Carbothermal Solid State Reduction of Manganese Ores: 1. Manganese Ore Characterisation

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(Received on November 5, 2008; accepted on April 10, 2009)

The South African Wessels and Australian Groote Eylandt manganese ores were characterized using XRD, optical, SEM and EPMA analyses. Two grades of Groote Eylandt ore were examined, one of them contained a high concentration of silica, 34.4 mass%. Wessels ore had high iron oxide and calcia content, and low concentration of silica. Major manganese-containing phases were bixbyite, braunite, manganite and haussmannite in Wessels ore, and pyrolusite in Groote Eylandt ore; both grades of Groote Eylandt ore contained silica inclusions. In the process of sintering in air and argon at 1 000°C, MnO2 was reduced to Mn3O4 and MnO, while in sintering in hydrogen manganese oxides were reduced to MnO and iron oxides to metallic iron. In the process of sintering of high-silica Groote Eylandt ore at 1 200°C in inert atmosphere, tephroite was formed which was partially decomposed to rhodonite and MnO with increasing sintering time to 30 min. In the ore sintered at 1 200°C in hydrogen for 1 h, major phases identified by XRD analysis were MnO, silica and tephroite.

KEY WORDS: manganese ore; phase composition; melting; Groote Eylandt ore; Wessels ore.
1.0CO₂ + 1.0C = 2.0CO ..................................(3)

- CO mass transfer from graphite to oxide
- CO mass transfer from the reactor

The gas atmosphere has a strong effect on the solid state–gas reactions. The paper series will study reduction of manganese ores in inert-helium and argon, and hydrogen gas atmospheres. Comparison of results obtained in argon and helium will allow an examination of the role of kinetic parameters in the gas phase (diffusion in helium is much faster than in argon); while difference in reduction in helium and hydrogen, in which kinetic parameters are about the same, will be due to involvement of hydrogen in the reduction process. No literature was found on carbothermal reduction of manganese ore in hydrogen.

The paper will study reduction of South African Wessels ore and two grades of Australian Groote Eylandt ore: GE-PF ore with low silica content and GE-PS ore with high silica content. This provides the variety in the chemical composition between the ores.

The paper will be presented in three sections:
1) Characterisation of manganese ores
2) Reduction in different gas atmospheres
3) Phase development in the process of reduction.

Reduction in the solid state has a kinetic advantage due to a well-developed gas–solid interface. Formation of liquid phases has a negative effect on the low-temperature reduction kinetics.

Mineralogy and geology of Wessels and Groote Eylandt ores were studied in works8)-(10) correspondingly and others. However, the chemistry and mineralogy of ores in different deposits are different.9) For understanding of the ore reduction behaviour it is important to characterise samples used in reduction. This section analyses chemical and phase composition of Wessels and Groote Eylandt ores and their change upon heating in different gas atmospheres. The aim of this analysis is to establish the ore behaviour upon heating and define the temperature range for the solid-state ore reduction.

2. Experimental

Manganese ores examined in the paper, Wessels ore and two grades of a Groote Eylandt ore (GE-PF and GE-PS) were supplied by TEMCO. Their chemical composition was determined by XRF method; oxygen content was measured by LECO. The ores were ground into different particle size fractions. The size fraction used in majority of manganese ore reduction experiments was 45–150 mm.

Samples of manganese ore were subjected to XRD, optical and electron microscope analyses. X-ray diffraction was done using a Siemens D5000 X-Ray diffractometer using a Cu-Kα X-ray source with a nickel monochromator. The scans were done from 20° to 70° at 1°/min and a step size of 0.02°. The voltage used was 30 kV, with a current of 30 mA. The XRD patterns were analysed qualitatively using “Traces” software from Diffraction Technology Pty. Ltd., with JCPDS-PDF2 database.

Samples for optical and electron microscope analyses were prepared by mounting in an epoxy resin mould. These moulds were prepared by drilling through an epoxy blank, and filling the holes with the ore. Resin was then poured over the top of the blank and sample, and mixed with the sample to ensure that the particles were tightly held. The samples were held within a vacuum chamber for around 30 min before being left to harden for around 24 h.

The samples were then ground using SiC paper, from 120 to 4000 grade; followed 4 μm, 1 μm and 0.5 μm diamond paste on a polishing wheel. The samples were washed using soap and water in an ultrasonic bath between the grinding and polishing, before being rinsed under ethanol.

Optical photomicrographs were obtained using a Nikon Epiphoto 200 (Nikon Corp., Japan) inverted stage metallurgical microscope with an attached Nikon DXM1200 digital camera. Images were captured using the Nikon ACT-1 software package.

Samples were coated with carbon for SEM EDS and EPMA analysis. Scanning electron microscopy (SEM) was carried out using a high resolution (1.5 nm) Hitachi S-4500 field emission SEM (FESEM) with a tilting stage, Robinson back-scatter detector and Oxford Instruments cathodoluminescence detector (MonoCL2/ISIS). FESEM was used to observe the morphologies and section profile of samples obtained at different reaction stages. Energy dispersive X-ray spectroscopy (EDS) was done using an Oxford Instruments Isis energy dispersive X-ray analyser. This was used to perform qualitative and semi-quantitative chemical analysis at different points and areas within the samples.

The mounted samples were analysed using the Cameca SX-50 electron microprobe. Standard operating procedure involved a 15 kV accelerating voltage, 1–3 μm beam size and a 20 nA beam current. The microprobe has four multi-crystal wavelength-dispersive spectrometer and was operated with a configuration involving two TAP, and LIF and one PET diffracting crystals.

3. Results and Discussion

3.1. Wessels Ore

The chemical composition of the Wessels ore is given in Table 1. This ore contains relatively high amounts of iron and calcium, low silicon and alkalis.

The XRD pattern, optical image and EPMA of this ore are presented in Fig. 1 and Table 2 respectively. XRD analysis identified four major phases in the Wessels ore: bixbyite, mangansite, hausmannite and calcite (Fig. 1). XRD spectrum for bixbyite is very close to that of braunite (PDF2 02-0895).

The presence of braunite was also supported by EPMA (see Table 2), which was found in two modifications—with high silica and low silica.10) The Mn/Fe weight ratio in the ore was 4.85. In the high silica braunite (8–10 at% Si), Mn content was relatively small, 17–20 at%; this phase is also characterised by high iron (4.5–6.5 at%) and calcium (8–10 at%) content. Iron was also detected in other phases except calcite.

Weight change of Wessels ore heated to 1000°C in air, argon and hydrogen atmospheres is plotted in Fig. 2. The highest weight loss was observed in hydrogen; while in air and argon the weight losses were similar. The XRD analysis of sintered samples showed that in hydrogen, the man-
ganese oxides in the ore were reduced to MnO and iron oxides to metallic iron (Fig. 3). This corresponds to 45% of the ore reduction. XRD patterns of samples sintered in air and argon were almost the same and showed that Mn$_2$O$_3$ and MnOOH were converted to Mn$_3$O$_4$.

3.2. Groote Eylandt GE-PF Ore

Chemical composition of Groote Eylandt GE-PF ore is given in Table 1. It is a high-grade manganese ore enriched with manganese to 55 mass% (71 mass% MnO). The diffraction pattern of this ore is shown in Fig. 4. The only phase identified in GE-PF ore by XRD was Mn$_3$O$_4$ (pyrolusite) (PDF-2 card No. 24-735). However, optical and SEM (Fig. 5) with EDS (Table 4) analyses revealed the complex mineralogical structure of the ore. Apart from pyrolusite, GE-PF ore contained iron silicate and silica; pyrolusite grains were distinguished by colour given by different impurities, specified in Table 3.

Manganese was mainly present as pyrolusite. Iron was mostly found in the form of iron alumo-silicates and in small amounts in the manganese oxides. Silicon was pres-
dent in the form of silica inclusions, in iron alumino-silicate, and also in manganese oxide. Pyrolusite and iron alumino-silicate contained potassium.

Behaviour of GE-PF ore upon heating was studied in air, argon and hydrogen atmospheres. The heating temperature was 1 000°C. Figure 2 shows the weight loss of sintered GE-PF ore at 1 000°C in different gas atmospheres. Most of the weight loss happened in first 5–10 min of heating in all atmospheres; then the weight of the ore decreased slightly with further heating in air and argon up to 30 min and did not change afterwards. The total weight loss in air and argon was about 13%, while in hydrogen it was 19%. The phase development during the sintering in different gas atmospheres examined by XRD analysis is shown in Figs. 6–8. Pyrolusite MnO$_2$ in GE-PF ore upon heating and holding at 1 000°C reduced to Mn$_2$O$_3$ and Mn$_3$O$_4$ in air and argon. MnO$_2$ became invisible in the XRD spectra after 3 min sintering. Mn$_3$O$_4$ fraction increased and Mn$_2$O$_3$ decreased with increasing sintering time. Only Mn$_3$O$_4$ was detected in the sample sintered in argon for 70 min.

![Fig. 5. SEM analysis of selected area of GE-PF ore. The EDS chemical analysis of numbered areas is presented in Table 4.](image)

**Table 3.** EPMA of selected grains of GE-PF ore and their typical composition, at%.

<table>
<thead>
<tr>
<th>Colour</th>
<th>Suggested Phase</th>
<th>Mn</th>
<th>Fe</th>
<th>Si</th>
<th>Al</th>
<th>K</th>
<th>O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light blue</td>
<td>MnO$_2$ oxide</td>
<td>32.3</td>
<td>0.28</td>
<td>0.47</td>
<td>0.53</td>
<td>0.04</td>
<td>66.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>32.9</td>
<td>0.25</td>
<td>0.33</td>
<td>0.45</td>
<td>0.02</td>
<td>65.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>32.2</td>
<td>0.43</td>
<td>0.36</td>
<td>0.72</td>
<td>0.06</td>
<td>65.1</td>
</tr>
<tr>
<td>Brown</td>
<td>MnO$_2$ oxide</td>
<td>30.8</td>
<td>0.51</td>
<td>0.31</td>
<td>0.29</td>
<td></td>
<td>68.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30.6</td>
<td>0.21</td>
<td>0.10</td>
<td>0.47</td>
<td></td>
<td>68.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>29.9</td>
<td>0.23</td>
<td>0.39</td>
<td>0.44</td>
<td></td>
<td>68.6</td>
</tr>
<tr>
<td>Dark blue</td>
<td>MnO$_2$ oxide</td>
<td>27.7</td>
<td>1.49</td>
<td>0.38</td>
<td>1.32</td>
<td>2.13</td>
<td>63.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>29.0</td>
<td>0.30</td>
<td>0.01</td>
<td>0.22</td>
<td>1.18</td>
<td>65.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>31.2</td>
<td>0.99</td>
<td>0.32</td>
<td>1.01</td>
<td>1.03</td>
<td>59.8</td>
</tr>
<tr>
<td>Red, Orange</td>
<td>Iron alumino-silicate</td>
<td>0.02</td>
<td>18.7</td>
<td>8.02</td>
<td>8.02</td>
<td>1.32</td>
<td>63.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.05</td>
<td>2.69</td>
<td>13.6</td>
<td>13.4</td>
<td>0.09</td>
<td>59.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.46</td>
<td>12.4</td>
<td>10.5</td>
<td>10.5</td>
<td>0.09</td>
<td>61.2</td>
</tr>
<tr>
<td>Transparent</td>
<td>SiO$_2$</td>
<td>0.02</td>
<td>30.7</td>
<td></td>
<td></td>
<td></td>
<td>69.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.04</td>
<td>30.9</td>
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<td>69.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.02</td>
<td>30.6</td>
<td></td>
<td></td>
<td></td>
<td>69.3</td>
</tr>
</tbody>
</table>

![Fig. 6. XRD patterns of GE-PF ore sintered at 1 000°C in air.](image)

![Fig. 7. XRD of sintered GE-PF ore in argon at 1 000°C.](image)

![Fig. 8. XRD of sintered GE-PF ore in hydrogen at 1 000°C.](image)

**Table 4.** EDS analysis of selected GE-PF ore grains (Fig. 5), at%.

<table>
<thead>
<tr>
<th>No.</th>
<th>(Phase)</th>
<th>O</th>
<th>Al</th>
<th>Si</th>
<th>K</th>
<th>Mn</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mn oxide</td>
<td>60.9</td>
<td>2.71</td>
<td>-</td>
<td>2.48</td>
<td>31.6</td>
<td>1.55</td>
</tr>
<tr>
<td>2</td>
<td>SiO$_2$</td>
<td>63.3</td>
<td>-</td>
<td>36.7</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>Mn oxide</td>
<td>61.0</td>
<td>-</td>
<td>-</td>
<td>0.7</td>
<td>38.1</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>Mn oxide</td>
<td>59.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>40.2</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>Fe alumino-silicate</td>
<td>64.2</td>
<td>8.35</td>
<td>10.8</td>
<td>-</td>
<td>0.77</td>
<td>15.5</td>
</tr>
<tr>
<td>6</td>
<td>Mn silicate</td>
<td>51.4</td>
<td>2.23</td>
<td>2.71</td>
<td>0.69</td>
<td>41.3</td>
<td>1.7</td>
</tr>
<tr>
<td>7</td>
<td>Fe alumino-silicate</td>
<td>63.6</td>
<td>7.73</td>
<td>10.4</td>
<td>0.41</td>
<td>1.35</td>
<td>16.6</td>
</tr>
</tbody>
</table>
When GE-PF was sintered in hydrogen at 1000°C, higher manganese oxides were reduced to MnO, and iron oxides were reduced to metallic iron. The XRD pattern of the ore pre-sintered at 1000°C in air for 3 h is shown in Fig. 9.

### 3.3. Groote Eylandt GE-PS Ore

Chemical analysis of Groote Eylandt GE-PS ore is presented in Table 1. The feature of this ore is high silica concentration, 34.4 mass%; much higher than in Groote Eylandt GE-PF or in Wessels ores. The concentration of iron oxide and alumina in the GE-PS ore is also higher than in the GE-PF ore. The main phases detected by XRD were MnO (pyrolusite) and silica SiO₂ (Fig. 10). Macroscopic and microscopic investigation revealed the complex mineralogical structure of the GE-PS ore. Grains in the GE-PS ore can be divided into three main groups: manganese oxides, iron silicates and silica. Manganese oxide appeared in two modifications which were distinguished by colour; light blue particles (pyrolusite) and dark-green particles with a banded structure, identified as cryptomelane (Table 5). Manganese oxide was also a major phase in dark-blue particles, which contained alumina, silica, iron and potassium oxide and other impurities. These impurities were also observed in other manganese oxide particles. Iron in the GE-PS ore was found mostly in the form of iron–aluminium silicate with the chemical composition matching almandine.

Upon heating in air at 1000°C high manganese oxide MnO₂ decomposed to Mn₂O₃ and Mn₃O₄, while heating in argon reduced MnO₂ to Mn₃O₄ (Fig. 11). In hydrogen, higher manganese oxides were reduced to MnO and iron oxides to metallic iron. This is seen in Fig. 2 with plots of the weight change in the process of sintering and Fig. 12 which presents the XRD patterns of the GE-PS ore sintered in air, argon and hydrogen. These reduction reactions during heating to 1000°C were very fast and completed in the
first 10 min of the experiment (Figs. 2 and 12). XRD pattern of GE-PS ore sintered at 1 000°C in air for 3 h is shown in Fig. 13.

Behaviour of the sintered ore was further tested at 1 200°C in hydrogen and helium. Heating of the GE-PS ore to 1 200°C led to formation of the slag phase, which had a profound effect on the ore phase composition. XRD spectra of the GE-PS ore sintered in helium and hydrogen at 1 200°C are shown in Figs. 14 and 15 correspondingly.

Mn$_2$O$_3$ and Mn$_3$O$_4$ oxides, which were the main manganese-containing phases in the ore, became invisible in the XRD spectra after 15 min sintering in helium, and silica peak height decreased significantly. This was a result of formation of tephroite, which became a dominant phase with traces of silica. It can be concluded that tephroite was formed by reaction of Mn$_3$O$_4$ with silica. XRD spectra of the GE-PS ore sintered further for 30 min revealed partial decomposition of tephroite (Mn$_2$SiO$_4$) to MnO and rhodonite (MnSiO$_3$). Both, tephroite and rhodonite contained iron oxide.

Different behaviour of the ore was observed in the process of sintering at 1 200°C in hydrogen. 10-min sintering resulted in the reduction of manganese oxides to MnO and iron oxides to metallic iron, and formation of tephroite. After 20-min sintering, major phases identified by XRD were silica, MnO and tephroite. Further formation of tephroite proceeded by reaction of MnO with silica. This process was slow; XRD spectra of a sample sintered for 60 min revealed the same phases as in the sample sintered for 20 min, although the height of MnO peaks decreased and height of tephroite peaks increased with increasing sintering time. Rhodonite was not detected in the sintered sample, while silica peaks in the XRD spectra remained strong even after 1 h of sintering (Fig. 15); silica was also visible in optical images. It can be concluded that fast reduction of higher manganese oxides to MnO in hydrogen retarded the formation of tephroite, which was much faster in the process of sintering in inert atmosphere.

The weight loss of samples preheated in air at 1 000°C and sintered at 1 200°C was slightly higher in hydrogen than in helium; the difference was due to reduction of iron oxides to metallic iron by hydrogen; while sintering in helium it was not observed and was not expected. The degree of reduction of higher manganese oxides to MnO and iron oxides to Fe corresponds to 40% of total reduction of manganese and iron oxides in the ore. The degree of reduction of GE-PS ore in hydrogen at 1 200°C was about the same as at 1 000°C. In sintering in an inert atmosphere, reduction of MnO$_2$ at 1 000°C did not go beyond Mn$_3$O$_4$.

3.4. Ore Melting Analysis

Reduction in the solid state, which has a kinetic advantage due to a well-developed gas–solid interface, is hampered by formation of liquid phases. This section analyses formation of liquid phases upon heating of Wessels and Groote Eylandt ores and their reduction.

The following should be noted regarding chemistry of Wessels and Groote Eylandt ores:
- Wessels ore has high iron oxide and calcia content, lowest concentration of silica and only traces of potassium.
- GE-PS ore is characterised by very high silica, relatively high alumina and low calcia concentrations; it also contains potassium.
- GE-PF ore contains the highest potassium concentration; it is also characterised by the highest Mn/Fe ratio.

Wessels ore major components are manganese, iron, silicon and calcium oxides; major oxides in the Groote Eylandt ore are manganese and iron oxides, silica and alumina. The ternary MnO–SiO$_2$–CaO phase diagram is most suitable to discuss Wessels manganese ore and its reduction path, particularly after reduction of iron oxides to metallic iron;
while the MnO–SiO₂–Al₂O₃ phase diagram is more appropriate for consideration of Groote Eylandt ores. MnO–SiO₂–CaO and MnO–SiO₂–Al₂O₃ phase diagrams are presented in Figs. 16 and 17.¹¹)

CaO/SiO₂ molar ratio in the Wessels ore is 2.14. The MnO reduction path, shown in Fig. 16 does not cross the molten phase at 1 200°C. On this basis, it can be expected that reduction of Wessels ore in the solid state is feasible.

The MnO reduction path for Groote Eylandt ores is shown in Fig. 17. SiO₂/Al₂O₃ molar ratio is equal to 1.56 for GE-PF ore and 10.5 for GE-PS ore. Based on the ternary diagram, it can be concluded that in the reduction of both GE-PF and GE-PS ores at 1 200°C the liquid phase is formed.

Such consideration on the basis of ternary diagrams is oversimplified; it does not take into account the presence of iron oxide and impurities. FeOₙ–SiO₂ system has two low temperature eutectics at 24 mass% SiO₂ (1 177°C) and 38 mass% SiO₂ (1 178°C).¹¹) FeO–Fe₂O₃–SiO₂ ternary system is characterised by eutectics at 1 150°C and 1 177°C.¹¹) FeOₙ–MnO–SiO₂ system forms eutectic at 1 185°C.¹¹)

In Wessels ore, complex (Mn, Fe, Ca)-silicates were detected; iron-alumo-silicates were found in both GE-PF and GE-PS ores. It follows from ternary FeOₙ–Al₂O₃–SiO₂

![Fig. 16. MnO–SiO₂–CaO phase diagram.¹¹) A thick line shows the MnO reduction path for the Wessels ore.](image1)

![Fig. 17. MnO–SiO₂–Al₂O₃ phase diagram.¹¹) Thick lines show the MnO reduction paths for Groote Eylandt ores.](image2)
phase diagram, those silicates with 60–80 mass% FeO, and up to 20 mass% Al₂O₃ (depending on iron oxide content) are molten at temperatures below 1 200°C. However, in the process of reduction, iron oxides are easily reduced to metallic iron and have no effect on the ore melting properties.

Alkali impurities have a profound effect on oxides melting temperature. Effect of K₂O on melting of MnO–SiO₂–Al₂O₃ slag was studied by Anacleto who showed that addition of 1–3 mass% K₂O to the 50%MnO–35%SiO₂–15%Al₂O₃ (by mass) system decreased its melting temperature from 1 180 to 1 132–1 148°C.

In carbothermal reduction of GE ores, silica is also reduced, which changes the overall reduction path of these ores, particularly of GE-PS which contains high silica concentration.

This analysis shows that Groote Eylandt manganese ores can have molten phases at 1 200°C prior to reduction and in the course of reduction. Molten phases can be fluxed manganese-alumino-silicate and iron-alumino-silicate. Formation of molten phases in the reduction of Wessels ore is not expected and was not observed; this ore contains relatively low concentrations of silica and alkali oxides.

Temperatures at which melting started of different ores were established by microscopic examination of samples heated in helium to different temperatures. Wessels ore was solid at temperatures up to 1 250°C and GE-PF ore up to 1 200°C; GE-PS started to melt at about 1 100°C. Above these temperatures, reduction of manganese oxide will proceed with formation of molten slag.

The melting temperature of ferromanganese carbide and ferromanganese-silicon carbide is close to 1 200°C; molten metal phase was observed in reduction of Wessels and GE-PS ore. However, sintering and melting of the metallic phase did not affect the reduction behaviour.

Solid state reduction of Wessels and Groote Eylandt ore will be presented in the next paper of this series.

4. Conclusions

Analysis of South African Wessels and Australian Groote Eylandt manganese ores revealed their chemical composition diversity and complex mineralogical structure.

Groote Eylandt GE-PS is characterised by very high silica, 34.4 mass%, relatively high alumina and low calcia concentrations. Groote Eylandt GE-PF contain the highest potassium concentration; it is also characterised by the highest Mn/Fe ratio among three ores studied in this paper. Wessels ore has high iron oxide and calcia content, lowest concentration of silica and only traces of potassium.

Major phases identified by XRD and EPMA analyses were in the Wessels ore: bixbyite, braunite, manganese, hausmannite and calcite; GE-PF ore: pyrolusite, manganese and iron silicates, and silica; GE-PS ore: pyrolusite, iron silicate, cryptomelane and silica.

Upon sintering in air and inert gas at 1 000°C, Mn₃O₄ and MnOOH in the Wessels ore were reduced to MnO, while MnO₂ in the Groote Eylandt ores was reduced to MnO₂ and MnO in air and to MnO in argon. Sintering of manganese ores in hydrogen at 1 000°C reduced higher manganese oxides to MnO and iron oxides to metallic iron.

In the process of sintering of the GE-PS ore at 1 200°C in helium, tephroite was formed by reaction of MnO₂ and MnO₃ oxides with silica; tephroite was partially decomposed to MnO and rhodone with extension of sintering time to 30 min. When this ore was sintered in hydrogen, higher manganese oxides were quickly reduced to MnO with formation of tephroite. Further formation of tephroite was by reaction of MnO with silica; rhodone was not observed in the sample sintered for 1 h.

Based on MnO–SiO₂–CaO and MnO–SiO₂–Al₂O₃ phase diagrams analysis, Wessels ore is expected to be solid in the process of reduction at 1 200°C; while reduction of Groote Eylandt ore will proceed with formation of molten slag.

Temperatures at which melting started of different ores were established by microscopic examination of samples heated in helium to different temperatures. Wessels ore was solid at temperatures up to 1 250°C and GE-PF ore up to 1 200°C; GE-PS ore started to melt at about 1 100°C.

Acknowledgements
This research was supported under Australian Research Council Linkage Project funding scheme (project number LP0560703). Professor Ostrovski is the recipient of an Australian Research Council Professorial Fellowship (project number DP0771059).

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