Ann. Naturhist. Mus. Wien, Serie A	121	113–124	Wien, 15 Jan. 2019

The Antarctic iron meteorite Steingarden Nunataks (STG) 07009

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(with 8 figures and 3 tables)

Manuscript submitted on August 8th 2018,
the revised manuscript on September 27th 2018.

Abstract

The Steingarden Nunataks (STG) 07009 iron meteorite was found in 2007 during a search campaign in Queen Maud Land, Antarctica, carried out by the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR, Hannover, Germany). It was collected as one complete individual specimen with regmaglypts and weighing ~ 32.6 kg. The main mass (32.2 kg) is stored at the BGR, whereas the type specimen (36.6 g) is kept at the Natural History Museum, Vienna. Macroscopically, the meteorite appears well preserved and does not show any oxidation features in its interior. Textural studies of etched platelets revealed that the meteorite is a plessitic octahedrite with almost all kamacite spindles (apparent width = 0.08 ± 0.03 mm, N = 30) having nuclei of schreibersite. Compositionally, kamacite and schreibersite are mainly uniform. However, a detailed electron microprobe investigation revealed that, in places, the spindles contain schreibersite-metal intergrowths, exhibiting complex textures and compositions. Based on bulk chemistry data, STG 07009 was classified as ungrouped iron with no close relatives. Age calculations based on accelerator mass spectroscopy of the cosmogenic radionuclides ^{10}Be, ^{26}Al, and ^{36}Cl gave for STG 07009 a cosmic-ray exposure age of 780 ± 100 Myr and a relatively young terrestrial age of 75 ± 33 kyr.

Keywords: meteorite, ungrouped iron, Queen Maud Land, Antarctica, terrestrial age.

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Zusammenfassung

Der Eisenmeteorit Steingarden Nunataks (STG) 07009 wurde 2007 im Rahmen einer von der Bundesanstalt für Geowissenschaften und Rohstoffe (BGR, Hannover, Deutschland) im Queen Maud Land, Antarktis durchgeführten Suchkampagne gefunden. STG 07009 wurde als 32,6 kg schweres komplettes Individuum mit Regmaglypten aufgesammelt. Die Hauptmasse (32,2 kg) wird an der BGR verwahrt, das Typmaterial (36,6 g) ist im Naturhistorischen Museum Wien deponiert. Makroskopisch erscheint der Meteorit in gut erhaltenem Zustand und weist keinerlei Rostanzeichen in seinem Inneren auf. Gefügestudien an geätzten Plättchen ergaben, dass es sich beim Meteoriten um einen plessitischen Oktaedriten handelt, wobei fast alle Kamazit-Spindeln (gemessene Breite = 0,08 ± 0,03 mm, N = 30) einen aus Schreibersit bestehenden Kern aufweisen. In den meisten Spindeln weisen Kamazit und Schreibersit jeweils denselben einheitlichen Chemismus auf. Detailuntersuchungen mittels Elektronenstrahlmikrosonde zeigten, dass die Spindeln bereichsweise Verwachsungen von Schreibersit und Metall enthalten, die komplexe Gefüge und Chemismen aufweisen. Aufgrund des ermittelten Pauschalchemismus wurde STG 07009 als ungruppierter Eisenmeteorit klassifiziert. Dabei konnte keine chemische Verwandtschaft mit anderen ungruppierten Eisen festgestellt werden. Basierend auf der mittels Beschleuniger-Massenspektrometrie gemessenen kosmogenen Radionuklide ^{10}Be, ^{26}Al, und ^{36}Cl wurde für STG 07009 ein kosmisches Bestrahlungsalter von 780 ± 100 Ma und ein relativ junges terrestrisches Alter von 75 ± 33 ka errechnet.

Schlüsselwörter: Meteorit, ungruppierter Eisenmeteorit, Queen Maud Land, Antarktis, terrestrisches Alter.

Introduction

Blue ice fields along the fringes of the Antarctic Plateau and along the Transarctic Mountains are known as meteorite stranding surfaces or meteorite traps where meteorites are concentrated by several mechanisms, involving control of ice flow by bedrock topography, exhumation due to wind ablation and preservation due to low weathering rates (*e. g.*, Koeberl & Cassidy 1991; Cassidy *et al.* 1992; Folco *et al.* 2002; Corti *et al.* 2003; Harvey 2003).

In 2007, the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR, Hannover, Germany) carried out a reconnaissance survey of a hitherto unexplored blue ice fields area in Queen Maud Land, Antarctica, to assess the regional potential of meteorite accumulations (Fig. 1). As a result of the search campaign, a total of 15 meteorites were found, consisting of 14 ordinary chondrites and one iron meteorite (Fig. 2). All meteorites were later officially named after the Steingarden Nunataks (STG), being the closest named geographical feature (Delisle *et al.* 2015). The iron meteorite, which was found as a single mass located on a snow-covered shoulder of an elongated S-N trending ice depression, obtained the official name STG 07009.

Here we report the results of a multi-disciplinary study of the iron meteorite STG 07009, including optical microscopy (OM), analytical scanning electron microscopy (ASEM), electron microprobe analysis (EMPA), instrumental neutron activation analysis (INAA), and accelerator mass spectrometry (AMS).

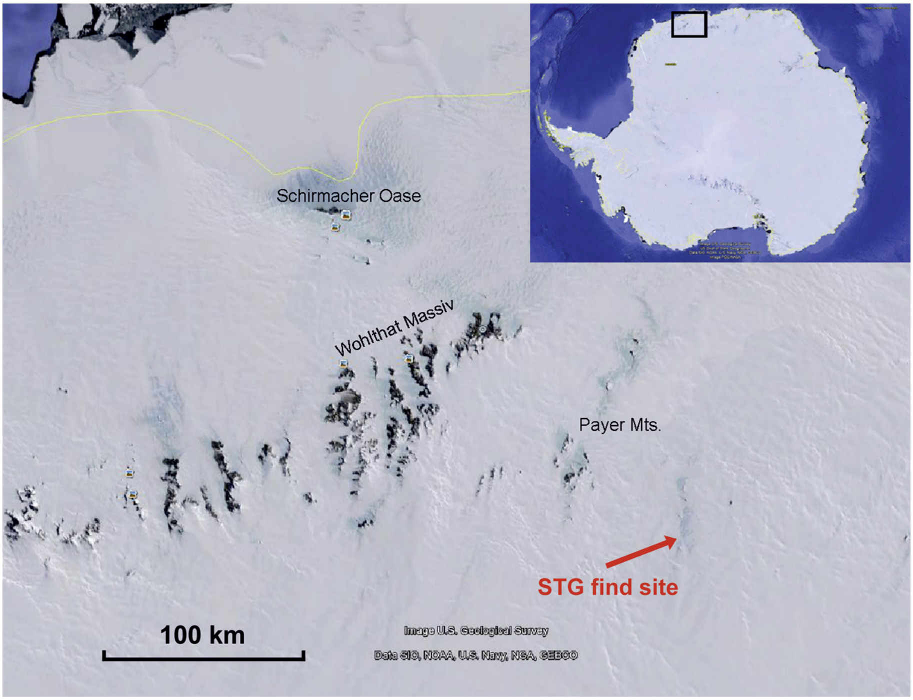

Fig. 1. Geographic overview. The rectangle within the inset shows the location of the investigated region. The Steingarden Nunataks (STG) find site is located on blue ice fields to the SE of the Wohlthat Massiv. Map data: Google, U.S. Geological Survey, Data SIO, NOAA, Navy, NGA, GEBCO.

Glaciological setting of the find location

The find location – a blue ice field at the western fringe of an elongated east-west trending topographic step (see Figs 1 and 2) – has previously been described in DELISLE *et al.* (2015). Two characteristics of the ice field along this step – the division into modest ice depressions and ice rises and the prevalent lack of small rock fragments on the majority of the blue ice surfaces – are notable. The latter observation can be attributed to the largely unimpeded frequent strong winds from the Antarctic interior. A ground based radar survey of a nearby blue ice field conducted during the BGR-expedition in 2007 is discussed in DELISLE *et al.* (2015). In addition, an earlier airborne radar reconnaissance survey in 1995/96 by MEYER *et al.* (2005) imply both an ice thickness in the investigated area of in general a few hundred meters, which, in turn, suggests slow ice movement. A satellite aperture radar interferometry survey of the Allan Hills meteorite concentration site in S. Victoria Land, which features a very similar glaciological setting, found ice flow velocities between near zero to 5 m per year as shown by COREN *et al.* (2003). Ice flow during the last cold stage, prior to about 12,000 years ago should have been even slower, as colder ice gets stiffer resulting in slower deformation. Given the young

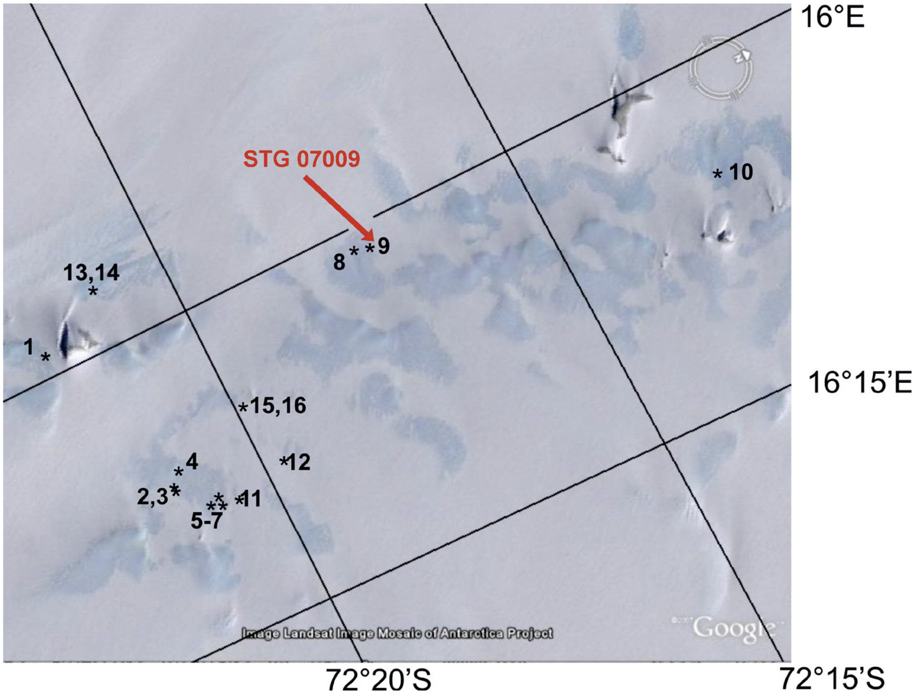

Fig. 2. Location of blue ice fields of the Steingarden Nunataks site with numbered positions of the recovered meteorites (DELISLE *et al.* 2015) and the find site (arrow) of STG 07009. Map data: Google, Landsat Image Mosaic of Antarctica Project.

Fig. 3. View of the main mass of the Steingarden Nunataks 07009 iron, exhibiting a greyish-black surface with well-developed regmaglypts.

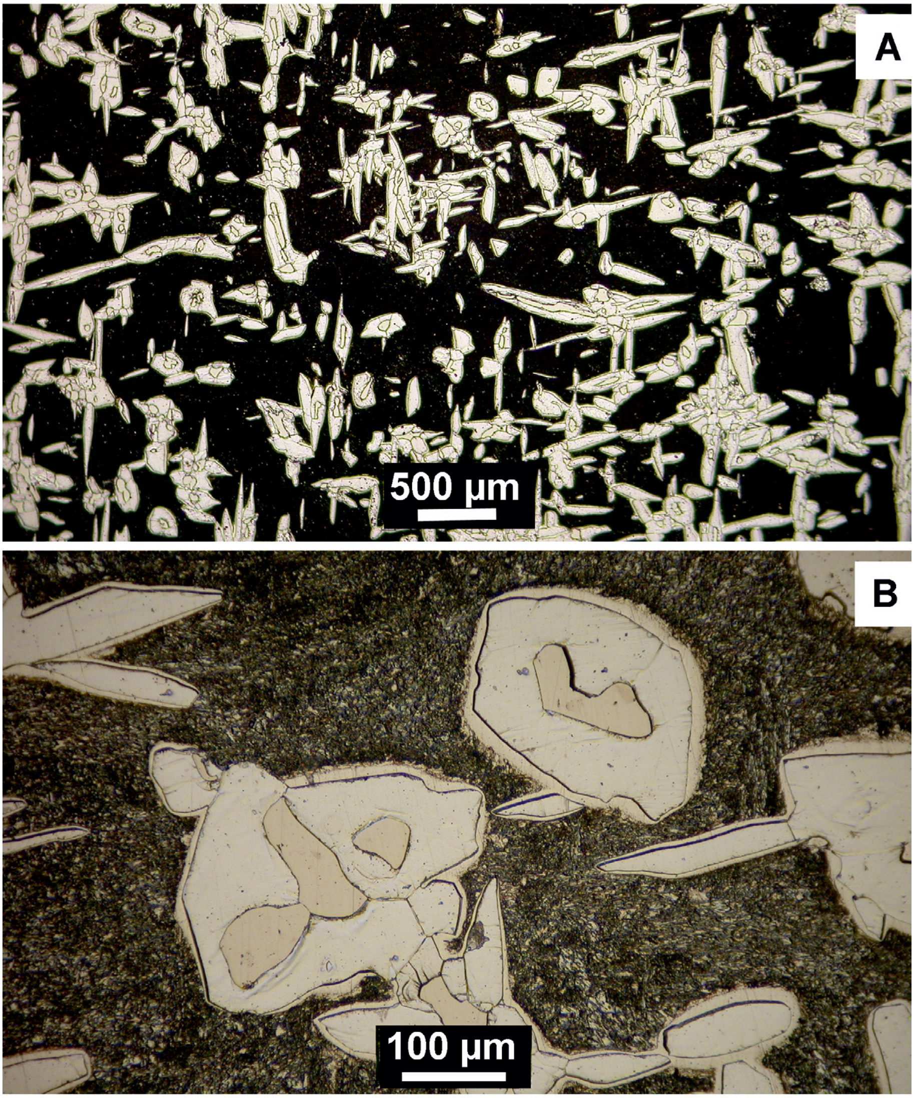

Fig. 4. Photomicrograph (reflected light) of a slightly etched section of STG 07009. A: Overview exhibiting numerous oriented kamacite spindles (light-grey) in plessite (black); B: detail of Fig. 4A showing kamacite with nuclei of schreibersite and thin rims of taenite.

terrestrial age of STG 07009 (see below), the impact of the meteorite on the Antarctic ice sheet occurred probably within 150 km from the find location. An upper limit of the travel distance is given by the nearest upstream ice divide about 300 km to the south.

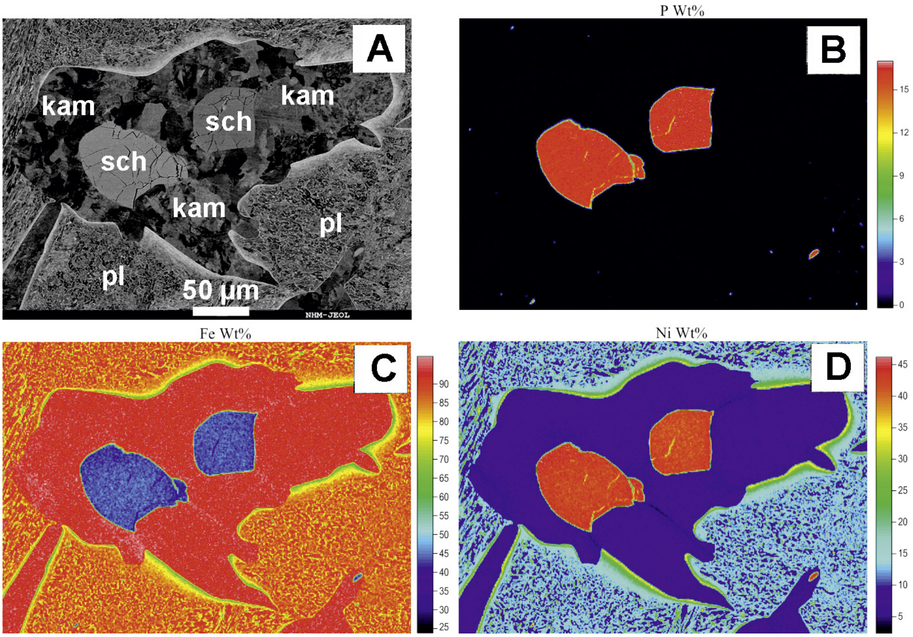

Fig. 5. A: High–contrast BSE image of an area exhibiting homogenous schreibersite nuclei in kamacite. Different shades of grey of kamacite are mainly due to orientation effects; B–D: quantitative X-ray maps (EMPA-WDS at 15 kV, in wt%) for the elements P (B), Fe (C), and Ni (D). kam = kamacite, pl = plessite, sch = schreibersite.

Samples and macroscopic description

Steingarden Nunataks 07009 originally consisted of one complete individual specimen weighing ~ 32.6 kg. The present main mass (Fig. 3) weighs 32.2 kg and is stored at the BGR, whereas the type specimen (36.6 g) is kept at the Natural History Museum, Vienna (Inv. no. O358). In addition, two polished sections embedded in 1-inch epoxy carriers were prepared, and one slightly etched and one non-etched section were used for OM studies and ASEM plus EMPA investigations, respectively.

Macroscopically, the meteorite appears well preserved, displaying a greyish-black surface with numerous cm-sized regmaglypts (Fig. 2). As a whole, the iron mass appears fresh and does not show any oxidation features in its interior.

Optical microscopy

OM investigation of an etched section of STG 07009 revealed the typical structure of a plessitic octahedrite (Fig. 4A). Numerous oriented kamacite spindles (apparent width = 0.08 ± 0.03 mm, N = 30) display a discontinuous microscopic Widmanstätten pattern. Almost all spindles have nuclei of schreibersite and are enveloped by thin rims of taenite (Fig. 4B).

No troilite or other mineral phases than mentioned above were observed in the investigated sections.

Metal and schreibersite composition

Microprobe investigations of selected metal and phosphide objects were done using a JXA-8530F field emission electron microprobe at the Natural History Museum (Vienna, Austria). Operating conditions for spot analysis (1 µm in diameter) were 15 kV accelerating voltage, 20 nA beam current, 10 s peak counting time, and 5 s background counting time. Analytical standards were synthetic metals of iron, nickel, cobalt, and natural schreibersite for Fe, Ni, Co, and P, respectively. Quantitative X-ray mappings (EMPA-WDS, 400 × 285 pixels, 250 µs counting time per pixel) were acquired at 15 kV. In addition, high-resolution quantitative X-ray mappings (EMPA-EDS, 1200 × 900 pixels, total counting time 3600 s) were performed at 10 kV to obtain chemical compositions of sub-µm sized objects.

Compositionally, kamacite and schreibersite nuclei of kamacite spindles are rather uniform (Tab. 1 and Fig. 5) in STG 07009 with averaged compositions (spot analyses) of (92.28 wt% Fe, 6.99 wt% Ni, 0.77 wt% Co, n = 32) and (45.23 wt% Fe, 39.6 wt% Ni, 0.13 wt% Co, 15.28 wt% P, n = 18), respectively. However, a detailed EMPA investigation revealed that in places, the spindles contain schreibersite-metal intergrowths exhibiting complex textures and compositions (Figs 6, 7). The quantitative X-ray mapping for the elements P, Fe, and Ni of such a complex intergrowth (Fig. 8 and Tab. 2) gave averaged compositions (in wt%, normalized to 100%) for the object's rim, the metal in the objects interior, and the schreibersite matrix of Fe 71.9, Ni 27.1, P 1.0; Fe 68.4, Ni 28.6, P 3.0, and Fe 56.5, Ni 30.1, P 13.4; respectively.

Table 1. Selected electron microprobe analyses of metal and schreibersite (in wt%) of kamacite spindles with homogenous schreibersite nuclei from the STG 07009 iron meteorite, bd = below detection limit, the formula calculation is based on total of atoms = 100.

	kamacite			taenite (rim)		schreibersite		
Fe	93.07	92.85	91.42	75.43	68.10	46.97	44.26	43.87
Ni	6.30	6.88	7.33	24.25	31.80	37.55	40.45	40.88
Co	0.79	0.77	0.85	0.50	0.30	0.10	0.14	0.13
P	bd.	bd.	bd.	bd.	bd.	15.44	15.09	15.45
Total	100.16	100.50	99.60	100.18	100.20	100.06	99.95	100.33
number of atoms								
Fe	93.25	92.74	92.16	76.21	69.04	41.92	39.69	39.11
Ni	6.00	6.53	7.03	23.31	30.67	33.15	35.79	35.94
Co	0.75	0.73	0.81	0.48	0.29	0.09	0.12	0.11
P	–	–	–	–	–	24.85	24.41	24.84

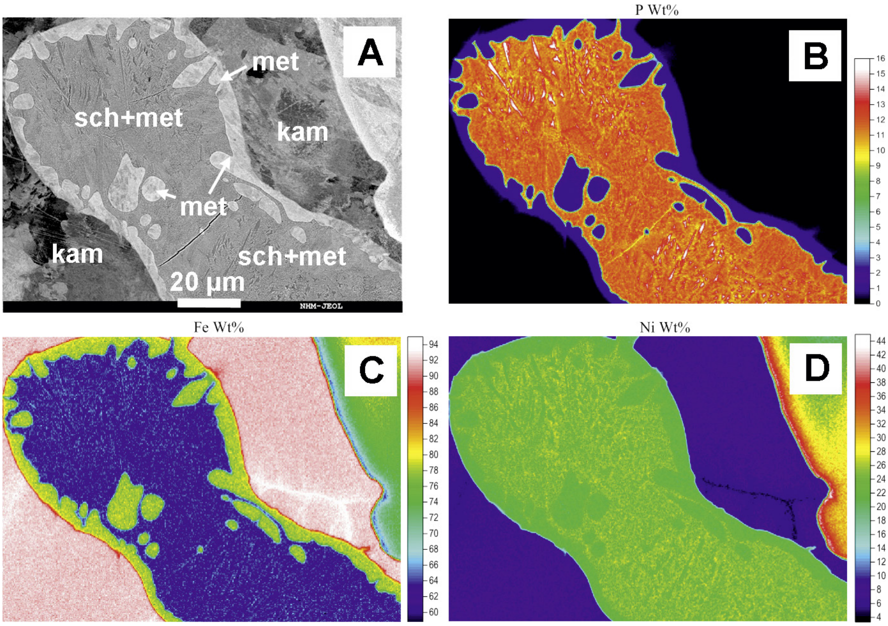

Fig. 6. A: High-contrast BSE image of an area exhibiting a complex intergrowth of metal and schreibersite in kamacite. Different shades of grey of kamacite are mainly due to orientation effects; B–D: quantitative X-ray maps (EMPA-WDS at 15 kV, in wt%) for the elements P (B), Fe (C), and Ni (D). kam = kamacite, met = metal, sch = schreibersite.

Bulk composition and classification

Based on bulk chemistry data obtained by INAA, STG 07009 is classified as an ungrouped iron. The corresponding INAA data (J. T. Wasson, UCLA, personal communication) are 20 µg/g Cr, 6.76 mg/g Co, 132 mg/g Ni, 282 µg/g Cu, 10.4 µg/g Ga, 166 µg/g Ge, 14.8 µg/g As, 74 ng/g Sb, 0.29 µg/g W, 16 ng/g Re, 0.13 µg/g Ir, 4.4 µg/g Pt, and 1.61 µg/g Au. For comparison, the bulk chemistry data of STG 07009 and other ungrouped irons are given in Table 3. For details of the INAA procedure, see Wasson *et al.* (1989).

Table 2. Composition (in wt%, normalized to 100%) of a complex schreibersite-metal intergrowth obtained by high-resolution quantitative X-ray mapping (EMPA-EDS at 10 kV). Spot numbers correspond to those shown in Figure 8A, m = mean.

	rim metal						schreibersite					interior metal						
spot	8	9	10	11	12	m	19	20	21	22	m	24	25	26	27	28	29	m
Fe	74.0	69.2	72.3	70.7	73.2	71.9	57.0	57.0	56.9	55.1	56.5	65.5	68.5	67.6	70.9	68.4	69.6	68.4
Ni	24.9	30.4	26.3	28.3	25.8	27.1	29.3	29.4	29.1	32.6	30.1	30.9	28.9	28.8	26.6	28.9	27.4	28.6
P	1.1	0.4	1.4	1.0	1.0	1.0	13.7	13.6	14.0	12.3	13.4	3.7	2.7	3.6	2.5	2.8	3.0	3.0

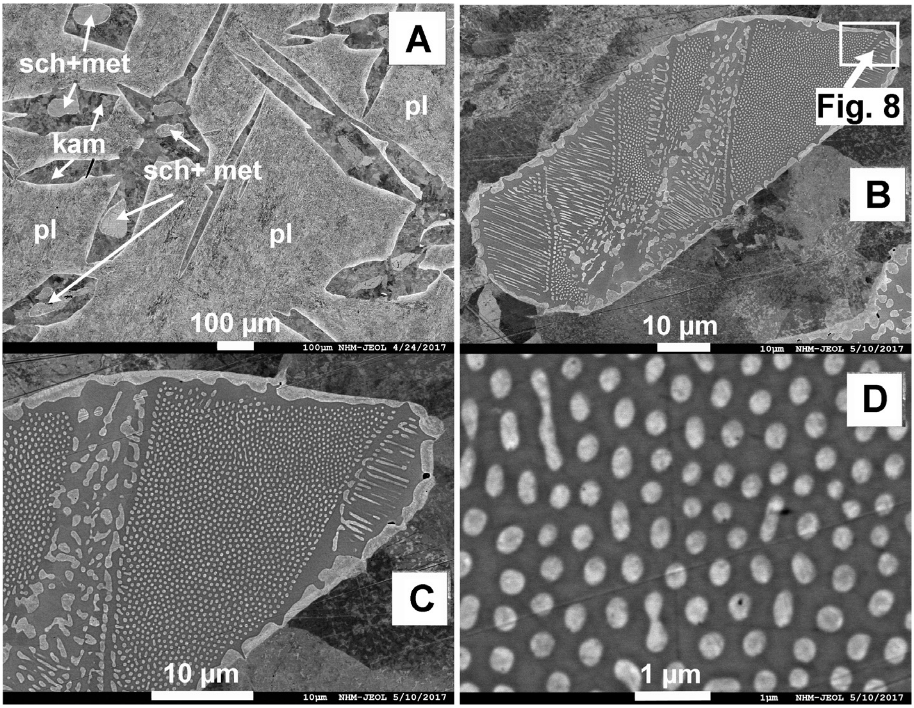

Fig. 7. A: BSE image exhibiting kamacite spindles in plessitic matrix; B–D: BSE images exhibiting the texture of a schreibersite-metal intergrowth at different magnifications. kam = kamacite, met = metal, pl = plessite, sch = schreibersite.

Table 3. Selected trace element abundances (replicate analyses obtained by INAA) of STG 07009 and other ungrouped irons having Co contents between 6.0 and 7.5 mg/g and Ni contents > 100 mg/g. All data from J. T. Wasson, UCLA (personal communication). Details on the INAA procedure are given by WASSON *et al.* (1989).

Meteorite	Cr µg/g	Co mg/g	Ni mg/g	Cu µg/g	Ga µg/g	Ge µg/g	As µg/g	Sb ng/g	W µg/g	Re ng/g	Ir µg/g	Pt µg/g	Au µg/g	Ga/Ge
STG 07009	**20**	**6.76**	**132**	**282**	**10.4**	**166**	**14.8**	**74**	**0.29**	**16**	**0.13**	**4.4**	**1.61**	**0.06**
Deep Springs	230	6.34	135	6.1	0.43	0.11	0.53		1.79	1210	10.5	12.7	0.13	3.94
Soroti	37	6.45	129	323	13.4	5.22	24.0	578	<0.2	<24	0.01	<0.9	1.60	2.57
El Qoseir	24	6.56	135	873	6.19	11.7	6.59		1.40	550	4.71		0.27	0.53
Prambanan	55	6.82	101	243	28.6	190	7.5		0.61	380	4.32		0.97	0.15
NWA 6932	45	6.84	123	312	9.45	102	6.45	38	1.10	685	7.87	19.8	0.78	0.09
Griffith	227	7.27	150	7	0.28	<50	0.19	<130	1.09	1064	10.0	13.0	0.06	0.35
Wiley	23	7.44	115	171	39.2	114	13.7	<200	0.93	224	6.85	32.8	1.51	
Laurens County	38	7.48	132	268	10.4	23.0	22.6		0.98	660	7.37		2.19	0.45

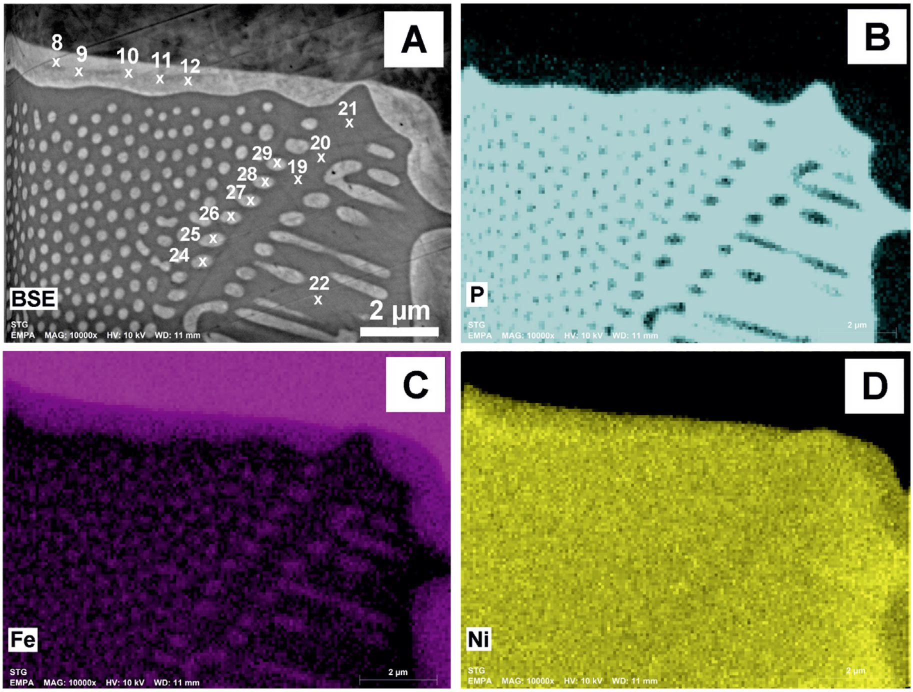

Fig. 8. High-resolution quantitative mapping (EMPA-EDS at 10 kV) of a schreibersite-metal intergrowth (detail of Fig. 7B). A: BSE image with locations of analysis spots of the object's rim (spots 8–12), the metal in the object's interior (spots 24–29) and the schreibersite (spots 19–22); B–D: X-ray maps for the elements P (B), Fe (C), and Ni (D).

At first, the high contents of As and Au indicate the possibility that STG 07009 might be a non-magmatic IAB iron (Choi *et al.* 1995). However, the high Au content in combination with very low Ir and low W implies formation by fractional crystallization, which in turn implies a magmatic origin. The Ga/Ge ratio that is a clue to the relatedness to other ungrouped irons is exceptionally low. Thus, STG 07009 is an ungrouped (magmatic) iron with no close relatives.

Accelerator mass spectroscopy

AMS measurements (performed by K. Nishiizumi and M. Caffee at PRIME Lab, Purdue University, USA) of the cosmogenic radionuclides ^{10}Be, ^{26}Al, and ^{36}Cl gave saturation activities (dpm per kg meteorite) of 4.28 ± 0.13, 3.44 ± 0.23, and 17.55 ± 0.72, respectively. Corresponding age calculations gave for STG 07009 a $^{36}Cl/^{36}Ar$ cosmic-ray exposure age of 780 ± 100 Myr and a ^{10}Be-$^{36}Cl/^{10}Be$ terrestrial age of 75 ± 33 kyr. The latter is rather young when compared to the overall terrestrial age distribution of Antarctic meteorites (Jull 2006).

Conclusion

The main results of this interdisciplinary study can be summarized as follows:

(1) Optical microscopy investigations revealed that STG 07009 has the typical structure of a plessitic octaedrite with almost all kamacite spindles having nuclei of schreibersite.

(2) A detailed electron microprobe investigation revealed that in places, the kamacite spindles contain schreibersite-metal intergrowths having complex textures and compositions.

(3) Based on bulk chemistry data obtained by INAA, STG 07009 is classified as an ungrouped (magmatic) iron with no close relatives.

(4) Age calculations based on AMS measurements of cosmogenic radionuclides gave for STG 07009 a cosmic-ray exposure age of 780 ± 100 Myr and a relatively young terrestrial age of 75 ± 33 kyr.

(5) Considering the glaciological setting and flow dynamics of the blue ice field where the meteorite was found and its terrestrial age, the impact of STG 07009 probably occurred within a radius of < 150 km from its find location.

Acknowledgments

We gratefully acknowledge funding of the Queenmet Expedition by the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), as well as flight and logistic support provided by DROMLAN. We thank J. T. WASSON (UCLA, USA) for the personal communication of INAA data, K. NISHIIZUMI and M. CAFFEE (PRIME Lab, Purdue University, USA) for performing the AMS measurements, and J. ERBACHER (BGR, Hannover, Germany) for providing a photograph of the meteorite's main mass. The authors thank M.E. VARELA (ICATE-CONICET, Argentina) and A. M. RUZICKA (Portland State University, USA) for their constructive reviews and helpful comments.

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