

# Supporting Information

## A Facile Protocol for Water-Tolerant ‘Frustrated Lewis Pair’-Catalyzed Hydrogenation

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## 1. General experimental considerations

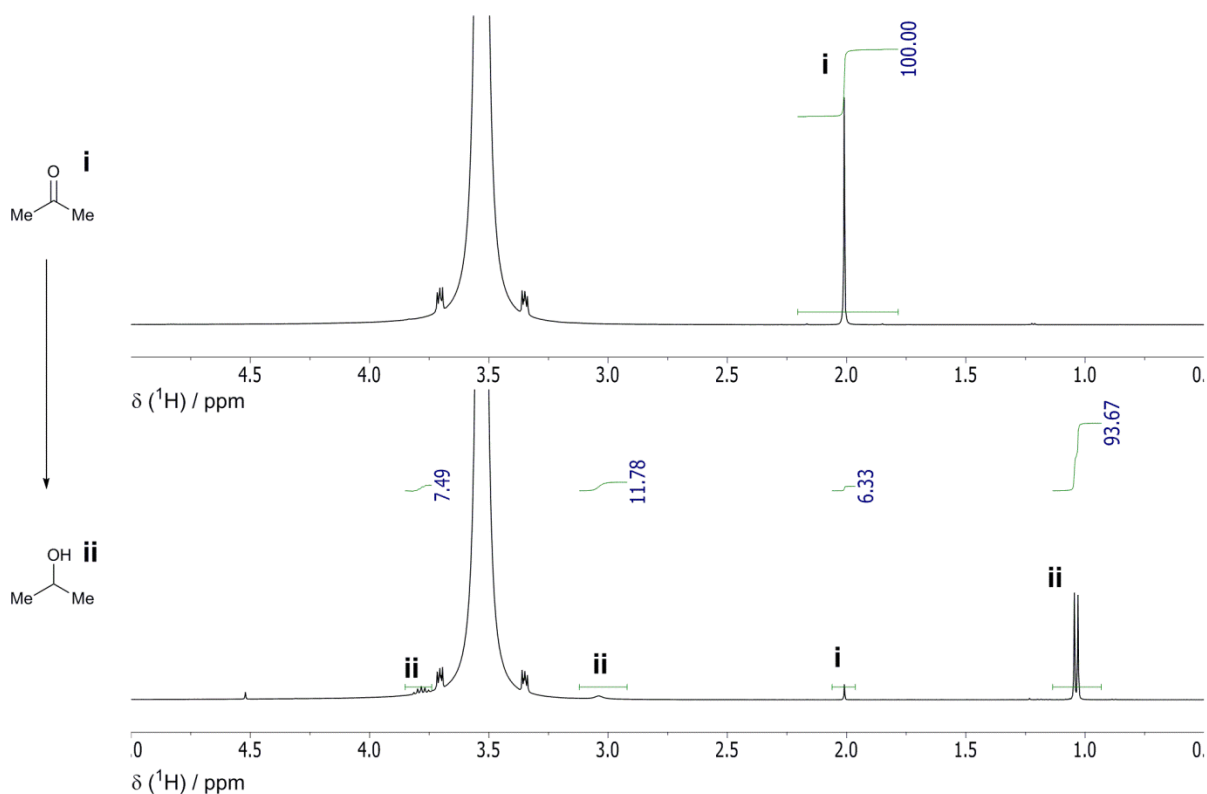
Unless stated otherwise all reactions were performed under N<sub>2</sub> atmosphere, and all manipulations were carried out either in an MBraun Labmaster DP glovebox or by using standard Schlenk line techniques. All glassware was dried by heating to 170 °C overnight before use, though stainless steel reactors were not. B(C<sub>6</sub>F<sub>5</sub>)<sub>3</sub> (**1**),<sup>1</sup> H<sub>2</sub>O·B(C<sub>6</sub>F<sub>5</sub>)<sub>2</sub> (**1**·OH<sub>2</sub>)<sup>2</sup> and 1,2,3,4,5-pentamethylcyclopentadiene<sup>3</sup> were prepared in accordance with the literature. Anhydrous 1,4-dioxane was purchased from Sigma Aldrich, degassed, and further dried by storing over 4 Å molecular sieves. Non-anhydrous 1,4-dioxane was purchased from Sigma Aldrich (ACS reagent grade) and used without further drying, degassing, or other purification: Karl-Fischer titration (performed by Mr Damion Box) indicated a water content of 220 ppm (0.022%) w/w. 1,2-difluorobenzene was dried over sequential batches of 4 Å molecular sieves. Acetone was degassed, dried over B<sub>2</sub>O<sub>3</sub> and distilled. All other substrates were purchased from major suppliers: solids were dried under vacuum, while liquids were degassed and dried over 4Å molecular sieves. H<sub>2</sub> was purchased from BOC (research grade) and, for NMR-scale reactions only, was dried by passage through a Matheson Tri-Gas Weldassure™ Purifier drying column. NMR spectra were recorded on Bruker AV-400 MHz, AV-500 MHz and DRX-400 spectrometers. <sup>1</sup>H spectra were referenced internally to residual proteo solvent signals, while <sup>19</sup>F and <sup>11</sup>B spectra were referenced externally to CFCl<sub>3</sub> and BF<sub>3</sub>·OEt<sub>2</sub> respectively.

High pressure reactions on 2 mmol and 8 mmol scales were performed in 25 mL and 100 mL Parr reactors, respectively. High pressure reactions on 4 mmol scale were performed in either size reactor.

Conversions were calculated by relative <sup>1</sup>H NMR integration of starting material and product resonances. In order to minimise any errors, integrations were generally performed on the most intense product/substrate resonances, and only on signals well separated from the solvent peak. Wherever possible, the intensity of a particular product resonance was compared to the intensity of the resonance for the same protons in the starting material.

## 2. Procedure for NMR-scale hydrogenation of acetone using **1**·OH<sub>2</sub>

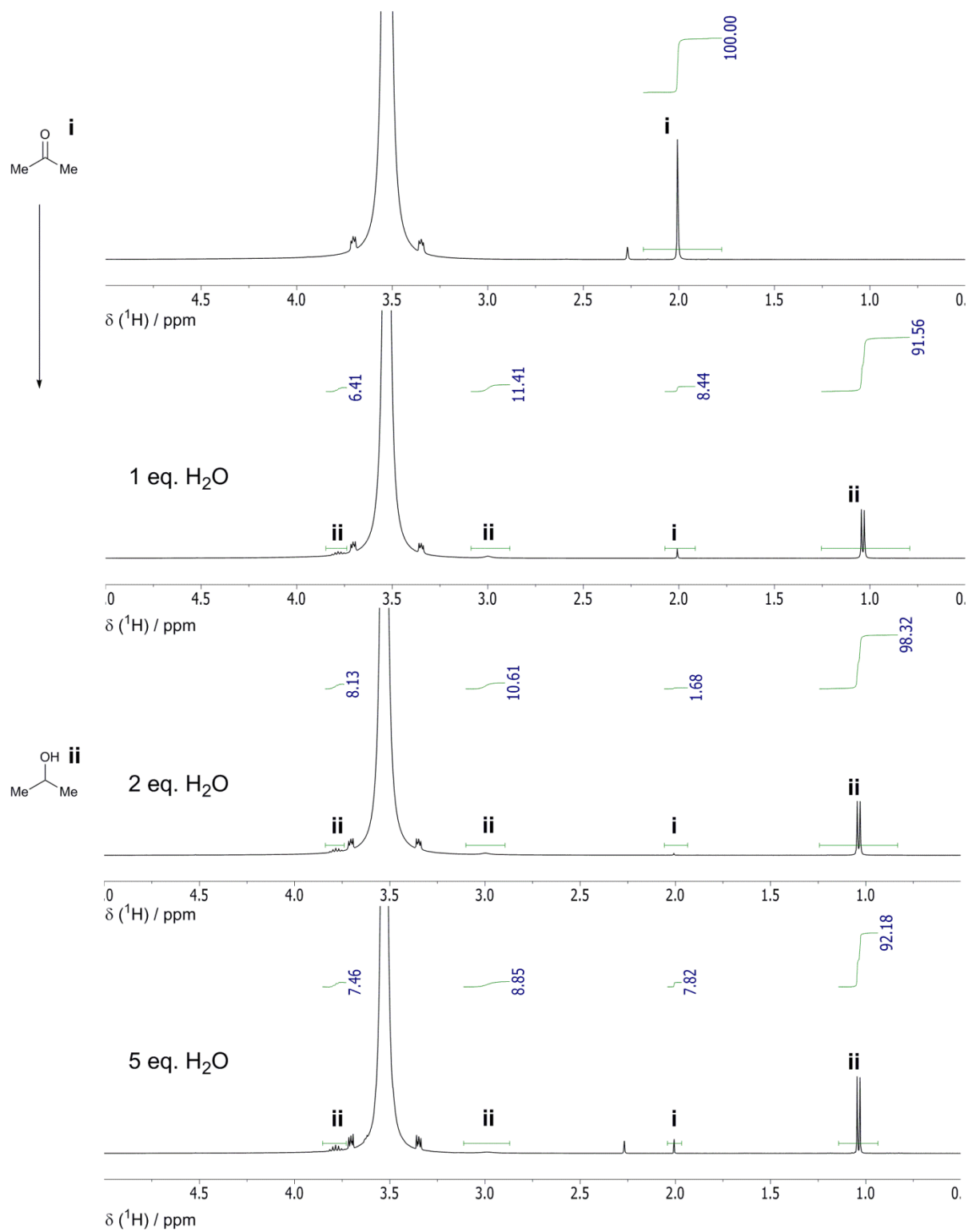
Inside a glovebox, acetone (15 µL, 0.20 mmol) was added to a solution of H<sub>2</sub>O·B(C<sub>6</sub>F<sub>5</sub>)<sub>3</sub> (**1**·OH<sub>2</sub>, 5.1 mg, 0.010 mmol) in anhydrous 1,4-dioxane (0.7 mL), and the reaction mixture was transferred into a Wilmad high pressure NMR tube fitted with a PV-ANV PTFE valve. H<sub>2</sub> was admitted at room temperature to a pressure of 10 bar (which equates to a pressure of approximately 13 bar at 100 °C) and the reaction mixture was briefly shaken by hand before being analysed by <sup>1</sup>H, <sup>19</sup>F and <sup>11</sup>B NMR spectroscopy. The reaction vessel was heated to 100 °C for 70 h without active mixing, and re-analysed.



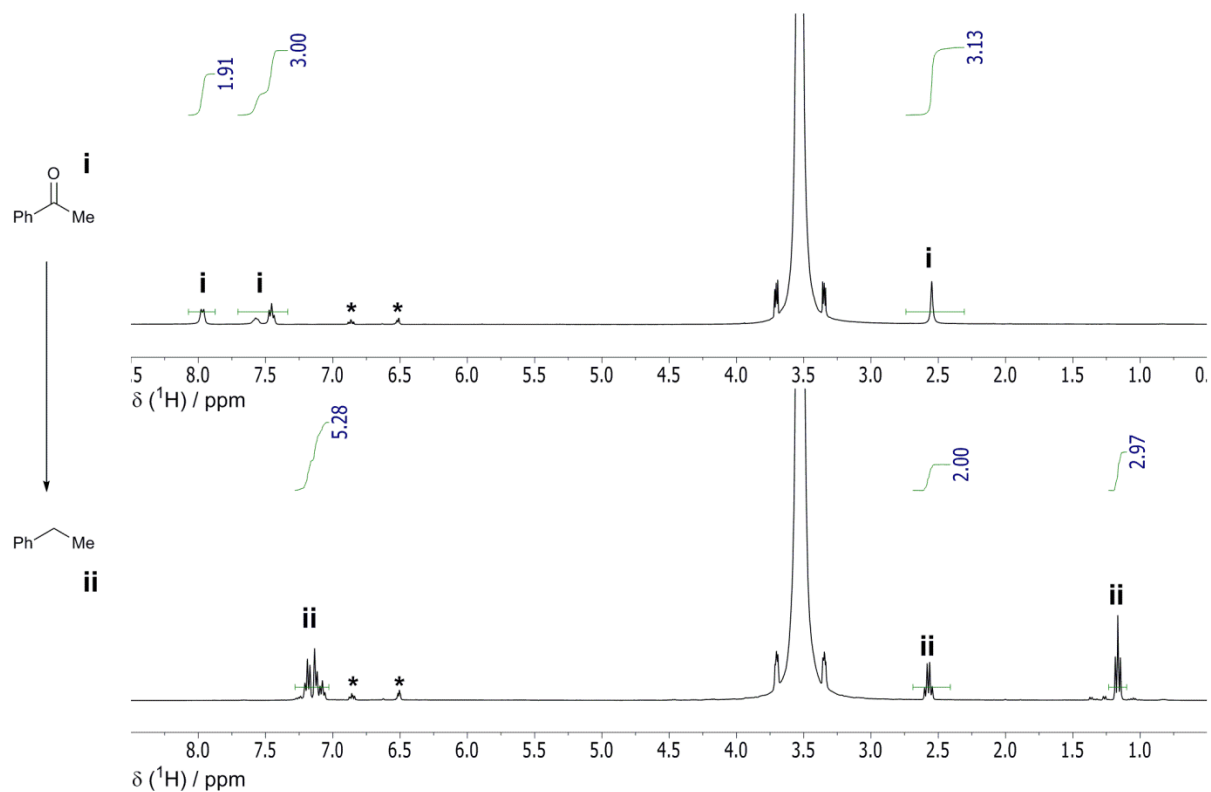
**Figure S1.**  $^1\text{H}$  NMR spectra for the hydrogenation of acetone catalyzed by 5 mol% **1**·OH<sub>2</sub> in 1,4-dioxane

### 3. Typical procedure for high-pressure hydrogenation with anhydrous solvent

Inside a glovebox, acetone (0.29 mL, 4.0 mmol) and  $\text{B}(\text{C}_6\text{F}_5)_3$  (**1**, 51 mg, 0.10 mmol) were dissolved in anhydrous 1,4-dioxane (15 mL).  $\text{H}_2\text{O}$  (9.0  $\mu\text{L}$ , 0.50 mmol) was subsequently added, and the reaction mixture transferred into a stainless steel Parr reactor (which had previously been evacuated and back-filled with dry  $\text{N}_2$  three times). An aliquot was taken *via* cannula, and analysed by  $^1\text{H}$ ,  $^{19}\text{F}$  and  $^{11}\text{B}$  NMR spectroscopy. The reaction vessel was filled with  $\text{H}_2$  to a pressure of 45 bar, before being heated with stirring to 100  $^\circ\text{C}$  for 39 h (during which time an internal pressure of approximately 50 bar was indicated). After returning to room temperature the reaction vessel was cooled in an ice bath, and the excess pressure slowly vented over the course of 30 minutes. Upon re-warming a new aliquot was removed for analysis.



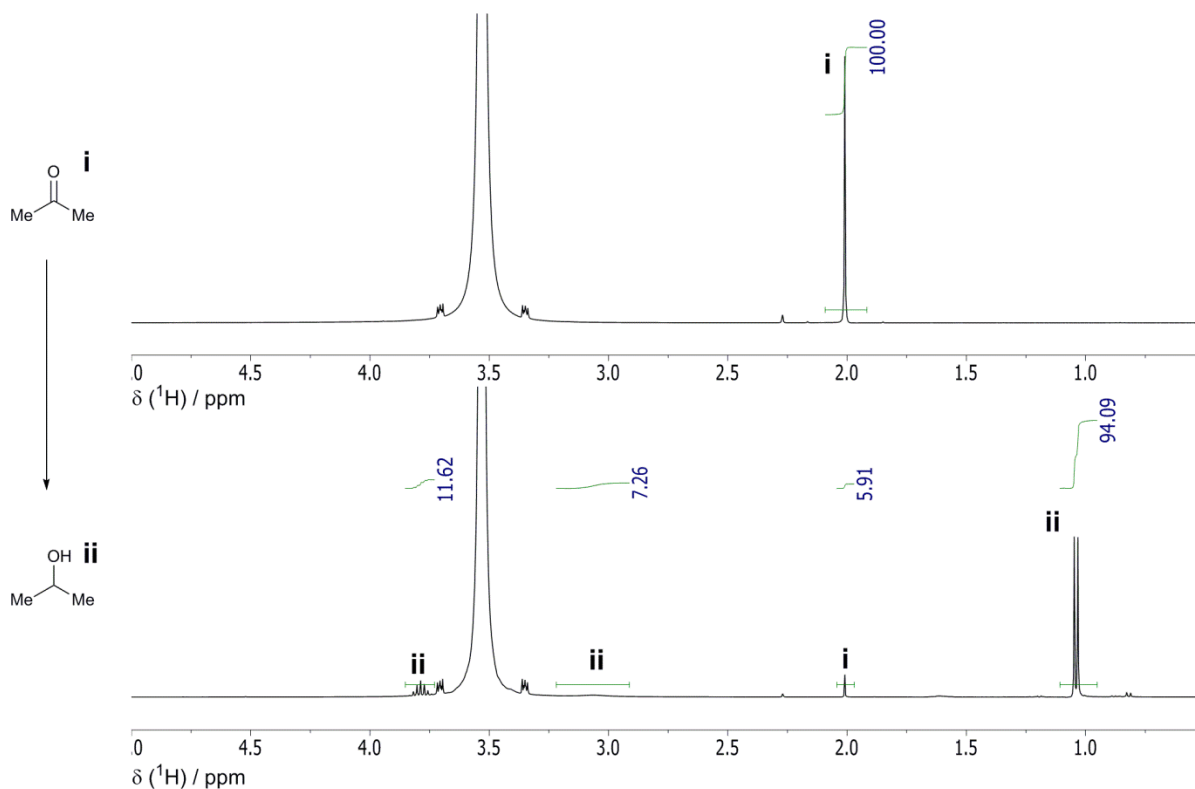
**Figure S2.**  $^1\text{H}$  NMR spectra for the hydrogenation of acetone catalyzed by 2.5 mol% **1** in 1,4-dioxane in the presence of varying amounts of water



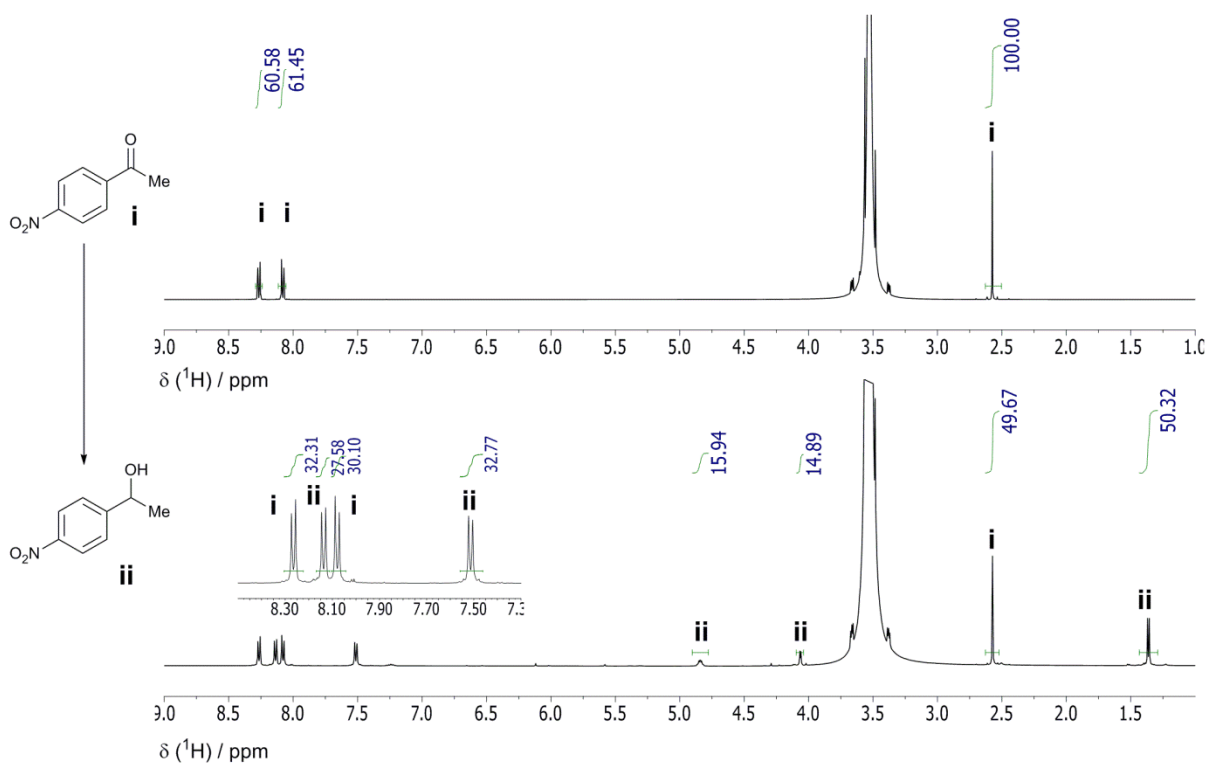
**Figure S3.**  $^1\text{H}$  NMR spectra for the hydrogenation of acetophenone catalyzed by 20 mol% **1** in 1,4-dioxane (signals marked \* due to capillary insert containing  $\text{PPh}_3$  in  $\text{C}_6\text{D}_6$ )

#### 4. Typical procedure for high-pressure hydrogenation with ‘non-anhydrous’ solvent

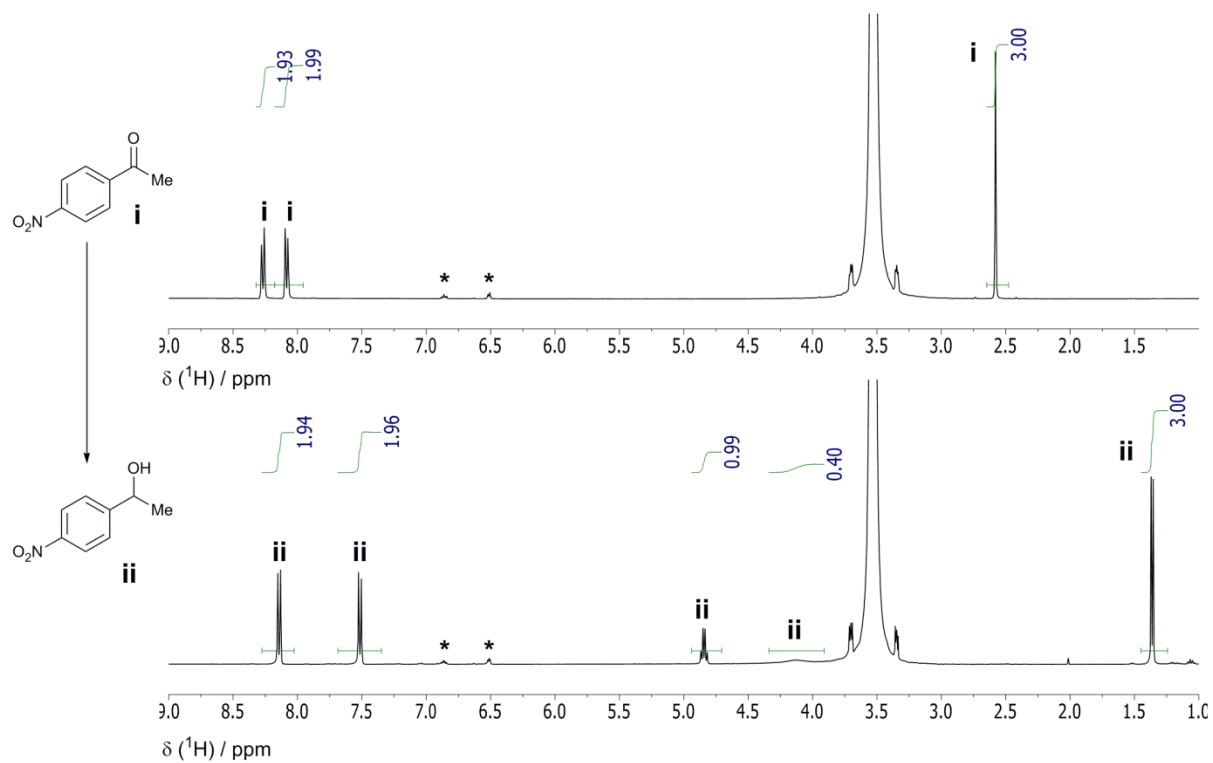
Inside a glovebox  $\text{B}(\text{C}_6\text{F}_5)_3$  (**1**, 102 mg, 0.20 mmol) and 2,6-dichlorobenzaldehyde (700 mg, 4.0 mmol) were weighed out into a vial. Undried 1,4-dioxane was added on the open bench, and the resulting solution quickly transferred into a stainless steel Parr reactor. An aliquot was taken *via* cannula, and analysed by  $^1\text{H}$ ,  $^{19}\text{F}$  and  $^{11}\text{B}$  NMR spectroscopy. The reaction vessel was filled with  $\text{H}_2$  to a pressure of 45 bar, before being heated with stirring to 100  $^\circ\text{C}$  for 17 h (during which time an internal pressure of approximately 50 bar was indicated). After returning to room temperature the reaction vessel was cooled in an ice bath, and the excess pressure slowly vented over the course of 30 minutes. Upon re-warming a new aliquot was removed for analysis.



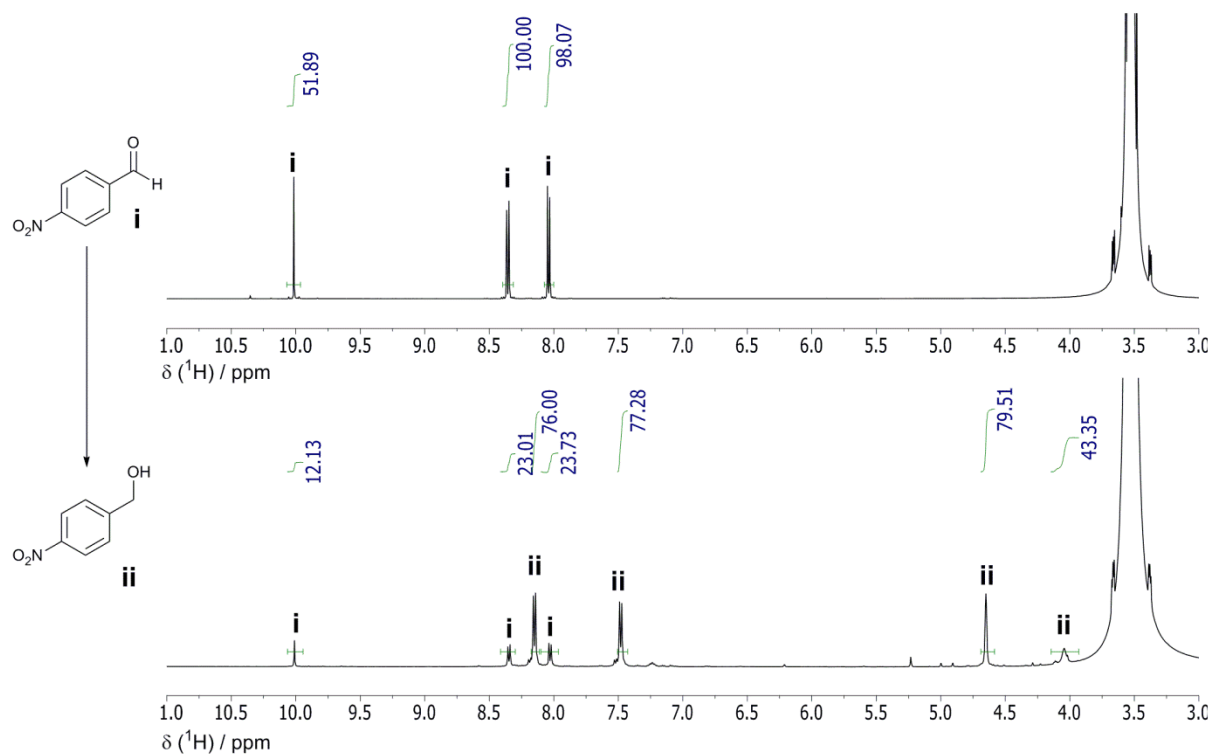
**Figure S4.**  $^1\text{H}$  NMR spectra for the hydrogenation of acetone catalyzed by 2.5 mol% **1** in undried 1,4-dioxane



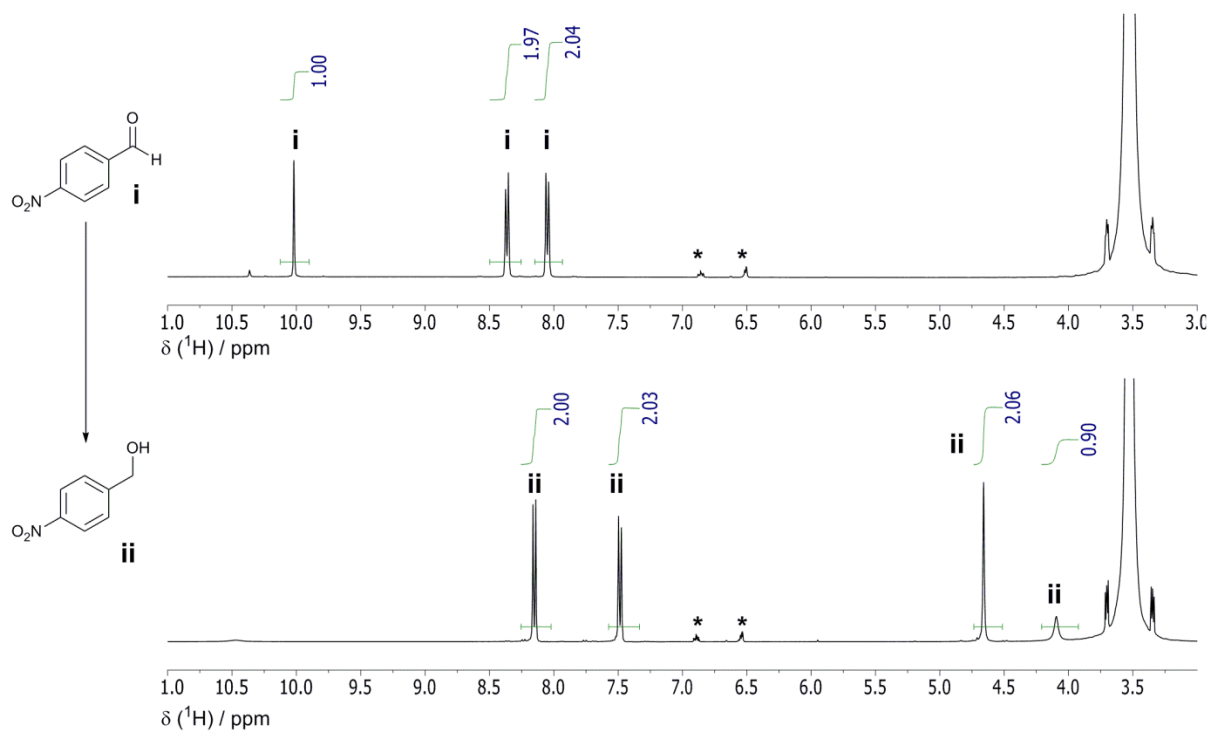
**Figure S5.**  $^1\text{H}$  NMR spectra for the hydrogenation of 4-nitroacetophenone catalyzed by 5 mol% **1** in undried 1,4-dioxane



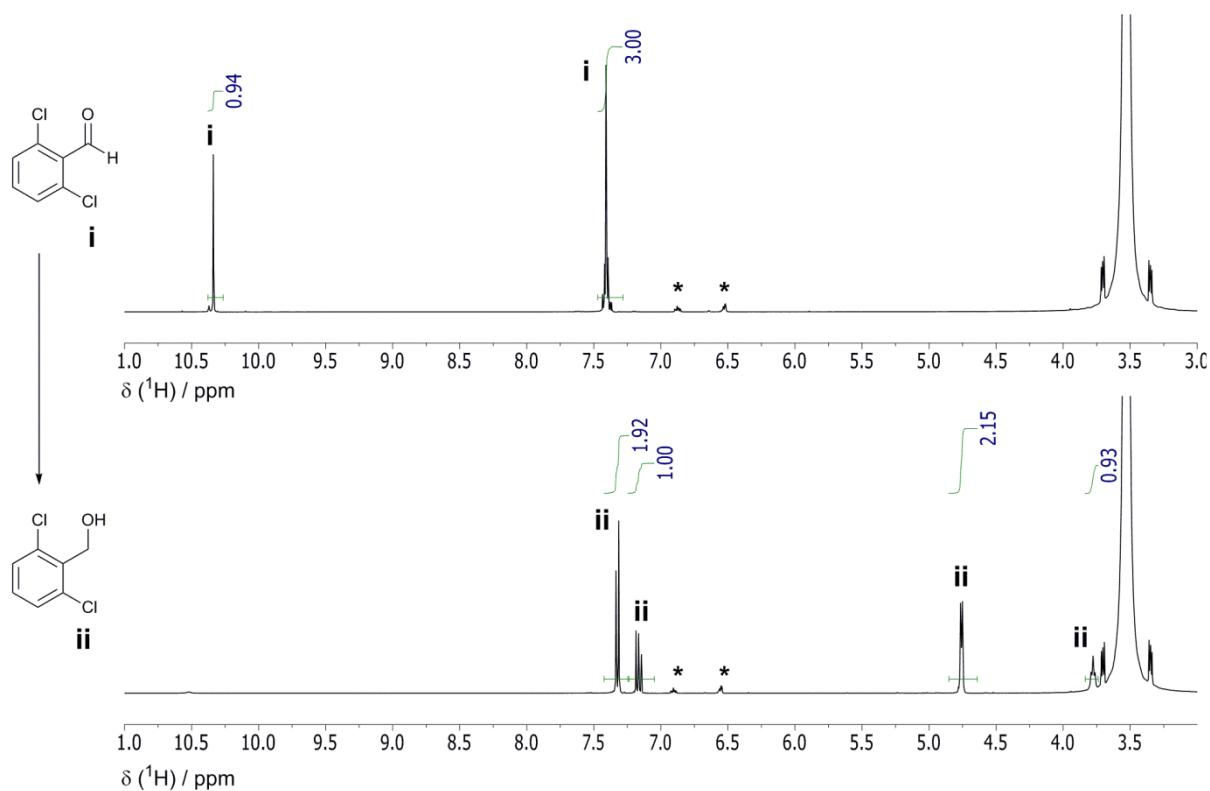
**Figure S6.**  $^1\text{H}$  NMR spectra for the hydrogenation of 4'-nitroacetophenone catalyzed by 10 mol% **1** in undried 1,4-dioxane (signals marked \* due to capillary insert containing  $\text{PPh}_3$  in  $\text{C}_6\text{D}_6$ )



**Figure S7.**  $^1\text{H}$  NMR spectra for the hydrogenation of 4-nitrobenzaldehyde catalyzed by 5 mol% **1** in undried 1,4-dioxane

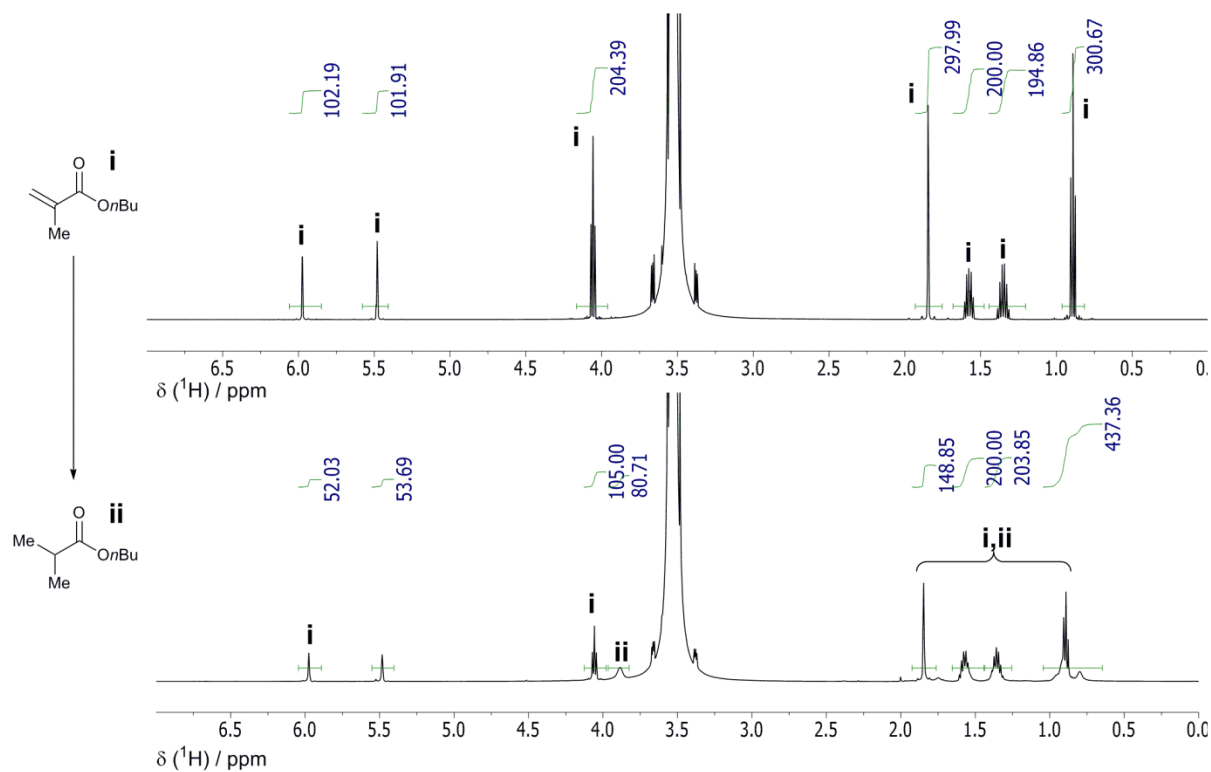


**Figure S8.**  $^1\text{H}$  NMR spectra for the hydrogenation of 4-nitrobenzaldehyde catalyzed by 10 mol% **1** in undried 1,4-dioxane (signals marked \* due to capillary insert containing  $\text{PPh}_3$  in  $\text{C}_6\text{D}_6$ )

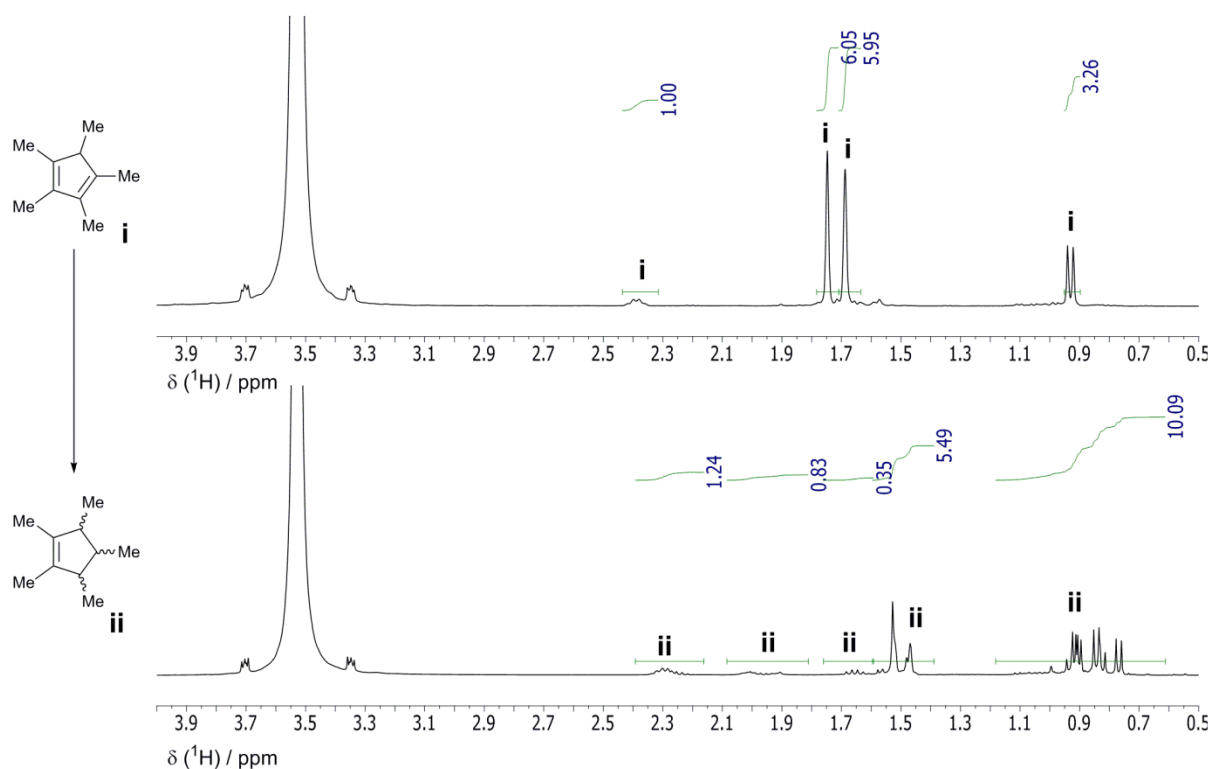


**Figure S9.**  $^1\text{H}$  NMR spectra for the hydrogenation of 2,6-dichlorobenzaldehyde catalyzed by **1** in undried 1,4-dioxane (signals marked \* due to capillary insert containing  $\text{PPh}_3$  in  $\text{C}_6\text{D}_6$ )

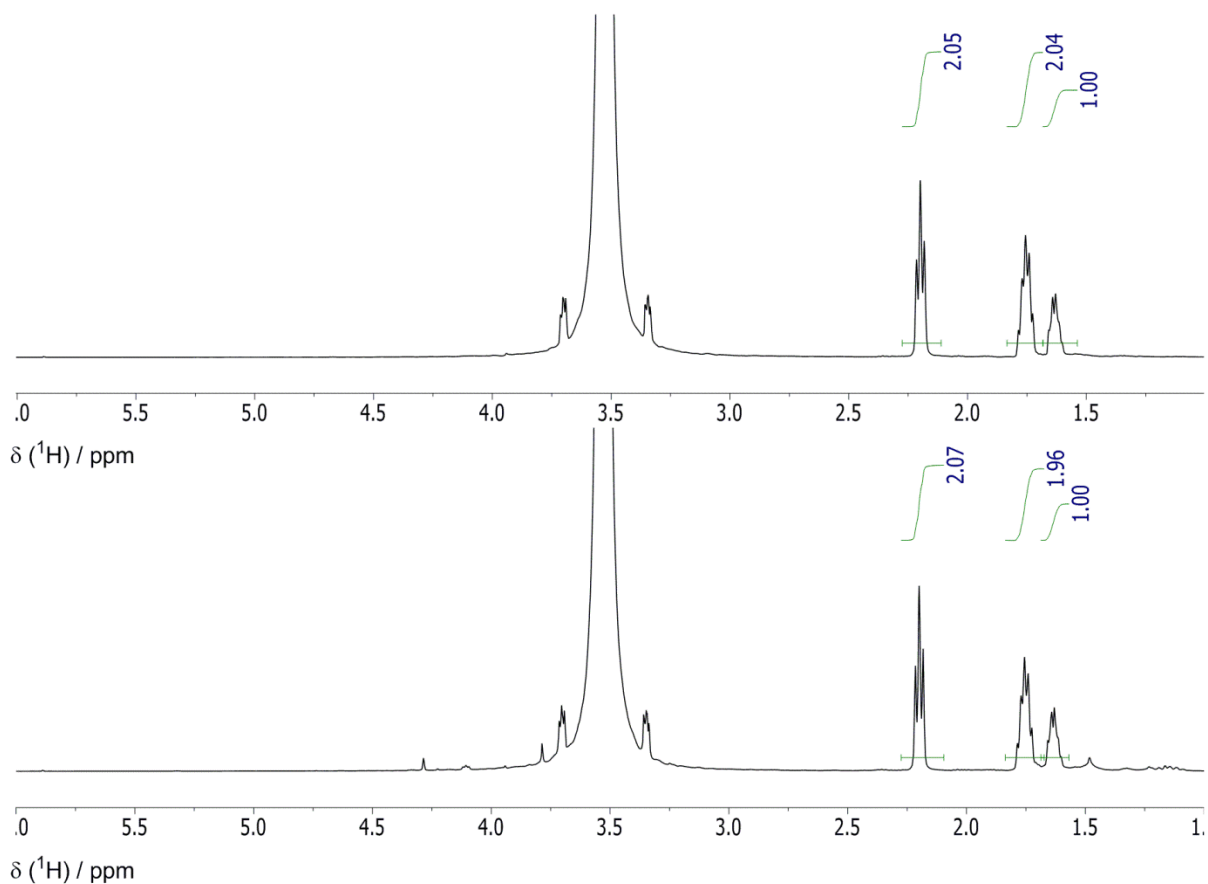




**Figure S10.**  $^1\text{H}$  NMR spectra for the hydrogenation of *n*-butyl methacrylate catalyzed by **1** in undried 1,4-dioxane



**Figure S11.**  $^1\text{H}$  NMR spectra for the hydrogenation of 1,2,3,4,5-pentamethylcyclopentadiene catalyzed by **1** in undried 1,4-dioxane



**Figure S12.**  $^1\text{H}$  NMR spectra for the attempted hydrogenation of cyclohexanone catalyzed by **1** in undried 1,4-dioxane

## 5. Discussion of $\text{H}_2\text{O}$ content in ‘non-anhydrous’ hydrogenations

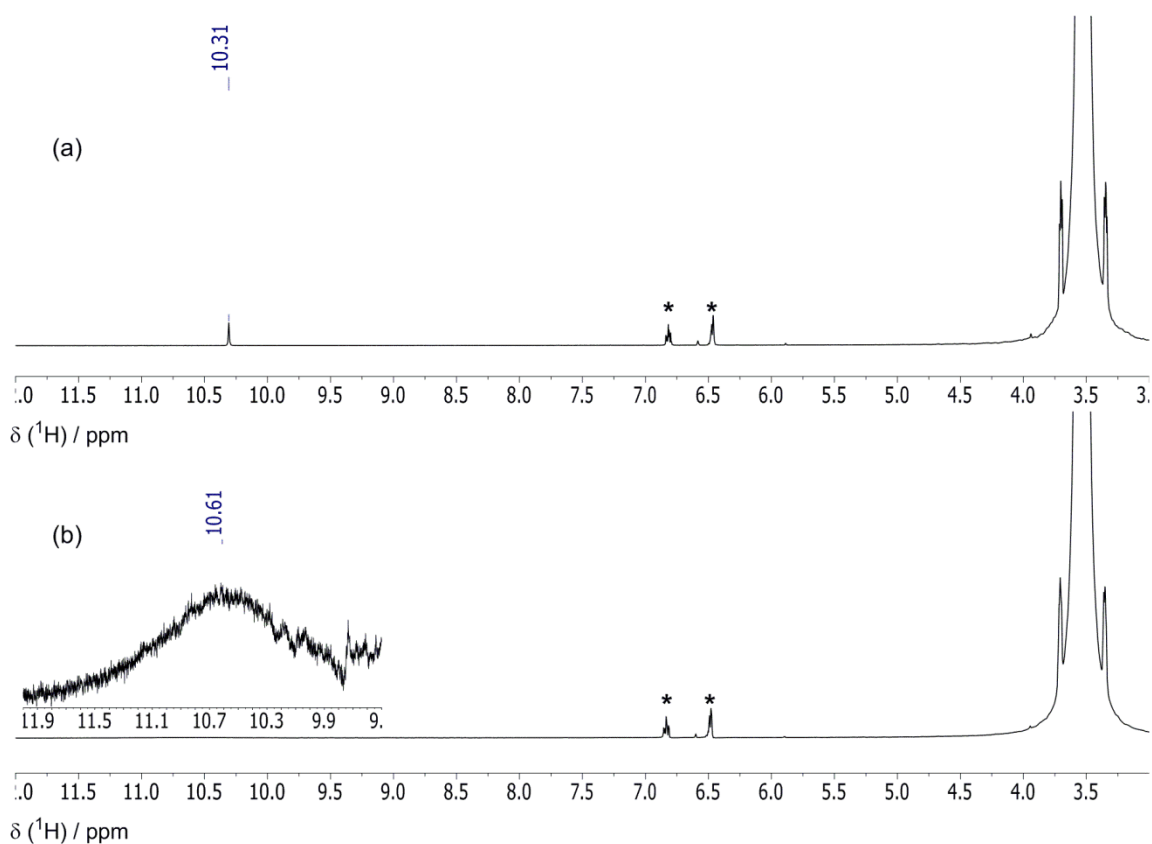
In order to confidently characterise the reported **1**-catalysed hydrogenations as truly  $\text{H}_2\text{O}$ -tolerant it is important to ascertain that the molar ratio  $[\text{H}_2\text{O}]/[\mathbf{1}]$  is greater than one (i.e. that the reaction is not simply catalysed by an excess of **1** relative to  $\text{H}_2\text{O}$ ). As stated in section 1, above, initial Karl-Fischer titration of the 1,4-dioxane used in the ‘non-anhydrous’ experiments indicated a moisture content of 220 ppm (0.022%) w/w, which corresponds to 0.013 M, or, at the concentrations used for all ‘non-anhydrous’ reactions, *ca.* 2.5 mol% relative to substrate. Crucially, though, the initial solvent  $\text{H}_2\text{O}$  content is only one of the sources of moisture for these reactions, and so this value fails to account for moisture absorbed from the reactor body, from the  $\text{H}_2$  used (which was not dried beyond the commercial grade supplied), or from preparation of the reaction mixture on the open bench.

To confirm that in the final reaction mixture  $[\text{H}_2\text{O}] > [\mathbf{1}]$ , control experiments were performed in which ‘blank’ reaction solutions containing no substrate, but which were otherwise identical to those used for ‘non-anhydrous’ reactions using 10 mol% **1** (i.e. containing 0.053 M **1**), were made up and transferred into reactors on the open bench, in the same manner. After an initial aliquot was taken for analysis by  $^1\text{H}$ ,  $^{19}\text{F}$  and  $^{11}\text{B}$  NMR spectroscopy the reactor was pressurised with  $\text{H}_2$  to 45 bar, and the reaction mixture stirred at room temperature for 90 minutes. The reactor was then cooled, vented and

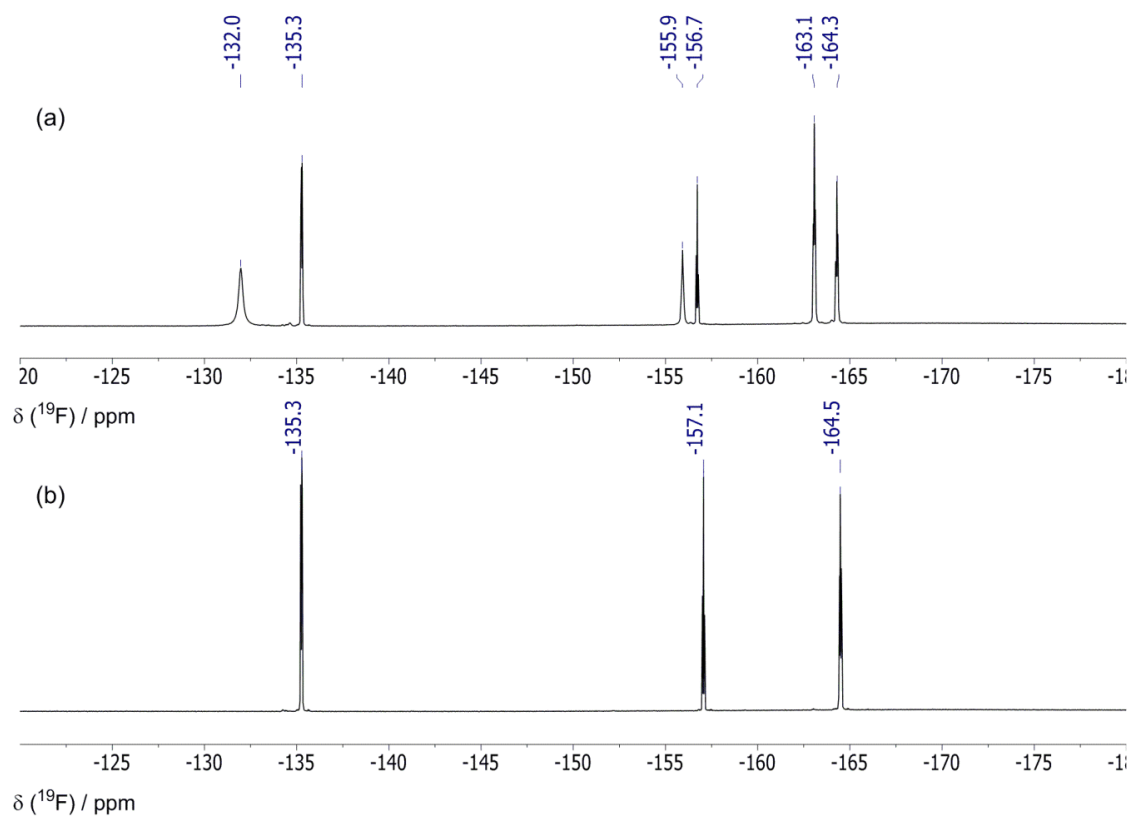
re-warmed in the manner described in section 4, above, and a final aliquot was removed under a flush of dry N<sub>2</sub>. For both aliquots, NMR tubes fitted with J. Young's valves were used. The tubes were previously flame-dried under vacuum, back-filled with dry N<sub>2</sub> and kept sealed until use.

In each case, these control experiments showed complete conversion of all **1** present to **1**·OH<sub>2</sub> in the final aliquot (as indicated by <sup>19</sup>F and <sup>11</sup>B NMR spectroscopy), despite only partial conversion in the initial aliquot.

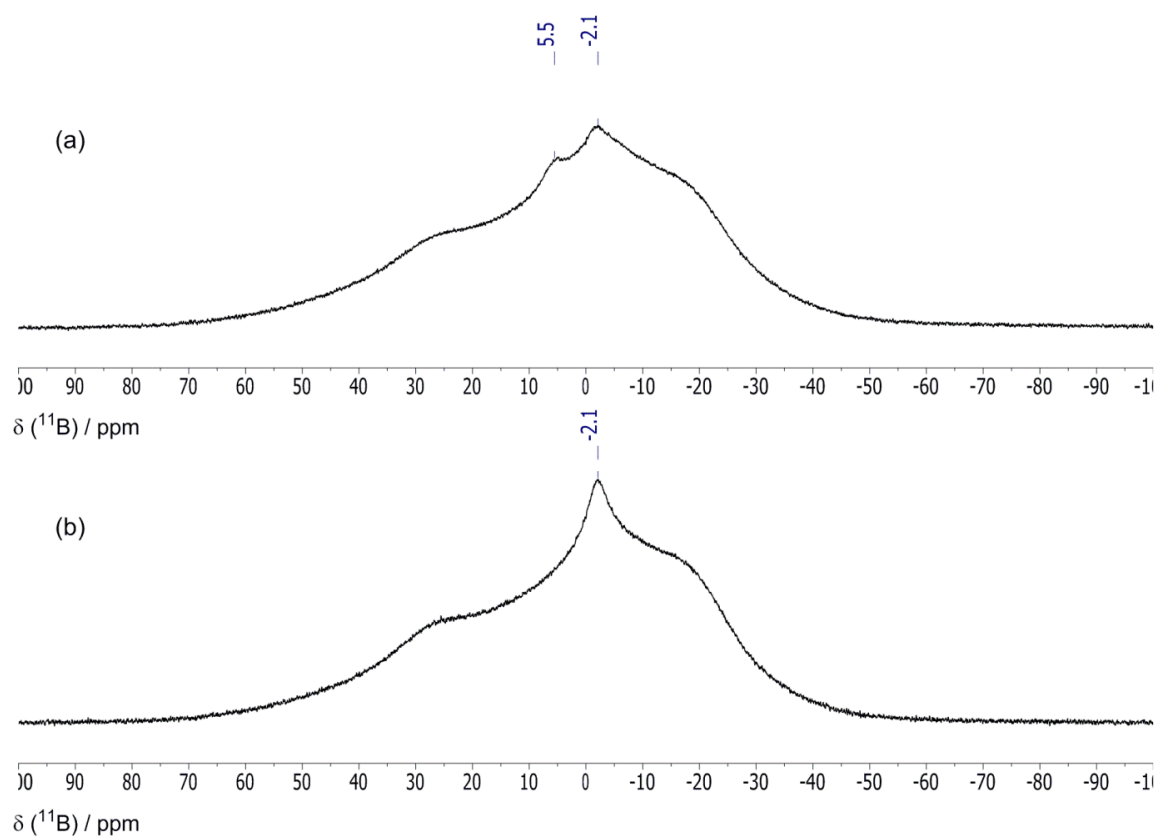
For reference, NMR spectra were also recorded of **1** in dry 1,4-dioxane following the addition of various equivalents of H<sub>2</sub>O. Because exchange of H<sub>2</sub>O is slow on the NMR timescale, for < 1 equivalent H<sub>2</sub>O, signals corresponding to both **1**·(1,4-dioxane) and **1**·OH<sub>2</sub> can clearly be distinguished. For ≥ 1 equivalent only the latter signals are observable (which is also the case for the final aliquots described above).



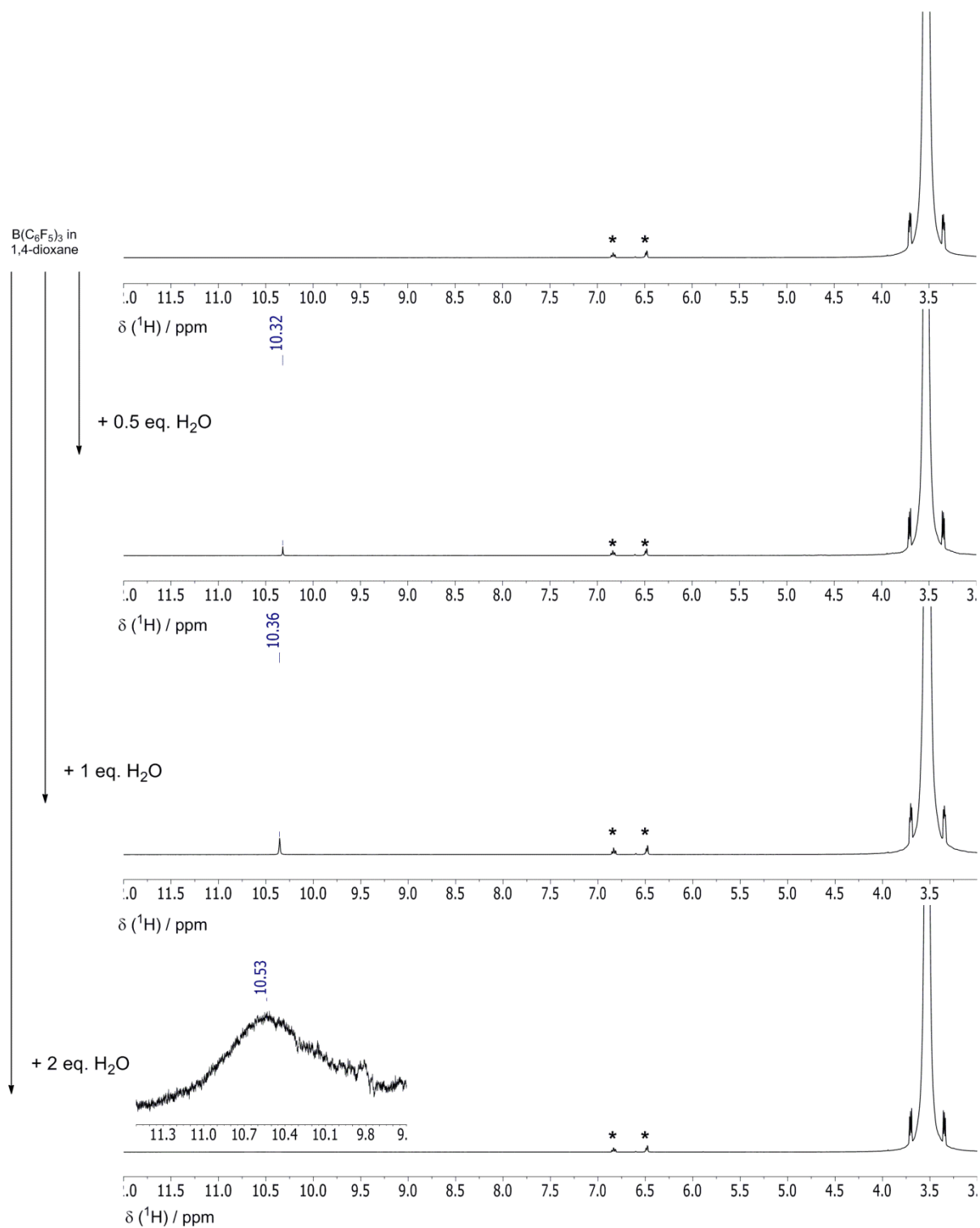
**Figure S13.** Initial (a) and final (b) <sup>1</sup>H NMR spectra for 'blank' solution of **1** in undried 1,4-dioxane



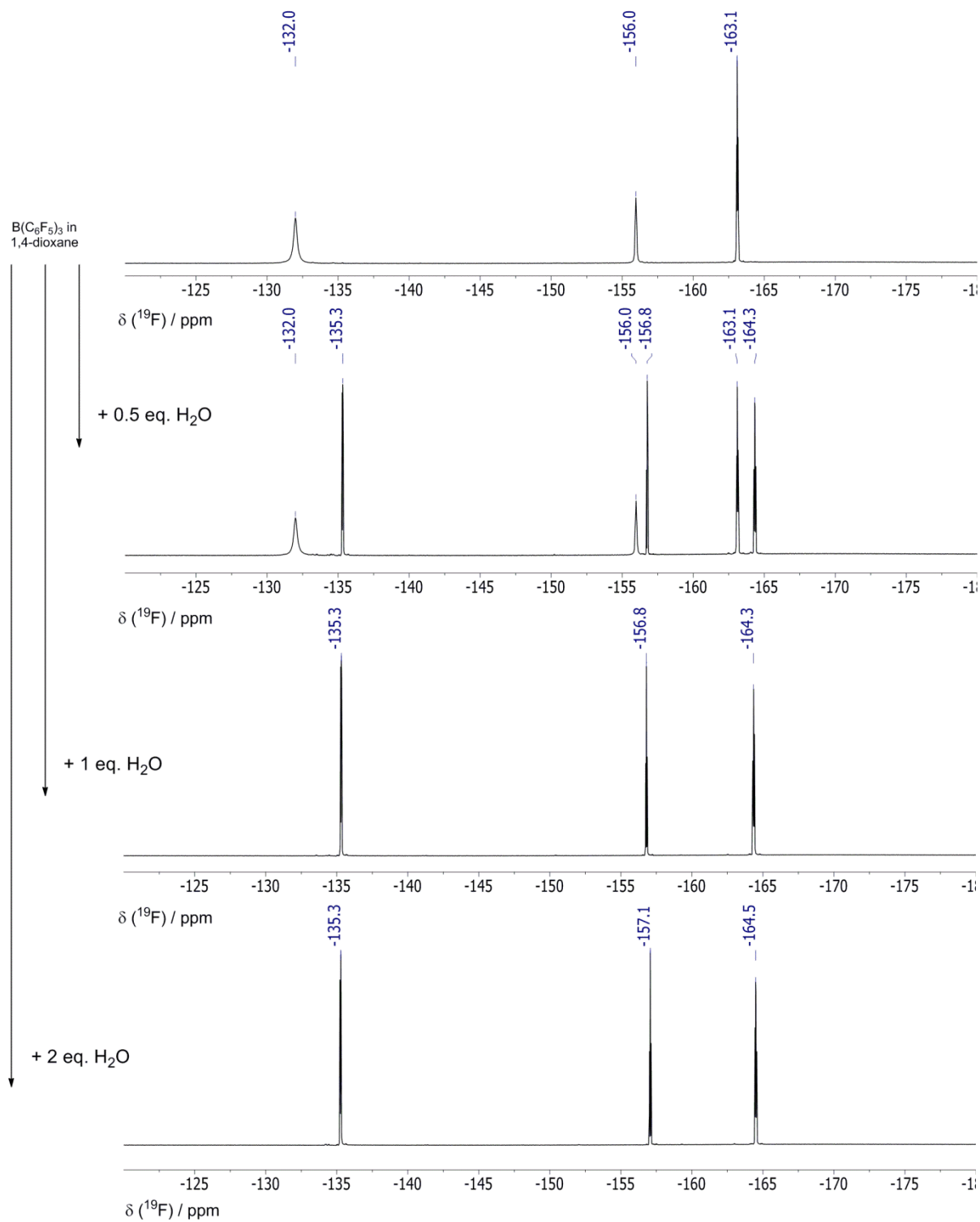
**Figure S14.** Initial (a) and final (b)  $^{19}\text{F}$  NMR spectra for 'blank' solution of **1** in undried 1,4-dioxane



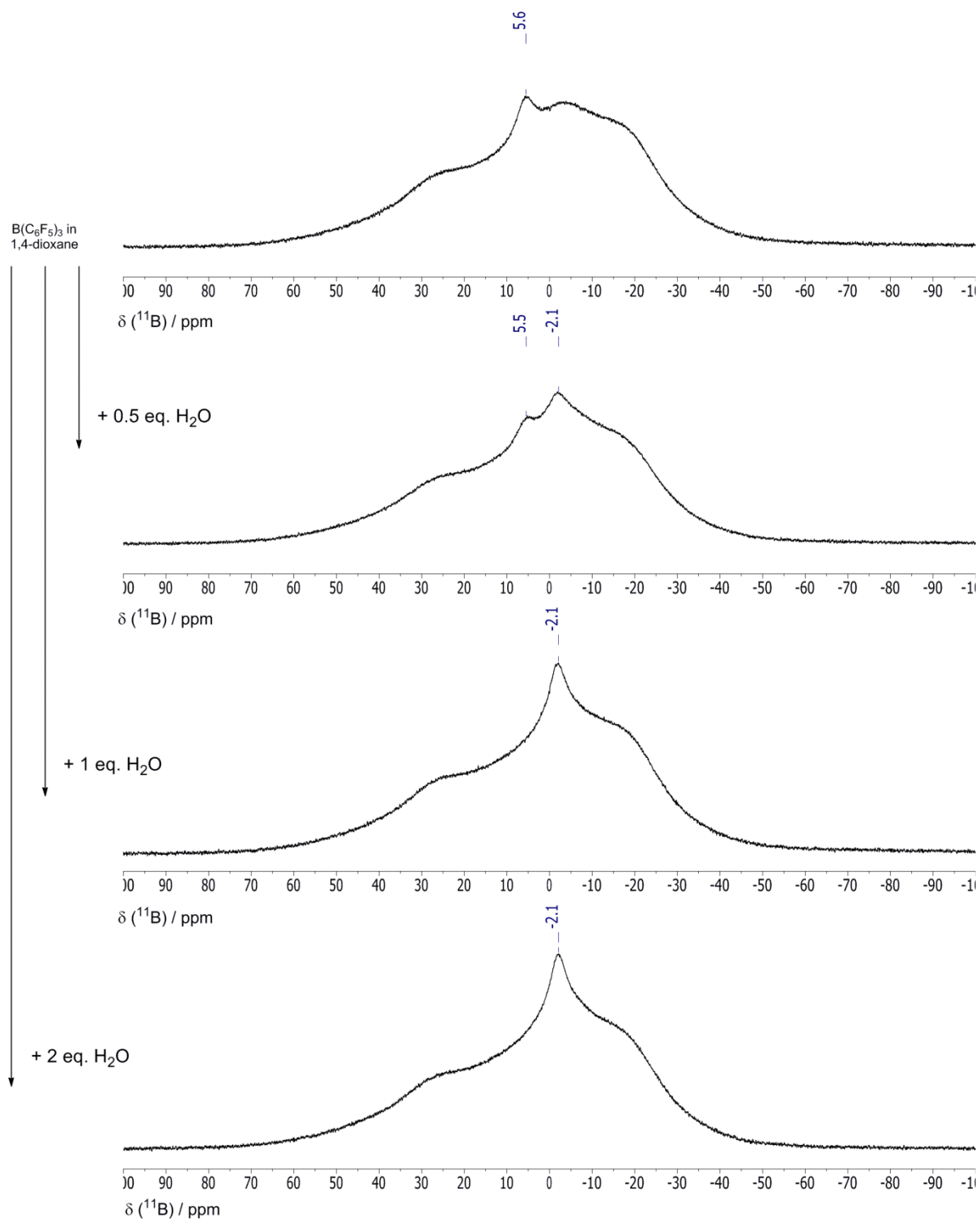
**Figure S15.** Initial (a) and final (b)  $^{11}\text{B}$  NMR spectra for 'blank' solution of **1** in undried 1,4-dioxane



**Figure S16.**  $^1H$  NMR spectra of **1** in the presence of various amounts of  $H_2O$  in 1,4-dioxane (signals marked \* due to capillary insert containing  $PPh_3$  in  $C_6D_6$ )



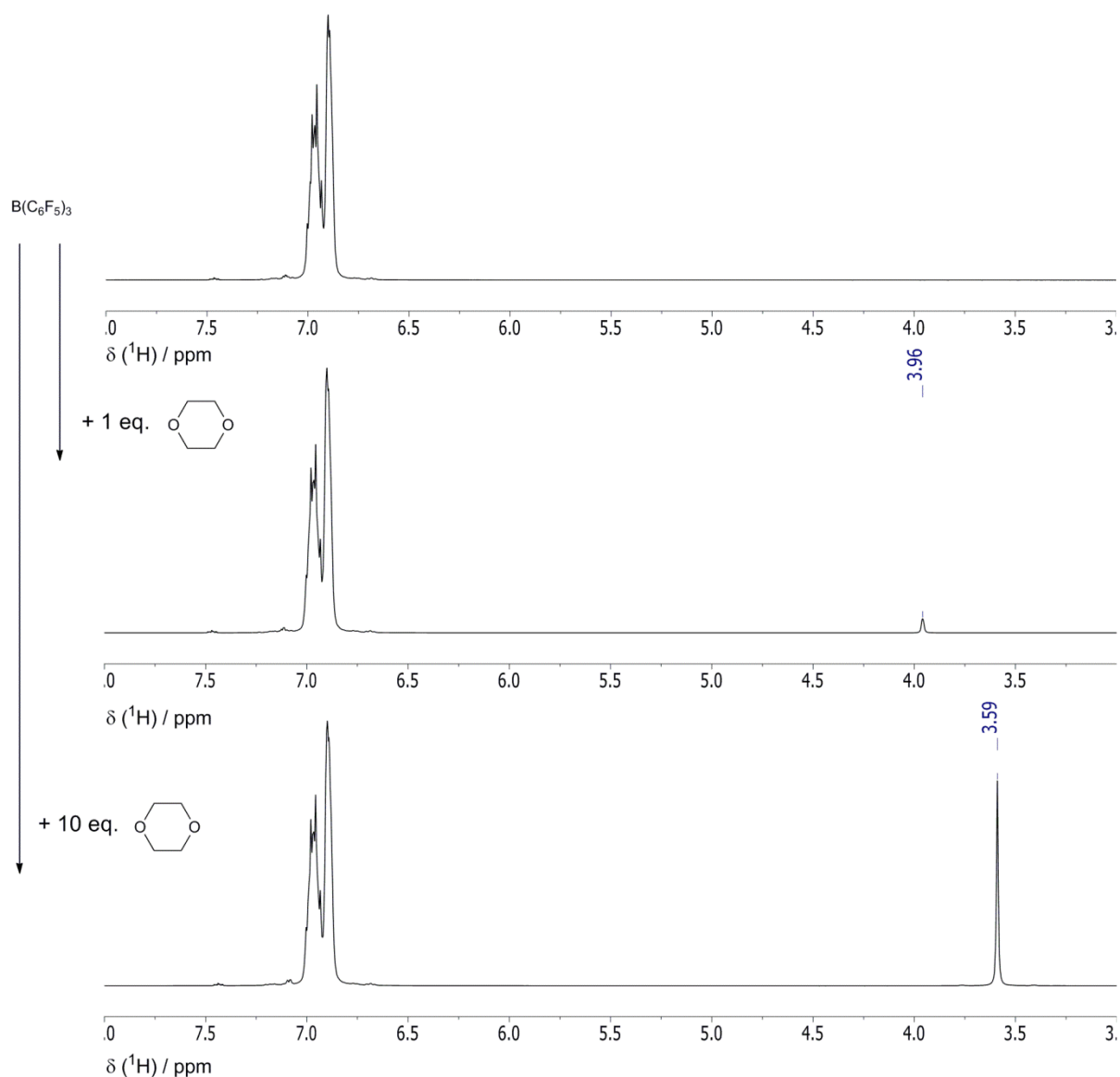
**Figure S17.**  $^{19}F$  NMR spectra of **1** in the presence of various amounts of  $H_2O$  in 1,4-dioxane



**Figure S18.**  $^{11}B$  NMR spectra of **1** in the presence of various amounts of  $H_2O$  in 1,4-dioxane

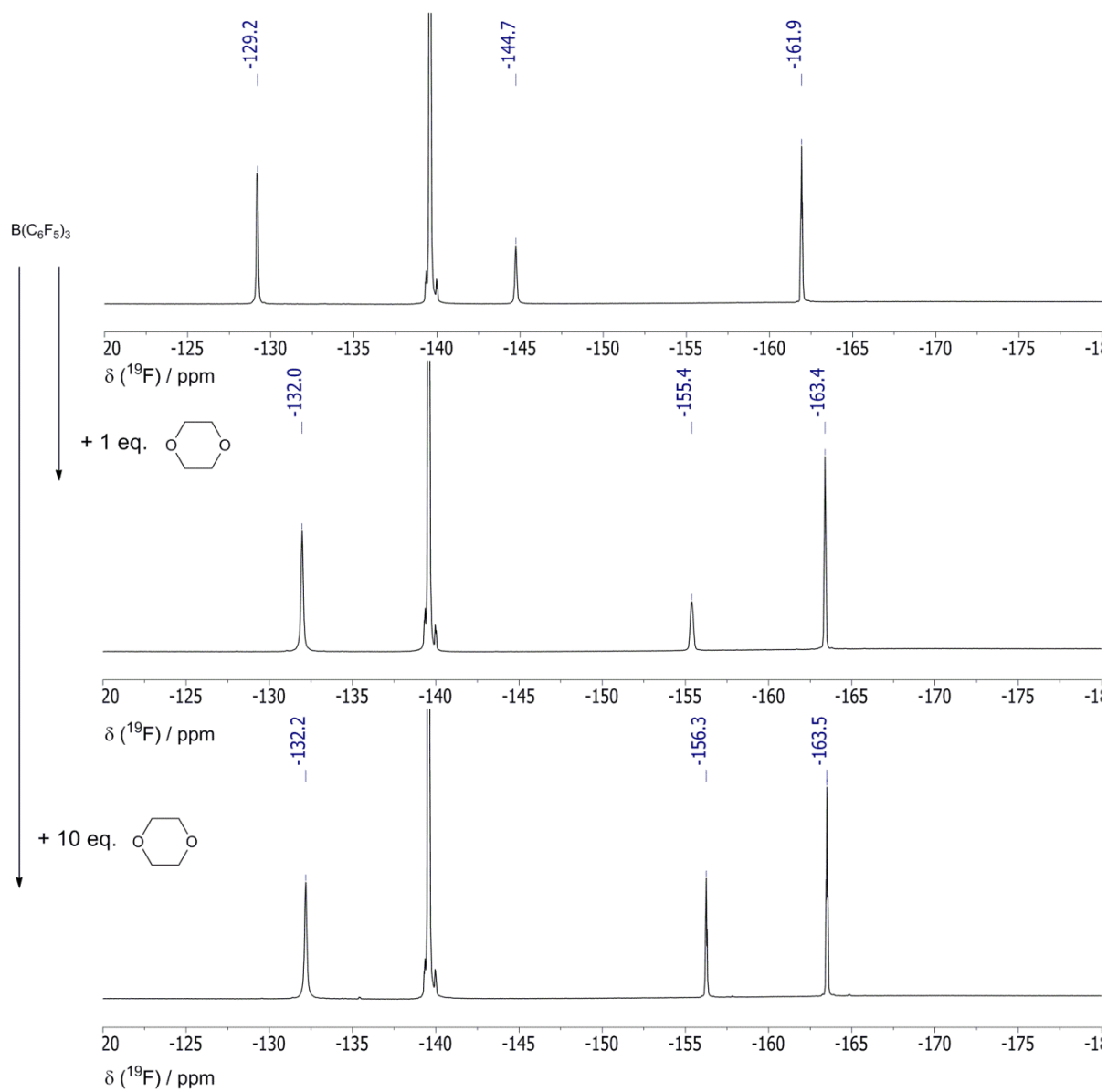
## 6. Interaction of **1** and **1**·OH<sub>2</sub> with 1,4-dioxane

Inside a glovebox B(C<sub>6</sub>F<sub>5</sub>)<sub>3</sub> (**1**, 10.2 mg, 0.020 mmol) or H<sub>2</sub>O·B(C<sub>6</sub>F<sub>5</sub>)<sub>3</sub> (**1**·OH<sub>2</sub>, 10.6 mg, 0.020 mmol) was dissolved in 1,2-difluorobenzene (0.4 mL), and the solution transferred into an NMR tube fitted with a J. Young's valve, to which was also added a sealed capillary insert containing PPh<sub>3</sub> in C<sub>6</sub>D<sub>6</sub>. The reaction mixture was analysed by <sup>1</sup>H, <sup>19</sup>F and <sup>11</sup>B NMR spectroscopy. 1,4-dioxane (1.7 μL, 0.020 mmol) was added and the reaction mixture reanalysed. Further 1,4-dioxane (15.3 μL, 0.18 mmol) was added, and the reaction mixture again re-analysed.

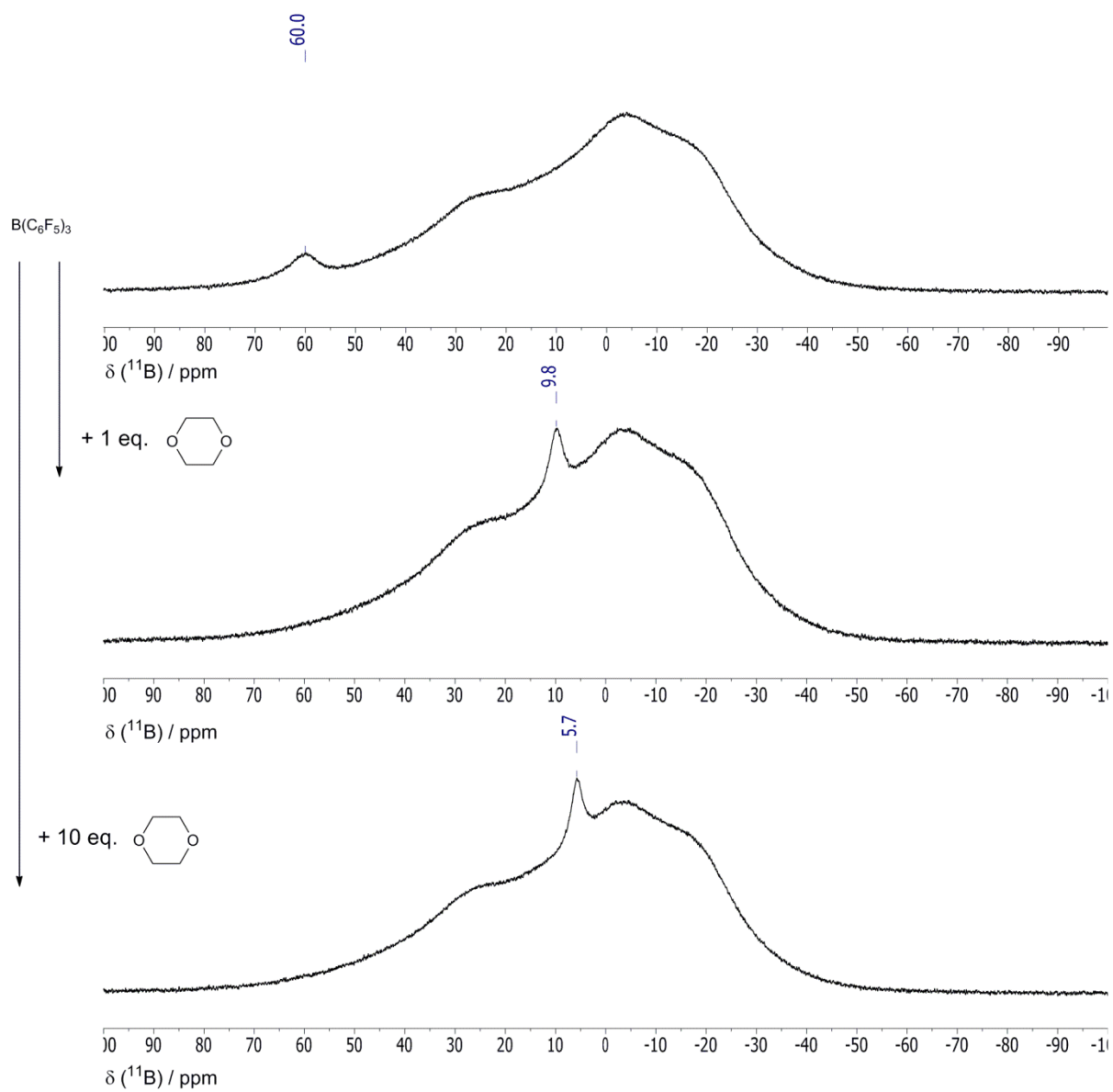


**Figure S19.** <sup>1</sup>H NMR spectra of **1** in the presence of 1,4-dioxane

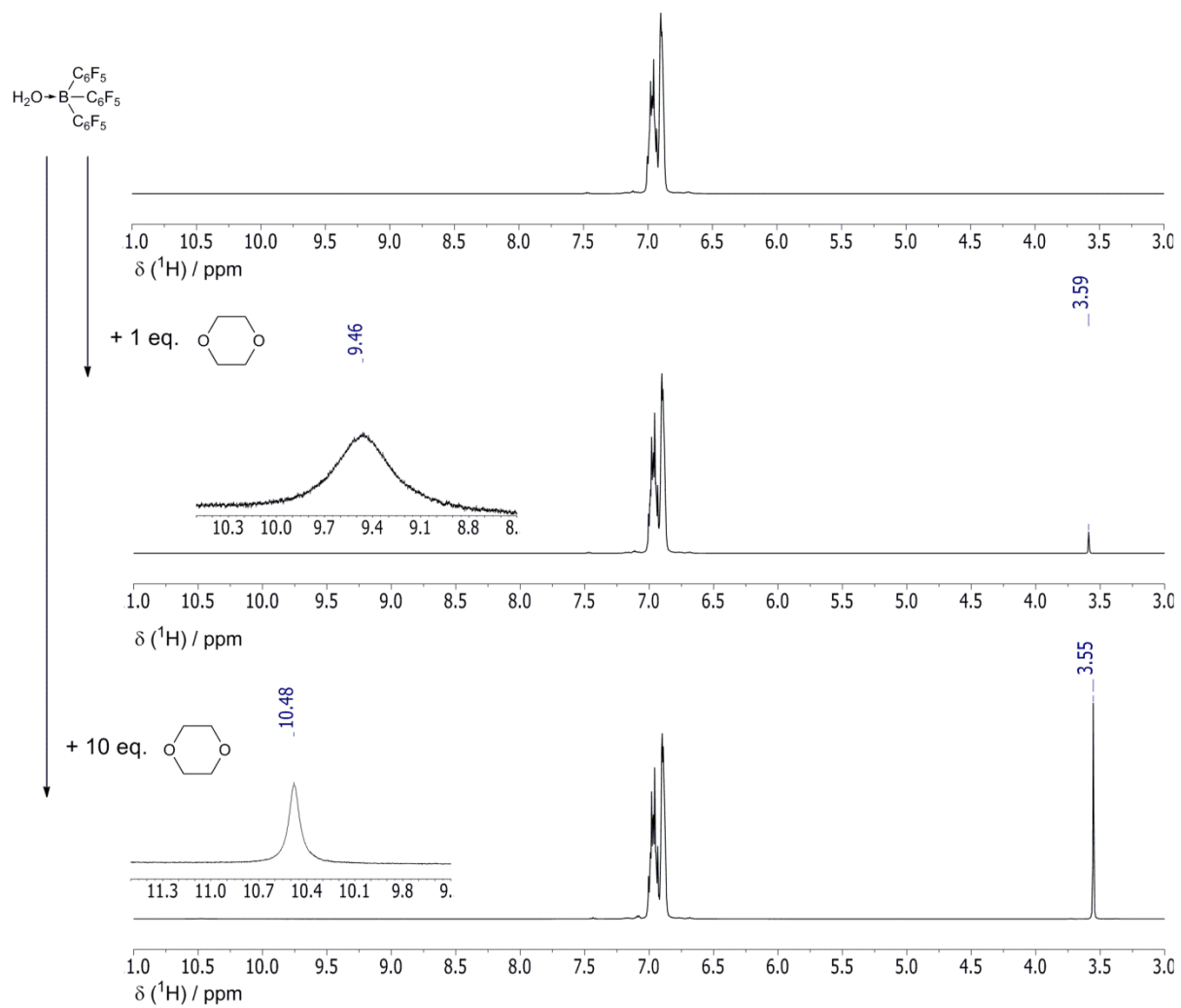




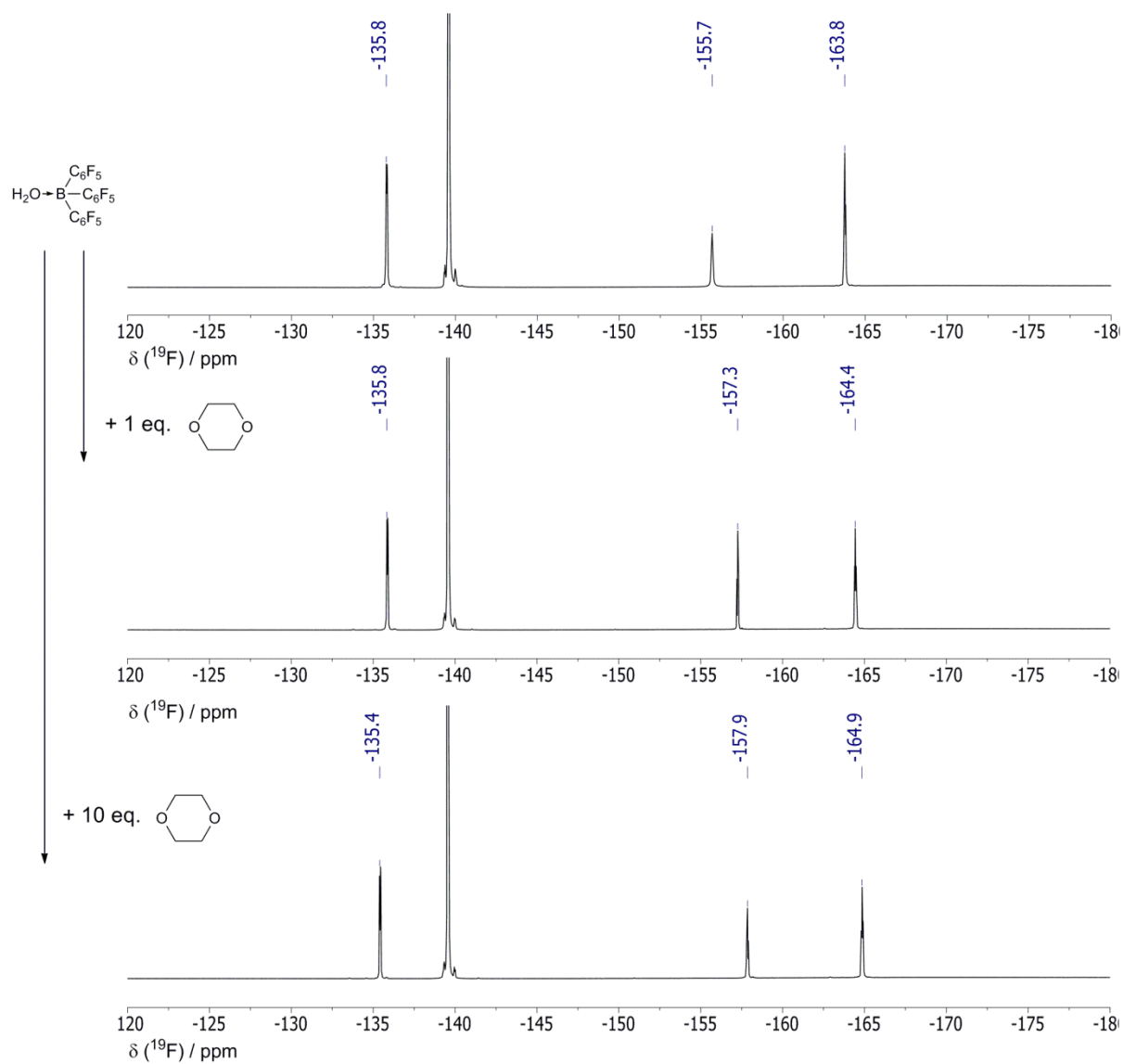
**Figure S20.**  $^{19}\text{F}$  NMR spectra of  $\mathbf{1}$  in the presence of 1,4-dioxane



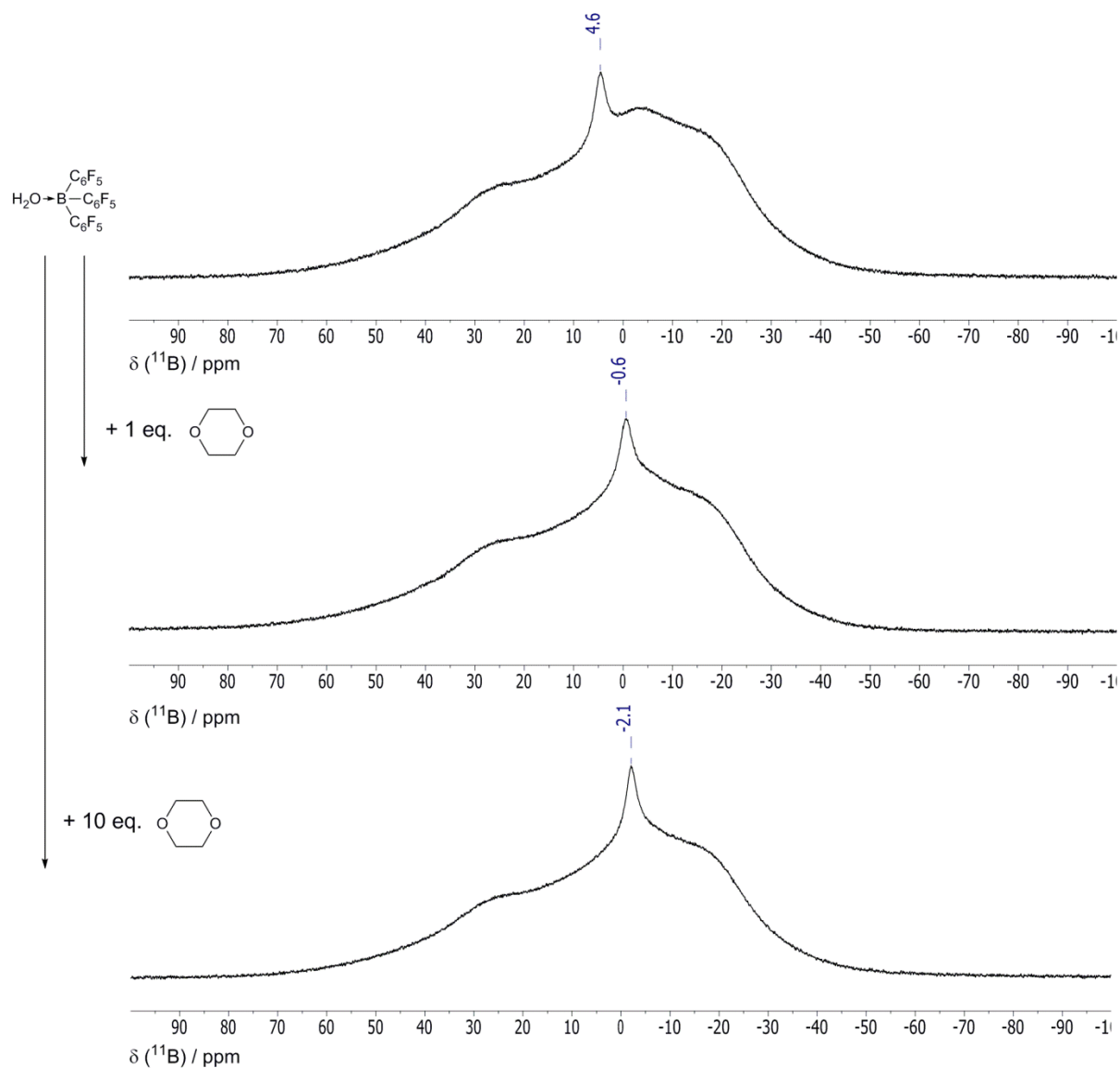
**Figure S21.**  $^{11}B$  NMR spectra of **1** in the presence of 1,4-dioxane



**Figure S22.**  $^1\text{H}$  NMR spectra of  $\mathbf{1} \cdot \text{OH}_2$  in the presence of 1,4-dioxane



**Figure S23.**  $^{19}\text{F}$  NMR spectra of  $\mathbf{1} \cdot \text{OH}_2$  in the presence of 1,4-dioxane



**Figure S24.**  $^{11}\text{B}$  NMR spectra of  $\mathbf{1} \cdot \text{OH}_2$  in the presence of 1,4-dioxane

## 7. References

- (1) Lancaster, S. J. *Chemspider Synthetic Pages*, **2003**, 215.
- (2) Bergquist, C.; Bridgewater, B. M.; Harlan, C. J.; Norton, J. R.; Friesner, R. A.; Parkin, G. *J. Am. Chem. Soc.* **2000**, *122*, 10581-10590.
- (3) Fendrick, C. M.; Schertz, L. D.; Mintz, E. A.; Marks, T. J.; Bitterwolf, T. E.; Horine, P. A.; Hubler, T. L.; Sheldon, J. A.; Belin, D. D. In *Inorganic Syntheses*, Grimes R. N. Ed.; Inorganic Syntheses, Inc. 1992, Vol. 29, p 193-198.