Abstract—This study presents compositional data and $^{57}$Fe Mössbauer spectra, taken at 295 K and 85 K, of two fragments of the enstatite (EL6) chondrite Neuschwanstein that fell near the famous Neuschwanstein castle (Bavaria, southern Germany) on April 6, 2002. Main silicate minerals are enstatite (Fs 2) and plagioclase (An 20), the main opaque minerals are kamacite and troilite. Small amounts of oldhamite, daubreelite, and schreibersite have been found. The presented Mössbauer data are the first data gathered for an EL6 chondrite. The dominant parts of each Mössbauer spectrum consist of two six-line patterns due to the presence of ferromagnetic phases kamacite and troilite. In contrast to other chondrites, peaks of other iron species in the central parts of the spectra are missing due to an extremely low content of Fe-bearing paramagnetic components. The hyperfine interaction parameters for kamacite are $H_{hf} = 333.2$ kOe, IS = 0.01 mm/s, quadrupole splitting $Q = 0$ mm/s, line width $W = 0.41$ mm/s. The data for troilite are $H_{hf} = 305.5$ kOe, IS = 0.75 mm/s, $Q = -0.85$ mm/s, $W = 0.34$ mm/s.

INTRODUCTION

On April 6, 2002 at 9:20 p.m. CET a brilliant fireball illuminated the firmament of the Bavarian-Austrian border. For a few seconds, the night became bright as day. The associated meteorite fall was well documented by the European Fireball Network (EFN). With the help of EFN photographs, Spurný et al. (2002) calculated the meteoroid’s orbit and the impact area, which three months later led to the recovery of the first fragment (1.75 kg) near the famous Neuschwanstein castle (Bavaria, southern Germany) on April 6, 2002. Main silicate minerals are enstatite (Fs 2) and plagioclase (An 20), the main opaque minerals are kamacite and troilite. Small amounts of oldhamite, daubreelite, and schreibersite have been found. The presented Mössbauer data are the first data gathered for an EL6 chondrite. The dominant parts of each Mössbauer spectrum consist of two six-line patterns due to the presence of ferromagnetic phases kamacite and troilite. In contrast to other chondrites, peaks of other iron species in the central parts of the spectra are missing due to an extremely low content of Fe-bearing paramagnetic components. The hyperfine interaction parameters for kamacite are internal magnetic hyperfine field $H_{hf} = 333.2$ kOe, isomer shift (relative to a metallic Fe foil) IS = 0.01 mm/s, quadrupole splitting $Q = 0$ mm/s, line width $W = 0.41$ mm/s. The data for troilite are $H_{hf} = 305.5$ kOe, IS = 0.75 mm/s, $Q = -0.85$ mm/s, $W = 0.34$ mm/s. The second fragment, Neuschwanstein II weighing 1.63 kg, was recovered on May 27, 2003 about 1 km north of the Neuschwanstein I locality. In contrast to Neuschwanstein I which shows only early signs of weathering, the second fragment has obvious rusty spots. Nevertheless, Neuschwanstein II is remarkably well preserved, considering that it was exposed to alpine climate conditions (snow, frost, and ice) for one year. Neuschwanstein II was cut in half and one of the pieces is in possession of the Bavarian Forest Administration and under the custody of the Mineralogical State Collection Munich (MSM 29488).

The third fragment (Neuschwanstein III) is the largest known part of the Neuschwanstein meteorite. It weighs 2.84 kg and was found on June 29, 2003 at the elevation of 1630 m in a scree of the Altenberg in Tyrol, Austria and off the calculated fall area.

A short petrographic and petrologic description of the mineral assemblage of the Neuschwanstein I fragment was given by Bischoff and Zipfel (2003) and Zipfel et al. (2003), but the mineralogy data of Neuschwanstein II do not exist. Here, we report also $^{57}$Fe Mössbauer spectroscopy of iron-bearing phases, which can be used for classification of chondrites (e.g., Verma et al. 2003). However, Mössbauer data on enstatite chondrites are scarce (Dunlap 1997) and no
data on EL6-type enstatite chondrites exist. Therefore, it is the scope of this study to determine the mineralogy of Neuschwanstein II and, in particular, to characterize the iron-bearing opaque phases by $^{57}$Fe Mössbauer spectroscopy.

**EXPERIMENTAL**

Samples were taken from fragments Neuschwanstein I and Neuschwanstein II (further called Neu1 and Neu2). Both samples (each about 5 × 5 mm) were extracted from the interiors of the respective meteorite fragments to prevent contamination by parts of the crust or rusty spots. Mineral analyses were carried out using an electron microprobe ( Camebax SX50 at the Department of Earth and Environmental Sciences of the LMU Munich). The probe was operated at 15 keV acceleration voltage and 20 nA beam current. Synthetic wollastonite (Ca, Si), periclase (Mg), corundum (Al), hematite (Fe), sphalerite (Zn, S), escolaite (Cr), bunsenite (Ni), natural ilmenite (Mn, Ti), apatite (P), orthoclase (K), and albite (Na) were used as standards and matrix correction was performed by using the PAP procedure (Pouchou and Pichoir 1984). Unlike traditional ZAF procedures, PAP is a general model for the calculation of X-ray intensities. Raw data processed by ZAF software are usually lower by ~1%, as demonstrated by Hunt et al. (1998). The reproducibility of standard analyses was <1% for each element routinely analyzed.

No separation of minerals was undertaken for $^{57}$Fe Mössbauer measurements. Pieces of the interior portion (about 200 mg) of both fragments were crushed and ground in a mortar under acetone to prevent oxidation. Neu1 was one compact piece, but Neu2 was an aliquot of many small samples (0.5–1 mm) taken from different points in the interior of Neuschwanstein II fragment, and thus provides better statistical data than Neu1. The powder was pressed between two plastic films resulting in an estimated density of ~2–4 mg Fe/cm$^2$. Spectra were taken with a constant acceleration 512-channel spectrometer using an ~10 mCi $^{57}$Co/Rh source. A cryostat was available for low temperature measurements at 85 K. The Mössbauer spectra were analyzed with the RECOIL program (Rancourt and Ping 1991) in the full static hyperfine interaction Hamiltonian approach and using symmetric Lorentzian-shaped subspectra. For the six-line patterns of the magnetically ordered phases, line intensities were constrained 3:2:1:1:2:3 and line widths were kept identical.

**RESULTS**

**Chemical Composition**

One sample of Neuschwanstein I was analyzed to compare it with the data reported by Bischoff and Zipfel (2003). The two fragments show very similar compositional data on minerals. Three samples taken from different parts of regions of Neuschwanstein II were analyzed and the averaged
## Table 1. Chemical compositions of main minerals in Neuschwanstein EL6 chondrite (wt%).

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Neuschwanstein I</th>
<th>Neuschwanstein II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kamacite</td>
<td>92.7 ± 0.8</td>
<td>92.7 ± 0.8</td>
</tr>
<tr>
<td>Troilite</td>
<td>59.2 ± 0.8</td>
<td>59.2 ± 0.8</td>
</tr>
<tr>
<td>Oldhamitea</td>
<td>0.26 ± 0.06</td>
<td>0.26 ± 0.06</td>
</tr>
<tr>
<td>Daubreelite</td>
<td>16.4 ± 0.1</td>
<td>16.4 ± 0.1</td>
</tr>
<tr>
<td>Schreibersitea</td>
<td>61.8 ± 1.1</td>
<td>61.8 ± 1.1</td>
</tr>
<tr>
<td>Enstatite</td>
<td>0.3 ± 0.1</td>
<td>0.3 ± 0.1</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>0.3 ± 0.1</td>
<td>0.3 ± 0.1</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>0.06 ± 0.05</td>
<td>0.06 ± 0.05</td>
</tr>
</tbody>
</table>

aRecalculated to 100 due to volatilization under the electron beam; b.d. = below detection limit; n.d. = not determined; I = Neuschwanstein I; II = Neuschwanstein II.

## Chemical Compositions

Compositions for each mineral are given in Table 1. The results of microprobe analyses are listed in Table 1. Only one small sample of Neuschwanstein I was analyzed for comparison, but three different samples of Neuschwanstein II were analyzed to investigate whether there are any differences between the two fragments. As our new data for Neuschwanstein I are identical to those published by Bischoff and Zipf (2003), most of the microprobe analyses were done on the Neuschwanstein II samples.

Neuschwanstein II shows a recrystallized texture with only very few relic chondrules. Major phases are enstatite, plagioclase, and kamacite. The enstatite is very homogenous with a very low FeO concentration of (0.3 ± 0.1 wt%), mean of 11 different grains.

The plagioclase has 2.9 ± 0.2 wt% CaO and only 0.7 ± 0.1 wt% K2O, again, in good agreement with the data of Neuschwanstein I (Bischoff and Zipf 2003).

Kamacite is the only metal phase in Neuschwanstein and taenite could not be found. Kamacite is rather homogeneous and shows 6.2 ± 0.3 wt% Ni and 1.2 ± 0.1 wt% Si.

The common sulfide is troilite which is nearly free of Ni, but shows a significant yet varying Cr content (1.2 ± 0.5 wt%) and a very constant Ti content (0.4 ± 0.1 wt%). Troilite is finely intergrown with other sulfides, e.g., oldhamite (CaS) and daubreelite (FeCr2S4). Very fine exsolution lamellae of the latter might be responsible for the varying chromium content of the troilites.

Daubreelite grains are embedded in or are in contact with troilite. They show a significant amount of Mn (2.0 ± 0.1 wt%). All other analyzed accessory elements are near or below detection limits.

The small oldhamite grains are very homogenous and show low Mn (1.2 ± 0.1 wt%), Mg (0.45 ± 0.05 wt%), and Fe (0.26 ± 0.06 wt%). Occasionally, the grains are surrounded by small Ca-rich alteration rims which may be portlandite as suggested by Bischoff and Zipf (2003) for similar alteration products in Neuschwanstein I.

Schreibersite has been found in small grains mostly embedded in troilite. It shows a relatively narrow range of Ni content (23.4 ± 1.3 wt%), and phosphorus (13.5 wt%, recalculated to 100% due to volatilization under the electron beam) is slightly lower than reported for schreibersites from the MAC 88136 enstatite chondrite (Lin and El Goresy 2002).

### Mössbauer Spectroscopy

The Mössbauer spectra of Neu1 at 295 K and 85 K and the spectrum of Neu2 at 295 K are shown in Figs. 2a–c. In addition, the spectrum of the Abee EH4 chondrite at 295 K (Fig. 1 in Dunlap 1997) is presented as Fig. 2d for comparison. The spectra of both Neuschwanstein fragments (Fig. 2a–c) are very similar. For each of the spectra, the dominant part arises from two sextet patterns of ferromagnetic components that can be attributed to troilite and kamacite. The hyperfine interaction parameters of all Mössbauer spectra are listed in Table 2. The kamacite subspectrum was fitted by keeping the asymmetry parameter of the electric field gradient (EFG) tensor η = 0. The angle between the internal magnetic hyperfine field H_{hf} and the principal axis V_{zz} of the EFG tensor was taken as θ = 0° and the azimuthal angle of H_{hf} within the axes of the EFG tensor was taken as φ = 0°. The same conditions were applied in previous studies on chondrites (e.g., Verma et al. 2002, 2003). The troilite subspectrum was fitted according to Grandjean et al. (1998) by imposing the constraints η = 0.3, θ = 48°, φ = 49° (marked with superscript “a” in Table 2). In most published studies of Mössbauer spectroscopy of troilite obviously a simplified model was applied with η = 0, φ = 0°.
φ = 0° (marked with superscript “b” in Table 2). In order to compare our data with literature results, both different fitting procedures are used for the troilite subspectra.

**Kamacite**

The application of the above models for troilite results in nearly identical Mössbauer hyperfine interaction parameters for kamacite. The magnetic hyperfine field of H_{hf} ~333 kOe for one strong sextet in the pattern of both Neuschwanstein fragments at 295 K (Fig. 2a and Fig. 2c) reflects the presence of kamacite. This assignment is consistent with near zero isomer shift and quadrupole splitting (see Table 2). The parameters are similar for both Neuschwanstein fragments, with the exception of the area fractions revealing kamacite at 54.7 wt% in Neuschwanstein I and at 62.5 wt% in Neuschwanstein II relative to troilite (see Table 2).

**Troilite**

The second strong sextet with H_{hf} = 305.5 kOe (Neu1a in Table 2)–306.2 kOe (Neu2a in Table 2) at 295 K, IS = 0.75 mm/s and QS = −0.85 mm/s is attributed to troilite by using the model of Grandjean et al. (1998). By applying the simplified model, the hyperfine parameters for troilite result in comparable values of H_{hf} = 308.4 kOe (Neu1b in Table 2)–309.6 kOe (Neu2b in Table 2) and IS = 0.76 mm/s, but with nearly identical quadrupole splitting of QS = −0.08 mm/s at 295 K.

The 85 K spectrum of Neuschwanstein I (Fig. 2b) shows only minor variations relative to the 295 K pattern (Fig. 2a). The hyperfine interaction parameters of kamacite and troilite at 85 K display slightly increasing H_{hf} values of both strong sextets from ~333 kOe to ~343 kOe (kamacite, see Table 2) and ~306 kOe to ~322 kOe (troilite, see Table 2). The increase in IS values relative to 295 K is consistent with the second order Doppler shift and the QS values remain constant. Variations of the magnetic coupling due to near-neighbor environments lead to the rise in line widths relative to 295 K.

Any possible contributions by doublets or singlets in the central part of the spectra cannot be resolved unequivocally due to low intensities and, therefore, they were not fitted. Consequently, there is some misfit in the center of all spectra of the very weak additional doublets or singlets. They appear to be slightly stronger for Neu2 than for Neu1, as shown in Fig. 2a–c. One may speculate which paramagnetic phases could be responsible for them. The amount of iron in enstatite and oldhamite is too low to considerably contribute to the 57Fe Mössbauer spectra. The other iron-bearing minerals are schreibersite and daubreelite. They occur in minor amounts only, implying a negligible contribution to the Mössbauer spectra.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mineral</th>
<th>T (K)</th>
<th>IS</th>
<th>QS</th>
<th>W</th>
<th>H_{hf}</th>
<th>F (%)</th>
</tr>
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<tbody>
<tr>
<td>Neu1a</td>
<td>Kamacite</td>
<td>295</td>
<td>0.01</td>
<td>~0</td>
<td>0.34</td>
<td>333.2</td>
<td>54.7</td>
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<td>Neu1a</td>
<td>Troilite</td>
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<td>−0.85</td>
<td>0.34</td>
<td>305.5</td>
<td>45.3</td>
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<td>~0</td>
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<td>−0.86</td>
<td>0.34</td>
<td>321.9</td>
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<td>~0</td>
<td>0.42</td>
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<td>62.5</td>
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<td>−0.85</td>
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<td>55.9</td>
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<td>−0.08</td>
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<td>308.4</td>
<td>44.1</td>
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<td>−0.02</td>
<td>0.47</td>
<td>342.6</td>
<td>52.4</td>
</tr>
<tr>
<td>Neu1b</td>
<td>Troilite</td>
<td>85</td>
<td>0.87</td>
<td>−0.08</td>
<td>0.31</td>
<td>324.7</td>
<td>47.6</td>
</tr>
<tr>
<td>Neu2b</td>
<td>Kamacite</td>
<td>295</td>
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<td>~0</td>
<td>0.36</td>
<td>333.1</td>
<td>62.8</td>
</tr>
<tr>
<td>Neu2b</td>
<td>Troilite</td>
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<td>0.75</td>
<td>−0.08</td>
<td>0.44</td>
<td>309.6</td>
<td>52.2</td>
</tr>
</tbody>
</table>

*Fitting constraints for troilite subspectra: η = 0.3, θ = 48°, φ = 49° according to Grandjean et al. (1998).

**DISCUSSION**

Our new data presented in this study indicate that both Neuschwanstein samples have nearly identical chemistry of their main minerals (Table 1). The chemical composition of enstatite and plagioclase is in good agreement with the data given by Bischoff and Zipfel (2003). The Si content of kamacite in Neuschwanstein EL6 chondrite of 1.2 wt% is slightly higher and more homogeneous than the range reported by Lin and El Goresy (2002) for the MAC 88136 EL3 chondrite (0.12–1.09 wt%). According to Lin and El Goresy (2002), the Si content in EL chondrites increases from EL3 to EL6, which is affirmed by this study. Neither taenite nor taenite-kamacite two-phase textures were found during the course of this study. This is in accordance with investigations on other EL6 chondrites, for example Eagle (Olsen et al. 1988), which also lack taenite. Our data on...
daubreelite in the Neuschwanstein samples (see Table 1) are in good agreement with the data for the MAC 88136 EL3 chondrite (Lin and El Goresy 2002). In contrast to the enstatite chondrites investigated by Lin and El Goresy (2002), we did not detect appreciable amounts of Zn in the Neuschwanstein daubreelite, which is in good agreement with the results of Chikami et al. (1998). These authors found that the Zn content in daubreelites decreases from lower to higher petrologic types in enstatite chondrites. Since Neuschwanstein is a chondrite of the highest petrologic type (EL6), an extremely low Zn content in this meteorite would be reasonable. This fits well into the Zn versus Mn plot of enstatite chondrites given by Lin and El Goresy (2002) where the field of EL6 chondrites is marked at Zn ≈ 0.

The Mössbauer spectrum of Abee EH4 chondrite in Fig. 2d (Dunlap 1997) is the only known spectrum of an enstatite chondrite and it differs considerably from the Neuschwanstein spectra (see Fig. 2a–c). This concerns in particular the strong central part in the Abee spectrum which is assigned to singlet lines due to niningerite (MgS) and the γ-phase of taenite. Apart of kamacite and troilite, the third sextet is attributed to ordinary taenite and these phases do not occur in Neuschwanstein EL6 chondrite. The position of the fitted sextet lines is indicated by bars in Fig. 2d, according to Dunlap (1997).

The $H_{hf}$ values for kamacite of $\sim$333 kOe in Neuschwanstein at 295 K plot in the lower region of the values reported for kamacite in chondrites and iron meteorites, which cover a range of $H_{hf}$ = 330–343 kOe (e.g., Verma et al. 2002, 2003). The IS and QS values of $\sim$0 mm/s for the Neuschwanstein kamacite are close to the lower end of literature data, too ($\sim$0.06 to +0.23 mm/s and 0.04 to $\sim$0.20 mm/s). The observed line widths of W $\sim$0.40 mm/s (full width at half maximum) are within the range observed for other meteoritic kamacites and document local disorder in the environment of Fe ions in the kamacite structure. The variation in Mössbauer parameters for kamacite in chondrites is mainly due to varying Ni contents. The magnetic hyperfine field for pure iron amounts to $H_{hf}$ = 330.5 kOe at 295 K. An increase of the Ni content leads to a continuous increase of $H_{hf}$ and, at the composition of 12–15 at% Ni, a magnetic hyperfine field of $H_{hf}$ = 340 kOe was observed (Vincze et al. 1974). The value of 333 kOe for Neuschwanstein kamacite would indicate a Ni-content of 2 atom%, whereas microprobe analyses reveal 6.2 wt% Ni (see Table 1). The appreciable Si-content of 1.2 wt% in the Neuschwanstein kamacite may be responsible for the somewhat lower value of $H_{hf}$.

Mössbauer parameters of troilite reported in the literature are conflicting. Based on the careful works of Hafner and Kalvius (1966) and Kruse and Ericsson (1988), Grandjean et al. (1998) have demonstrated that an adequate fit of the troilite sextet requires the adjustment of five hyperfine parameters, i.e., IS, QS, $H_{hf}$, $\eta$, $\theta$, and $\phi$. The data on the Mössbauer parameters of the Neuschwanstein troilite from this study, i.e., the quadrupole interaction $QS = -0.85$ mm/s, are in accordance with Hafner and Kalvius (1966), Kruse and Ericsson (1988), Abdu and Ericsson (1997), Grandjean et al. (1998), and Baghat et al. (2000). The application of the simplified first-order approximation leads to a lower value of the quadrupole interaction, i.e., $-0.08$ mm/s, as shown in Table 2. This value plots in the range of $QS = -0.14$ to $+0.31$ mm/s, respectively.
mm/s, reported in previous studies by using the simplified model (Verma et al. 2002, 2003). Line widths of troilite in Neuschwanstein are similar to those reported in literature and the lines are narrower $(W = 0.34 \text{ mm/s}; \text{Table 2})$ than those of the kamacite pattern $(W = 0.41 \text{ mm/s})$ indicating a more homogeneous composition of troilite. The variation of experimental QS values in the literature (determined using the simplified model) may be attributed to additional components such as Ni, Co, Mn, Cr, Ti, commonly observed in troilite from other chondrites (Mason 1966; Van Schmus and Wood 1967; Keil 1968; Lin and Kimura 1998; Lin and El Goresy 2002). Unfortunately, in many Mössbauer studies of troilite, compositional data are missing and prevent a detailed information on the variation of hyperfine interaction parameters with composition. Kruse and Ericsson (1988) reported a $QS = -0.85 \text{ mm/s}$ for troilite from the Agpalilik meteorite containing 0.12–0.47 wt% Cr and all other elements below 0.02 wt%. The chromium content of 1.2 wt% in the meteorite containing 0.12–0.47 wt% Cr and all other elements reported a $QS = -0.85 \text{ mm/s}$ for troilite from the Agpalilik meteorite.

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Editorial Handling—Dr. Alexander Deutsch

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