Electronic Supplementary Material (ESI) for Organic & Biomolecular Chemistry

Supporting information

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Making Fe(BPBP)-catalyzed C-H and C=C oxidations more affordable

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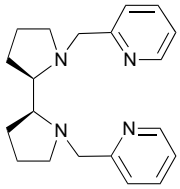
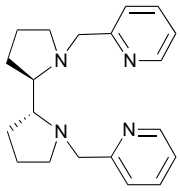
Contents

1. General remarks. All reactions were performed under nitrogen atmosphere unless stated otherwise. Tetrahydrofuran, diethyl ether, acetonitrile were dried on a MBRAUN MB SPS-800 solvent purification system. Column chromatography was performed using Merck silica gel (60-200 mesh). ^{1}H (400 MHz) and ^{13}C (100 MHz) NMR spectra were recorded on a Varian AS400 spectrometer at 25 °C, chemical shifts (δ) are given in ppm referenced to the residual solvent peak. GC analyses were performed on a PerkinElmer AutosystemXL Gas Chromatograph using the Alltech Econo-Cap EC5 column (30 m x 0.32 mm), (5% phenyl)-(95% methyl)polysiloxane. ESI-MS measurements were carried out on a LCT PremierXE KE317 instrument in acetonitrile as a solvent. All reagents, substrates and reaction products (**7**, **8**, **11**-**18**, **24**, **32**-**40**, **41a**-**44a**) were purchased from Sigma-Aldrich and were used as received. The diastereomeric mixture of 2,2'-bipyrrolidine,[1] $Fe(OTf)_2.2MeCN$[2] and the complexes *R,R*- and *S,S*-**1**[3] were prepared following previously reported protocols. Substrates 2-adamntyl acetate (**21**) was synthesized from 2-adamantanol in a high yield and purity.[4] Reference samples of alcohols and carbonyl compounds **19**, **22**, **23**, **25**-**31** were prepared using the known *S,S*-**1**/H_2O_2 system;[3] required reference epoxides **41b**-**44b** were synthesized oxidizing commercial alkenes with *meta*-chloroperbenzoic acid to give good yields of the corresponding epoxides.[5]

2. Synthesis of BPBP ligands.

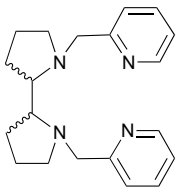


R,S-BPBP. Solid sodium hydroxide (1.08 g, 27.0 mmol) was added to a vigorously stirred suspension of *R,S*-bipyrrolidine sesquioxalate salt (1.01 g, 3.67 mmol) in CH_2Cl_2 (6 mL) and water (6 mL) at RT forming a colourless homogeneous biphasic mixture. Then solid 2-picolyl chloride hydrochloride salt (1.20 g, 7.34 mmol) was added at once to the reaction mixture turning it intensely pink. After stirring overnight the yellowish organic phase was separated and the aqueous phase was extracted with DCM (3 x 5 mL). Organic extracts were combined, dried over Na_2SO_4 and concentrated under reduced pressure yielding a brownish oily residue, which was subsequently taken up in *n*-pentane (50 mL) and stirred over 1 h. The obtained transparent solution was separated from the dark oil and concentrated to dryness to afford the spectroscopically pure target compound as colourless oil (1.05 g, 89%). ^{1}H NMR ($CDCl_3$, 400 MHz): d 8.47 (d, *J* = 6.6 Hz, 2H, 6-Py-H), 7.58 (t, *J* = 7.6 Hz, 2H, 5-Py-H), 7.45 (d, *J* = 7.8 Hz, 2H, 4-Py-H), 7.09 (t, *J* = 5.0 Hz, 2H, 3-Py-H), 4.67 (d, *J* = 14.3 Hz, 2H, C*H*$_2$-Py), 3.38 (d, *J* = 14.3 Hz, 2H, C*H*$_2$-Py), 2.95-2.89 (m, 2H), 2.83 (t, *J* = 7.5 Hz, 2H), 2.15 (q, *J* = 8.5 Hz, 2H), 1.91-1.80 (m, 4H), 1.72-1.62 (m, 4H). ^{13}C NMR ($CDCl_3$, 100 MHz) δ: 161.0, 148.6, 136.4, 122.5, 121.5, 65.4, 61.9, 55.4, 30.0, 23.3. IR ($\tilde{\nu}$, cm^{-1}): 2960, 2793, 1588, 1568, 1473, 1431, 1358, 1145, 1115, 752. HRMS (ESI-MS, MeCN) calcd. *m/z* for $C_{20}H_{27}N_4$ $(M+H)^+$ 323.2236, found 323.2214.



R,R-BPBP. Colourless oil (758 mg, 81%). $[a]_D^{20}$ +99.4 (*c* 1.05 $CHCl_3$). ^{1}H NMR ($CDCl_3$, 400 MHz): d 8.43 (d, *J* = 6.6 Hz, 2H, 6-Py-H), 7.53 (t, *J* = 7.6 Hz, 2H, 5-Py-H), 7.33 (d, *J* = 7.8 Hz, 2H, 4-Py-H), 7.04 (t, *J* = 5.3 Hz, 2H, 3-Py-H), 4.13 (d, *J* = 14.3 Hz, 2H, C*H*$_2$-Py), 3.44 (d, *J* = 14.3 Hz, 2H, C*H*$_2$-Py), 2.95-2.89 (m, 2H), 2.77-2.68 (m, 2H), 2.15-2.11 (m, 2H), 1.80-1.68 (m, 4H), 1.68-1.59 (m, 4H). ^{13}C NMR ($CDCl_3$, 100 MHz) δ: 160.4, 148.8, 136.2, 122.6, 121.6, 65.4, 61.2, 55.3, 25.9, 23.6. IR ($\tilde{\nu}$, cm^{-1}): 2961, 2796, 1588, 1569, 1474, 1431, 1369, 1119, 750. HRMS (ESI-MS, MeCN) calcd. *m/z* for $C_{20}H_{27}N_4$ $(M+H)^+$ 323.2236, found 323.2224. Spectral properties of the product are in agreement with the literature data.[3,6]

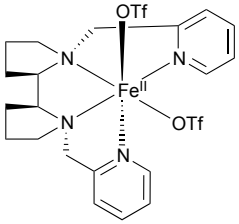
S,S-BPBP. Colourless oil (857 mg, 71%). $[a]_D^{20}$ -98.7 (*c* 0.99 $CHCl_3$). HRMS (ESI-MS, MeCN) calcd. *m/z* for $C_{20}H_{27}N_4$ $(M+H)^+$ 323.2236, found 323.2229.



mix-BPBP. Solid sodium hydroxide (2.40 g, 60.0 mmol) was added to a vigorously stirred solution of crude *dl/meso*-2,2'-bipyrrolidine (2.00 g, 14.26 mmol, *dr* ca. 50/50) in CH_2Cl_2 (25 mL) and water (25 mL) at RT. Then solid 2-picolyl chloride hydrochloride salt (4.68 g, 28.5 mmol) was added at once to the reaction mixture turning it red. After stirring overnight the yellowish organic phase was separated and the aqueous phase was extracted with CH_2Cl_2 (3 x 20 mL). Organic extracts were combined, dried over Na_2SO_4 and concentrated under reduced pressure yielding crude product (4.54 g, 99%, *dr* ca. 50/50), which was subsequently loaded on a short pad of neutral alumina slurry in CH_2Cl_2 (ca. 200 mL), flushed subsequently with CH_2Cl_2 (400 mL) and $CHCl_3$ (900 mL). The last fractions (ca. 600 mL) were combined and evaporated. The obtained oil was partitioned between CH_2Cl_2 (20 mL) and a 1 M aq. NaOH solution (30 mL). The organic layer was separated and the aqueous layer was extracted with CH_2Cl_2 (2 x 20 mL). Organic extracts were combined, dried over Na_2SO_4 and concentrated to dryness yielding the title product as colourless oil: run 1 (3.82 g 83%), run 2 (205 mg, 62%). The product is a mixture of *rac*-BPBP (major) and *R,S*-BPBP (minor) with *dr* estimated by ^{1}H NMR: run 1 (55/45), run 2 (50/50). *rac*-BPBP (major). ^{1}H NMR ($CDCl_3$, 400 MHz, indicative signals): δ 7.33 (d, *J* = 7.8 Hz, 2H, 4-Py-H) and 4.13 (d, *J* = 14.3 Hz, 2H, C*H*$_2$-Py). *R,S*-BPBP (minor). ^{1}H NMR ($CDCl_3$, 400 MHz, indicative signals): δ 7.45 (d, *J* = 7.8 Hz, 2H, 4-Py-H) and 4.67 (d, *J* = 14.3 Hz, 2H, C*H*$_2$-Py). HRMS (ESI-MS, MeCN) calcd. *m/z* for $C_{20}H_{27}N_4$ $(M+H)^+$ 323.2236, found 323.2233.

3. Synthesis of iron complexes.

Λ/Δ-[Fe(R,S-BPBP)(OTf)$_2$] (*R,S*-**1**). A solution of *R,S*-BPBP (1.05 g, 3.25 mmol) in THF (5 mL) was added to a vigorously stirred clear solution of Fe(OTf)$_2$.2MeCN (1.42 g, 3.26 mmol) in THF (15 mL) at RT. A pale yellow suspension immediately formed. After stirring overnight the solids were allowed to sediment and the supernatant (ca. 10 mL) was removed *via* cannula. The remaining heavy precipitate was repetitively suspended-sedimented in dry THF (6 mL), a 3:2 v/v THF-Et$_2$O mixture (2 x 10 mL), and dry Et$_2$O (2 x 10 mL) and dried under vacuum at 50 °C over 3 h to afford a pale yellow powder (1.75 g, 80%). Crystals of X-ray diffraction quality were obtained by slow liquid-diffusion crystallization out of a CH_2Cl_2:Et$_2$O mixture. ^{1}H NMR (CD_2Cl_2, 400 MHz): δ 119.5 (s), 66.3 (s), 54.2 (s), 51.4 (s), 9.9 (s), 0.9 (s), -7.1 (s), -13.6 (s). ^{19}F NMR (CD_2Cl_2, 375 MHz): δ -28.1. IR ($\tilde{\nu}$, cm^{-1}): 2921, 1605, 1483, 1445, 1307, 1243, 1215, 1186, 1163, 1104.8, 1034, 906, 847, 769. HRMS (ESI-MS, MeCN) calcd. *m/z* for $C_{21}H_{26}F_3FeN_4O_3S$ (M-OTf)$^+$ 527.1027, found 527.1043.



Λ-[Fe(S,S-BPBP)(OTf)$_2$] (*S,S*-**1**). Lemon-colored powder (576 mg, 91%). ^{1}H NMR (CD_2Cl_2, 400 MHz): δ 179.0 (s), 126.6 (s), 78.2 (s), 54.9 (s), 51.9 (s), 30.4 (s), 27.3 (s), 16.6 (s), 14.4 (s), 0.9 (s), -3.7 (s), -9.5 (s), -18.8 (s). ^{19}F NMR (CD_2Cl_2, 375 MHz): δ -31.2. IR ($\tilde{\nu}$, cm^{-1}): 2971, 2902, 1610, 1486, 1445, 1307, 1233, 1211, 1156, 1024, 901, 761. HRMS (ESI-MS, MeCN) calcd. m/z for $C_{21}H_{26}F_3FeN_4O_3S$ (M-OTf)$^+$ 527.1027, found 527.1025. Spectral properties of the product are in agreement with the literature data.[3,7]

Δ-[Fe(R,R-BPBP)(OTf)$_2$] (*R,R*-**1**). Lemon-colored powder (972 mg, 88%). Identical spectral properties to *S,S*-**1**.

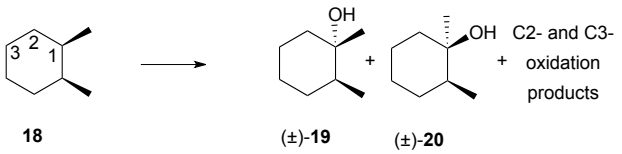
mix-[Fe(BPBP)(OTf)$_2$] (*mix*-**1**). A solution of *mix*-BPBP (1.80 g, 5.60 mmol) in THF (10 mL) was added to a vigorously stirred clear solution of Fe(OTf)$_2$.2MeCN (2.44 g, 5.60 mmol) in THF (25 mL) at RT. A lemon-colored suspension immediately formed. After stirring overnight the solids were allowed to sediment and the supernatant (ca. 20 mL) was removed *via* cannula. The remaining heavy precipitate was repetitively suspended-sedimented in dry THF (10 mL), a 1:1 v/v THF-Et$_2$O mixture (2 x 10 mL), and dry Et$_2$O (2 x 10 mL) and dried under vacuum at 50 °C over 3 h to afford a bright yellow powder: run 1 (2.68 g, 71%), run 2 (2.81 g, 74%) and run 3 (321 mg, 75%). The product is a mixture of *rac*-**1** (major) and *R,S*-**1** (minor). HRMS (ESI-MS, MeCN) calcd. *m/z* for $C_{21}H_{26}F_3FeN_4O_3S$ (M-OTf)$^+$ 527.1027, found 527.0985. Elemental analysis calcd. (%) for $C_{22}H_{26}F_6FeN_4O_6S_2$ C 39.06, H 3.87, N 8.28, found 38.86, H 3.76, N 8.35.

Diastereomeric composition of *mix*-1. A 25% NH_4OH aq. solution (1 mL) was added to a stirred solution of *mix*-**1** (46.2 mg, 68.3 mmol) in CH_2Cl_2 (2 mL) at RT. The reaction mixture gradually turned rusty-brown. After ca. 15 min the reaction mixture was diluted with water (5 mL) and extracted with CH_2Cl_2 (3 x 5 mL). Organic extracts were combined, dried over Na_2SO_4 and concentrated under reduced pressure leaving a brownish oily residue, which was passed through a pipet column of neutral alumina using EtOAc as eluent. Solvent removal afforded *mix*-BPBP: run 1 (22.0 mg, 97%), run 2 (19.9 mg, 91%) and run 3 (8.50 mg, 80%). Basing on ^{1}H-NMR data the actual *dr* of analysed *mix*-**1** (*rac*-/*R,S*-BPBP) was estimated: run 1 (75/25), run 2 (75/25) and run 3 (70/30). See *mix*-BPBP characterization for details.

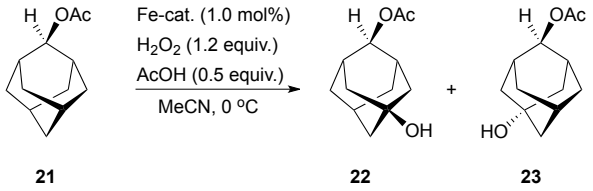
4. General conditions for catalytic C-H oxidation of 11, 18, 21 and 24.

Small-scale protocol. (**1**/substrate/H_2O_2/AcOH *x*:100:120:50, where *x* stands for the catalyst loading with respect to the substrate and varies from 0.05 to 4 mol%.). A 10 mL glass vial was charged with a 0.20 M substrate solution in MeCN (1.0 mL, 0.20 mmol), 1.74 M AcOH solution in MeCN (60 μL, 0.10 mmol), dry MeCN ({400-100*x*} μL) and cooled on an ice bath with stirring. Subsequently, a 0.020 M catalyst solution in MeCN (100*x* μL, 2.0*x* μmol) was injected into the reaction medium and a 1.5 M H_2O_2 solution in MeCN (160 μL, 0.24 mmol, diluted from a 35% aq. H_2O_2) was delivered *via* a syringe pump over 6 min. At the end of the oxidant addition the resulting mixture was stirred for additional 10 min. Subsequently, an internal standard 0.20 M solution in MeCN ($PhNO_2$, 0.50 mL, 0.10 mmol) was added. A sample (ca. 0.2 mL) of the final solution was diluted with Et$_2$O (ca. 0.8 mL) to precipitate the iron complex, passed through a cotton wool filter and subjected to GC analysis.
Remarks. The (-)-ambroxide (**7**) oxidation was carried out at RT due to a poor solubility of this substrate in MeCN at 0 °C using **1**/**7**/H_2O_2/AcOH 3:100:260:150. (+)-Sclareolide (**8**) oxidation required **1**/**8**/H_2O_2/AcOH 3:100:360:150. Adamantane (**14**) is poorly soluble in MeCN; thus, it was grinded before use and added to the reaction mixture as powder along with additional amount of MeCN to maintain the total reaction volume at a usual level. Also in this case, the reaction mixture containing internal standard was diluted 4-fold using EtOAc prior GC analysis.

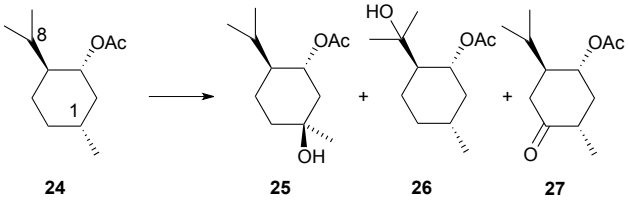
5. Preparative catalytic C-H oxidations.



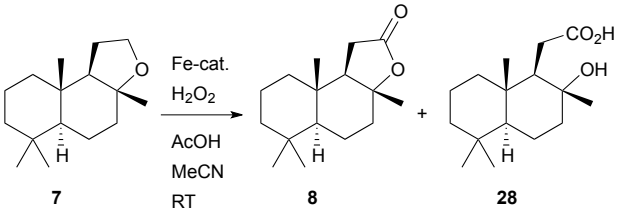
*(±)-Z-1,2-Dimethylcyclohexane **18** oxidation.* The reaction was performed as in case of **24** using **18** (5.0 g, 44.6 mmol), AcOH (1.3 mL, 22.3 mmol), *mix*-**1** (150 mg, 0.223 mmol) and a 1.5 M H_2O_2 solution (35 mL). Unreacted **18** was distilled off under ambient pressure (1.68 g, 15.0 mmol, 34%). The residue was purified by column chromatography on silica gel (hexanes: EtOAc 3:1) to afford (±)-**19** (1.61 g, 12.6 mmol, 28%). Spectral properties of the product are in agreement with literature data.[3]



*2-Adamantyl acetate **21** oxidation.* A 10 mL glass vial was charged with **21** (195.0 mg, 1.00 mmol), 1.74 M AcOH solution in MeCN (0.29 mL, 0.50 mmol), dry MeCN (5.9 mL) and cooled on an ice bath with stirring. Subsequently, a 0.020 M catalyst solution in MeCN (0.50 mL, 10 mmol) was injected into the reaction medium and a 1.5 M H_2O_2 solution in MeCN (0.80 mL, 1.20 mmol, diluted from a 35% aq. H_2O_2) was delivered *via* a syringe pump over 6 min. After the end of the oxidant addition the resulting mixture was stirred for additional 10 min. The product mixture was concentrated under vacuum and the residue was purified *via* column chromatography (hexane/ethyl acetate) to separate starting material. The products were eluted without separation and their ratio was assigned *via* GC and ^{13}C NMR. (Obtained {*Z*-**22**+*E*-**23**}; recovered **21**; *Z/E*-ratio): for *S,S*-**1** (72.2 mg, 34%; 67.9 mg, 35%; 2.6), for *R,R*-**1** (64.2 mg, 30%; 81.4 mg, 42%; 2.0), for *mix*-**1** (73.1 mg; 74.9 mg, 38%; 2.2). ^{13}C NMR ($CDCl_3$, 100 MHz) δ: [major *Z*-**22**] 170.4, 74.8 (*C*-OAc), 67.36 (*C*-OH), 44.9, 39.5 (x2), 34.7 (x2), 34.5 (x2), 29.3, 21.3 (CH_3); [minor *E*-**23**] 170.5, 75.6 (*C*-OAc), 67.33 (*C*-OH), 45.1, 43.3 (x2), 33.5 (x2), 30.3 (x2), 29.5, 21.3 (CH_3). Spectral properties of the products are in agreement with literature data.[4a]



*L-(-)-Menthyl acetate (**24**) oxidation.* A round bottom flask was charged with *L*-menthyl acetate **24** (10.9 mL, 50.4 mmol), AcOH (1.50 mL, 26.2 mmol), dry MeCN (100 mL) and cooled to 0 °C on and ice-salt bath with stirring. Subsequently, *mix*-**1** (340 mg, 0.50 mmol) was added and a 1.5 M H_2O_2 solution in MeCN (30 mL, 60 mmol, diluted from a 35% aq. H_2O_2) was delivered dropwise at such a rate to maintain the internal reaction temperature between 0 and 5 °C. This reaction is quite exothermic, so the oxidant addition can take up to 15 min depending on the cooling bath efficiency. Also the last portions of H_2O_2 did not essentially trigger the reaction temperature. The reaction mixture was concentrated under reduced pressure to ca. 15 mL, diluted with Et_2O (150 mL) and centrifuged (5 min, 2400 rpm). A semi-solid dark residue (410 mg) was formed and further used to retrieve the *mix*-BPBP ligand (see ligand recovery protocol A below). The liquid phase was separated, washed with brine (30 mL), saturated aq. $NaHCO_3$ (30 mL), dried over Na_2SO_4 and concentrated until a constant weight (10.2 g). Unreacted *L*-menthyl acetate **24** (6.94 g, 35.0 mmol, 69%) was distilled off at 85-86 °C / 3 mmHg. The viscous residue boiled at 122-125 °C / 3 mmHg without essential separation of its components and was further purified by column chromatography (silica, hexanes) to afford the target alcohol **25** (1.61 g, 7.51 mmol, 15%), isomeric alcohol **26** (146 mg, 0.68 mmol, 1.4%), ketone **27** (120 mg, 0.57 mmol, 1.1%) and starting *L*-menthyl acetate **24** (152 mg, 0.77 mmol, 1.5%). An additional amount of target alcohol **25** (170 mg, 0.79 mmol, 1.6%) was obtained by purifying the combined impure fractions collected during the first column chromatography. Spectral properties of the product are in agreement with literature data.[3]



*(-)-Ambroxide **7** oxidation.* A round bottom flask was charged with (-)-ambroxide **7** (1.50 g, 6.35 mmol), AcOH (0.55 mL, 9.5 mmol), dry MeCN (30 mL) and *mix*-**1** (86.0 mg, 0.127 mmol) at RT with stirring. The reaction vessel was placed on an ice bath only when most of the substrate was dissolved. A 1.5 M H_2O_2 solution in MeCN (11.0 mL, 16.5 mmol, diluted from a 35% aq. H_2O_2) was manually added to the reaction mixture at such a rate to maintain the internal temperature between 15 and 20 °C. This reaction is quite exothermic, so the oxidant addition can take up to 10 min depending on the cooling bath efficiency. GC analysis indicated a 99% substrate conversion right at the end of H_2O_2 addition. The reaction mixture was concentrated under reduced pressure to ca. 5 mL, diluted with Et_2O (50 mL) and centrifuged (5 min, 2400 rpm). A semisolid dark residue was formed and further used to retrieve the *mix*-BPBP ligand (see ligand recovery protocol B). The liquid phase was washed with brine (20 mL) and shaken with a 10% aq. $NaHCO_3$ (20 mL) causing partial solidification of the aqueous layer. The upper layer was washed one more time with saturated $NaHCO_3$ (10 mL) and brine (10 mL), dried over Na_2SO_4, concentrated and passed through a short silica column with EtOAc to decolorize crude (+)-sclareolide **8**. Additionally, **8** was recrystallized from hot hexanes yielding the pure lactone (860 mg, 3.43 mmol, 54%). In turn, the aqueous layer with solids was extracted with Et_2O (2 x 20 mL), acidified with 4 M HCl and

extracted with CH_2Cl_2 (2 x 20 mL). The CH_2Cl_2 extracts were combined, dried over Na_2SO_4 and concentrated. This crude acid **28** was additionally recrystallized from a minimal volume of hot MeCN to afford colourless crystalline solid product (494 mg, 1.84 mmol, 29%). ^{1}H NMR ($CDCl_3$, 400 MHz): d 2.52-2.45 (dd, *J* = 6.0 Hz, *J* = 16.3 Hz, 1H), 2.36-2.29 (dd, *J* = 4.5 Hz, *J* = 16.3 Hz, 1H), 1.96-1.89 (dt, *J* = 3.2 Hz, *J* = 12.4 Hz, 1H), 1.82-1.79 (m, 1H), 1.72-1.74 (m, 1H), 1.59-1.52 (m, 2H), 1.49-1.22 (m, 4H), 1.22-1.11 (m, 1H), 1.17 (s, 3H), 1.02-0.95 (m, 2H), 0.86 (s, 3H), 0.77 (s, 6H). ^{13}C NMR ($CDCl_3$, 100 MHz) δ: 178.9, 73.9 (indicative), 57.5, 55.8, 44.4, 41.7, 39.12, 38.5, 33.29, 33.21, 30.1, 23.3, 21.4, 20.4, 18.3, 15.3. Spectral properties of the product are in agreement with the literature data.[8]

6. BPBP ligand recovery.

Protocol A.[9] A dark semisolid residue that was obtained in the multi-gram oxidation of *L*-menthyl acetate **24** with *mix*-**1** (340 mg, 0.502 mmol) upon redissolving the product mixture in Et_2O was partitioned between CH_2Cl_2 (10 mL) and water (5 mL) and mixed with a 25% NH_4OH aq. solution (5 mL) at RT with vigorous stirring. The reaction mixture gradually turned rusty-brown. After ca. 30 min the reaction mixture was diluted with water (10 mL) and extracted with CH_2Cl_2 (3 x 10 mL). Organic extracts were combined, washed with brine (20 mL), dried over Na_2SO_4 and concentrated under reduced pressure leaving a brownish oily residue, which was passed through a short column of neutral alumina eluting with CH_2Cl_2-EtOAc (100:0 to 0:100). Solvent removal afforded diastereomerically pure *rac*-BPBP (95.6 mg, 0.297 mmol, 59%) as a slightly brownish oil.

Protocol B. A dark semisolid residue that was obtained in the preparative oxidation of (-)-ambroxide **7** with *mix*-**1** (86.0 mg, 0.127 mmol) upon redissolving the product mixture in Et_2O was dissolved in CH_2Cl_2 (20 mL) and extracted with saturated aq. Na_2EDTA solution (4 x 10 mL) adjusting every time the system pH to 12 with 4 M aqueous NaOH. The colourless organic layer was dried over Na_2SO_4 and concentrated under reduced pressure yielding the diastereomerically pure r*ac*-BPBP ligand (25.7 mg, 63%). If the isolated polyamine ligand contains unacceptable amounts of (+)-sclareolide **8** it can be further purified by a casual acid-base pH switching protocol.

Protocol C. A dark semisolid residue that was obtained in the preparative oxidation of *Z*-1,2-dimethylcyclohexane (**18**) with *mix*-**1** (150 mg, 0.223 mmol) upon redissolving the product mixture in Et_2O was partitioned between CH_2Cl_2 (3 mL) and water (2 mL). Then, a 5% polyacrylic acid (Mw 100 kDa) aq. solution (1.0 mL, prepared from a 35% aq. PAA, 250 mg) was added to it with vigorous stirring. The obtained suspension was centrifuged (5 min, 2400 rpm) forming a three-layer system: transparent CH_2Cl_2 and aqueous phases and a sponge-like dense brownish layer in between. The CH_2Cl_2 layer was disposed and the residue was basified with a 4 M aqueous NaOH solution till pH 12 and extracted with new portions of CH_2Cl_2 (3 x 10 mL). Combined organic extracts were dried over Na_2SO_4 and concentrated under reduced pressure yielding the diastereomerically pure r*ac*-BPBP ligand (42.5 mg, 58%).

7. General conditions for catalytic C=C oxidation of 32a-37a.

Small-scale protocol. (**1**/substrate/H_2O_2/AcOH *x*:100:150:*y*, where *x* stands for the catalyst loading in respect to the substrate and varies from 0.10 to 0.67 mol%; *y* corresponds to the amount of acetic acid added and varies between 0.0 and 2.0 mol% in respect to the substrate). A 10 mL glass vial was charged with neat substrate (1.0 mmol), $PhNO_2$ (103 μL, 1.0 mmol), 0.010 M AcOH solution in MeCN ({*y*} mL, 0.010*y* mmol), a 0.020 M catalyst solution in MeCN (500*x* μL, 10*x* mmol, injected into the reaction medium), dry MeCN ({5.0-0.50*x*-*y*} mL) and cooled on an ice bath with stirring. Subsequently, a 1.5 M H_2O_2 solution in MeCN (1.0 mL, 1.5 mmol, diluted from a 35% aq. H_2O_2) was delivered to it *via* a syringe pump over 60 min. After oxidant addition the resulting mixture was stirred for additional 30 min. The reaction progress was monitored by taking samples (ca. 0.1 mL) periodically, diluting them with Et_2O (ca. 0.9 mL) and analysing *via* GC.

*Isolation of **32b-37b***. The oxidation was carried out under the optimal conditions described in Table A. The reaction mixture was filtered through a short silica column to remove AcOH and water. The column was flushed with small amounts of EtOAc (pentane for **37b**). The products were obtained sufficiently pure after careful evaporation of the eluted fractions under vacuum.

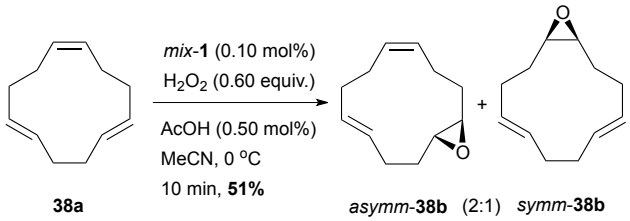
Table A. Alkene epoxidation with **1**/H_2O_2/AcOH.[a)]

Alkene	Fe-Cat. (mol%)	AcOH, mol%	Yield,[b)] % / Conv.,[b)] %
32a	*mix*-**1** (0.13)	0.50	92[c)]/98
33a	*mix*-**1** (0.52)	2.0	89[c)]/95
34a	*mix*-**1** (0.26)	1.0	92[c)]/99
35a	*mix*-**1** (0.26)	1.0	95[c)]/99
36a	*mix*-**1** (0.26)	1.0	89[c)]/98
37a	*mix*-**1** (0.26)	1.5	90[c)]/99

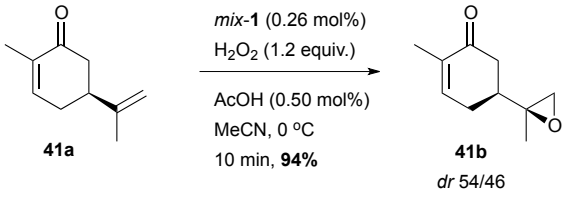
[a)] *Reaction conditions:* alkene (1.0 mmol), H_2O_2 (1.5 mmol over 60 min), AcOH, Fe-cat., MeCN (5 mL), 0 °C, 90 min. [b)] Determined by GC. [c)] Isolated yield.

Competitive alkene epoxidation. (*mix*-**1**/H_2O_2/substrate_A/substrate_B/AcOH 1:300:200:200:8)
A 10 mL glass vial was charged with neat substrate_A (1.0 mmol), substrate_B (1.0 mmol), $PhNO_2$ (103 mL, 1.0 mmol), 0.010 M AcOH solution in MeCN (4.0 mL, 0.040 mmol), a 0.020 M catalyst solution in MeCN (250 μL, 5.0 mmol, injected into the reaction medium), dry MeCN (0.75 mL) and cooled on an ice bath with stirring. Subsequently, a 1.5 M H_2O_2 solution in MeCN (1.0 mL, 1.5 mmol, diluted from a 35% aq. H_2O_2) was delivered to it *via* a syringe pump over 60 min. After the end of the oxidant addition the resulting mixture was stirred for additional 30 min. The reaction progress was monitored by taking samples (ca. 0.1 mL) periodically, diluting them with Et_2O (ca. 0.9 mL) and analysing *via* GC.

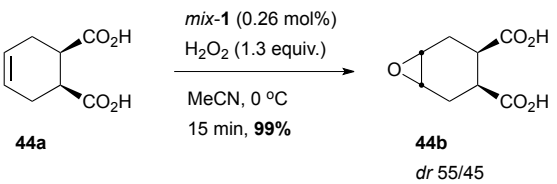
8. Preparative catalytic C=C oxidations of 38a-44a



E,E,Z-1,5,9-Cyclododecatriene ***38a*** *oxidation*. A round bottom flask was charged with *E,E,Z*-1,5,9-Cyclododecatriene **38a** (10 mL, 54.8 mmol), 0.010 M AcOH solution in MeCN AcOH (30 mL, 0.3 mmol), dry MeCN (170 mL) and cooled to 0 °C on and ice-salt bath with stirring. Subsequently, *mix*-**1** (37.1 mg, 0.055 mmol) was added and a 1.5 M H_2O_2 solution in MeCN (22 mL, 33 mmol, diluted from a 35% aq. H_2O_2) was delivered to it dropwise over 10 min on cooling. The reaction mixture was concentrated under reduced pressure to ca. 15 mL, diluted with Et_2O (150 mL) and centrifuged (5 min, 2400 rpm). The liquid phase was separated, washed with brine (30 mL), saturated aq. $NaHCO_3$ (30 mL), dried over Na_2SO_4 and concentrated and the residue was distilled under vacuum. Low boiling fractions were collected until 70 °C / 3 mmHg. The monoepoxide **38b** was collected at 103-105 °C / 3 mmHg (4.93 g, 27.7 mmol, 50.5%). ^{1}H NMR ($CDCl_3$, 400 MHz) δ: 5.13-5.41 (m, 4H, alkenyl-H), 2.93-2.84 (bd, *J* = 9.72 Hz, 0.67 H, indicative for *cis*-epoxide in *symm*-**38b**), 2.74 (dt, *J* = 2.49 Hz, *J* = 10.3 Hz, 0.67 H, indicative for *trans*-epoxide in a*symm*-**38b**), 2.51 (dt, *J* = 2.49 Hz, *J* = 8.83 Hz, 0.67 H, indicative for *trans*-epoxide in a*symm*-**38b**), 2.38-1.77 (10H), 1.37-1.24 (0.67 H, *symm*-**38b**), 1.22-1.04 (1.33 H, *asymm*-**38b**). ^{13}C NMR ($CDCl_3$, 100 MHz) δ: [for a*symm*-**38b**] 130.13, 130.08, 129.8, 128.9, 59.6, 58.9, 31.93, 31.90, 30.0, 28.3, 26.8, 23.5; [for *symm*-**38b**] 132.7, 128.2, 59.4, 29.8, 28.3, 26.9. Spectral properties of the product are in agreement with the literature data.[10]
The epoxides **39b** (54% yield) and **40b** (79% yield) were prepared as above, but using different amounts of H_2O_2 (0.75 and 0.90 equiv., respectively). Compound **39b** was purified *via* vacuum distillation and compound **40b** was purified by column chromatography using hexanes as eluent. The isomeric composition of products was assigned *via* GC by comparing with commercially available samples of **39b** and **40b**.



S-(+)-Carvone ***41a*** *oxidation*. To a solution of **41a** (1.52 g, 10.0 mmol) in MeCN (45 mL) was added *mix*-**1** (17.5 mg, 25.9 mmol), and a 0.010 M AcOH solution in MeCN (5.0 mL, 50 mmol). Next the mixture was cooled on an ice bath with stirring to ca. 5 °C. Subsequently, a 1.5 M H_2O_2 in MeCN (8.5 mL, 12.0 mmol, diluted from a 35% aq. H_2O_2) was delivered to it dropwise over ca. 10 min. Then the solution was concentrated under reduced pressure, loaded onto a short silica pad and eluted with EtOAc. The target product **41b** was obtained as a colourless oil (1.55 g, 9.36 mmol, 94%, *dr* 54/46). Spectral properties of the product are in agreement with the literature data.[11]
The oxidation of *S*-citronellol **42a** and (±)-citronellyl acetate **43a** was carried out as above, however slightly higher amounts of H_2O_2 (1.3 equiv.) were used and delivered over 45 min.[12]



*cis-1,2,3,6-Tetrahydrophtalic acid (****44a****) oxidation*. To a solution of **44a** (1.00 g, 5.88 mmol) in MeCN (25 mL) was added *mix*-**1** (9.94 mg, 14.7 mmol). (No AcOH was used). Subsequently, a 1.5 M H_2O_2 in MeCN (5.1 mL, 7.64 mmol, diluted from a 35% aq. H_2O_2) was delivered to it dropwise over ca. 10 min at RT, because the substrate is poorly soluble in MeCN. The reaction mixture turned yellowish and the solids dissolved. Then the solution was stirred for extra 5 min, concentrated under reduced pressure and dried under high vacuum. The target product **44b** was obtained as an oil solidifying upon standing (1.09 g, 9.36 mmol, 99%, *dr* 46/54). ^{1}H NMR (CD_3CN, 400 MHz) δ: (mixture of two diastereomers) 3.17 (bs, 2H, C*H*-O), 3.14 (bs, 2H, C*H*-O), 2.88-2.81 (m, 2H, C*H*-CO), 2.76-2.74 (m, 2H, C*H*-CO), 2.50-2.45 (m, 2H), 2.29-2.22 (m, 2H), 2.15-2.11 (m, 4H). ^{13}C NMR (CD_3CN, 100 MHz) δ: 174.82, 174.79, 51.2, 50.9, 36.9, 36.7, 24.6, 24.4. The esterified derivatives were previously reported.[13]

9. X-ray crystal structure determination of *R,S*-1.

$C_{22}H_{26}F_6FeN_4O_6S_2$, F_w = 676.44, pale yellow block, 0.51 × 0.32 × 0.16 mm3, triclinic, P $\overline{1}$ (no. 2), a = 9.5255(3), b = 10.2017(4), c = 15.6299(4) Å, α = 96.696(1), β = 95.281(2), γ = 117.086(2) º, V = 1324.83(7) Å^3, Z = 2, D_x = 1.696 g/cm^3, μ = 0.82 mm^{-1}. (For main bond lengths and angles see Table B below). 32618 Reflections were measured on a Bruker Kappa ApexII diffractometer with sealed tube and Triumph monochromator (λ = 0.71073 Å) at a temperature of 150(2) K up to a resolution of (sin θ/λ)max = 0.65 Å^{-1}. Intensity data were integrated with the Eval15 software.[14] Absorption correction and scaling was performed with SADABS[15] based on multiple measured reflections (correction range 0.68-0.75). 6085 Reflections were unique (Rint = 0.015), of which 5694 were observed [I>2σ(I)]. The structure was solved with Direct Methods using the program SIR-97.[16] Least-squares refinement was performed with SHELXL-97[17] against F^2 of all reflections. Non-hydrogen atoms were refined freely with anisotropic displacement parameters. All hydrogen atoms were located in difference Fourier maps and refined with a riding model. 370 Parameters were refined with no restraints. R1/wR2 [I > 2σ(I)]: 0.0245 / 0.0622. R1/wR2 [all refl.]: 0.0265 / 0.0633. S = 1.047. Residual electron density between -0.40 and 0.50 e/Å^3. Geometry calculations and checking for higher symmetry was performed with the PLATON program.[18]

CCDC 969747 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

Table B. Selected bond lengths [Å] and angles [º] in the crystal structure of *R,S*-**1**[a)]

Fe1-O1	2.0870(11)	O4-Fe1-N1	99.01(4)
Fe1-O4	2.1251(10)	O4-Fe1-N2	173.48(4)
Fe1-N1	2.2321(11)	O4-Fe1-N3	93.39(4)
Fe1-N2	2.2120(11)	O4-Fe1-N4	94.78(4)
Fe1-N3	2.2076(11)	N1-Fe1-N2	77.97(4)
Fe1-N4	2.1608(11)	N1-Fe1-N3	82.23(4)
O1-Fe1-O4	85.81(4)	N1-Fe1-N4	155.32(4)
O1-Fe1-N1	98.23(5)	N2-Fe1-N3	91.93(4)
O1-Fe1-N2	88.89(4)	N2-Fe1-N4	90.12(4)
O1-Fe1-N3	179.12(4)	N3-Fe1-N4	76.58(4)
O1-Fe1-N4	103.13(5)		

[a)] For atom labelling see Figure 2 in the article

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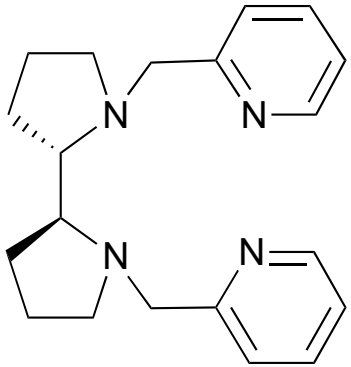
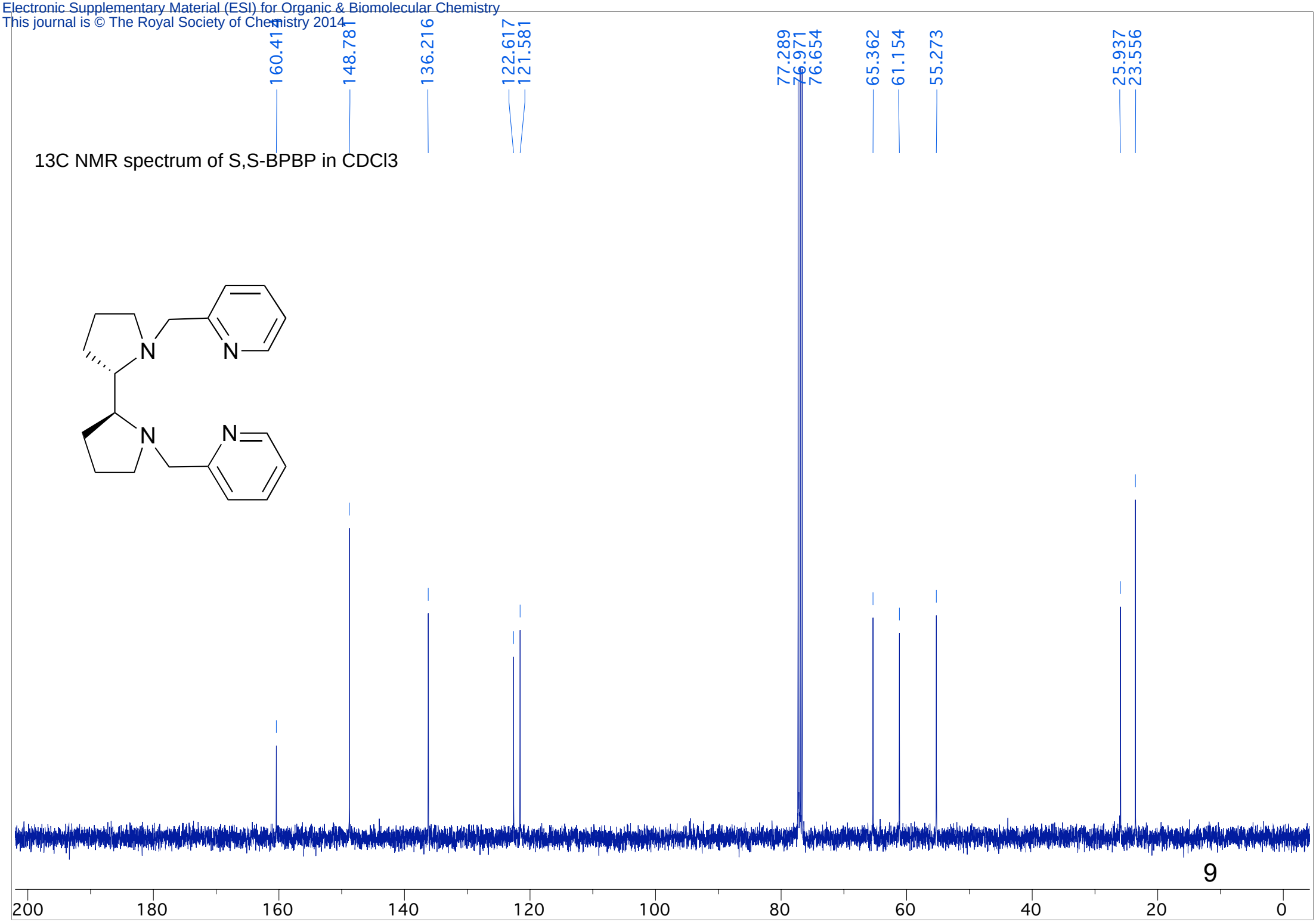
1H NMR spectrum of S,S-BPBP in CDCl3





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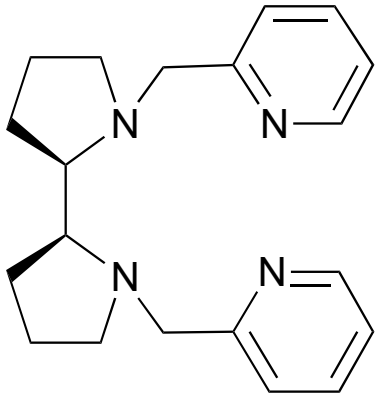
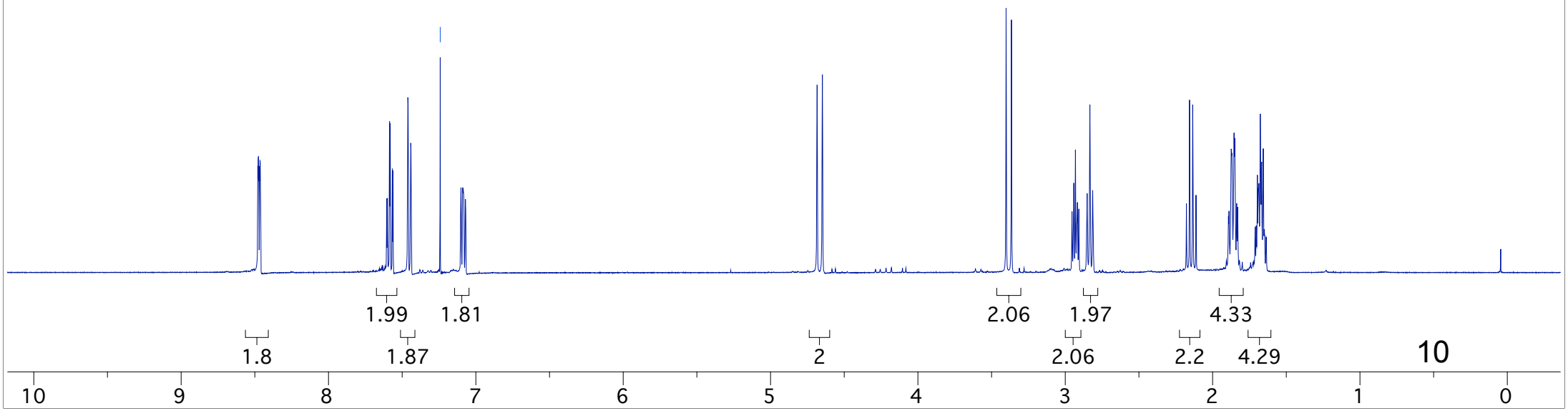
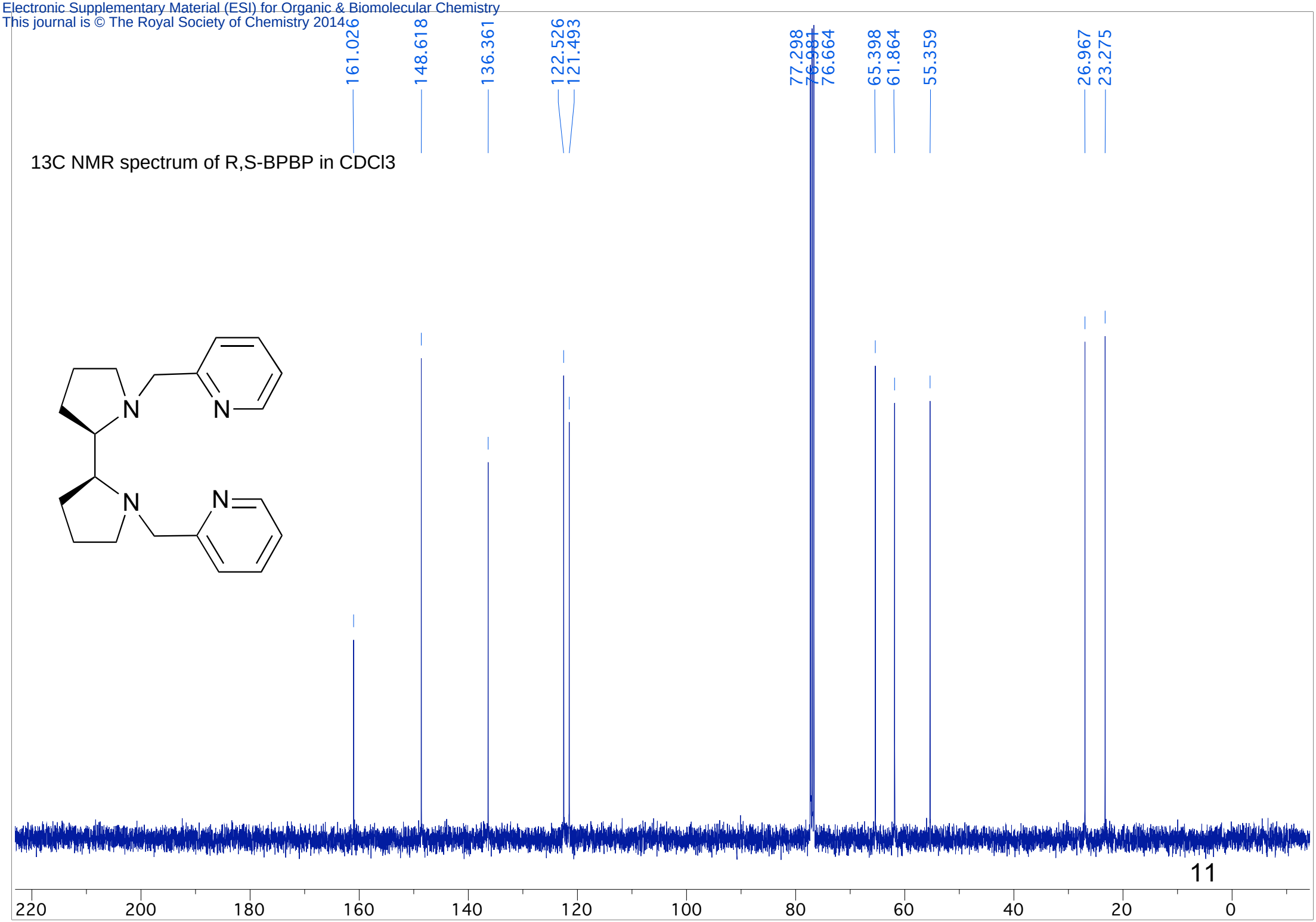
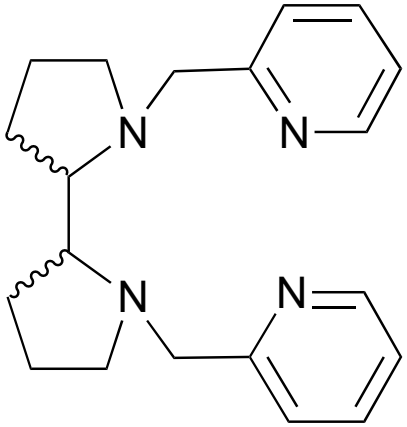
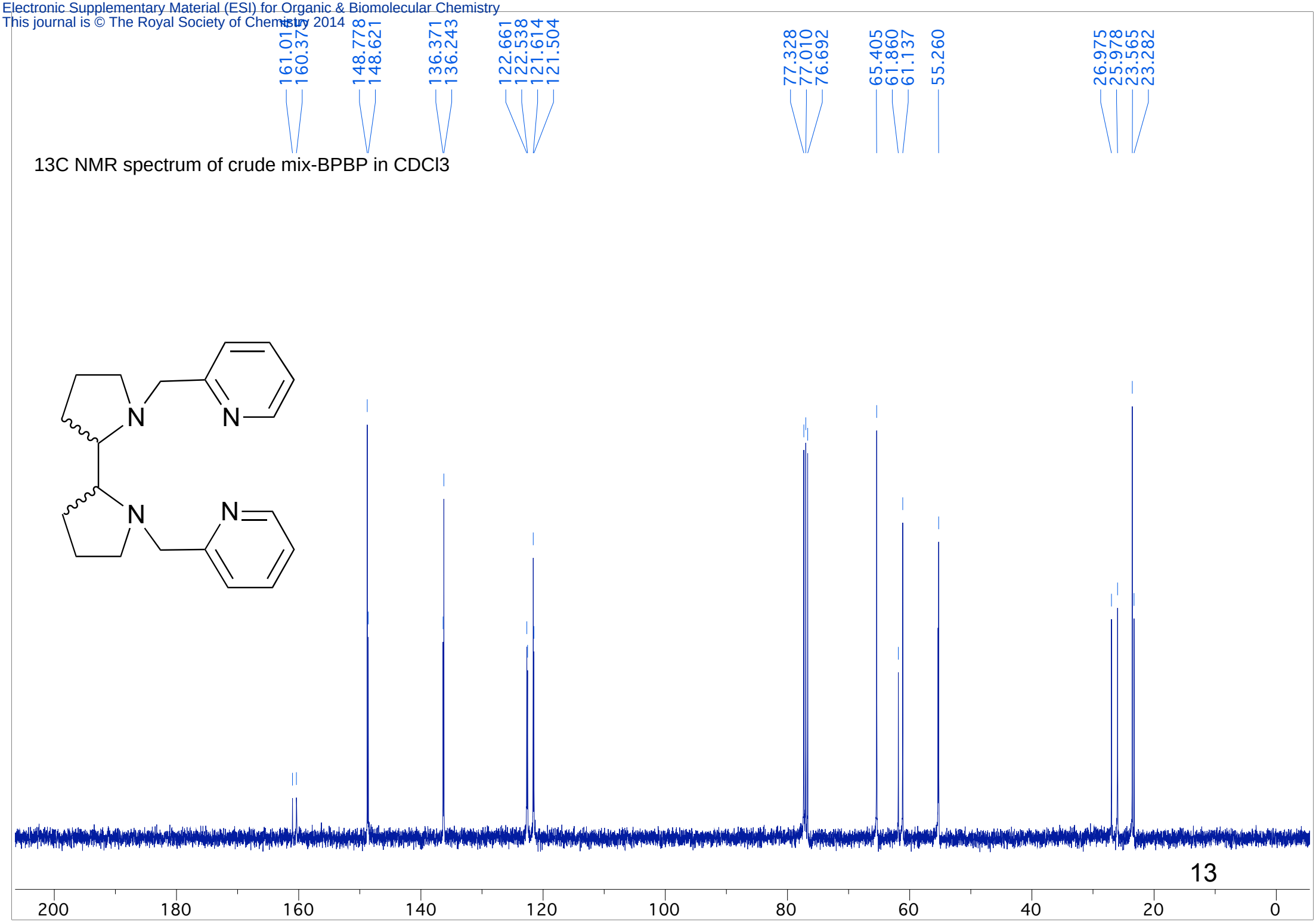




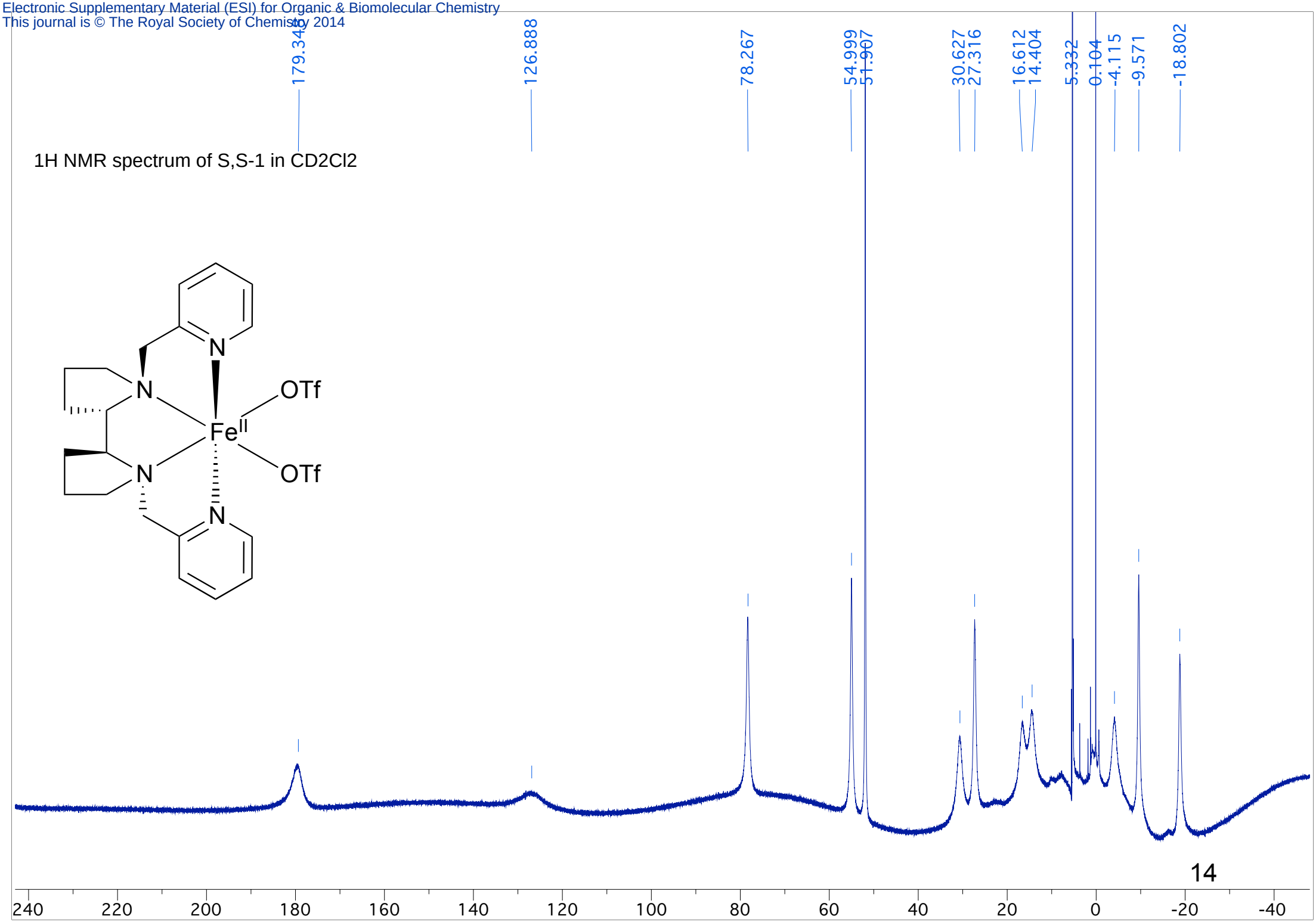


1H NMR spectrum of mix-BPBP (rac-BPBP/R,S-BPBP ca. 75/25) in CDCl3

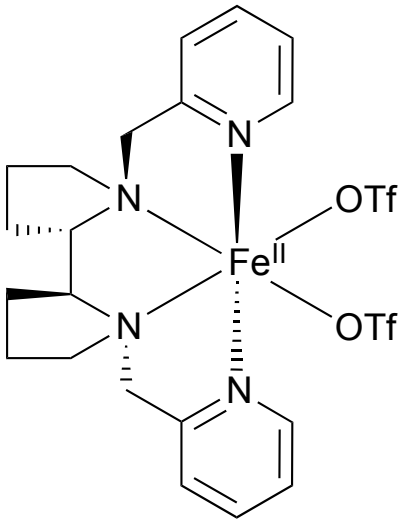




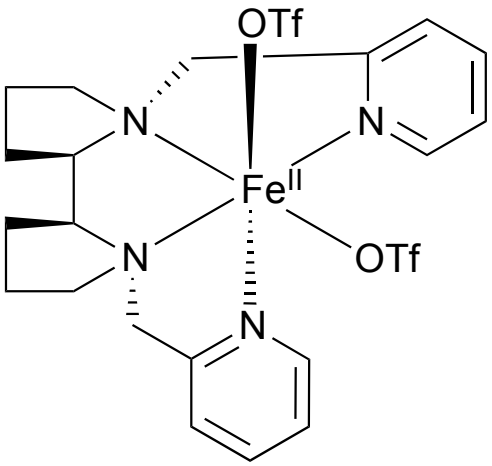
13C NMR spectrum of crude mix-BPBP in CDCl3



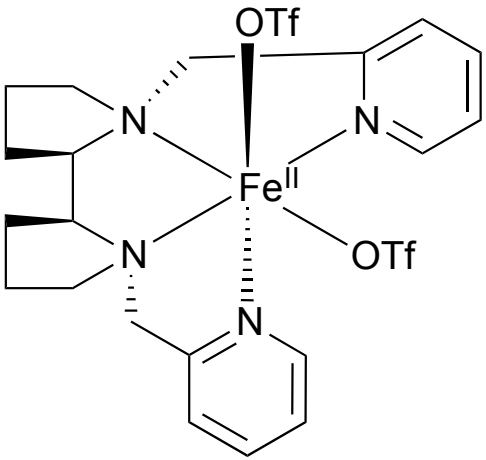
19F NMR spectrum of S,S-1 in CD2Cl2

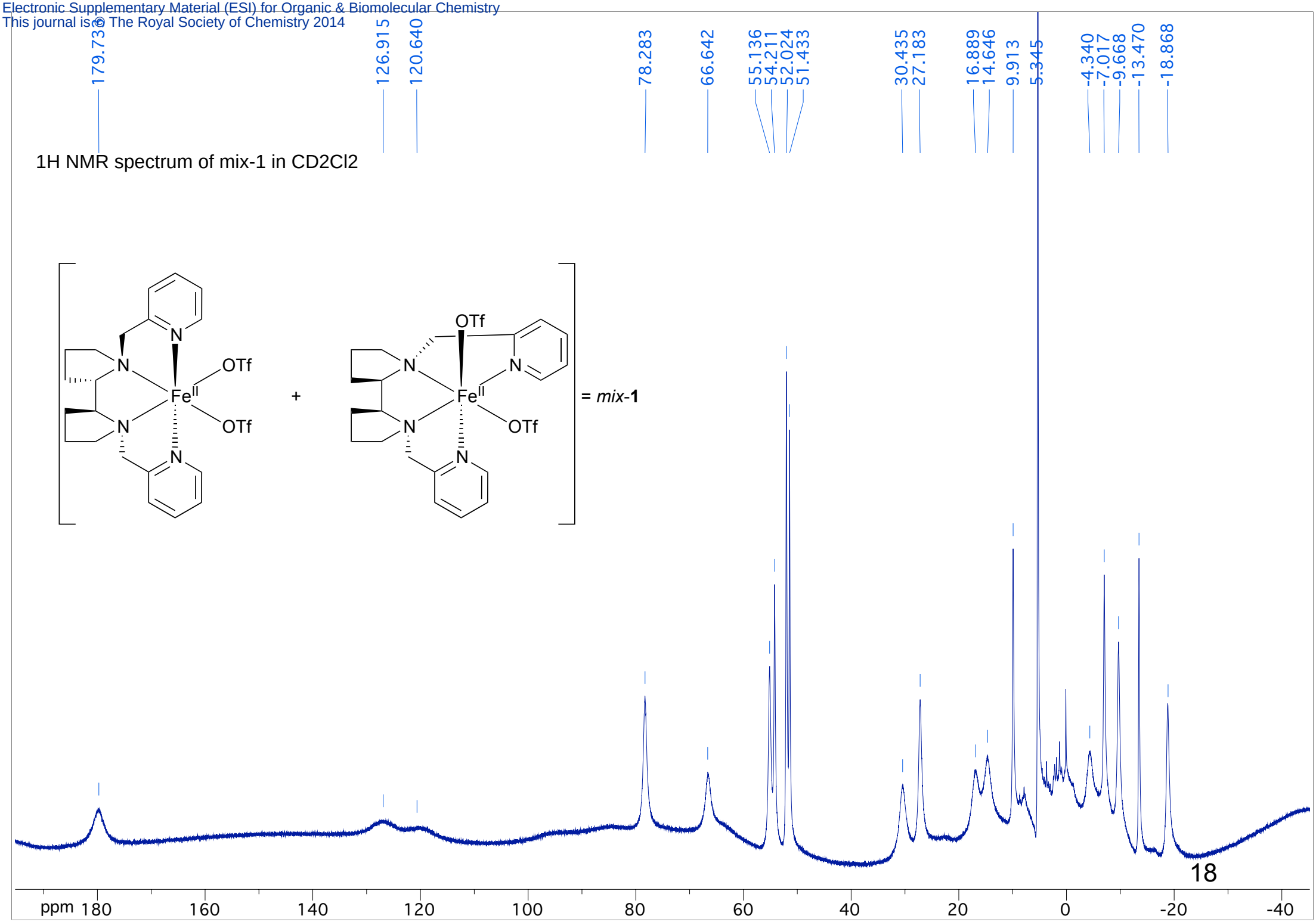


1H NMR spectrum of R,S-1 in CD2Cl2



19F NMR spectrum of R,S-BPBP in CD2Cl2





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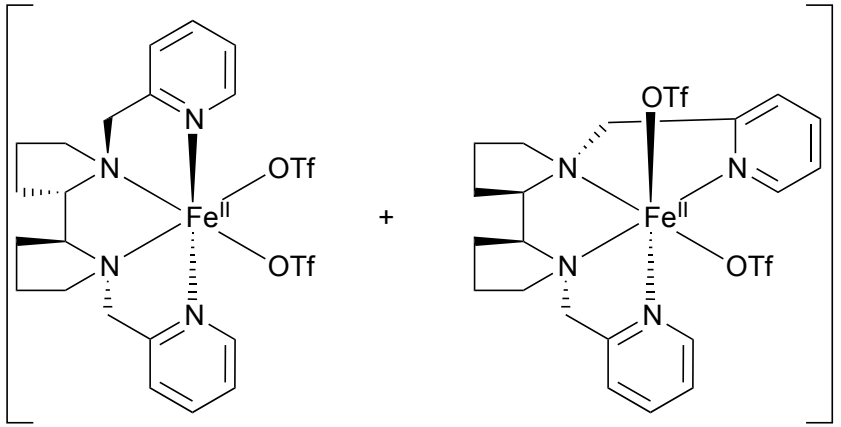
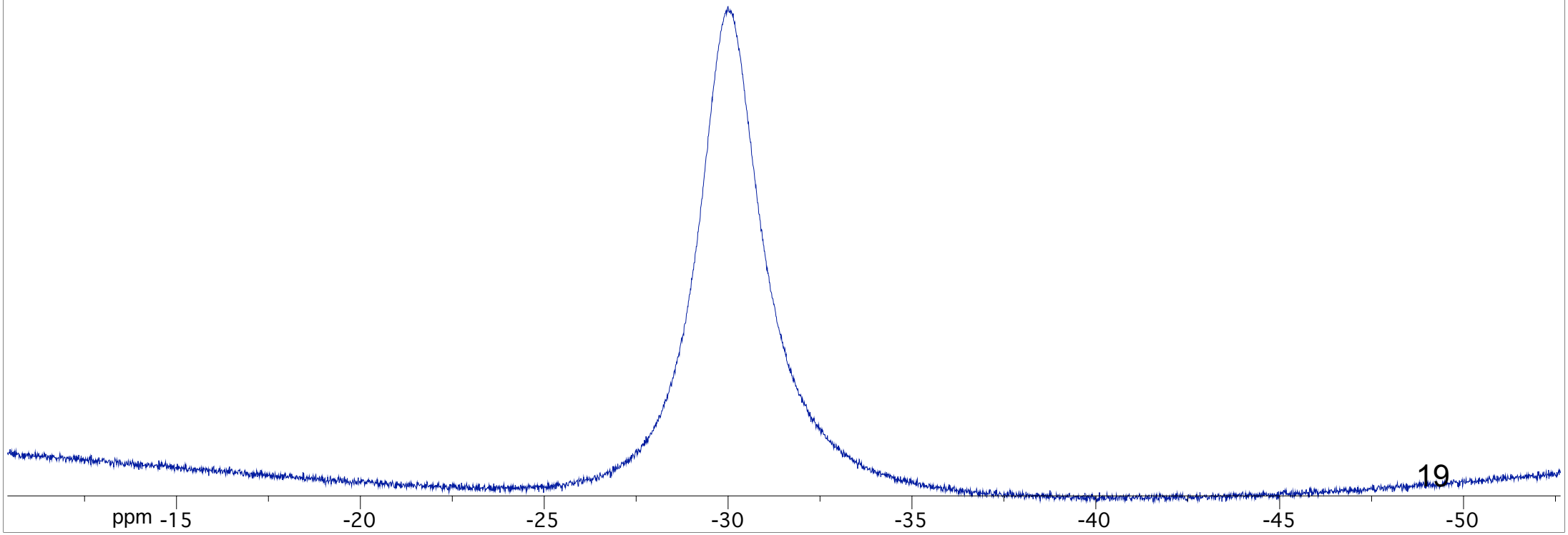
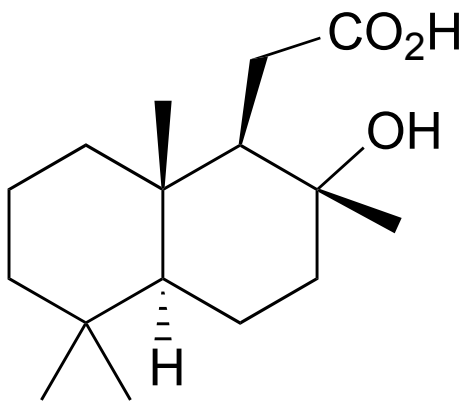
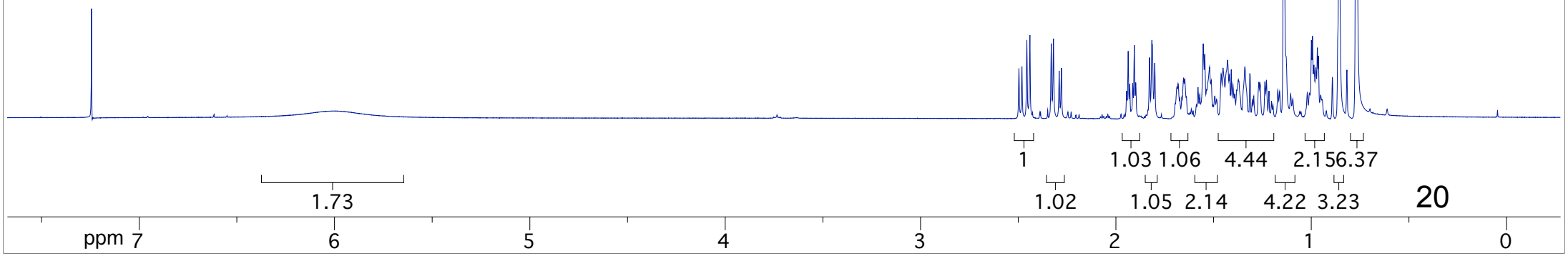


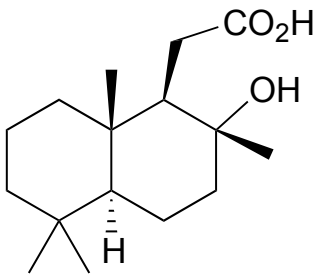


1H NMR spectrum of 8 in CDCl3

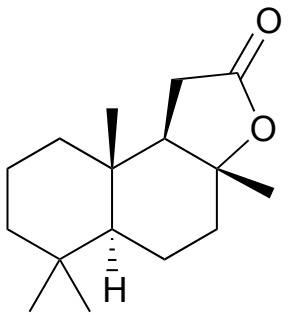




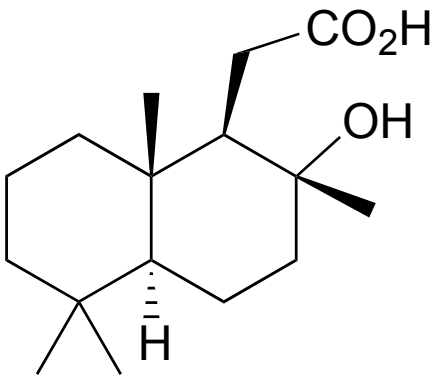
1H NMR spectrum of 28 in CDCl3 (magnification 0.0-2.8 ppm)



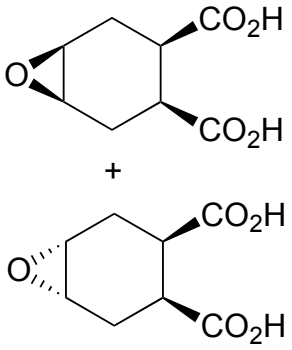
1H NMR spectrum of 8 in CDCl3 (magnification 0.0-2.8 ppm)

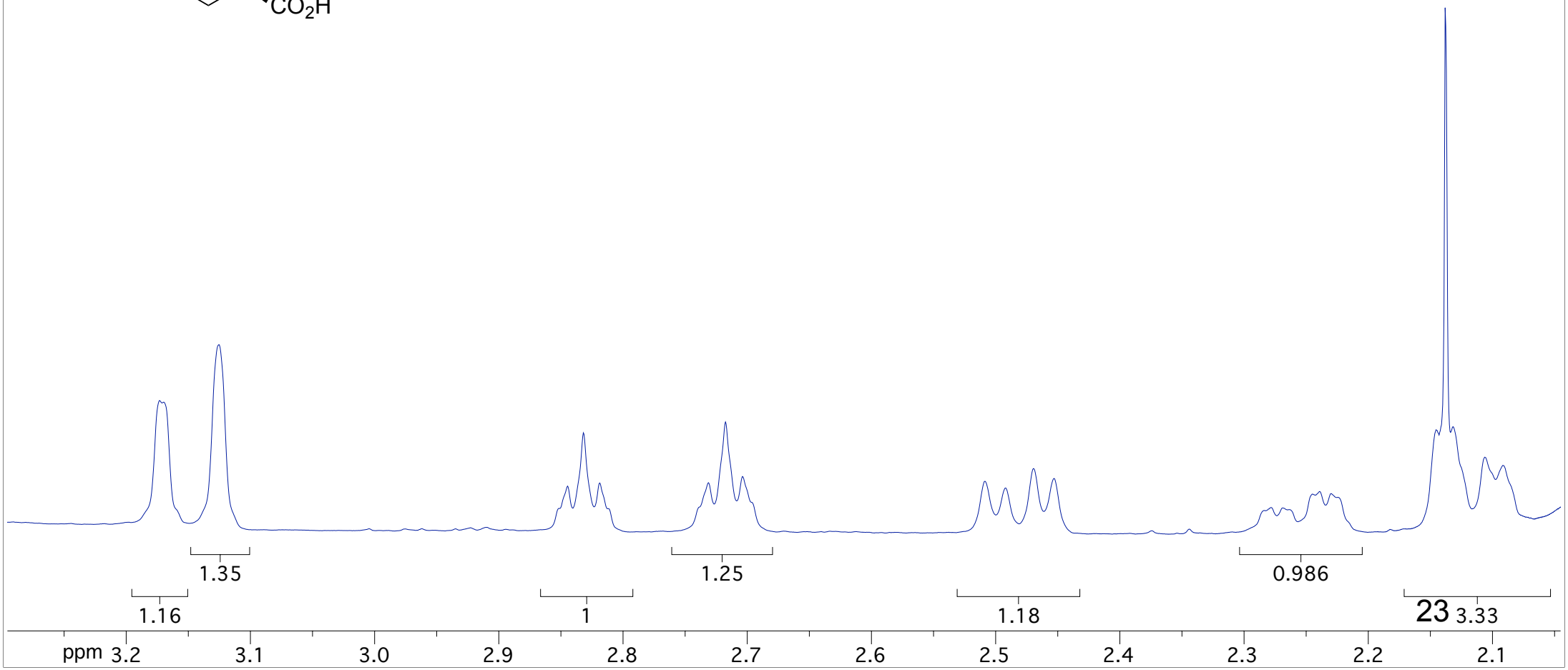


13C NMR spectrum of 28 in CDCl3

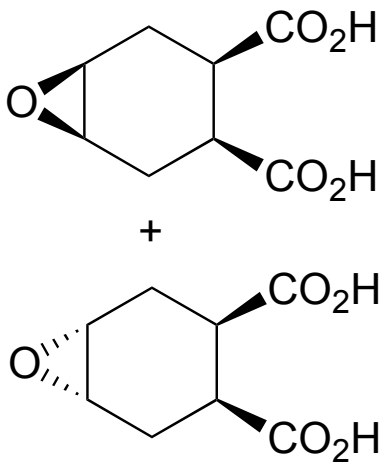


1H NMR spectrum of 44b in CD3CN





13C NMR spectrum of 44b in CD3CN



174.822
174.794
117.336
65.312
51.183
50.869
36.917
36.708
24.601
24.438
14.546
0.534
0.329
0.123
CD3CN
CD3CN
Et2O
Et2O
24
ppm 200 180 160 140 120 100 80 60 40 20 0