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Itqiy: A study of noble gases and oxygen isotopes including its terrestrial age and a comparison with Zakłodzie

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Abstract–We report noble gas, oxygen isotope, ^{14}C and ^{10}Be data of Itqiy as well as noble gas, ^{14}C and ^{10}Be results for Zakłodzie. Both samples have been recently classified as anomalous enstatite meteorites and have been compared in terms of their mineralogy and chemical composition.

The composition of enstatite and kamacite and the occurrence of specific sulfide phases in Itqiy indicate it formed under similar reducing conditions to those postulated for enstatite chondrites. The new results now seem to point at a direct spatial link.

The noble gas record of Itqiy exhibits the presence of a trapped subsolar component, which is diagnostic for petrologic types 4–6 among enstatite chondrites. The concentration of radiogenic ^{4}He is very low in Itqiy and indicates a recent thermal event. Its ^{21}Ne cosmic-ray exposure age is 30.1 ± 3.0 Ma and matches the most common age range of enstatite chondrites (mostly EL6 chondrites) but not that of Zakłodzie.

Itqiy's isotopic composition of oxygen is in good agreement with that observed in Zakłodzie as well as those found in enstatite meteorites suggesting an origin from a common oxygen pool. The noble gas results, on the other hand, give reason to believe that the origin and evolution of Itqiy and Zakłodzie are not directly connected.

Itqiy's terrestrial age of 5800 ± 500 years sheds crucial light on the uncertain circumstances of its recovery and proves that Itqiy is not a modern fall, whereas the ^{14}C results from Zakłodzie suggest it hit Earth only recently.

INTRODUCTION

Itqiy is a unique coarse-grained, metal-rich, enstatite meteorite that was recovered from Western Sahara in July 2000 and displays an achondritic texture (Grossman and Zipfel, 2001; Patzer *et al.*, 2001a,b). The dominating mineral phase is a low-Ca pyroxene that partly resembles EL chondritic enstatite. Another main constituent (~25 vol%) of this meteorite is kamacite, which shows EH chondritic compositional characteristics. Aside from pyroxene and metal, a few tiny intergrowths of different sulfides with kamacite were identified. The sulfides are generally similar to those found in enstatite chondrites, but yield distinct elemental abundances that complicate an assignment to either EH or EL chondrites. In contrast to the main metal phase, the kamacite associated with the sulfide regions exhibits EL chondritic Si and Ni concentrations (Patzer *et al.*, 2001a,b).

As to the thermal history of Itqiy, two principal stages can be distinguished. The composition and structure of the silicate phase are probably due to a long-term igneous event that involved slow cooling. The sulfide phases of Itqiy, on the other hand, hint at a short-term heating process with subsequent quenching. This second heating event might have been induced by shock since many enstatite grains show shock stage S3 features (Patzer *et al.*, 2001a,b).

Overall, Patzer *et al.* (2001b) classified Itqiy as a partial melt residue with an unusually high amount of metal that was formed under similar reducing conditions as the enstatite chondrites (E chondrites) possibly reflecting a spatial relationship. The specific association of enstatite, sulfides, phosphites, and nitrides in E chondrites requires a C/O ratio of ~1 that could have been achieved within localized zones of the inner solar system upon cooling of the nebular disk (see Krot *et al.*, 1998, and references therein). A direct genetic link between Itqiy and E chondrites, however, does not necessarily exist. In order to further explore Itqiy's composition and the character of its connection to E chondrites, we carried out noble gas and oxygen isotope analyses. ^{14}C and ^{10}Be were determined to calculate its terrestrial age.

In addition, a comparison of the noble gas records, oxygen isotopic data, and terrestrial ages of Itqiy and Zakłodzie is reported. Zakłodzie is another ungrouped, anomalous enstatite meteorite, which was recently found in Poland (Stepniewski *et al.*, 2000; see also Burbine *et al.*, 2000). Similar to Itqiy, it is composed mainly of euhedral and subhedral enstatite, but unlike Itqiy, interstices are filled with plagioclase acting as a groundmass. Additional accessory phases of Zakłodzie are kamacite and troilite. Schreibersite was also identified. In general, the chemical composition and mineralogy of Zakłodzie display parallels to EL chondrites whereas its texture can be described as either highly metamorphosed or achondritic. Patzer *et al.* (2001b) concluded that owing to petrologic–chemical reasons both meteorites neither represent the same material nor that Itqiy was derived from Zakłodzie-like matter. This conclusion is here reviewed in the light of noble gases and oxygen isotope data.

The most interesting feature of the noble gas record of E chondrites is manifested in the trapped component of Ar, Kr, and Xe. Basically, two main signatures can be distinguished discriminating between E3 and E4–6 chondrites (Patzer and Schultz, 2002). All solar gas-free E3 chondrites exhibit relatively low trapped $^{36}Ar/^{132}Xe$ ratios that follow a trend to a significantly lower value than known for the ordinary chondrites (a mixture of Q and "sub-Q" with a mean $^{36}Ar/^{132}Xe$ ratio of 32.9 ± 16.9). Q represents the typical noble gas composition of ordinary and carbonaceous chondrites (Lewis *et al.*, 1975; see also Busemann *et al.*, 2000). In contrast to that, E4–6 chondrites are characterized by high ^{36}Ar contributions and varying amounts of ^{132}Xe spanning an array of trapped $^{36}Ar/^{132}Xe$ ratios of 582 ± 270 (a mixture of Q and subsolar).

Regarding the oxygen isotopic composition of E chondrites, a recent comprehensive investigation revealed relative abundances of ^{17}O and ^{18}O close to the terrestrial fractionation line for most samples (Newton *et al.*, 2000; see also Clayton *et al.*, 1984). However, a systematic increase in $\delta^{18}O$ from both, EH and EL chondrites of petrologic type 3 to those of type 6 appears to exist. In addition, Newton *et al.* (2000) found good evidence that EH chondrites plot slightly off the terrestrial fractionation line on a line of slope 0.66. Their results point to a complex accretion history or parent body evolution, or both. Another, previous study also observed an oxygen isotopic composition of E chondrites along the terrestrial fractionation line as well as a relatively heavier isotopic composition of the metamorphosed petrologic types EH5 and EL6 compared to types 3 (Weisberg *et al.*, 1995).

SAMPLES AND ANALYTICAL METHODS

Noble Gases

For the noble gas analyses of the Itqiy sample, three bulk specimens of 80.4, 98.7, and 101.4 mg, taken from UA1888 were available. Also, five separates including three silicate fractions of 60.68, 46.32, and 55.32 mg as well as two metal fractions of 46.46 and 54.24 mg were prepared in order to obtain information on possible host phases of the trapped gases. For this purpose, a piece of UA1888 was crushed and the two main phases were separated by hand thereby favoring grains in the millimeter and upper submillimeter range. The purity of the separates is estimated to be 90%. From Zakłodzie, a chip off the meteorite's interior weighing 106.6 mg was taken and analyzed.

The concentrations and isotopic compositions of noble gases were determined with an all-metal mass spectrometer (MAP215) showing a magnetic sector field of 90° and a so-called extended geometry. For the gas extraction, a tungsten crucible with a double vacuum was used and heated in one step to ~1800 °C. Purification of the rare gases was sequentially performed by means of a titanium and a zirconium-aluminum getter. In order to avoid mass interference, the purified noble gas amount was finally split into two fractions, He plus Ne and Ar plus Kr plus Xe, using temperature-controlled charcoal. Sample preparation, experimental procedure and corrections are given by Patzer (2000; see also Loeken *et al.*, 1992; Scherer *et al.*, 1998). Blank contributions were generally small (*e.g.*, <1.5% for Ne) and taken into account in the course of data processing. The noble gas inventories of all analyzed specimens are compiled in Table 1.

To evaluate cosmic-ray exposure ages (CREAs), methods were applied as described in Scherer *et al.* (1998). The production rates for cosmogenic ^{3}He, ^{21}Ne, and ^{38}Ar (P^3, P^{21}, and P^{38} in 10^{-8} cm³ STP/g Ma; STP = standard temperature and pressure; Ma = million years) and cosmic-ray exposure ages were calculated on the basis of the cosmogenic $^{22}Ne/^{21}Ne$ ratio as shielding parameter (Eugster, 1988). As distinct from Eugster (1988), however, the production rate of ^{38}Ar was reduced by 13% (Schultz *et al.*, 1991):

$$P^3 = F(2.09 - 0.43(^{22}\mathrm{Ne}/^{21}\mathrm{Ne})_c)$$

$$P^{21} = 1.61F(21.77(^{22}\mathrm{Ne}/^{21}\mathrm{Ne})_c - 19.32)^{-1}$$

$$P^{38} = F(0.125 - 0.071(^{22}\mathrm{Ne}/^{21}\mathrm{Ne})_c)$$

Eugster (1988) determined P^3, P^{21}, and P^{38} using L chondritic chemistry. Consequently, an appropriate chemical correction factor F had to be applied for bulk samples of Itqiy. The factors for P^3, P^{21}, and P^{38}, respectively, were determined from recently published instrumental neutron activation analysis (INAA) and

TABLE 1. Noble gas concentrations and $^{129}Xe/^{132}Xe$ ratios of Itqiy and Zakłodzie.

Sample	Mineral	Mass (mg)	^{3}He	^{4}He	^{20}Ne	^{21}Ne	^{22}Ne	^{36}Ar	^{38}Ar	^{40}Ar	^{84}Kr	^{132}Xe	$^{129}Xe/^{132}Xe$
			(10^{-8} cm^3 STP/g)								(10^{-12} cm^3 STP/g)		
Itqiy, bulk 1	–	101.4	53.5	233	11.3	8.29	10.1	87.8	17.7	84.9	1830	760	1.01
Itqiy, bulk 2	–	98.7	42.7	215	10.6	8.34	10.1	40.2	8.65	102	600	130	1.04
Itqiy, bulk 3	–	80.4	49.0	244	11.9	8.70	10.6	81.5	16.4	102	1640	450	1.04
Itqiy, separate	Enstatite	60.0	61.7	292	20.3	9.93	13.0	806	153	82.0	13590	2360	1.08
Itqiy, separate	Enstatite	45.7	61.3	279	13.9	9.61	12.1	228	43.3	81.0	4820	1460	1.10
Itqiy, separate	Enstatite	54.6	62.5	281	13.6	10.0	12.5	127	24.3	51.0	2380	450	1.19
Itqiy, separate	Kamacite	46.2	36.7	135	2.37	2.05	2.42	14.3	5.13	11.0	220	30.0	0.99
Itqiy, separate	Kamacite	53.6	37.9	134	1.75	1.63	1.92	6.18	3.42	9.0	90.0	20.0	1.12
Zakłodzie, bulk	–	106.6	105	1171	22.6	23.6	26.4	2.65	2.01	5947	460	220	7.42

Uncertainties of gas concentrations vary from 5 to 10% for He, Ne, Ar, and from 10 to 15% for Kr and Xe. The isotopic ratio of Xe is believed to be known to better than 20%.

electron microprobe data (Patzer *et al.*, 2001b) according to the following equations (element concentrations in weight percent):

$P3^* = 1.74(Ti + Cr + Mn + Fe + Ni) +$
$2.66(100 - (Ti + Cr + Mn + Fe + Ni))$
(Cressy and Bogard, 1976)

$P21^* = 1.63(Mg) + 0.6(Al) + 0.32(Si) + 0.22(S) + 0.07(Ca) +$
$0.021(Fe + Ni)$ (Schultz and Freundel, 1985)

$P38^* = 2.6(K) + 1.58(Ca) + 0.33(Ti + Cr + Mn) +$
$0.086(Fe + Ni)$ (Eugster, 1988)

Based on Itqiy's chemical composition, F for $P3$, $P21$, and $P38$ is 0.99, 1.17, and 0.83, respectively. In Table 2, cosmogenic and radiogenic isotope abundances as well as calculated cosmic-ray exposure ages are listed. The uncertainty of the ^{21}Ne exposure ages is estimated to be 10%. Table 3 compiles important concentrations and ratios of trapped noble gases in Itqiy and Zakłodzie.

Oxygen Isotopes

For the oxygen isotope analyses (results see Table 4), a 70 mg aliquot of Itqiy (from UA1888,4) was powdered in an agate pestle and mortar. Metal grains were magnetically separated following the technique of Gardiner *et al.* (1977). For each of the two measurements, ~1.5 mg of homogenized nonmagnetic material was taken. The extraction of oxygen was performed by means of a laser fluorination technique developed by Franchi *et al.* (1992) and improved according to Miller *et al.* (1999). The laser used was a 25W CO_2 laser with 10.6 μm radiation. As reagent, BrF_5 was chosen. $\Delta^{17}O$ was calculated as follows (Clayton and Mayeda, 1996):

$$\Delta^{17}O = \delta^{17}O - (0.52 \times \delta^{18}O)$$

Carbon-14 Extraction

A 277.5 mg piece of Itqiy (UA1885,3) and 156 mg of Zakłodzie were crushed to powder, re-weighed and treated with 100% H_3PO_4 in order to dissolve carbonates. The residues were washed with distilled water, dried, mixed with ~5 g of iron chips as a combustion accelerator and finally placed in an Al crucible. Before melting the material in a flow of oxygen by means of a radio frequency (RF) induction furnace, it was heated to 500 °C in order to remove most low-temperature contaminants. CO_2 from the melted sample was collected, its volume measured, diluted to 1–2 cm^3 with ^{14}C-free CO_2, and then converted into graphite over a Fe catalyst. The graphite powder was pressed into a target holder and mounted in a 32-position wheel in the ion source of the tandem accelerator mass spectrometer (AMS) at the University of Arizona where the $^{14}C/^{13}C$ ratio of the sample was compared to that of known

TABLE 2. Cosmogenic and radiogenic noble gas concentrations, cosmic-ray exposure and gas retention ages of Itqiy and Zakłodzie.

Sample	^3He_c	^4He_r	$^{21}Ne_c$	$^{38}Ar_c$*	$^{40}Ar_r$	$(^{22}Ne/^{21}Ne)_c$	T_3	T_{21}	T_{38}	T_4	T_{40}
Itqiy, bulk 1	53.5	–	8.29	1.41	84.9	1.180	34.1	29.2	47.5	–	5.3
Itqiy, bulk 2	42.7	–	8.34	1.24	102	1.186	27.3	30.0	42.2	–	5.5
Itqiy, bulk 3	49.0	–	8.70	1.24	102	1.184	31.3	31.1	42.2	–	5.5
Zaklodzie, bulk	105	541	23.6	1.73	5947	1.116	65.2	55.3	67.9	2.1	4.4

Concentrations in 10^{-8} cm^3 STP/g. T_3, T_{21}, T_{38} = cosmic-ray exposure ages based on cosmogenic ^3He, ^{21}Ne, ^{38}Ar in Ma. T_4, T_{40} = gas retention ages evaluated with radiogenic ^4He, ^{40}Ar in Ga. Concentrations and the cosmogenic Ne ratio are believed to be known to better than 15%, the uncertainty of exposure ages is estimated at 10%, of retention ages at 30%. Abbreviations: c = cosmogenic, r = radiogenic.
*Assumed ratio of trapped $^{36}Ar/^{38}Ar = 5.32$.

TABLE 3. Trapped noble gas concentrations and ratios of Itqiy and Zakłodzie.

Sample	$^{36}Ar_{tr}$	$^{36}Ar/^{84}Kr$	$^{36}Ar/^{132}Xe$
Itqiy, bulk 1	86.9	475	1143
Itqiy, bulk 2	39.4	657	3031
Itqiy, bulk 3	80.6	492	1792
Zaklodzie, bulk	1.49	32.4	67.8

tr = trapped. Concentrations in 10^{-8} cm^3 STP/g. Measured ^{84}Kr and ^{132}Xe amounts are assumed entirely trapped. The uncertainty of $^{36}Ar_{tr}$ is estimated at 15%, elemental ratios are believed to be known to better than 20%.

TABLE 4. Oxygen isotopic composition of Itqiy and Zakłodzie.

Sample	$\delta^{17}O$	$\delta^{18}O$	$\Delta^{17}O$*
Itqiy	2.53	4.80	0.035
Itqiy	2.82	5.25	0.092
Zaklodzie†	2.90	5.35	0.188
Zaklodzie†	2.56	4.86	0.033

*$\Delta^{17}O = \delta^{17}O - (0.52 \times \delta^{18}O)$ (Clayton and Mayeda, 1996).
†From Stepniewski *et al.* (2000). Uncertainties are: $\delta^{17}O \pm 0.04$, $\delta^{18}O \pm 0.08$, $\Delta^{17}O \pm 0.025$ (see Miller *et al.*, 1999).

NIST standards. Procedures of the AMS analyses have been reported by Jull *et al.* (1990, 1993) and details of the calculations by Donahue *et al.* (1990).

Beryllium-10 Extraction

Approximately 50 mg of Itqiy powder were mixed with a 1 mg Be carrier, digested in solution of HF and HNO_3 and heated overnight. This treatment followed further heating, first with $HClO_4/HNO_3$, and then with 3:1 HNO_3/HCl. Be, in a 10% solution of EDTA with acetylacetone, was separated from other elements into $CHCl_3$ and subsequently HCl. This solution was subsequently treated with aqua regia and heated, and the Be carrier precipitated as $Be(OH)_2$. After centrifuging and redissolving four times, the purified $Be(OH)_2$ was combusted to BeO in quartz tube over an open flame and pressed into a copper target holder with 3:1 Ag/BeO powder (by weight). The holder was finally placed into the source of the AMS at the University of Arizona (for details on the AMS analysis of ^{10}Be see Kring *et al.*, 2001).

RESULTS AND DISCUSSION

Noble Gases in Bulk Samples of Itqiy

A prominent feature of the noble gas record of E chondrites is the presence of two different patterns of trapped heavy noble gases depending on the petrologic type (see above).

Like metamorphosed E chondrites (types 4–6), Itqiy shows a subsolar signature (Figs. 1 and 2). The average $^{36}Ar/^{132}Xe$ ratio is ~1989, $^{36}Ar/^{84}Kr$ is ~541 (Table 3). These findings are consistent with the thermal history of the meteorite as a partial melt residue and might hint at a general connection between heating and trapping of subsolar noble gases in enstatite meteorites. They also support the idea that Itqiy's parent body formed under similar environmental conditions as E chondrites (Patzer *et al.*, 2001b). Noteworthy at this point is the discrepancy between the measured amounts of trapped Ar, Kr and Xe. The considerably lower, yet still unequivocally subsolar concentrations in one of the three Itqiy samples may be the result of sample heterogeneity or a variation in the efficiency of the trapping mechanism.

The Ne content of Itqiy displays a predominantly cosmogenic signature. Cosmogenic ^{21}Ne as well as ^3He and ^{38}Ar are commonly used to calculate cosmic-ray exposure ages. Itqiy's ^{21}Ne exposure age (T_{21}) of 30.1 ± 3.0 Ma matches the typical age range of enstatite chondrites, which in turn show the same range of cosmic-ray exposure ages as ordinary chondrites (*e.g.*, Lipschutz and Schultz, 1999; Patzer and Schultz, 2001). In fact, T_{21} of Itqiy matches that of most EL6 chondrites but this specific agreement does not necessarily imply a common origin (Fig. 3). Thus, interpreting the exposure age, we can only conclude that Itqiy's parent body has been likely located in a similar region as the source asteroids of

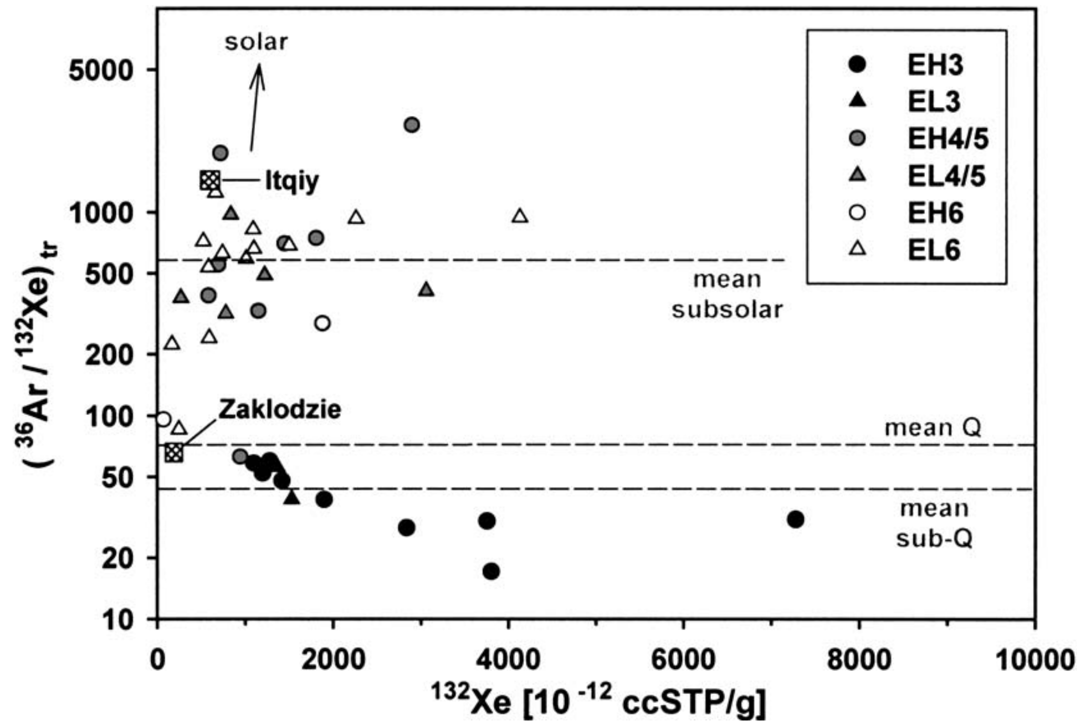

FIG. 1. Trapped heavy noble gases in enstatite chondrites, Itqiy, and Zakłodzie (data of enstatite chondrites taken from Patzer and Schultz, 2001). The diagram reveals a systematic discrimination between enstatite chondrites of petrologic type 3 and types 4 to 6. While the metamorphosed samples display a subsolar gas pattern characterized by high trapped ^{36}Ar/^{132}Xe ratios, the unequilibrated enstatite chondrites show characteristic ratios that scatter around or below Q, the normal chondritic gas signature (Patzer and Schultz, 2002; Busemann *et al.*, 2000). Interestingly, Itqiy exhibits a subsolar component whereas Zakłodzie contains trapped Q gases.

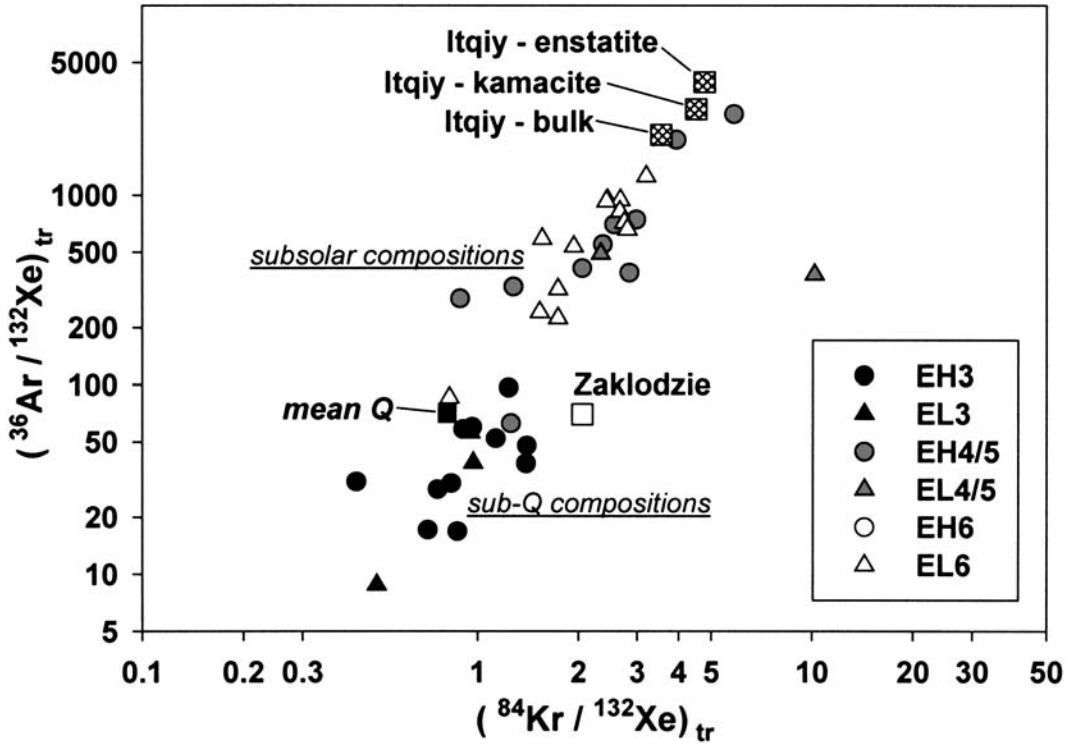

FIG. 2. Trapped ^{36}Ar/^{132}Xe *vs.* trapped ^{84}Kr/^{132}Xe for enstatite chondrites, Itqiy, Zakłodzie, and the mineral separates of Itqiy (data of enstatite chondrites taken from Patzer and Schultz, 2001). Enstatite as well as kamacite (possibly contaminated with enstatite) of Itqiy reveal a subsolar signature and agree fairly well with the ratios determined for the bulk sample. As opposed to Itqiy, Zakłodzie incorporated a Q-like component with a relatively high ^{84}Kr/^{132}Xe ratio.

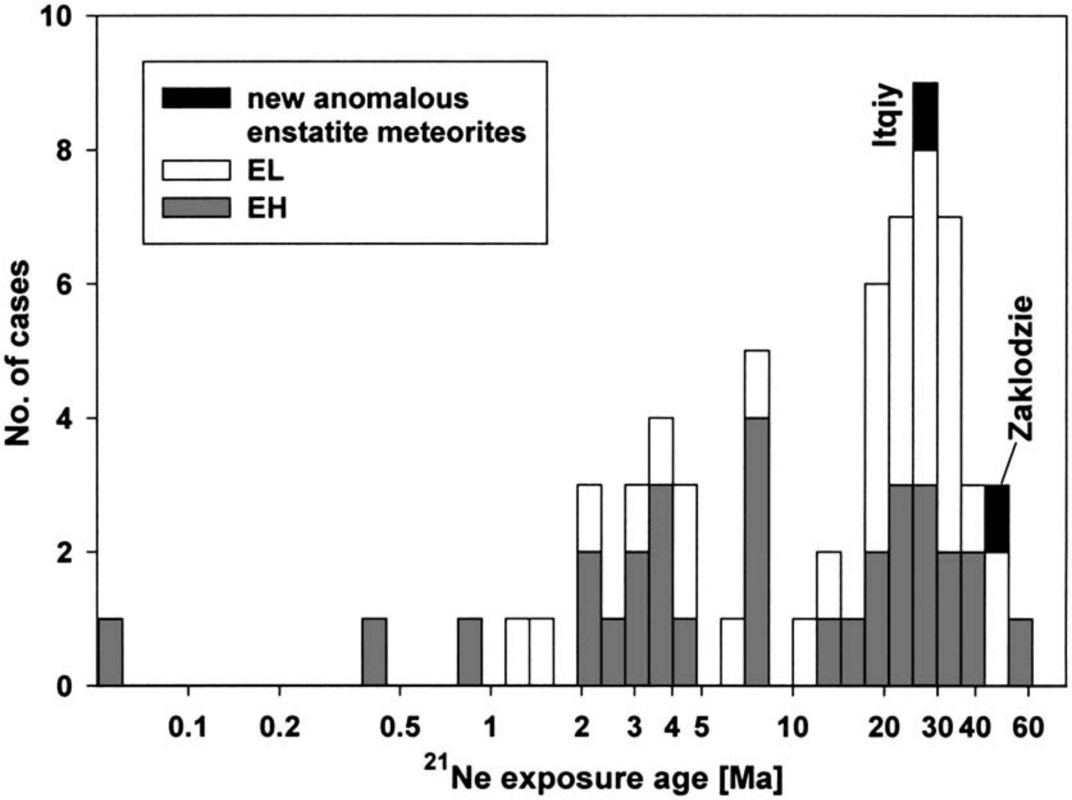

FIG. 3. ^{21}Ne cosmic-ray exposure ages of Itqiy and Zakłodzie as compared to the spectrum of enstatite chondrites (Patzer and Schultz, 2001). Zakłodzie plots at the high end of this range (55.3 Ma). Itqiy yields an age (30.1 Ma) that is very typical among enstatite chondrites in general and EL6 chondrites in particular.

enstatite and ordinary chondrites (*i.e.*, the main asteroid belt). This constraint is consistent with dynamical simulations of Morbidelli and Gladman (1998; see also Gladman *et al.*, 1997; Farinella *et al.*, 1993) who developed a model explaining the relatively broad range of chondritic exposure ages in the restricted frame of comparatively fast acting resonances. Morbidelli and Gladman (1998) consider the 3:1 and ν_6 resonances to be primarily responsible for the delivery of chondrites to Earth. Both resonances are located within the main asteroid belt at ~2.5 and 2 AU, respectively. Any conclusion on the location of Itqiy's parent body going further than outlined above would be highly speculative. However, the exposure age is in agreement with the spatial constraints on the formation area of Itqiy's parent body as drawn here from trapped noble gases and earlier from petrologic–chemical evidence (Patzer *et al.*, 2001b).

T_{21} is generally believed to be the most reliable exposure age because T_3 (calculated from cosmogenic ^{3}He) can be affected by diffusive loss due to solar heating on orbits with small perihelia (Hintenberger *et al.*, 1966; Schultz and Weber, 1995, 1997). For Itqiy, T_3 is consistent with T_{21} and hence, ^{3}He is apparently still entirely present. Thermally induced release of ^{3}He or even its precursor ^{3}H can also be excluded as inferred from the noble gas record of Itqiy's metal fractions, which reveal no deficit of ^{3}He (see below). T_{38} (from cosmogenic ^{38}Ar), on the other hand, turned out to be higher than T_{21}. The ^{38}Ar exposure age potentially proves more uncertain for samples that have been considerably affected by terrestrial weathering (Patzer and Schultz, 2001) or that exhibit high amounts of trapped Ar. Terrestrial alteration unambiguously left its fingerprint on Itqiy. About one-third of the metal has been converted into "limonitic" mineral assemblages (Patzer *et al.*, 2001a,b). At the same time, trapped ^{36}Ar concentrations are high. The presence of subsolar gases complicates any meaningful correction for air contamination. It also prevents the precise calculation of cosmogenic ^{38}Ar as the trapped ratio ^{36}Ar/^{38}Ar is unknown (the assumed value of 5.32 for trapped ^{36}Ar/^{38}Ar leads to ~10% cosmogenic ^{38}Ar, which in turn results in a relatively high ^{38}Ar-exposure age).

U/Th-He (T_4) and K-Ar (T_{40}) gas retention ages are determined from the concentrations of U, Th, and K and those of their radiogenic decay products ^{4}He (^{4}He$_r$) and ^{40}Ar (^{40}Ar$_r$). They ideally correspond to the crystallization time of meteoritic matter. In most cases, however, heating or severe shock events on the meteorite's parent body led to a loss of radiogenic gases. Hence, the calculated retention ages commonly reflect the thermal history of the material analyzed.

For Itqiy, the abundance of radiogenic ^{4}He is very low, in fact too low to be translated into a meaningful concentration. The measured ^{4}He/^{3}He ratios range between 5.1 and 6.5 and thus can be interpreted as completely cosmogenic. Consequently, Itqiy must have been heated late in its history, presumably during excavation from its parent body ~30 Ma ago.

If compared to most E chondrites, the radiogenic concentration of ^{40}Ar is low as well (~5000 cm^3 STP/g as opposed to ~100 cm^3 STP/g for Itqiy). This can be mainly attributed to the low amount of K of 4.1 ppm as measured by INAA (Patzer *et al.*, 2001b). Calculated K-Ar ages exceed 5 Ga implying that the amount of radiogenic ^{40}Ar was overestimated. This is possibly due to atmospheric contamination or, alternatively, the determined concentration of K was altered by K loss during the residence time of the meteorite on Earth. The calculated terrestrial age of Itqiy supports this interpretation (see below).

Noble Gases in Mineral Fractions of Itqiy

The three silicate and two metal separates basically show similar noble gas records for trapped ^{36}Ar, ^{84}Kr, and ^{132}Xe. This part of rare gases in Itqiy is clearly related to the subsolar component and it becomes obvious that it resides in enstatite. The observation is consistent with earlier findings of Crabb and Anders (1982) who considered enstatite or a closely related phase as the main carrier of the subsolar gas pattern. However, the abundance of subsolar gases in Itqiy's silicate fraction varies considerably (Table 1). This may imply that the component in question was trapped in a heterogeneous manner. Interestingly, the mean ratios of trapped ^{36}Ar/^{84}Kr/^{132}Xe as determined for the silicate and the metal fractions, respectively, agree fairly well (Fig. 2). Possibly, enstatite does not represent the only host phase of subsolar gases but a minor amount was also incorporated into kamacite. However, absolute concentrations in the metal phase are comparatively low (~2%). Thus, if one takes into account the impurity of the separates, the agreement may well reflect the presence of enstatite within in the kamacite aliquots.

Itqiy and Zakłodzie: A Comparison of Noble Gas Records

From the noble gas point of view, no similarity between Itqiy and Zakłodzie can be inferred. The ^{21}Ne cosmic-ray exposure age (T_{21}) of Zakłodzie of 55.3 ± 5.5 Ma (Table 2) is significantly higher than that of Itqiy and therefore requires a different exposure history. It rather fits into the typical range of high exposure ages known for aubrites, which tend to reveal relatively long exposure to cosmic rays in general (*e.g.*, Norton County: ~82 Ma; Herzog *et al.*, 1977) and cluster around 50 Ma (Eberhardt *et al.*, 1965; Graf and Marti, 1992). T_{21} of Zakłodzie is therefore consistent with a possible connection of this meteorite to the parent body of enstatite achondrites (*e.g.*, Burbine *et al.*, 2000).

Also unlike Itqiy, Zakłodzie unambiguously exhibits radiogenic ^{4}He and ^{40}Ar resulting in a U/Th-He gas retention age of 2.1 Ga and a K-Ar retention age of 4.4 Ga (Table 2). The relatively low U/Th-He age suggests the influence of a moderate heating event some time in Zakłodzie's history. In contrast to radiogenic ^{40}Ar, ^{4}He is already mobilized at a few hundred degrees Celsius. Hence, the corresponding U,Th-^{4}He$_r$ age is more easily modified or reset by increased temperatures than the K-^{40}Ar$_r$ age of the same sample (Anders, 1964; Wänke, 1966). The expected thermal overprinting leading to the highly metamorphosed or igneous texture of Zakłodzie (Stepniewski *et al.*, 2000) must have taken place early in its history in order to explain the relatively high K-Ar age. In contrast to that, Itqiy experienced a major thermal event rather recently, likely related to its excavation, judging from the negligible amounts of radiogenic gases present (see above).

Regarding the heavy noble gases, further significant differences between Itqiy and Zakłodzie come to light. First, the latter meteorite reveals Q-type trapped noble gases while Itqiy shows a prominent subsolar signature (Figs. 1 and 2). In analogue to the characteristics of trapped heavy noble gases in E chondrites (Patzer and Schultz, 2002), both patterns testify to different evolutionary histories on, most likely, individual parent bodies. Second, Zakłodzie contains a high amount of excess ^{129}Xe produced by the decay of now extinct ^{129}I. This attribute is typical of E chondrites in general (Crabb and Anders, 1981) but nonexistent in Itqiy. The discrepancy cannot be satisfactorily explained by terrestrial contamination of the Itqiy sample. In fact, Itqiy falls well off the mixing line between Q and Earth's atmosphere when plotting trapped ^{36}Ar/^{132}Xe as a function of trapped ^{84}Kr/^{132}Xe suggesting that weathering is insignificant. Even when taking into account some terrestrial alteration of this meteorite as a find (see below) and assuming some absorption of atmospheric ^{84}Kr as well as ^{132}Xe (*e.g.*, Scherer *et al.*, 1994), high excess ^{129}I-related ^{129}Xe as observed in Zakłodzie should be still identifiable.

Overall, the noble gas records of Itqiy and Zakłodzie are considerably different and support the conclusion related to petrologic and chemical evidence excluding a close genetic relationship of these meteorites (Patzer *et al.*, 2001b).

Itqiy and Zakłodzie: A Comparison of Oxygen Isotopic Compositions

Enstatite chondrites and aubrites show isotopic compositions of oxygen that are indistinguishable from each other and similar to that of terrestrial materials (Clayton *et al.*, 1984; Weisberg *et al.*, 1995; Newton *et al.*, 2000). Focusing on E chondrites, an interesting correlation becomes evident: samples with increasing petrologic type (*i.e.*, higher metamorphic grade and equilibration) reveal a gradually heavier oxygen signature (*i.e.*, are gradually less enriched in ^{16}O). Newton *et al.* (2000) suggest the loss of shock-induced plagioclase-rich melt to be the explanation for this

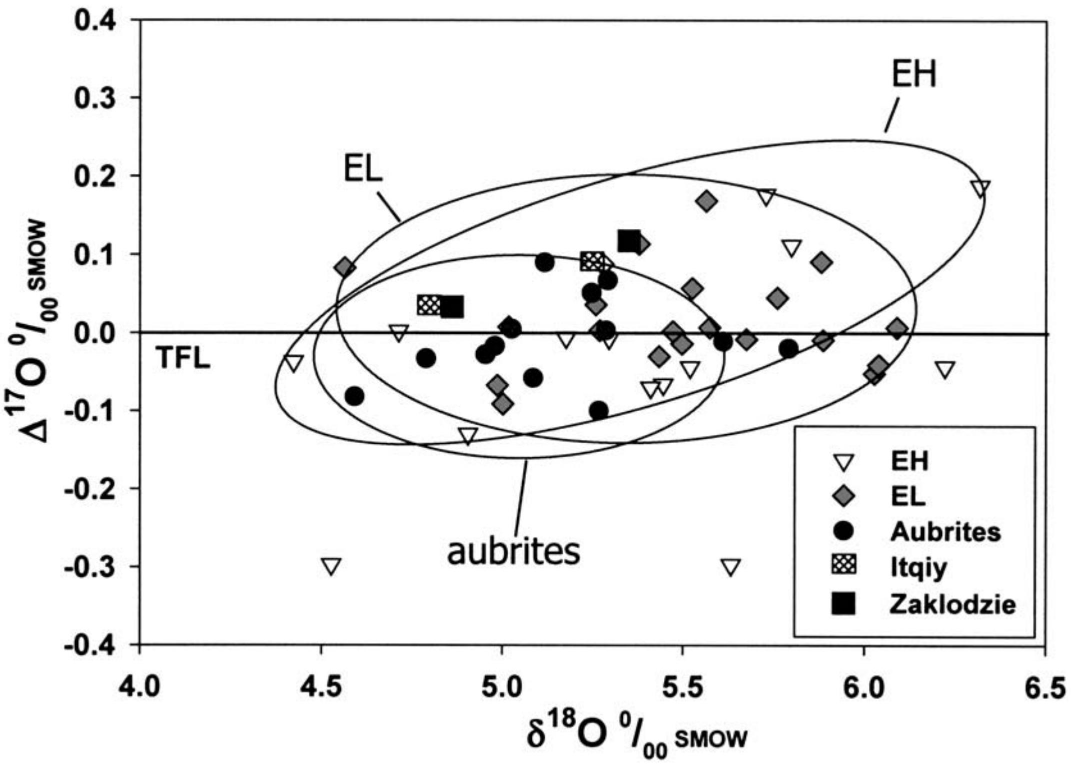

FIG. 4. The isotopic compositions of oxygen in Itqiy (reported here) and Zakłodzie (from Stepniewski *et al.*, 2000) turned out to be very similar. Both signatures overlap with $\Delta^{17}O$ and $\delta^{18}O$ ratios found in aubrites and are also indistinguishable from EL and EH chondritic compositions (TFL = terrestrial fractionation line; data of enstatite meteorites taken from Newton *et al.*, 2000).

phenomenon (see also Clayton *et al.*, 1976; Weeks and Sears, 1985).

Projecting the mean isotopic composition of oxygen in Itqiy (Table 4) into a $\Delta^{17}O/\delta^{18}O$ diagram, it falls into an area where all three enstatite meteorite groups (EH chondrites, EL chondrites, and aubrites) overlap (*i.e.*, no clear preferential association is observed) (Fig. 4). At first glance, Itqiy seems to plot closest to the mean value of EH chondrites, but all samples of this group exhibiting low $\Delta^{17}O$ and $\delta^{18}O$ values are from Antarctica and thus are potentially altered by terrestrial oxygen. The same conclusion is applicable to EL chondrites. Hence, ignoring those possibly contaminated E chondrites, Itqiy rather appears to show a connection to aubrites.

If one compares Itqiy's oxygen composition with that of the different petrologic types of E chondrites, the best match turns out to exist with E4–6 chondrites (Fig. 5). This observation is consistent with the detection of subsolar noble gases in Itqiy. The subsolar component is diagnostic for E4–6 chondrites, but not restricted to either EH or EL chondrites. Apparently, this same, latter attribute is attached to Itqiy's oxygen data. It is not possible to confidently constrain a genetic relation between either aubrites, EH or EL chondrites and Itqiy, but the results may suggest a link between E4–6 chondrites and Itqiy.

Isotopic data of oxygen for Zakłodzie have been published by Stepniewski *et al.* (2000). Interestingly, all attributes displayed by the oxygen signature of Itqiy also apply to Zakłodzie and the respective patterns turn out to be very similar. In contrast to this agreement, the constraints inferred from noble gas and mineralogical data (see Patzer *et al.*, 2001a,b), converge to a non-related picture on the history of both meteorites. Hence, the oxygen data appear to solely reveal a (expected) link to the enstatite meteorite clan in general but fail to offer more distinctive information on the exact origin as well as evolution of Itqiy and Zakłodzie.

Carbon-14 and Beryllium-10 Results for Itqiy

Itqiy was found in Western Sahara in 2000 (Grossman and Zipfel, 2001). Its recovery was connected to the observation of a nomad who supposedly witnessed Itqiy's fall ~10 years ago. The general physical condition of the different specimens, especially of those cut without water (*i.e.*, aliquot UA1888; see Patzer *et al.*, 2001b), supports this assessment. However, the circumstances of Itqiy's collection have been still considered uncertain. The determination of its terrestrial age was carried out in order to clarify the most recent, terrestrial part of the meteorite's history.

Terrestrial ages of meteorites are commonly calculated by means of cosmogenic nuclides, for instance the radionuclides ^{10}Be and ^{14}C (*e.g.*, Jull *et al.*, 2000; Welten *et al.*, 2001). ^{10}Be

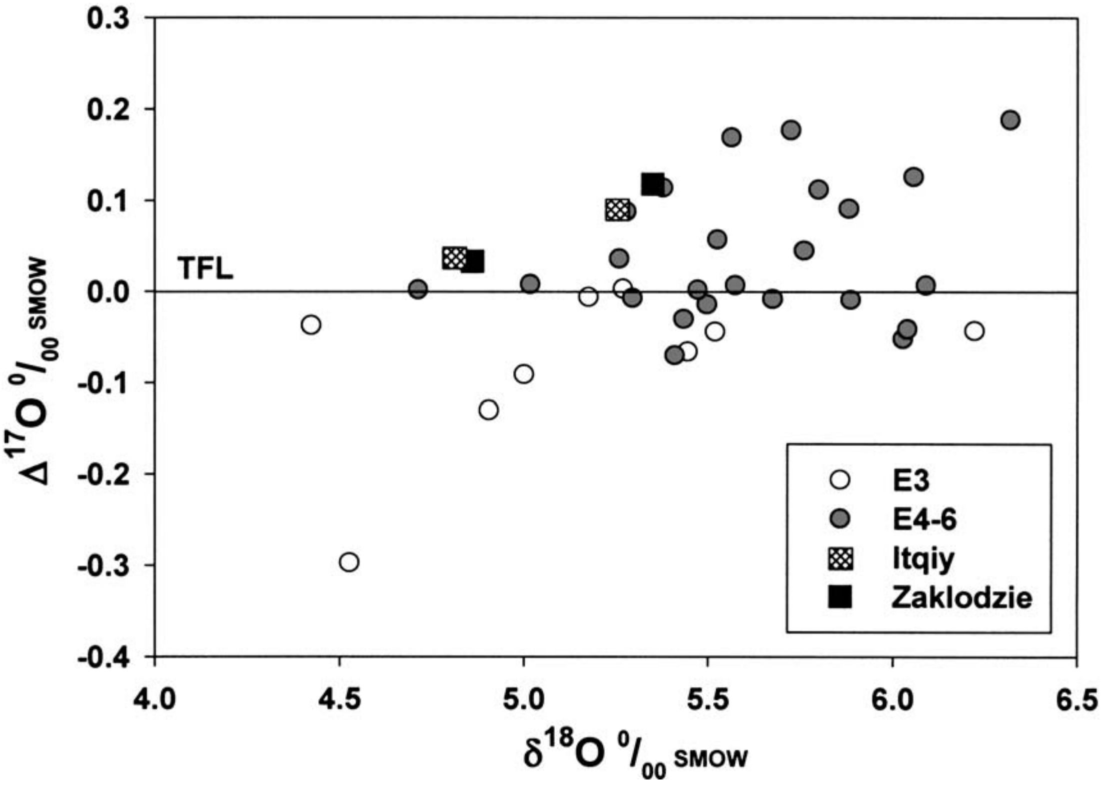

FIG. 5. In comparison with the isotopic composition of the different petrologic types of enstatite chondrites (Newton *et al.*, 2000), both Itqiy and Zakłodzie rather match $\Delta^{17}O$ and $\delta^{18}O$ ratios as observed for E4–6 chondrites and plot perceptibly above the terrestrial fractionation line (TFL).

TABLE 5. Results of ^{14}C and ^{10}Be for Itqiy and Zakłodzie.

Sample	^{10}Be (dpm/kg)	^{14}C (dpm/kg)	$^{14}C/^{10}Be$	Terrestrial age (years)
Itqiy	14.0 ± 0.5	17.4 ± 0.6	1.24 ± 0.06	5800 ± 500
Zaklodzie	3.6 ± 0.1	37.9 ± 0.5	10.6 ± 0.4*	recent fall

*The high value indicates that ^{10}Be is undersaturated, equivalent to a ^{10}Be exposure age of 560 ± 40 ka.

and ^{14}C data of Itqiy and Zakłodzie are given in Table 5. The ratio $^{14}C/^{10}Be$ at production is ~2.5 and observed in recently fallen meteorites (Jull *et al.*, 1990; see also Jull *et al.*, 2000). For Itqiy, a $^{14}C/^{10}Be$ ratio of 1.24 ± 0.06 was determined leading to a terrestrial age of 5800 ± 500 years (see Eq. (2) in Kring *et al.*, 2001). The age indicates that Itqiy is not a recent fall. In this light, the low degree of weathering of the sample is either primarily related to the original size of the meteorite (4.3 kg) or suggests a relatively dry climate at its find location in Western Sahara for the last ~6000 years. The ^{14}C results for Zakłodzie suggest it is likely a modern fall, since the amount of ^{14}C measured is close to the average saturated activity for a meteorite of this type. However, the low ^{10}Be concentration is puzzling. The observed $^{14}C/^{10}Be$ ratio can only be produced by a low ^{10}Be exposure age of 0.56 ± 0.04 Ma. This value is inconsistent with the exposure age based on cosmogenic ^{21}Ne (55.3 ± 5.5 Ma) and requires a two-stage exposure history for this meteorite (see, for example, Herzog *et al.*, 1997). Due to the lack of additional radionuclide data, however, a more detailed outline of a possible exposure scenario appears too speculative. Nonetheless, we believe it to be reasonable to infer that not only the absolute exposure ages but also the exposure histories of Itqiy and Zakłodzie differ from one another.

CONCLUSIONS

The aim of this work was to investigate additional compositional aspects of Itqiy after having described the basic mineralogical and chemical characteristics of this unique achondritic enstatite meteorite in a former publication (Patzer *et al.*, 2001b).

Most notably, regarding the noble gas record of Itqiy, the meteorite reveals a distinct, so-called subsolar component, which is, among E chondrites, typical and only known for the petrologic types 4 to 6. This finding seems to gain support from Itqiy's oxygen signature. Within errors, it agrees with the $\Delta^{17}O/\delta^{18}O$ ratios of E4–6 chondrites. However, if focusing on chemical groups as opposed to petrologic types, Itqiy's oxygen pattern falls into a range of $\Delta^{17}O/\delta^{18}O$ ratios where EH chondrites, EL chondrites, and aubrites overlap and are basically indistinguishable.

Another interesting aspect of Itqiy's noble gas content is the low abundance of radiogenic rare gases. It can be explained by the thermal history of the meteorite, which experienced probably two different heating events. According to the negligible concentrations of radiogenic ^{4}He and ^{40}Ar, the second overprinting must have occurred rather recently. The observed gas loss was most likely related to shock heating induced by impact as also suggested by mineralogical evidence. The same event probably launched Itqiy onto its way to Earth.

Calculated on the basis of cosmogenic ^{21}Ne, Itqiy exhibits a cosmic-ray exposure age of 30.1 ± 3.0 Ma. This value, when compared with the age spectrum of enstatite chondrites, coincides with the typical age range of this clan and, at the same time, matches the exposure age of most EL6 chondrites.

In brief, the agreements between Itqiy and the enstatite chondrites with respect to their mineral and chemical composition (Patzer *et al.*, 2001b) as well as to oxygen isotopes, noble gases and cosmic-ray exposure age, as established in this work, lead to a picture where Itqiy not only formed under apparently similar reducing conditions (*e.g.*, Keil, 1968) but possibly also comes from the same solar system area where enstatite chondrites accreted (*e.g.*, Krot *et al.*, 1998).

In order to complete the genetic distinction between Itqiy and another new ungrouped enstatite meteorite, called Zakłodzie, the noble gas and oxygen isotope records as well as terrestrial ages of both meteorites are compared (see Patzer *et al.*, 2001b). While the oxygen patterns match surprisingly closely, the noble gas contents of Itqiy and Zakłodzie differ considerably and support the view gained from their chemical and mineralogical compositions testifying to individual origins and histories of the samples. The terrestrial age of Itqiy has been determined (5800 ± 500 years) and comfortably assures that the meteorite is not a modern fall. In contrast to that, Zakłodzie yields ^{14}C and ^{10}B data that suggest it is a recent fall and in addition, appear to reveal a two-stage exposure history for this meteorite.

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