Analytical electron microscope study of eight ataxites

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Abstract—Optical and electron optical (SEM, TEM, AEM) techniques were employed to investigate the fine structure of eight ataxite-iron meteorites. Structural studies indicated that the ataxites can be divided into two groups; a Widmanstätten decomposition group and a martensite decomposition group. The Widmanstätten decomposition group has a Type I plessite microstructure and the central taenite regions contain highly dislocated lath martensite. The steep M shape in the taenite is consistent with the fast cooling rates, >500°C/my, observed for this group. The martensite decomposition group has a Type III plessite microstructure and contains all the chemical group IVB ataxites. The maximum taenite Ni contents vary from 47.5 to 52.7 wt% and are consistent with slow cooling to low temperatures ≤350°C at cooling rates ≤25°C/my. Ordered FeNi and the cloudy border structure were not observed in any of the ataxites. Modest reheating to ≤350°C may have been responsible for the lack of these structures.

INTRODUCTION

The ataxites are a class of iron meteorites, which have a structure too fine to be discerned by the unaided eye (Buchwald, 1975). Meteorites of chemical group IVB as well as several anomalous iron group IVB ataxites. The general ataxite structure consists of occasional kamacite (α-bcc) plates or rods in a Widmanstätten orientation within a matrix of fine plessite, a fine-grained intergrowth of kamacite and taenite. The submicron size of the kamacite and taenite (γ-fcc) phases within the plessite has generally discouraged investigation of this class of iron meteorites since optical or electron microprobe techniques lack the necessary resolution.

Recently, Jago (1981) has investigated several ataxites and plessitic octahedrites by transmission electron microscope (TEM) techniques. Of the three ataxites that were studied, one, Artunga, contains a plessite matrix consisting of a micro-Widmanstätten pattern of kamacite plates and residual taenite. Massalski et al. (1966) has termed this structure Type I plessite; the structure forms by reaction γ → α + γ where untransformed taenite transforms to kamacite and taenite. Two other ataxites, Warburton Range and Tawallah Valley, contain a plessite matrix consisting of fine rods of taenite in a kamacite matrix. Massalski et al. (1966) have termed this structure Type III plessite. Buchwald (1966) observed the same structure in Kokomo, a typical IVB ataxite. The structure forms by the reaction γ → α + γ where untransformed taenite first transforms to martensite, α2, below the martensite start, Ms, temperature. The γ → α2 transformation structure is called Type II plessite. At lower temperatures the martensite may decompose to α + γ through a diffusion-controlled process. For Type III plessite α2 decomposes to form γ rods in an α matrix. This plessite structure was first observed by Buchwald (1975) for Hoba, Kokomo, Chinga and other IVBs using optical techni-
TABLE 1
Ataxites Investigated in this Study

<table>
<thead>
<tr>
<th>Meteorite</th>
<th>UDMP</th>
<th>Chemical Group</th>
<th>Ni(wt%)</th>
<th>Co(wt2.)</th>
<th>P(wt2.)</th>
<th>Cooling Rate (°C/My)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aritunga</td>
<td>2467</td>
<td>Anom.</td>
<td>9.91</td>
<td>0.63</td>
<td>0.24</td>
<td>&gt; 500</td>
</tr>
<tr>
<td>Guffey</td>
<td>4822</td>
<td>Anom.</td>
<td>10.3</td>
<td>0.55</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Nordheim</td>
<td>3190</td>
<td>Anom.</td>
<td>11.67</td>
<td>0.51</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>Cape of Good Hope</td>
<td>2705</td>
<td>IVB</td>
<td>16.32</td>
<td>0.86</td>
<td>0.12</td>
<td>~ 7</td>
</tr>
<tr>
<td>Hoba</td>
<td>3390</td>
<td>IVB</td>
<td>16.4</td>
<td>0.76</td>
<td>0.07</td>
<td>~ 3</td>
</tr>
<tr>
<td>Chinga</td>
<td>1585</td>
<td>IVB</td>
<td>16.38</td>
<td>0.55</td>
<td>0.05</td>
<td>~ 35</td>
</tr>
<tr>
<td>Tawallah Valley</td>
<td>1458</td>
<td>IVB</td>
<td>17.6</td>
<td>0.69</td>
<td>0.1</td>
<td>~ 20</td>
</tr>
<tr>
<td>Weaver Mts.</td>
<td>1624</td>
<td>IVB</td>
<td>17.72</td>
<td>0.82</td>
<td>0.10</td>
<td>~ 20</td>
</tr>
</tbody>
</table>

* Chemical analyses listed by Buchwald (1975)
* Goldstein and Short (1967)

RESULTS

Light and SEM microstructure examination

Typical micrographs of the structure of the eight ataxites are shown in Figs. 1 to 8. These micrographs indicate that, on the basis of the plessite structure, the ataxites can be divided into two groups, namely, a Widmanstätten decomposition group and a martensite decomposition group. The Widmanstätten decomposition group consisting of the meteorites Aritunga, Nordheim and Guffey, has a Type I plessite microstructure where Widmanstätten kamacite forms in a taenite matrix. Kamacite grains are separated by ribbon-like rims of taenite (Figs. 1, 2 and 3). In some of the wider taenite rims some internal structure can be observed (Fig. 1b). The kamacite is multigranular and several kamacite grains are found between the...
taenite ribbons. No cloudy zone was observed in these meteorites.

The martensite decomposition group consists of the meteorites Tawallah Valley, Hoba, Weaver Mountains, Cape of Good Hope, and Chinga. The structure of these meteorites contains some optically resolvable Widmanstätten \( \gamma \) precipitates (Fig. 4a) but consists mainly of Type III plessite formed from martensite by the decomposition reaction \( \gamma \rightarrow \alpha_2 \rightarrow \alpha + \gamma \) (Figs. 4–8). Typical Type III plessite consists of oriented \( \gamma \) rods in an \( \alpha \) matrix. The prior \( \alpha_2 \)-martensite plates are outlined by the \( \gamma \) rims that surround regions of \( \gamma \) rods in the \( \alpha \) matrix (Figs. 4b and 5c). Some Type II plessite, that is retained \( \alpha_2 \)-martensite, can be observed in a few regions at the edge of the taenite rims of Widmanstätten \( \alpha \) precipitates (Figs. 6 and 8). Within the martensite decomposition group, Tawallah Valley and Weaver Mountains have a much higher number of Widmanstätten \( \alpha \) precipitates than the other three members of the group. No cloudy zone was observed by optical or SEM examination.

![Image](image1.png)

**FIG. 2a.** Light photomicrograph of Nordheim. Large Widmanstätten \( \alpha \) platelets can be seen in center of picture. 2\% nital etch. Marker = 25 \( \mu \)m. 2b. SEM photograph of Nordheim. No internal structure is seen within the taenite. 2\% nital etch. Marker = 2.5 \( \mu \)m.

![Image](image2.png)

**FIG. 3a.** Light photomicrograph of Guffey showing Widmanstätten \( \alpha \rightarrow \alpha + \gamma \) type plessite. 2\% nital etch. Marker = 10 \( \mu \)m. 3b. SEM photomicrograph of Guffey. Fine structure within taenite can be seen. 2\% nital etch. Marker = 5 \( \mu \)m.
TEM microstructure examination

Since the microstructures of the meteorites within each structural group were very similar, only two meteorites from each group were chosen for examination by TEM. Arltunga and Nordheim represented the Widmanstätten decomposition group, while Tawallah Valley and Hoba represented the martensite decomposition group.

TEM examination of taenite in the Widmanstätten decomposition group was consistent with SEM evidence and showed that the structure of the central regions of the taenite was martensite. Figures 9 and 10 illustrate the highly dislocated lath martensite in the rim-like taenite from Arltunga and Nordheim respectively. The kamacite and taenite phases of Nordheim are more highly dislocated than those of Arltunga. No orientation relationships between $\alpha$, $\gamma$ and $\alpha_2$ were obtained due to the complex mixture of the three phases. In addition no cloudy zone was observed.

TEM examination of plessite in the martensite decomposition group was consistent with the SEM evidence and showed that the decomposed martensite in the plessite consists of fine $\gamma$ rods in an $\alpha$ matrix surrounded by a taenite rim. Figures 11 and 12 illustrate the plessite structure in Tawallah Valley and Hoba respectively. In some cases one plessite region containing fine $\gamma$ rods is adjacent to another plessite region containing large $\gamma$ rods. The Type III plessite structure observed is similar to that shown by the IIICD irons (Lin et al. 1979). Type III plessite structure was also observed by Jago (1981) during TEM examination of the Tawallah Valley and Wabar Burton Range axites. Diffraction results from the Tawallah Valley meteorite indicate that the orientation relationship between the Widmanstätten $\alpha$ precipitates and the clear taenite rim and between the $\gamma$ rods and the $\alpha$ matrix of the plessite regions is Nishyama-Wasserman, namely $\{111\}_\gamma/[\{011\}_\alpha$ and $\langle011\rangle_\gamma/[\langle001\rangle_\alpha$. No cloudy zone or ordered taenite (tetrataenite) in the high Ni taenite rims was observed.

AEM X-ray microanalysis

Composition profiles were obtained across thin (≤2 μm) $\gamma$ rims (Figs. 9 and 10) in the plessite of the Widmanstätten decomposition group. Typical data are illustrated in Fig. 13 for Arltunga and Nordheim. The $\gamma$ rims in both meteorites exhibit "M"-shaped composition profiles. Ni contents less than 25 to 29 wt% are observed within the lath martensite region in the center of the taenite. The highest Ni content in the taenite at the $\alpha/\gamma$ boundary was approximately 48 wt% in Arltunga and Nordheim. Most analyses however yielded maximum Ni contents between 30 and 40 wt%. The lowest Ni content measured in the martensite regions was 12 wt% in Arltunga, close to the bulk Ni content of the meteorite.

Composition profiles were also obtained in $\alpha$ and $\gamma$ regions of the martensitic decomposition group. Figure 14a shows a composition profile across a Widmanstätten $\alpha$-kamacite platelet/taenite interface in Tawallah Valley. This composition profile is typical of those measured for the IIICD irons (Lin et al. 1979) where diffusion-controlled Widmanstätten growth occurs. The highest Ni content in $\gamma$ at the $\alpha/\gamma$ interface was 48 ± 2 wt%. Figure 14b shows a composition profile across a ~3000 Å wide taenite rim between two regions of kamacite in the plessite matrix of Tawallah Valley. The taenite Ni compo-
sition is constant at 52 ± 2 wt%. Although the Ni content of this and other >1000 Å wide taenite rims in Tawallah Valley ranged from 47.5 to 52.7 wt% Ni, no ordered FeNi phase (tetrataenite) was observed. The compositions of very fine rods, <1000 Å wide, were not measured because these rods did not extend completely through the thin foil. In the Hoba meteorite several Ni composition profiles were obtained across taenite rims between Type III plessite regions (Fig. 12). In these profiles the maximum Ni content in the taenite was ~50 wt%.

DISCUSSION

The eight ataxites that were examined fall into two microstructural groups. The separation of the eight
ataxites into the same two groups occurs when comparing bulk Ni contents and cooling rates. The three meteorites, Arltunga, Guffey and Nordheim, of the Widmanstätten decomposition group, have low bulk Ni contents, 9.9 to 11.7% Ni, while the five ataxites in the martensite decomposition group are in chemical Group IVB and have bulk Ni contents ranging from 16.3 to 17.7% Ni (Table 1). Similarly, the Widmanstätten decomposition group has fast cooling rates, >500°C/10^6 yrs, while the martensite decomposition group has cooling rates ≤25°C/10^6 yrs (Table 1). Arltunga is the only one of the three Widmanstätten decomposition group meteorites to have a published cooling rate (Goldstein and Short, 1967). However, the similar microstructures of Guffey and Nordheim indicate that they too have cooling rates ≥500°C/10^6 yrs.

The microstructures of the meteorites in each decomposition group are consistent with the cooling rates of the meteorites. The martensite in the center of the taenite and the very steep “M” composition profiles of the Widmanstätten decomposition group meteorites are indicative of fast cooling. The taenite regions in these meteorites are the remnants of the original taenite that was the host γ phase in the γ → α + γ reaction. As the α-kamacite nucleated and grew, excess Ni was rejected into the taenite. However, because of the very fast cooling rate, diffusion did not occur at a rate which allowed for the redistribution of Ni within the taenite. As a result the very steep “M” shaped composition profile was retained. The low Ni content regions of the “M” composition profile in taenite decomposed to martensite at low temperatures. Further decomposition to Type III plessite probably did not occur due to the fast cooling rates.

The five martensite decomposition group meteorites have microstructures indicative of slow cooling. The relatively flat Ni gradient observed in the taenite (Fig. 14a) is indicative of a slow cooled microstructure such as those observed in the IIICD irons (Lin et al., 1979). Slow cooling probably allowed Type III plessite to form after α2 was formed in untransformed taenite.

No ordered FeNi (tetrataenite) or cloudy zone was observed in any of the meteorites. In the Widmanstätten decomposition group the maximum Ni content of the taenite did not exceed 40% Ni. Therefore ordered FeNi would not form although the cloudy zone which contains 30 to 40 wt% Ni would be expected to develop. For the martensite decomposition group, AEM composition profiles indicate that the Ni content of the taenite was high enough for the cloudy zone (30–40 wt% Ni) or even ordered FeNi.
Eight ataxites

The lack of ordered taenite and the cloudy zone indicates that these five meteorites may have been reheated. Alternately the low temperature cooling history was too rapid for ordered taenite or the cloudy zone to form.

In agreement with this study, Jago (1981) did not observe cloudy zone or ordered FeNi in Arlitunga or Tawallah Valley. However a cloudy zone was observed by Jago in Warburton Range which is a member of the martensite decomposition group. In contrast to this result, all five ataxites of the martensite decomposition group considered in this study did not contain a cloudy zone structure. Jago (1981) argues that a significant reheating episode took place which removed the cloudy zone structure in Tawallah Valley. Apparently such a reheating episode did not occur in Warburton Range. None of the theories for the formation of the cloudy zone have been confirmed and the temperature at which the structure develops is unknown. However if reheating does obliterate the cloudy zone, it must not affect the delicate structure of Type III plessite. Therefore the cloudy zone must decompose at relatively low temperatures, probably <350°C. In this case a modest reheating event probably occurred in all eight of the ataxites studied. Alternatively there may be a critical cooling rate, ~10 to 20°C/my, above which the cloudy zone and the ordered FeNi structure will not form.

SUMMARY

Several microstructural and microchemical observations of the fine structure of 8 ataxites have been made using optical and electron optical techniques. The ataxites were divided into two groups: (1) the Widmanstätten decomposition group containing a Type I plessite microstructure (Widmanstätten kamacite surrounded by retained taenite) with fast cooling rates, ≥500°C/my and (2) the martensitic decomposition group containing a Type III plessite microstructure, (fine taenite rods in a kamacite matrix) formed by the decomposition of retained martensite, with cooling rates ≤25°C/my. All chemical group IVB ataxites belonged to this group.

In the Widmanstätten decomposition group, the central taenite regions contained highly dislocated lath martensite. The Ni composition data across the taenite phase, displayed an M shaped profile. The Ni gradients were steep with central Ni contents approaching the bulk Ni content. Such steep gradients are consistent with high cooling rates. In the martensite decomposition group the maximum taenite Ni content was 47.5 to 52.7 wt% indicating slow cooling to low temperatures, ≤350°C. Ordered Fe-Ni (tetra-taenite) was not observed in the taenite.

Fig. 11a. Detail of TEM bright field image of plessite structure in Tawallah Valley. TEM bright field image clearly shows various size taenite rods in α matrix. Marker = 0.5 μm. 11b. TEM bright field image of another plessite region in Tawallah Valley. Marker = 0.2 μm.

Fig. 12. TEM bright field of very fine γ rods in plessite of Hoba. Note rim of taenite (T). Marker = 0.2 μm.
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FIG. 13a. Ni composition profile of a γ rim in Arltunga taken with the AEM. Note "M" shaped composition profile. Low Ni content in center is characteristic of martensite (M).
13b. Ni composition profile of a γ rim in Nordheim taken with the AEM. Note "M" shape.

FIG. 14a. Ni composition profile taken with the AEM across a Widmanstätten α/γ rim/clear taenite/martensite region in Tawallah Valley. 14b. Ni composition profile obtained with the AEM across an α/γ rim/α region in the plessite of Tawallah Valley.
The cloudy border structure was not observed in any of the ataxites. Modest reheating to \( \leq 350^\circ C \) may have been responsible for the lack of this structure.

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**REFERENCES**


