The Twannberg (Switzerland) IIG iron meteorites: Mineralogy, chemistry, and CRE ages

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Abstract—The original mass (15915 g) of the Twannberg IIG (low Ni-, high P) iron was found in 1984. Five additional masses (12 to 2488 g) were recovered between 2000 and 2007 in the area. The different masses show identical mineralogy consisting of kamacite single crystals with inclusions of three types of schreibersite crystals: cm-sized skeletal (10.5% Ni), lamellar (17.2% Ni), and 1–3 × 10 µm-sized microprismatic (23.9% Ni). Masses I and II were compared in detail and have virtually identical microstructure, hardness, chemical composition, cosmic-ray exposure (CRE) ages, and 10Be and 26Al activities. Bulk concentrations of 5.2% Ni and 2.0% P were calculated. The preatmospheric mass is estimated to have been at least 11,000 kg. The average CRE age for the different Twannberg samples is 230 ± 50 Ma. Detrital terrestrial mineral grains in the oxide rinds of the three larger masses indicate that they oxidized while they were incorporated in a glacial till deposited by the Rhône glacier during the last glaciation (Würm). The find location of mass I is located at the limit of glaciation where the meteorite may have deposited after transport by the glacier over considerable distance. All evidence indicates pairing of the six masses, which may be part of a larger shower as is indicated by the large inferred pre-atmospheric mass.

INTRODUCTION AND CIRCUMSTANCES OF FINDS

In this work, we present the information about the find circumstances and characteristics of six iron meteorite masses that were collected on the Twann Mt. (Twannberg) and its surroundings, about 28 km northwest of Bern, Switzerland (Table 1). Representative views of the three larger masses are shown in Fig. 1. Mass I was found by Margrit Christen during the removal of stones from a freshly ploughed field on Twannberg (Twann Mt.) near the Gruebmatt farm where it was kept as a curiosity for about a year. It was then reported to the curator of the meteorite collection of the Bally Museum in Schönenwerd, Switzerland, who recognized it as a meteorite and initiated an investigation (Bühler 1986a, 1986b). It was classified as an ungrouped hexahedrite to coarsest octahedrite and was named “Twannberg” (Graham 1986), and is here identified as Twannberg I. The circumstances of the find of Twannberg I and a summary of detailed investigations by several laboratories are given by Bühler (1986b).

Mass II was discovered by Marc Jost in the attic of a 17th century house (built around 1650) in the village of Twann, 3.5 km SW of the find location of Twannberg I. The find was reported to the first author on September 5, 2000, and one day later, the main mass was inspected in Twann and then brought to Bern for further investigation. The exact find locality in the attic was visited by the first author on December 20, 2000, with the finder. This fragment had been placed together with iron utensils on top of a stone wall in the attic inside the house just below the roof. The meteorite had been covered with a thick layer of dust and dust-free area showing the exact position of the
meteorite was still clearly visible. This meteorite must have been moved to the attic some time during the last 350 years. The find of this mass triggered a comparison of masses I and II.

Mass III: after the near completion of the study of masses I and II, mass III was discovered in 2005 in a rock collection transferred from the Schwab Museum in Biel to the Natural History Museum Bern (NMBE). This mass was labeled as "Eisenglanz" (hematite) in the handwriting of Fritz Antenen (1867–1944), who reorganized the collection in 1932. It can thus be assumed that this mass was found before 1932, but not recognized as a meteorite.

Masses IV, V, and VI were discovered in the summer of 2007 in the Twannbach canyon a few 100 m NW of Twann by Marcel Wälti while searching for gold, and by Daniel Ducрест while searching for interesting pebbles.

The newly discovered masses are clearly paired (see below) with the original Twannberg mass (TW I) and thus represent additional fragments of the Twannberg fall, bringing the total mass to 20.771 kg. General information on the six masses of Twannberg is given in Table 1. After the discovery of TW II, its finder Marc Jost searched the Twannberg area for more than 100 hours using a metal detector, but found no more meteorites.

After its discovery, Twannberg I was hosted in the Bally Museum, Schönenvord, Switzerland, from 1985 until 2002 when it was acquired by NMBE on the dissolution of the Bally Museum collection. Twannberg II was acquired from the finder by NMBE in 2000. Twannberg III is at NMBE as a permanent loan from the Museum Schwab. Masses IV to VI are in private collections, with small samples being deposited at NMBE. Because Twannberg has never been fully described in the literature, data are scattered in specialized (Wasson et al. 1989; Schultz and Franke 2004) and popular articles (Bühler 1986a, 1986b, 1988; Hofmann 2005). In this paper, several characteristics of the different masses are discussed and tested for pairing, with special emphasis on masses I and II.

First, the results of the mineralogical and chemical investigations are presented in order to establish the pairing of the masses. Based on the conclusions concerning mineralogy, chemistry, and cosmic-ray exposure history, it will be shown that Twannberg I and II are two fragments of the same meteorite fall. Twannberg III–VI have been investigated in less detail due to their finding during an advanced stage of this study, but the identical and otherwise very rare structure, combined with indications for weathering in a similar environment, clearly indicate pairing as well.

Second, the cosmic-ray exposure (CRE) history will be characterized. The relevance of the determination of CRE ages of iron meteorites was demonstrated by Lavielle et al. (1999) for the question of the constancy of the galactic cosmic ray flux (CRF) during the period of 150–700 Ma before the present. For this time interval, based on the average 36Cl or 36Ar production rates, these authors found a 28% lower CRF when compared to production rates commonly used for the recent CRF.

Twannberg is a member of iron meteorite group IIG. With the classification of Twannberg in 1986 and Guanaco in 2001 as IIG meteorites, the minimum population (5) for group designation was reached, and the grouplet once known as the Bellsbank trio became group IIG. All of these meteorites are hexahedrites being very low in nickel (4.1 to 4.9% Ni in metal) and high in P, leading to characteristic large inclusions of skeletal schreibersite (Fe,Ni)3P.

**REGIONAL CONTEXT AND GEOLOGY**

Twannberg I was found on top of the Twannberg, at an altitude of 975 m. Twannberg is the southernmost anticlinal fold of the SW-NE-trending Jura mountain chain of Pliocene age. The mountains consists of Upper Jurassic (Tithonian) to Lower Cretaceous (Valanginian) limestones and minor marls and are partially covered by up to several meters of Quaternary glacial till (Schär et al. 1971), resulting in an

| Table 1. Main characteristics of the Twannberg iron meteorite masses. |
|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
|                  | Twannberg I      | Twannberg II     | Twannberg III    | Twannberg IV     | Twannberg V      | Twannberg VI     |
| Date of find or recognition | May 9, 1984      | August 2000      | September 2, 2005| Summer 2007      | Summer 2007      | Summer 2007      |
| Place of find | Twannberg, Canton of Bern, Switzerland | Dorfagasse 7, Twann, Canton of Bern, Switzerland | Museum Schwab, Biel, Canton of Bern, Switzerland | Twannbach | Twannbach | Twannbach |
| Type of find place | Field after plowing | Attic of 17th century house | Old museum collection | River bed | River bed | River bed |
| Longitude and latitude¹ | 47°7.39'N; 7°10.63'E | 47°5.73'N; 7°9.45'E | 47°8.33'N; 7°14.48'E | 47°5.80'N; 7°8.83'E | 47°5.80'N; 7°8.83'E | 47°5.80'N; 7°8.83'E |
| Altitude (m) | 975 | 445 | 440 | 560 | 560 | 560 |
| Finder | Margrit Christen | Marc Jost | Marcel Wälti | Daniel Ducrest | Marcel Wälti | Marcel Wälti |
| Original dimensions | 18 × 15 × 12 cm | 13 × 9 × 6 cm | 12 × 10 × 7 cm | 3.3 × 2.4 × 1.6 cm | 2.6 × 1.3 × 0.9 cm | 2.1 × 1.9 × 1.1 cm |
| Recovered mass | 15,915 g | 2246 g | 2533 g | ~50 g | 14.2 g | 12.7 g |
| Main mass as of December 2007 | 9347 g | 1962 g | 2487.5 g | 48.7 g | 12.8 g | 12.3 g |
| NMBE inv. nr. | 36,467 | 35,119 | 37,777 | 39,378 | 39,307 | 39,308 |

¹As determined with GPS, WGS 84 map datum.
abundance of scattered pebbles and blocks of crystalline and sedimentary rocks. This debris was transported by the Rhône glacier from the Alps over a distance of 100 to 250 km. The find location of Twannberg I is close to the northern maximal extension of the Rhône glacier during the last (Würm) ice age (Fig. 2). The village of Twann, where TWII was found in a house, is located on the NW shore of the Lake of Biel, at an altitude of 430 m, among local outcrops of Cretaceous limestone and glacial till. Twann is located at the boundary between the Jura fold belt and the Tertiary molasse basin (Swiss plateau) to the SW. The area is covered by vineyards at low elevations wherever the hillsides face S-SE, but is
dominated by forest on the higher slopes. Relatively flat areas at higher elevations on Twannberg are partly forested and partly agricultural land. The city of Biel with museum Schwab, where mass III was discovered, is located at the northeastern end of the Lake of Biel, 8 km NE of Twann. The (secondary) find places of TWII and III are just 3.5 and 5 km from that of TW I. The shores of the Lake of Biel have been inhabited since at least 4000 B.C. Abundant Neolithic artifacts were recovered at Twann and other sites nearby. Reports of rusted masses found in these Neolithic sites were checked, but all evidence indicates that they were due to oxidized pyrite used to make fire.

EXPERIMENTAL PROCEDURES

Bulk Characteristics and Mineralogy

The mineralogy of Twannberg I and II was studied on polished sections using optical microscopy. Hardness measurements were carried out using a Leitz Durimet hardness microscope with a load of 100 g. The volume proportion of schreibersite was determined from an image of a large section of Twannberg I and from several X-ray tomographic images of Twannberg II processed by using image analysis software (NIH image, see below). Troilite abundance was estimated from reflected light microphotographs. Mineral compositions were determined by electron microprobe analysis using a JEOL JXA 8200 instrument with the following analytical conditions: 15 kV, 20 nA, 2 µm beam diameter on sample, K X-ray lines, and ϕ(ρZ) matrix correction. The standards used included metallic Fe, Co and Ni, Cu₃PS₄ (S), Cr₂O₃ (Cr), FeTiO₃ (Ti), almandine (Si, Al), and fluorapatite (P). Additional mineral compositional analyses were obtained by standardless EDS analysis using a CamScan CS4 SEM. The mineralogical composition of the oxidation rind was determined by X-ray diffraction (XRD) using a Guinier-De Wolff camera and Fe-radiation. A Zeiss Evo 50 scanning electron microscope
operated at 20 kV, coupled with an energy dispersive system (EDS) was used to perform spot analyses. X-ray tomographs were obtained at EMPA Dübendorf, Switzerland, using an industrial CT scanner operated at 400 kV, 2.25 mA with linear array detectors and a detector aperture of 0.25 × 0.5 mm. Pixel size was 0.25 mm.

Elemental Composition

The fragments of the meteorites taken for the chemical analysis by inductively coupled plasma spectroscopy were cleaned by acid leaching prior to dissolution. Leaching was performed by submerging the whole fragments of the meteorites to be analyzed into a solution of 1.5 M HNO₃ for 90 seconds. Of the fragments 0.25% and 1.2% of their mass, respectively, were dissolved by this procedure. The masses remaining after leaching—typically 0.2 g—along with HNO₃ and H₂O₂ were placed in Teflon pressure bombs and heated with microwave excitation. The concentrations of Fe, Ni, Co, and 10 trace elements in the resulting solutions were measured by ICP-OES or by Quadrupole ICP-MS. Instrumental neutron activation analysis was carried out using protocols described elsewhere (e.g., Wasson and Choi 2004). Duplicate samples of TW I and TW II were studied in separate irradiations. Meteorite bulk compositions were calculated from schreibersite modes, mineral compositions and mineral densities. The minerals considered were mean bulk metal, skeletal schreibersite and a small amount of troilite (0.14% of volume of skeletal schreibersites, based on volume estimate from photomicrographs). A bulk metal P content of 0.34% was adopted, as this is the lower of two bulk measurements (assuming no contamination from skeletal schreibersite).

Noble Gases

Noble gas analyses of samples of about 0.1 g were performed at the Physics Institute of the University of Bern. The samples were heated in vacuum at 90 °C for several days in the storage arm of the extraction system to reduce adsorbed atmospheric gases. The Mo crucible of the extraction system was preconditioned by melting about 0.5 g of stone meteorite material to avoid the reaction of meteoritic Fe₃Ni with the Mo of the crucible. This pretreatment was also used to check the proper functioning of the total analytical system. Gases were extracted by RF-heating in a single step at 1700 °C. Completeness of the gas release was checked by adding a final extraction step at 1740 °C. The mass spectrometric analyses and background corrections were performed according to the description by Eugster et al. (1993) using system B. The following blanks were subtracted (units of 10⁻⁸ cm³ STP/g): ³He = <0.00004, ⁴He = 0.04, ²⁰Ne = 0.0008, ⁴⁰Ar = 0.4. The errors correspond to a 95% confidence level.

Cosmogenic Radionuclides

The Twannberg samples analyzed for cosmogenic radionuclides were dissolved in mineral acids after the addition Al, Be, and/or Cl carriers. Al, Be, and Cl were separated by standard methods (Vogt and Herpers 1988). ¹⁰Be/⁹Be, ²⁶Al/²⁷Al, and ³⁶Cl/Cl isotope ratios for the Twannberg samples were measured by accelerator mass spectrometry (AMS) at Purdue University. The ²⁶Al/²⁷Al and ³⁶Cl/Cl ratios were converted to ²⁶Al and ³⁶Cl activities, respectively using Purdue’s in-house standards for ²⁶Al (t₁/₂ = 0.7 Ma) and ³⁶Cl (t₁/₂ = 0.3 Ma). Details of procedures and standards are reported in Vogt et al. (1994). For ¹⁰Be (t₁/₂ = 1.5 Ma) the ¹⁰Be/⁹Be ratio was converted to a ¹⁰Be activity by using the measured ¹⁰Be/⁹Be ratio of Dhurmsala material prepared by Rolf Michel, and an activity of 22 ± 1 dpm/kg for that material.

RESULTS

Morphology and Mineralogy

Twannberg I originally measured approximately 18 × 15 × 12 cm with a rather isometric shape. Twannberg II has maximum dimensions of 13 × 9 × 6 cm, and mass III of 12 × 10 × 7 cm. The surface of all three large masses is made up of the same type of dark brown oxide rind, up to 6 mm thick locally. Abundant inclusions of grains of quartz, mica and fragments of mica-rich schist are present in the oxide crust of the three masses. The small masses IV to VI were covered by an oxide crust lacking these mineral inclusions, probably because of abrasion during transport in the riverbed.

The mineralogy of Twannberg is simple. Kamacite and schreibersite constitute the majority (99.99%) of the modal composition. We use schreibersite together with a descriptive term for all morphotypes of Fe₃P in this paper. The term “rhabdite” is avoided because this is not an official mineral name and the use has not always been consistent in the literature. Typically the type we call “microprismatic schreibersite,” and sometimes also the “lamellar schreibersite,” were called “rhabdite.” The Twannberg individuals consist of single large kamacite crystals. Neumann bands are common in the kamacite (Fig. 1g). Schreibersite occurs as three types (Fig. 3): Skeletal schreibersite forms crystals up to 4.5 cm long and 2–4 mm wide. These constitute 6–12 vol% of the meteorite. Thin (5–20 μm) lamellar schreibersite having lengths >3.5 cm are found in kamacite (aspect ratio ~1000). The abundance of lamellar schreibersite is relatively low with spacings of at least 1 mm (typically 2–3 mm) between lamellae. Close to skeletal schreibersite, lamellar schreibersite is less common but still present. Microprismatic schreibersite forms 1–3 μm wide and up to 10 m long oriented inclusions in kamacite. Microprismatic schreibersite occurs only at a distance >250 μm
from schreibersite lamellae while kamacite closer to schreibersite lamellae is free of such inclusions. The types of schreibersite observed in Twannberg are very similar to those in other members of group IIE such as Bellsbank (Clarke and Goldstein 1978) and also in hexahedrites with higher bulk Ni (Buchwald 1975; Randich and Goldstein 1978). In Twannberg, the abundance of schreibersite lamellae is lower and the size of microprismatic schreibersites is smaller, however.

Troilite occurs as grains up to 60 µm in size at schreibersite-kamacite grain boundaries and as exsolutions in schreibersite (maximum size 4 × 30 µm). The modal abundance of troilite was estimated relative to schreibersite because troilite was never observed in kamacite. Troilite abundance is 0.14 vol% of skeletal schreibersite, or 0.007–0.014 vol% of the bulk meteorite.

Electron microprobe (EMP) analyses of schreibersite, troilite and kamacite are presented in Table 2. Schreibersite varieties (skeletal crystals, lamellae, and microprisms) are significantly different in terms of their Ni concentrations. The large skeletal schreibersites show the lowest Ni-concentrations (mean 10.47 ± 0.20 wt%). Schreibersite lamellae have an average Ni concentration of 17.15 ± 0.63 wt%. The microprismatic schreibersites, finally, show a mean of 23.9 ± 1.9 wt% Ni. The strong enrichment of Ni in schreibersite relative to kamacite is consistent with results of Randich and Goldstein (1978), Clarke and Goldstein (1978) and Geist et al. (2005). The Ni content in Twannberg schreibersites is considerably lower than that in IIAB hexahedrites, however (~25 to 40 wt% Ni, Randich and Goldstein 1978). The EMP analyses of kamacite show lower Ni (EMP: 3.33, bulk ~4.5 wt%) and Co (EMP: 0.34, bulk 0.5%) than the bulk metal analyses.

Fig. 3. Types of schreibersite in Twannberg, as observed by reflected light microscopy/SEM. a) Skeletal schreibersite (S) showing brittle fracturing in unfractured kamacite (K). Along the boundary some grains of troilite (Tr) are located. b) Lamellar schreibersite, strongly fractured, in kamacite. Kamacite shows strong alteration in vicinity of fractured schreibersite. Oil immersion. c) BSE image of oriented microprismatic schreibersites in kamacite. Note heterogeneity in kamacite, probably due to microexsolutions of schreibersite. d) Lamellar schreibersite more resistant to weathering than kamacite. Oxidation products (Ox) include magnetite and maghemite (brighter) and darker goethite.
For Ni this might be due to the presence of microprismatic schreibersites and Ni-depleted zones in the kamacite near schreibersite, the reason for the low Co remains unclear.

On large cut surfaces, fractures that follow the schreibersite lamellae are quite common (Figs. 1a–d). Fracturing along the brittle schreibersite lamellae resulted in preferred and deep oxidation along lamellar schreibersites. Between 7 (TW II) and up to 10 (TW I) orientations of lamellar schreibersites could be observed, consistent with a complex crystallographic orientation parallel to \{221\} and possibly \{100\}. Similar observations have been reported for the hexahedrites North Chile and Coahuila (Buchwald 1975). Based on cut surfaces, the abundance of large schreibersite inclusions was estimated at 12.2 vol\% (TW I), 6.0 vol\% (TW II) and 9.3 vol\% (TW III), similar to the value of 11\% obtained by V. Buchwald (in Bühler 1986a, 1986b) on different sections.

Microhardness measurements carried out on kamacite yielded a Vickers hardness of 253 ± 13 (n = 17) for TW I and 240 ± 6 (n = 17) for TW II. Measurements by V. Buchwald (in Bühler 1986a) are identical at 235 ± 15. Schreibersite in TW I has a hardness of 1207 ± 42 (n = 7). The presence of Neumann bands (Fig. 1g) and the kamacite hardness are indicative of medium to strong shock of up to 13 GPa (Buchwald 1975).

The oxidation rinds of TW I and TW II both consist of a mixture of iron oxyhydroxides with mineral grains (mainly quartz, feldspar, mica) derived from the local till (Fig. 1f). Optical microscopy and XRD revealed the presence of goethite, maghemite and magnetite. Locally vivianite \(Fe_3(PO_4)_2\cdot8H_2O\) was observed in TW II and III in corroded kamacite in contact with schreibersite. In contact with the oxidized rim, schreibersite is clearly more resistant to weathering than kamacite. Oxidation of kamacite in the interior of all Twannberg specimens typically propagates along fractured lamellar schreibersites (Figs. 1d and 3b) and also along skeletal schreibersites. The thickness of the oxidation rind on all masses ranges from 1 to 15 mm, but oxidation along grain boundaries was observed as deep as 30 mm from the surface.

### Chemical Composition

Major and trace element contents of Twannberg I and Twannberg II are given in Table 3. With a few exceptions, the respective concentrations in the two samples are identical within the quoted errors. Differences are observed for Ir, Pt, and Re. The higher Ir contents determined by ICP are close to the detection limits; for this element the INAA gives better results (lower by a factor of 2 to 3) and are preferred. For Pt, signals were well above detection limits for both methods and there is no reason to prefer one set of results to the other. For Re, only upper limits are obtained with INAA. The new distinct values for Re based on ICP are compatible with the lower range for octahedrites. Bulk P contents were measured by ICP analysis of cuttings that were taken from a large (17 × 10 cm) section in an attempt to obtain a representative bulk sample. The values of 1.33 wt\% P for TW I and 0.34 wt\% for TW II likely reflect different losses of brittle schreibersite during sectioning as the values are intermediary between those for kamacite (0.14%, Table 2) and calculated bulk compositions (1.1 to 2.0%, Table 4). Due to the extremely
Table 3. Concentrations of major and trace elements in bulk metal for Twannberg I and II.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Fe</th>
<th>Ni</th>
<th>Co</th>
<th>Cu</th>
<th>Ga</th>
<th>Ge</th>
<th>As</th>
<th>Sb</th>
<th>W</th>
<th>Re</th>
<th>Ir</th>
<th>Pt</th>
<th>Au</th>
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<tbody>
<tr>
<td>Twannberg I</td>
<td>4.42</td>
<td>5210</td>
<td>90</td>
<td>37.9</td>
<td>51.4</td>
<td>17.9</td>
<td>0.163</td>
<td>0.20</td>
<td>0.086</td>
<td>&lt;20</td>
<td>0.086</td>
<td>1.35</td>
<td></td>
</tr>
<tr>
<td>Twannberg I</td>
<td>95.4</td>
<td>4.31</td>
<td>5120</td>
<td>71</td>
<td>32.0</td>
<td>48</td>
<td>16.9</td>
<td>0.135</td>
<td>0.10</td>
<td>0.01</td>
<td>0.22</td>
<td>0.24</td>
<td>1.05</td>
</tr>
<tr>
<td>Twannberg II</td>
<td>4.50</td>
<td>5220</td>
<td>89</td>
<td>38.4</td>
<td>-</td>
<td>18.1</td>
<td>0.14</td>
<td>0.14</td>
<td>0.101</td>
<td>0.9</td>
<td>1.406</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Twannberg II</td>
<td>95.5</td>
<td>4.79</td>
<td>5170</td>
<td>73</td>
<td>32.5</td>
<td>47</td>
<td>17.6</td>
<td>0.146</td>
<td>0.15</td>
<td>0.012</td>
<td>0.34</td>
<td>0.22</td>
<td>1.04</td>
</tr>
</tbody>
</table>

Table 4. Calculated bulk composition for Twannberg.

<table>
<thead>
<tr>
<th>Schreibersite (vol%)</th>
<th>TW I</th>
<th>TW II</th>
<th>TW III</th>
<th>TW IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>wt%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td>92.4</td>
<td>93.5</td>
<td>92.9</td>
<td>92.4</td>
</tr>
<tr>
<td>Ni</td>
<td>5.1</td>
<td>4.83</td>
<td>5.01</td>
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</tr>
<tr>
<td>Co</td>
<td>0.47</td>
<td>0.49</td>
<td>0.48</td>
<td>0.50</td>
</tr>
<tr>
<td>P</td>
<td>1.95</td>
<td>1.14</td>
<td>1.58</td>
<td>2.00</td>
</tr>
<tr>
<td>S</td>
<td>0.01</td>
<td>0.006</td>
<td>0.01</td>
<td>-</td>
</tr>
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</table>

DISCUSSION

Geological Environment

The grains of quartz, mica, and mica-rich rock fragments present in the oxide rind of the three large masses clearly indicate that they were in contact with glacial till and not more than 5 cm or so. This range of depths refers to the last few million years in space. The activities of the cosmogenic radionuclides do not constrain either the lateral distances between samples in space at any time, assuming a more or less spherical meteoroid, or the vertical distances at times greater than a few million years ago. On the other hand, the small mass of the analyzed Twannberg individuals suggests that the samples analyzed were close together for some time.

The 10Be activities are quite low, about 40 times lower than the values of 5–6 dpm/kg typical of small iron meteorites (Fig. 4).

The 26Al activities are also a factor of about 40 lower than the value (3.5 dpm/kg) typical of small iron meteorites. The relative uncertainties of 15–30% are unusually large; they reflect the low measured 26Al/27Al ratios, 5–10 × 10⁻¹⁴, which were due in part to low sample activities and in part to the relatively large masses of Al carrier added, ~3 mg. In addition, blank corrections (~1 × 10⁻¹⁴) were appreciable. Although the 26Al activities apparently vary by a factor of two, from 0.056 ± 0.018 to 0.118 ± 0.023, the extreme values differ by only 1.5 (σ₁ + σ₂). In light of the limited range of 10Be activities, it seems likely that either experimental error or differences in composition account for most of the variation in 26Al activities. Twannberg contains 1–2% S. Elements other than Fe and Ni with Z ≥ 14 (Si) contribute appreciably to the production rate of 26Al. In Twannberg, 26Al would probably be produced mainly in schreibersite.

The results for 36Cl scatter appreciably—by a factor of about two. Although production rates of 36Cl from K and Ca are high enough to have caused measurable increases in the 36Cl activities of some samples, unknown analytical problems seem a more likely cause of the observed variations of this radionuclide. The average 36Cl activity for the samples reported in Table 6 is a factor of about 30 lower than found in small iron falls.

The 10Be activities are fairly uniform—the total observed variation is less than 10%, which suggests that the samples analyzed came from within a range of (vertical) depths of less than 5 cm or so. This range of depths refers to the last few million years in space. The activities of the cosmogenic radionuclides do not constrain either the lateral distances between samples in space at any time, assuming a more or less spherical meteoroid, or the vertical distances at times greater than a few million years ago. On the other hand, the small mass of the analyzed Twannberg individuals suggests that the samples analyzed were close together for some time.

The 10Be activities are quite low, about 40 times lower than the values of 5–6 dpm/kg typical of small iron meteorites (Fig. 4).

The 26Al activities are also a factor of about 40 lower than the value (3.5 dpm/kg) typical of small iron meteorites. The relative uncertainties of 15–30% are unusually large; they reflect the low measured 26Al/27Al ratios, 5–10 × 10⁻¹⁴, which were due in part to low sample activities and in part to the relatively large masses of Al carrier added, ~3 mg. In addition, blank corrections (~1 × 10⁻¹⁴) were appreciable. Although the 26Al activities apparently vary by a factor of two, from 0.056 ± 0.018 to 0.118 ± 0.023, the extreme values differ by only 1.5 (σ₁ + σ₂). In light of the limited range of 10Be activities, it seems likely that either experimental error or differences in composition account for most of the variation in 26Al activities. Twannberg contains 1–2% S. Elements other than Fe and Ni with Z ≥ 14 (Si) contribute appreciably to the production rate of 26Al. In Twannberg, 26Al would probably be produced mainly in schreibersite.

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DISCUSSION

Geological Environment

The grains of quartz, mica, and mica-rich rock fragments present in the oxide rind of the three large masses clearly indicate that they were in contact with glacial till and not
limestone during weathering. This confirms that TW II and III were originally located in a similar environment as TW I. Given the obvious contact with glacial sediments during weathering, it seems likely that the meteorites were transported by the Rhône glacier and deposited in the till.

Mineralogy

The occurrence of three types of schreibersite reflects crystallization/exsolution under conditions of decreasing temperature. For skeletal schreibersite, a formation temperature of >850 °C was estimated by Doan and Goldstein (1969) and Clarke and Goldstein (1978). These authors argue for an exsolution origin of skeletal schreibersite. We do not exclude a combination of crystallization from melt followed by growth by diffusion of P out of kamacite. Lamellar and microprismatic schreibersites clearly were formed by exsolution. Distances of diffusion for Ni and P can be estimated: In the case of large skeletal schreibersites several mm to cm, in case of schreibersite lamellae ~250 µm (width of zone free of microprismatic schreibersites) and for the microprismatic schreibersites ~10–20 µm (mean spacing divided by 2). The exsolution of schreibersite during cooling caused a redistribution of nickel (and probably of other elements) within the large kamacite crystals and is most likely the reason for the differences observed between bulk metal and microprobe analyses.

The mixture of ductile kamacite with brittle schreibersite present in three very different forms strongly influenced the fracturing pattern of Twannberg. Especially, the very extensive (several cm²) schreibersite lamellae served as fracturing planes and led to a deep penetration of cracks and, later on, to terrestrial alteration.

Elemental Composition

The two analyzed masses (I and II) are closely similar in composition consistent with derivation from the same parent mass. With a content of 6–12 vol% of schreibersite, it is evident that the chemical analyses, performed on metal-dominated samples, do not properly reflect the bulk composition; skeletal schreibersite was almost entirely excluded from these analyses.

To allow for this, we calculated a bulk composition based on the modal abundance and composition of schreibersite following a procedure used by Buchwald (in Bühler 1986b); this is listed in Table 4. With about 2 wt% P, Twannberg (like the other IIG irons) belongs to the most P-rich iron meteorites. In Fig. 5 we compare the INAA data of Twannberg I and II with those of the other four IIG irons on Ga-Au, As-Au and Co-Au diagrams. All four of these elements are useful for distinguishing among iron meteorite groups. The data are consistent with IIG being a group. The two Twannberg points plot close together on all three diagrams; they are very similar in composition to Bellsbank, the latter having a slightly lower Au content. The two Twannberg analyses are resolvably different in their Ir contents (INAA data in Table 3) and may also be different in their Au contents. This difference could be explained by small local differences in the fraction of trapped melt. However, Wasson et al. (2007) noted that Ir and Au values were slightly lower near massive schreibersite in the Santa Luzia iron, so the small differences might also reflect a similar effect caused by solid-state diffusion during cooling.

In group IIAB, Wasson et al. (2007) noted that the skeletal schreibersite and the associated troilite formed from trapped melt. Metal compositions also supported this conclusion. It is probable that IIG schreibersite also formed as a liquidus phase. The size of these crystals increased appreciably as a result of exsolution of P from the cooling taenite, as discussed by Clarke and Goldstein (1978).

It seems possible that the low S contents of IIG irons reflect liquid immiscibility, as discussed for IIAB by Wasson et al. (2007). This explanation would require that S partition very strongly into the S-rich liquid. The low S content could
also result if there were minimal amounts of trapped melt. In this case, the high P content might be best understood if schreibersite were a liquidus phase at the time the IIG irons were crystallizing from the melt.

CRE Ages

The CRE ages can be based on the $^{36}$Cl-$^{36}$Ar method as outlined in detail by Lavielle et al. (1999). Chlorine-$^{36}$ and $^{36}$Ar in iron meteorites are produced by spallation reactions with Fe and Ni. Chlorine-$^{36}$ decays to $^{36}$Ar with a branching ratio of 0.981. Since both $^{36}$Cl and $^{36}$Ar are produced from the same targets and have similar production pathways, their production ratio is almost independent of shielding effects. This circumstance makes them ideal for the calculation of CRE ages. Assuming a constant cosmic ray flux, the $^{36}$Cl-$^{36}$Ar age $T_{36}$ is given by

$$T_{36} = 511 \times \frac{P(^{36}\text{Cl})}{P(^{36}\text{Ar})} \times \frac{[^{36}\text{Ar}]/[^{36}\text{Cl}]}{(^{36}\text{Cl})}$$

(1)

where $P(^{36}\text{Cl})/(^{36}\text{Ar}) = 0.835$ and $^{36}$Ar and $^{36}$Cl are the $^{36}$Ar (10$^{-8}$ cm$^3$/g) and $^{36}$Cl (dpm/kg) concentrations measured in the same sample, respectively.

For Twannberg II an age of 276 Ma is obtained. The Ar data of Twannberg I, sample 56006.3 are not reliable for age dating, considering the high $^{36}$Ar/$^{38}$Ar ratio due to schreibersite inclusions. If the $^{36}$Ar value for Twannberg I given in Schultz and Francke (2004) is used, and adopting 0.75 dpm/kg $^{36}$Cl, an age of 182 Ma is calculated. CRE ages can also be calculated using the $^{21}$Ne-$^{10}$Be and $^{21}$Ne-$^{26}$Al methods of Lavielle et al. (1999). Assuming that the $^{21}$Ne analysis of Twannberg I is affected by schreibersite inclusions, it seems fair to average the $^{21}$Ne content for the other two samples (Twannberg II and the data given by Terribilini et al. 2004) to about 1000 Ma (cf. Wieler 2002). If one then uses average $^{10}$Be and $^{26}$Al concentrations, a terrestrial age of ~10 kyr, and equations of Lavielle (1999), one finds a $^{21}$Ne-$^{10}$Be age of 246 Ma and a $^{21}$Ne-$^{26}$Al age of 229 Ma. Thus, an average CRE age for the investigated Twannberg samples of 230 ± 50 Ma is proposed. This age is typical for iron meteorites (Eugster 2003). Their CRE ages are in a range of about 7 Ma for the Rafrüti anomalous ataxite (Terribilini et al. 2000) to about 1000 Ma (cf. Wieler 2002).

Terrestrial Age

The ratios of the $^{36}$Cl to the $^{10}$Be activities for the six Twannberg samples analyzed yield a value of 6.69 ± 0.96. This ratio can be used to calculate a terrestrial age for Twannberg from the relation

$$\frac{^{36}\text{Cl}}{^{10}\text{Be}} = \frac{P(^{36}\text{Cl})}{P(^{10}\text{Be})} \times e^{-\lambda_{36}T_{terr}} = \frac{P(^{36}\text{Cl})}{P(^{10}\text{Be})} \times e^{-\lambda_{36}T_{terr}}.$$  

(2)

Because $^{36}$Cl has a smaller half-life than $^{10}$Be, the measured $^{36}$Cl/$^{10}$Be activity ratio is expected to decrease as terrestrial age increases. The production rate ratio, $P(^{36}\text{Cl})/P(^{10}\text{Be})$, is...
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fairly constant in iron meteorites. For relatively small irons, the ratio $P(^{36}\text{Cl})/P(^{10}\text{Be})$ is $\approx 22/5 = 4.4$. As shown in Fig. 4, a line with a slope of 4.4 and passing through the origin fits the experimental data for many iron meteorites reasonably well. For Twannberg, however, the average of the measured $^{36}\text{Cl}$/

$^{10}\text{Be}$ activity ratios lies above the trend line. This is a hint that Twannberg was probably large.

Lavielle et al. (1999) made a more detailed study of the $^{36}\text{Cl}/^{10}\text{Be}$ production rate ratio. They found that the equation below describes the activities measured in iron meteorites:

$$^{36}\text{Cl} = 5.97 \times [^{10}\text{Be}] - 0.184 \times ^{10}\text{Be}^2 - 0.024 \times [^{10}\text{Be}]^3. \quad (3)$$

For the average $^{10}\text{Be}$ activity of the Twannberg samples, 0.114 dpm/kg, the formula of Lavielle et al. (1999) predict a $^{36}\text{Cl}$ activity (at saturation) of 0.68 dpm/kg and a production rate ratio $P(^{36}\text{Cl})/P(^{10}\text{Be}) = 5.95$.

The measured $^{36}\text{Cl}/^{10}\text{Be}$ activity ratio of 6.7 ± 1.0 is somewhat higher than, but agrees within error with, with the expected production rate ratio of 6.0. It is concluded that the terrestrial age of Twannberg is zero within the uncertainties of the calculation (maximum age allowed within error is 28 kyr). Analogous treatment of the $^{26}\text{Al}/^{10}\text{Be}$ ratio leads to the same conclusion with a larger uncertainty (maximum age 170 kyr). These values are consistent with a fall during the last glaciation, as indicated with the geological setting.

The activity of $^{36}\text{Cl}$ evidently changed by at most a few percent since the time of fall. The activities of the shorter-lived cosmogenic radionuclides $^{41}\text{Ca}$ or $^{14}\text{C}$ would have changed by larger percentages and could therefore provide better estimates of Twannberg’s terrestrial age. The measurements would be difficult however, as production rates in the samples of Twannberg analyzed so far were quite low.

**Shielding and Pretatmospheric Size**

Excluding the cosmogenic $^{21}\text{Ne}$ concentration of Twannberg I, sample 56006.3 (schreibersite inclusions, see above), an average $^{21}\text{Ne}$ production rate, $P(^{21}\text{Ne})$, of 0.043 $\times 10^{-10}$ cm$^3$ STP/g·Ma is calculated from the data in Table 5 and a CRE age of 230 ± 50 Ma. Furthermore, a cosmogenic ratio $^4\text{He}/^{21}\text{Ne}$ of 415 is obtained. With these data for $P(^{21}\text{Ne})$ and $^4\text{He}/^{21}\text{Ne}$, Twannberg plots in the lower right hand corner of Fig. 7 of Voshage and Feldmann (1979), close to Anoka and several other irons thought to have been very large in space.

Some additional information about the sample locations and meteoroid size can be obtained by comparing measured and modeled radionuclide activities. Michlovich et al. (1994) presented modeling calculations for Canyon Diablo, which although likely much larger than Twannberg, provides a rough guide for comparison. Their Figs. 1–4 (LAHET code particle fluxes) indicate that the activities measured in Twannberg correspond to the following shielding depths $^{36}\text{Cl}$, 68 cm; $^{26}\text{Al}$, 69; $^{10}\text{Be}$, 63 cm. Calculations for a smaller body might increase these estimates of depth slightly. A radius of 69 cm implies a minimum mass of 11,000 kg for a spherical object with a density of 8 g/cm$^3$. Given the fact that TW I and TW II are derived from a similar depth, it may be speculated that these masses were derived from the same individual due to breakup during terrestrial residence. Arguments for such speculations are missing, however.

**CONCLUSIONS**

The similarity of the meteoritic iron masses I and II recovered in the Twannberg area in terms of chemical
composition, structure, mineralogy, alteration history, noble gas concentrations, CRE ages, and concentrations of cosmogenic radioisotopes demonstrate without doubt that they are paired. The similarity of TW III–VI to TW I and II are also numerous: skeletal schreibersite of unusual size, high bulk P based on schreibersite mode, and the adhesion of local glacial till material (quite uncommon in iron meteorites) demonstrate pairing as well.

The indication of a large pretatmospheric mass of about 10,000 kg and the independent discovery of six fragments indicate that very likely more fragments are present in the area. The high abundance of brittle schreibersite may have facilitated breakup during atmospheric entry. The CRE age of Twannberg (about 230 Ma) is within the range typically observed for iron meteorites.

Abundant quartz grains and rock fragments present in the alteration rinds of the three large masses indicate intimate contact with glacial till material of the Rhône glacier during weathering. It appears possible, therefore, that the meteorites were transported by the Rhône glacier during the Würm ice age and the actual place of fall might be anywhere in the large catchment area (up to 150 km upstream). Other fragments of this fall might be scattered over a very large area, therefore, and are most likely to be found in areas covered by till of the Rhône glacier.

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