THERMAL ANALYSIS OF GOETHITE - RELEVANCE TO AUSTRALIAN
INDIGENOUS ART

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Abstract

Differential scanning calorimetry shows two endotherms at 75 and 225°C for synthetic goethite. The latter endotherm is strongly asymmetric on the low temperature side. The endotherms were attributed to the loss of water and the dehydroxylation of the goethite. The temperature of the endotherms and the enthalpy of the phase change were found to be linear functions of the % of aluminium substitution into the goethite. High-resolution thermogravimetric analysis of goethite showed three weight loss steps, occurring at ~ 175, 196 and 263°C. The temperatures of these weight loss steps and the % weight loss were also linearly related to the degree of Al substitution. The use of infrared emission spectroscopy confirmed the temperature of dehydroxylation. The observation of the low temperature dehydroxylation of goethite and its relation to ancient aboriginal cave art is discussed.

Keywords: dehydration, dehydroxylation, goethite, haematite, differential scanning calorimetry, high-resolution thermogravimetric analysis

Introduction

Goethite was a commonly used colorant amongst indigenous tribes in prehistoric times [1]. The Australian aboriginals used goethite for face, body and cave paintings. The major deposit of goethite is in the Flinders ranges of South Australia and is not commonly found in other parts of Australia. One commonly accepted point of view is that minerals such as goethite, haematite and kaolinite may have been used for trade or as a monetary device. Most aboriginal cave paintings such as may be found at Chillagoe in North Queensland contain extensive ancient aboriginal paintings. Most of the paintings are now coloured red from haematite. Two basic questions arise: firstly were the paintings originally painted yellow/gold with goethite and the heat of the camp fires converted the goethite to haematite and secondly did the indigenous people of prehistory take goethite and place the mineral at or near a camp fire to convert the goethite to haematite. It is well known that goethite was used in mediaeval times as a colorant [2-4]. The question arises as to whether prehistoric tribes of Australia possessed the knowledge of the goethite haematite phase change if only as a change in colours of the mineral.

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Dehydroxylation of goethite to form hematite occurs due to natural and managed thermal transformation, and is a component of some manufacturing processes [5]. Since goethite and hematite are the most common forms of the crystalline iron oxides and the major impurities in bauxite, an understanding of the thermally topotactic transformation of goethite to hematite is of importance in the study of colorants of antiquity. The structure of goethite is based on the hexagonal close packing of oxygen atoms with 6-fold coordinated Fe atoms occupying octahedral position. The Fe atoms are arranged in double row to form what can be described as double chains of octahedra, which run the length of the c-axis. Within the double chains in the b-c plane, all bonds are covalent with each octahedron sharing four of its edges with neighbouring octahedra. In contrast, bonding between double chains consists of relatively weak hydrogen bonding directed through apical oxygen ions directed along the a-axis [6]. In this case, stacking of double chains along the a-axis can be easily disrupted and this consequently induces structural defects, such as non-stoichiometric hydroxyl units incorporated into the goethite structure during crystal growth [5, 7-9].

When heated, goethite alters to hematite by the removal of hydroxyl sheets and some of the oxygen in strips parallel to the c-axis to form water. In this transformation the (100), (010) and (001) directions in goethite become the (001), (110) and (111) directions in the trigonal hematite cell [10]. The application of infrared spectroscopy is most useful for determining the phase transformation of goethite to haematite. Hematite formed by dehydroxylation of goethite at low temperatures retains the residual of non-stoichiometric hydroxyl units from goethite and this feature is clearly shown in the hydroxyl-stretching region [11]. Recently a study of the mechanism of thermal transformation of goethite to haematite was reported [12, 13]. Other studies distinguished between bulk and surface properties in the dehydration-dehydroxylation of synthetic goethites [14] and the effect of mechanochemical activation of goethites [12, 13]. The objective of this research is to report the thermal transformation of Al-substituted goethites to haematite and compare the thermal transformations of the synthetic goethite with two naturally occurring goethites.

**Experimental**

**Goethite minerals**

Two naturally occurring goethites were obtained (a) from the ancient aboriginal source in the Flinders ranges in South Australia and from an aboriginal cave known as fern cave near Chillagoe in North Queensland. These minerals were checked for phase purity by X-ray diffraction.

The goethite used in this study was synthesized from a ferrous salt. The Al goethites were synthesised from aluminium chloride (AlCl₃.6H₂O) and ferrous chloride (FeCl₂.4H₂O). The chemicals were mixed such that (Al³⁺/Fe²⁺ + Al³⁺) mole percentages of 0, 10, 20 and 30% were obtained. Total cation concentrations were set at 0.1M in a total volume of 4 litres. Sodium bicarbonate was used to buffer the system at pH of 7 during the oxidation process. The solution was oxidised by bubbling air at a rate of 25 cm³ per minute through a glass sinter. A solution of 0.2M ammonium oxalate was used to extract the poorly crystalline compounds from the precipitates. The precipitate was washed...
several times with distilled water and finally by acetone before drying in an oven at 110°C.
The chemical composition of the Al-substituted goethites was confirmed by atomic
absorption spectroscopy. Phase composition was checked by X-ray diffraction. A detailed
description of this synthetic goethite was published elsewhere [5].

**Thermal Analysis**

Differential Thermogravimetric Analysis (TGA) was conducted on TA
Instruments Thermogravimetric Analyser (TGA, Q500) equipped with Evolved Gas
Analysis (EGA) furnace, which was connected to a Quadrupole Mass Spectrometer
(PFEIFFER, QMS 200 Prisma) through a 1/8 inch, in diameter, transfer line. Nitrogen was
used as the purging gas and the flow rate was controlled precisely at 80ml/min. For each
run, sample powders were loaded onto platinum sample pan and heated to 1000°C at high-
resolution heating rate of 2°C/min, where the heating rate was dynamically and
continuously modified in response to the changes in the rate of sample’s weight loss,
termed as controlled rate thermal analysis (CRTA).

Differential Scanning Calorimetry (DSC) was performed on a TA instrument DSC
Q10 analyser. Sample powders were loaded into sealed alumina pan and heated to 500°C at
heating rate of 2°C/min. The empty alumina pan was used as reference and the heat flow
between the sample and reference pans was recorded.

**Infrared emission spectroscopy**

FTIR emission spectroscopy was carried out on a Nicolet spectrometer equipped
with a TGS detector, which was modified by replacing the IR source with an emission cell.
A description of the cell and principles of the emission experiment have been published
elsewhere. [15-19] Approximately 0.2 mg of the goethite mineral was spread as a thin
layer (approximately 0.2 microns) on a 6 mm diameter platinum surface and held in an
inert atmosphere within a nitrogen-purged cell during heating.

In the normal course of events, three sets of spectra are obtained: firstly the black
body radiation over the temperature range selected at the various temperatures, secondly
the platinum plate radiation is obtained at the same temperatures and thirdly the spectra
from the platinum plate covered with the sample. Normally only one set of black body and
platinum radiation is required. The emittance spectrum \( E \) at a particular temperature was
calculated by subtraction of the single beam spectrum of the platinum backplate from that
of the platinum + sample, and the result ratioed to the single beam spectrum of an
approximate blackbody (graphite). The following equation was used to calculate the
emission spectra.

\[ E = -0.5 \log \frac{Pt - S}{Pt - C} \]

This spectral manipulation is carried out after all the spectral data has been
collected. The emission spectra were collected at intervals of 50°C over the range 200 -
750 °C. The time between scans (while the temperature was raised to the next hold point)
was approximately 100 seconds. It was considered that this was sufficient time for the
heating block and the powdered sample to reach temperature equilibrium. The spectra were acquired by coaddition of 64 scans for the whole temperature range (approximate scanning time 45 seconds), with a nominal resolution of 4 cm\(^{-1}\). Good quality spectra can be obtained providing the sample thickness is not too large. If too large a sample is used then the spectra become difficult to interpret because of the presence of combination and overtone bands. Spectral manipulation such as baseline adjustment, smoothing and normalisation was performed using the GRAMS® software package (Galactic Industries Corporation, Salem, NH, USA).

**Results and discussion**

**Differential Scanning Calorimetry**

The number of differential scanning calorimetry studies of the goethite-haematite transition is scarce [12]. Figure 1 displays the differential scanning calorimetric curves of the synthesised goethite and aluminium-substituted goethite. The results of the DSC are reported in Table 1. Two endotherms are observed and are complex. The 30% Al-substituted goethite displays a third endotherm. Clearly these endotherms shift to higher temperature with increasing Al substitution. The first endotherm is observed at around 75°C and is associated with water loss as is shown from the mass spectrometric results of the evolved gases. Table 1 shows that there is a regular increase in the temperature of the endotherms and the % heat flow with increasing Al composition. This is illustrated in Figure 2. The amount of heat required for the first endotherm decreases with increase in % Al substitution and concurrently the quantity of heat required for the second endotherm increase with % Al substitution. The temperature of both the endotherms increases with % Al substitution.

The first endotherm is observed at 71°C for synthetic goethite and the temperature increase to 99°C for 20% Al substitution. Two endotherms are associated with the 30% Al-substituted goethites. These are observed at 76 and 140°C. Such phase changes due to dehydration at these temperatures have not been previously reported. For the second endotherm, for pure synthetic goethite, the temperature of the phase change is 224°C and increases to 245°C for 30% Al substituted goethite. The endotherms become broader with increasing Al substitution. This endotherm is attributed to the goethite-haematite phase transition, which occurs at dehydroxylation.

**Thermogravimetric and differential thermogravimetric analysis**

The thermogravimetric and differential thermogravimetric curves for goethite and Al-substituted goethites are shown in Figure 3. Included are the TG and DTG analyses of two naturally occurring goethite samples associated with the production of ancient aboriginal art. The results of the component analyses of the differential thermogravimetric curves are provided in Table 2. Included in table 2 for comparison are the weight changes as determined by mass spectrometry. A steady weight loss of adsorbed water is observed over the ambient to 150°C temperature range, as is indicated by the TG curve. The principal weight loss occurs over the 196 to 224°C temperature range, depending on the amount of Al substitution. A second weight loss is observed at slightly lower temperatures. A third weight loss is observed in the 263 to 282°C temperature range. The
theoretical weight loss for the conversion of goethite to haematite according to the equation:

\[ 2\text{FeO(OH)} \rightarrow \text{Fe}_2\text{O}_3 + \text{H}_2\text{O} \]

should be precisely 10.1%. The weight loss step for the 0% Al substituted goethite is 10.13% which agrees well with the theoretical value. As the Al substitutes for the Fe in the goethite according to the formula: \( \text{Fe}_{x}\text{Al}_{(1-x)}\text{O(OH)} \), the weight loss increases. For example for the 10% Al substituted goethite, the theoretical weight loss is 10.5%. The measured result according to the TG pattern measured between 150 and 245°C is 11.9%.

The variation of the temperature of the weight loss steps and the % heat flow as a function of the %Al substitution is illustrated in Figures 4a and b. The temperature of the weight loss steps increases regularly with the increase in %Al substitution. Such an effect is in harmony with the results of the changes in the temperature of the endotherms as observed through DSC measurements. The weight loss for weight loss steps 2 and 3 decreases with increasing Al substitution. The weight loss for step 1 increases with increasing Al substitution. Such an observation suggests that this step is associated with the Al in the goethite and that the two weight loss steps 2 and 3 are associated with the Fe in the goethite.

The mineral goethite was of extreme importance to the indigenous ancient peoples of Australia. Figures 4e and f display the TG/DTG curves for two goethites firstly from Fern Cave, near Chillagoe and secondly from a deposit used by the aboriginal peoples over a long period of time. The major weight loss step occurs around the 250°C temperature mark. Two steps in the DTG curves are observed at 231 and 270°C for the goethite found in the base of Fern Cave. For the Flinders ranges sample two DTG steps at 243 and 272°C are observed. The weight loss for both goethites is precisely 10.1%. One proposition is that goethite was used as a monetary mechanism and was exchanged for goods. Thus goethite from South Australia was in all likelihood transported across the country. Goethite has been found in locations where no goethite as been known to exist.

**Infrared emission spectroscopy**

In order to assess the molecular changes of the goethite structure as a function of temperature and with % aluminium substitution, the complimentary technique of infrared emission spectroscopy has been used. This technique allows for the infrared spectrum of the goethite in situ at the elevated temperatures to be obtained. Figures 5 and 6 display the infrared spectra at 25°C intervals starting at 100°C for the hydroxyl stretching and hydroxyl deformation regions respectively. A number of spectral features are present. Two major emission bands are present centred upon 3184 and 3429 cm\(^{-1}\). These two bands are assigned to the hydroxyl stretching bands of goethite. Bands of low intensity are observed 2908 cm\(^{-1}\) and are attributed to impurities of ammonium adsorbed upon the surface of the goethite and result from the synthesis of the goethite.

The IES spectra clearly show that the hydroxyl stretching bands are lost over the 175 to 275°C temperature range. For the 0% Al substituted goethite, the OH stretching band observed at 3184 cm\(^{-1}\) appears to be lost and the band at 3429 cm\(^{-1}\) shifts to higher wavenumbers with temperature increase. This band shows zero intensity at 325°C. The observation of the loss of hydroxyls in two steps is in harmony with the DTG curves,
where two steps in the DTG curves were observed. Figure 7 shows the hydroxyl
deformation modes and in harmony with the observation of two hydroxyl-stretching
modes, two hydroxyl deformation modes are observed. The intensity of these bands is lost
by 225°C.

Conclusions

There are a two phase changes observed using differential scanning calorimetry for
the synthetic and Al-substituted goethites. These occur at ~75°C and in the 224 to 245°C
temperature range. The temperature of these endotherms and the enthalpy of the phase
change is a linear function of the % Al substitution. The first endotherm occurs without
any weight change and is attributed to a structural rearrangement at the molecular level.
The temperatures of the weight loss steps and the % weight loss were also found to be
linear functions of the % Al substitution. DTGA shows the presence of three definable
weight loss steps (a) in the 175 to 207°C temperature range (b) in the 196 to 224°C
temperature range and (c) in the 263 to 282°C temperature range. These temperatures are
in excellent correspondence with the results of the mass spectrometry of the evolved water
vapour from the dehydroxylation of the goethite.

This work has shown that the thermal transformation of goethite occurs over a wide
temperature range. Such temperatures are readily achievable through camp fires of the
indigenous Australian aboriginals such as might occur in their caves. Whilst no proof
exists that the aboriginals painted their primitive drawings with goethite, such an event is
highly likely. It is probable that the goethite was then transformed to haematite through
very low heating.

Acknowledgments

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support, the Centre for Instrumental and Developmental Chemistry, Queensland University
of Technology for providing the infrastructure to this research.

References

    2575.


Table 1 Results of the Differential Scanning Calorimetry of Al substituted goethites
(a) 0% (b) 10% (c) 20% (d) 30%.

<table>
<thead>
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<th>20%</th>
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<td>°C/%</td>
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<td>298 -14%</td>
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6
Table 2 Results of the weight losses of the DTG and MS for Al substituted goethites

<table>
<thead>
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<td>MS</td>
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<td>20.0</td>
<td>7.3</td>
<td>10.8</td>
<td>4.3</td>
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Table 1 Results of the Differential Scanning Calorimetry of Al substituted goethites (a) 0% (b) 10% (c) 20% (d) 30%.

Table 2 Results of the weight losses of the DTG and MS for Al substituted goethites
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Figure 2 Variation of the temperature of the first endotherm and the % heat gain as a function of the Al substitution.

Figure 3a to d. Thermogravimetric and differential thermogravimetric curves for (a) 0% (b) 10% (c) 20% (d) 30%.

Figure 3e Thermogravimetric and differential thermogravimetric curves for a sample of goethite used in indigenous art.

Figure 3f Thermogravimetric and differential thermogravimetric curves for a sample of goethite used in indigenous art from the Flinders Ranges, South Australia.

Figure 4a Variation of the temperature of the differential weight loss as a function of % Al substitution. The numbers represent the weight loss step.

Figure 4b Variation of the % differential weight loss as a function of % Al substitution. The numbers represent the weight loss step.

Figure 5a Infrared emission spectra of the hydroxyl-stretching region of synthesised 0% Al substituted goethite.

Figure 5b Infrared emission spectra of the hydroxyl-stretching region of synthesised 10% Al substituted goethite.

Figure 5c Infrared emission spectra of the hydroxyl-stretching region of synthesised 20% Al substituted goethite.

Figure 5d Infrared emission spectra of the hydroxyl-stretching region of synthesised 30% Al substituted goethite.

Figure 6a Infrared emission spectra of the hydroxyl deformation region of synthetic goethite.

Figure 6b Infrared emission spectra of the hydroxyl deformation region of 10% Al substituted synthetic goethite.

Figure 6c Infrared emission spectra of the hydroxyl deformation region of 20% Al substituted synthetic goethite.

Figure 6d Infrared emission spectra of the hydroxyl deformation region of 30% Al substituted synthetic goethite.