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■ Scandium speciation in a world-class lateritic deposit

M. Chassé^{1,2*}, W.L. Griffin², S.Y. O'Reilly², G. Calas¹



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Abstract

Scandium (Sc) has unique properties, highly valued for many applications. Future supply is expected to rely on unusually high-grade (up to 1000 ppm) lateritic Sc ores discovered in Eastern Australia. To understand the origin of such exceptional concentrations, we investigated Sc speciation in one of these deposits. The major factors are unusually high concentrations in the parent rock together with lateritic weathering over long time scales in a stable tectonic context. At microscopic and atomic scales, by combining X-ray absorption near-edge structure spectroscopy, X-ray diffraction and microscopic and chemical analyses, we show that Sc-rich volumes are associated with iron oxides. In particular, Sc adsorbed on goethite accounts for *ca.* 80 % of the Sc budget in our samples. The remaining Sc is incorporated in the crystal structure of haematite, substituting for Fe³⁺. Scandium grades reflect the high capacity of goethite to adsorb this element. In contrast, the influence of haematite is limited by the low levels of Sc that its structure can incorporate. These crystal-chemical controls play a major role in lateritic Sc deposits developed over ultramafic–mafic rocks.

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Introduction

Scandium is embedded in the very fabric of modern society, making it one of the most valuable elements. End-uses range from biomedical research to electronics, lasers and ceramics but the demand is driven by energy issues (Emsley, 2014). Scandium finds applications in Al–Sc superalloys, increasing tensile strength and improving weldability while maintaining light weight, an energy-saving factor in

aerospace and automotive industries. In solid oxide fuel cells, the addition of Sc to the electrolyte improves conductivity and lowers the operating temperature, extending fuel cell life.

Despite a crustal abundance of *ca.* 22 ppm (Rudnick and Gao, 2014), comparable to common elements such as copper or lead, current Sc production is limited to 10 t to 15 t per year (U.S. Geological Survey, 2016). The large ratio of ionic radius to charge of Sc³⁺ hinders the concentration of scandium during most geochemical processes (Samson and Chassé, 2016). A notable exception concerns lateritic deposits developed over ultramafic–mafic rocks where Sc concentrations up to 100 ppm make it a potential by-product (Aiglsperger *et al.*, 2016; Maulana *et al.*, 2016). Recently, lateritic deposits with Sc concentrations high enough to mine as a primary product have been reported in Eastern Australia (Jaireth *et al.*, 2014). Among these, the Syerston–Flemington deposit contains about 1350 t of Sc at an average concentration of 434 ppm Sc (Pursell, 2016), providing a century-long resource at the present levels of world consumption.

We present the first data on Sc speciation in lateritic deposits by combining quantitative mineralogy, geochemical analysis and X-ray absorption near-edge structure (XANES) spectroscopy on drill-core samples from the lateritic profile of the Syerston–Flemington deposit. The results explain the geochemical conditions required to form such exceptional Sc concentrations and improve our understanding of the geochemical behaviour of this under-explored element.

Geological Context

In Eastern Australia, lateritic profiles developed under seasonally dry humid tropical climatic conditions that resulted in intensive weathering during the Tertiary; the present occurrences are often erosional remnants of fossil laterite (Milnes *et al.*, 1987). The Syerston–Flemington deposit (Fig. 1a and Table S-1) is part of the lateritic cover developed over the Tout complex, an ultramafic–mafic ‘Alaskan-type’ intrusive complex in the Lachlan Fold Belt (Johan *et al.*, 1989). Scandium anomalies have been found over a body of nearly pure clinopyroxenite (Fig. S-1), with Sc concentrations (*ca.* 80 ppm; Table S-3) twice as high as those in typical mantle clinopyroxenites (Samson and Chassé, 2016). Similar concentrations (60 ppm to 80 ppm) occur in other ‘Alaskan-type’ clinopyroxenites (Burg *et al.*, 2009) and in clinopyroxenes from ocean-island basalts (Dorais, 2015). This suggests the accumulation of clinopyroxene in subvolcanic feeder conduits during fractional crystallisation of a mantle-derived melt. Anomalies of Sc concentration in the parent rock result from specific conditions of formation and are not shared by all ultramafic–mafic bedrocks.

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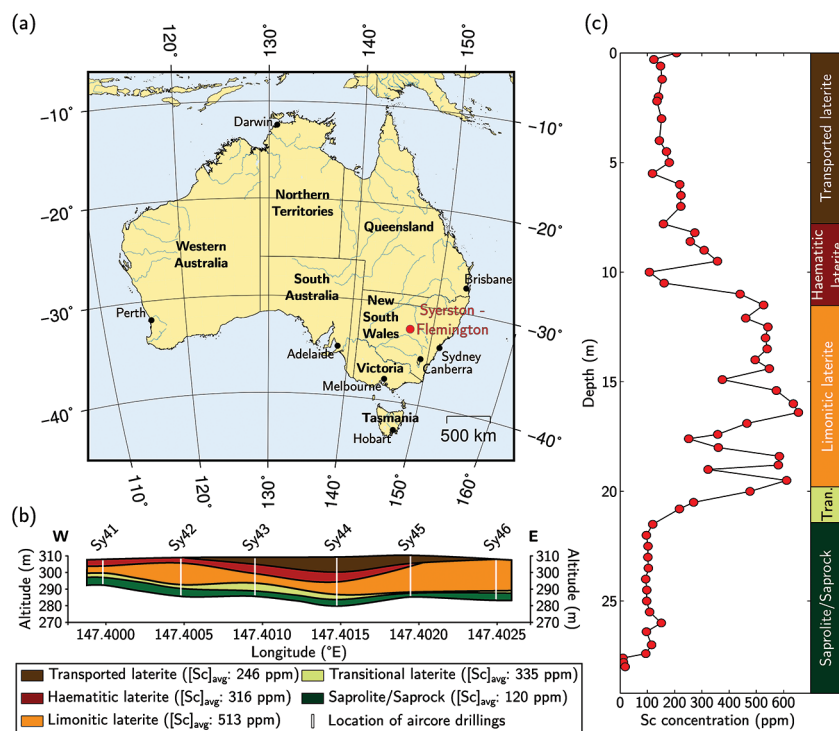


Figure 1 (a) Geographical location of the Syerston–Flemington deposit. (b) Schematic cross section of the lateritic cover forming the Syerston–Flemington deposit, constructed from petrographic analysis of drill-cores. Average Sc concentrations ($[Sc]_{avg}$) are calculated for each layer from ICP-MS analyses of samples collected every metre on each core. (c) Distribution of Sc with depth along the different levels of a typical profile (Tran.: transitional laterite).

Core Sampling and Analytical Methods

Each metre of 26 vertical aircore holes has been analysed for Sc and two diamond drill-cores of about 30 m length have been sampled to collect rock chips from the limonitic part of the lateritic cover. Quantitative mineralogical compositions were determined by X-ray diffraction (XRD) and Rietveld refinement. Major and trace elements were determined by X-ray fluorescence (XRF) analysis and inductively coupled plasma mass spectrometry (ICP-MS), respectively. Mapping of major elements was done using scanning electron microscopy–energy dispersive X-ray spectroscopy (SEM–EDXS) on polished sections of samples embedded in epoxy resin. The electron microprobe (EMP) gave point analyses for major and minor elements along with Sc. The distribution of Sc was mapped by synchrotron

micro-X-ray fluorescence (μ -XRF). Scandium speciation was determined by synchrotron-based micro-X-ray absorption near-edge structure (μ -XANES) spectroscopy at Sc and Fe K-edges. Detailed descriptions are given in the Supplementary Information.

Characteristics of the Lateritic Deposit

The lateritic profile shows five levels (Fig. 1b; see also Supplementary Information, Section 2 and Table S-2); from bottom to top: saprolite, with smectite from the weathering of clinopyroxene, which is still visible in the deepest parts; transitional laterite where smectite is progressively replaced by Fe oxides and kaolinite; limonitic laterite dominated by goethite with haematite, kaolinite and gibbsite; haematitic laterite dominated by haematite with goethite, kaolinite and gibbsite; and transported laterite of similar composition but containing clasts and evidence of former alluvial channels. Similar lateritic profiles are developed over other ultramafic–mafic rocks in Australia (Anand and Paine, 2002), with most of the weathering profile directly inherited from the parent rock except for the transported level. The depth of the profile indicates that the weathering occurred over long time scales, possibly starting as early as 430 million years ago (Fergusson, 2010), in a stable tectonic context. Bulk assays show that Sc concentration increases upward, from *ca.* 100 ppm in the transitional laterite to *ca.* 500 ppm in the limonitic laterite (Fig. 1b,c and Table S-3). The concentration then decreases in the haematitic laterite and drops to *ca.* 250 ppm in the transported laterite.

Identification of Iron Oxides as Main Scandium Hosts

The mineralogy is typical of lateritic profiles developed over ultramafic rocks (Freyssinet *et al.* (2005); Fig. 2a,b and Table S-4). The ore is dominated by haematite and Al-bearing goethite, associated with kaolinite and gibbsite. Minor phases include anatase, quartz and an Fe oxide with an inverse spinel structure, either maghemite or magnetite. The broad X-ray diffraction lines (Fig. 2a) reflect the poor crystallinity or small particle size (<100 nm) of the Fe oxides. The bulk Sc content is correlated with the proportion of Al-bearing goethite, indicating its potential role as a Sc host in the ore (Fig. 2c).

Systematic SEM–EDXS mapping confirms the absence of discrete Sc phases, as expected from the scarcity of such phases in nature (Samson and Chassé, 2016). The EMP analyses of Si, Ti, Al, Fe and Sc have been averaged on each grain type, as identified by combining SEM images, major elements and Sc contents and applying statistical clustering (Supplementary Information, Section 6 and Table S-6). Scandium contents are low to extremely low in Al-rich grains (*ca.* 300 ppm), Ti-rich oxides (*ca.* 100 ppm) and quartz (below detection limit, *ca.* 30 ppm). The highest Sc contents (*ca.* 1300 ppm) are encountered in Fe



oxide grains that contain Al (*ca.* 7 wt. %) and have low EMP analytical totals (*ca.* 85 wt. %). These grains appear to correspond to the Al-bearing goethite identified by XRD. Another type of Fe oxide grains, with a lower concentration of Sc (*ca.* 200 ppm) and high Fe could correspond to the haematite phase identified using XRD.

Much of each sample consists of a fine-grained matrix with three distinct compositions. Two correspond to mixtures of Fe oxides with different Sc contents, *ca.* 650 ppm for one and *ca.* 400 ppm for the other. The former contains slightly less Fe but more Al and has a lower analytical sum than the latter, reflecting a

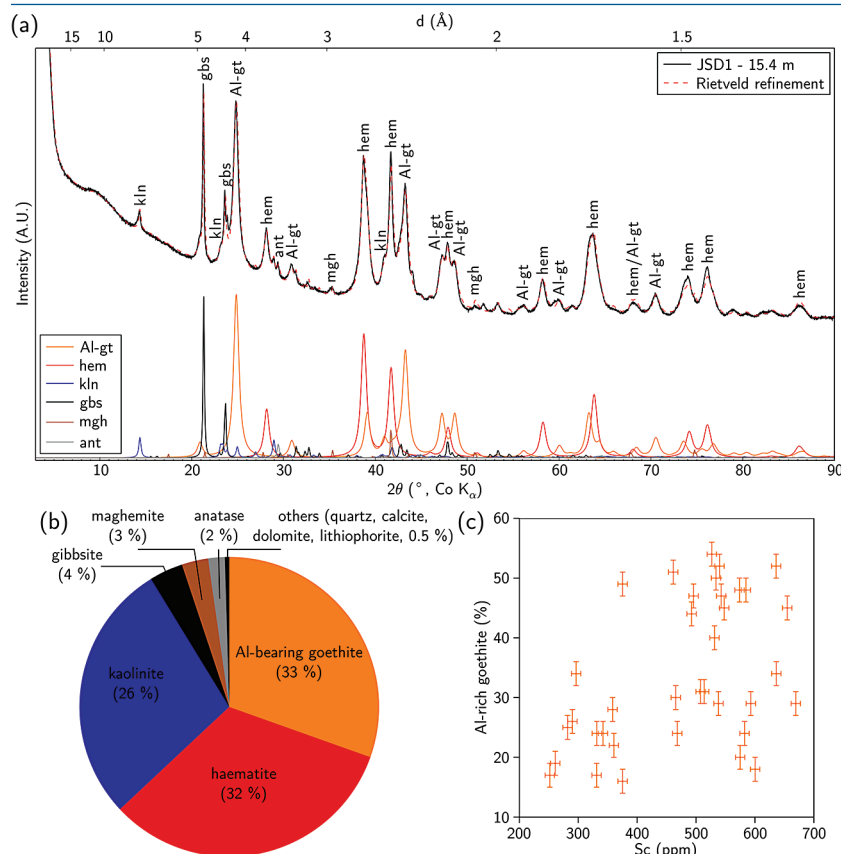


Figure 2 (a) X-ray diffraction pattern of ore sample JSD-1 – 15.4 m and associated multiphase Rietveld refinement (Al-gt: Al-bearing goethite, hem: haematite, kln: kaolinite, gbs: gibbsite, mgh: maghemite, ant: anatase). (b) Average phase proportions in the samples calculated from Rietveld refinement. (c) Bulk Sc concentration versus proportion of Al-bearing goethite estimated from Rietveld refinement.

higher goethite component. A third type of matrix is slightly enriched in both Al and Si, which is consistent with the presence of minor kaolinite mixed with Fe oxides. The Sc content of this matrix is *ca.* 400 ppm, which suggests that kaolinite is only a minor Sc host.

To distinguish between goethite and haematite, we also used Fe K-edge XANES spectra. Using the relative normalised intensity of the absorption maxima of goethite and haematite, at 7133.8 eV and 7136.9 eV, respectively (Combes *et al.*, 1989), we obtained Fe-speciation maps (Fig. 3a). Comparison with μ -XRF maps of Sc (Fig. 3b) indicate that Sc-poor and Sc-rich grains mostly contain haematite and goethite, respectively. Iron K-edge XANES spectra in the complete range of energy confirm these observation (Fig. 4a), showing a good match between spectra of goethite and Sc-rich zones and between spectra of haematite and Sc-poor zones.

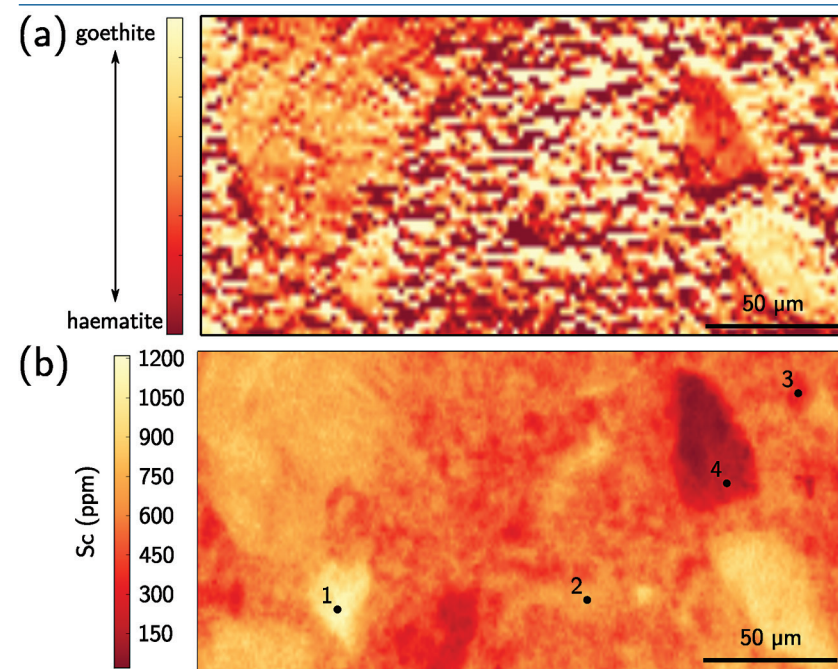


Figure 3 (a) Map of Fe speciation obtained by subtracting normalised synchrotron μ -XRF maps at 7133.9 eV, the energy characteristic of goethite and 7136.7 eV, the energy characteristic of haematite. (b) Synchrotron μ -XRF mapping of Sc.



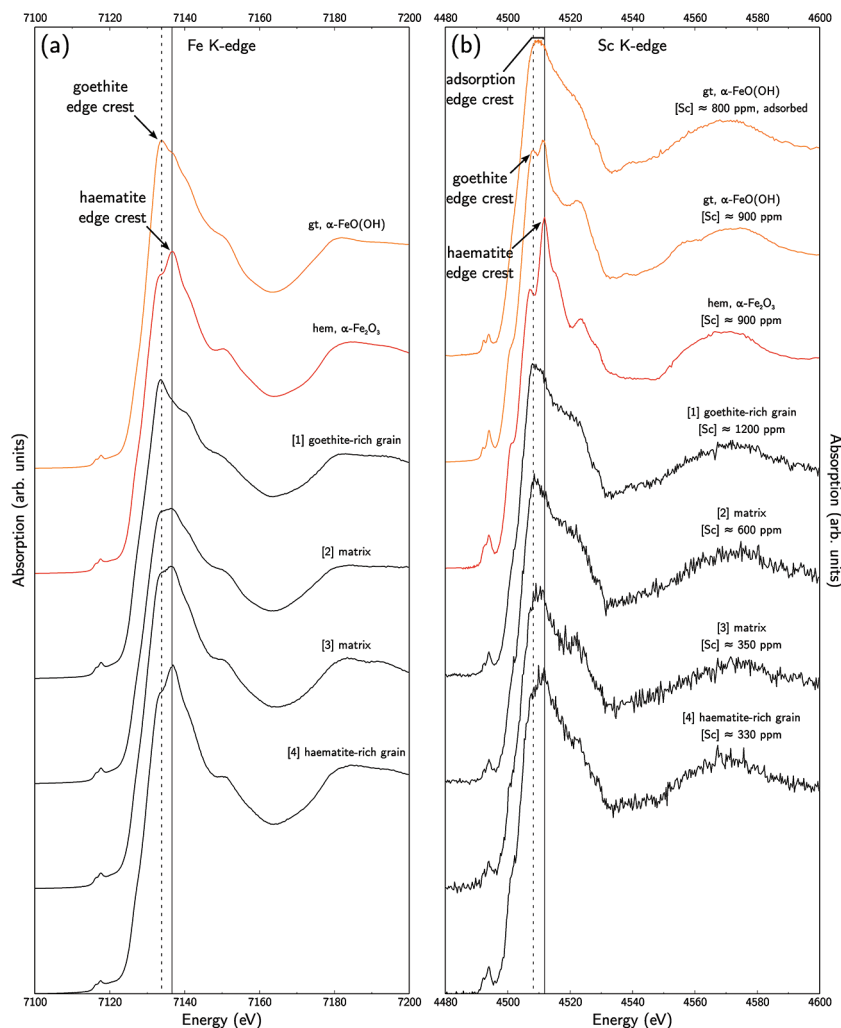


Figure 4 XANES spectra at the (a) Fe K-edge. (b) Sc K-edge (gt: goethite and hem: haematite). The numbers in brackets refer to the position given in Figure 3.

Using the EMP-derived Sc concentration in goethite, around 1300 ppm, and the proportion of goethite obtained from Rietveld refinement, about 30 %, we calculate that goethite hosts about 400 ppm Sc out of the average *ca.* 500 ppm of Sc in the samples, *i.e.* *ca.* 80 % of total Sc. Average EMP-derived concentrations

in haematite are about 200 ppm Sc. As haematite accounts for about 30 % of the mineral phases, Sc in haematite may represent *ca.* 50 ppm, corresponding to most of the remaining 20 % of total Sc.

Scandium Speciation in the Ore

Scandium K-edge XANES spectra of synthetic reference materials show that Sc incorporation in goethite or in haematite can be distinguished using the position of the edge crest at 4508.2 eV and 4511.8 eV, respectively (Fig. 4b), while Sc adsorbed on goethite is identified by a broad, featureless edge crest extending from 4508 eV to 4511.5 eV. On the low energy side, a pre-edge feature bears additional information (*e.g.*, Galois *et al.*, 2001). There is a noteworthy enhancement of the intensity of this feature in the substituted samples due to the distortion of the Sc site. The Sc K-edge XANES spectra on lateritic goethite grains show a broad edge crest and a low-intensity pre-edge feature, consistent with Sc adsorbed on goethite. In contrast, lateritic haematite grains show an edge crest at 4512 eV and a more intense pre-edge feature, corresponding to Sc incorporated in haematite. The same distinction holds when investigating the matrix: the high Sc concentrations are associated with Sc-adsorbed goethite. However, lateritic samples give less resolved spectra than the crystalline references. Comparison is limited because Sc K-edge XANES spectra are scarce in the literature, but this may reflect a poor crystallinity in fine-grained natural phases, or some minor contribution of other Sc species.

A Mechanism for Scandium Enrichment

Due to the high concentration of Sc in clinopyroxenes, weathering leads to Sc-rich waters circulating in the regolith below the water table. Seasonal precipitation of goethite allows the adsorption of Sc³⁺. During dry periods, haematite develops from goethite, and may incorporate part of the adsorbed Sc in its crystal structure. However, this process is limited by the size difference between six-fold coordinated Sc³⁺ and Fe³⁺ but such size differences will not influence the adsorption capacity of goethite under near-neutral pH conditions.

Scandium is often associated with the rare earth elements (REE). The ionic radius of Sc³⁺ is slightly smaller than those of heavy REE for the same coordination number. During lateritic weathering of ultramafic-mafic rocks, Sc behaves like the heavy REE. The enrichment factor of Sc between the ore and fresh saprolite is *ca.* 5 (Table S-5, Fig. S-2). For the REE, it increases continuously with decreasing ionic radii, from *ca.* 2 for the light REE to *ca.* 3.5 for the heavy REE. The low prospectivity of the lateritic deposits for REE reflects the low REE content in the parent rock compared to average crustal concentrations (two to ten times lower, Rudnick and Gao, 2014).



Lateritic profiles over ultramafic–mafic rocks usually show Sc concentrations lower than 100 ppm, corresponding to enrichment by a factor of ten during lateritic weathering (Aiglsperger *et al.*, 2016; Maulana *et al.*, 2016). This is similar to the maximum factor of enrichment found in the Syerston–Flemington deposit where the limonitic laterite reaches 800 ppm Sc compared to *ca.* 80 ppm in the parent rock. This observation rules out any need for peculiar lateritic conditions in Eastern Australia, and the proposed genetic model for Sc concentration during lateritic weathering may thus be extrapolated to other lateritic deposits developed over ultramafic–mafic rocks. Nonetheless, the duration of the weathering process and tectonic stability are key factors leading to the development of such volumes of ore.

Exceptional concentration of Sc in lateritic deposits thus results from a combination of three circumstances: (1) anomalously high Sc concentration in the parent rock, (2) long time scales of alteration in stable tectonic environment and (3) lateritic conditions during weathering, allowing the trapping of Sc by Fe oxides.

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Additional Information

Supplementary Information accompanies this letter at www.geochemicalperspectivesletters.org/article1711

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References

- AIGLSPERGER, T., PROENZA, J.A., LEWIS, J.F., LABRADOR, M., SVOJTKA, M., ROJAS-PURÓN, A., LONGO, F., ĐURIŠOVÁ, J. (2016) Critical Metals (REE, Sc, PGE) in Ni Laterites from Cuba and the Dominican Republic. *Ore Geology Reviews* 73, 127–147.
- ANAND, R.R., PAINE, M. (2002) Regolith Geology of the Yilgarn Craton, Western Australia: Implications for Exploration. *Australian Journal of Earth Sciences* 49, 3–162.
- BURG, J.-P., BODINIER, J.-L., GERYA, T., BEDINI, R.-M., BOUDIER, F., DAUTRIA, J.-M., PRIKHODKO, V., EFIMOV, A., PUPIER, E., BALANEC, J.-L. (2009) Translithospheric Mantle Diapirism: Geological Evidence and Numerical Modelling of the Kondyor Zoned Ultramafic Complex (Russian Far-East). *Journal of Petrology* 50, 289–321.
- COMBES, J.-M., MANCEAU, A., CALAS, G., BOTTERO, J.-Y. (1989) Formation of Ferric Oxides from Aqueous Solutions: A Polyhedral Approach by X-ray Absorption Spectroscopy: I. Hydrolysis and Formation of Ferric Gels. *Geochimica et Cosmochimica Acta* 53, 583–594.
- DORAIS, M.J. (2015) Exploring the Mineralogical Heterogeneities of the Louisville Seamount Trail. *Geochemistry, Geophysics, Geosystems* 16, 2884–2899.
- EMSLEY, J. (2014) Unsporting Scandium. *Nature Chemistry* 6, 1025.
- FERGUSON, C.L. (2010) Plate-Driven Extension and Convergence along the East Gondwana Active Margin: Late Silurian–Middle Devonian Tectonics of the Lachlan Fold Belt, Southeastern Australia. *Australian Journal of Earth Sciences* 57, 627–649.
- FREYSSINET, P., BUTT, C.R.M., MORRIS, R.C., PIANTONE, P. (2005) Ore-Forming Processes Related to Lateritic Weathering. *Economic Geology* 100th Anniversary Volume, 681–722.
- GALOISY, L., CALAS, G., ARRIO, M.-A. (2001) High-Resolution XANES Spectra of Iron in Minerals and Glasses: Structural Information from the Pre-Edge Region. *Chemical Geology* 174, 307–319.
- JAIRETH, S., HOATSON, D.M., MIEZITIS, Y. (2014) Geological Setting and Resources of the Major Rare-Earth-Element Deposits in Australia. *Ore Geology Reviews* 62, 72–128.
- JOHAN, Z., OHNENSTETTER, M., SLANSKY, E., BARRON, L.M., SUPPEL, D.W. (1989) Platinum Mineralization in the Alaskan-type Intrusive Complexes near Fifield, New South Wales, Australia Part 1. Platinum-Group Minerals in Clinopyroxenites of the Kelvin Grove Prospect, Owendale Intrusion. *Mineralogy and Petrology* 40, 289–309.
- MAULANA, A., SANEMATSU, K., SAKAKIBARA, M. (2016) An Overview on the Possibility of Scandium and REE Occurrence in Sulawesi, Indonesia. *Indonesian Journal on Geoscience* 3, 139–147.
- MILNES, A.R., BOURMAN, R.P., FITZPATRICK, R.W. (1987) Petrology and Mineralogy of ‘Laterites’ in Southern and Eastern Australia and Southern Africa. *Chemical Geology* 60, 237–250.
- PURSELL, D.C. (2016) *Quarterly Report*. Jervois Mining Ltd, Cheltenham, Australia.
- RUDNICK, R.L., GAO, S. (2014) Composition of the Continental Crust. In: Holland, H., Turekian, K.K. (Eds.) *Treatise on Geochemistry*, 2nd Edition. Elsevier Ltd, Amsterdam, Netherlands, 1–51.
- SAMSON, I.M., CHASSÉ, M. (2016) Scandium. In: White, W.M. (Ed.) *Encyclopedia of Geochemistry*. Springer International Publishing, Cham, Switzerland, 1–5.
- U.S. GEOLOGICAL SURVEY (2016) Scandium. In: *Mineral Commodity Summaries*. U.S. Geological Survey, Reston, USA, 146–147.



■ Scandium speciation in a world-class lateritic deposit

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Supplementary Information

This supplementary information includes:

- 1. Location of the Diamond Core Drillings and Geology of the Area
- 2. Typical Core Logging of a Core Drilling
- 3. Procedures and Results of the Chemical Analyses on Aircore Drillings
- 4. Mineralogical Analyses Procedures
- 5. Chemical Analyses Procedures and Data
- 6. Procedures for Spatially Resolved Chemical Analyses
- 7. Procedures for the Synthesis of Reference Materials
- 8. Characterisation of the Synthetic Compounds
- 9. Synchrotron Measurement Procedures
- Tables S-1 to S-6
- Figures S-1 to S-3
- Supplementary Information References

1. Location of the Diamond Core Drillings and Geology of the Area

Table S-1 Latitude and longitude coordinates, altitude and dip angle of the two diamond core drillings.

Drill hole	Latitude	Longitude	Altitude	Dip
JSD-001	−32°44′42.91901″	147°24′7.42757″	309.211 m	−90°
JSD-002	−32°44′43.326 11″	147°24′3.72856″	309.067 m	−90°

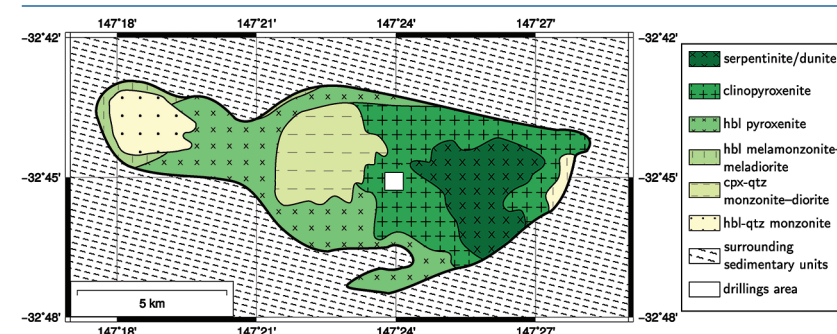


Figure S-1 Geological map of the Tout complex showing the locations of the drilling sites (cpx: clinopyroxene, hbl: hornblende, qtz: quartz).

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2. Typical Core Logging of a Core Drilling

Table S-2 Detailed log of the JSD-001 drill core.

Horizon	Depth	Colour	Fabric and/or texture
Transported laterite	0 m – 0.3 m	Red-brown	Brecciated; coarsely grained (>5 mm); mixture of soil (≈ 25 %) and residual lateritic material (≈ 25 %), supporting Fe pisoliths (≈ 50 %); cavernous and interstitial porosity.
Transported laterite	0.3 m – 2.5 m	Red mottled with orange spots	Massive with a breccia-like texture; fine to coarse grains (<0.002 mm – 5 mm); matrix of lateritic material, probably a mixture of Fe oxides and oxyhydroxides with kaolinites (>80 %), associated with few Fe pisoliths (≈ 10 %), lateritic clasts (≈ 10 %) and fine sandy grains, possibly quartz, accessory orange areas (<5 %) without pisoliths or clasts and probably richer in Fe oxyhydroxides; interstitial porosity.
Transported laterite	2.5 m – 5.2 m	Dark red	Massive; fine grains when visible (<1 mm); dominated by a matrix of fine grains with clayey content (>95 %), probably a mixture of Fe oxides and oxyhydroxides with kaolinite, rare sandy grains (<2 mm), possibly quartz; interstitial porosity.
Transported laterite	5.2 m – 8 m	Dark red to dark orange-red	Massive with breccia-like texture; fine grains when visible (<1 mm) with coarse clasts (>3 mm); dominated by a fine grained matrix with minor clay content (≈ 75 %), probably a mixture of Fe oxides and oxyhydroxides with kaolinite, common angular clasts of lateritic material (≈ 20 %); interstitial porosity.
Haematitic laterite	8 m – 10.2 m	Dark red to dark orange-red	Massive to cemented granular material; fine to coarse grains (<0.002 mm – 5 mm); dominated by a clayey matrix with fine grains (>70 %), probably a mixture of Fe oxides and oxyhydroxides with kaolinite, common to minor Fe pisoliths (5 % – 25 %); interstitial porosity.
Haematitic laterite	10.2 m – 11.2 m	Dark brown to red	Massive; fine grains when visible (<1 mm); dominant matrix of fine grains and clays (>90 %), probably a mixture of Fe oxides and oxyhydroxides with kaolinite, a homogeneous dark-brown vein at the bottom of the level, possibly rich in Al oxyhydroxides; interstitial and cavernous porosity.
Limonitic laterite	11.2 m – 14.2 m	Dark to medium orange-red	Massive to cemented granular material; fine to coarse grains (<0.002 mm – >5 mm); dominant to minor Fe pisoliths (5 % – 70 %) in a common to dominant matrix of fine grains and clays (30 % – 90 %), probably a mixture of Fe oxides and oxyhydroxides with kaolinite, rare to common orange areas, richer in Fe oxyhydroxides; interstitial and cavernous porosity.
Limonitic laterite	14.2 m – 16.7 m	Medium to light orange-red mottled with rare orange spots	Massive to cemented granular material; similar to the above level, with rarer orange areas (<10 %).
Limonitic laterite	16.7 m – 18.2 m	Red-pink mottled with orange spots	Massive to cemented granular material; fine grains when visible (<1 mm); dominated by a matrix of fine pinkish grains associated with clayey material (>90 %), probably Fe oxides and oxyhydroxides associated with kaolinites, with minor orange areas (≈ 10 %), probably rich in Fe oxyhydroxides; interstitial to cavernous porosity.
Limonitic laterite	18.2 m – 18.7 m	Tan-brown to khaki-brown	Massive; fine grains when visible (<1 mm); dominated by a matrix of fine grains and clayey material (>80 %), probably Fe oxides and oxyhydroxides associated with kaolinite, accessory white crystals (≈ 1 %); interstitial porosity.



Table S-2 cont.

Horizon	Depth	Colour		Fabric and/or texture
Transitional laterite	18.7 m – 20.5 m	Variable, mottled with green, orange, red, purple, brown and black spots		Granular; medium to fine grains (<0.002 mm – 3 mm); dominated by a red-brown finely grained matrix (50 % – 80 %), probably a mixture of Fe oxides and oxyhydroxides, common green clayey areas becoming accessory in the upper parts ($\approx$ 20 % – <1 %), two types of veins, filled-in by a black fine-grained matrix, possibly Mn oxides or by a white homogeneous matrix, possibly calcite; important interstitial porosity with fractures.
Transitional laterite	20.5 m – 21.5 m	Green-grey mottled with orange and black spots		Clay texture; dominant clay matrix ($\approx$ 70 %), possibly smectite, minor fine grained orange areas (<10 %) possibly clays coated with Fe oxides and oxyhydroxides, accessory crystalline black areas (<5 %), remnants of primary pyroxenes; probably important porosity but pores are not visible.
Saprolite	21.5 m – 27.6 m	Green to light green-grey mottled with orange and black spots		Crystalline to granular; medium to fine grains (<0.002 mm – 3 mm); dominated by green clay minerals (>70 %), possibly smectite, with accessory remnants of black crystals (<5 %) identified as pyroxenes and minor rust-coloured areas (<10 %) formed by weathered crystals covered by Fe oxides; limited interstitial porosity increasing in the upper levels.
Saprolite	27.6 m – 29.2 m	Dark brown-grey with light green to green brown fractures		Mesh texture with filled-in fractures; rare sandy grains (<5 %) in a dominant serpentinized groundmass (C90 %), fractures filled with clay fibres, probably serpentines; low porosity except in fractures.

3. Procedures and Results of the Chemical Analyses on Aircore Drillings

Twenty-six vertical aircore drillings have been carried out in the EL 7805 mining tenement, in the Syerston–Flemington area. Every metre, a sample has been analysed for Sc by ALS in Brisbane using a fusion inductively coupled plasma-atomic emission spectroscopy (ICP-AES) method (Table S-3).

Table S-3 Sc concentration (in ppm) at each metre of the 26 vertical aircore drillings performed in the Syerston–Flemington area.

Drill hole-depth (m)	Sc (ppm)	Drill hole-depth (m)	Sc (ppm)	Drill hole-depth (m)	Sc (ppm)	Drill hole-depth (m)	Sc (ppm)		Drill hole-depth (m)	Sc (ppm)	Drill hole-depth (m)	Sc (ppm)	Drill hole-depth (m)	Sc (ppm)
SY34-0-1	344	SY35-0-1	362	SY36-0-1	114	SY37-0-1	205		SY38-0-1	432	SY39-0-1	140	SY40-0-1	189
SY34-1-2	464	SY35-1-2	330	SY36-1-2	136	SY37-1-2	186		SY38-1-2	394	SY39-1-2	90	SY40-1-2	82
SY34-2-3	484	SY35-2-3	368	SY36-2-3	137	SY37-2-3	161		SY38-2-3	443	SY39-2-3	95	SY40-2-3	78
SY34-3-4	460	SY35-3-4	418	SY36-3-4	123	SY37-3-4	158		SY38-3-4	451			SY40-3-4	81
SY34-4-5	562	SY35-4-5	482	SY36-4-5	120	SY37-4-5	161		SY38-4-5	455			SY40-4-5	79
SY34-5-6	532	SY35-5-6	519	SY36-5-6	176	SY37-5-6	188		SY38-5-6	461			SY40-5-6	92
SY34-6-7	706	SY35-6-7	544	SY36-6-7	211	SY37-6-7	203		SY38-6-7	457				
SY34-7-8	800	SY35-7-8	550	SY36-7-8	243	SY37-7-8	224		SY38-7-8	467				
SY34-8-9	724	SY35-8-9	606	SY36-8-9	320	SY37-8-9	265		SY38-8-9	479				



Table S-3 cont.

Drill hole-depth (m)	Sc (ppm)	Drill hole-depth (m)	Sc (ppm)	Drill hole-depth (m)	Sc (ppm)	Drill hole-depth (m)	Sc (ppm)		Drill hole-depth (m)	Sc (ppm)	Drill hole-depth (m)	Sc (ppm)	Drill hole-depth (m)	Sc (ppm)
SY34-9-10	874	SY35-9-10	646	SY36-9-10	361	SY37-9-10	318		SY38-9-10	507				
SY34-10-11	796	SY35-10-11	642	SY36-10-11	324	SY37-10-11	331		SY38-10-11	519				
SY34-11-12	565	SY35-11-12	583	SY36-11-12	300	SY37-11-12	409		SY38-11-12	578				
SY34-12-13	502	SY35-12-13	610	SY36-12-13	349	SY37-12-13	506		SY38-12-13	547				
SY34-13-14	505	SY35-13-14	576	SY36-13-14	353	SY37-13-14	438		SY38-13-14	438				
SY34-14-15	410	SY35-14-15	665	SY36-14-15	362	SY37-14-15	446		SY38-14-15	392				
SY34-15-16	322	SY35-15-16	764	SY36-15-16	255	SY37-15-16	507		SY38-15-16	439				
SY34-16-17	226	SY35-16-17	945	SY36-16-17	160	SY37-16-17	606		SY38-16-17	445				
SY34-17-18	200	SY35-17-18	770	SY36-17-18	181	SY37-17-18	514		SY38-17-18	455				
SY34-18-19	266	SY35-18-19	690	SY36-18-19	283	SY37-18-19	808		SY38-18-19	385				
SY34-19-20	174	SY35-19-20	535	SY36-19-20	354	SY37-19-20	661		SY38-19-20	267				
SY34-20-21	128	SY35-20-21	446	SY36-20-21	298	SY37-20-21	449		SY38-20-21	268				
		SY35-21-22	374	SY36-21-22	274	SY37-21-22	281		SY38-21-22	222				
		SY35-22-23	343	SY36-22-23	268	SY37-22-23	440		SY38-22-23	140				
		SY35-23-24	329	SY36-23-24	128	SY37-23-24	155		SY38-23-24	117				
		SY35-24-25	331	SY36-24-25	106	SY37-24-25	133							
		SY35-25-26	338	SY36-25-26	97	SY37-25-26	114							
		SY35-26-27	304	SY36-0-26	232	SY37-26-27	109							
		SY35-27-28	159											
		SY35-28-29	126											
		SY35-29-30	126											
SY41-0-1	200	SY42-0-1	373	SY43-0-1	128	SY44-0-1	107		SY45-0-1	147	SY46-0-1	358	SY47-0-1	158
SY41-1-2	306	SY42-1-2	460	SY43-1-2	178	SY44-1-2	129		SY45-1-2	157	SY46-1-2	514	SY47-1-2	381
SY41-2-3	496	SY42-2-3	477	SY43-2-3	179	SY44-2-3	134		SY45-2-3	165	SY46-2-3	512	SY47-2-3	424
SY41-3-4	590	SY42-3-4	569	SY43-3-4	183	SY44-3-4	147		SY45-3-4	182	SY46-3-4	612	SY47-3-4	475
SY41-4-5	747	SY42-4-5	795	SY43-4-5	225	SY44-4-5	117		SY45-4-5	191	SY46-4-5	546	SY47-4-5	451
SY41-5-6	598	SY42-5-6	655	SY43-5-6	213	SY44-5-6	107		SY45-5-6	235	SY46-5-6	603	SY47-5-6	505
SY41-6-7	591	SY42-6-7	588	SY43-6-7	195	SY44-6-7	110		SY45-6-7	500	SY46-6-7	594	SY47-6-7	567
SY41-7-8	566	SY42-7-8	595	SY43-7-8	229	SY44-7-8	120		SY45-7-8	511	SY46-7-8	540	SY47-7-8	588



Table S-3 cont.

Drill hole-depth (m)	Sc (ppm)	Drill hole-depth (m)	Sc (ppm)	Drill hole-depth (m)	Sc (ppm)	Drill hole-depth (m)	Sc (ppm)		Drill hole-depth (m)	Sc (ppm)	Drill hole-depth (m)	Sc (ppm)	Drill hole-depth (m)	Sc (ppm)
SY41-8-9	525	SY42-8-9	540	SY43-8-9	323	SY44-8-9	152		SY45-8-9	564	SY46-8-9	577	SY47-8-9	492
SY41-9-10	476	SY42-9-10	618	SY43-9-10	396	SY44-9-10	201		SY45-9-10	545	SY46-9-10	600	SY47-9-10	641
SY41-10-11	469	SY42-10-11	574	SY43-10-11	506	SY44-10-11	239		SY45-10-11	475	SY46-10-11	590	SY47-10-11	865
SY41-11-12	361	SY42-11-12	505	SY43-11-12	618	SY44-11-12	282		SY45-11-12	525	SY46-11-12	607	SY47-11-12	689
SY41-12-13	300	SY42-12-13	617	SY43-12-13	647	SY44-12-13	253		SY45-12-13	401	SY46-12-13	504	SY47-12-13	810
SY41-13-14	275	SY42-13-14	756	SY43-13-14	667	SY44-13-14	226		SY45-13-14	453	SY46-13-14	397	SY47-13-14	847
SY41-14-15	208	SY42-14-15	606	SY43-14-15	695	SY44-14-15	249		SY45-14-15	514	SY46-14-15	485	SY47-14-15	874
SY41-15-16	132	SY42-15-16	577	SY43-15-16	553	SY44-15-16	312		SY45-15-16	482	SY46-15-16	433	SY47-15-16	622
		SY42-16-17	556	SY43-16-17	484	SY44-16-17	359		SY45-16-17	516	SY46-16-17	469	SY47-16-17	268
		SY42-17-18	549	SY43-17-18	463	SY44-17-18	407		SY45-17-18	596	SY46-17-18	304	SY47-17-18	184
		SY42-18-19	343	SY43-18-19	349	SY44-18-19	380		SY45-18-19	625	SY46-18-19	152		
		SY42-19-20	230	SY43-19-20	248	SY44-19-20	335		SY45-19-20	595	SY46-19-20	204		
		SY42-20-21	133	SY43-20-21	268	SY44-20-21	532		SY45-20-21	835	SY46-20-21	212		
		SY42-21-22	119	SY43-21-22	160	SY44-21-22	630		SY45-21-22	980	SY46-21-22	163		
		SY42-22-23	121	SY43-22-23	240	SY44-22-23	492		SY45-22-23	687	SY46-22-23	121		
		SY42-23-24	105	SY43-23-24	212	SY44-23-24	322		SY45-23-24	404	SY46-23-24	101		
						SY44-24-25	285		SY45-24-25	243	SY46-24-25	83		
						SY44-25-26	257		SY45-25-26	280	SY46-25-26	81		
						SY44-26-27	238							
						SY44-27-28	225							
						SY44-28-29	261							
						SY44-29-30	242							
SY48-0-1	203	SY49-0-1	150	SY50-0-1	111	SY51-0-1	358		SY52-0-1	156	SY53-0-1	206	SY54-0-1	206
SY48-1-2	216	SY49-1-2	120	SY50-1-2	108	SY51-1-2	388		SY52-1-2	118	SY53-1-2	299	SY54-1-2	136
SY48-2-3	229	SY49-2-3	102	SY50-2-3	106	SY51-2-3	401		SY52-2-3	96	SY53-2-3	341	SY54-2-3	136
SY48-3-4	211	SY49-3-4	106	SY50-3-4	114	SY51-3-4	NSS		SY52-3-4	98	SY53-3-4	393	SY54-3-4	140
SY48-4-5	217	SY49-4-5	122	SY50-4-5	153	SY51-4-5	513		SY52-4-5	116	SY53-4-5	457	SY54-4-5	200
SY48-5-6	222	SY49-5-6	113	SY50-5-6	199	SY51-5-6	500		SY52-5-6	103	SY53-5-6	457	SY54-5-6	192



Table S-3 cont.

Drill hole-depth (m)	Sc (ppm)	Drill hole-depth (m)	Sc (ppm)	Drill hole-depth (m)	Sc (ppm)	Drill hole-depth (m)	Sc (ppm)		Drill hole-depth (m)	Sc (ppm)	Drill hole-depth (m)	Sc (ppm)	Drill hole-depth (m)	Sc (ppm)
SY48-6-7	264	SY49-6-7	116	SY50-6-7	245	SY51-6-7	425		SY52-6-7	108	SY53-6-7	479	SY54-6-7	212
SY48-7-8	335	SY49-7-8	118	SY50-7-8	274	SY51-7-8	327		SY52-7-8	121	SY53-7-8	400	SY54-7-8	247
SY48-8-9	416	SY49-8-9	133	SY50-8-9	277	SY51-8-9	347		SY52-8-9	115	SY53-8-9	510	SY54-8-9	251
SY48-9-10	427	SY49-9-10	156	SY50-9-10	212	SY51-9-10	386		SY52-9-10	142	SY53-9-10	574	SY54-9-10	308
SY48-10-11	486	SY49-10-11	155	SY50-10-11	278	SY51-10-11	522		SY52-10-11	166	SY53-10-11	466	SY54-10-11	416
SY48-11-12	480	SY49-11-12	144	SY50-11-12	282	SY51-11-12	371		SY52-11-12	213	SY53-11-12	597	SY54-11-12	433
SY48-12-13	427	SY49-12-13	163	SY50-12-13	349	SY51-12-13	456		SY52-12-13	265	SY53-12-13	656	SY54-12-13	275
SY48-13-14	500	SY49-13-14	187	SY50-13-14	341	SY51-13-14	365		SY52-13-14	393	SY53-13-14	671	SY54-13-14	264
SY48-14-15	552	SY49-14-15	236	SY50-14-15	472	SY51-14-15	384		SY52-14-15	431	SY53-14-15	968	SY54-14-15	225
SY48-15-16	612	SY49-15-16	351	SY50-15-16	502	SY51-15-16	470		SY52-15-16	499	SY53-15-16	531	SY54-15-16	369
SY48-16-17	672	SY49-16-17	400	SY50-16-17	600	SY51-16-17	475		SY52-16-17	561	SY53-16-17	348	SY54-16-17	400
SY48-17-18	659	SY49-17-18	451	SY50-17-18	513	SY51-17-18	614		SY52-17-18	650	SY53-17-18	321	SY54-17-18	360
SY48-18-19	582	SY49-18-19	353	SY50-18-19	404	SY51-18-19	533		SY52-18-19	611	SY53-18-19	232	SY54-18-19	419
SY48-19-20	513	SY49-19-20	338	SY50-19-20	228	SY51-19-20	540		SY52-19-20	455	SY53-19-20	256	SY54-19-20	354
SY48-20-21	376	SY49-20-21	217	SY50-20-21	322	SY51-20-21	600		SY52-20-21	449	SY53-20-21	315	SY54-20-21	400
SY48-21-22	316	SY49-21-22	143	SY50-21-22	332	SY51-21-22	480		SY52-21-22	340	SY53-21-22	274	SY54-21-22	494
SY48-22-23	318	SY49-22-23	114	SY50-22-23	309	SY51-22-23	396		SY52-22-23	316	SY53-22-23	258	SY54-22-23	313
		SY49-23-24	89	SY50-23-24	277	SY51-23-24	290		SY52-23-24	314	SY53-23-24	191	SY54-23-24	263
				SY50-24-25	217	SY51-24-25	213		SY52-24-25	307	SY53-24-25	105	SY54-24-25	234
				SY50-25-26	213	SY51-25-26	295		SY52-25-26	140			SY54-25-26	281
				SY50-26-27	159	SY51-26-27	192		SY52-26-27	107			SY54-26-27	268
				SY50-27-28	178	SY51-27-28	133						SY54-27-28	266
				SY50-28-29	137								SY54-28-29	289
													SY54-29-30	140
													SY54-30-31	84
SY55-1-2	576	SY56-1-2	441	SY57-1-2	390	SY58-1-2	137		SY59-1-2	137				
SY55-2-3	574	SY56-2-3	479	SY57-2-3	582	SY58-2-3	186		SY59-2-3	142				
SY55-3-4	664	SY56-3-4	492	SY57-3-4	598	SY58-3-4	191		SY59-3-4	133				
SY55-4-5	569	SY56-4-5	490	SY57-4-5	500	SY58-4-5	212		SY59-4-5	117				
SY55-5-6	481	SY56-5-6	493	SY57-5-6	594	SY58-5-6	223		SY59-5-6	103				



Table S-3 cont.

Drill hole-depth (m)	Sc (ppm)	Drill hole-depth (m)	Sc (ppm)	Drill hole-depth (m)	Sc (ppm)	Drill hole-depth (m)	Sc (ppm)		Drill hole-depth (m)	Sc (ppm)					
SY55-6-7	429	SY56-6-7	475	SY57-6-7	594	SY58-6-7	243		SY59-6-7	110					
SY55-7-8	358	SY56-7-8	432	SY57-7-8	673	SY58-7-8	257		SY59-7-8	108					
SY55-8-9	379	SY56-8-9	488	SY57-8-9	783	SY58-8-9	298		SY59-8-9	104					
SY55-9-10	244	SY56-9-10	500	SY57-9-10	899	SY58-9-10	315		SY59-9-10	101					
SY55-10-11	161	SY56-10-11	543	SY57-10-11	617	SY58-10-11	327		SY59-10-11	109					
SY55-11-12	120	SY56-11-12	508	SY57-11-12	214	SY58-11-12	329		SY59-11-12	120					
		SY56-12-13	375	SY57-12-13	153	SY58-12-13	384		SY59-12-13	133					
		SY56-13-14	411	SY57-13-14	118	SY58-13-14	500		SY59-13-14	161					
		SY56-14-15	426	SY57-14-15	110	SY58-14-15	558		SY59-14-15	150					
		SY56-15-16	471			SY58-15-16	688		SY59-15-16	148					
		SY56-16-17	314			SY58-16-17	444		SY59-16-17	133					
		SY56-17-18	214			SY58-17-18	195		SY59-17-18	130					
		SY56-18-19	230			SY58-18-19	133		SY59-18-19	130					
		SY56-19-20	192			SY58-19-20	99		SY59-19-20	137					
		SY56-20-21	119			SY58-20-21	104		SY59-20-21	187					
									SY59-21-22	252					
									SY59-22-23	228					
									SY59-23-24	149					



4. Mineralogical Analyses Procedures

The mineralogical composition of bulk powder samples was determined by X-ray diffraction (XRD). The data were collected in Bragg-Brentano geometry with a PANalytical X'Pert PRO MPD diffractometer equipped with an X'Celerator detector. Co K α radiation ($\lambda_{K\alpha 1} = 1.78897 \text{ \AA}$, $\lambda_{K\alpha 2} = 1.79285 \text{ \AA}$) was used in order to minimise the effect of Fe fluorescence on background. Data were recorded over the $3^\circ 2\theta$ to $90^\circ 2\theta$ range, with $0.017^\circ 2\theta$ steps and a total counting time of 6 hours. Aluminium-bearing goethite, anatase, calcite, dolomite, gibbsite, haematite, kaolinite, lithiophorite, magnetite/maghemite and quartz were identified using International Centre for Diffraction Data (ICDD) references (PDF-2 database).

Table S-4 Nature and proportion of the phases identified for each sample (b.d.l.: below detection limit using Rietveld refinement but present in the sample, abs.: absent from the sample).

Core	Sample Name	Depth (m)	Kaolinite	Al-rich goethite	Haematite	Maghemite		Gibbsite	Quartz	Anatase	Calcite	Dolomite	Lithiophorite
JSD-001	jsd1_115	11.5	abs.	54	30	1		13	abs.	1	abs.	1	abs.
JSD-001	jsd1_121	12.1	abs.	51	33	1		13	abs.	1	abs.	2	abs.
JSD-001	jsd1_125	12.5	abs.	47	34	1		17	abs.	1	abs.	abs.	abs.
JSD-001	jsd1_130	13.0	abs.	50	28	1		20	abs.	1	abs.	abs.	abs.
JSD-001	jsd1_135	13.5	abs.	52	26	1		21	abs.	b.d.l.	abs.	abs.	abs.
JSD-001	jsd1_140	14.0	abs.	47	27	1		25	abs.	b.d.l.	abs.	abs.	abs.
JSD-001	jsd1_144	14.4	1	45	23	1		29	abs.	1	abs.	abs.	abs.
JSD-001	jsd1_149	14.9	22	49	27	1		abs.	abs.	2	abs.	abs.	abs.
JSD-001	jsd1_154	15.4	6	48	29	1		15	abs.	1	abs.	abs.	abs.
JSD-001	jsd1_160	16.0	23	52	23	b.d.l.		abs.	abs.	2	abs.	abs.	abs.
JSD-001	jsd1_164	16.4	33	45	29	1		abs.	abs.	2	abs.	abs.	abs.
JSD-001	jsd1_169	16.9	42	30	23	1		abs.	abs.	3	abs.	abs.	abs.
JSD-001	jsd1_174	17.4	43	28	22	4		abs.	abs.	3	abs.	abs.	abs.
JSD-001	jsd1_176	17.6	6	17	60	16		abs.	b.d.l.	1	abs.	abs.	abs.
JSD-001	jsd1_180	18.0	38	22	33	5		abs.	b.d.l.	2	abs.	abs.	abs.
JSD-001	jsd1_184	18.4	9	48	37	6		abs.	b.d.l.	1	abs.	abs.	abs.
JSD-002	jsd2_083	8.3	28	31	34	2		abs.	abs.	1	abs.	4	abs.
JSD-002	jsd2_089	8.9	36	34	27	1		abs.	abs.	2	abs.	abs.	abs.

Least squares refinement of the experimental XRD patterns were performed using the Rietveld method, fitting the experimental patterns with theoretical ones calculated from the crystal structure of each phase identified in the sample. Those refinements were carried out with the FullProf suite of programmes (Rodríguez-Carvajal, 1993). Unit cell parameters, atomic positions, and isotropic Debye-Waller factors were refined from the following structure refinements: Hazemann *et al.* (1991) for goethite [α -FeOOH]; Parker (1923) for anatase [TiO₂]; Chessin *et al.* (1965) for calcite [CaCO₃]; Wasastjerna (1924) for dolomite [CaMg(CO₃)₂]; Saalfeld and Wedde (1974) for gibbsite [α -Al(OH)₃]; Blake and Hessevic (1966) for haematite [α -Fe₂O₃]; Bish and Von Dreele (1989) for kaolinite [Al₂Si₂O₅(OH)₄]; Post and Appleman (1994) for lithiophorite; Pecharróman *et al.* (1995) for maghemite [γ -Fe₂O₃] and Wei (1935) for α -quartz [α -SiO₂]. Mineral proportions were estimated from those refinements (Table S-4).



Table S-4 cont.

Core	Sample Name	Depth (m)	Kaolinite	Al-rich goethite	Haematite	Maghemite		Gibbsite	Quartz	Anatase	Calcite	Dolomite	Lithiophorite
JSD-002	jsd2_096	9.6	59	25	12	1		abs.	abs.	2	abs.	abs.	1
JSD-002	jsd2_100	10.0	28	40	28	1		abs.	abs.	2	abs.	abs.	1
JSD-002	jsd2_107	10.7	35	31	31	1		abs.	abs.	2	abs.	0	abs.
JSD-002	jsd2_110	11.0	44	17	34	2		abs.	abs.	2	abs.	1	abs.
JSD-002	jsd2_117	11.7	42	24	29	2		abs.	abs.	2	abs.	1	abs.
JSD-002	jsd2_120	12.0	26	24	36	10		abs.	abs.	1	abs.	3	abs.
JSD-002	jsd2_125	12.5	33	27	36	2		abs.	abs.	2	abs.	0	abs.
JSD-002	jsd2_130	13.0	32	26	37	3		abs.	abs.	2	abs.	abs.	abs.
JSD-002	jsd2_140	14.0	39	20	36	2		abs.	abs.	2	abs.	1	abs.
JSD-002	jsd2_145	14.5	42	24	31	1		abs.	abs.	2	abs.	abs.	abs.
JSD-002	jsd2_150	15.0	38	18	38	3		abs.	abs.	2	abs.	1	abs.
JSD-002	jsd2_160	16.0	41	16	38	3		abs.	abs.	2	abs.	0	abs.
JSD-002	jsd2_165	16.5	36	29	31	3		abs.	abs.	1	abs.	abs.	abs.
JSD-002	jsd2_170	17.0	31	29	36	2		abs.	abs.	2	abs.	abs.	abs.
JSD-002	jsd2_175	17.5	22	24	50	2		abs.	abs.	2	abs.	abs.	abs.
JSD-002	jsd2_180	18.0	29	29	38	2		abs.	abs.	2	0	abs.	abs.
JSD-002	jsd2_185	18.5	20	44	31	3		abs.	abs.	2	abs.	abs.	abs.
JSD-002	jsd2_190	19.0	28	34	34	3		abs.	abs.	1	abs.	abs.	abs.
JSD-002	jsd2_195	19.5	34	19	42	3		abs.	abs.	2	abs.	abs.	abs.
Average			25.6	33.5	32.2	2.5		4.1	0	1.6	0	0.4	0.1



5. Chemical Analyses Procedures and Data

Chemical analyses have been carried out in the Geochemical Analytical Unit (GAU) of the ARC Centre of Excellence for Core to Crust Fluid Systems (CCFS) and the Department of Earth and Planetary Sciences at Macquarie University. Selected chip samples were powdered using a tungsten carbide mill to obtain a fine powder (below 50 µm in size). Thorough care was taken when cleaning the mill with ethanol and Milli-Q® water between samples to avoid cross-contamination.

Standard X-ray fluorescence (XRF) technique was used for bulk sample major and minor elements analysis (e.g., Potts *et al.*, 1984). Approximately 1 g of powder of each sample was mixed with 10 g of lithium tetraborate–meta-borate flux (12:22 mixture), fused in a Pt crucible and cooled to give glass discs. The discs were analysed using a PANalytical Axios 1 kW energy-dispersive XRF spectrometer. Loss on ignition was determined for each sample at 1100 °C overnight. The deviations from reference values from GeoReM (Jochum and Nohl, 2008) for standards BIR-1 and BHVO-2 have been used, along with replicates, to estimate the error. Analyses of the samples are listed in Table S-5.

Scandium concentrations in the bulk samples, along with the other rare earth elements, have been determined by standard inductively coupled plasma mass spectrometry (ICP-MS) methods (e.g., Eggins *et al.*, 1998). Approximately 100 mg of powder samples were weighed into clean Savillex® Teflon beakers. Samples were then digested following the next steps:

- (1) Digestion in a 1:1 mixture of HF (Merck, Suprapur grade) and HNO₃ (Merck, AR grade, Teflon distilled) for 24 h at 160 °C followed by evaporation to dryness at 150 °C.
- (2) Digestion in a 1:1 mixture of HF and perchloric acid (HClO₄, Merck, Suprapur grade) for 3 days at 170 °C followed by evaporation to dryness at 120 °C, 150 °C and then 170 °C.

Table S-5 Bulk geochemical analyses for major and minor elements along with Sc and the rare earth elements.

Core	Sample Name	Depth (m)	SiO ₂ (wt. %)	TiO ₂ (wt. %)	Al ₂ O ₃ (wt. %)	Fe ₂ O ₃ (wt. %)	Cr ₂ O ₃ (wt. %)	MnO (wt. %)		NiO (wt. %)	MgO (wt. %)	CaO (wt. %)	BaO (wt. %)	Na ₂ O (wt. %)	K ₂ O (wt. %)	P ₂ O ₅ (wt. %)	SO ₃ (wt. %)	L.O.I. (wt. %)	Total (wt. %)
JSD-001	jsd1_115	11.5	3.41	2.25	17.69	59.69	0.40	0.15		0.04	0.38	0.19	-0.01	0.09	-0.01	0.06	0.12	14.45	98.90
JSD-001	jsd1_121	12.1	3.10	2.19	17.36	59.09	0.39	0.17		0.05	0.68	0.59	0.00	0.12	-0.01	0.06	0.12	15.37	99.27
JSD-001	jsd1_125	12.5	4.60	1.83	17.03	57.42	0.33	0.21		0.06	0.40	0.12	-0.01	0.10	-0.01	0.03	0.09	15.42	97.63
JSD-001	jsd1_130	13.0	3.30	2.04	17.25	60.28	0.34	0.21		0.05	0.32	0.08	-0.01	0.02	-0.01	0.05	0.10	14.77	98.77
JSD-001	jsd1_135	13.5	3.51	1.85	17.21	59.38	0.34	0.23		0.07	0.41	0.07	-0.02	0.06	-0.01	0.03	0.10	15.57	98.81
JSD-001	jsd1_140	14.0	4.95	1.79	18.30	57.00	0.33	0.21		0.07	0.44	0.08	0.00	0.10	-0.01	0.03	0.09	15.76	99.13
JSD-001	jsd1_144	14.4	6.20	1.46	19.97	45.10	0.27	0.16		0.05	0.52	0.20	-0.02	0.04	-0.01	0.03	0.07	17.21	91.26

- (3) Digestion in a 1:1:1 mixture of HF, HCl (Merck, AR grade, Teflon distilled) and HClO₄ for 3 days at 170 °C followed by evaporation to dryness at 170 °C to 190 °C.
- (4) Digestion in aqua regia (HNO₃ + 3 HCl) for 3 days at 150 °C followed by evaporation to dryness at 150 °C.
- (5) Digestion in 6 N HCl solution for 12 h at 150 °C followed by evaporation to dryness at 150 °C.
- (6) Digestion in 6 N HNO₃ for 12 h at 150 °C followed by evaporation at 120 °C.

The samples were then diluted to 100 mL in a 2 % HNO₃ and 0.25 % HF solution. These 1:1000 dilutions of each sample were individually spiked with a 15 µL aliquot of a solution of Li⁶, As, Rh, In, Tm and Bi in 2 % HNO₃. The samples and standards were analysed by quadrupole ICP-MS on an Agilent 7500c/s ICP-MS system. BCR-2 standard was used as a calibration standard to correct for instrument sensitivity. Run drift was corrected using the aliquot of solution added to each sample. The background was measured on a 2 % HNO₃ rinse solution. The deviations from reference values from GeoReM (Jochum and Nohl, 2008) for standards BIR-1 and BHVO-2 have been used, along with replicates, to estimate the error. Analyses of the samples are given in Table S-5.

From these analyses, the enrichment factor of each REE, including Sc, has been calculated and shows a correlation with the ionic radii of these elements in octahedral coordination (Fig. S-2). Cerium does not follow this trend as under atmospheric conditions, Ce³⁺ can be oxidised to Ce⁴⁺ which is easily trapped by Mn oxides, commonly formed in lateritic profiles.



Table S-5 cont.

Core	Sample Name	Depth (m)	SiO ₂ (wt. %)	TiO ₂ (wt. %)	Al ₂ O ₃ (wt. %)	Fe ₂ O ₃ (wt. %)	Cr ₂ O ₃ (wt. %)	MnO (wt. %)		NiO (wt. %)	MgO (wt. %)	CaO (wt. %)	BaO (wt. %)	Na ₂ O (wt. %)	K ₂ O (wt. %)	P ₂ O ₅ (wt. %)	SO ₃ (wt. %)	L.O.I. (wt. %)	Total (wt. %)
JSD-001	jsd1_149	14.9	14.53	1.62	15.82	52.61	0.41	0.16		0.08	0.21	0.08	0.00	0.10	-0.01	0.03	0.05	14.00	99.69
JSD-001	jsd1_154	15.4	8.35	1.84	17.00	55.01	0.35	0.22		0.07	0.46	0.09	-0.01	0.09	-0.01	0.04	0.07	15.60	99.16
JSD-001	jsd1_160	16.0	16.07	1.65	16.88	48.76	0.31	0.19		0.08	0.23	0.08	-0.00	0.11	-0.01	0.04	0.05	14.46	98.90
JSD-001	jsd1_164	16.4	17.88	1.70	17.45	47.51	0.32	0.17		0.07	0.28	0.10	-0.01	0.18	-0.00	0.02	0.05	13.24	98.97
JSD-001	jsd1_169	16.9	24.57	1.32	20.34	37.88	0.24	0.13		0.05	0.26	0.11	0.01	0.12	0.00	0.02	0.03	14.69	99.76
JSD-001	jsd1_174	17.4	21.89	1.19	17.71	44.87	0.23	0.20		0.04	0.27	0.12	-0.00	0.14	-0.00	0.02	0.04	11.94	98.65
JSD-001	jsd1_176	17.6	4.59	0.39	3.78	83.90	0.10	0.62		0.06	0.21	0.08	0.01	0.09	-0.01	0.01	0.02	4.81	98.66
JSD-001	jsd1_180	18.0	17.98	1.17	14.95	52.25	0.15	0.47		0.05	0.25	0.15	0.00	0.11	-0.00	0.04	0.02	11.17	98.76
JSD-001	jsd1_184	18.4	4.77	0.55	5.53	76.62	0.21	0.42		0.20	0.34	0.09	0.01	0.16	-0.01	0.03	0.07	8.54	97.52
JSD-002	jsd2_083	8.3	17.37	1.53	15.42	48.03	0.20	0.84		0.06	0.96	1.35	0.01	0.06	0.00	0.02	0.00	13.41	99.26
JSD-002	jsd2_089	8.9	18.37	1.55	17.27	47.20	0.19	1.16		0.06	0.23	0.17	0.01	0.09	-0.00	0.02	0.01	13.21	99.52
JSD-002	jsd2_096	9.6	24.98	1.08	22.60	33.13	0.15	1.62		0.10	0.21	0.12	0.04	0.07	-0.00	0.02	-0.00	14.92	99.04
JSD-002	jsd2_100	10.0	15.23	1.64	14.28	52.20	0.19	1.55		0.13	0.24	0.14	0.03	0.05	-0.00	0.03	-0.00	13.03	98.75
JSD-002	jsd2_107	10.7	17.79	1.59	15.35	50.32	0.16	0.75		0.06	0.28	0.24	0.01	0.06	-0.00	0.03	-0.00	12.70	99.32
JSD-002	jsd2_110	11.0	20.41	1.40	16.06	47.78	0.11	0.61		0.04	0.33	0.51	0.00	0.06	-0.00	0.03	-0.01	12.02	99.34
JSD-002	jsd2_117	11.7	20.08	1.27	16.50	47.49	0.20	0.54		0.06	0.29	0.32	0.01	0.06	0.00	0.03	-0.00	12.83	99.68
JSD-002	jsd2_120	12.0	12.68	0.84	10.25	61.98	0.16	0.57		0.06	0.83	1.15	0.04	0.05	-0.00	0.03	-0.00	10.70	99.34
JSD-002	jsd2_125	12.5	16.87	1.51	13.47	54.18	0.44	0.43		0.06	0.23	0.22	0.02	0.05	-0.00	0.03	-0.01	11.93	99.43
JSD-002	jsd2_130	13.0	17.20	1.37	13.46	52.70	0.50	1.05		0.07	0.20	0.20	0.01	0.06	0.00	0.02	-0.01	12.30	99.12
JSD-002	jsd2_140	14.0	17.92	1.45	14.17	52.17	0.19	0.35		0.04	0.35	0.56	0.01	0.10	-0.00	0.06	-0.01	12.43	99.79
JSD-002	jsd2_145	14.5	17.49	1.47	12.99	48.27	0.29	0.42		0.05	0.16	0.19	0.01	0.02	0.00	0.02	-0.01	11.61	92.98
JSD-002	jsd2_150	15.0	17.12	1.44	13.31	51.26	0.35	0.98		0.11	0.40	0.41	0.05	0.04	-0.00	0.01	-0.01	12.58	98.05
JSD-002	jsd2_160	16.0	18.84	1.48	14.41	50.82	0.16	0.41		0.05	0.33	0.48	0.02	0.03	-0.01	0.04	-0.01	11.59	98.65
JSD-002	jsd2_165	16.5	17.84	1.48	13.61	52.30	0.20	0.42		0.10	0.28	0.19	-0.00	0.07	-0.01	0.05	-0.01	12.65	99.16
JSD-002	jsd2_170	17.0	17.28	1.26	12.75	45.81	0.12	0.41		0.08	0.24	0.20	0.01	0.04	-0.00	0.03	-0.01	12.89	91.11
JSD-002	jsd2_175	17.5	16.47	1.58	11.62	53.52	0.16	2.24		0.10	0.22	0.28	0.02	0.02	-0.00	0.05	-0.01	12.23	98.50
JSD-002	jsd2_180	18.0	18.28	1.56	13.07	50.49	0.61	0.06		0.07	0.27	0.87	-0.00	0.02	0.00	0.05	-0.01	13.04	98.35
JSD-002	jsd2_185	18.5	16.61	1.60	13.22	52.40	0.43	0.14		0.09	0.29	0.21	0.00	0.05	0.00	0.04	-0.01	13.28	98.34



Table S-5 cont.

Core	Sample Name	Depth (m)	SiO ₂ (wt. %)	TiO ₂ (wt. %)	Al ₂ O ₃ (wt. %)	Fe ₂ O ₃ (wt. %)	Cr ₂ O ₃ (wt. %)	MnO (wt. %)		NiO (wt. %)	MgO (wt. %)	CaO (wt. %)	BaO (wt. %)	Na ₂ O (wt. %)	K ₂ O (wt. %)	P ₂ O ₅ (wt. %)	SO ₃ (wt. %)	L.O.I. (wt. %)	Total (wt. %)
JSD-002	jsd2_190	19.0	15.53	1.49	12.35	54.40	0.57	0.12		0.12	0.39	0.17	0.02	0.08	-0.01	0.03	-0.01	13.13	98.36
JSD-002	jsd2_195	19.5	20.91	1.48	13.35	48.85	0.10	0.64		0.08	0.34	0.26	-0.01	0.09	0.00	0.02	-0.01	12.59	98.69
	Error (wt. %)		0.10	0.01	0.02	0.11	0.05	0.00		0.05	0.01	0.02	0.00	0.01	0.00	0.00	0.00	0.36	
	Saprolite (average)		49.99	0.27	2.32	8.31	0.26	0.17		0.05	14.66	19.45	-0.01	0.21	-0.01	0.00	-0.01	4.64	100.31
Core	Sample Name	Depth (m)	La (ppm)	Ce (ppm)	Pr (ppm)	Nd (ppm)	Sm (ppm)	Eu (ppm)		Gd (ppm)	Tb (ppm)	Dy (ppm)	Ho (ppm)	Er (ppm)	Yb (ppm)	Lu (ppm)	Y (ppm)	Sc (ppm)	
JSD-001	jsd1_115	11.5	11.3	50.9	4.2	19.3	6.2	1.7		5.6	0.9	5.3	1.0	2.9	3.2	0.5	23.9	526.7	
JSD-001	jsd1_121	12.1	6.0	47.7	2.2	10.5	3.5	1.0		3.2	0.5	3.1	0.6	1.7	1.9	0.3	11.6	461.2	
JSD-001	jsd1_125	12.5	12.0	152.7	5.4	24.5	8.7	2.4		7.2	1.2	7.2	1.4	3.9	4.7	0.7	20.1	542.6	
JSD-001	jsd1_130	13.0	11.3	234.9	4.7	21.3	7.1	2.0		6.3	1.1	6.1	1.2	3.4	3.8	0.6	21.0	533.8	
JSD-001	jsd1_135	13.5	8.1	183.4	4.1	18.6	6.9	1.9		5.7	1.0	5.8	1.1	3.1	3.9	0.6	12.9	539.8	
JSD-001	jsd1_140	14.0	6.8	66.2	3.1	14.0	5.2	1.4		4.1	0.7	4.2	0.8	2.2	2.7	0.4	11.4	495.8	
JSD-001	jsd1_144	14.4	9.5	77.5	4.5	20.4	7.6	2.0		6.1	1.1	6.3	1.2	3.4	4.3	0.6	17.4	547.9	
JSD-001	jsd1_149	14.9	25.3	56.2	10.8	48.9	15.1	3.9		11.6	1.8	9.7	1.8	5.0	4.8	0.7	24.8	375.2	
JSD-001	jsd1_154	15.4	17.0	62.6	5.9	28.5	9.5	2.6		8.4	1.3	7.2	1.4	3.9	3.7	0.5	31.0	573.8	
JSD-001	jsd1_160	16.0	26.1	124.8	11.3	53.8	16.8	4.6		13.7	2.2	11.9	2.2	6.0	6.2	0.9	32.9	635.9	
JSD-001	jsd1_164	16.4	27.9	138.9	12.0	54.9	15.7	4.4		13.9	2.2	12.1	2.2	6.0	6.0	0.9	32.7	654.8	
JSD-001	jsd1_169	16.9	29.5	234.2	11.7	52.7	12.1	3.3		10.6	1.6	8.1	1.5	3.9	3.4	0.5	24.8	465.5	
JSD-001	jsd1_174	17.4	22.9	116.9	8.7	38.5	8.9	2.6		9.2	1.4	7.5	1.4	3.8	3.3	0.5	25.8	358.3	
JSD-001	jsd1_176	17.6	33.9	138.8	10.4	45.3	10.5	3.1		11.1	1.6	8.6	1.7	4.5	3.8	0.6	30.5	251.6	
JSD-001	jsd1_180	18.0	25.1	71.5	8.6	36.6	8.6	2.5		8.9	1.3	7.1	1.3	3.5	3.0	0.4	23.0	360.5	
JSD-001	jsd1_184	18.4	28.5	38.3	7.7	34.9	8.7	2.7		12.2	1.7	9.8	2.1	5.7	4.2	0.7	47.0	584.7	
JSD-002	jsd2_083	8.3	24.6	77.1	7.1	31.6	6.7	1.9		7.5	1.0	5.2	1.1	2.8	1.9	0.3	32.0	507.7	
JSD-002	jsd2_089	8.9	23.4	155.4	6.1	27.1	5.5	1.6		6.1	0.8	3.9	0.8	1.9	1.2	0.2	17.9	296.3	
JSD-002	jsd2_096	9.6	18.2	320.2	4.8	21.5	4.8	1.4		5.6	0.8	3.9	0.8	2.0	1.3	0.2	16.8	281.8	
JSD-002	jsd2_100	10.0	13.0	61.0	4.1	19.4	4.9	1.5		5.8	0.8	4.6	0.9	2.5	1.9	0.3	28.4	531.3	
JSD-002	jsd2_107	10.7	7.5	39.6	2.4	11.0	2.8	0.8		3.4	0.5	2.7	0.6	1.4	1.1	0.2	19.6	513.7	
JSD-002	jsd2_110	11.0	9.8	59.2	3.2	14.3	3.5	1.0		3.6	0.5	2.8	0.5	1.4	1.2	0.2	15.7	331.1	



Table S-5 cont.

Core	Sample Name	Depth (m)	La (ppm)	Ce (ppm)	Pr (ppm)	Nd (ppm)	Sm (ppm)	Eu (ppm)		Gd (ppm)	Tb (ppm)	Dy (ppm)	Ho (ppm)	Er (ppm)	Yb (ppm)	Lu (ppm)	Y (ppm)	Sc (ppm)	
JSD-002	jsd2_117	11.7	12.4	90.1	4.0	18.4	4.6	1.3		4.8	0.7	3.9	0.7	2.0	1.7	0.2	15.9	468.0	
JSD-002	jsd2_120	12.0	10.6	66.5	3.9	18.6	5.6	1.7		6.1	0.9	5.3	1.1	2.9	2.8	0.4	27.7	582.4	
JSD-002	jsd2_125	12.5	5.2	21.0	2.0	9.5	2.7	0.8		2.8	0.4	2.4	0.5	1.3	1.0	0.2	15.6	749.6	
JSD-002	jsd2_130	13.0	8.8	71.2	2.8	12.5	3.1	0.9		3.0	0.4	2.1	0.4	1.0	0.8	0.1	9.6	290.0	
JSD-002	jsd2_140	14.0	5.9	29.0	2.4	11.3	3.3	1.0		3.5	0.5	3.1	0.6	1.7	1.5	0.2	17.4	574.9	
JSD-002	jsd2_145	14.5	4.2	18.8	1.6	7.9	2.2	0.6		2.2	0.3	1.7	0.3	0.9	0.7	0.1	8.6	331.5	
JSD-002	jsd2_150	15.0	8.9	55.9	3.0	13.5	3.5	1.1		3.3	0.5	2.6	0.5	1.3	1.0	0.1	12.3	600.3	
JSD-002	jsd2_160	16.0	5.1	11.9	2.3	10.6	3.2	0.9		2.7	0.4	2.4	0.4	1.2	1.3	0.2	7.9	375.2	
JSD-002	jsd2_165	16.5	8.4	15.6	3.6	18.3	6.0	1.8		6.1	1.0	6.0	1.2	3.3	3.7	0.6	16.2	538.1	
JSD-002	jsd2_170	17.0	11.6	18.6	4.3	20.6	6.5	2.0		6.7	1.1	6.5	1.3	3.7	4.3	0.7	22.0	593.0	
JSD-002	jsd2_175	17.5	20.9	61.5	6.4	29.8	8.1	2.3		7.5	1.1	6.2	1.2	3.2	3.0	0.4	21.9	342.0	
JSD-002	jsd2_180	18.0	12.3	3.8	5.1	24.8	7.5	2.2		7.6	1.2	6.9	1.3	3.7	3.7	0.6	24.8	669.3	
JSD-002	jsd2_185	18.5	6.0	5.6	3.3	16.9	5.4	1.6		5.3	0.9	5.0	0.9	2.5	2.4	0.4	14.6	492.4	
JSD-002	jsd2_190	19.0	8.3	5.4	4.4	22.9	7.3	2.3		7.7	1.2	7.2	1.4	3.7	3.3	0.5	23.2	636.3	
JSD-002	jsd2_195	19.5	21.8	20.2	9.0	44.9	11.6	3.3		10.7	1.5	8.2	1.6	4.0	3.2	0.4	28.4	260.9	
	Error (ppm)		0.3	1.7	0.2	0.5	0.2	0.0		0.1	0.0	0.1	0.0	0.1	0.1	0.0	0.5	8.0	
	Saprolite (average)		5.7	5.9	2.2	10.6	2.7	0.8		2.8	0.4	2.1	0.4	1.1	0.8	0.1	11.9	99.4	
	Enrichment factor (JSD-001)		2.6	13.7	2.5	2.4	2.6	2.6		2.4	2.6	2.7	2.7	2.8	3.4	3.6	1.8	4.9	



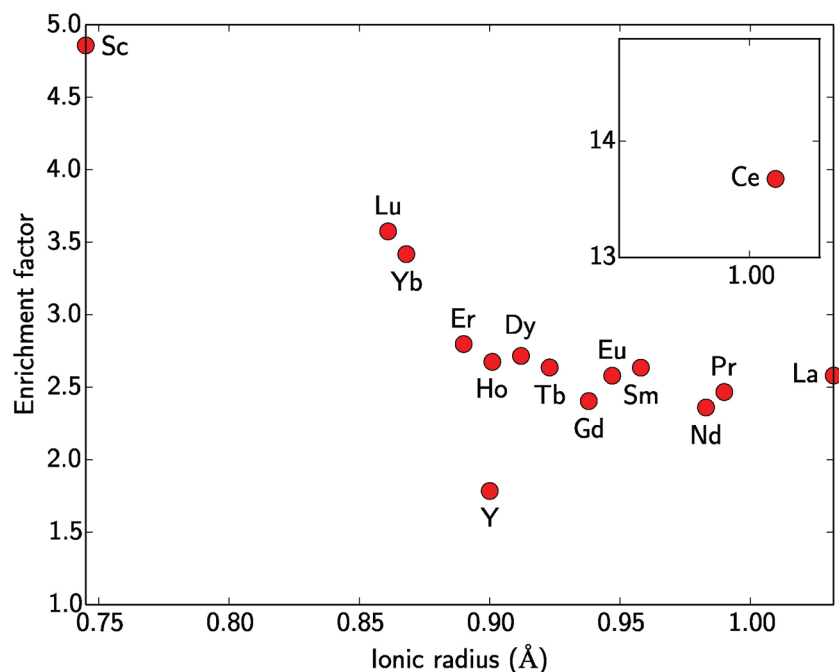


Figure S-2 Enrichment factor of rare earth elements in the lateritic deposit versus ionic radius in octahedral coordination. Values are after Shannon (1976).

6. Procedures for Spatially Resolved Chemical Analyses

Polished sections were obtained by impregnating dry chip samples in polyester resin diluted with acetone and polishing on cloth with diamond pastes. Microscopic observations and chemical mapping of major elements of these polished sections have been carried out on a ZEISS SUPRATM 55VP scanning electron microscope (SEM) at University Pierre et Marie Curie (UPMC), Paris. The SEM is equipped with a field emission gun (FEG) operating at 15 kV. The working distance was set to 15 mm. Backscattered electron (BSE) images were collected using an AsB detector. Chemical mapping was performed using the energy dispersive X-ray (EDX) microanalysis system (Bruker XFlash[®] QUAD silicon drift detector) coupled to the SEM.

Electron microprobe (EMP) analyses were performed for major and minor elements on selected points of the polished sections using a Cameca SXFive EMP equipped with five wavelength-dispersive spectrometers (WDS) at the Centre d'Analyse des Minéraux de PARIS (CAMPARIS, Université Pierre et Marie Curie, Paris, France). Each point has been probed with a focused 20 kV, 40 nA beam for major elements and with a focused 20 kV, 200 nA beam for minor and trace elements. Major elements: Na, Mg, Al, Si, P, Cl, K, Ca, Ti, Cr, Mn, Fe and Ba were analysed with a 20 s (peak + background) counting time. Minor and trace elements were Sc, V, Ni; all of these were analysed with 60 s (peak + background) counting time. The WDS were used with the following monochromators: a large area (1320 mm²) thallium acid phthalate (TAP); a regular (660 mm²) TAP; a regular (660 mm²) pentaerythritol (PET) and two large (1320 mm²) lithium fluoride (LiF) to collect, respectively, Na, Mg and P K α X-rays; Si and Al K α X-rays; K, Ca and Cl K α X-rays and Ba L α , Cr, Mn, Fe, Ti, V, Ni and Sc K α X-rays. The two large LiF monochromators were used simultaneously to analyse each of the minor and trace elements. This allowed us to achieve detection limits as low as 60 ppm to 30 ppm. WDS analyses were performed using the following standards: albite for Na; diopside for Mg, Si and Ca; apatite Durango for P; orthoclase for Al and K; scapolite for Cl, Cr₂O₃ for Cr; MnTiO₃ for Mn and Ti; haematite for Fe; BaSO₄ for Ba; vanadite for V; NiO for Ni and Sc₂O₃ for Sc.

The different EMP analyses have been classified in groups in order to distinguish between different types of grains or phases. In order to do that, analyses for Si, Ti, Fe, Al, Sc and the analytical total have been selected as they exhibited repeated patterns with similar concentrations. Using the R software (version 3.1.3) and the k-means function of the "stats" package (version 3.4.0), a k-means clustering method has been applied to our EMP analyses distinguishing 5 clusters. Based on those results, each cluster has been carefully studied by analysing the position of the analysis on the SEM images as well as the concentrations in the selected element. From these analyses, 8 groups of grains could be distinguished (Table S-6): Fe-rich oxyhydroxides, Fe-rich oxides, Ti-rich oxides, Al-rich oxyhydroxides, quartz, Sc-rich groundmass, kaolinite-rich groundmass and Sc-poor groundmass.



Table S-6 Median, mean and standard deviation of Si, Ti, Fe, Al, analytical total and Sc concentrations in the different grain types distinguished by SEM imaging, EMP and cluster analysis.

Grain type	Num. Obs.	SiO ₂ (wt. %)			TiO ₂ (wt. %)				Al ₂ O ₃ (wt. %)			Fe ₂ O ₃ (wt. %)			Sc (ppm)			Total (wt. %)		
		Median	Mean	Std. Dev.	Median	Mean	Std. Dev.		Median	Mean	Std. Dev.	Median	Mean	Std. Dev.	Median	Mean	Std. Dev.	Median	Mean	Std. Dev.
Fe-rich oxyhydroxide	43	4.30	4.50	1.06	1.72	1.76	0.75		6.27	6.58	2.16	70.56	68.10	8.84	1190	1339	351	85.49	83.01	9.01
Fe-rich oxide	16	0.07	0.25	0.67	1.24	1.28	1.02		0.31	0.48	0.51	95.61	95.93	3.25	201	195	85	100.34	100.45	2.41
Ti-rich oxide	3	0.05	0.04	0.02	57.38	62.63	11.50		-1.23	-1.27	0.12	41.75	37.22	9.77	102	92	50	104.96	104.16	2.10
Al-rich oxyhydroxide	7	3.67	5.50	5.16	1.05	1.02	0.70		52.30	48.28	8.26	19.65	15.84	10.72	336	271	161	68.49	71.64	12.38
Quartz	4	99.13	98.58	2.80	0.02	0.02	0.00		0.04	0.04	0.04	0.39	0.37	0.06	-2	-0	10	99.61	99.08	2.75
High-Sc matrix	31	4.43	5.02	3.19	1.88	2.23	1.40		7.13	9.05	7.39	61.52	65.28	12.44	640	658	107	85.61	83.45	8.81
Kaolinite-rich matrix	9	38.91	36.30	9.97	0.08	0.32	0.42		31.14	30.26	7.67	3.77	12.33	14.64	364	408	139	82.41	80.01	6.45
Low-Sc matrix	12	2.73	5.54	6.02	1.79	1.91	0.60		6.42	7.30	4.31	76.05	70.53	13.62	391	382	83	90.48	86.59	8.93

7. Procedures for the Synthesis of Reference Materials

Sc-Bearing Goethite

Ferrihydrite was precipitated by adding 50 mL of 1.35 M NaOH to 25 mL of 0.5 M Fe(NO₃)₃ and 25 mL of 1 M ScCl₃ solutions. The suspension was then diluted to 1 L with a 33 mM NaOH solution. The solution was heated to 65 °C in a water-bath for 48 h, transforming the ferrihydrite suspension into a precipitate of goethite. The solid product was separated by centrifugation, washed at 45 °C for 2 h in a 3 M H₂SO₄ solution, in order to remove any adsorbed species and dried at 45 °C for 24 h giving 1 g of Sc-bearing goethite.

Sc-Bearing Hematite

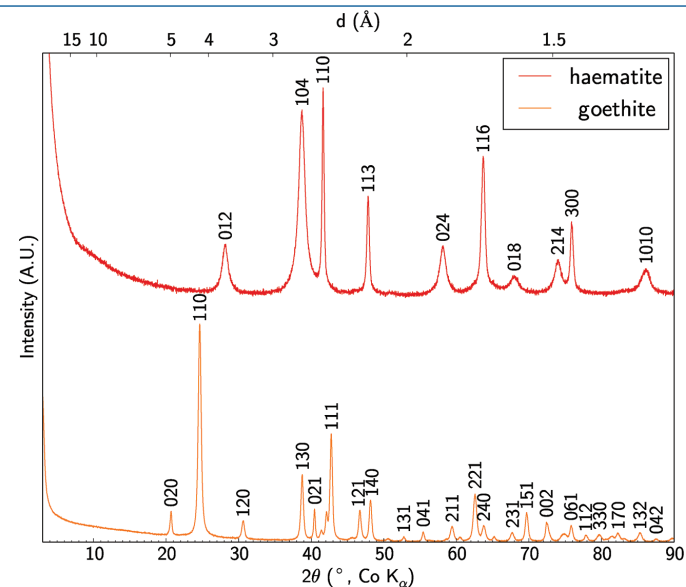
Sc-bearing haematite was obtained by dehydroxylation of the previously synthesised goethite at 300 °C.

Sc-Adsorbed Goethite

10 mL of ScCl₃ solution at 1000 ppm Sc was added to 1 g of pure α-FeOOH obtained following the synthesis method previously described without addition of ScCl₃. The near neutral pH of the solution prohibits any dissolution and reprecipitation of Sc-bearing goethite, considering the stability diagram of goethite. The solid and the solution were shaken together for 24 h. The solid was then separated by centrifugation and dried at 45 °C for 24 h.

8. Characterisation of the Synthetic Compounds

The crystal structure of the mineral phases obtained has been checked by XRD (Fig. S-3) using the method described in SI-4.

**Figure S-3** XRD patterns of synthetic Sc-bearing goethite and haematite.

The incorporation or adsorption of Sc was then verified using ICP-MS. The amount of Sc incorporated in the crystal lattice of the synthetic Sc-bearing goethite, Sc-bearing haematite or adsorbed on goethite has been determined to be 898 ppm $\pm$ 0.025 %, 872 ppm $\pm$ 0.025 % and 819 ppm $\pm$ 0.025 %, respectively. The analyses were performed on a Thermo Scientific XSERIES 2 quadrupole instrument at the Université Pierre et Marie Curie. About 50 mg of powdered sample were digested in 2 mL of concentrated HNO₃-HCl solution at 90 °C for 24 h and then evaporated to dryness at 60 °C. The residue was then diluted in a 2 % HNO₃ solution (1:1000 dilution) for analysis. A standard solution of ScCl₃ at 10 ppb in Sc was prepared by dilution of commercial 99.99 % ScCl₃ powder and used to correct for instrumental shifts and to calculate the Sc content of the samples.

9. Synchrotron Measurement Procedures

Micro-X-ray absorption near-edge structure (XANES) and micro-fluorescence X-ray spectroscopy (μ -XRF) data were collected on the LUCIA beamline at the SOLEIL synchrotron in Paris (France) and on the ID21 beamline at the European Synchrotron Radiation Facility (ESRF) in Grenoble (France). The former operated with a storage ring current of 450 mA and an energy of 2.75 GeV while the latter operated with a storage ring current of 200 mA and an energy of 6 GeV. The layouts of the LUCIA and ID21 beamlines are described in Vantelon *et al.* (2016) and Salomé *et al.* (2013), respectively. XANES spectra were collected using an Si(311) and an Si(220) double crystal monochromator on LUCIA and ID21, respectively. The monochromators were calibrated against the maximum intensity of the first inflection of the first derivative of a Fe foil (7112.0 eV) or a Sc₂O₃ standard (4492.8 eV) for XANES measurements at the Fe or Sc K-edge, respectively.

Iron and Sc K-edge XANES measurements were performed in the energy range 7060 eV to 7300 eV and 4400 eV to 4800 eV, respectively. The energy step at the Fe K-edge was (5, 0.1, 0.3, 0.5 and 1) eV for energy ranges of (7060 to 7110) eV, (7110 to 7125) eV, (7125 to 7170) eV, (7170 to 7219) eV and (7219 to 7300) eV, respectively. The energy step at the Sc K-edge was (5, 0.2, 0.5 and 1) eV for energy ranges of (4400 to 4485) eV, (4485 to 4534) eV, (4534 to 4586) eV and (4586 to 4800) eV, respectively. Spectra were collected at room temperature, under vacuum. For Fe reference materials, the spectra were collected on ID21 in transmission mode on powder samples diluted in a cellulose pellet and mounted on a holder between two Ultralene® films. Two spectra were recorded for each reference with a counting time of about 50 s per spectrum. For Sc reference materials, the spectra were collected on LUCIA in XRF mode on pellets obtained from powdered material and mounted on a holder between two Ultralene® films, using a four-element silicon drift detector (SDD).

For natural samples, the data were collected on ID21 in XRF mode on polished sections for both Fe and Sc K-edges using a photodiode and a large area (80 mm² collimated area) SDD, respectively. The beam was focused with a Kirkpatrick-Baez mirror system, down to 0.7 μ m (horizontal) $\times$ 0.3 μ m (vertical) at the Fe X-edge and 0.9 μ m (horizontal) $\times$ 0.3 μ m (vertical) at the Sc K-edge. The selection of the spots for analysis was made by combining prior SEM and EMP analyses and imaging with chemical mapping of Sc using μ -XRF mapping. The maps were recorded with step sizes of 1 μ m $\times$ 1 μ m with an incident energy of 4800 eV and a dwell time of 100 ms. The XRF spectra obtained for each pixel was then fitted using the PyMCA software to obtain Sc maps. At the Sc K-edge, 10 to 40 XANES spectra were acquired for each spot with a counting time of about 80 s per spectrum. At the Fe X-edge, 2 XANES spectra were acquired for each spot with a counting time of about 50 s. Individual spectra acquired on each spot were merged to obtain average spectra before background subtraction and normalisation using the PyMCA software (Solé *et al.*, 2007). Due to the high Fe concentration in the natural samples, self-absorption occurred during XRF Fe K-edge XANES measurements. This phenomenon has been corrected using the FLUO algorithm from the ATHENA software (Ravel and Newville, 2005). The input parameters have been chosen considering the geometry of the experiment and the chemical composition obtained from EMP measurement on the same spot.

In order to map qualitative Fe speciation, we recorded μ -XRF maps on ID21 in the same area but with three incident energies: 7133.8 eV, corresponding to the maximum intensity of the Fe K-edge XANES spectrum of goethite; 7136.9 eV, corresponding to the maximum intensity of the Fe K-edge XANES spectrum of haematite and 7165.0 eV corresponding to an identical intensity in the normalised Fe K-edge XANES spectra of goethite and haematite. These maps were recorded with step sizes of 2 μ m $\times$ 2 μ m and a dwell time of 50 ms. As for μ -XRF mapping of Sc, the three maps have been obtained by fitting the spectra at each pixel using the PyMCA software. The map of Fe speciation shown in the paper corresponds to the difference between the 7133.8 eV and the 7136.9 eV maps normalised to the 7165.0 eV map.

Supplementary Information References

- BISH, D.L., VON DREELE, R.B. (1989) Rietveld Refinement of Non-Hydrogen Atomic Positions in Kaolinite. *Clays and Clay Minerals* 37, 289–296.
- BLAKE, R.L., HESSEVIC, R.E. (1966) Refinement of the Hematite Structure. *American Mineralogist* 51, 123–129.
- CHESSIN, H., HAMILTON, W.C., POST, B. (1965) Position and Thermal Parameters of Oxygen Atoms in Calcite. *Acta Crystallographica* 18, 689–693.
- EGGINS, S.M., RUDNICK, R.L., McDONOUGH, W.F. (1998) The Composition of Peridotites and their Minerals: a Laser-Ablation ICP-MS Study. *Earth and Planetary Science Letters* 154, 53–71.
- HAZEMANN, J.-L., BÉRAR, J.F., MANCEAU, A. (1991) Rietveld Studies of the Aluminium-Iron Substitution in Synthetic Goethite. *Material Sciences Forum* 79, 821–826.



- JOCHUM, K.P., NOHL, U. (2008) Reference Materials in Geochemistry and Environmental Research and the GeoReM Database. *Chemical Geology* 253, 50–53.
- PARKER, R.L. (1923) Zur Kristallographie von Anatas und Rutil. *Zeitschrift für Kristallographie – Crystalline Materials* 58, 522–582.
- PECHARROMÁN, C., GONZÁLEZ-CARREÑO, T., IGLESIAS, J.E. (1995) The Infrared Dielectric Properties of Maghemite, γ -Fe₂O₃, from Reflectance Measurement on Pressed Powders. *Physics and Chemistry of Minerals* 22, 21–29.
- POST, J.E., APPLEMAN, D.E. (1994) Crystal Structure Refinement of Lithiophorite. *American Mineralogist* 79, 370–374.
- POTTS, P.J., WEBB, P.C., WATSON, J.S. (1984) Energy-Dispersive X-Ray Fluorescence Analysis of Silicate Rocks for Major and Trace Elements. *X-Ray Spectrometry* 13, 2–15.
- RAVEL, B., NEWVILLE, M. (2005) ATHENA, ARTEMIS, HEPHAESTUS: Data analysis for X-ray absorption spectroscopy using IFEFFIT. *Journal of Synchrotron Radiation* 12, 537–541.
- RODRÍGUEZ-CARVAJAL, J. (1993) Recent Advances in Magnetic Structure Determination by Neutron Powder Diffraction. *Physica B: Condensed Matter* 192, 55–69.
- SAALFELD, H., WEDDE, M. (1974) Refinement of the Crystal Structure of Gibbsite, Al(OH)₃. *Zeitschrift für Kristallographie – Crystalline Materials* 139, 129–135.
- SALOMÉ, M., COTTE, M., BAKER, R., BARRETT, R., BENSENY-CASES, N., BERRUYER, G., BUGNAZET, D., CASTILLO-MICHEL, H., CORNU, C., FAYARD, B., GAGLIARDINI, E., HINO, R., MORSE, J., PAPILLON, E., POUYET, E., RIVARD, C., SOLÉ, V.A., SUSINI, J., VERONESI, G. (2013) The ID21 Scanning X-ray Microscope at ESRF. *Journal of Physics: Conference Series* 425, 1–5.
- SHANNON, R.D. (1976) Revised Effective Ionic Radii and Systematic Studies of Interatomic Distances in Halides and Chalcogenides. *Acta Crystallographica Section A: Foundations and Advances* A32, 751–767.
- SOLÉ, V.A., PAPILLON, E., COTTE, M., WALTER, P., SUSINI, J. (2007) A Multiplatform Code for the Analysis of Energy-Dispersive X-ray Fluorescence Spectra. *Spectrochimica Acta – Part B: Atomic Spectroscopy* 62, 63–68.
- VANTELON, D., TRCERA, N., ROY, D., MORENO, T., MAILLY, D., GUILLET, S., METCHALOV, E., DELMOTTE, F., LASSALLE, B., LAGARDE, P., FLANK, A.M. (2016) The LUCIA Beamline at SOLEIL. *Journal of Synchrotron Radiation* 23, 635–640.
- WASASTJERNA, J.A. (1924) Crystal Structure of Dolomite. *Societas Scientiarum Fennica. Commentationes Physicomathematicae II* 11, 14–14.
- WEI, P.H. (1935) Die Bindung im Quarz. *Zeitschrift für Kristallographie – Crystalline Materials* 92, 355–362.

