has been found about 2 km away from the nearest strewn field samples (see Fig. 2).

Samples And Methods

In this study, eight meteorites (labeled kumtag-2 - kumtag-9) from the strewn field were selected for petrographic studies and mineral in situ chemical analysis. One sample was selected for measurements of the isotopic concentrations of the light noble gases (He, Ne, and Ar). The petrographic investigations and the backscattered electron (BSE) images were performed at the Lunar and Planetary Science Research Center, Institute of Geochemistry, Chinese Academy of Sciences, using an FEI-Scios Feld Emission Scanning Electron Microscope (FE-SEM). The instrument was operated at an acceleration voltage of 15–20 kV, a beam current of 3.2–6.4 nA, and a working distance of 7–10 mm. The electron microprobe analysis of olivine and low-calcium pyroxene was carried out at the Guilin University of Technology. The instrument used was a JXA 8230 electron probe, the analysis voltage was 15 kV, the beam current was 20 nA, and the beam spot diameter was 1 μm . The analysis results were corrected using the ZAF method. The noble gas isotopic concentrations were measured using two self-made noble gas mass spectrometers at the University of Bern, Switzerland, following the procedure previously described by Li et al. (2017).

Results And Discussion

The Appearance and Petrology of Meteorites

Kumtag meteorites show various surface characteristics. Some stones are completely covered with black fusion crust and show well developed regmaglypts (Fig. 3a). Part of the meteorites in contact with the desert sand are often covered with rust (Fig. 3b), which was formed during terrestrial weathering. Note that the rusty spot on the ground-touching surface is very often a strong indicator for hot-desert meteorites, especially for relatively iron-rich ordinary chondrites, particularly from the H group. The largest meteorite of the strewn field with a mass of 10.05 kg is shown in Fig. 3c. The individual is only on one side covered with fusion crust and regmaglypts; the broke surface indicates the meteorite fragment was even bigger (Fig. 3c). Highly fractured meteorites were also collected; their cracks were often partially filled with sand (Fig. 3d). In hot desert environments, meteorites often break into dozens of pieces during their landing and/or during terrestrial weathering (Fig. 3e). Two meteorites with a secondary fusion crust were collected. From the geometry is obvious that these two objects belong to the same fragment of the meteorite shower (Fig. 3f).

The eight studied Kumtag meteorite samples have similar mineral composition, shock characteristics, and weathering grade. The meteorites are mainly composed of olivine, pyroxene, plagioclase, Fe-Ni metal, troilite, and some weathering products (Fig. 4). Texturally, the boundaries of the chondrules are vague but distinct. The plagioclase grain size is mostly between 2 ~ 50 μm . Consequently, Kumtag is a type 5 chondrite (Van Schmus and Wood 1967). The average fayalite (Fa) content of olivines and the average ferrosilite (Fs) content of the low-Ca pyroxenes are 18.50 ± 0.31 mol% and 16.60 ± 0.69 mol% (Table 1), respectively, clearly indicating that Kumtag is a H chondrite (Brearley and Jones 1998; Weisberg et al. 2006). On the polished section and under the electron microscope most of the olivine grains show irregular fractures and wavy edges. None of the studied sections showed shock induced melt veins, which suggests that the meteorites suffered relatively weak shock corresponding to shock stage S1 or S2 (Stoffler et al. 1991). In the studied sections, about 25 vol% of the Fe-Ni metal has been replaced by weathering products, indicating weathering degree W2 (Wlotzka 1993).

Table 1

Electron probe analysis of olivine (Ol) and pyroxene (Pyx) in Kumtag meteorite. The uncertainties are 1SD, Ol represents olivine and Pyx represents pyroxene.

Sample	mineral	Na ₂ O	MgO	Al ₂ O ₃	K ₂ O	FeO	MnO	TiO ₂	CaO	NiO	Cr ₂ O ₃	SiO ₂	Total	Fa/Fs
Kumtag-2	Ol	0.01 ± 0.01	29.6 ±0.9	0.16 ± 0.02	0.03 ± 0.01	10.8 ±0.1	1.16 ± 0.07	0.41 ± 0.18	0.84 ± 0.03	0.05 ± 0.07	0.19 ± 0.05	56.1 ±1.2	99.4 ±0.4	18.6 ±0.3
	Pyx	0.00 ± 0.01	42.0 ±0.9	0.01 ± 0.01	0.01 ± 0.01	17.2 ±0.5	1.06 ± 0.10	0.07 ± 0.09	0.03 ± 0.01	0.03 ± 0.02	0.02 ± 0.02	39.1 ±0.6	99.6 ±0.9	16.9 ±0.3
Kumtag-3	Ol	0.00 ± 0.00	29.9 ±1.9	0.12 ± 0.03	0.03 ± 0.05	10.8 ±0.2	1.15 ± 0.30	0.06 ± 0.06	0.53 ± 0.29	0.03 ± 0.01	0.13 ± 0.01	55.6 ±1.6	98.5 ±0.6	18.3 ±0.2
	Pyx	0.01 ± 0.02	43.2 ±0.4	0.00 ± 0.00	0.04 ± 0.03	17.2 ±0.1	1.13 ± 0.04	0.06 ± 0.03	0.03 ± 0.01	0.02 ± 0.02	0.00 ± 0.00	38.2 ±0.1	100.0 ±0.3	16.4 ±0.6
Kumtag-4	Ol	0.03 ± 0.01	30.3 ±0.1	0.30 ± 0.15	0.04 ± 0.05	11.3 ±0.5	1.08 ± 0.11	0.59 ± 0.18	0.78 ± 0.01	0.03 ± 0.04	0.23 ± 0.14	54.4 ±.9	99.0 ±1.1	18.5 ±0.3
	Pyx	0.01 ± 0.01	42.6 ±1.1	0.00 ± 0.01	0.00 ± 0.00	17.2 ±0.1	0.99 ± 0.16	0.14 ± 0.07	0.02 ± 0.01	0.03 ± 0.22	0.01 ± 0.01	37.6 ±0.5	98.6 ±0.5	16.9 ±0.7
Kumtag-5	Ol	0.02 ± 0.01	30.1 ±0.6	0.21 ± 0.02	0.02 ± 0.03	11.0 ±0.3	1.15 ± 0.13	0.39 ± 0.12	0.82 ± 0.01	0.04 ± 0.01	0.18 ± 0.03	55.1 ±0.5	98.9 ±0.7	18.7 ±0.4
	Pyx	0.10 ± 0.19	42.3 ±1.4	0.01 ± 0.01	0.02 ± 0.03	17.3 ±0.2	1.09 ± 0.11	0.05 ± 0.10	0.03 ± 0.02	0.01 ± 0.01	0.01 ± 0.03	38.0 ±0.9	98.9 ±0.4	16.8 ±0.1
Kumtag-6	Ol	0.04 ± 0.01	30.9 ±0.1	0.15 ± 0.03	0.01 ± 0.01	11.4 ±0.5	1.16 ± 0.04	0.14 ± 0.09	0.68 ± 0.03	0.01 ± 0.01	0.15 ± 0.01	53.9 ±0.2	98.6 ±0.7	18.5 ±0.4
	Pyx	0.01 ± 0.01	42.4 ±0.3	0.01 ± 0.02	0.01 ± 0.01	17.2 ±0.4	1.01 ± 0.04	0.04 ± 0.05	0.03 ± 0.02	0.03 ± 0.03	0.01 ± 0.01	38.0 ± 0.40	98.7 ±0.5	17.0 ±0.6
Kumtag-7	Ol	0.01 ± 0.01	30.9 ±.01	0.26 ± 0.09	0.00 ± 0.00	10.7 ±0.1	1.11 ± 0.15	0.59 ± 0.11	0.67 ± 0.13	0.02 ± 0.02	0.18 ± 0.10	55.3 ±0.1	99.8 ±0.6	18.5 ±0.4
	Pyx	0.03 ± 0.02	42.8 ±0.7	0.01 ± 0.02	0.00 ± 0.01	17.2 ±0.3	0.95 ± 0.11	0.03 ± 0.05	0.01 ± 0.01	0.01 ± 0.02	0.01 ± 0.01	38.9 ±0.6	100.0 ±1.0	16.1 ±0.1
Kumtag-8	Ol	0.00 ± 0.00	31.3 ±0.6	0.26 ± 0.15	0.04 ± 0.06	10.9 ±0.2	1.25 ± 0.09	0.45 ± 0.13	0.69 ± 0.03	0.03 ± 0.01	0.41 ± 0.35	53.2 ±1.1	98.5 ±0.7	18.5 ±0.3
	Pyx	0.02 ± 0.01	42.8 ±0.8	0.02 ± 0.02	0.01 ± 0.01	17.4 ±0.2	0.93 ± 0.15	0.03 ± 0.04	0.05 ± 0.03	0.06 ± 0.07	0.02 ± 0.02	38.4 ±0.4	99.7 ±0.9	16.1 ±0.5
Kumtag-9	Ol	0.02 ± 0.01	30.7 ±0.8	0.11 ± 0.01	0.01 ± 0.01	11.2 ±1.0	1.10 ± 0.09	0.11 ± 0.19	0.64 ± 0.19	0.06 ± 0.06	0.12 ± 0.01	55.8 ±0.7	99.8 ±0.8	18.5 ±0.3
	Pyx	0.01 ± 0.02	43.0 ±0.6	0.01 ± 0.01	0.00 ± 0.01	17.4 ±0.4	1.11 ± 0.10	0.12 ± 0.10	0.03 ± 0.01	0.03 ± 0.02	0.02 ± 0.02	38.5 ±0.7	100.2 ±0.6	16.8 ±1.5

Cosmic-Ray Exposure Ages, Preatmospheric size, and Gas Retention Ages

The concentrations and isotopic ratios of the light noble gases He, Ne, and Ar were measured in one Kumtag meteorite. The results, corrected for blank contributions and instrumental mass fractionation, are shown in Table 2. For the component deconvolution, we assume that the measured Ne and Ar concentrations are mixtures between cosmogenic (“c”) and trapped (“tr”) components, the latter being atmospheric contamination. Note that atmospheric contamination is very common for hot desert, weathered meteorites (e.g., Huber et al. xxx). For calculating $^{21}\text{Ne}_c$ and $^{38}\text{Ar}_c$ via the component deconvolution we use the following endmembers: $(^{20}\text{Ne}/^{22}\text{Ne})_c = 0.84$, $(^{36}\text{Ar}/^{38}\text{Ar})_c = 0.65$, $(^{20}\text{Ne}/^{22}\text{Ne})_{\text{air}} = 9.80$, $(^{21}\text{Ne}/^{22}\text{Ne})_{\text{air}} = 0.029$, and $(^{36}\text{Ar}/^{38}\text{Ar})_{\text{air}} = 5.35$ (Eberhardt et al. 1965; Lee et al. 2006). Note that the cosmogenic endmember composition $(^{20}\text{Ne}/^{22}\text{Ne})_c = 0.84$ corresponds to the measured ratio, which clearly indicates that the amount of atmospheric contamination for Ne isotopes is only very minor. We further assume that the measured ^3He concentration is entirely cosmogenic. The thus calculated cosmogenic $^{21}\text{Ne}_c$ and $^{38}\text{Ar}_c$ concentrations are given in Table 3. The production rates were calculated using the model by Eugster (1988) and the cosmic-ray exposure (CRE) ages are given in Table 4. The CRE ages T_3 , T_{21} , and T_{38} , based on $^3\text{He}_c$, $^{21}\text{Ne}_c$, and $^{38}\text{Ar}_c$ concentrations, respectively, of the Kumtag meteorite are 6.3 ± 1.9 Ma, 6.2 ± 1.9 Ma, and 7.7 ± 2.4 Ma, respectively. The grand average CRE age is 6.7 ± 0.8 Ma, which represents the CRE age of the Kumtag strewn field meteorite. The weathering degree of the Kumtag strewn field is W2, indicating a relatively short terrestrial age. From this finding it is therefore safe to assume that the CRE age of Kumtag is very close to the ejection age, i.e., 6.7 ± 0.8 Ma. The thus determined CRE (or ejection) age is consistent with typical CRE ages for other H chondrites, which have a peak centered at about 7 Ma in the CRE age histogram (Herzog 2007). The preatmospheric size and the mass of a meteorite can be estimated using the cosmogenic $(^{22}\text{Ne}/^{21}\text{Ne})_c$ ratio, which is a known indicator for shielding (Bhandari et al. 1980; Leya and Masarik 2009). From the empirical equation given by Bhandari et al. (1980) and the $(^{22}\text{Ne}/^{21}\text{Ne})_c$ ratio of 1.083 ± 0.017 , we calculate a preatmospheric mass of 115.8 ± 32.6 kg, which is in contradiction to the total recovered mass of all Kumtag meteorites of > 180 kg. Possibilities to account for such a difference are i) Kumtag was not a spherical object and the effective radius was much smaller than the estimated radius, ii) the correlation between $(^{22}\text{Ne}/^{21}\text{Ne})_c$ and spherical size deduced from Bhandari et al. (1980) is not applicable for the Kumtag meteorite because this special sample might come from an outer layer of the meteorite. Note also that the correlation given by Bhandari et al. (1980) only gives a lower limit for the preatmospheric mass (Zeng et al. 2018). From the total recovered mass of ~ 180 kg, an average bulk density of 3.567 g/cm^3 , and assuming an ablation loss of $\sim 87\%$ (Bhandari et al. 1980) we calculate a pre-atmospheric radius of ~ 45 cm (Li et al. 2019).

Table 2

He, Ne, and Ar isotopic concentrations of the Kumtag meteorite ($10^{-8} \text{ cm}^3 \text{ STP g}^{-1}$).

Meteorite	Type	Mass (mg)	^3He	^4He	^{22}Ne	^{36}Ar	^{40}Ar	$^{20}\text{Ne}/^{22}\text{Ne}$	$^{21}\text{Ne}/^{22}\text{Ne}$	$^{36}\text{Ar}/^{38}\text{Ar}$
Kumtag	H5	71.33	10.1 ± 0.6	877 ± 48	2.61 ± 0.19	0.989 ± 0.034	4367 ± 76	0.846 ± 0.013	0.919 ± 0.014	1.88 ± 0.05

Table 3

Cosmogenic and radiogenic noble gases of the Kumtag meteorite ($10^{-8} \text{ cm}^3 \text{ STP g}^{-1}$). “c” and “r” represent cosmogenic and radiogenic nuclides components.

Meteorite	Type	Mass (mg)	$^3\text{He}_c$	$^{21}\text{Ne}_c$	$^{38}\text{Ar}_c$	$(^{22}\text{Ne}/^{21}\text{Ne})_c$	$^4\text{He}_r$	$^{40}\text{Ar}_r$
Kumtag	H5	71.33	10.1 ± 0.6	2.40 ± 0.18	0.385 ± 0.027	1.083 ± 0.017	827 ± 48	4147 ± 72

Table 4

Cosmic-ray exposure ages and retention ages of the Kumtag meteorite (in Ma). The gas retention ages were calculated using average K, U, Th, and Sm concentrations for H ordinary chondrites (Lodders and Fegley 1998).

Meteorite	Type	Mass (mg)	T_3	T_{21}	T_{38}	Adopted age	T_4	T_{40}	T_3/T_{21}	T_4/T_{40}
Kumtag	H5	71.33	6.3 ± 1.9	6.2 ± 1.9	7.7 ± 2.4	6.7 ± 0.8	2508 ± 170	3908 ± 227	1.02 ± 0.44	0.64 ± 0.06

For calculating the ^4He gas retention age of the Kumtag meteorite, we use the average U, Th, and K concentrations for H-group ordinary chondrites given by Lodders and Fegley (1998). The concentration of radiogenic ^4He ($^4\text{He}_r$) and ^{40}Ar ($^{40}\text{Ar}_r$) have been determined by

subtracting cosmogenic ^4He and trapped ^{40}Ar contributions, respectively (Table 3). The thus determined gas retention ages are $T_4 = 2508 \text{ Ma}$ and $T_{40} = 3908 \text{ Ma}$ (Table 4), i.e., T_4 is significantly lower than T_{40} . Consequently, the Kumtag meteorite plots to the left of the solid line with slope 1 (Fig. 5). In this diagram, samples with identical CRE ages based on ^3He and ^{21}Ne plot close to 1 on the y-axis and samples with identical T_4 and T_{40} plot close to 1 on the x-axis. Samples that simultaneously lost ^3He and ^4He move along the line with slope 1. For the studied meteorite we have $T_3/T_{21} = 1.02 \pm 0.44$ and $T_4/T_{40} = 0.64 \pm 0.06$. The T_3/T_{21} ratio of 1.02 ± 0.44 suggests no or only minor losses of cosmogenic ^3He and/or ^3He . This finding is further confirmed when studying the data in a diagram $(^3\text{He}/^{21}\text{Ne})_c$ vs. $(^{22}\text{Ne}/^{21}\text{Ne})_c$, i.e., in the Bern-plot (Nishiizumi et al. 1980) (Fig. 6). Also, this data indicates no or only little losses of cosmogenic ^3He and/or ^3He .

In contrast, the ratio T_4/T_{40} of 0.64 ± 0.06 is significantly lower than 1, indicating loss of radiogenic ^4He . Since the ^4He loss is not accompanied by ^3He loss, it likely occurred before ejection of the Kumtag meteorite from the H chondrite parent body. The exact reason for the loss of radiogenic He is unclear but it might be connected to the severe heating of the H-chondrite parent body, remember that Kumtag is a type 5 H-chondrite. It is unlikely that the ^4He loss was caused by a shock event, because the studied Kumtag individual has a shock stage of only S2. However, it cannot be excluded that the ^4He and/or ^{40}Ar gas retention age are too high or too low due to wrong assumptions about U, Th, and K concentrations.

Conclusions

The Kumtag meteorite strewn field has an elliptical shape with a long axis of about 7.9 km and a short axis of about 2.5 km. The entry direction of the Kumtag meteorite was in the direction northeast-southwest. The meteorites collected in the Kumtag strewn field are typical H5 ordinary chondrites, which suffered relative weak shock and low weathering. Compared to most other desert meteorites, the Kumtag meteorites show a relatively low degree of weathering. This either suggest that the terrestrial ages of Kumtag is low and/or that the extremely dry conditions slow weathering processes down. The CRE age of Kumtag is $6.7 \pm 0.8 \text{ Ma}$, which is likely very close to the ejection age. The ^3He and ^{21}Ne CRE ages and ^4He and ^{40}Ar gas retention ages indicate that the material now forming the Kumtag meteorite likely lost radiogenic ^4He before ejection from the parent body.

Abbreviations

MBD: Meteoritical Bulletin Database

ASL: above sea level

BSE: backscattered electron

Fa: fayalite

Fs: ferrosilite

CRE: cosmic-ray exposure

Declarations

Availability of data and materials

The data and materials are available upon request from the first author Ke Du (e-mail: duke@mail.gyig.ac.cn).

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Author Contributions

Ke Du prepared the paper draft. Shijie Li, Ingo Leya, Thomas Amith and Dongliang Zhang determined the noble gas data, and calculated the element ratios and CRE ages. Peng Wang collected and provided the samples. All authors participated in the discussion of results and contributed to the editing of the final manuscript. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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Figures

Figure 1

Surface features of the Kumtag meteorite collection area. (a) The meteorite collection area consists of granite (reddish) and gabbro (dark areas); (b, c) The surface is covered with the mixture of gravel and sand. The lower right of panel (b) shows a meteorite (indicated by the arrow), to the left of the meteorite there is a GPS for scale. The black rock shown in the middle of panel (c) is also a meteorite (indicated by the arrow). (d) The lower part of the meteorite strewn field is covered with a thin layer of sand.

Figure 2

Map of the Kumtag meteorites strewn field (Kumtag desert, Xinjiang Province, China). The green circles represent the meteorites found in the strewn field. The position of the (unpaired) L group meteorite Kumtag 049 (the red solid spot) is also shown. (The base map from Google Earth).

Figure 3

Photographs of the selected Kumtag meteorites. (a, b) A single meteorite having a mass of 7470 g. Panel (a) shows the surface with black fusion crust and well developed regmaglypts. Panel (b) shows the surface buried in desert. (c) A 10.05 kg meteorite with brown-black surface and fusion crust. (d, e) Broken meteorites of this strewn field. (f) Two meteorites that are part of the same fragment showing secondary fusion crust.

Figure 4

Backscattered electron images of Kumtag. Panels a-h show the images for Kumtag-2 to Kumtag-9 respectively. The visible minerals include olivine, pyroxene, plagioclase, and veinlets filled with iron oxide. The Fe-Ni metal has been partially replaced by weathering products. The labeled minerals include olivine (ol), pyroxene (px), plagioclase (pl), and Fe-oxides (Fe-ox).

Figure 5

Ratio of CRE ages (T_3/T_{21}) versus ratios of gas retention ages (T_4/T_{40}) for the studied Kumtag meteorite (red solid circle). T_3/T_{21} ratios between the two dotted lines indicate that there is no ^3He deficit, which is very often due to ^3He and/or ^3He losses. The relatively low T_4/T_{40} ratio of the Kumtag meteorite indicates loss of radiogenic ^4He before its ejection from the parent body.

Figure 6

Correlation of $(^3\text{He}/^{21}\text{Ne})_c$ versus $(^{22}\text{Ne}/^{21}\text{Ne})_c$ for the Kumtag meteorite (the red circle). The solid line is the best fit line given by Nishiizumi et al. (1980). The dashed lines represent the $\pm 15\%$ variations from this correlation.

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