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Phenoxyl radical Fe^{III} complex of *cis,cis*-1,3,5-tris(3′,5′-di-*tert*-butylsalicylaldimino)cyclohexane, spectro-electrochemical and structural studies

Alison K. Nairn,[a] Rajiv Bhalla,[a] Simon P. Foxon,[a] Xiaoming Liu,[b] Lesley J. Yellowlees,[b] Bruce C. Gilbert[a] and Paul H. Walton *[a]

[a] *University of York, Heslington, York, UK YO10 5DD. E-mail: phw2@york.ac.uk*
[b] *University of Edinburgh, Kings Buildings, West Mains Road, Edinburgh, UK EH9 3JJ*

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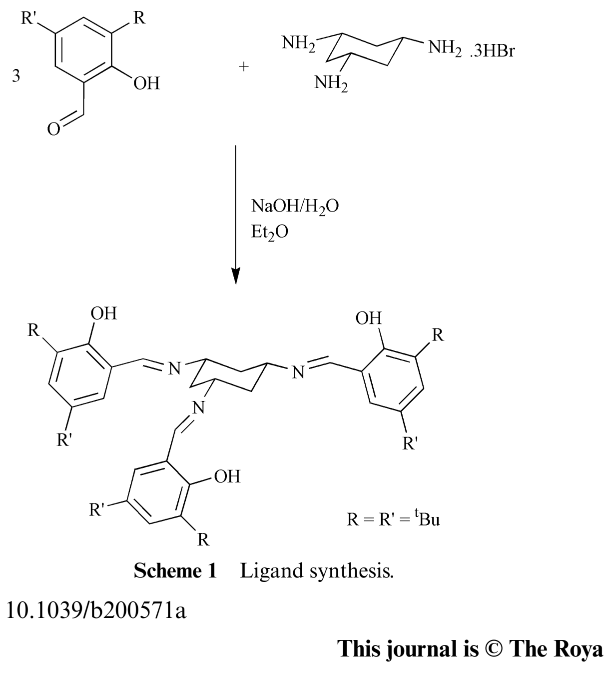
Complexation of *cis,cis*-1,3,5-tris(3′,5′-di-*tert*-butylsalicylaldimino)cyclohexane ($H_3t Bu_2$saltach) with M^{III} (M = Fe and Ga) followed by subsequent one electron oxidation results in the formation of stable phenoxyl-radical complexes.

The tyrosyl radical is known to play an essential role in the catalytic mechanisms of a range of metalloenzymes.[1] For instance galactose oxidase[2,3] and ribonucleotide reductase[4] both make use of stable tyrosyl radicals in their catalytic mechanisms. The catalytic efficiency of these metalloenzymes, and the low oxidation potentials for the formation of the tyrosyl radical, have led to an interest in the syntheses of model compounds that incorporate stable phenoxyl radicals. Several workers—most notably Wieghardt *et al.*—have shown that metal-phenoxyl complexes can be prepared, which provide insights into the chemical factors that govern the generation and stability of tyrosyl radicals.[5–7] Our own interest has centred around the preparation of very stable metal-phenoxyl radical complexes, in which the radical is stabilised through a combination of electronic and steric effects. Herein we report the synthesis of a novel tris-phenolate-tach ligand (tach = *cis,cis*-1,3,5-triaminocyclohexane)[8–10] and its corresponding Fe(III) complex. Our investigations demonstrate that by using this rigid N_3O_3 hexadentate ligand and appropriate substitution on the phenolate groups, very stable co-ordinated phenoxyl-radical complexes can be prepared easily.

cis,cis-1,3,5-tris(3′,5′-di-*tert*-butylsalicylaldimino)cyclohexane ($H_3t Bu_2$saltach) was synthesised in 55% yield by the condensation of 3,5-di-*tert*-butylsalicylaldehyde with tach (Scheme 1).† Intensely red coloured crystals of Fe($t Bu_2$saltach) (**1**) were prepared (>90% yield) by reacting $H_3t Bu_2$saltach with $Fe(NO_3)_3{\cdot}9H_2O$ in 1 : 1 MeOH–CH_2Cl_2.‡ The asymmetric unit of **1** contains two independent molecules of the Fe^{III} complex and a disordered dichloromethane of solvation. A view of one of the Fe complexes is presented in Fig. 1.§ In both Fe complexes, the Fe^{III} ion is co-ordinated by three imine nitrogens and three phenolate oxygens; the geometry around the FeN_3O_3 core is slightly deviated from octahedral (X–Fe–X angles; X = N, O: 83.3°–97.2°). The Fe–N and Fe–O distances are comparable with those found in related compounds with a FeN_3O_3 core.[11,12] Fig. 1 also demonstrates that the *t*Bu groups in the 3 position of each phenolate ring ‘cover’ one face of an adjacent phenyl ring.



Scheme 1 Ligand synthesis.

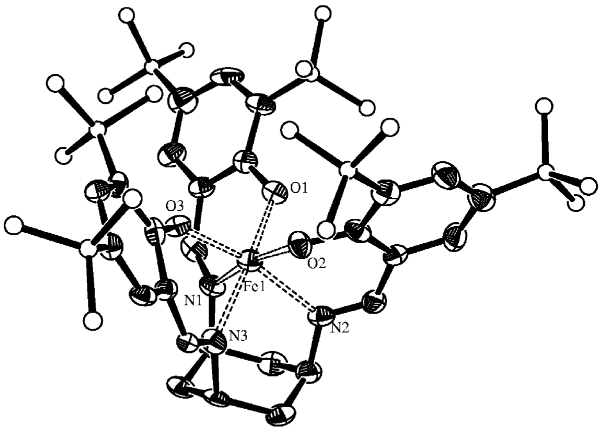


Fig. 1 ORTEP[21] view (30% probability ellipsoids) of the X-ray crystal structure of Fe$^{III}t Bu_2$saltach. Note that C atoms of *t*Bu groups are shown as isotropic spheres for clarity. Selected distances: Fe1–O2, 1.914(7); Fe1–O3, 1.916(7); Fe1–O1, 1.918(7); Fe1–N1, 2.101(8); Fe1–N3, 2.103(8); Fe1–N2, 2.125(8) Å.

The cyclic voltammogram (CV) of a solution of **1** in 0.5 mol dm^{-3} [*n*-NBu_4][BF_4] in CH_2Cl_2 (Fig. 2) was recorded over the region −2.0 V to +1.0 V (*vs.* $FeCp_2$/[$FeCp_2$]$^+$). Redox potentials are referenced *versus* the $FeCp_2$/[$FeCp_2$]$^+$ couple, (+0.55 V *vs.* Ag/AgCl).¶ The process at $E_{1/2}$ = −1.88 V (ΔE = 130 mV), is attributed to the Fe$^{II/III}$ couple of **1**. This process is reversible on the CV time scale ($i_a/i_c \approx 1$), however the process shows less reversibility than the ligand-based processes and attempts to isolate the Fe^{II} species by bulk electrolysis were unsuccessful.

There are three processes at anodic potentials. The two redox processes at potentials, $E_{1/2}$ = +0.20 V (ΔE = 80 mV) and $E_{1/2}$ = +0.55 V (ΔE = 70 mV), are attributed to the reversible successive one-electron oxidations of a phenolate to phenoxyl radical. A third process (+1.07 V) appears to be irreversible. Differential pulse experiments and coulometric studies of the ligand-based processes confirmed that only one electron is involved in each of the two reversible ligand oxidations. Bulk electrolysis at +0.45 V and +0.75 V yielded the intensely green coloured mono-cation [Fe($t Bu_2$saltach)]$^+$ (**2**) and the dark-blue

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Table 1 Redox potentials (*vs.* $FeCp_2/[FeCp_2]^+$) of Fe(*t*Bu$_2$saltach) in CH_2Cl_2 and CH_3CN compared to FeL[a]

Complex/solvent	Fe(II/III) couple	1st ligand oxidation	2nd ligand oxidation	Ref.
Fe(*t*Busaltach)/CH_2Cl_2	−1.88	0.20	0.55	This paper
Fe(*t*Busaltach)/CH_3CN	−1.89	0.30	0.60	This paper
FeL/CH_3CN	−1.78	0.38	0.65	13

[a] L = 1,4,7-tris(3,5-di-*tert*-butyl-2-hydroxy-benzyl)-1,4,7-triazacyclononane). All values in volts.

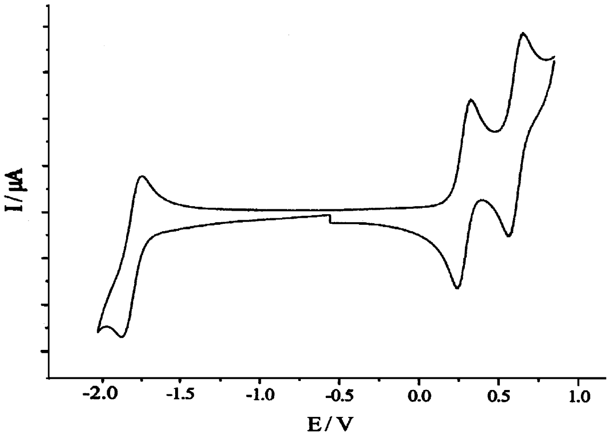

Fig. 2 Cyclic voltammogram of Fe^{III}*t*Bu$_2$saltach in 0.5 mol dm^{-3} [*n*-NBu_4][BF_4] in CH_2Cl_2. Referenced against ferrocene.

di-cation [Fe(*t*Bu$_2$saltach)]$^{2+}$ (**3**) respectively. Both **2** and **3** possess cyclic voltammograms identical to that seen for **1**; **2** can be quantitatively regenerated from **3** as can **1** from **2**.

A solution of **2** in CH_2Cl_2 in air at room temperature was generated chemically by the oxidation of **1** with the 'mild' oxidant $Cu(CF_3SO_3)_2$ or with $(NH_4)_2Ce(NO_3)_6$; remarkably this solution showed little change in its visible spectrum over a period of days. At higher temperatures (315 K) UV/visible spectroscopy showed that a CH_2Cl_2 solution of **2** decays with a half life of about 12 h to give back a solution of **1**. An electrochemical investigation of the analogous complex, Fe^{III}-(saltach)[9] (where R = R′ = H, see Scheme 1), which possesses no *t*Bu groups, showed no distinct oxidation or reduction processes whatsoever, demonstrating that the *t*Bu groups are essential for reversible redox processes. EPR spectra of frozen solutions of both **1** and **2** were featureless and uninformative.

Spectro-electrochemical studies of the two phenolate-phenoxyl radical redox processes reveal clean conversions of **2** to **1** and **3** to **2**. The UV/vis spectrum of **1** is characterised by the presence of an intense absorption at 510 nm (ε = 4520 dm^3 mol^{-1} cm^{-1}) due to the phenolate to Fe^{III} ligand to metal charge transfer (LMCT). One-electron oxidation to **2** results in the growth of a band at 405 nm (3940 dm^3 mol^{-1} cm^{-1}) due to the phenoxyl radical to Fe^{III} LMCT[13,14] and a decrease in the intensity of the phenolate to Fe^{III} LMCT band (2400 dm^3 mol^{-1} cm^{-1}). Further oxidation to **3** results in an increase in intensity of the band at 405 nm (5100 dm^3 mol^{-1} cm^{-1}) and a further decrease in the phenolate to Fe^{III} LMCT band (1060 dm^3 mol^{-1} cm^{-1}). The growth of another band at 930 nm (3770 dm^3 mol^{-1} cm^{-1}) corresponds well with bands associated with the phenoxyl radical seen in previous metal-phenoxyl complexes.[15]

The corresponding complex [Ga(*t*Bu$_2$saltach)] (**4**) was also prepared.‖ The complex shows analogous ligand redox behaviour (two pseudo reversible anodic potentials at $E_{1/2}$ = 0.46 and 0.71 V). Remarkably, the complex oxidises aerobically to give a red/orange-coloured material (**5**). This oxidised complex has a simple four line EPR spectrum (g = 2.0049, A = 0.49 mT) which is readily interpreted as a phenoxyl radical coordinated to the Ga^{III} centre (^{69}Ga and ^{71}Ga both have I = 3/2 and so the spectrum suggests that some of the spin density resides at the metal centre). **5** has a cyclic voltammogram identical to **4**.

Table 1 includes a comparison of the redox properties of **1** with Fe^{III}L [where L is 1,4,7-tris(3,5-di-*tert*-butyl-2-hydroxy-benzyl)-1,4,7-triazacyclononane].[13] The low potential for phenolate oxidation of **1** to **2** and **3** shows that the phenoxyl radicals in **2** and **3** are very stable. The high stability of the phenoxyl radicals in **2** and **3** can be explained using a combination of steric and electronic arguments. First, the steric bulk of the *tert*-butyl groups not only prevents radical decomposition by dimerisation,[16,17] but also provides steric protection of adjacent phenoxyl radicals in the complex (Fig. 1). Second, the phenoxyl radicals in **2** and **3** are held in a very rigid conformation by the tach, and, therefore, the phenoxyl radicals in **2** and **3** cannot dissociate easily from the Fe^{III} ion (The irreversible process at +1.07 V can be assigned to the oxidation of the third phenolate followed by a chemical reaction, probably the loss of coordination of the ligand). Delocalisation of the unpaired electron density probably occurs over the whole salicylimine moiety and onto the metal centre (with the +I *tert*-butyl groups stabilising the unpaired electron still further).

We have demonstrated that by using a rigid and sterically demanding novel tach-based phenolate ligand we can generate metal complexes, which can easily be oxidised to give highly stable metal-phenoxyl complexes. From this work, phenoxyl-radical stability appears to be linked to steric bulk along with a conformationally rigid co-ordination of the phenoxyl to the metal.

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Notes and references

† *cis*,*cis*-1,3,5-tris(3′,5′-di-*tert*-butylsalicylaldimino)cyclohexane, H_3*t*Bu$_2$saltach: A solution of tach·3HBr[10] (0.81 g, 2.2 mmol) and NaOH (0.27 g, 6.8 mmol) in water (10 mL) was added to 3,5-di-*tert*-butylsalicylaldehyde (1.53 g, 6.6 mmol) in Et_2O (10 mL). The mixture was stirred for *ca.* 12 h and the resultant yellow precipitate was collected by filtration, washed with MeOH and dried under vacuum. Yield 0.93 g (55%); ^1H NMR (270 MHz, $CDCl_3$): δ 8.4 (s, 3H, –CH=N–), 7.3 (d, J = 2 Hz, 3H), 7.0 (d, J = 2 Hz, 3H), 3.5 (m, 3H), 2.0 (m, 6H), 1.4 (s, 27H, *t*Bu), 1.2 (s, 27H, *t*Bu). ^{13}C NMR DEPT (270 MHz, $CDCl_3$): δ 29 (CH_3), 31 (CH_3), 34 (C), 35 (C), 41 (CH_2), 64 (CH), 118 (C), 126 (CH), 127 (CH), 137 (C), 140 (C), 158 (C), 165 (CH). MS (EI): *m*/*z* 777.4 (M^+). IR/cm^{-1} (KBr pressed disk): 3352 (m), 3480 (m), 3415 (s), 3957 (s), 2907 (m), 2870 (m), 1631 (s, –CH=N–), 1459 (s), 1441 (s), 1381 (m), 1361 (m), 1273 (m), 1252 (m), 1201 (m), 1174 (m), 1125 (w), 1016 (w), 877 (w), 774 (m). Calc. for $C_{51}H_{75}O_3N_3$: C 78.70, H 9.70, N 5.40. Found C 78.90, H 9.75, N 5.15%.

‡ Fe^{III}(*t*Bu$_2$saltach) (**1**): A solution of $Fe(NO_3)_3 \cdot 9H_2O$ (54 mg, 0.13 mmol) in MeOH (10 mL) was added to H_3*t*Bu$_2$saltach (103 mg, 0.13 mmol) in CH_2Cl_2 (10 mL). Stirring for 1 h at room temperature resulted in the formation of an intensely coloured purple solution. Evaporation of the solvent yielded **1** as intensely coloured red crystals. Yield 104 mg (98%); MS (FAB): *m*/*z* 830.5 (M^+). IR/cm^{-1} (KBr pressed disk): 3447 (w), 2951(s), 2903 (m), 2867 (m), 1624 (s, –CH=N–), 1610 (s), 1534 (m), 1465 (w), 1411 (m), 1388 (m), 1317 (m), 1247 (m), 1168 (w), 1130 (w), 835 (w), 784 (w). Calc. for $C_{51}H_{72}O_3N_3Fe \cdot 1/2CH_2Cl_2$: C 70.90, H 8.38, N 4.81. Found C 71.50, H 8.45, N 4.95%.

§ Crystal structure analysis for **1**: $C_{51}H_{72}N_3O_3Fe$. The asymmetric unit cell contains two crystallographically independent molecules of Fe(III)*t*Bu$_2$saltach and a dichloromethane molecule disordered over two closely adjacent sites, $C_{102}H_{144}N_6O_6Fe_2 \cdot CH_2Cl_2$, M_r = 1746.92, red block, crystal dimensions 0.60 × 0.40 × 0.30 mm, triclinic, space group $P\bar{1}$ (no. 2), a = 16.709(18), b = 19.77(2), c = 16.444(12) Å, β = 108.58(6)°, V = 5014(9) Å^3, T = 293(2) K, Z = 2, ρ_{calc} = 1.157 g cm^{-3}, μ(Mo-Kα) = 0.396 mm^{-1}, F(000) = 1880, MSC Rigaku AFC6S four-circle diffractometer, λ = 0.71069 Å, $\omega/2\theta$ scan, 14079 measured reflections, of which 13519 are symmetry-independent reflections in the range $1.78 \le \theta \le 22.90°$, R_{int} = 0.1186, 3529 reflections with $F_o > 4\sigma(F_o)$, Lorentz and polarization correction, absorption correction PSI scan, min./max. transmission 0.797/0.891, structure solution was by direct methods and expanded using Fourier techniques with DIRDIF94,[19] full-matrix least-squares refinement against F_o^2 (SHELXL-97)[20] with all non-hydrogen atoms anistropic and hydrogens refined using a rigid model, 1135 parameters, 11 restraints, $R1_{obs} = 0.0625$ and $wR2_{obs} = 0.1291$, GooF = 0.940, min./max. residual electron density $-0.402/0.305$ e Å^{-3}. CCDC reference number 168207. See http://www.rsc.org/suppdata/dt/b2/b200571a/ for crystallographic data in CIF or other electronic format.

¶ Cyclic voltammetry was performed using a standard three-electrode configuration with platinum working (0.5 mm diameter disk) and counter electrodes and a Ag/AgCl reference which gave the FeCp/[FeCp$^+$] couple at +0.55 V at 20 °C. Bulk electrolyses were executed in an 'H-type' cell with platinum basket and mesh as working and counter electrodes, respectively. All measurements were made in a nitrogen-purged solution of CH_2Cl_2/0.5 mol dm^{-3} [*n*-Bu$_4$N][BF$_4$], over a range of scan rates (from 50 to 500 mV s^{-1}). *In situ* UV/vis/near-IR spectroelectrochemistry was performed on solutions in CH_2Cl_2/0.5 mol dm^{-3} [*n*-Bu$_4$N][BF$_4$] at 0 °C in an OTTLE cell in a Perkin-Elmer Lambda 9 spectrometer.[18]

|| Ga^{III}*t*Bu$_2$saltach: H$_3$*t*Bu$_2$saltach (51.9 mg, 0.07 mmol, 1.00 equiv.) was dissolved in CH_2Cl_2 (25 mL) to give a yellow solution. $Ga(NO_3)_3\cdot xH_2O$ (18.9 mg, 0.07 mmol, 1.00 equiv.) was dissolved in MeOH (25 mL) to give a colourless solution. The two solutions were added together, no colour change was observed, the solution was then left to stir for 18 h. The volume of solvent was reduced and an orange powder formed which was collected and dried under vacuum (30.9 mg, 55%, 0.04 mmol). MS (ES): *m*/*z* = 845 (M$^+$). IR/cm^{-1} (KBr pressed disk): 2955 (s), 2903 (m), 2869 (m), 1642 (s), 1617 (s, –CH=N–), 1594 (m), 1534 (w), 1465 (w), 1416 (m), 1384 (s), 1361 (m), 1315 (s), 1273 (m), 1170 (w), 1132 (w), 1026 (w), 967 (w), 833 (w), 785 (w), 721 (w), 668 (s).

1 J. Stubbe and W. A. van der Donk, *Chem. Rev.*, 1998, **98**, 705.

2 J. W. Whittaker, in *Metalloenzymes Involving Amino Acid Residues and Related Radicals*, H. Sigel and A. Sigel, eds., Marcel Dekker, New York, 1994, vol. 30, p. 315.

3 P. F. Knowles, N. Ito, *Perpectives in Bio-inorganic Chemistry*, vol. 2, R. W. Hay, J. R. Dilworth and K. B. Nolan, eds., Jai, London, 1994, p. 207.

4 P. Norlund, B.-M. Sjöberg and H. Eklund, *Nature*, 1990, **345**, 593.

5 (*a*) P. Chaudhuri, M. Hess, U. Flörke and K. Wieghardt, *Angew. Chem., Int. Ed.*, 1998, **37**, 2217; (*b*) P. Chaudhuri, M. Hess, T. Weyhermüller and K. Wieghardt, *Angew. Chem., Int. Ed.*, 1999, **38**, 1095; (*c*) P. Chaudhuri, M. Hess, K. Hildenbrand, E. Bill, T. Weyhermüller and K. Wieghardt, *Inorg. Chem.*, 1999, **38**, 2781; (*d*) P. Chaudhuri, M. Hess, J. Müller, K. Hildenbrand, E. Bill, T. Weyhermüller and K. Wieghardt, *J. Am. Chem Soc.*, 1999, **121**, 9599.

6 Y. Wang, J. L. Dubois, B. Hedman, K. O. Hodgson and T. D. P. Stack, *Science*, 1998, **279**, 537.

7 (*a*) B. A. Jazdzewski and W. B. Tolman, *Coord. Chem. Rev.*, 2000, **200**, 633; (*b*) J. A. Halfen, B. A. Zazdzewski, S. Mahapatra, L. M. Berreau, E. C. Wilkinson, L. Que and W. B. Tolman, *J. Am. Chem. Soc.*, 1997, **119**, 8217; (*c*) C. N. Verani, E. Bothe, D. Burdinski, T. Weyhermüller, U. Flörke and P. Chaudhuri, *Eur. J. Inorg. Chem.*, 2001, 2161; (*d*) L. Benisvy, A. J. Blake, D. Collison, E. S. Davies, C. D. Garner, E. J. L. McInnes, J. McMaster, G. Whittaker and C. Wilson, *Chem. Commun.*, 2001, 1824.

8 (*a*) J. E. Bollinger, J. T. Mague, C. J. O'Connor, W. A. Banks and D. M. Roundhill, *J. Chem. Soc., Dalton. Trans.*, 1995, 1677; (*b*) J. E. Bollinger, W. A. Banks, A. J. Kastin and D. M. Roundhill, *Inorg. Chim. Acta*, 1996, **242**, 201; (*c*) J. E. Bollinger, J. T. Mague, W. A. Banks, A. J. Kastin and D. M. Roundhill, *Inorg. Chem.*, 1995, **34**, 2143; (*d*) J. E. Bollinger, J. T. Mague and D. M. Roundhill, *Inorg. Chem.*, 1994, **33**, 1241.

9 D. A. Rudman, J. C. Huffman, R. F. Childers, W. E. Streib and R. A. D. Wentworth, *Inorg. Chem.*, 1975, **14**, 747.

10 T. Bowen, R. P. Planalp and M. W. Brechbiel, *Bioorg. Med. Chem. Lett.*, 1996, **6**, 810.

11 D. F. Cook, D. Cummins and E. D. Mckenzie, *J. Chem. Soc., Dalton. Trans.*, 1976, 1369.

12 Y. Elerman, M. Kabak, I. Sroboda, H. Fuess and O. Atakol, *J. Chem. Crystallogr.*, 1995, **25**, 227.

13 B. Adam, E. Bill, E. Bothe, B. Goerdt, G. Haselhorst, K. Hildenbrand, A. Sokolowski, S. Steenken, T. Weyhermüller and K. Wieghardt, *Chem. Eur. J.*, 1997, **3**, 308.

14 S. Itoh, S. Takayama, R. Arakawa, A. Furuta, M. Komatsu, A. Ishida, S. Takamuku and S. Fukuzumi, *Inorg. Chem.*, 1997, **36**, 1407.

15 (*a*) M. A. Halcrow, L.-M.-L. Chiu, X. Liu, E. J. L. McInnes, L. J. Yellowlees, F. E. Mabbs and J. E. Davies, *Chem. Commun.*, 1998, 2465; (*b*) M. L. McGlashen, D. D. Eads, T. G. Spiro and J. W. Whittaker, *J. Phys. Chem.*, 1995, **99**, 4918; (*c*) M. M. Whittaker, P. J. Kersten, N. Nakamura, J. Sanders-Loehr, E. S. Schweizer and J. W. Whittaker, *J. Biol. Chem.*, 1996, **271**, 681.

16 (*a*) A. Sokolowski, J. Müller, T. Weyhermüller, R. Schnepf, P. Hildebrandt, K. Hildenbrand, E. Bothe and K. Wieghardt, *J. Am. Chem. Soc.*, 1997, **119**, 8889; (*b*) A. Sokolowski, E. Bothe, E. Bill, T. Weyhermüller and K. Wieghardt, *Chem. Commun.*, 1996, 1671; (*c*) J. Müller, T. Weyhermüller, E. Bill, P. Hildebrandt, L. Ould-Moussa, T. Glaser and K. Wieghardt, *Angew. Chem., Int. Ed.*, 1998, **37**, 616; (*d*) A. Sokolowski, H. Leutbecher, T. Weyhermüller, R. Schnepf, E. Bothe, E. Bill, P. Hildebrandt and K. Wieghardt, *J. Biol. Inorg. Chem.*, 1997, **2**, 444.

17 Y. Wang and T. D. P. Stack, *J. Am. Chem. Soc.*, 1996, **118**, 13097.

18 S. A. MacGregor, E. J. L. McInnes, R. J. Sorbie and L. J. Yellowlees, in *Molecular Electrochemistry of Inorganic, Bioinorganic and Organometallic Compounds*, A. J. L. Pombeiro and J. A. McCleverty, eds., Kluwer, Dordrecht, 1993, p. 503.

19 (*a*) teXsan, Single Crystal Structural Analysis Software, version 1.7, Molecular Structure Corporation, 3200 Research Forest Drive, The Woodlands, TX 778381, USA, 1997; (*b*) P. T. Beurskens, G. Admiraal, G. Beurskens, G. Bosman, W. P. Garcia-Granda, R. O. Gould, J. M. M. Smits and C. Smykalla, The DIRDIF program system, Technical report of the crystallography laboratory, University of Nijmegen, The Netherlands, 1992.

20 G. M. Sheldrick, SHELXL97, Program for the Refinement of Crystal Structures, University of Göttingen, Germany, 1997.

21 C. K. Johnson, ORTEP-II, A FORTRAN Thermal Ellipsoid Plot Program, Report ORNL-5138, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1976.