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Rhenium(I) Tricarbonyl Complexes with Poly(azolyl)borates Generated in Situ from an Organometallic Precursor Containing the B−H···Re Coordination Motif

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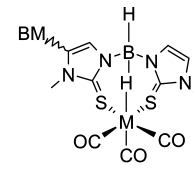
Complex *fac*-[Re(κ^3-H(μ-H)$_2$B(tim^{Me}))(CO)$_3$] (**1**) reacts with protic azoles, like 2-mercapto-1-methylimidazole (tim^{Me}H), 2-mercaptobenzothiazole (bztH), or pyrazoles (pz*H), to afford *fac*-[Re(κ^3-H(μ-H)B(tim^{Me})$_2$(CO)$_3$] (**2**), *fac*-[Re(κ^3-H(μ-H)B(tim^{Me})(bzt))(CO)$_3$] (**3**), *fac*-[Re(κ^3-H(μ-H)B(tim^{Me})(pz))(CO)$_3$] (**4**), *fac*-[Re(κ^3-HB(tim^{Me})(pz)$_2$)(CO)$_3$] (**5**), and *fac*-[Re(κ^3-H(μ-H)B(tim^{Me})(3,5-Me$_2$-4-EtOOCCH$_2$pz))(CO)$_3$] (**6**). Complexes **2**−**6** are stabilized by tridentate poly(azolyl)borates generated in situ, and their formation involves most probably a metal-assisted process which is considerably faster for the pyrazole derivatives. The characterization of the novel complexes, **3**−**6**, has been done by common analytical techniques, including single crystal X-ray diffraction analysis. The solid state structures confirmed the presence of hybrid heteroscopionates, presenting (κ^3-H, S, S′), (κ^3-H, S, N), or (κ^3-S, N, N) binding motifs. Multinuclear (^{1}H, ^{13}C, and ^{11}B) NMR studies have also shown that the coordination mode found in the solid state is retained in solution.

Introduction

In the past few years, hard and soft poly(azolyl)borates, commonly designated as scorpionates, have played a prominent role in coordination and organometallic chemistry. These chelators have been explored either for stoichiometric or catalytic transformations of organic substrates or for biomimicry.[1−6] More recently, scorpionates have also been studied for the synthesis of organometallic bioconjugates with potential relevance for in vitro and/or in vivo biomedical applications.[7−12] In this field, our research group has synthesized and biologically evaluated several complexes of the type *fac*-[M(κ^3-H(μ-H)B(tim^{BM})(tim^{Me}))(CO)$_3$] (M = Re, ^{99m}Tc; BM = biomolecule; Figure 1). As reported, the corresponding asymmetric dihydro(mercaptoimidazolyl)borates were prepared by reacting $NaBH_4$ with tim^{Me}H and with a mercaptoimidazole bearing a biomolecule (tim^{BM}H).[9,10] Such synthetic procedure was quite demanding because of the simultaneous formation of the symmetric chelators [Na[H$_2$B(tim^{BM})$_2$] and Na[H$_2$B(tim^{Me})$_2$]. The strictly pure asymmetric bifunctional chelators were normally obtained



M = Re , ^{99m}Tc ; BM = Bioactive fragment

Figure 1. Molecular Structures of a Re(I)/^{99m}Tc(I) tricarbonyl bioconjugates containing an asymmetric dihydro(mercaptoimidazolyl)borate carrying one bioactive fragment (BM).

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(1) Trofimenko, S. *Scorpionates: The Coordination Chemistry of Polypyrazolylborate Ligands*; Imperial College Press: London, 1999.
(2) Marques, N.; Sella, A.; Takats, J. *J. Chem. Rev.* **2002**, *102*, 2137–2160.
(3) Paulo, A.; Correia, J. D. G.; Campello, M. P. C.; Santos, I. *Polyhedron* **2004**, *23*, 331–360.
(4) Santos, I.; Paulo, A.; Correia, J. D. G. *Top. Curr. Chem.* **2004**, *252*, 45–84.
(5) Parkin, G. *Chem. Commun.* **2000**, 1971–1985.
(6) Morlok, M. M.; Janak, G. Z.; Quarless, D. A.; Parkin, G. *J. Am. Chem. Soc.* **2005**, *127*, 14039–14050; and references therein.
(7) Kuchta, M. C.; Gemel, C.; Metzler-Nolte, N. *J. Organomet. Chem.* **2007**, *692*, 1310–1314.
(8) Kuchta, M. C.; Gross, A.; Pinto, A.; Metzler-Nolte, N. *Inorg. Chem.* **2007**, *46*, 9400–9404.
(9) Garcia, R.; Xing, Y. H.; Paulo, A.; Domingos, A.; Santos, I. *J. Chem. Soc., Dalton Trans.* **2002**, 4236–4241.
(10) Garcia, R.; Gano, L.; Maria, L.; Paulo, A.; Santos, I.; Spies, H. *J. Biol. Inorg. Chem.* **2006**, *11*, 769–782.
(11) Garcia, R.; Paulo, A.; Domingos, A.; Santos, I.; Ortner, K.; Alberto, R. *J. Am. Chem. Soc.* **2000**, *122*, 11240–11241.
(12) Garcia, R.; Paulo, A.; Domingos, A.; Santos, I. *J. Organomet. Chem.* **2001**, *632*, 41–8.

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in low yield, after a long and tedious purification process. These difficulties hampered a fast screening of the biological properties of the Re(I) tricarbonyl complexes, used as surrogates of target-specific ^{99m}Tc-radiopharmaceuticals, being important to find a more efficient alternative.

Recently, we have also synthesized the unprecedented *fac*-[Re(κ^3-H(μ-H)$_2$B(tim^{Me}))(CO)$_3$] (**1**),[13] showing that the Re···H−B bonds in **1** can be cleaved by neutral substrates forming promptly the mixed-ligand complexes *fac*-[Re(κ^3-H$_2$(μ-H)B(tim^{Me}))(L)(CO)$_3$] (L = PPh$_3$, ^{t}BuNC, EtOOCCH$_2$NC).[14] On the basis of these results, we anticipated that **1** would react with protic substrates, such as mercaptoimidazoles and pyrazoles, yielding Re(I) tricarbonyl complexes anchored by asymmetric poly(azolyl)borates generated *in situ*. Such reactions would avoid the tedious synthesis of the chelators by the conventional method. Searching for the proof-of-principle of this strategy, we decided to evaluate the reactivity of **1** toward different azole derivatives. Herein, we report on these reactivity studies which led to the synthesis of *fac*-[Re(κ^3-H(μ-H)B(tim^{Me})$_2$(CO)$_3$] (**2**), [Re(κ^3-H(μ-H)B(tim^{Me})(bzt))(CO)$_3$] (**3**), [Re(κ^3-H(μ-H)B(tim^{Me})-(pz))(CO)$_3$] (**4**), [Re(κ^3-HB(tim^{Me})(pz)$_2$)(CO)$_3$] (**5**), and [Re(κ^3-H(μ-H)B(tim^{Me})(3,5-Me$_2$-4-EtOOCCH$_2$pz))(CO)$_3$] (**6**). All the new complexes (**3**−**6**), anchored by heteroscorpionates, have been fully characterized by the common spectroscopic techniques, including by X-ray crystallography.

Experimental Section

General Procedures. All chemicals and solvents were of reagent grade and were used without purification unless stated otherwise. The synthesis of the complexes were carried out under a N_2 atmosphere, using solvents which have been dried and distilled prior to use, according to described procedures; the workup was performed under air. Thin layer chromatography (TLC) was done using plates from Merck (Silica gel 60 F254). Column chromatography was performed in silica gel 60 (Merck). The compounds ethyl 3-acetyl-4-oxopentanoate[15] and [Re(κ^2-H(μ-H)$_2$B(tim^{Me}))-(CO)$_3$] (**1**)[13] were prepared as described in the literature.[1]H, ^{11}C, and ^{11}B NMR spectra were recorded on a Varian Unity 300 MHz spectrometer. ^{1}H and ^{11}C chemical shifts (ppm) were referenced with the residual solvent resonances relative to tetramethylsilane. The ^{11}B NMR spectra were recorded in ppm relative to a $BF_3 \cdot Et_2O$ external reference. IR spectra were recorded as KBr pellets on a Bruker, Tensor 27 spectrometer. C, H, and N analyses were performed on an EA 110 CE Instruments automatic analyzer.

Synthesis of Ethyl 2-(3,5-dimethyl-1*H*-pyrazol-4-yl)acetate. To a solution of ethyl 3-acetyl-4-oxopentanoate (9.676 g, 51.96 mmol) in ethanol, at 0 °C, was added slowly a solution of hydrazine hydrate (2.990 g, 59.75 g) in absolute ethanol. The reaction mixture was warmed to room temperature and stirred for 2 h. After removal of ethanol under vacuum, dichloromethane and water were added to the crude product and the organic layer was separated. The aqueous layer was extracted further with dichloromethane, and the combined organic extracts were washed with water. After drying over $MgSO_4$ and evaporation of the solvent under reduced pressure, the pyrazole was isolated as a yellow oil. Yield: 72% (6.777 g, 37.2 mmol).

^{1}H NMR ($CDCl_3$) δ_H 4.09 (2H, q, 7 Hz, CH_2), 3.32 (2H, s, CH_2), 2.21 (6H, s, CH_3), 1.22 (3H, t, 7 Hz, CH_3).^{13}C NMR ($CDCl_3$): δ_C 171.52 (COOEt), 142.98 (C(3/5)-pz), 108.60 (C(4)-pz), 60.74 (CH_2), 29.36 (CH_2), 14.16 (CH_3), 10.85 (CH_3).

Synthesis of *fac*-[Re(κ^3-H(μ-H)B(tim^{Me})$_2$)(CO)$_3$] (2). To a solution of **1** (24 mg, 0.060 mmol) in toluene was added 2-mercapto-1-methylimidazole (7.4 mg, 0.065 mmol), and the mixture was heated under reflux for 2 days. After this time, the solvent was removed under vacuum, the crude was applied on the top of a silica-gel column, and the product was recovered by elution with CH_2Cl_2/*n*-hexane (70:30). The analysis of the recovered product by ^{1}H and ^{11}B NMR confirmed the formation of **2** by comparison with the spectroscopic data that we have previously reported for this complex.[11] Yield: 62% (19 mg, 0.037 mmol).

Synthesis of *fac*-[Re(κ^3-H(μ-H)B(tim^{Me}) (bzt))(CO)$_3$] (3). Complex **3** was synthesized as above-described for **2**. After 4 days of reflux and starting with 50 mg (0.13 mmol) of **1** and 21 mg (0.13 mmol) of 2-mercaptobenzothiazole. Complex **3** was recovered using silica-gel chromatography and elution with CH_2Cl_2/*n*-hexane (50:50). Recrystallization of **3** from THF/*n*-hexane gave yellow crystals suitable for X-ray diffraction analysis. Yield: 38% (27 mg, 0.05 mmol). Anal. Calcd (Found) for $C_{14}H_{11}N_3S_3O_3BRe$**:** C, 29.90 (29.53); H, 1.97 (2.01); N, 7.47 (7.32). IR (ν/cm^{-1}): 2476 (ν(B−H)); 2166, 2119 (ν(B−H···Re)); 2021, 1910, 1896 (ν(CO)).^{1}H NMR ($CDCl_3$): δ_H 7.85 (1H, d, H−Ar), 7.46 (2H, m, H−Ar), 7.29 (1H, m, H−Ar), 6.78 (1H, d, J_{H-H} = 2.1 Hz, CH), 6.72 (1H, d, J_{H-H} = 2.1 Hz, CH), 3.54 (3H, s, CH_3−N), −6.62 (1H, br, B−H···Re). ^{13}C NMR ($CDCl_3$): δ_C (ppm) 196.49 (S−C═S), 191.89 (CO), 190.94 (CO), 189.89 (CO), 165.48 (N−C═S), 144.48 (CH), 133.78 (CH), 127.10 (C−Ar), 124.82 (C−Ar), 122.62 (C−Ar), 122.02 (C−Ar), 121.81 (C−Ar), 116.19 (C−Ar), 34.84 (CH_3). ^{11}B-NMR ($CDCl_3$) δ_B −7.52 (m). R_f (silica-gel, CH_2Cl_2/*n*-hexane (50:50)) = 0.30.

Synthesis of *fac*-[Re(κ^3-H(μ-H)B(tim^{Me}) (pz))(CO)$_3$] (4). To a solution of **1** (55 mg, 0.139 mmol) in tetrahydrofuran (THF, 20 mL) was added pyrazole (9.5 mg, 0.139 mmol). The resulting solution was stirred under reflux overnight. After cooling to room temperature, the solvent was removed under vacuum, and compound **4** was purified by silica-gel chromatography using CH_2Cl_2/*n*-hexane (45:55) as eluent. Single crystals adequate for X-ray diffraction analysis were obtained by recrystallization from CH_2Cl_2/*n*-hexane. Yield: 89% (57 mg, 0.12 mmol). Anal. Calcd (Found) for $C_{10}H_{10}N_4SO_3BRe$: C, 25.86 (25.89); H, 2.17 (2.23); N, 12.07 (12.16). IR (ν/cm^{-1}): 2478 (ν(B−H)); 2026, 1933, 1909 (ν(CO)). ^{1}H NMR ($CDCl_3$): δ_H (ppm) 7.40 (1H, d, J_{H-H} = 1.5 Hz, H(3,5)-pz), 7.13 (1H, d, J_{H-H} = 2.4 Hz, H(3,5)-pz); 6.86 (1H, d, J_{H-H} = 2.4 Hz, CH), 6.82 (1H, d, J_{H-H} = 1.8 Hz, CH), 6.10 (1H, t, H(4)-pz), 3.53 (3H, s, CH_3−N), −3.97 (1H, br, J_{B-H} = 75 Hz, B−H···Re). ^{13}C NMR ($CDCl_3$): δ_C (ppm) 193.93 (CO), 193.05 (CO), 192.03 (CO), 163.90 (C═S), 140.60 (CH), 135.66 (CH), 122.31 (C(3,5)-pz), 121.41 (C(3,5)-pz), 107.40 (C(4)-pz), 34.43 (CH_3). ^{11}B-NMR ($CDCl_3$): δ_B (ppm) −11.28 (m). R_f (silica-gel, CH_2Cl_2/*n*-hexane (50:50)) = 0.40.

Synthesis of *fac*-[Re(κ^3-HB(tim^{Me})(pz)$_2$)(CO)$_3$] (5). To a solution of [Re(κ^3-H(μ-H)B(tim^{Me})(pz))(CO)$_3$] (**4**) (15 mg, 0.032 mmol) in toluene (20 mL) was added pyrazole (2.5 mg, 0.037 mmol). The resulting solution was heated under reflux overnight. After cooling to room temperature, the solvent was removed under vacuum. Compound **5** was purified by column chromatography using an isocratic elution with CH_2Cl_2/*n*-hexane (45:55). Recrystallization

(13) Maria, L.; Paulo, A.; Santos, I. C.; Santos, I.; Kurz, P.; Spingler, B.; Alberto, R. *J. Am. Chem. Soc.* **2006**, *128*, 14590–14598.
(14) Videira, M.; Maria, L.; Paulo, A.; Santos, I. C.; Santos, I.; Vaz, P. D.; Calhorda, M. J. *Organometallics* **2008**, *27*, 1334–1337.
(15) Shrout, D. P.; Lightner, D. A. *Synth. Commun.* **1990**, *20*, 2075.

Table 1. Crystallographic Data for **3**−**6**

compound	**3**	**4**	**5**	**6**
lattice	triclinic	monoclinic	monoclinic	triclinic
formula	$C_{14}H_{11}BN_3O_3ReS_3$	$C_{10}H_{10}BN_4O_3ReS$	$C_{13}H_{12}BN_6O_3ReS$	$C_{15}H_{20}BN_5O_5ReS$
F_w	562.45	463.29	529.36	579.43
space group	$P\bar{1}$	$P21/c$	$P21/n$	$P\bar{1}$
a/Å	7.1208(2)	7.06080(2)	8.3300(2)	7.1432(3)
b/Å	9.5960(4)	13.8156(2)	15.7288(2)	11.8530(5)
c/Å	13.8327(4)	14.4289(2)	12.8497(3)	12.5983(6)
α/deg	84.516(4)	90	90	106.6540(10)
β/deg	89.8630(10)	95.9560(10)	91.2430(10)	91.5020(10)
γ/deg	68.3330(10)	90	90	95.9390(10)
Z	2	4	4	2
T/K	150(2)	150(2)	150(2)	150(2)
ρ(calcd.)/g cm^{-3}	2.138	2.198	2.089	1.896
μ (Mo Kα)/mm^{-1}	7.330	8.839	7.370	6.127
θ_{max}/deg	25.7	25.7	25.0	25.7
no. of data	3298	2657	2481	3822
no. of params	234	190	227	264
R_1	0.0294	0.0166	0.0203	0.0243
wR_2	0.0706	0.0334	0.0441	0.0544
GOF	1.035	1.039	1.063	1.015

of compound **5** from CH_2Cl_2/*n*-hexane gave yellow crystals suitable for X-ray diffraction analysis. Yield: 64% (11 mg, 0.02 mmol). IR (ν/cm^{-1}): 2490 ν(B−H); 2019, 1933, 1912 ν(CO). Anal. Calcd (Found) for $C_{13}H_{12}N_6SO_3BRe$: C, 29.50 (28.17); H, 2.28 (2.83); N, 15.88 (15.64). ^{1}H NMR ($CDCl_3$): δ_H (ppm) 7.90 (2H, d, J_{H-H} = 2.1 Hz, H-pz(3,5)), 7.59 (2H, d, J_{H-H} = 2.4 Hz, H-pz(3,5)), 6.85 (1H, d, J_{H-H} = 1.8 Hz, CH), 6.63 (1H, d, J_{H-H} = 2.1 Hz, CH), 6.27 (2H, t, H(4)-pz), 3.48 (3H, s, CH_3−N). ^{13}C NMR ($CDCl_3$) δ_C (ppm): 195.24 (CO), 192.36 (CO), 155.25 (C═S), 146.46 (CH), 137.12 (CH), 123.12 (C(3,5)-pz), 119.40 (C(3,5)-pz); 106.51 (C(4)-pz), 34.50 (CH_3−N). ^{11}B-NMR ($CDCl_3$) δ_B (ppm): −2.45 (d, J_{B-H} = 120 Hz). R_f (silica-gel, CH_2Cl_2/*n*-hexane (50:50)) = 0.35.

Synthesis of *fac*-[Re(κ^3-H(μ-H)B(tim^{Me})(3,5-Me$_2$-4-EtOOC-CH$_2$pz))(CO)$_3$] (6). To a solution of **1** (80 mg, 0.201 mmol) in THF (20 mL) was added 3,5-dimethyl-4-ethylacetatepyrazole (40 mg, 0.219 mmol), and the mixture was refluxed overnight. After this time the solvent was removed under vacuum and compound **6** was purified by silica-gel chromatography using CH_2Cl_2/CH_3OH (90:10 → 25:75) as eluent. Recrystallization of **6** from CH_2Cl_2/*n*-hexane gave yellow crystals suitable for X-ray diffraction analysis. Yield: 60% (70 mg, 0.121 mmol). IR ν/cm^{-1}): 2491 ν(B−H); 2030, 1947, 1927 ν(CO); 1734 ν(C═O). Anal. Calcd (Found) for $C_{16}H_{20}N_4SO_5BRe$: C, 33.28 (33.63); H, 3.49 (4.03); N, 9.70 (9.54). δ_H (ppm) 6.85 (1H, d, CH), 6.78 (1H, d, CH), 4.08 (2H, q, CH_2−O), 3.53 (3H, s, CH_3−N), 3.25 (2H, s, CH_2), 2.12 (3H, s, CH_3), 2.00 (3H, s, CH_3), 1.21 (3H, t, CH_3), −4.20 (2H, br, B−H···Re). ^{13}C NMR ($CDCl_3$): δ_C (ppm) 194.15 (CO), 193.80 (CO), 191.82 (CO), 171.03 (C═O), 164.07 (C═S), 147.90 (CH), 143.58 (CH), 122.11 (C(3/5)-pz), 121.33 (C(3/5)-pz), 109.75 (C(4)-pz), 60.86 (CH_2−O), 34.36 (CH_3−N), 29.42 (CH_2), 14.11 (CH_3), 11.46 (CH_3), 8.43 (CH_3). ^{11}B NMR ($CDCl_3$): δ_B (ppm) −12.46 ppm (m).

X-ray Diffraction Analysis. The X-ray diffraction analysis of **3**−**6** (Table 1) has been performed on a Bruker AXS APEX CCD area detector diffractometer, using graphite monochromated Mo Kα radiation (0.71073 Å). Empirical absorption correction was carried out using SADABS.[16] Data collection and data reduction were done with the SMART and SAINT programs.[17] The structures were solved by direct methods with SIR97[18] and refined by full-matrix least-squares analysis with SHELXL97[19] using the WINGX[20] suite of programs. All non-hydrogen atoms were refined anisotropically. The hydrogen atoms linked to the boron atoms were located in the difference Fourier map and refined isotropically. The remaining hydrogen atoms were placed in calculated positions. Molecular graphics were prepared using ORTEP3.[21]

Results and Discussion

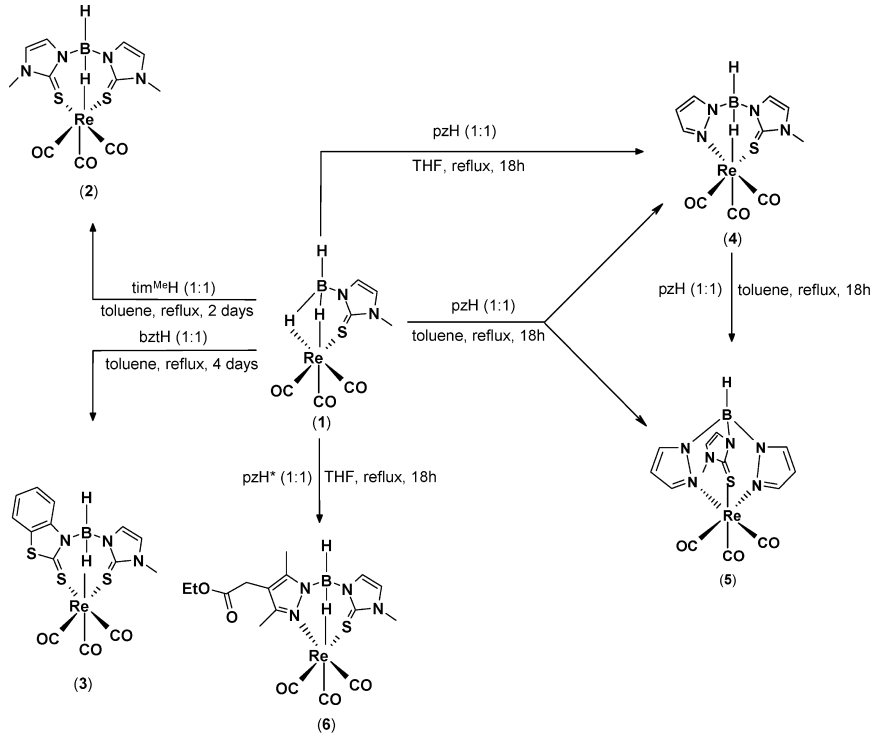
Synthesis. As discussed in the introductory part of this manuscript, we have hypothesized that *fac*-[Re(κ^3-H(μ-H)$_2$B(tim^{Me}))(CO)$_3$] (**1**) would react with azole derivatives yielding new organometallic complexes anchored by asymmetric azolylborates, upon release of hydrogen and linkage of the incoming azole to the boron atom. To confirm such hypothesis we have studied reactions of **1** with 2-mercapto-1-methyl-imidazole (tim^{Me}H), 2-mercaptobenzothiazole (bztH), pyrazole (pzH) and ethyl 2-(3,5-dimethyl-1*H*-pyrazol-4-yl)acetate. The latter is a novel ester derivative of 3,5-dimethylpyrazole, which has been prepared by cyclization of the corresponding diketone with hydrazine.

Reactions of **1** with 2-mercapto-1-methylimidazole and 2-mercaptobenzothiazole were run in THF, using approximately equimolar amounts of the reagents. After overnight reflux, the control of the reactions by ^{1}H NMR and TLC has shown essentially the presence of the starting materials. However, the same reactions in refluxing toluene yielded the complexes *fac*-[Re(κ^3-H(μ-H)B(tim^{Me})$_2$)(CO)$_3$] (**2**)[11] and [Re(κ^3-H(μ-H)B(tim^{Me})(bzt))(CO)$_3$] (**3**) which, after appropriate workup, were isolated as yellow microcrystalline solids in 62% and 38% isolated yields, respectively (Scheme 1).

Taking into consideration the behavior exhibited by the mercaptoazolyl derivatives, the reaction of **1** with pyrazole

(16) *SADABS, Area-Detector Absorption Correction*; Bruker AXS Inc.: Madison, WI, 2004.
(17) *SAINT, Area-Detector Integration Software*, Version7.23; Bruker AXS Inc: Madison, WI, 2004.
(18) Altomare, A.; Burla, M. C.; Camalli, M.; Cascarano, G.; Giacovazzo, G.; Guagliardi, A.; Moliterini, A. G. G.; Polidoro, G.; Spagna, R. *J. Appl. Crystallogr.* **1999**, *32*, 115.
(19) Sheldrick G. M. *SHELXL-97, Program for the Refinement of Crystal Structure*; University of Göttingen: Göttingen, Germany, 1997.
(20) Farrugia, L. J. *J. Appl. Crystallogr.* **1999**, *32*, 837–838.
(21) ORTEP-3: Farrugia, L. J. *J. Appl. Crystallogr.* **1997**, *30*, 565.

Scheme 1. Synthesis of Complexes **2**−**6**



was initially evaluated in refluxing toluene. However, this reaction was considerably faster than those with the sulfur-donor azoles, and a mixture of *fac*-[Re(κ^3-H(μ-H)B(tim^{Me})(pz))(CO)$_3$] (**4**) and *fac*-[Re(κ^3-HB(tim^{Me})(pz)$_2$)(CO)$_3$] (**5**) was obtained after overnight reflux, in spite of using a 1:1 molar ratio of the reagents. A more careful analysis of this reaction has shown that **5** forms in a stepwise way and can be obtained in a pure form by reacting **4** with pyrazole in refluxing toluene (Scheme 1). Complex **4** can also be selectively prepared by reacting **1** with pyrazole in the molar ratio 1:1, using THF as solvent. These results reflect most probably the largest activation energy associated with the introduction of the second pyrazolyl ring. In refluxing THF, the preparation of *fac*-[Re(κ^3-H(μ-H)B(tim^{Me})(3,5-Me$_2$-4-EtOOCCH$_2$pz))(CO)$_3$] (**6**), containing an ester-functionalized heteroscorpionate, was also achieved quite straightforwardly by reacting **1** with an ester derivative of pyrazole (Scheme 1). Complexes **4**−**6** were obtained in moderate to high isolated yield (60−89%) after appropriate workup.

Mechanistically, two possibilities can be considered to explain the formation of complexes **2**−**4** and **6**. The first one involves a direct interaction of the azole with the electron-deficient boron atom in complex **1**, followed by a concerted elimination of H_2.[22] Alternatively, the azole can interact directly with the metal, cleave the Re···H−B bond, forming intermediates of the type "*fac*-[Re(κ^2-H$_3$B(tim^{Me}))(azoleH)(CO)$_3$]". Such intermediates can be seen as [2 + 1] mixed-ligand Re(I) complexes, analogous to *fac*-[Re(κ^2-H$_3$B(tim^{Me}))(L)(CO)$_3$] (L = isonitrile and phosphine) recently reported.[14] Because of the protic nature of the azoles, the [2 + 1] intermediates are converted into the final complexes **2**−**6**, upon release of H_2 and formation of a boron−nitrogen bond, leading to the (κ^3-H, S, S′) or (κ^3-H, S, N) heteroscorpionates. Although experimental data to support any of these two possibilities does not exist, we consider that the involvement of [2 + 1] intermediates appears as the more plausible one, taking into consideration our previous results[14] and the kinetics of the reactions. If these reactions would involve a direct interaction with the boron atom, one could expect a kinetic trend analogous to the one observed when these azoles react with alkali borohydrides. In fact, 2-mercapto-1-methylimidazole reacts with borohydrides much faster than pyrazole because of the highest Brönsted acidity of the former.[23,24] So, most probably our results reflect a better ability of pyrazole to cleave the Re···H−B bond, with formation of [2 + 1] intermediates, being for these species the limiting step. The synthesis of **5** may involve a similar mechanism, with involvement of the [2 + 1] intermediate "*fac*-[Re(κ^2-H$_2$B(tim^{Me})(pz))(pzH)(CO)$_3$]".[25]

The heteroscorpionates in complexes **3**, **4**, and **6** represent the first examples of dihydrobis(azolyl)borates combining a 2-mercaptoimidazolyl ring with 2-mercaptobenzothiazolyl and pyrazolyl rings, respectively. Other hydrotris(azolyl)borates with 2-mercaptoimidazolyl and pyrazolyl derivatives were reported in the literature, but almost all of them have been synthesized by reacting borohydrides with the corresponding azoles.[26−32] To the best of our knowledge, the synthesis of [HB(tim^{Me})$_2$pz]ZnI via reaction of [H$_2$B-

(22) Rasika Dias, H. V.; Alidori, S.; Lobbia, G. G.; Papini, G.; Pellei, M.; Santini, C. *Inorg. Chem.* **2007**, *46*, 9708–9714.

(23) Bailey, P. J.; Lorono-Gonzales, D.; McCormack, C.; Millican, F.; Parsons, S.; Pfeifer, R.; Pinho, P. P.; Rudolphi, F.; Perucha, A. S. *Chem.—Eur. J.* **2006**, *12*, 5293–5300.

(24) Ojo, J. F.; Slavin, P. A.; Reglinski, J.; Garner, M.; Spicer, M. D.; Kennedy, A. R.; Teat, S. J. *Inorg. Chim. Acta* **2001**, *313*, 15–20.

(25) Garcia, R.; Paulo, A.; Domingos, A.; Santos, I.; Alberto, R. *Inorg. Chem.* **2002**, *41*, 2422–2428.

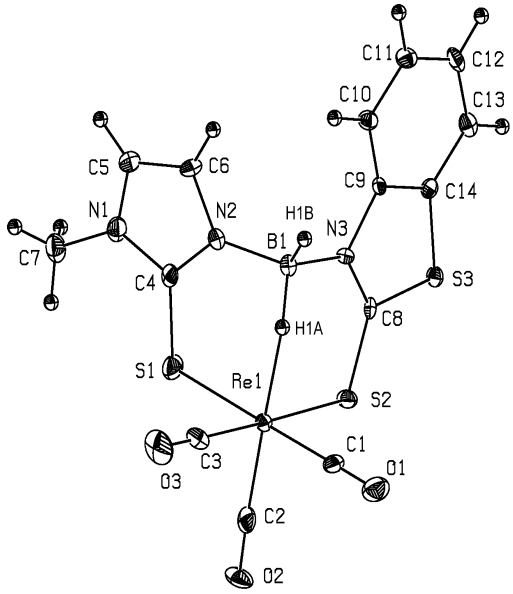


Figure 2. ORTEP view of *fac*-[Re(κ^3-H(μ-H)B(tim^{Me})(bzt))(CO)$_3$] (**3**) with ellipsoids drawn at the 40% probability level. Selected bond distances (Å): Re−C(1) 1.911(5), Re−C(2) 1.925(5), Re−C(3) 1.925(5), Re−H(1A) 1.91(6), Re−S(1) 2.5017(12), Re−S(2) 2.4457(11).

(tim^{Me})$_2$]ZnI with pyrazole was the unique example of a hydrotris(azolyl)borate obtained by a metal-mediated process.[33]

Characterization. The novel complexes **3**−**6** have been characterized by elemental analysis, IR, multinuclear NMR spectroscopy (^{1}H, ^{13}C, and ^{11}B) and by X-ray diffraction analysis.

The structures of **3**−**6** consist of discrete mononuclear units with the rhenium atom in a slightly distorted octahedral environment. Oak Ridge Thermal Ellipsoid Plot (ORTEP) views of **3**−**6** are shown in Figures 2−4, together with a selection of bond distances.

For all the structures, the hydrogen atoms coordinated to the boron have been located in the difference Fourier map and were refined isotropically. In the case of complexes **3**, **4**, and **6**, this confirmed the coordination to the metal of one hydride from the respective (κ^3-H, S, S′) or (κ^3-H, S, N) heteroscorpionates. The distances found for the Re···H−B bonds appear within a relatively narrow range (1.90(4)−1.95(3) Å) and can be considered comparable to those previously found in *fac*-[Re(κ^3-H(μ-H)$_2$B(tim^{Me}))(CO)$_3$] (**1**) (av. Re···H−B = 1.96 Å).[13] For complex **5**, the X-ray diffraction analysis has shown the presence of a (κ^3-S, N, N) hydrotris(azolyl)borate, without any B−H···Re interaction.

The Re−S bond distances (2.4945(6)−2.5086(9) Å) of the coordinated 2-mercapto-1-methylimidazolyl rings in the complexes anchored by dihydrobis(azolyl)borates (**3**, **4**, and **6**) are within the range (2.462(6)−2.5190(11) Å) previously reported for *fac*-[Re(κ^3-R(μ-H)B(tim^{Me})$_2$)(CO)$_3$] (R = H, Me, Ph).[11,12] For complex **3**, the Re−S distance of 2.4457(11) Å found for 2-mercaptobenzothiazolyl is slightly shorter, being almost coincident with the same distance in *fac*-[Re(κ^3-H(μ-H)$_2$B(bzt))(CO)$_3$] (Re−S: 2.4454(11) Å).[13] The Re−N bond distances of the coordinated pyrazolyl rings in **4**−**6** span between 2.158(3) and 2.178(3) Å, being within the range (2.052(7)−2.241(10) Å) reported for other Re(I) complexes with [HB(pz)$_3$]$^-$ or [HB(3,5-Me$_2$pz)$_3$]$^-$.[34,35] The longest Re−N bond distances (av. 2.178(3) Å) have been found for **5** which contains a (κ^3-S, N, N) heteroscorpionate, reflecting most probably the greatest steric requirement of this ligand in comparison with the congener dihydrobis(azolyl)borates in **4** and **6**. However, the same effect was not observed for the Re−S bond distance of the coordinated 2-mercapto-1-methylimidazolyl in **5** (2.4995(10) Å) which appears well within the range obtained for the same bond distance in complexes **3**, **4**, and **6**.

In the solid state, the presence of the B−H···Re bond was confirmed by IR spectroscopy only for **3**. The IR spectrum of this complex presented two weak bands at 2166 and 2119 cm^{-1}, unequivocally assigned to the ν(B−H···Re) stretches. For complexes **4** and **5**, these ν(B−H···Re) bands could not be identified in the spectra as they overlap with the intense ν(CO) bands, which appear between 1909 and 2030 cm^{-1}. By contrast, terminal ν(B−H) bands, appearing between 2476 and 2491 cm^{-1}, were easily identified in the IR spectra of all complexes (**3**−**6**). For the complexes with dihydrobis(azolyl)borates (**3**, **4**, and **6**) there is a blue shift of the ν(CO) frequencies when a pyrazolyl ring (**4** and **6**) replaces a 2-mercaptobenzothiazolyl ring (**3**, ν(CO) = 1896−2021 cm^{-1}). This shift indicates that the presence of thione donors in the structure of poly(azolyl)borates make this type of chelators better σ/π donors than their congeners containing pyrazolyl rings, as already verified by other authors.[36] In **4** and **6**, the poor σ/π donor capability of the pyrazolyl-containing heteroscorpionates may induce the strengthening of the B−H···Re bonds, causing the overlap of the B−H···Re stretching bands with those of the CO ligands.

Multinuclear NMR studies (^{1}H, ^{13}C, and ^{11}B) of **3**−**6** have indicated that the structures found for these compounds in the solid state are maintained in solution. For **3**, **4**, and **6**, the most striking feature of their ^{1}H NMR spectra is the presence of a high-field shifted resonance, between −6.62

(26) Seebacher, J.; Mouhai, S.; Vahrenkamp, H. *Chem. Commun.* **2001**, 1026–1027.
(27) Benkmil, B.; Ji, M.; Vahrenkamp, H. *Inorg. Chem.* **2004**, *43*, 8212–8214.
(28) Mian, J.; Benkmil, B.; Vahrenkamp, H. *Inorg. Chem.* **2005**, *44*, 3518–3523.
(29) Shu, M.; Walz, R.; Wu, B.; Seebacher, J.; Vahrenkamp, H. *Eur. J. Inorg. Chem.* **2003**, 2502–2511.
(30) Ibrahim, M. M.; He, G.; Seebacher, J.; Boumahdi, B.; Vahrenkamp, H. *Eur. J. Inorg. Chem.* **2005**, 4070–4077.
(31) Cammi, R.; Gennari, M.; Giannetto, M.; Lanfranchi, M.; Marchio, L.; Mori, G.; Paiola, C.; Pellingh elli, M. A. *Inorg. Chem.* **2005**, *44*, 4333–4345.
(32) Kimblin, C.; Bridgewater, B. M.; Churchill, D. G.; Hascall, T.; Parkin, G. *Inorg. Chem.* **2000**, *39*, 4240–4243.
(33) Kimblin, C.; Hascall, T.; Parkin, G. *Inorg. Chem.* **1997**, *36*, 5680–5681.
(34) Gunnoe, T. B.; Sabat, M.; Harman, W. D. *Organometallics* **2000**, *19*, 728–740.
(35) Joachim, J. E.; Apostolidis, C.; Kanellakopulos, K.; Meyer, D.; Nuber, B.; Raptis, K.; Rebizant, J.; Ziegler, M. L. *J. Organomet. Chem.* **1995**, *492*, 199–210.
(36) Graham, L. A.; Fout, A. R.; Kuehne, K. R.; White, J. L.; Mookherji, B.; Marks, F. M.; Yap, G. P. A.; Zakharov, L. N.; Rheingold, A. L.; Rabinovich, D. *Dalton Trans.* **2005**, 171–180.

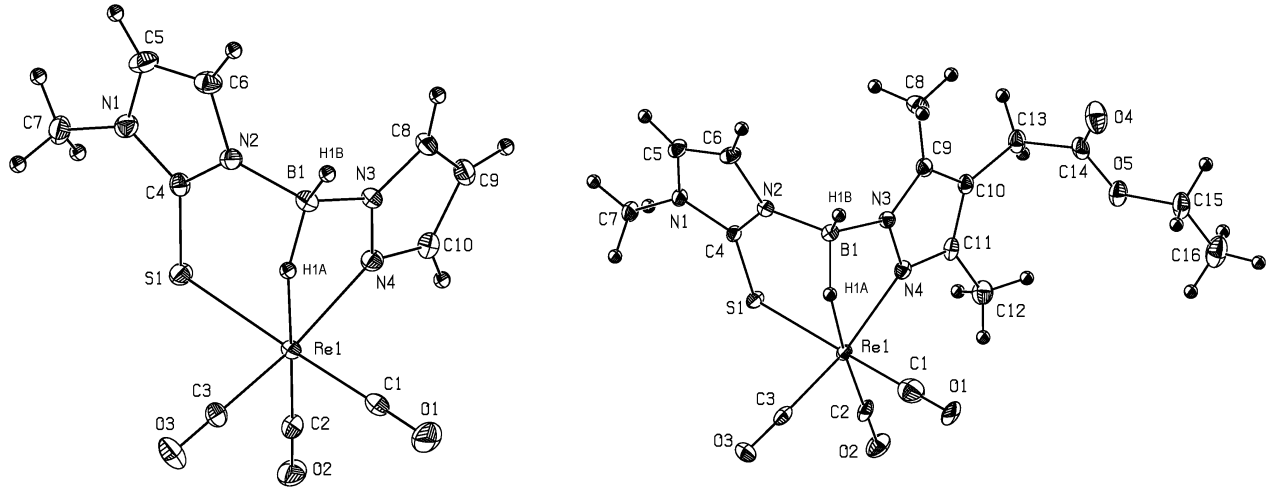


Figure 3. ORTEP views of *fac*-[Re(κ^3-H(μ-H)B(tim^{Me})(pz))(CO)$_3$] (**4**) (left) and *fac*-[Re(κ^3-H(μ-H)B(tim^{Me})(3,5-Me$_2$-4-EtOOCCH$_2$pz))(CO)$_3$] (**6**) (right) with ellipsoids drawn at the 40% probability level. Selected bond distances (Å): complex **4** - Re−C(1) 1.930(3), Re−C(2) 1.913(4), Re(1)−C(3) 1.914(3), Re−H(1A) 1.95(3), Re−S(1) 2.4945(7), Re−N(4) 2.169(2); complex **6** - Re−C(1) 1.932(4), Re−C(2) 1.916(4), Re−C(3) 1.931(4), Re−H(1A) 1.90(4), Re−S(1) 2.5086(9), Re−N(4) 2.158(3).

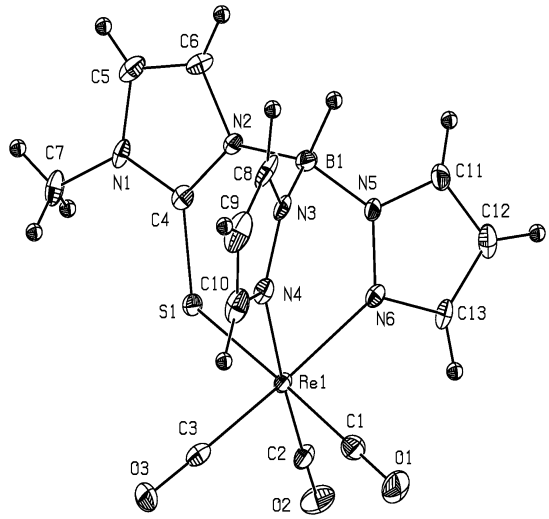


Figure 4. ORTEP view of *fac*-[Re(κ^3-HB(tim^{Me})(pz)$_2$)(CO)$_3$] (**5**) with ellipsoids drawn at the 40% probability level. Selected bond distances (Å): Re−C(1) 1.921(5), Re−C(2) 1.913(4), Re−C(3) 1.912(4), Re−N(4) 2.179(3), Re−N(6) 2.178(3), Re−S(1) 2.4995(10).

and −3.97 ppm, because of the bridging hydride involved in the B−H···Re bond. This resonance suffers a higher shift (−6.62 ppm) for **3** than for **4** and **6** (−3.97 and −4.20 ppm), indicating that the B−H···Re bond has a less hydridic character in **4** and **6**. The ^{1}H NMR spectrum of **5** did not show any high field shifted resonance assignable to a coordinated B−H, corroborating the presence of a (κ^3-S, N, N) chelator. For all the complexes, the resonances of the terminal B−H proton could not be unequivocally identified because of their broadness.

In the ^{11}B NMR spectra of **3**, **4**, and **6** the resonances appear as broad multiplets between −12.46 and −7.52 ppm. Although the multiplicity of these resonances could not be ascertained accurately, their profile showed that the ^{11}B nuclei are coupled to magnetically different ^{1}H nuclei, that is, to the terminal and bridging hydrides. In contrast, for **5** the ^{11}B NMR spectra present a well defined doublet (J_{B-H} = 120 Hz) at −2.45 ppm because of the coupling to the terminal hydride.

The ^{1}H and ^{13}C NMR spectra of **3**−**6** show all the expected resonances for the respective heteroscorpionates and for the three CO ligands, in agreement with the solid state structure of the compounds. In particular, the ^{13}C NMR spectra of **3**, **4**, and **6** display three resonances for the CO ligands, between 189.89 and 194.15 ppm, reflecting the presence of asymmetric (κ^3-H, S, S′) and (κ^3-H, S, N) donor atom sets. For complex **5** the ^{13}C NMR spectrum shows only two signals at 195.24 and 192.36 ppm, roughly in a 2:1 ratio, corresponding to the two carbonyls *trans* to the pyrazolyl and 2-mercaptoimidazolyl rings, respectively.

Conclusions

In summary, we have shown that reactions of **1** with 2-mercaptoimidazoles or with pyrazole derivatives afford, *in situ*, novel organometallic complexes (**3**−**6**) stabilized by bis- or tris(azolyl)borates of the (κ^3-H, S, S′), (κ^3-H, S, N), or (κ^3-S, N, N) type. These complexes were formed in situ by breaking the Re···H−B bond in *fac*-[Re(κ^3-H(μ-H)$_2$B(tim^{Me}))(CO)$_3$] (**1**), release of H$_2$, and formation of boron−nitrogen bonds. The reactions with 2-mercapto-1-methylimidazole and 2-mercaptobenzothiazole led to the unique and well defined complexes *fac*-[Re(κ^3-H(μ-H)-B(tim^{Me})$_2$(CO)$_3$] (**2**) and *fac*-[Re(κ^3-H(μ-H)B(tim^{Me})(bzt))-(CO)$_3$] (**3**), respectively. Pyrazole reacts faster with **1** affording *fac*-[Re(κ^3-H(μ-H)B(tim^{Me})(pz))(CO)$_3$] (**4**) and *fac*-[Re(κ^3-HB(tim^{Me})(pz)$_2$)(CO)$_3$] (**5**) most probably because of a stepwise attack to the boron and release of H$_2$. However, a fine-tuning of the reaction temperature allowed the selective formation of **4** and **5**.

Unlike the alkaline salts of the corresponding asymmetric heteroscorpionates, complexes **3**−**6** are readily purified,

namely by column chromatography, because of their remarkable stability in the presence of air and wet solvents. Therefore, the approach described herein represents a great advantage to obtain more straightforwardly Re(I) organometallic complexes anchored by hybrid poly(azolyl)borates. The synthesis of complex *fac*-[Re(κ^3-H(μ-H)B(tim^{Me})(3,5-Me_2-4-EtOOCCH$_2$pz))$(CO)_3$] (**6**), as a model, indicates that this approach can be used to prepare Re(I) tricarbonyl complexes with bifunctional asymmetric scorpionates bearing a biomolecule. This possibility is expected to provide a fast *in vitro* screening of the biological and/or pharmacological properties of such Re complexes, avoiding at a first stage the independent synthesis of scorpionates carrying bioactive vectors, which is a challenging and time-consuming task. Therefore, this alternative synthetic procedure is expected to allow an easy and fast selection of the best performing complexes to be prepared with ^{99m}Tc.

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Supporting Information Available: Crystallographic data in CIF file format. This material is available free of charge via the Internet at http://pubs.acs.org.

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