The Tucson meteorite

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Abstract—Tucson is an unusual iron meteorite which contains highly reduced silicate inclusions and elemental silicon and chromium in solution. The metal matrix of Tucson was found to be chemically uniform, suggesting that homogenization has occurred at elevated temperatures. The microstructure of the metal consists of plessite and thin ribbons of kamacite. Nickel and phosphorus concentrations indicate that kamacite nucleated along prior taenite grain boundaries at ~650°C, and grew upon cooling to 500°C. Kamacite growth calculations show that Tucson cooled at ~1°C/1000 yr, a rate which corresponds to a depth of burial at the center of a 15 km radius parent body or closer to the surface of parent bodies of larger sizes. The shapes of the Tucson irons, and the presence and distribution of silicate inclusions in the Fe–Ni matrix appear to be a result of a solidification process.

INTRODUCTION

DURING its history, a meteorite can be altered by any of a number of sources of shock and/or heating. Preterrestrial events provide the most important sources of alteration and among these are the disruption of the parent bodies of meteorites and collisions between meteorites and other bodies in space. AXON et al. (1968) and LIPSCHUTZ (1968) noted that as a result of such events, there is a continuous range of alteration structures observed in the irons. Slight impact can produce shock twins in the metal, which are known as Neumann bands, while a severe collision can result in the total remelting of a metallic mass.

In many instances, it has been possible to establish the shock and thermal history of altered meteorites. Tucson is one mass, however, whose formation has remained unexplained. Based on the data from electron microprobe analyses of structural features, we have calculated a cooling rate for Tucson, and have proposed conditions under which it may have formed.

BACKGROUND

The Tucson meteorite consists of two large masses. One is ring-shaped with a diameter of 4 ft, and is appropriately named the Ring meteorite. The greatest thickness at right angles to the plane of the ring is 10 in., while the width varies from 3 to 18 in. along the ring. The other mass is the Carleton iron which has the shape of a flattened, elongated slab. It weighs 287 kg and measures approximately 48 × 18 × 3 in. Early investigators (FARRINGTON, 1915) have concluded that both masses belong to the same fall.

Among the first to notice the unique structure of Tucson was Wadsworth in 1884 (FARRINGTON, 1915). He described the meteorite as having silicates arranged in approximately regular rows in a metal matrix, and speculated that this resembled a fluid structure. BUNCH and FUCHS (1969) noted that since the matrix does not
appear to be mechanically deformed, the arrangement of silicate inclusions probably originated before solidification. They analyzed the silicate phases in Tucson and found the most abundant silicate mineral to be forsterite ($\text{Mg}_2\text{SiO}_4$). Forsterite occurs either as rounded or euhedral grains, ranging from 3 mm to a few microns across. Located near forsterite–metal interfaces are: (1) small, irregular to rounded grains of enstatite, (2) small amounts of aluminous diopside, and (3) irregular patches of anorthite and feldspathic glass. In addition, Bunch and Fuchs identified a new mineral, brezinaite, $\text{Cr}_3\text{Si}_4$. Because of the highly reduced states of the silicates in Tucson, Wai and Wasson (1969) suspect that the silicate inclusions and metal either (1) represent a high temperature equilibrium assemblage or (2) were never in equilibrium at all. They point out that the type I enstatite chondrites are somewhat analogous to Tucson in this respect.

The metal matrix is composed of two different structures (Bunch and Fuchs, 1969): (1) a fine mixture of kamacite and taenite (plessite), and (2) narrow, continuous, irregular bands of kamacite ($\alpha$) with rims of taenite ($\gamma$). The absence of a Widmanstätten pattern in Tucson (Wai and Wasson, 1969) suggests that it has cooled more rapidly than most iron meteorites. Chemically, the matrix contains 9-68 per cent Ni, 0-43 per cent Co, 0-22 per cent Cr and 0-06 per cent P (Moore et al., 1969). The Ni content of $\alpha$ is about 7-5 per cent, higher than that predicted from band width measurements; while that of $\gamma$, 22 per cent, lower than that measured in most irons (Wai and Wasson, 1969). Tucson contains an unusually high amount of Si, 0-8 per cent, and based on point counts across $\alpha$–$\gamma$ interfaces, Wai and Wasson concluded that Si did not strongly favor one phase over the other.

**Experimental Methods**

We used the optical and scanning microscopes to observe the structures in Tucson. Phase identification and quantitative analyses were performed with an ARL electron probe with a solid state detector. All X-ray data were corrected for atomic number, absorption and fluorescence (Goldstein and Comella, 1969) and converted to weight percentages.

A mathematical convolution technique was used to determine ‘true’ concentration profiles across $\alpha$–$\gamma$ interfaces in Tucson. Such a technique takes into account the finite volume from which X-rays are excited in a sample. By assuming a probe function which is Gaussian, the size effect of the electron beam can be described by the equation (Gilmour, 1970):

$$f(x) = \frac{1}{d} \exp \left[ -\frac{x^2}{4\left(\frac{d}{2}\right)^2} \right].$$

(1)

The probe function, $f(x)$, can be experimentally determined by passing the beam across a known concentration step and plotting the observed profile. Figure 1 shows the results of such a step scan across an $\alpha$-phosphide interface in Tucson. The parameter ‘$d$’ is determined by drawing a tangent to the midpoint of the curve. The convolution of the probe function $f(x)$ across a predicted true concentration profile $g(x)$ will give a result $h(x)$. If $h(x)$ corresponds to the measured experimental data, then the predicted true profile is correct; if not, then a new set of values for $g(x)$ need be assumed. The mathematical convolutions were performed with the aid of a computer program (Norkiewicz, 1972).

**Results**

Although samples from both the Carleton (USNM 757) and Ring meteorites (USNM 368, 369) were examined, we note that the Carleton samples appear damaged.
The Tucson meteorite

![Diagram of nickel concentrations]

**Fig. 1.** The use of measured X-ray intensity to determine \( d \) for the probe function.

Probably reheated by man, metallography revealed that areas of plessite have been transformed to \( \alpha_2 \). The analyses and results which follow were obtained from section No. 369 of the Ring.

**Macrostructure**

Figures 2a and 2b are views of two surfaces of section No. 369 which are perpendicular to each other. The silicate inclusions appear to be aligned in a common direction in Fig. 2a, and dispersed such that there are clear metal areas visible in Fig. 2b. The possibility exists that the silicates in Tucson were incorporated and uniquely distributed during solidification of an originally Fe–Ni melt. Uhlmann et al. (1964) have shown that the interaction of an advancing solid–liquid interface with insoluble particles can influence the final particle distribution. In the Fe–Ni system, solidification occurs by the formation of primary, tree-like crystals known as dendrites. In Tucson, silicate inclusions present during the solidification of the melt may have been 'pushed' to the interdendritic regions to form the observed pattern.

In the Fe–Ni system, solute elements are known to be redistributed to interdendritic regions during freezing. If, as we suggest, the silicate inclusions in Tucson were redistributed, then there should be a correlation between the microsegregation of solute elements and the distribution of the silicate inclusions. As shown in Fig. 2a, a sample of Tucson was sectioned both parallel and perpendicular to the aligned pattern of silicates. Electron probe analyses were taken along selected paths, such as across clear metal areas surrounded by silicate inclusions. Point counts were recorded while the beam scanned a 50 \( \times \) 40 \( \mu \text{m} \) area, at locations spaced 200 \( \mu \text{m} \).
apart. No concentration gradients were detected, and the metal matrix appears chemically uniform with a composition of $88.3 \pm 0.6$ per cent Fe, $10.7 \pm 0.3$ per cent Ni, $0.2 \pm 0.02$ per cent Cr, $0.44 \pm 0.03$ per cent Co, $0.15 \pm 0.03$ per cent P and $0.87 \pm 0.06$ per cent Si. If microsegregation did develop during solidification, it is apparent that homogenization has occurred upon slow cooling through the high temperature range. It should be noted that we have measured about 1 per cent more Ni than Moore et al. (1969).

**Microstructure**

The microstructure of the metal in Tucson is composed of plessite and thin ribbons of kamacite ($\alpha$) which measure about 20 $\mu$m across. Taenite ($\gamma$) is often associated with kamacite in these regions and elsewhere. In addition to brezinaite, Cr$_3$S$_4$, phosphide precipitates are abundantly found in Tucson.

As Bunch and Fuchs have noted, the macrostructure is very homogeneous. Plessite, when etched in nital, appears as a continuous gray areas, but is actually a fine aggregate of $\alpha$ and $\gamma$. This is evident in Fig. 3 which is a scanning micrograph of plessite and a region of $\alpha$. Electron probe analyses revealed that plessite is composed of both $\gamma$ and phosphide precipitates in a matrix of $\alpha$.

The $\alpha$ phase occurs primarily at prior $\gamma$ grain boundaries (Fig. 3). However, $\alpha$ also surrounds silicate inclusions (Fig. 4a) and less frequently appears as platelets in the plessitic matrix. For most iron meteorites, these nucleation sites are not available. Kamagate, which is observed at the grain boundaries, is often associated with $\gamma$ such as in Fig. 4b. In other areas, $\alpha$ is rimmed by only a thin boundary of $\gamma$, or is continuous with the matrix.

To measure $\alpha-\gamma$ boundary compositions, the electron probe was operated at 20 kV and 0.01 $\mu$A to decrease the spot size of the beam. Intensities were recorded for Ni, P, Cr, Co and Si, at the $\alpha-\gamma$ boundaries, and the corrected compositions are shown in Table 1 together with data from Bunch and Fuchs (1969). In this study, higher Ni concentrations were measured in both $\alpha$ and $\gamma$ phases than those reported by Bunch and Fuchs. The Ni concentration measured in $\alpha$, 7-90 per cent, is high compared to values observed in most iron meteorites. Reed (1965) and Goldstein (1965) report the highest Ni concentrations in $\alpha$ to be about 7-4 per cent. One explanation for this apparent discrepancy is that the presence of P is known (Doan and Goldstein, 1970) to increase Ni solubility in $\alpha$. Another factor is that $\alpha$

<table>
<thead>
<tr>
<th></th>
<th>Kamagate (wt. %)</th>
<th>Taenite (wt. %)</th>
<th>Bunch and Fuchs</th>
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</thead>
<tbody>
<tr>
<td>Ni</td>
<td>7.90 ± 0.08</td>
<td>22.54 ± 0.14</td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>17.8</td>
</tr>
<tr>
<td></td>
<td><em>26.0</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>0.13 ± 0.02</td>
<td>0.03 ± 0.02</td>
<td>0.26</td>
</tr>
<tr>
<td>Cr</td>
<td>0.16 ± 0.02</td>
<td>0.22 ± 0.02</td>
<td>0.78</td>
</tr>
<tr>
<td>Si</td>
<td>0.87 ± 0.06</td>
<td>1.05 ± 0.06</td>
<td>0.39</td>
</tr>
<tr>
<td>Co</td>
<td>0.46 ± 0.04</td>
<td>0.22 ± 0.03</td>
<td>0.37</td>
</tr>
</tbody>
</table>

* Determined by convolution technique.
Fig. 2a. Polished but unetched surface of a section of Tucson. Top view showing the lines along which the section was cut. Field of view: $4.2 \times 3.2$ cm.

Fig. 2b. Side view. Field of view: $4.2 \times 3.2$ cm.
Fig. 3. Kamacite ribbons and plessite in Tucson. One per cent nital, marker length: 50 μm.

Fig. 4a. Kamacite (solid arrow) and taenite (open arrow) associated with a silicate. Marker length: 15 μm.

Fig. 4b. Kamacite (solid arrow) and taenite (open arrow). Marker length: 15 μm.

Fig. 7. Phosphides within kamacite in Tucson. Carbon contamination from the electron beam is apparent across one precipitate. One per cent nital, marker length: 30 μm.
Fig. 9. Schematic representation of the formation of the Tucson irons. Shock-melted metal enters a cavity within a silicate mass, and solidifies in the shape of the internal void.
stabilizers, such as Si and Cr may increase the solubility limits of Ni in α with respect to the binary Fe–Ni diagram.

In addition to the analyses presented in Table 1, point counting traces were taken across γ areas in Tucson. Figure 5 shows the result of one analysis for Ni, Si, Co and P. The Ni profile is M-shaped and develops in a way described classically in the literature (Goldsstein and Axon, 1973).

As mentioned in the experimental section, the finite volume from which X-rays are generated in a target sample, tends to smear ‘true’ concentration profiles. Convolution techniques were used to determine the peak Ni concentrations in the γ phase at α–γ interfaces. At 20 kV and 0.01 μA, an average d value of 0.45 μm was measured. The probe function was generated across a predicted true concentration profile to produce the calculated curve illustrated in Fig. 6. In the analysis shown, a peak Ni concentration of 21.7 per cent was calculated for a true Ni value of 24.6 per cent at the interface. Since the actual measured data correspond closely to the calculated profile, we can conclude that the true composition of γ in equilibrium with α is about 25 per cent Ni. Other determinations of predicted concentration profiles gave similar results, and, in general, indicate that the true Ni content in γ at α–γ boundaries is 3–4 per cent higher than that measured. The compositions of α and γ in equilibrium indicate, from the ternary (Fe–Ni–P) data of Doan and Goldstein (1970), that the last temperature of equilibration between phases was about 500°C.

Fig. 5. Concentration vs distance profiles across taenite.
Phosphides

Phosphide precipitates occur primarily within α regions as in Fig. 7. Occasionally phosphides are found at α-brezenaitne interfaces or α-silicate interfaces. The phosphide precipitates consist of 15.3–15.5 per cent P, and 29–33 per cent Ni. Analyses show that α in equilibrium with phosphide has a lower Ni and P concentration than α in equilibrium with γ. Kamacite in equilibrium with phosphides contained 7.0 ± 0.2 per cent Ni and 0.07 ± 0.01 per cent P. The P concentration measured in α represents one of maximum solubility and can be used to determine the last temperature of equilibrium between α and phosphide. By extrapolating the data of DOAN and GOLDSTEIN (1970) for maximum P solubility in α as a function of temperature, the α–phosphide equilibration temperature was found to be about 420°C.

Discussion

Cooling rate calculations

Kamacite is observed primarily at prior taenite grain boundaries. If no undercooling occurs before nucleation, the Ni content of the metal (10.7 per cent) indicates that α forms at about 650°C. During cooling from 650°C to 500°C, α grew to an observed width of approximately 20 μm. In order to estimate the required time $t$ for growth, isothermal growth was assumed and calculations were performed using
the model shown in Fig. 8. The required time $t$ was obtained from a solution given by Jost (1952):

$$t = \frac{\xi^2}{4\beta^2D_{Ni}},$$

where $\xi$ is one-half the width of the $\alpha$ plate thickness, $D_{Ni}$ is the diffusion coefficient of Ni in $\gamma$, and $\beta$ is defined by the relationship:

$$\sqrt{\pi\beta e^{\beta^2}[1 - \text{erf}(\beta)]} = \frac{C' - C''}{C'' - C'}.$$  

$C'$ is the bulk Ni content of $\gamma$ from which $\alpha$ precipitates, while $C''$ and $C'$ are the Ni concentrations in $\alpha$ and $\gamma$, respectively, at the phase boundary.

Independent calculations were carried out by assuming that $\alpha$ nucleated and grew isothermally ($\xi = 10 \mu m$) at each of three temperatures, 650, 600 and 550°C. The value of $\beta$ was determined using $C'$ and $C''$ values from sections of the Fe–Ni–P phase diagram, and a $C'$ value of 10–7 per cent Ni (the average Ni content measured). Since 0.15 per cent P was found to be present in the metal of Tucson, the ternary diffusion coefficient (Heyward and Goldstein, 1974), $D_{Ni} = D_{NiNi} = 1.13 \exp(-68,600/RT)$, in $\gamma$ containing 13 per cent Ni and 0.2 per cent P was used. A summary of $C'$, $C''$, $\beta$ and $D_{NiNi}$ values used in the calculations is given in Table 2 as well as the calculated isothermal growth times. Two factors influence the solutions obtained from equation (2), $D_{NiNi}$ and $\beta$. As shown in Table 2, the diffusion coefficient decreases with temperature, while the driving force $\beta$ increases with decreasing temperature. Although diffusion conditions favor growth at 650°C, so little undercooling occurs that the interfacial Ni concentrations in $\alpha$ and $\gamma$ are such that little driving force is provided for growth. Kamacite growth is seen to occur most rapidly at 600°C, with $\alpha$ forming in about 8000 yr.

Armstrong (1958) has shown that the effect of diffusion with a linearly varying temperature can be related to diffusion conditions at one temperature, and has derived the equation:

$$t_{\text{equiv}} = \frac{RT\xi^2}{SQ},$$
Table 2. Cooling rates for Tucson calculated from 'equivalent' times

<table>
<thead>
<tr>
<th>Nucleation and growth temperatures</th>
<th>650°C</th>
<th>600°C</th>
<th>550°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C' ) (wt. % Ni)</td>
<td>11.0</td>
<td>15.0</td>
<td>19.1</td>
</tr>
<tr>
<td>( C' ) (wt. % Ni)</td>
<td>10.7</td>
<td>10.7</td>
<td>10.7</td>
</tr>
<tr>
<td>( C'' ) (wt. % Ni)</td>
<td>5.3</td>
<td>5.5</td>
<td>7.4</td>
</tr>
<tr>
<td>( \beta )</td>
<td>0.03</td>
<td>0.06</td>
<td>0.85</td>
</tr>
<tr>
<td>( D_{\text{Ni}} ) (cm²/sec)</td>
<td>( 6.4 \times 10^{-17} )</td>
<td>( 7.6 \times 10^{-18} )</td>
<td>( 6.8 \times 10^{-19} )</td>
</tr>
<tr>
<td>( \xi ) (µm)</td>
<td>6</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Calculated ( t ) (yr)</td>
<td>( 1.3 \times 10^5 )</td>
<td>( 8.1 \times 10^3 )</td>
<td>( 1.6 \times 10^4 )</td>
</tr>
<tr>
<td>( S ) (°C/1000 yr)</td>
<td>0.2</td>
<td>2.7</td>
<td>1.2</td>
</tr>
</tbody>
</table>

where \( t_{\text{equiv}} \) is the equivalent time, \( T_N \) the initial nucleating temperature, \( S \) the linear cooling rate, and \( Q \) the activation energy for diffusion. Essentially, if a diffusion-controlled process is started at a temperature \( T_N \) which decreases linearly at a rate \( S \), the total effect is the same as though diffusion had occurred at the initial nucleating temperature for a time, \( t_{\text{equiv}} \). In the case of kamacite growth, equation (4) was used to determine effective linear cooling rates assuming equivalent times at initial nucleating temperatures \( T_N \) of 650, 600 and 550°C. The results of these calculations are also presented in Table 2. They indicate that Tucson has cooled at about 1°C/1000 yr, almost irrespective of the assumed value of \( T_N \). In addition, a computer program (RANDICH, 1973) was used to determine \( \alpha \) growth under conditions of continuous cooling. Good agreement was found with isothermal growth calculations by assuming 75°C of undercooling; that is, nucleation at 575°C, and a cooling rate of about 2°C/1000 yr.

The above calculations are subject to a number of possible sources of error. One factor which critically affects the accuracy of the cooling rate is the diffusion coefficient. In general, the frequency factor and the activation energy of diffusion are determined at high temperatures, and errors arise in calculating diffusion coefficients at low temperatures. In addition, the presence of Si (0.9 per cent), Cr (0.2 per cent) and Co (0.4 per cent) affects Ni diffusion in \( \gamma \) to some extent. GOLDSTEIN and DOAN (1972) have shown that the addition of P to Fe–Ni alloys substantially influences both the \( \gamma \rightarrow \alpha \) transformation temperature and the solubility limits of Ni in \( \alpha \) and \( \gamma \). Although Ni concentrations in \( \alpha \) and \( \gamma \) were taken from the Fe–Ni–P diagram, the effect of other elements is again ignored and are also sources of error.

A cooling rate of 1°C/1000 yr or 1000°C/million yr implies that Tucson has cooled more rapidly than most iron meteorites. As GOLDSTEIN and SHORT (1967) point out, the fastest rate at which iron meteorites have cooled is \( \sim 500°C/\text{million yr} \). Two meteorites which fall into this category are Arltunga and Monahans (GOLDSTEIN and SHORT, 1967). Both irons are nickel-rich ataxesites and contain similar Ni contents to Tucson, that is, 10.0 and 10.9 per cent, respectively. It is interesting to note that Tucson has cooled only twice as fast as these meteorites.

It is possible to estimate a maximum depth of burial for Tucson based on the calculated cooling rate. Assuming that Tucson is contained in a spherical silicate body, which is cooled by simple conduction, the central temperature, \( T_c \), of this
body can be expressed by the equation (cf. Carslaw and Jaeger, 1947):

$$T_e = 2(T_0 - T_i) \left[ \exp \left( -\frac{\pi^2 \alpha t}{r^2} \right) - \exp \left( -\frac{4\pi^2 \alpha t}{r^2} \right) \right] + T_i,$$

where $T_0$ is the initial temperature of the body, $T_i$ is the surface temperature, $\alpha$ is the thermal diffusivity, $r$ is the radius of the body and $t$ is the cooling time. The values of the constants used in this calculation are $T_0 = 1783^\circ K$, $T_i = 100^\circ K$ and $\alpha = 0.01$ cm$^2$/sec. Since we are interested in a cooling rate $\partial T_e/\partial t$ of about $1^\circ C/1000$ yr at 600$^\circ$C, we can solve equation (5) and the differential of equation (5) with respect to time for the appropriate body size. It was found that the center of a body of radius $r = 15$ km cools at the appropriate rate. The calculated size of the body is only varied slightly if other values of $T_0$, down to $1273^\circ K$, are assumed. Tucson could have also cooled in larger sized bodies (>15 km radius) if it was buried closer to the surface of the parent body.

**Theories of formation**

As the above calculations show, Tucson formed at a significant depth below the surface of its parent body. The highly reduced silicate inclusions in Tucson, and the presence of elemental Si and Cr in the metal give chemical evidence that a severe reduction process has occurred. Although silicate inclusions are found in other iron meteorites, rarely are they so free of Fe. In addition, negligible Si or Cr is detected in the metal of these iron meteorites which contain such inclusions. As Wai and Wasson (1969) point out, it is probable that the silicates and metal in Tucson represent a high temperature equilibrium assemblage. The silicates, therefore, could have been reduced in the solid state, while in contact with liquid metal.

Although a reduction process accounts for the Cr and Si in solid solution, the presence and unique distribution of silicate inclusions (Fig. 2) remain unexplained. As one possibility, we propose that liquid metal may have interacted with and accumulated solid silicate particles during solidification of the melt. If the metal solidified in a dendritic manner, the accumulated silicate inclusions could have been 'pushed' to the interdendritic regions of the melt. Alternatively, if cellular type growth occurred, the inclusions could have been 'pushed' to the cell boundaries. In either case, the silicates would be preserved in such locations on further cooling. A second possibility is the shock emplacement of the silicates. At elevated temperatures, the silicates could have been introduced into the metal by the movement of silicate overburden. Such a process would essentially be one of 'hot working' the inclusions into the metal. This could also account for the presence and aligned pattern of silicates in Tucson. Both possibilities tend to be consistent with the high degree of reduction observed in Tucson.

As mentioned earlier, Uhlmann et al. (1964) have studied the interaction between particles and an advancing solid–liquid interface both experimentally and theoretically. They have defined a parameter known as the 'critical velocity' to describe the particle–interface interaction. If particles are encountered by an advancing solid–liquid interface which is moving faster than the 'critical velocity', the particles become 'trapped' in the solid and are frozen in place. If the interface velocity is slower than the critical value, however, particles will be 'pushed' by the interface.
In the latter instance, final particle position will be a function of the mode of solidification. We should emphasize that these investigators have studied an ideal situation where factors such as convection are ignored. Uhlmann et al. (1964) have formulated an expression for the critical velocity:

$$V_c = \frac{d_s L a_0 d_1}{6 \eta R_0 R^2 n} \left[ -1 + \left[ 1 + \frac{6 \eta R_0 n (n + 1) V_0 D}{d_s h d_k T} \right]^{1/2} \right],$$

where $d_s$ is the minimum separation distance of the particle and the interface, $h$ a parameter to account for particle surface irregularities, $L$ the latent heat of fusion, $a_0$ a size parameter defined by the Gibbs–Thompson relation, $d_1$ the separation between irregularities and the interface, $\eta$ the liquid viscosity, $R_0$ the particle radius, $R$ the radius of the irregularity, $n$ a parameter which relates surface free energy with particle–solid separation, $V_0$ the atomic volume, $D$ the diffusion coefficient of the liquid, $k$ Boltzmann’s constant, and $T$ the temperature. Calculations using this equation were made for a system of silicate particles in a matrix of liquid iron. Table 3 lists the values used in equation (6), and the results for particles ranging in size from 1 to 1000 μm. Since some of the variables involved are known to only ±20 per cent, order of magnitude calculations for $V_c$ are all that can reasonably be obtained. Calculations show the critical velocity for the largest particles found in Tucson (about 1000 μm in radius) to be approximately 10 μm/sec.

Myers and Flemings (1972) point out that the relevant growth velocity in dendritically solidified metallic alloys is very low, and on the order of 1 μm/sec. The above calculations using the Uhlmann equation imply, therefore, that if Tucson did solidify in a dendritic manner, the silicate particles should have been pushed to the interdendritic regions. The observations in Tucson which support such an occurrence are the presence of metallic areas free of silicates. In Fig. 2a, the silicates tend to be aligned in a direction perpendicular to the primary dendritic growth.

<table>
<thead>
<tr>
<th>$R_0$ (μm)</th>
<th>$V_c$ (μm/sec)</th>
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<tbody>
<tr>
<td>1</td>
<td>297</td>
</tr>
<tr>
<td>10</td>
<td>96</td>
</tr>
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<td>100</td>
<td>31</td>
</tr>
<tr>
<td>1000</td>
<td>10</td>
</tr>
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direction, while in Fig. 2b, the clear metal areas possibly represent the results of sectioning through the primary dendritic arms. Growth conditions could have been such that Tucson solidified in a cellular, rather than dendritic manner. A cellular structure may be envisioned as one of rods which are oriented parallel to the growth direction. UHLMANN et al. (1964) observed the interaction of a cellular interface with solid particles in the ice-water system, and found that particles were pushed between cell boundaries where they remained entrapped. This resulted in lines of particles in the solid, separated by the cell dimensions. Cellular solidification also offers a possible explanation for the flow pattern distribution of silicates in Tucson.

Although the silicates tend to be positioned along straight lines (Fig. 2a), certain sections of Tucson reveal the silicates to be located along slightly curved lines. Deformation following solidification could cause the aligned pattern to be curved, and at elevated temperatures have aided in the homogenization of solute segregation.

The shapes of the Tucson irons appear to be a result of a solidification process. One way in which such shapes can be explained is by assuming a vein origin for Tucson. A collision, for example, involving the parent body of Tucson could have produced a fissure into which shock-melted metal was injected. This process is shown schematically in Fig. 9, which illustrates a region of silicate material within the parent body. If the collision occurred early in the parent body’s history, the silicate material may have still been quite hot (>1000°C). The arrows indicate how liquid metal could have entered a cavity, and solidified by taking the shape of the internal void. A cutaway view in Fig. 9 shows how the Ring iron may have formed. The Ring and Carleton irons were probably an originally continuous metallic mass, and the fact that two sections presently exist may be a result of a fracture which occurred at the junction of the ring-shaped and slab-like components of the mass (Fig. 9, region of the two diverging arrows).

The solidification formation process could also account for the source of silicate inclusions in Tucson. In steel-making processes (SIMS, 1959) the refractories which are in contact with the liquid metal are a primary source of exogenous inclusions. Inclusions in the melt can result from the erosion of refractories, or be products of surface reactions between the refractories and the liquid metal. In the case of Tucson, silicates could have ‘eroded’ from the walls of the cavity during the injection of liquid metal into the void.

**Conclusions**

1. The metal matrix of Tucson is chemically and structurally homogeneous. Implications are that if microsegregation did develop during solidification, substantial homogenization at high temperatures occurred during further cooling.

2. Kamacite phase growth calculations indicate that Tucson cooled at about 1°C/1000 yr through lower temperatures. Such a rate requires Tucson to be buried in the center of a 15 km radius parent body or closer to the surface of parent bodies of larger sizes.

3. The shapes of the Tucson irons and the presence and distribution of silicate inclusions in the metal appear to be a result of a solidification process. An alternative, but less probable idea, considers the shock emplacement of silicates into the metal.
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