Supporting Information

Carboxylation of C-H Bonds Using N-Heterocyclic Carbene Gold(I) Complexes

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Experimental procedures and characterization data.

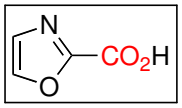
General:

All reactions were carried out in air without special precautions using commercially available reagents. Flash column chromatography was performed on silica gel SiliaFlash® F60, 40-63µm. IR spectra were recorded on a Perkin Elmer Spectrum GX IR spectrometer and are quoted in cm^{-1}. NMR spectra were recorded on Varian Gemini spectrometer. ^{1}H NMR spectra were recorded at 400 MHz and are referenced to TMS, ^{13}C NMR spectra were recorded at 100 MHz and are referenced to TMS, ^{19}F NMR spectra were recorded at 376.5 MHz and are referenced to $CFCl_3$, all reported in ppm. Elemental analyses were performed using a Carlo Erba CHNS analyzer at the University of St Andrews.

General procedure for catalytic carboxylation of aromatics with gold(I) complexes:

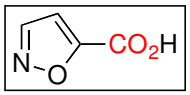
A reaction tube was charged with a solution of [(IPr)AuOH] (9.0 mg, 0.015 mmol) and KOH (58.9 mg, 1.05 mmol) in THF (1.2 mL) under 1.5 bar pressure of CO_2. The mixture was incubated for ~15 minutes at 20°C with vigorous stirring (1450 rpm). A solution of the aromatic substrate (1 mmol) in THF (0.3 mL) was introduced *via* CO_2-flushed syringe. The reaction was run at 20°C for 12 hours, then quenched with 1M aqueous HCl (2 mL). The product was taken up with EtOAc (3 × 3 mL) and the combined organic extracts were washed with 15% aqueous NaCl (4 mL), dried over Na_2SO_4 and concentrated under reduced pressure. Purification by flash chromatography (hexane/EtOAc = 5/1) afforded the corresponding carboxylic acid.

Characterisation data:

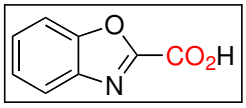


Oxazole-2-carboxylic acid (**3a**)[1]: ^{1}H NMR ($CDCl_3$, 400 MHz): δ 12.08 (1H, s), 7.72 (1H, d, *J* = 1.2 Hz), 7.08 (1H, d, *J* = 1.2 Hz). $^{13}C\{^{1}H\}$NMR ($CDCl_3$, 100 MHz): δ 171.6,

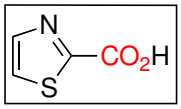
150.5, 138.2, 126.9.



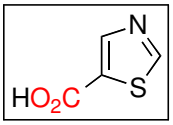
Isoxazole-5-carboxylic acid (**3b**): ^{1}H NMR ($CDCl_3$, 400 MHz): δ 12.03 (1H, s), 8.47 (1H, d, J = 0.9 Hz), 6.31 (1H, d, J = 0.9 Hz). $^{13}C\{^{1}H\}$NMR ($CDCl_3$, 100 MHz): δ 175.1, 158.7, 149.9, 100.6. This compound is unstable with respect to decarboxylation in time, and the NMR data corresponds well with that for **4b**.



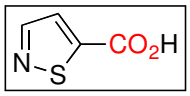
Benzoxazole-2-carboxylic acid (**3c**)[3]: ^{1}H NMR ($CDCl_3$, 400 MHz): δ 11.84 (1H, s), 7.79 (1H, m), 7.58 (1H, m), 7.41 (1H, m), 7.34 (1H, m). $^{13}C\{^{1}H\}$NMR ($CDCl_3$, 100 MHz): δ 171.8, 152.7, 150.0, 140.1, 125.6, 124.4, 120.7, 110.9. This compound is unstable with respect to decarboxylation in time, and the NMR data corresponds well with that for **4c**.



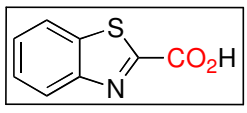
Thiazole-2-carboxylic acid (**3di**)[2]: ^{1}H NMR ($CDCl_3$, 400 MHz): δ 11.95 (1H, s), 7.61 (1H, d, J = 3.6 Hz), 7.31 (1H, d, J = 3.6 Hz). $^{13}C\{^{1}H\}$NMR ($CDCl_3$, 100 MHz): δ 164.1, 161.2, 143.0, 135.9, 123.2.



Thiazole-5-carboxylic acid (**3d*ii***)[2]: ^{1}H NMR ($CDCl_3$, 400 MHz): δ 12.05 (1H, s), 9.23 (1H, d, J = 0.8 Hz), 8.66 (1H, d, J = 0.8 Hz). $^{13}C\{^{1}H\}$NMR ($CDCl_3$, 100 MHz): δ 168.5, 155.1, 143.4, 123.6.

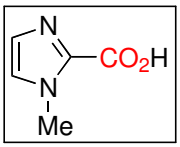


Isothiazole-2-carboxylic acid (**3e**)[3]: ^{1}H NMR ($CDCl_3$, 400 MHz): δ 12.05 (1H, s), 8.54 (1H, d, J = 1.7 Hz), 7.26 (1H, d, J = 1.7Hz). $^{13}C\{^{1}H\}$NMR ($CDCl_3$, 100 MHz): δ 168.8, 159.6, 147.8, 129.4.

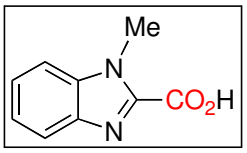


Benzothiazole-2-carboxylic acid (**3f**)[4]: ^{1}H NMR ($CDCl_3$, 400 MHz): δ 11.87 (1H, s), 7.93 (1H, m), 7.74 (1H, m), 7.46 (1H, m), 7.38 (1H, m). $^{13}C\{^{1}H\}$NMR ($CDCl_3$,

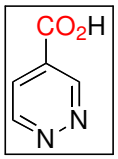
100 MHz): δ 161.3, 158.7, 153.1, 150.9, 136.0, 126.6, 125.7, 122.7, 121.0.



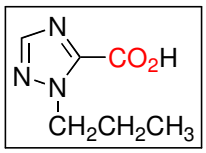
N-Methylimidazole-2-carboxylic acid (**3g**)[5]: ^{1}H NMR ($CDCl_3$, 400 MHz): δ 12.04 (1H, s), 7.02 (1H, d, *J* = 0.8 Hz), 6.86 (1H, d, *J* = 0.8 Hz), 3.65 (3H, s). $^{13}C\{^{1}H\}$NMR ($CDCl_3$, 100 MHz): δ 172.3, 145.1, 129.6, 123.2, 33.9.



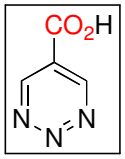
N-Methylbenzimidazole-2-carboxylic acid (**3h**)[6]: ^{1}H NMR ($CDCl_3$, 400 MHz): δ 11.91 (1H, s), 7.61 (2H, m), 7.23 (2H, m). $^{13}C\{^{1}H\}$NMR ($CDCl_3$, 100 MHz): δ 171.9, 141.5, 138.1, 134.3, 121.7, 115, 3, 111.0, 33.9.



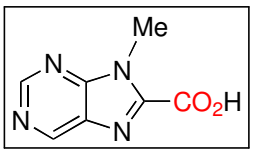
Pyridazine-4-carboxylic acid (**3i**)[7]: ^{1}H NMR ($CDCl_3$, 400 MHz): δ 12.12 (1H, s), 9.59 (1H, dd, *J* = 2.2, 3.0 Hz), 9.26 (1H, dd, *J* = 3.0, 5.1 Hz), 7.87 (1H, dd, *J* = 2.2, 5.1 Hz). $^{13}C\{^{1}H\}$NMR ($CDCl_3$, 100 MHz): δ 166.3, 150.5, 148.2, 129.4, 125.2.



1-Propyl-1, 2, 4-triazole-5-carboxylic acid (**3j**): ^{1}H NMR ($CDCl_3$, 400 MHz): δ 12.07 (1H, s), 8.44 (1H, s), 4.47 (2H, t, *J* = 6.4 Hz), 1.66 (2H, qt, *J* = 6.4, 7.2 Hz), 0.92 (3H, t, *J* = 7.2 Hz). $^{13}C\{^{1}H\}$NMR ($CDCl_3$, 100 MHz): δ 172.4, 153.0, 145.9, 50.6, 23.4, 10.8. HRMS (EI) calc. (M^+), 155.0695; found (M^+), 155.0695.



1, 2, 3-Triazine-5-carboxylic acid (**3k**): ^{1}H NMR ($CDCl_3$, 400 MHz): δ 12.13 (1H, s), 9.72 (1H, s). $^{13}C\{^{1}H\}$NMR ($CDCl_3$, 100 MHz): δ 164.1, 144.3, 121.5. HRMS (EI) calc. (M^+), 125.0225; found (M^+), 125.0225.



N-Methylpurine-8-carboxylic acid (**3l**): ^{1}H NMR ($CDCl_3$, 400 MHz): δ 12.06 (1H, s), 9.28 (1H, d, *J* = 0.4 Hz), 9.04(1H, d, *J* = 0.4 Hz), 3.71 (3H, s). $^{13}C\{^{1}H\}$ NMR ($CDCl_3$, 100 MHz): δ 167.6, 162.8, 152.6, 151.4, 134.7, 132.1, 28.4. HRMS (EI)

calc. (M^+), 178.0491; found (M^+), 178.0491.

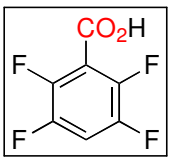
Methyloxazole-2-carboxylate (**4a**)[8]: 85% isolated yield. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.73 (1H, d, *J* = 1.2 Hz), 7.06 (1H, d, *J* = 1.2 Hz), 3.86 (3H, s). $^{13}C\{^1H\}$NMR ($CDCl_3$, 100 MHz): δ 155.8, 150.5, 138.1, 127.0, 51.1.

Methylisoxazole-5-carboxylate (**4b**)[9]: 81% isolated yield. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.45 (1H, d, *J* = 0.9 Hz), 6.33 (1H, d, *J* = 0.9 Hz), 3. 90 (3H, s). $^{13}C\{^1H\}$NMR ($CDCl_3$, 100 MHz): δ 168.9, 158.8, 150.1, 100.5, 54.5.

Methylbenzoxazole-2-carboxylate (**4c**)[8]: 91% isolated yield. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.79 (1H, m), 7.58 (1H, m), 7.41 (1H, m), 7.34 (1H, m), 3.78 (3H, s). $^{13}C\{^1H\}$NMR ($CDCl_3$, 100 MHz): δ 155.6, 152.7, 140.1, 124.7, 123.9, 119.1, 110.6, 51.4.

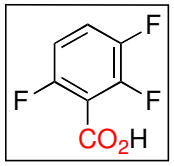
Methylisothiazole-2-carboxylate (**4e**)[9]: 86% isolated yield. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.59 (1H, d, *J* = 1.7 Hz), 7.22 (1H, d, *J* = 1.7Hz), 3.77 (3H, s). $^{13}C\{^1H\}$NMR ($CDCl_3$, 100 MHz): δ 169.0, 159.5, 147.4, 130.0, 50.9.

Methylbenzothiazole-2-carboxylate (**4f**)[9]: 83% isolated yield. ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.90 (1H, m), 7.81 (1H, m), 7.42 (1H, m), 7.35 (1H, m), 3. 82 (3H, s). $^{13}C\{^1H\}$NMR ($CDCl_3$, 100 MHz): δ 161.9, 158.7, 152.7, 150.6, 136.2, 126.5, 124.9, 123.0, 120.6, 51.4.

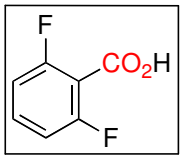


2, 3, 5, 6-Tetrafluorobenzoic acid (**8a**)[10]: ^{1}H NMR (CD_2Cl_2, 400 MHz): δ 11.85 (1H, s), 7.01 (1H, tt, *J* = 3.5, 7.2 Hz). $^{13}C\{^1H\}$NMR (CD_2Cl_2, 100 MHz): δ 167.5, 155.1-154.6 (dm, *J* = 223 Hz), 148.0-146.6 (dm, *J* = 244 Hz), 131.1 (weak), 101.9 (t, *J* = 22.6 Hz).

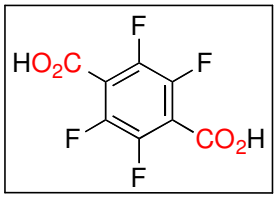
$^{19}F\{^{1}H\}$ NMR (CD_2Cl_2, 376.5 MHz): δ -144.8 (dd, *J* = 13.9, 23.5 Hz), -139.1 (dd, *J* = 13.6, 23.2 Hz).



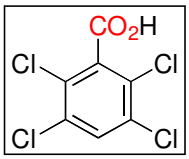
2, 3, 6-Trifluorobenzoic acid (**8b**)[10]: ^{1}H NMR (CD_2Cl_2, 400 MHz): δ 12.00 (1H, s), 7.54 (1H, m), 7.20 (1H, m). $^{13}C\{^{1}H\}$NMR (CD_2Cl_2, 100 MHz): δ 168.0, 154.9-153.6 (d, *J* = 226 Hz), 153.2-152.4 (dm, *J* = 224 Hz), 147.2-145.5 (dm, *J* = 235 Hz), 130.7 (weak), 103.4 (d, *J* = 20 Hz), 101.5 (d, *J* = 18 Hz). $^{19}F\{^{1}H\}$NMR (CD_2Cl_2, 376.5 MHz): δ -143.2 (dd, *J* = 15.8, 23.0 Hz), -139.4 (d, *J* = 22.2 Hz), -120.9 (d, *J* = 16.2).



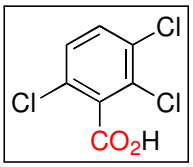
2,6-Difluorobenzoic acid (**8c**)[10]: ^{1}H NMR (CD_2Cl_2, 400 MHz): δ 12.04 (1H, s), 7.62 (1H, m), 7.22 (2H, ddd, *J* = 0.8, 7.2, 8.1 Hz). $^{13}C\{^{1}H\}$NMR (CD_2Cl_2, 100 MHz): δ 170.3, 149.3-134.9 (d, *J* = 226 Hz), 129.4, 118.3. $^{19}F\{^{1}H\}$NMR (CD_2Cl_2, 376.5 MHz): δ - 116.



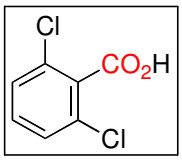
2, 3, 5, 6-Tetrafluoroterephthalic acid (**8d**)[10]: ^{1}H NMR (CD_2Cl_2, 400 MHz): δ 12.01 (2H, s). $^{13}C\{^{1}H\}$ NMR (CD_2Cl_2, 100 MHz): δ 167.1, 154.8-154.2 (dm, *J* = 223 Hz), 147.5-145.3 (dm, *J* = 245 Hz), 133.5 (m). $^{19}F\{^{1}H\}$ NMR (CD_2Cl_2, 376.5 MHz): δ -144.3 (dd, *J* = 14.1, 24.0 Hz), -138.2 (dd, *J* = 14.0, 22.5 Hz).



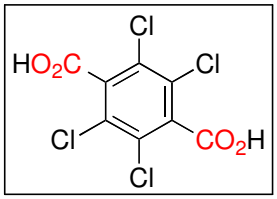
2, 3, 5, 6-Tetrachlorobenzoic acid (**8e**)[11]: ^{1}H NMR (CD_2Cl_2, 400 MHz): δ 11.97 (1H, s), 6.88 (1H, s). $^{13}C\{^{1}H\}$ NMR (CD_2Cl_2, 100 MHz): δ 166.6, 153.1, 144.1, 129.8, 105.2.



2, 3, 6-Trichlorobenzoic acid (**8f**)[12]: ^{1}H NMR (CD_2Cl_2, 400 MHz): δ 12.02 (1H, s), 7.57 (1H, d, *J* = 7.9 Hz), 7.16 (1H,d, *J* = 7.9 Hz). $^{13}C\{^{1}H\}$NMR (CD_2Cl_2, 100 MHz): δ 169.2, 146.7, 152.3, 144.9, 132.5, 105.1, 99.8.



2,6-Dichlorobenzoic acid (**8g**)[12]: ^{1}H NMR (CD_2Cl_2, 400 MHz): δ 12.08 (1H, s), 7.63 (1H, t, *J* = 8.1 Hz)., 7.34 (2H, d, *J* = 8.1 Hz). $^{13}C\{^{1}H\}$NMR (CD_2Cl_2, 100 MHz): δ 169.8, 142.6, 127.1, 119.2.



2, 3, 5, 6-Tetrachloroterephthalic acid (**8h**)[11]: ^{1}H NMR (CD_2Cl_2, 400 MHz): δ 12.04 (2H, s). $^{13}C\{^{1}H\}$NMR (CD_2Cl_2, 100 MHz): δ 165.8, 151.4, 144.4, 130.8.

Stoichiometric reactions of (IPr)Au complexes:

Synthesis of [(IPr)AuOH] (**1**)

Method A: **1** was prepared according to the literature procedure.[13]

Method B: A scintillation vial was charged with a solution of **6** (40.0 mg, 0.0574 mmol) and KOH (3.22 mg, 0.0574 mmol) in THF (0.8 mL). The reaction mixture was stirred for 1 hour at 20°C, then percolated through a short column of Celite. The filtrate was concentrated under reduced pressure to give **1** as a white microcrystalline solid (31.8 mg, 92%). ^{1}H NMR (CD_2Cl_2, 400 MHz): δ 7.56 (2H, t, *J* = 7.8 Hz), 7.35 (4H, d, *J* = 7.8 Hz), 7.20 (2H, s), 2.58 (4H, sept, *J* = 6.9 Hz), 1.35 (12H, d, *J* = 6.9 Hz), 1.23 (12H, d, *J* = 6.9 Hz). $^{13}C\{^{1}H\}$ NMR (CD_2Cl_2, 100 MHz): δ 171.9, 146.2, 134.8, 130.7, 124.5, 123.4, 29.1, 24.4, 24.1. IR (KBr): 3681, 3620, 3385, 3160, 3133, 3063, 2955, 2930, 2864, 1471, 1420, 1366, 1228, 811, 755.

Synthesis of [(IPr)Au-C_3H_2NO] (**5**)*:* A scintillation vial was charged with a solution of **1** (50.0 mg, 0.083 mmol) and **2a** (5.7 mg, 0.083 mmol) in THF (1.0 mL). The reaction mixture was stirred for 2 hours at 20°C, then concentrated to ~0.3 mL under reduced pressure and crystallised from pentane (5 mL). The resulting precipitate was collected on a frit and dried *in vacuo* to give **5** as a white powdery solid (50.4 mg, 93%). ^{1}H NMR (CD_2Cl_2, 400 MHz): δ 7.64 (1H, d, *J* = 1.3 Hz), 7.51 (2H, t, *J* = 7.7 Hz),

7.32 (4H, d, *J* = 7.7 Hz), 7.20 (2H, s), 7.06 (1H, d, *J* = 1.3 Hz), 2.53 (4H, sept, *J* = 6.8 Hz), 1.35 (12H, d, *J* = 6.8 Hz), 1.25 (12H, d, *J* = 6.8 Hz).$^{13}C\{^{1}H\}$ NMR (CD_2Cl_2, 100 MHz): δ 185.1, 150.9, 145.1, 135.5, 138.2, 127.0, 126.3, 123.9, 110.8, 30.1, 23.0. IR (KBr): 3163, 3140, 2926, 2869, 1582, 1550, 1471, 1416, 1355, 1327, 1212, 1177, 1059. Anal. calc. for $C_{30}H_{40}AuN_3O$: C 54.96, H 6.15, N 6.41. Found: C 55.13, H 6.18, N 6.40.

Synthesis of [(IPr)Au-O(C=O)C$_3$H$_2$NO] (**6**)*:* A scintillation vial was charged with a solution of **3** (45.0 mg, 0.069 mmol) in THF (1.0 mL), cooled to -100°C and then purged with CO_2 for 5 minutes. The solution was incubated for 20 minutes at -100°C, then gradually warmed to 25°C. The solvent was removed under reduced pressure, and the residue was recrystallised from toluene to afford **6** as a white microcrystalline solid (41.4 mg, 86%). ^{1}H NMR (CD_2Cl_2, 400 MHz): δ 7.70 (2H, d, *J* = 8.6 Hz), 7.65 (1H, d, *J*= 1.3 Hz), 7.37 (4H, d, *J* = 8.0 Hz), 7.21 (2H, s), 7.11 (1H, d, *J* = 1.3 Hz), 2.64 (4H, s), 1.35 (12H, d, *J* = 6.8 Hz), 1.25 (12H, d = 7.0 Hz). $^{13}C\{^{1}H\}$ NMR (CD_2Cl_2, 100 MHz): δ 174.6, 166.4, 150.6, 144.8, 137.9, 134.6, 126.2, 124.1, 111.6, 29.2, 23.4. IR (KBr): 2967, 2930,2873, 1735, 1616, 1495, 1375, 1257, 1178, 1023, 949, 817, 757. Anal. calc. for $C_{30}H_{36}AuN_3O_3$: C 52.71, H 5.31, N 6.15. Found: C 52.94, H 5.29, N 6.20.

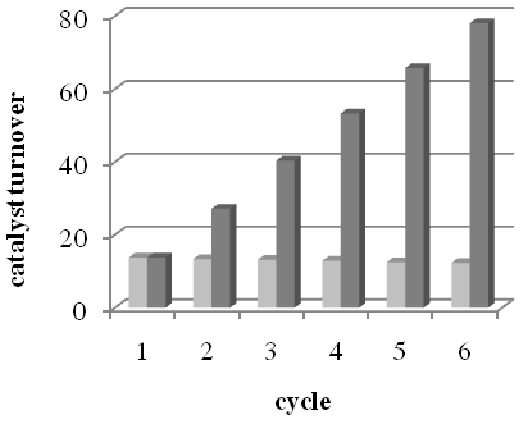
Recycling experiments:

A reaction tube was charged with a solution of [(IPr)AuOH] (9.0 mg, 0.015 mmol) and KOH (58.9 mg, 1.05 mmol) in THF (1.2 mL) under 1.5 bar pressure of CO_2. The mixture was incubated for ~15 minutes at 20°C with vigorous stirring (1450 rpm). A solution of the aromatic substrate (1 mmol) in THF (0.3 mL) was introduced *via* CO_2-flushed syringe. The reaction was run at 45°C for 12 hours. The addition of water (2.5 mL) gave immediate phase separation and the biphasic system was stirred for 10 minutes at 45°C. The organic phase was carefully transferred to a volumetric flask *via* syringe and fresh THF was added to make up 1.5 mL volume. This solution was re-applied in catalysis. The aqueous

phase was quenched as before (*vide supra*).

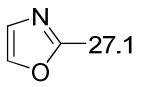
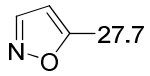
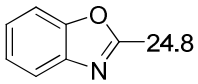
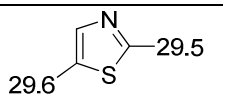
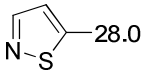
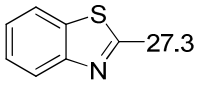
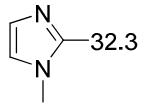
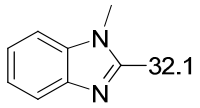
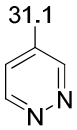
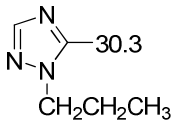
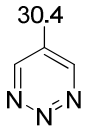
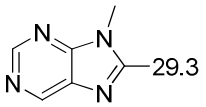
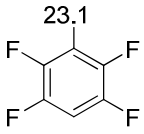
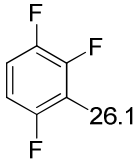
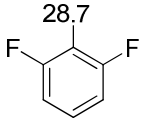
Recycling [(IPr)AuOH] for the carboxylation of **2a**:

(■) turnover frequency (h^{-1}), (■) cumulative turnover number (mol product per mol catalyst).

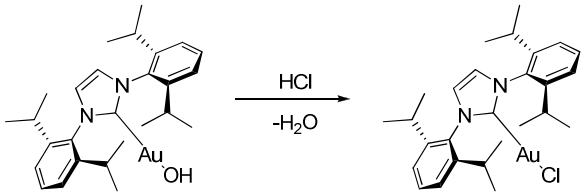


p*Ka* data.

Calculated p*Ka* data for 2a-2l, 7a-7c:[14]

2a		**2b**		**2c**		**2d**	
2e		**2f**		**2g**		**2h**	
2i		**2j**		**2k**		**2l**	
7a		**7b**		**7c**			

Titration logs:

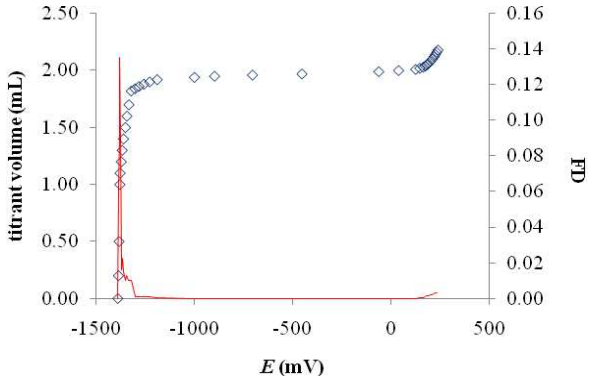


Titrations were monitored on a Metrohm Titrando® Model 836 fitted with a Dosino® 800 (1 µL resolution), using a Solvotrode® electrode. The IUPAC Buffer Series solutions of pH 7.00 and pH 12.45 were used to perform a two-point calibration at 25°C. The titration solutions were prepared in anhydrous DMSO (Karl Fischer titration > 0.05% H_2O) as 0.500 M [(NHC)AuOH] and 0.625 M HCl. Experiments were performed at 25°C in triplicate. The First Derivative Methodology was applied for

analysis, using ORIGIN·08[15] to create smooth interpolations.

Titration of 0.5 M[(IPr)AuOH] in DMSO with 0.625 M HCl in DMSO at 25°C:

(■) empirical point, (■) First Derivative point.

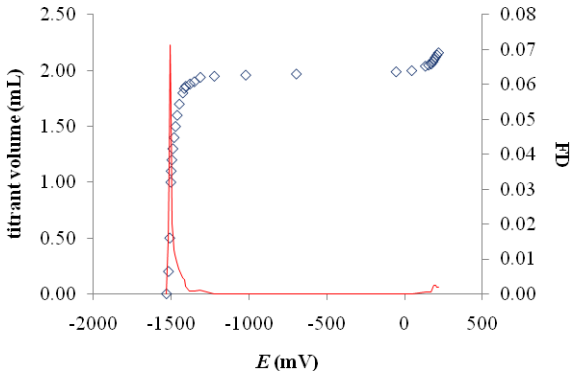


Midpoint, E = -1381 mV = pH 30.3

pKa range = 30.28-30.40

Titration of 0.5 M[(I*t*Bu)AuOH] in DMSO with 0.625 M HCl in DMSO at 25°C:

(■) empirical point, (■) First Derivative point.



Midpoint, E = -1504 mV = pH 32.4

pKa range = 32.36-32.48

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