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Technetium and rhenium oxo-complexes of new tetradentate ligands with N_2S_2 and NS_3 donor sets†

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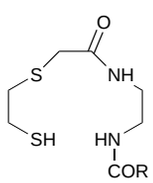
A series of new tetradentate, nitrogen–sulfur donor proligands with amido or amino donor groups have been synthesized and their rhenium and technetium oxo-complexes prepared. The substitution pattern and length of the ligand backbone can be varied without affecting the co-ordination chemistry. The NS_3H_3 amido-proligands reacted rapidly with the technetium(V) precursor $[TcOCl_4]^-$ at reflux in methanol to give the technetium(IV) species $[TcO(NS_3)]^-$ in very high radiochemical purity (*ca.* 100%), but these complexes decompose over a period of hours or days. They also reacted with the rhenium(V) precursors $[ReO_2(py)_4]Cl$ (py = pyridine) or $[ReOCl_3(PPh_3)_2]$ at reflux in methanol, but only in the presence of a base. Stable neutral rhenium(V) complexes of the type $[ReO(NS_3)]$ were formed, and the crystal structures of two determined. A reduced amino version of the NS_3H_3 proligand gave an analogous $[ReO(NS_3)]$ complex, and its crystal structure was determined.

Technetium, as the radioisotope ^{99m}Tc, is the isotope of choice for many diagnostic nuclear medicine applications due to its virtually ideal characteristics.[1] However, it is only produced at very low concentrations and has a half-life of only about 6 h. Consequently, the study of its co-ordination chemistry is difficult. The long-lived isotope ^{99}Tc can be safely handled in milligram quantities and is therefore generally used for chemical and structural studies. Rhenium is of interest not only because it forms many complexes which are directly analogous to those of technetium, but also because the β-emitting radionuclide ^{188}Re has potential therapeutic applications in nuclear medicine.

Complexes of technetium, as $[TcO]^{3+}$, with ligands possessing a tetradentate N_2S_2 donor set are well known.[2] The stability and versatility of such complexes is demonstrated by the wide range which has been published. However, the N_2S_2 ligands used to date have invariably featured both sulfur atoms as terminal thiol groups and both nitrogen atoms as part of the ligand backbone. If the nitrogen atoms are not derivatised, *i.e.* they are secondary amines or amides, then there are four labile protons. Only three of these should be removed to give a trianion which will form neutral complexes with the technetium core $[Tc{=}O]^{3+}$.

We have attempted to prepare complexes of ^{99}Tc with hydrophilic N_2S_2 ligands of the general formula shown in which there is one terminal thiolate sulfur and one terminal carboxamide group. Variants with substituents capable of forming links to biomolecules were also prepared by derivatisation of the terminal carboxamide. These compounds have only three labile protons and it was hoped that they would readily form stable, neutral complexes with a $[Tc{=}O]^{3+}$ core. As has been reported in a previous communication,[3] stable complexes were formed at the technetium-99m level and found to have very promising preliminary biodistribution characteristics. At the technetium-99 level, however, we found it very difficult to form or isolate pure technetium-99 complexes with these compounds. While the reasons are not entirely clear, it may be that the thioether and thiolate sulfurs are slightly better donors than the nitrogens for Tc in these complexes and so unstable 2:1 (ligand:metal) complexes may form, with each ligand bound only through the sulfur atoms. Such complexes would be stable at the technetium-99m level, where the ligand would be present in a large excess.



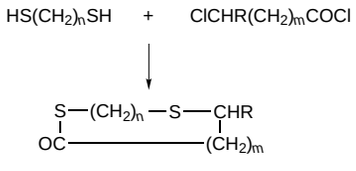
The outcome of the complexation reaction between these compounds and technetium-99 precursors was very sensitive to the nature of the terminal N-substituent, indicating that steric or small electronic factors affect the affinity of the proligand for $[TcO]^{3+}$. This is consistent with the amide nitrogen being relatively weakly bound. Kinetic studies with S-substituted N_2S_2 compounds have also suggested that it is the thiol groups of a polydentate ligand which are of primary importance in dictating the stability of a complex with Tc.[4]

Owing to these difficulties with this class of N_2S_2, potentially trianionic ligands, we endeavoured to design dithiolates which would form neutral monooxotechnetium(V) complexes and be capable of derivatisation in a straightforward manner. It was reasoned that an NS_3 ligand, with two terminal thiolate donor atoms, would meet these requirements. We were also interested to observe the effects of imposing an asymmetric co-ordination about the metal ion.

We here report the synthesis of such a range of NS_3 compounds of general formula shown in Scheme 2 and the results of our attempts to form complexes with both ^{99}Tc and Re. While this work was in progress a patent was published which showed that a similar type of proligand, prepared in analogous fashion, could be effectively used at the technetium-99m level to conjugate a technetium-99m oxo-core to a peptide or peptide fragment.[5] However it made no mention of the synthesis of complexes of ^{99}Tc or Re or of proligands with longer carbon backbones.

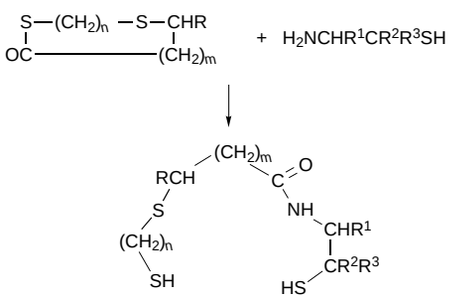
The synthesis of the 'expanded' NS_3 proligand H_3L^2, from the seven-membered, cyclic mercapto-thioester **2**, also reported here, is new. Attempts to prepare the corresponding H_3L^3 from the seven-membered **3** were not successful.

† *Non-SI unit employed:* mmHg ≈ 133 Pa.

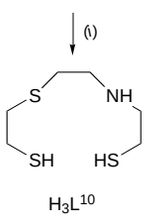


1 m = 0, n = 2, R = H
2 m = 0, n = 3, R = H
3 m = 1, n = 2, R = H
4 m = 0, n = 2, R = Me
5 m = 0, n = 2, R = Ph

Scheme 1



Ligand	m	n	R^1	R^2	R^3	R
H_3L^1	0	2	H	H	H	H
H_3L^2	0	3	H	H	H	H
H_3L^3	1	2	H	H	H	H
H_3L^4	0	2	CO_2Et	H	H	H
H_3L^5	0	2	H	Me	Me	H
H_3L^6	0	2	H	H	H	Me
H_3L^7	0	2	H	Me	Me	Me
H_3L^8	0	2	H	H	H	Ph
H_3L^9	0	2	H	Me	Me	Ph
H_3L^{10}	0	2	H	H	H	H



H_3L^{10}

Scheme 2 *i*, reduction, BH_3, thf R = R^1 = R^2 = R^3 = H, *m* = 0, *n* = 2 only

Results and Discussion

Synthesis of proligands and precursors

The cyclic mercapto-thioesters **1**–**5** were synthesized according to the general method shown in Scheme 1, and the NS_3H_3 pro-ligands according to Scheme 2.

Although a derivative of the seven-membered cyclic mercapto-thioester **2** has been prepared previously,[6] the method we have used is considerably more straightforward. Also, the use of seven-membered rings in the synthesis of tetradentate nitrogen–sulfur donor pro-ligands with enlarged chelate rings (H_3L^2 and H_3L^3) is unprecedented. It is curious that while H_3L^2 was readily prepared from **2**, H_3L^3 could not be prepared from the surprisingly unreactive **3**. We also attempted to prepare expanded analogues of H_3L^4 by using the ethyl ester of homocysteine [$HS(CH_2)_2CH(CO_2Et)NH_2$] instead of that of cysteine [$HSCH_2CH(CO_2Et)NH_2$], but were unable to find a suitable solvent in which the reagents were mutually soluble. Other variants of the proligands were prepared in a straightforward manner from the appropriate cyclic thioester and dithiol. The reduced proligand H_3L^{10} was prepared by treatment of H_3L^1 with borane in tetrahydrofuran (thf) under reflux.

Synthesis of rhenium complexes

The common rhenium(V) precursors [$ReOCl_3(PPh_3)_2$] and [$ReO_2(py)_4$]Cl (py = pyridine) both reacted with proligands H_3L^1, H_3L^2 and H_3L^4–H_3L^{10} (H_3L^3 was not successfully prepared) to form the neutral complexes [$ReO(L^n)$]. The reactions were carried out in methanol under reflux in the presence of sodium acetate and under a nitrogen atmosphere. No reaction occurred with the precursors in the absence of a base (sodium acetate). The choice of base and solvent were also important, and no pure complexes could be isolated using triethylamine–methanol or –thf. Significantly in terms of their possible application for radiopharmaceuticals, we have also been able to prepare the same [ReO(L)] complexes directly from perrhenate with the addition of citric acid (3-carboxy-3-hydroxypentane-1,5-dioic acid) and $SnCl_2$ as the reducing agent. In the absence of citric acid only intractable black solids were obtained. The HPLC of the reaction solutions immediately after the reflux, for all precursors including perrhenate, showed that although isolated yields were low a single product predominated, and that the retention times were identical to those of the finally isolated products. Only in the cases where [$ReOCl_3(PPh_3)_2$] was used as precursor a small variable amount (< 5%) of insoluble green solid was formed which was filtered off but not identified.

Complexes of the asymmetric tetradentate ligands without substituents on the backbone exist in principle in two isomeric forms, differing in the disposition of the Re=O group. These are non-superimposable enantiomers. As expected only one isomer is observed in solution by NMR spectroscopy or HPLC which are unable to discriminate between the two forms. There are also possible isomers involving different conformations of the backbones which should occur for all of the complexes, but are not apparently observed. The introduction of one or three substituents onto the backbone as in proligands H_3L^6–H_3L^9 results in two further possible isomers, differing in the orientation of the substituent R or R′ with respect to the Re=O group (*syn* and *anti* forms). However the presence of isomers in solution was observed by NMR spectroscopy and HPLC (comparable ratios with both techniques) only for complexes [$ReO(L^4)$], [$ReO(L^7)$] and [$ReO(L^9)$]. The reasons for this are not entirely clear, but it appears that the steric hindrance offered by the two methyl groups adjacent to a thiolate sulfur in the last two complexes above may prevent facile equilibration between the isomers.

All the new rhenium complexes were fully characterised by elemental analysis, IR, FAB and ^1H and ^{13}C NMR spectroscopy. Where necessary, full assignments of peaks in the ^1H and ^{13}C NMR spectra were made using two-dimensional correlated spectroscopy (COSY). In the case of [$ReO(L^1)$], [$ReO(L^2)$] and [$ReO(L^{10})$], crystals suitable for X-ray diffraction analysis were grown from dichloromethane–isopropyl alcohol.

Crystal structures of [$ReO(L^1)$], [$ReO(L^2)$] and [$ReO(L^{10})$]

The ORTEP views of the three structures appear in Figs. 1–3, details of the determinations in Table 1 and selected bond lengths and angles in Table 2.

The three structures are generally similar, and the increase in backbone segment length (L^2 complex) and reduction of the carboxamide group (L^{10} complex) cause relatively little variation in the bond distances and angles. The overall structures can be described as square pyramidal with the oxygen at the apical position and the basal plane comprising S(1), S(2), N and S(3). The chief effect of introducing the trimethylene backbone in the complex of L^2 is to contract the O–Re–N(1) angle with a concomitant increase in the N–Re–S(1) angle; other parameters are remarkably similar. A least-squares plane analysis for N, Re, C(5) or C(4) and C(5) or C(6) shows that the nitrogen atoms are virtually planar in the amide complexes whereas in the reduced species the nitrogen is more pyramidal with the nitrogen an average (over the two molecules in the unit cell) of 0.26 Å above the plane.

Table 1 Details of crystal structure determinations

	[ReO(L^1)]	[ReO(L^2)]	[ReO(L^{10})]
Empirical formula	$C_6H_{10}NO_2ReS_3$	$C_7H_{12}NO_2ReS_3$	$C_6H_{12}NOReS_3$
Formula weight	410.53	424.56	396.54
Scan rate/° min^{-1}	1–7 (in ω)		1–7 (in ω)
Crystal system	Orthorhombic	Orthorhombic	Monoclinic
Space group	*Pbca*	$Pna2_1$	*Pn*
a/Å	10.688(3)	10.706(4)	11.495(3)
b/Å	13.785(5)	14.866(10)	7.1182(2)
c/Å	14.204(4)	7.030(5)	13.020(4)
U/Å^3	2092.8(10)	1118.9(12)	1058.2(5)
Z	8	4	4
D_c/Mg m^{-3}	2.606	2.520	2.489
μ/mm^{-1}	12.178	11.393	12.030
F(000)	1536	800	744
Crystal size/mm, colour	0.42 × 0.42 × 0.42, dark red	0.28 × 0.07 × 0.07, dark brown	0.23 × 0.12 × 0.12, dark brown
θ Range for data collection/°	2.81–24.95	2.34–25.03	2.24–24.98
h,*k*,*l* Ranges	−12 to 0, −16 to 0, −16 to 0	−11 to 11, −16 to 16, −5 to 7	−13 to 13, 0–8, 0–15
Reflections collected	1842	4481	1946
Independent reflections	1842	1598 (R_{int} = 0.1447)	1946
Standard decay correction (%)	1.5		2.4
Weighting scheme, w^{-1}	$[\sigma^2(F_o)^2 + (0.0672P)^2 + 7.6221P]$	$[\sigma^2(F_o)^2 + (0.0839P)^2]$	$[\sigma^2(F_o)^2 + (0.0455P)^2 + 3.4269P]$
Data, restraints, parameters	1842, 0, 159	1543, 7, 128	1946, 44, 215
Goodness of fit on F^2	1.070	1.096	1.032
*R*1, *wR*2 (all data)	0.0356, 0.0960	0.0645, 0.1665	0.0283, 0.0665
Largest difference peak and hole/e Å^{-3}	2.330, −1.283	4.039, −2.383	1.541, −1.241
Maximum shift/e.s.d.	0.255	−0.001	0.063

Table 2 Comparison of selected bond lengths (Å) and angles (°)

			[ReO(L^{10})]	
	[ReO(L^1)]	[ReO(L^2)]	Molecule 1	Molecule 2
Re–O	1.686(5)	1.703(9)	1.689(11)	1.72(2)
Re–N	2.003(6)	2.015(11)	2.09(2)	1.99(2)
Re–S(3)	2.293(2)	2.294(4)	2.282(7)	2.276(5)
Re–S(1)	2.281(2)	2.303(4)	2.303(5)	2.309(8)
Re–S(2)	2.368(2)	2.406(4)	2.330(6)	2.385(5)
C(3)–O	1.217(10)	1.27(2)		
C–N	1.378(10) [C(4)–N]	1.34(2) [C(5)–N]	1.44(2) [C(4)–N]	1.47(2) [C(04)–N]
O–Re–N	119.8(3)	114.8(5)	118.8(7)	112.0(8)
O–Re–S(1)	114.5(2)	111.9(3)	111.0(4)	114.3(6)
N–Re–S(1)	125.5(2)	133.3(3)	137.0(5)	133.5(5)
O–Re–S(3)	106.6(2)	105.4(4)	109.2(5)	110.4(5)
N–Re–S(3)	81.9(2)	82.8(3)	82.9(5)	82.0(4)
S(1)–Re–S(3)	86.13(7)	85.8(3)	87.0(2)	86.1(2)
O–Re–S(2)	100.3(2)	102.3(3)	101.7(5)	100.3(5)
N–Re–S(2)	82.3(2)	81.2(3)	81.3(4)	82.0(4)
S(1)–Re–S(2)	85.27(7)	88.5(2)	86.4(2)	85.9(2)
S(2)–Re–S(3)	152.87(7)	151.84(14)	148.7(2)	148.9(2)

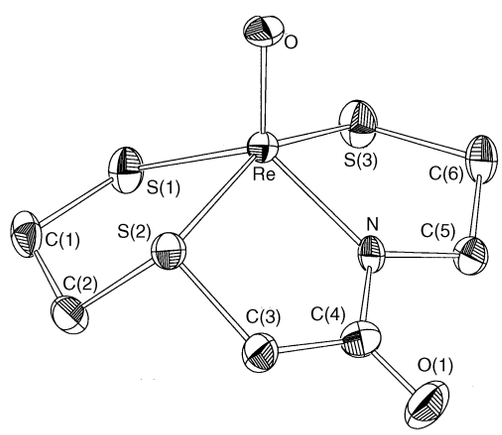


Fig. 1 An ORTEP[7] representation of the structure of [ReO(L^1)] showing the atom labelling scheme

Synthesis of technetium-99 complexes

The proligand H_3L^1 (*ca*. 2 equivalents) reacted rapidly with $[NBu_4][TcOCl_4]$ in methanol at reflux to produce a pure, single technetium species (as shown by HPLC, β and UV detection, and by analytical TLC) which remained in solution and an insoluble precipitate. The HPLC measurements on the technetium complexes were made using a mixed-solvent system and are not directly comparable to the data reported elsewhere in the paper for the rhenium complexes nor to the data in ref. 5 for ^{99m}Tc. The technetium complex of L^1 was easily isolated as an amber coloured oil, but decomposed over a period of days. A peak at 948 cm^{-1} in the IR spectrum of the freshly prepared product was assigned to a Tc=O stretch, although it was weaker than would normally be expected for this vibration. No peaks which could be assigned to ν(NH) or ν(SH) were seen. The ^{1}H and ^{13}C NMR spectra showed only peaks which could be attributed to NBu_4^+, and no peaks for the bound ligand were seen. This indicates that the product is both NMR silent and anionic, both of which can be understood if we formulate the product as a paramagnetic technetium(IV) species $[NBu_4][Tc^{IV}O(L^1)]$. Further characterisation was not possible because of decomposition.

The complex has an HPLC retention time of 9 min (aqueous NaO_2CMe–thf, solvent gradient), and over a period of several hours decomposes to a secondary product having a retention time of 6 min. We have some qualitative HPLC evidence which indicates that this step is at least partially reversed when a base (NaOMe) is added, and the oxotechnetium(IV) complex is reformed. The secondary product in turn decomposes to a species with a retention time of about 2 min, similar to that of $[NBu_4][TcO_4]$. This decomposition product has been isolated by column chromatography, and an IR spectrum contained a very strong peak at 895 cm^{-1}. This is attributed to the Tc–O stretching vibration of $[TcO_4]^-$, and indicates that the complex has decomposed to pertechnetate which necessarily involves oxidation of the technetium core. As yet we have been unable to isolate the initial decomposition product having a retention time of 6 min. Direct comparison of our results with those obtained in the technetium-99m work of ref. 5 is not possible as different HPLC systems were used.

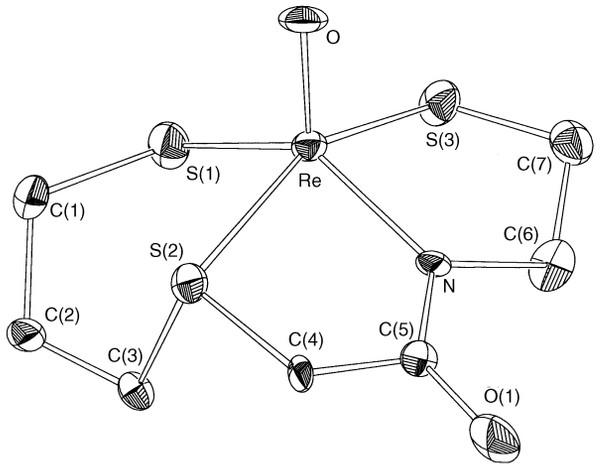


Fig. 2 An ORTEP representation of the structure of [ReO(L^2)] showing the atom labelling scheme

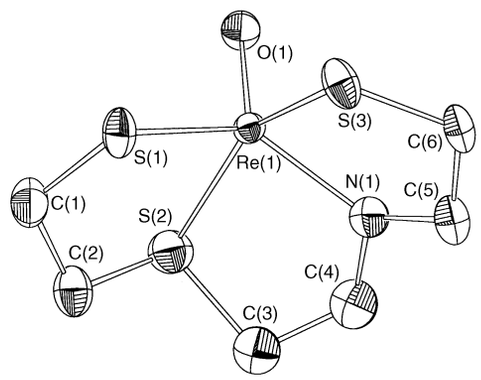


Fig. 3 An ORTEP representation of one of the two non-equivalent molecules of [ReO(L^{10})] showing the atom labelling scheme

When the reaction between $[TcOCl_4]^-$ and H_3L^1 is carried out in the presence of a base (NaO_2CMe), the same technetium species is formed. The formation of the latter occurs in the absence of base, in contrast to the rhenium complexes. This is probably due to the greater substitutional lability of the technetium core.

A similar product was formed from the reaction between $[NBu_4][TcOCl_4]$ and proligand H_3L^4. In this case, the CO_2Et substituent acts as a model for the precursor of a complex in which the Tc–NS_3 moiety is coupled to a small, biologically active molecule *via* an activated ester group. In all other respects (^{1}H, ^{13}C NMR, HPLC retention time) the products were very similar. This product has a HPLC retention time of 8.5 min and also decomposes to species having retention times of 5.5 and 2 min. We have not examined this decomposition.

With proligand H_3L^2 the reaction appeared to proceed in an analogous manner. Analysis of the crude product by HPLC indicated that the major product was a technetium species with retention time of 9 min, but there were two other, relatively minor technetium species having retention times of 2 and 6 min. An attempt to purify the product was made by column chromatography, but decomposition on the column prevented the isolation of pure product.

Conclusion

We have prepared a variety of [ReO(L)] complexes, where L is triply deprotonated, which have been fully characterised. Technetium-99 complexes with the same ligands have been prepared in high radiochemical purity, which appear to contain $[TcO(L^n)]^-$, but their instability has prevented complete characterisation. We have isolated and characterised the final decomposition product of the technetium complex with ligand H_3L^1 and found that it is $[NBu_4][TcO_4]$. The HPLC analysis indicates that this decomposition is at least a two-step process, with the first step reversed by the addition of sodium methoxide, suggesting that protonation is involved.

The available data therefore indicate that the complexes of Re and Tc are not directly analogous. We propose that the $[Tc{=}O]^{3+}$ core is reduced by the ligand, whereas the less easily reduced $[Re{=}O]^{3+}$ core remains as Re^V.

The decomposition of the technetium complexes is slow compared to the half-life of ^{99m}Tc, and so is likely to be unimportant in radiopharmaceutical terms. The results of labelling the series of ligands with the technetium-99m isotope will be reported elsewhere. We envisage using NS_3 compounds similar to H_3L^4, in which the ethyl ester group will be replaced by more biologically relevant molecules such as small polypeptides, allowing us to target particular receptor sites.

Experimental

CAUTION: technetium-99 is a low-energy β emitter [292 keV (*ca.* 4.67×10^{-14} J, $t_{\frac{1}{2}} = 2.14 \times 10^5$ years). Normal radiation safety procedures were followed at all times. All manipulations of solutions and solids were performed in an efficient fume-hood to prevent contamination and inadvertent inhalation. When handled in milligram quantities these compounds do not present a serious health hazard since common laboratory glassware provides adequate shielding. Bremsstrahlung radiation is not a significant problem due to the low energy of the β-particle emission.

Potassium pertechnetate was kindly donated by Amersham International plc, and used as received. All other reagents were obtained from Aldrich Chemical Co. and used as received. The salt $[NBu_4][TcOCl_4]$ was prepared from $K[TcO_4]$ according to standard methods.[8] $[ReOCl_4(PPh_3)_2]$ and $[ReO_2(py)_4]Cl$ from NH_4ReO_4.[9] Infrared spectra were recorded as KBr discs or thin films on salt plates, using a Perkin-Elmer 1600 series FTIR spectrometer, NMR spectra on a JEOL EX 270 Fourier-transform spectrometer at 270 (^{1}H) or 67.5 MHz (^{13}C) and mass spectra using an MS 50 instrument. Elemental analyses were performed using a Carlo-Elba elemental analyser. For the technetium complexes, HPLC was carried out using a Hamilton PRP-1 reversed-phase column and a solvent flow of 1.5 cm^3 min^{-1} with a 15 min 50 mmol aqueous sodium acetate–thf solvent gradient; UV (285 nm) and β (custom-built) detectors were used to monitor the column eluent. For the rhenium complexes, HPLC employed a Gilson S5ODS1 (octadecylsilane) column, with an isocratic system and flow rate 1 cm^3 min^{-1} with CH_2Cl_2 elution and UV (254 nm) detection.

Preparations

2-Oxo-1,4-dithiacyclohexane 1. A three-necked round-bottomed flask (1 l) was equipped with a pressure-equalised dropping funnel (500 cm^3), a thermometer and a nitrogen inlet. The flask was charged with dichloromethane (250 cm^3), ethane-1,2-dithiol (16.6 g, 0.17 mol) and triethylamine (49.3 cm^3, 0.3 mol) under a nitrogen atmosphere. The dropping funnel was charged with chloroacetyl chloride (20.0 g, 0.17 mol) in dichloromethane (150 cm^3), also under a nitrogen atmosphere. The contents of the flask were cooled to about − 10 °C in an ice–acetone bath, and the solution of chloroacetyl chloride solution added dropwise, while stirring, over 1.5 h, during which time a precipitate of triethylamine hydrochloride formed. The mixture was allowed to warm to room temperature and stirred for 2 h. The precipitate was filtered off and the organic layer washed with water (2 × 75 cm^3) and dried over $MgSO_4$. The drying agent was filtered off and the solvent evaporated at reduced pressure. The residue was purified by distillation under vacuum to give a clear, colourless oil. Yield: 13 g (60%). B.p. 105–108 °C, 1 mmHg (lit.,[10] b.p. 92–93 °C, 0.7 mmHg). IR (KBr

disc): 1656 cm^{-1} [ν(C=O)]. NMR ($CDCl_3$): ^{1}H, δ 3.44 (2 H, s, C^3H), 3.41–3.37 (2 H, t, J = 5.7, 6.5, CH_2), 3.16–3.11 (2 H, t, J = 6.5, 5.7 Hz, CH_2); ^{13}C, δ 196.94 (C^2), 35.40 (C^3), 31.18 (C^5) and 25.88 (C^6). Electron impact (EI) mass spectrum: m/z = 134 (M^+).

2-Oxo-1,4-dithiacycloheptane 2. The method used was analogous to that for compound **1**, but with propane-1,3-dithiol (15.0 g, 0.138 mmol) in place of ethane-1,2-dithiol. The quantities of the other reagents were adjusted accordingly, and an identical work-up procedure gave a pale yellow oil. Spectroscopic analysis of the product indicated that it was contaminated with small amounts of triethylamine hydrochloride and starting material, and repeated distillations of the oil did not improve the purity. The impure compound was successfully used in the synthesis of proligand H_3L^2 without further purification. Alternatively, the crude produce (undistilled) could be used without purification. Yield: 3.5 g (17%). IR (KBr disc): 1681 cm^{-1} [ν(C=O)]. NMR ($CDCl_3$): ^{1}H, δ 3.41 (2 H, s, C^3H), 3.10–2.94 (2 H, m, CH_2), 2.77–2.55 (2 H, m, CH_2) and 1.99–1.84 (2 H, m, CH_2); ^{13}C, δ 196.29 (C^2), 42.16 (C^3), 32.75 (C^5), 31.47 (C^7) and 24.50 (C^6). EI mass spectrum: m/z = 73, $[M - SCHOCH_2]^+$; 106, $[M - CHOCH_2]^+$; and 148, M^+.

5-Oxo-1,4-dithiacycloheptane 3. The method used was analogous to that procedure given for compound **1**, but with 3-chloropropanoyl chloride (15.0 g, 0.138 mmol) in place of chloroacetyl chloride. The quantities of the other reagents were adjusted accordingly, and an identical work-up procedure gave a white solid. Yield: 12.6 g (62%). IR (KBr disc): 1669 cm [ν(C=O)]. NMR ($CDCl_3$): ^{1}H, δ 3.11 (2 H, t, J = 7.5, 6 Hz, C^3H), 2.93 (2 H, s, C^6H), 2.90 (2 H, s, C^7H) and 2.75 (2 H, s, C^4H); ^{13}C, δ 196.7 (C^2), 44.1 (C^3), 32.2 (C^4), 29.0 (C^6) and 27.2 (C^7). EI mass spectrum: m/z = 148, M^+.

3-Methyl-2-oxo-1,4-dithiacyclohexane 4. The method used was analogous to that for compound **1**, but with 2-chloropropanoyl chloride (20.0 g, 0.157 mol) in place of chloroacetyl chloride. The quantities of the other reagents were adjusted accordingly, and an identical work-up procedure gave a pale yellow oil. The crude product could be used without further purification. Yield: 12 g (52%). IR (KBr disc): 1666 cm^{-1} [ν(C=O)]. NMR ($CDCl_3$): ^{1}H, δ 3.84–3.79 (1 H, q, ^2J = 6.45, 6.85, ^3J = 13.3, C^3H), 2.89–2.77 (4 H, m, $C^{5,6}H$) and 1.38 (3 H, d, J = 6.9 Hz, CH_3); ^{13}C, δ 199.28 (C^2), 49.89 (C^3), 31.30 (C^5), 27.76 (C^6) and 13.69 (*C*Me). EI mass spectrum: m/z = 105, $[M - CH_2CH_2]^+$; and 148, M^+.

2-Oxo-3-phenyl-1,4-dithiacyclohexane 5. The method used was analogous to that given for compound **1**, but with (+)-chloro(phenyl)acetyl chloride (20.0 g, 0.105 mol) in place of chloroacetyl chloride. The quantities of the other reagents were adjusted accordingly, and an identical work-up procedure gave a white solid. The compound could be used without further purification. Yield: 13 g (59%). IR (KBr disc): 1654 cm^{-1} [ν(C=O)]. NMR ($CDCl_3$): ^{1}H, δ 7.37–7.30 (5 H, m, aryl), 4.81 (1 H, s, C^3H) and 3.42–3.01 (4 H, m, $C^{5,6}H$); ^{13}C, δ 196.91 (C^2), 128.88 (Ph), 128.82 (Ph), 128.69 (Ph), 128.40 (Ph), 126.53 (Ph), 51.87 (C^3), 31.16 (C^5) and 27.71 (C^6). EI mass spectrum: m/z = 105, $[M - CH_2CH_2Ph]^+$; 172, $[M - CH_2CH_2]^+$; and 210, M^+.

Proligand H_3L^1. 2-Oxo-1,4-dithiacyclohexane (1.5 g, 11 mmol) was dissolved in dry, degassed dichloromethane (50 cm^3) under a nitrogen atmosphere. A solution of 2-aminoethanethiol hydrochloride (1.3 g, 11 mmol) and triethylamine (1.6 cm^3, 11 mmol) in dry degassed dichloromethane (100 cm^3) was added dropwise. The mixture was allowed to stir for 12 h under a nitrogen atmosphere before washing with 2% aqueous citric acid (2 × 70 cm^3) and then water (2 × 70 cm^3). The organic layer was dried over $MgSO_4$ and then filtered. Solvent was removed under reduced pressure and the residue dried under vacuum to give the required compound as a clear, colourless oil. Yield: 1.4 g (60%). IR (KBr disc): 3290 [ν(NH)], 2544 [ν(SH)] and 1649 cm^{-1} [ν(C=O)]. NMR [$(CD_3)_2SO$]: ^{1}H, δ 8.20 (1 H, br s, NH), 3.25–3.18 (2 H, q, ^2J = 6, ^3J = 12 Hz, C^5H), 3.13 (2 H, s, C^3H), 2.80–2.70 (4 H, m), 2.67–2.49 (3 H, m) and 2.35 (1 H, br, SH); ^{13}C, δ 169.0 (C^4), 42.15 (C^5), 35.52 (C^3), 34.0 (C^2), 23.68 (C^1) and 23.31 (C^6). EI mass spectrum: m/z = 119, $[M - SCH_2CH_2S]^+$; 151, $[M - CH_2CH_2S]^+$; and 211, M^+.

Proligand H_3L^2. The method used was similar to that for H_3L^1, but with compound **2** (1.0 g, 6.75 mmol) in place of **1**. The quantities of the other reagents were adjusted accordingly. An identical work-up procedure gave the required compound as a pale yellow oil. Yield: 0.45 g (30%). IR (KBr disc): 3290 [ν(NH)], 2547 [ν(SH)] and 1650 cm^{-1} [ν(C=O)]. NMR ($CDCl_3$): ^{1}H, δ 7.36 (1 H, br s, NH), 3.51–3.42 (2 H, q, ^2J = 6, ^3J = 12, C^6H), 3.24 (2 H, s, C^4H), 2.76–2.59 (6 H, m, $C^{1,3,7}H$), 1.90 (2 H, t, J = 7, C^2H), 1.49–1.42 (1 H, t, J = 8, SH) and 1.44–1.38 (1 H, t, J = 8 Hz, SH); ^{13}C, δ 168.95 (C^5), 42.48 (C^6), 35.89 (C^4), 32.62 (C^3), 31.14 (C^2), 24.50 (C^1) and 23.25 (C^7). EI mass spectrum: m/z = 106, $[M - CH_2CONHCH_2CH_2SH]^+$; 163, $[M - HSCH_2CH_2]^+$; and 224, M^+.

Proligand H_3L^3. Using a method similar to that for H_3L^1, but with compound **3** in place of **1**, only unchanged starting materials could be recovered from the reaction. The reasons for this are not certain, but may be related to lower ring strain and therefore reduced reactivity of **3**.

Proligand H_3L^4. The method used was similar to that for H_3L^1, but the ethyl ester of L-cysteine hydrochloride was employed in place of 2-aminoethanethiol. The quantities of the other reagents were adjusted accordingly. An identical work-up procedure gave the required compound as a clear, colourless oil, which solidified on standing overnight. Yield: 1.8 g (58%), m.p. 37 °C (Found: C, 38.5; H, 6.2; N, 4.7. Calc. for $C_9H_{17}NO_3S_3$: C, 38.2; H, 6.1; N, 4.9%). IR (KBr disc): 3290 [ν(NH)], 2544 [ν(SH)], 1735 [ν(C=O)] and 1632 cm^{-1} [ν(C=O)]. NMR ($CDCl_3$): ^{1}H, δ 7.62 (1 H, br d, J = 7, NH), 4.88–4.82 (1 H, m, C^5H), 4.35–4.20 (2 H, m), 3.31 (2 H, s, C^3H), 3.13–3.01 (2 H, m), 2.99–2.73 (4 H, m), 1.73 (1 H, t, J = 8, SH), 1.44 (1 H, t, J = 9, SH) and 1.32 (3 H, t, J = 7 Hz, C^9H); ^{13}C, δ 169.68 (C^7), 168.00 (C^4), 62.08 (C^5), 53.69 (C^8), 36.63 (C^3), 35.63 (C^2), 26.76 (C^1), 24.20 (C^6) and 14.21 (C^9). EI mass spectrum: m/z = 223, $[M - HSCH_2CH_2]^+$; 250, $[M - SH]^+$; and 283, M^+.

Proligand H_3L^5. The method used was similar to that for H_3L^1, but with 1-amino-2-methylpropane-2-thiol hydrochloride (1.62 g, 0.11 mol) in place of 2-aminoethanethiol. The quantities of the other reagents were adjusted accordingly. An identical work-up procedure gave the required compound as a clear, colourless oil. Yield: 1.10 g (40%). IR (KBr disc): 3302 [ν(NH)], 2543 [ν(SH)] and 1649 cm^{-1} [ν(C=O)]. NMR ($CDCl_3$): ^{1}H, δ 7.36 (1 H, br, NH), 3.37 (2 H, d, J = 6, C^5H), 3.30 (2 H, s, C^3H), 2.88–2.72 (4 H, m, $C^{1,2}H$), 1.75 (2 H, t, J = 6.5, 8 Hz, SH) and 1.37 (6 H, s, $C^{6A,6B}H$); ^{13}C, δ 168.80 (C^4), 52.30 (C^5), 45.21 (C^6), 36.74 (C^3), 35.70 (C^2), 29.97 ($C^{6A,6B}$) and 24.16 (C^1). EI mass spectrum: m/z = 179, $[M - CH_2CH_2SH]^+$; 206, $[M - SH]^+$; and 240, M^+.

Proligand H_3L^6. The method used was similar to that for H_3L^1, but with compound **4** (1.5 g, 0.01 mol) in place of **1**. The quantities of the other reagents were adjusted accordingly, and an identical work-up procedure gave the required compound as a clear, colourless oil. Yield: 1.2 g (53%). IR (KBr disc): 3298 [ν(NH)], 2548 [ν(SH)] and 1650 cm^{-1} [ν(C=O)]. NMR ($CDCl_3$): ^{1}H, δ 7.15 (1 H, br, NH), 3.51–3.41 (3 H, m, $C^{3,5}H$), 2.89–2.67 (6 H, m, $C^{1,2,6}H$), 1.75–1.67 (1 H, m, SH), 1.49–1.47

(3 H, d, $J = 7.2$, $C^{3A}H$) and 1.45–1.39 (1 H, t, $J = 8.4$ Hz, SH); ^{13}C, δ 172.59 (C^4), 44.13 (C^5), 42.47 (C^3), 35.43 (C^2), 24.53 (C^1), 24.49 (C^6) and 18.58 (C^{3A}). EI mass spectrum: $m/z = 133$, $[M - HSCH_2CH_2]^+$; 192, $[M - SH]^+$; and 225, M^+.

Proligand H_3L^7. The method used was similar to that for H_3L^6, but with 1-amino-2-methylpropane-2-thiol hydrochloride (0.97 g, 6.8 mmol) in place of 2-aminoethanethiol. The quantities of the other reagents were adjusted accordingly. An identical work-up procedure gave the required compound as a colourless oil. Yield: 0.7 g (40%). IR (KBr disc): 3303 [ν(NH)], 2548 [ν(SH)] and 1670 cm^{-1} [ν(C=O)]. NMR ($CDCl_3$): ^1H, δ 7.15 (1 H, br, NH), 3.37–3.34 (1 H, q, $J = 7.3$, C^3H), 3.13 (1 H, br, SH), 2.92–2.70 (6 H, m, $C^{1,2,5}H$), 1.77–1.70 (1 H, t, $J = 7$, SH), 1.51–1.49 (3 H, d, $J = 7$ Hz, $C^{3A}H$), 1.38 (3 H, s, $C^{6A}H$) and 1.37 (3 H, s, $C^{6B}H$); ^{13}C, δ 172.50 (C^4), 52.28 (C^5), 45.42 (C^3), 44.54 (C^6), 35.62 (C^2), 30.15 (C^1), 29.94 (C^{6A}), 24.53 (C^{6B}) and 18.79 (C^{3A}). EI mass spectrum: $m/z = 132$, $[M - HSCH_2CH_2SCHMe]^+$; and 254, M^+.

Proligand H_3L^8. The method used was similar to that for H_3L^1, but with compound **5** (1 g, 4.78 mmol). The quantities of the other reagents were adjusted accordingly. An identical work-up procedure gave the required compound as a thick, colourless oil. Yield: 0.7 g (51%). IR (KBr disc): 3294 [ν(NH)], 2554 [ν(SH)] and 1650 cm^{-1} [ν(C=O)]. NMR ($CDCl_3$): ^1H, δ 7.62–7.27 (5 H, m, Ph), 7.18 (1 H, br s, NH), 4.63 (1 H, s, C^3H), 3.59–3.39 (2 H, m, C^5H), 2.86–2.60 (6 H, m, $C^{1,2,6}H$), 1.71–1.65 (1 H, t, $J = 7.9$, SH) and 1.49–1.25 (1 H, t, $J = 8.5$ Hz, SH); ^{13}C, δ 169.87 (C^4), 136.59 (Ph), 128.95 (Ph), 128.89 (Ph), 128.52 (Ph), 128.01 (Ph), 127.74 (Ph), 54.49 (C^5), 42.61 (C^3), 36.31 (C^2), 24.39 (C^6) and 24.20 (C^1). EI mass spectrum: $m/z = 209$, $[M - HSCH_2CH_2S]^+$; and 287, M^+.

Proligand H_3L^9. The method used was similar to that for H_3L^8, but with 1-amino-2-methylpropane-2-thiol hydrochloride (0.68 g, 4.78 mmol) in place of 2-aminoethanethiol and a solvent mixture (70% CH_2Cl_2–30% thf) in place of CH_2Cl_2. The quantities of the other reagents used were adjusted accordingly. An identical work-up procedure gave the required compound as a thick, colourless oil. Yield: 0.7 g (51%). IR (KBr disc): 3326 [ν(NH)], 2556 [ν(SH)], 1657 [ν(C=O)] and 729–698 cm^{-1} (Ph). NMR ($CDCl_3$): ^1H, δ 7.8–7.46 (5 H, m, Ph), 7.03 (1 H, br s, NH), 4.65 (1 H, s, C^3H), 3.35–3.33 (2 H, d, $J = 6$, C^5H), 2.88–2.68 (4 H, m, $C^{1,2}H$), 1.71–1.65 (1 H, t, $J = 8$ Hz, SH), 1.59 (1 H, s, SH), 1.32 (3 H, s, $C^{6A}H$) and 1.28 (3 H, s, $C^{6B}H$); ^{13}C, δ 169.77 (C^4), 136.65 (Ph), 129.00 (Ph), 128.90 (Ph), 128.34 (Ph), 128.01 (Ph), 54.81 (C^5), 52.41 (C^3), 45.49 (C^6), 36.37 (C^2), 30.03 (C^{6A}), 29.86 (C^{6B}) and 24.29 (C^1). EI mass spectrum: $m/z = 224$, $[M - HSCH_2CH_2]^+$; 316, M^+.

Proligand H_3L^{10}. Compound H_3L^1 (2 g, 9.47 mmol) was dissolved in dry, degassed thf (50 cm^3) and borane in thf (46 cm^3, 5 equivalents) was added. The mixture was heated under reflux overnight, under a nitrogen atmosphere. Solvent was removed under vacuum, distilled water (10 cm^3) was added (to hydrolyse the borane complex), and H_3L^{10} was extracted with CH_2Cl_2 (75 cm^3), and washed with water (2 × 20 cm^3). The organic layer was dried over $MgSO_4$ and then filtered. Solvent was removed under reduced pressure and the residue dried under vacuum to give the required compound as a clear, colourless oil. Yield: 1.1 g (59%). IR (KBr disc): 3288 [ν(NH)] and 2542 cm^{-1} [ν(SH)]. NMR [$(CD_3)_2SO$]: ^1H, δ 8.26 (1 H, s, NH), 2.93–2.53 (12 H, m), 1.35 (1 H, br, SH) and 0.89–0.87 (1 H, t, SH, $J = 7$ Hz); ^{13}C, δ 51.58 (C^5), 48.24 (C^4), 35.13 (C^3), 31.22 (C^2), 24.32 (C^1) and 24.15 (C^6). EI mass spectrum: $m/z = 164$, $[M - SH]^+$; and 198, M^+.

Technetium-99 complexes. *Ligand* L^1. The salt [NBu_4][$TcOCl_4$] (75 mg, 0.15 mmol) was dissolved in dry methanol (3 cm^3) under a nitrogen atmosphere. Proligand H_3L^1 (61 mg, 0.28 mmol) was added as a solution in methanol (1 cm^3), causing the immediate formation of a red-brown precipitate and the solution changed from green to orange. The mixture was heated at reflux for 1 h, but no further changes were apparent. The solid was filtered off and analysis of the filtrate by TLC and HPLC showed that it contained a single, clean technetium species. Solvent was removed under vacuum to give the pure product as an amber coloured oil. Yield: 61 mg (131% if product is [$TcOL^1$], 72% if [NBu_4][$TcOL^1$]). IR (thin film, salt plate): 1634 [ν(C=O)] and 948 cm^{-1} [ν(Tc=O)]. NMR ($CDCl_3$): ^1H, δ 3.39 (2 H, br s), 1.71 (2 H, br s), 1.49 (2 H, two br s, overlapping) and 1.04 (3 H, t, $J = 7$ Hz); ^{13}C, δ 59.6, 24.4, 19.9 and 13.8. HPLC: retention time 9 min. TLC: $R_f = 0.57$ (silica, 10% methanol in dichloromethane).

Ligand L^2. This complex was prepared in the same manner using [NBu_4][TcOCl] (51 mg, 0.101 mmol) and proligand H_3L^2 (42 mg, 0.19 mmol) in place of H_3L^1. An identical work-up procedure was used, but the golden oil isolated was purified by column chromatography (silica, 10% methanol in dichloromethane) to give the product as a yellow solid. Although the crude product was isolated in good yield, most was lost during chromatography. IR (thin film): 3309 [ν(NH)], 2919 [ν(CH)], 1651 [ν(C=O)], 1434, 1350 and 1298 cm^{-1}. HPLC: retention time 9 min. TLC: $R_f = 0.69$ (silica, 10% methanol in dichloromethane).

Ligand L^4. This complex was prepared in the same manner with [NBu_4][TcOCl] (38 mg, 0.076 mmol) and proligand H_3L^4 (34 mg, 0.12 mmol) in place of H_3L^1. An identical work-up procedure was employed, giving the product as an amber coloured oil. Yield: 43 mg (143% if product [TcOL], 89% if [NBu_4][TcOL]. IR (thin film, salt plate): 3416 [ν(NH)], 2960 [ν(CH)], 2874 [ν(CH)], 1738 [ν(C=O)], 1643 [ν(C=O)], 1468, 954 [ν(Tc=O)] and 883w cm^{-1}. NMR ($CDCl_3$): ^1H δ 3.36 (2 H, br s), 1.70 (2 H, br s), 1.49 and 1.47 (2 H, br s, overlapping) and 1.02 (3 H, t, $J = 13$ Hz); ^{13}C, δ 65.52 (br), 26.84, 21.32 and 14.57. HPLC: retention time 8.5 min. TLC: $R_f = 0.56$ (silica, 10% methanol in dichloromethane).

[$ReO(L^1)$]. The complex [$ReOCl_3(PPh_3)_2$] (0.78 g, 0.947 mmol) was added as a solid to stirred solution of H_3L^1 (0.2 g, 0.947 mmol) and 1 mol dm^{-3} aqueous sodium acetate (20 cm^3, 20 mmol) in methanol (10 cm^3). The mixture was heated under reflux for 2 h, during which time it became deep, red-purple. It was cooled to room temperature and a green solid filtered off. No attempts were made to analyse this solid. Solvent was removed from the filtrate under reduced pressure and the residue taken up in dichloromethane (50 cm^3). The filtered solution was washed with water (2 × 50 cm^3) and dried over $MgSO_4$. (Improved yields were obtained when the water–dichloromethane phases were allowed fully to partition on standing overnight.) The drying agent was filtered off and the solution concentrated under vacuum to about 5 cm^3. A red-orange precipitate was formed upon addition of hexane, filtered off, washed with diethyl ether and dried under vacuum to give the required compound. An identical product was obtained in similar yield using [$ReO_2(py)_4$]Cl in place of [$ReOCl_3(PPh_3)_2$]. Yield: 0.12 g (31%) (Found: C, 18.1; H, 2.5; N, 3.4. Calc. for $C_6H_{10}NO_2Re$: C, 17.5; H, 2.5; N, 3.4%). IR (KBr disc): 1634 [ν(C=O)] and 964 cm^{-1} [ν(Re=O)]. NMR [$(CD_3)_2SO$]: ^1H, δ 4.90–4.83 (1 H, d, $J = 17$, C^3H), 4.47–4.38 (1 H, m, C^5H), 4.10–4.02 (1 H, d, $J = 17$, C^3H), 4.00–3.96 (2 H, m, $C^{1,6}H$), 3.80–3.75 (1 H, d, d, $J = 2.3$, 2.64, C^2H), 3.30–3.25 (2 H, m, $C^{1,5}H$), 2.88–2.77 (1 H, t, d, $^3J = 3.74$, $^2J = 13.77$, C^6H), 2.06–1.95 (1 H, d, d, d, $^3J = 4.4$, $^2J = 14.6$ Hz, C^2H); ^{13}C, δ 190.38 (C^4), 61.74 (C^5), 44.41 (C^2), 42.41 (C^1), 42.27 (C^6) and 40.44 (C^3). FAB mass spectrum: $m/z = 289$, $[M - SCH_2CH_2SCH_2O]^+$; and 412, $[M + 1]^+$. HPLC: retention time = 8.5 min, single species. Crystals suitable for X-ray diffraction analysis were obtained from dichloromethane–isopropyl alcohol.

[ReO(L^2)]. The method used was similar to that for [ReO(L^1)], but with H_3L^2 (0.2 g, 0.83 mmol) in place of H_3L^1. The quantities of the other reagents used were adjusted accordingly. An identical work-up procedure gave the required compound as a brown-red solid. Yield: 0.12 g (34%) (Found: C, 19.9; H, 2.8; N, 3.3. Calc. for $C_7H_{12}NO_2ReS_3$: C, 19.7; H, 2.9; N, 3.3%). IR (KBr disc): 1637 [ν(C=O)] and 959 cm^{-1} [ν(Re=O)]. NMR [$(CD_3)_2SO$]: ^{1}H, δ 4.56 (1 H, d, J = 17, C^{4}H), 4.53–4.38 (1 H, m, C^{6}H), 4.20 (1 H, d, J = 17 Hz, C^{4}H), 4.13–3.99 (1 H, m, C^{6}H), 3.96–3.79 (2 H, m), 3.64–3.33 (2 H, m), 3.26–3.11 (2 H, m), 2.44–2.34 (1 H, m) and 2.19–2.10 (1 H, m); ^{13}C, δ 190.15 (C^5), 61.46 (C^6), 43.49 (C^3), 38.08 (C^4), 35.92 (C^1), 35.23 (C^7) and 24.29 (C^2). FAB mass spectrum: m/z = 426, $[M + 1]^+$. HPLC: retention time = 7.75 min, single species. Crystals suitable for X-ray diffraction analysis were obtained from dichloromethane–isopropyl alcohol.

[ReO(L^4)]. The method used was similar to that for [ReO(L^1)], but with H_3L^4 (0.2 g, 0.7 mmol) in place of H_3L^1. The quantities of the other reagents used were adjusted accordingly. An identical work-up procedure gave the required compound as a purple solid which is a mixture of two distinct species, probably *syn* and *anti* isomers. Yield: 0.12 g (36%) (Found: C, 22.0; H, 2.9; N, 2.8. Calc. for $C_9H_{14}NO_2ReS_3$: C, 22.3; H, 2.9; N, 2.9%). IR (KBr disc): 1731 [ν(C=O)], 1650 [ν(C=O)] and 9.71 cm^{-1} [ν(Re=O)]. NMR ($CDCl_3$): ^{1}H, δ 5.54–5.52 (1 H, d, J = 6), 4.80–4.73 (1 H, d, J = 17), 4.46–4.58 (1 H, d, J = 17), 4.59 (1 H, m), 4.55–4.53 (1 H, d, J = 6), 4.26–4.01 (7 H, m), 3.99–3.72 (4 H, m), 3.65–3.50 (2 H, m), 3.01–2.88 (2 H, m), 1.85–1.74 (2 H, m), 1.32–1.27 (3 H, t, ^2J = 7, ^3J = 15, Me), 1.24–1.19 (3 H, t, ^2J = 7, ^3J = 15 Hz, C^{9}H); ^{13}C, δ 190.17 (C^4, isomer A), 188.58 (C^4, isomer B), 172.01 (C^{7A}), 170.17 (C^{7B}), 73.61 (C^{5A}), 73.1 (C^{5B}), 61.56 (C^{8A}), 61.42 (C^{8B}), 47.58 (C^{2A}), 46.34 (C^{2B}), 45.94 (C^{3A,3B}), 43.18 (C^{1A}), 43.05 (C^{6A}), 40.83 (C^{1B}), 40.64 (C^{6B}), 14.19 (C^{9A}) and 14.16 (C^{9B}). FAB mass spectrum: m/z = 437, $[M - SCH_2]^+$; and 483, M^+. HPLC: retention time = 6.5, 7.25 min; two species, ratio 1:1.

[ReO(L^5)]. The method used was similar to that for [ReO(L^1)], but with H_3L^5 (0.25 g, 1 mmol) in place of H_3L^1. The quantities of the other reagents were adjusted accordingly. An identical work-up procedure gave the required compound as a red-orange solid. Yield: 0.18 g (40%) (Found: C, 21.9; H, 3.3; N, 3.1. Calc. for $C_8H_{14}NO_2ReS_3$: C, 21.8; H, 3.2; N, 3.2%). IR (KBr disc): 1633 [ν(C=O)] and 959 cm^{-1} [ν(Re=O)]. NMR [$(CD_3)_2SO$]: ^{1}H, δ 4.82–4.75 (1 H, d, J = 17, C^{3}H), 4.27–4.23 (1 H, d, J = 13, C^{5}H), 4.03–3.95 (1 H, d, J = 17, C^{3}H), 4.01–3.95 (1 H, m, C^{1}H), 3.79–3.74 (1 H, d, d, J = 2 , C^{2}H), 3.2–3.24 (1 H, d, J = 13, C^{5}H), 2.88–2.76 (1 H, t, d, ^2J = 3.5, ^3J = 14, C^{1}H), 2.02–1.93 (1 H, d, d, d, ^2J = 4.5, ^3J = 10.5 Hz, C^{2}H), 1.77 (3 H, s, 6-Me$_A$) and 1.50 (3 H, s, 6-Me$_B$); ^{13}C, δ 191.00 (C^4), 72.99 (C^5), 58.29 (C^6), 44.28 (C^2), 42.39 (C^1), 39.28 (C^3), 30.11 (Me$_A$) and 28.17 (Me$_B$). FAB mass spectrum: m/z = 440, $[M + 1]^+$. HPLC: retention time = 7.75 min, single species.

[ReO(L^6)]. The method used was similar to that for complex [ReO(L^1)], but with H_3L^6 (0.2 g, 0.88 mmol) in place of H_3L^1. The quantities of the other reagents were adjusted accordingly. An identical work-up procedure gave the required complex as a red-orange solid. Yield: 0.12 g (32%) (Found: C, 20.0; H, 2.9; N, 3.3. Calc. for $C_7H_{12}NO_2ReS_3$: C, 19.8; H, 2.8; N, 3.3%). IR (KBr disc): 1632 [ν(C=O)] and 974 cm^{-1} [ν(Re=O)]. NMR [$(CD_3)_2SO$]: ^{1}H, δ 4.44–4.38 (1 H, q, d, C^{3}H), 4.14–4.02 (2 H, m, C^{1,2}H), 3.96–3.91 (d, d, J = 2.67, 3.29, C^{5}H), 3.89–3.84 (1 H, t, d, ^3J = 2.19, ^2J = 5.65, C^{6}H), 3.65–3.28 (1 H, m, C^{5}H), 3.32–3.21 (1 H, m, C^{6}H), 2.87–2.75 (1 H, m, C^{1}H), 2.13–2.0 (1 H, d, d, d, ^3J = 4.5, ^2J = 10.26, C^{6}H) and 1.77–1.80 (3 H, d, J = 7.4 Hz, 3-Me); ^{13}C, δ 190.97 (C^3), 61.75 (C^5), 50.99 (C^3), 44.41 (C^2), 42.25 (C^1), 41.05 (C^6) and 18.94 (3-Me). FAB mass spectrum: m/z = 367, $[M - CH_2CH_2S]^+$; and 426, M^+. HPLC: retention time = 7 min, single species.

[ReO(L^7)]. The method used was as described for [ReO(L^1)], but with H_3L^7 (0.2 g, 0.79 mmol) in place of H_3L^1. The quantities of the other reagents were adjusted accordingly. An identical work-up procedure gave the required compound as a brown-orange solid. The ^{13}C NMR spectrum indicated two isomers, A and the predominant B, in *ca*. 1:3 ratio. Yield: 0.155 g (43%) (Found: C, 23.9; H, 3.6; N, 3.1. Calc. for $C_9H_{16}NO_2ReS_3$: C, 23.8; H, 3.5; N, 3.1%). IR (KBr disc): 1644 [ν(C=O)] and 954 cm^{-1} [ν(Re=O)]. ^{13}C NMR [$(CD_3)_2SO$]: isomer A, δ 191.87 (C^4), 73.95 (C^5), 57.36 (C^6), 49.80 (C^3), 44.34 (C^2), 42.30 (C^1), 29.99 (6-Me$_A$), 27.84 (6-Me$_B$) and 14.71 (3-Me); isomer B, 191.41 (C^4), 72.98 (C^5), 57.03 (C^6), 49.80 (C^3), 44.34 (C^2), 42.30 (C^1), 30.09 (6-Me$_A$), 28.25 (6-Me$_B$) and 18.87 (3-Me). FAB mass spectrum: m/z = 426, $[M - CH_2CH_2]^+$; 454, M^+. HPLC: retention time = 4.5, 5.5 min; two species, ratio 1:3.

[ReO(L^8)]. The method used was as for [ReO(L^1)], but with H_3L^8 (0.2 g, 0.69 mmol) in place of H_3L^1. The quantities of the other reagents were adjusted accordingly, and an identical work-up procedure gave the required compound as a purple solid. Yield: 0.12 g (36%) (Found: C, 29.9; H, 3.1; N, 2.9. Calc. for $C_{12}H_{14}NO_2ReS_3$: C, 29.6; H, 2.9; N, 2.9%). IR (KBr disc): 1643 [ν(C=O)] and 965 cm^{-1} [ν(Re=O)]. NMR [$(CD_3)_2SO$]: ^{1}H, δ 8.02–7.32 (5 H, m, Ph), 4.50–4.48 (1 H, m), 4.00–3.64 (3 H, m), 3.40–3.36 (2 H, m), 2.88–2.78 (2 H, m) and 2.33–2.29 (1 H, m); ^{13}C, δ 189.52 (C^4), 142.05 (Ph), 137.44 (Ph), 129.23 (Ph), 128.80 (Ph), 128.24 (Ph), 127.16 (Ph), 62.38 (C^5), 57.86 (C^3), 44.80 (C^2), 41.94 (C^1) and 41.72 (C^6). FAB mass spectrum: m/z = 488, $[M + 1]^+$. HPLC: retention time = 5 min, single species.

[ReO(L^9)]. The method used was as described for [ReO(L^1)], but with H_3L^9(0.2 g, 0.63 mmol) in place of H_3L^1. The quantities of the other reagents were adjusted accordingly, and an identical work-up procedure gave the required compound as a purple solid. Yield: 81 mg (25%) (Found: C, 33.3; H, 3.8; N, 2.6. Calc. for $C_{14}H_{18}NO_2ReS_3$: C, 32.6; H, 3.5; N, 2.7%). IR (KBr disc): 1607 [ν(C=O)] and 961 cm^{-1} [ν(Re=O)]. ^{13}C NMR ($CDCl_3$): isomer A, δ 190.55 (C^4), 146.70 (Ph), 141.95 (Ph), 128.38 (Ph), 128.29 (Ph), 127.72 (Ph), 127.35 (Ph), 60.00 (C^5), 57.89 (C^3), 56.70 (C$_6$), 41.94 (C^2), 41.32 (C^1), 30.13 (6-Me$_A$) and 29.68 (6-Me$_B$); isomer B, 190.20 (C^4), 142.79 (Ph), 142.45 (Ph), 128.98 (Ph), 127.97 (Ph), 127.24 (Ph), 127.22 (Ph), 58.85 (C^5), 55.83 (C^3), 51.04 (C^6), 41.63 (C^2), 41.02 (C^1), 29.44 (6-Me$_A$) and 28.21 (6-Me$_B$). FAB mass spectrum: m/z = 456, $[M - SCH_2CH_2]^+$; 489, $[M - CH_2CH_2]^+$; and 516, $[M + 1]^+$. HPLC: retention time = 3.75, 4.5 min; two species, ratio 1:3.

Oxorhenium(v) oxo complexes from [ReO$_4$]$^-$, $SnCl_2$ and citric acid. [ReO(L^1)]. Tin(II) chloride (0.07 g, 0.37 mmol) was dissolved in 0.5 mol dm^{-3} citric acid (5 cm^3) and a solution of NH_4ReO_4 (0.1 g, 0.37 mmol) in methanol (5 cm^3) was added. The compound H_3L^1 (0.078 g, 0.37 mmol) was dissolved in NaO_2CMe–MeOH (10 mmol, 10 cm^3), heated to boiling and the hot solution added to the rhenium citrate solution. The pH was adjusted to *ca*. 8 by adding NaO_2CMe, and the mixture was heated under reflux for 2 h, then filtered when cool. The solvent was removed under reduced pressure, and the complex extracted with CH_2Cl_2 (50 cm^3), filtered, and the solvent volume reduced to 3 cm^3. Diethyl ether was added and the solvent volume again reduced to 3 cm^3. Addition of water precipitated an orange-red solid which was washed with water, acetone and Et_2O. Yield: 30 mg (20%). IR (KBr disc): 1633 [ν(C=O)] and 964 cm^{-1} [ν(Re=O)]. FAB mass spectrum: m/z = 411, M^+. This had identical spectroscopic properties to the sample prepared above from $[ReOCl_3(PPh_3)_2]$.

[ReO(L^5)]. The method used was similar to that for [ReO(L^1)] from [ReO$_4$]$^-$, but with H_3L^3 (0.09 g, 0.37 mmol) in place of

H_3L^1. The quantities of the other reagents were adjusted accordingly. An identical work-up procedure gave the required compound as a red-orange solid. Yield: 36 mg (21%). IR (KBr disc): 1633 [ν(C=O)] and 959 cm^{-1} [ν(Re=O)]. FAB mass spectrum: $m/z = 440$, $[M + 1]^+$. Identical spectroscopic properties to those of the compound prepared above.

[ReO(L^6)]. The method used was similar to that for [ReO(L^1)] from $[ReO_4]^-$, but with H_3L^6 (0.084 g, 0.37 mmol) in place of H_3L^1. The quantities of the other reagents were adjusted accordingly. An identical work-up procedure gave the required compound as a deep red-orange solid. Yield: 33 mg (21%), single species by HPLC. IR (KBr disc): 1633 [ν(C=O)] and 969 cm^{-1} [ν(Re=O)]. FAB mass spectrum: $m/z = 426$, $[M + 1]^+$.

[ReO(L^{10})]. The method used was similar to that for [ReO(L^1)], but with H_3L^{10} (0.2 g, 1.01 mmol) in place of H_3L^1. The quantities of the other reagents were adjusted accordingly. The mixture was heated under reflux for 2 h, at which time it was brown-purple. An identical work-up procedure gave the required compound as a brown-orange solid. Yield: 0.16 g (40%) (Found: C, 18.3; H, 3.2; N, 3.5. Calc. for $C_6H_{12}NOReS_3$: C, 18.1; H, 3.1; N, 3.5%). IR (KBr disc): 941 cm^{-1} [ν(Re=O)]. NMR [$(CD_3)_2SO$]: ^{1}H, δ 4.28–4.13 (3 H, m, C^4H_2, C^5H), 4.02–3.96 (1 H, d, d, $J = 4.2$, 4.6, C^6H), 3.92–3.87 (1 H, d, d, $J = 4.23$, 1.82, C^1H), 3.75–3.69 (1 H, d, d, $J = 3.8$, 4, C^2H), 3.53–3.47 (1 H, d, d, $J = 5.64$, C^2H), 3.39–3.28 (1 H, m, C^5H), 2.98–2.86 (1 H, d, t, $J = 11.08$, 11.88, C^6H), 2.73–2.61 (1 H, t, d, $^3J = 4.02$, $^2J = 13.59$, C^3H), 2.50–2.37 (1 H, t, d, $^3J = 7.58$, $^2J = 11.33$, C^3H) and 1.95–1.84 (1 H, d, d, d, $^3J = 4.48$, $^2J = 10.32$ Hz, C^2H); ^{13}C, δ 71.11 (C^4), 70.81 (C^5), 46.29 (C^2), 45.43 (C^3), 43.34 (C^1) and 41.09 (C^6). FAB mass spectrum: $m/z = 398$, $[M + 1]^+$. HPLC: retention time = 3 min, single species. Crystals suitable for X-ray diffraction analysis were obtained from dichloromethane–isopropyl alcohol.

Crystallography

Data collection. Intensity data were collected at 293(2) K on an Enraf-Nonius CAD 4 diffractometer {or in the case of [ReO(L^2)] on a Delft instruments FAST area detector[10]} with monochromated Mo-Kα radiation (λ 0.710 73 Å). Cell constants were obtained from least-squares refinement of the setting angles of 25 centred reflections. The data were collected in the ω–2θ scan mode and three standard reflections were measured every 2 h of exposure. The losses of intensity reported in Table 1 were observed and linearly corrected during processing. Three standard reflections were measured every 200 to check the crystal orientation. The data were corrected for Lorentz–polarisation factors and an absorption correction was applied using ψ scans of nine reflections.

Structure analysis and refinement. The structures were solved by direct methods (SHELXS 86)[11] and refined on F_o^2 by full-matrix least squares (SHELXL 93)[12]. In the cases of [ReO(L^2)] and [ReO(L^{10})] the structure determinations were performed using the instructions TWIN, BASF1 in the refinement procedure. All non-hydrogen atoms were refined with anisotropic thermal parameters. The hydrogen atoms were included in idealised positions with U_{iso} free to refine. The weighting schemes used gave satisfactory agreement analyses. The scattering factors were taken from the sources given in ref. 1. Atomic co-ordinates, thermal parameters, and bond lengths and angles have been deposited at the Cambridge Crystallographic Data Centre (CCDC). See Instructions for Authors, *J. Chem. Soc., Dalton Trans.*, 1997, Issue 1. Any request to the CCDC for this material should quote the full literature citation and the reference number 186/398.

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