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t-BuOK promoted C-C bond oxidative cleavage of β-O-4 and β-1 lignin models to benzoic acids at room temperature

Liguo Wang[1 a], Miao He [1 a], Xinwei Liu[a], Lianjing Zhai[a], Lianxi Niu[a], Zilu Xue[a], Hetong Wu[a]*

Contents

1. General Experimental Methods

1.1 Materials

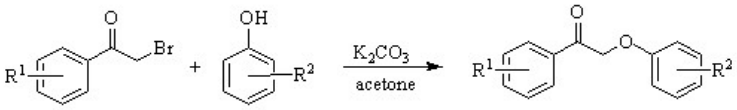
All reagents and solvents were purchased from Accela, Adamas, Innochem, Psaitong and Aladdin. Unless otherwise noted, materials obtained from commercial suppliers were used without furtherpurification.

1.2 Instrumentation

Products were purified by flashchromatography on silica gel. Analysis of crude reaction mixture was performed on an Agilent 7820A GC System with a HP-INNOWAX capillary column (30 m×0.25 mm×0.32 μm) and an FID detector. The following GC temperature program was used: 60°C is maintained for 2 minutes, rises to 150 °C at 10 °C/min, rises to 260 °C at 30 °C/min, then rises to 280 °C at 5 °C/min, and finally rises to 300°C at a rate of 20°C/min, and hold for 2 minutes.

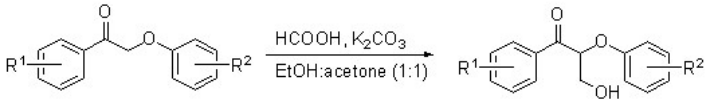
Nitrogen was used as a carrier gas. The injector temperature was held at 250 °C. GC-MS analysis was carried out on a SHIMADZU GCMS-QP2010 with a DB-5 capillary column (30 m×0.25 mm×0.32μm). ^{1}H NMR spectra were recorded in $CDCl_3$ or DMSO using internal reference (the residue proton peaks of $CHCl_3$ at 7.26 ppm and DMSO at 2.5 ppm) on Bruker 400 spectrometer. Liquid ^{13}C NMR was recorded at 100.6 MHz in $CDCl_3$ using residual $CHCl_3$ as internal reference (the residue proton peaks of $CHCl_3$ at 77.02ppm and DMSO at 40.03 ppm).

2.Synthesis of lignin models



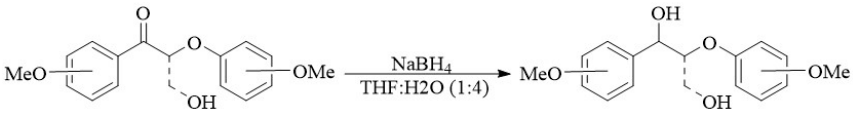
Scheme S1 synthetic ketone lignin model.

The synthesis reaction was carried out in a 150 mL round glass flask containing a condenser. 2-phenoxyacetophenone were synthesized by the reaction of the corresponding phenol with 2-bromoacetophenone according to the reported procedure.[S1] Typically, 2-bromoacetophenone (5 mmol) is dissolved in a solution of K_2CO_3 (7.5 mmol, 1.036 g) and phenol (5 mmol) in acetone (50 mL) and loaded in a reactor. The reaction mixture is then stirred at reflux temperature for 5 hours, filtered and vacuumized. The residue was purified by column chromatography with hexane: ethyl acetate a stirring. For the other methoxy substituted 2-phenoxy-1-phenylethanone, the preparation procedure is the same as described above, except of using different stating materials.



Scheme S2 synthetic 3-hydroxy-2-phenoxy-1-phenylpropan-1-one.

To a stirring suspension of K_2CO_3 (0.6 g, 4.3 mmol) in ethanol/acetone (v/v=1/1, 20 mL) and 2-phenoxyacetophenones (0.78 g, 4 mmol) at rt., a water solution of formaldehyde (36.5~38 wt %, 0.6 mL, 7.3 mmol) was added. After 4 h, the reaction mixture was filtered to remove K_2CO_3 and concentrated in vacuo to get a solid product. The crude product was purified with petroleum ether: ethyl acetate (3:1) to obtain the required 2-phenoxyacetophenone, on silica gel to obtain 3-hydroxy-1,2-diphenylpropan-1-one in 90% yield.



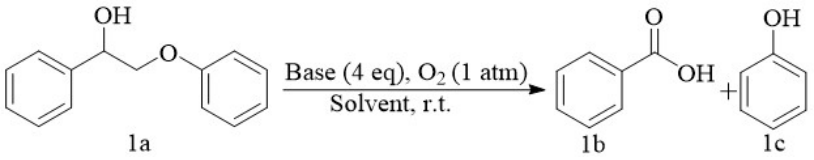
Scheme S3 synthetic lignin model compounds.

The resulting compound (3.5 mmol, 0.847 g) was dissolved in the mixture of THF: H_2O (5:1) (25 mL), and sodium borohydride (7 mmol, 0.26 g) was added portionwise to maintain a gentle evolution of gas. Then, the mixture was stirred for 6 h at room temperature. The reaction mixture was quenched with saturated aqueous NH_4Cl (50 mL) and diluted with 30 mL water. The aqueous portion was extracted with ethyl acetate (3×30 mL). The organic parts were combined, dried over $MgSO_4$, filtered and concentrated under vacuum. The residue was purified by column chromatography with hexane:ethyl acetate (2:1)

3.Screening of Reaction Conditions

3.1Screening of parameters for oxidative cleavage of lignin model compound.

Table S1 Screening of parameters for oxidative cleavage of lignin model compound.



Entry	Base	Solvent	Conv. (%)
1	^{t}BuOK	1,4-Dioxane	99
2	K_2CO_3	1,4-Dioxane	64
3	Na_2CO_3	1,4-Dioxane	43
4	$BaCO_3$	1,4-Dioxane	9
5	KOH	1,4-Dioxane	11
6	NaOH	1,4-Dioxane	16
7	^{t}BuOK	THF	98
8	^{t}BuOK	CH_2Cl_2	96
9	^{t}BuOK	Toluene	97
10	^{t}BuOK	Methanol	88
11	^{t}BuOK	H_2O	0
12[a]	^{t}BuOK	1,4-Dioxane	78
13[b]	^{t}BuOK	1,4-Dioxane	22
14[c]	^{t}BuOK	1,4-Dioxane	85

General conditions: 1a (0.5 mmol), Base (4 equiv), solvent (2 mL), O_2 (1 atm). 18-Crown-6 (2 equiv)，30°C, 15h. [a]Without 18-Crown-6, [b]N_2 instead of O_2, [c]air instead of O_2. GC conversion using dodecane as internal standard.

Table S2 Effect of temperature on reaction.

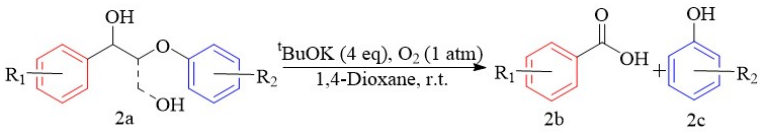
Entry	Temperature °C	Conv. (%)	Yields of 1b(%)	Yields of 1c(%)
1	30	88	69	83
2	50	92	83	90
3	65	95	88	92
4	80	99	73	89
5	100	99	38	72

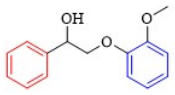
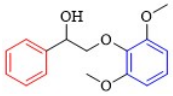
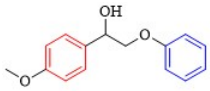
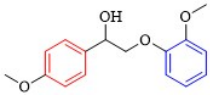
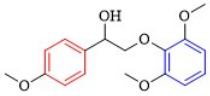
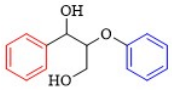
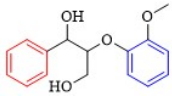
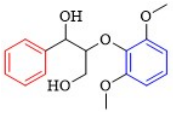
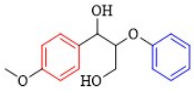
Reaction time 12 h, the other reaction conditions are the same as Table s1.

After the reaction, the reaction mixture was treated with HCl with pH=1, extracted with CH_2Cl_2, and the organic phase was purified by column chromatography.

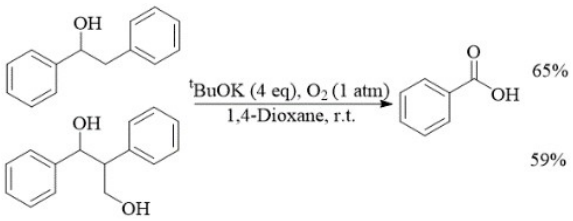
3.2 Reaction scope.

Table S3 Reaction scope.



Entry	Substrate	Yields of 2b(%)	Yields of 2c(%)	Conv. (%)
1		68	65	83
2		83	73	87
3		86	84	97
4		80	77	91
5		83	73	87
6		65	82	87
7		88	83	91
8		81	78	88
9		66	67	79

General conditions: 2a (0.5 mmol), ^{t}BuOK (4 equiv), 18-Crown-6 (2 equiv), 1,4-Dioxane (2 mL), O_2 (1 atm), room temperature(30°C), 15h.

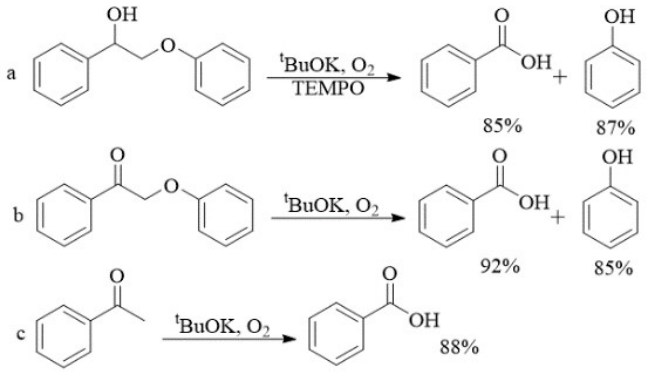


Scheme S4 Transformation of β-1 lignin model compounds.

General conditions: β-1 model compound (0.5 mmol), ^{t}BuOK (4 equiv), 18-Crown-6 (2 equiv),1,4-Dioxane (2 mL), O_2 (1 atm), room temperature, 15h.

4. Mechanistic Experiments

4.1 Control experiments



Scheme S5 The control experiments.

General conditions: substrate (0.5 mmol), ^{t}BuOK (4 equiv), 18-Crown-6 （2 equiv）, 1, 4-Dioxane (2 mL), TEMPO (1 eq), room temperature (30°C), 15h.

4.2Electron paramagnetic resonance (EPR) spectroscopy experiments

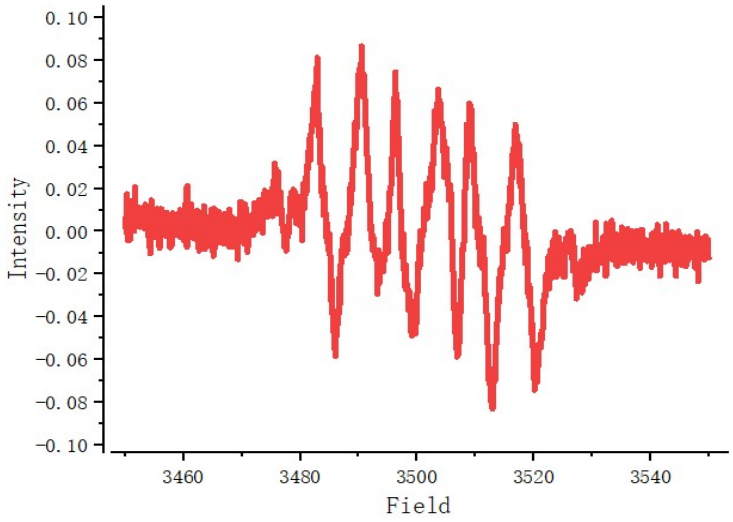


Figure S1 EPR examinations

EPR conditions: Center Field: 3500.00 G, Sweep Width:100.0 G, Power: 6.325 mW, Power Atten:15.0 dB Frequency Mon: 9.830200 GHz, Sweep Time: 30.00 s, Mod Amp 1.000 GHz, Mod Freq: 100.00 kHz.

Direct reactive oxygen species (ROS) detections were performed on an electron paramagnetic resonance spectrometer. The experimental details are described as follows:2-Phenoxy-1-phenyl-ethanol (0.5 mmol), ^{t}BuOK (4

equiv), 18-Crown-6 (2 equiv), 1,4-Dioxane (2 mL), Stir for two hours at room temperature, take 30ul of sample, add 30ul of DMPO (200mM methanol as solvent), mix evenly, absorb a certain amount of mixture with capillary tube, cover it with quartz tube, and put it into EPR sample chamber for free radical test.

4.3Detection of reaction intermediates

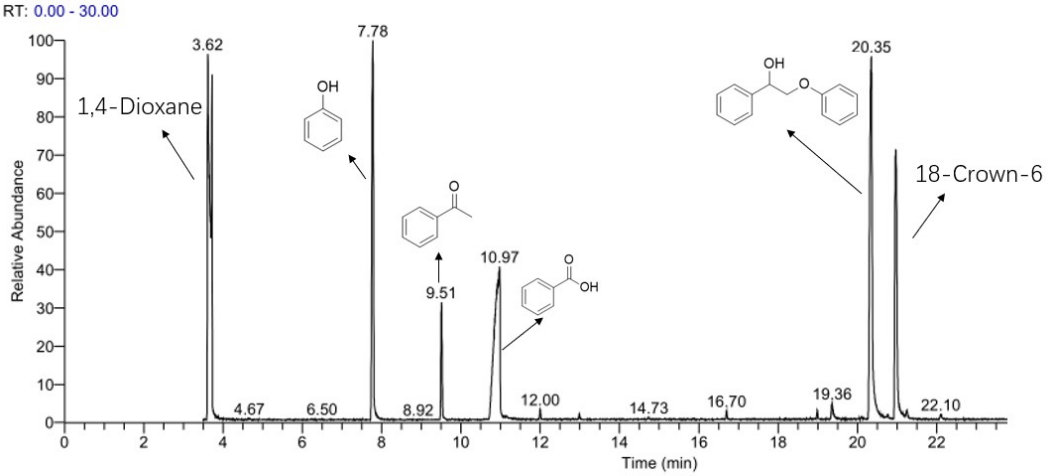


Figure S2 GC detection of intermediate products

Reaction conditions: substrate (0.5 mmol), ^{t}BuOK (4 equiv), 18-Crown-6 （2 equiv）, 1, 4-Dioxane (2 mL), room temperature (30°C), Take samples after reaction for 5 hours for GC detection.

5. Degradation of real lignin

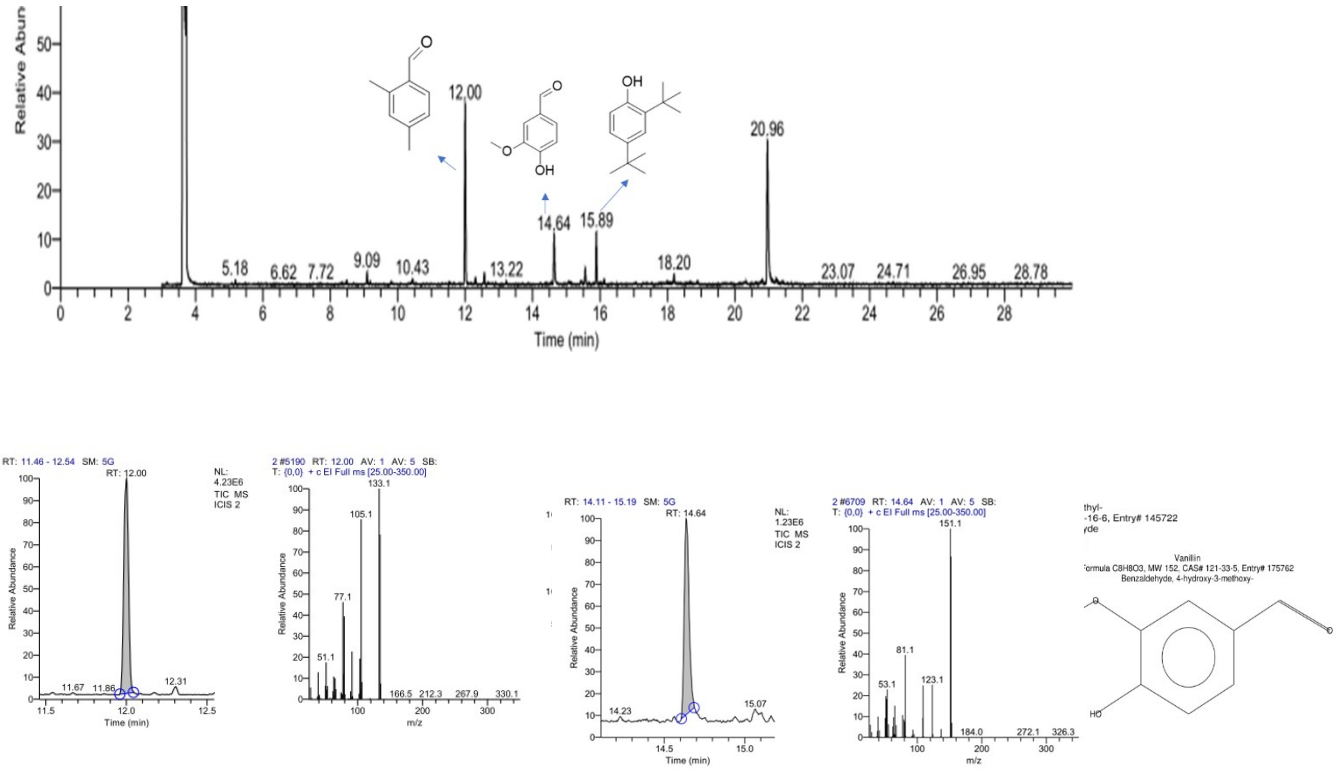
5.1 Extraction of lignin

We charged a round bottom flask with 10.3 g poplar sawdust, 50 mL 1,4-dioxane, and 1.75 mL HCl (37 wt %), and heated to reflux at 85 °C in an oil bath for 3 h. After cooling to RT, the mixture was added with 3.36 g sodium bicarbonate ($NaHCO_3$), stirred for another 30 min, after which it was filtered and washed with 10 mL of dioxane. Then the solution was concentrated at 40 °C under reduced pressure. The resulting dark-brown oil was diluted with 30 mL ethyl acetate (EtOAc) and added dropwise to 500 mL of hexane to precipitate the lignin. After filtration, the collected lignin was washed with hexane (50 mL). The recovered lignin was dried overnight at RT in a desiccator to afford 1.36 g poplar lignin.[2]

5.2 Depolymerization of lignin

Dissolve 107 mg poplar lignin, 227 mg t-BuOK, 279 mg 18-Crown-6 in 2 mL 1,4-Dioxane in a 10 mL Eggplant shaped flask. React at room temperature and 1 atm O_2 atmosphere for 15 hours. After the reaction, acidify with alkenyl hydrochloric acid and extract with CH_2Cl_2. The reaction products were detected by GC-MS.

5.3 GC-MS analysis



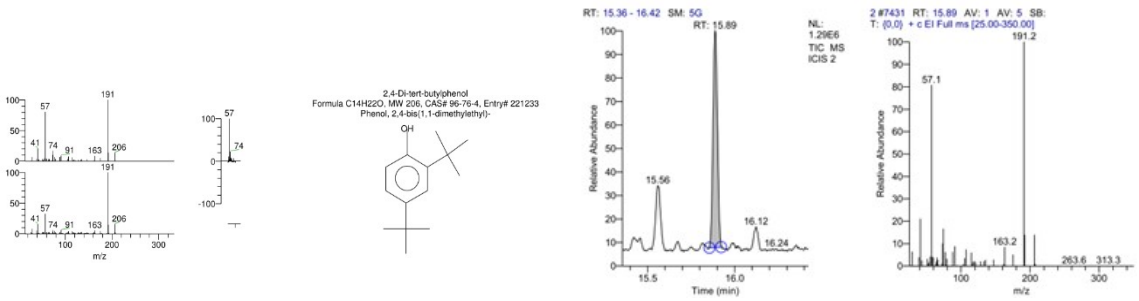


Figure S3 GC-MS analysis of natural lignin depolymerization.

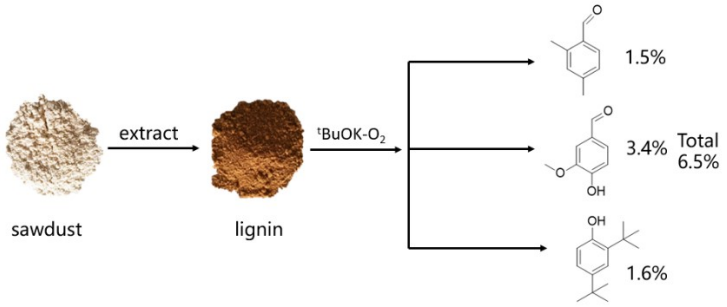


Figure S4 ^{t}BuOK-O_2 depolymerization of natural lignin.

6. ^{1}H NMR and ^{13}C NMR spectra of compounds

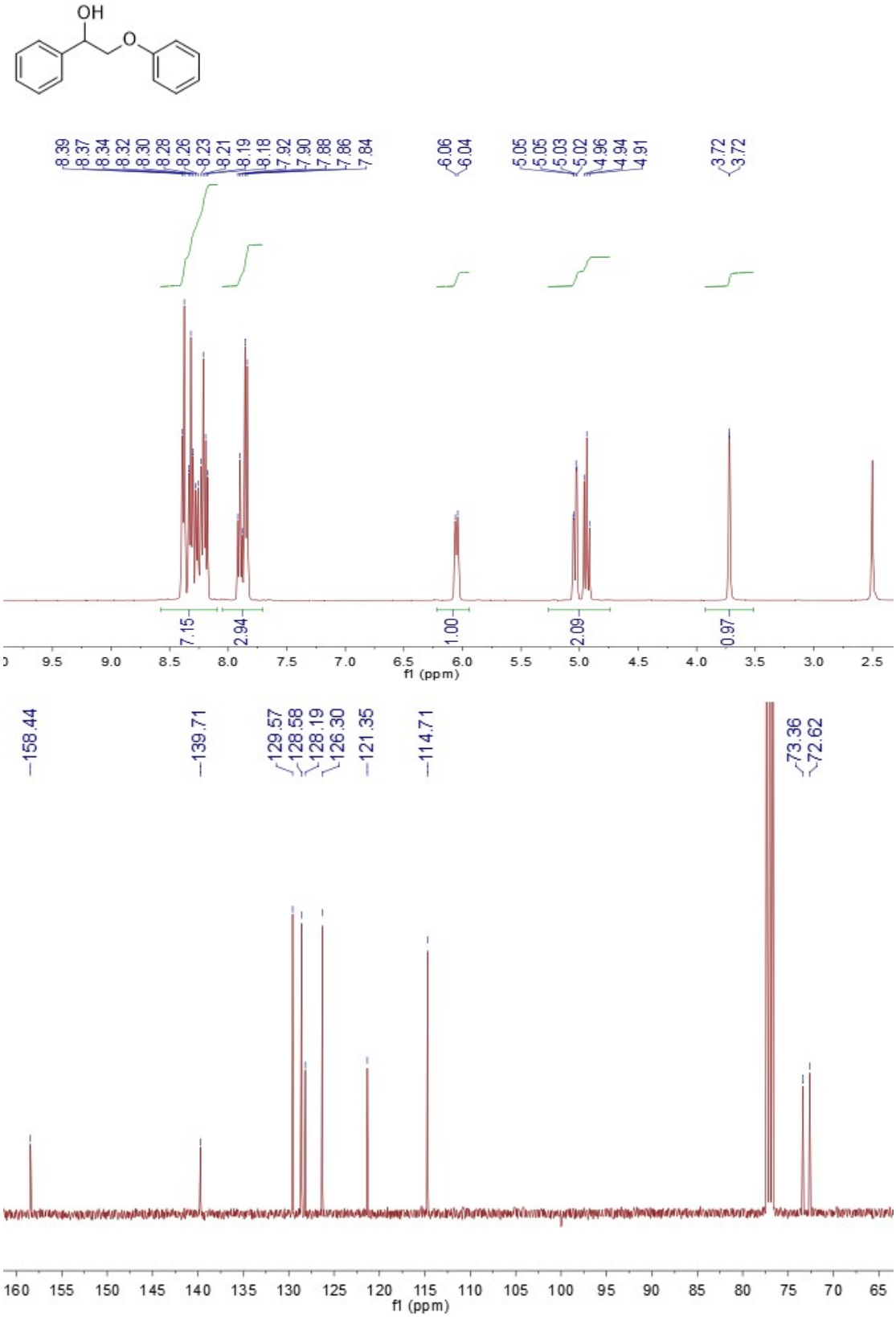


Figure S5^{1}H (top) and ^{13}C (bottom) NMR spectra of 2-Phenoxy-1-phenyl-ethanol.

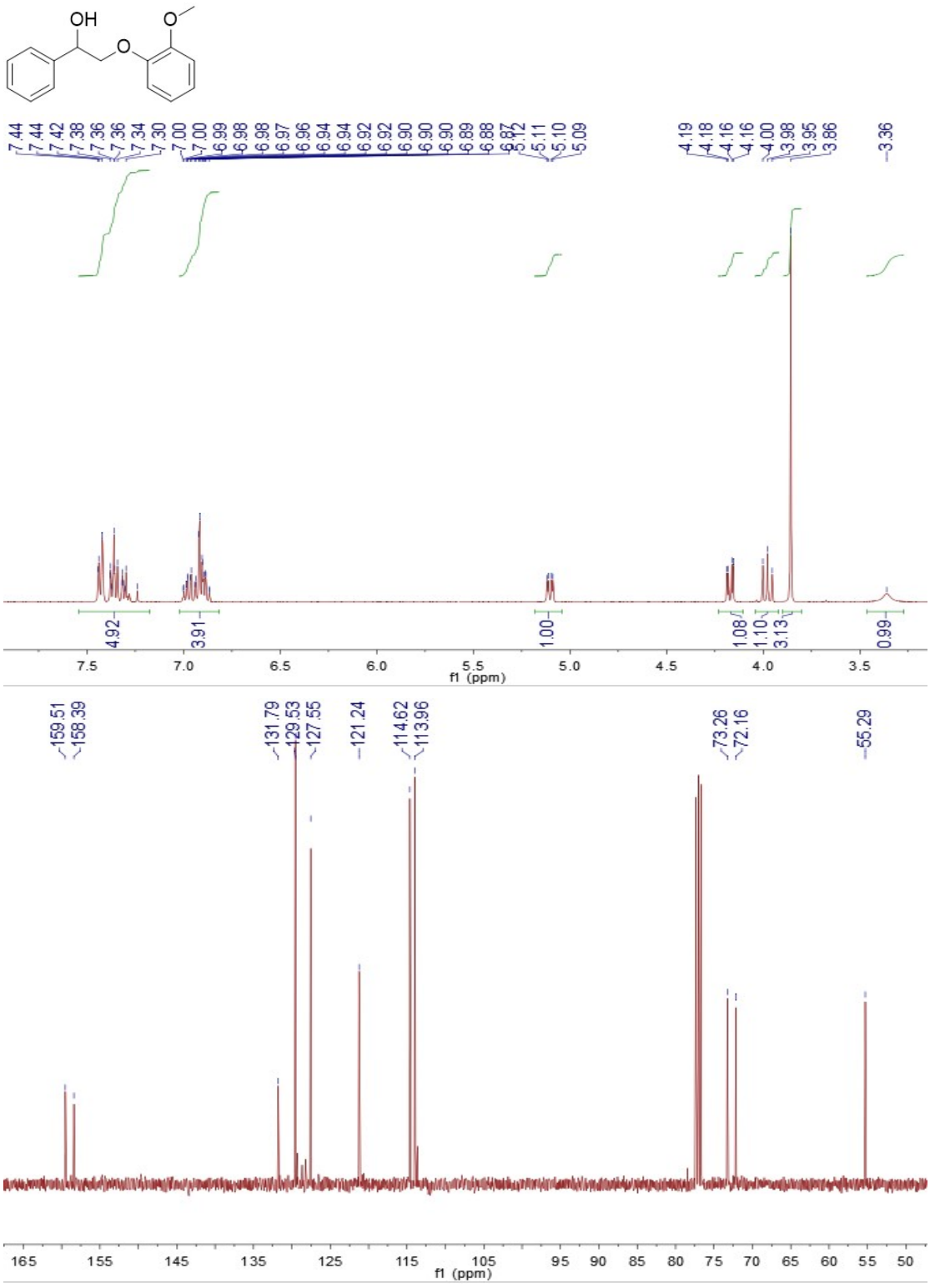


Figure S6 ^{1}H (top) and ^{13}C (bottom) NMR spectra of 2-(2-methoxyphenoxy)-1-phenylethan-1-ol.

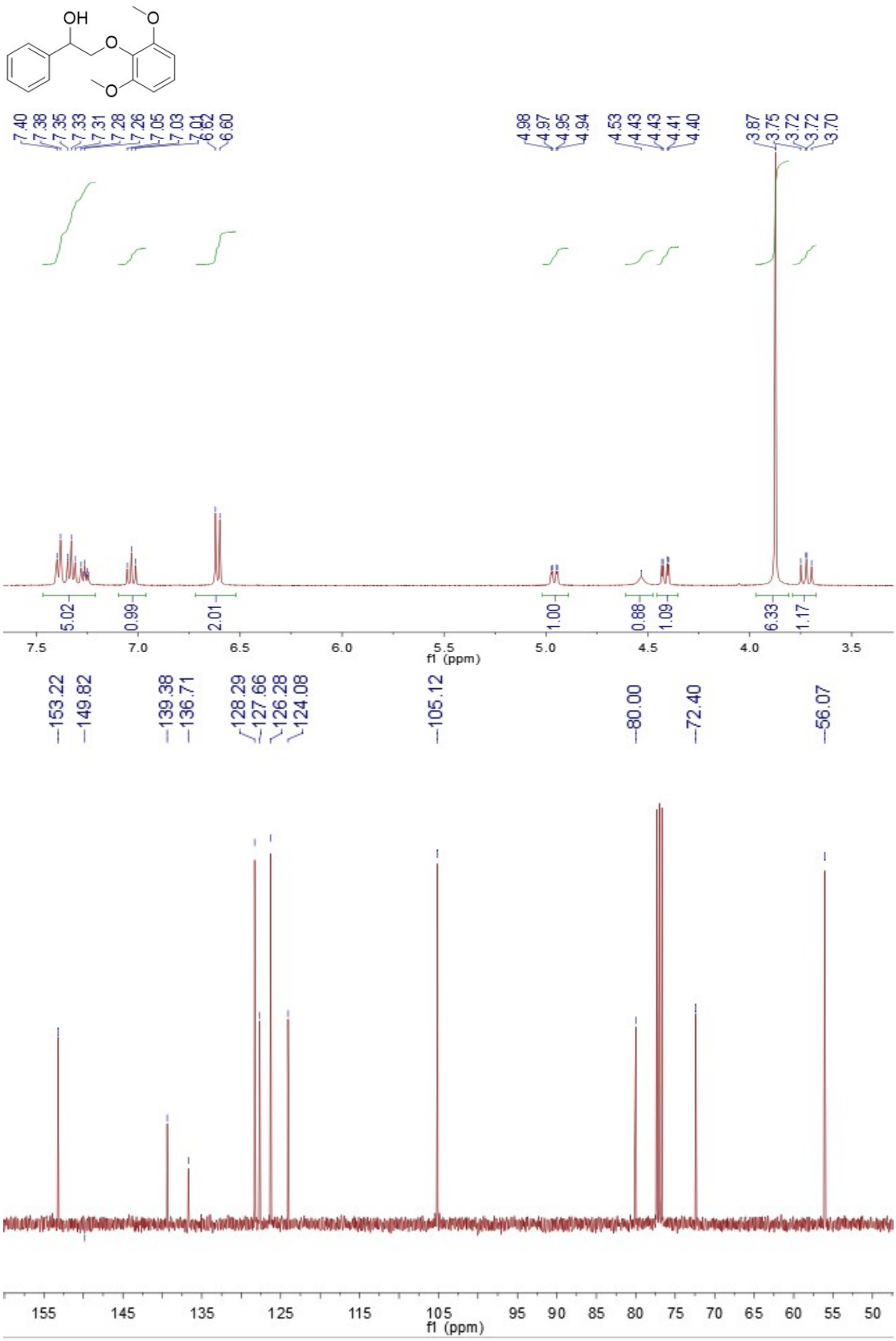


Figure S7[1]H (top) and [13]C (bottom) NMR spectra of 2-(4-chlorophenoxy)-1-phenylethan-1-ol.

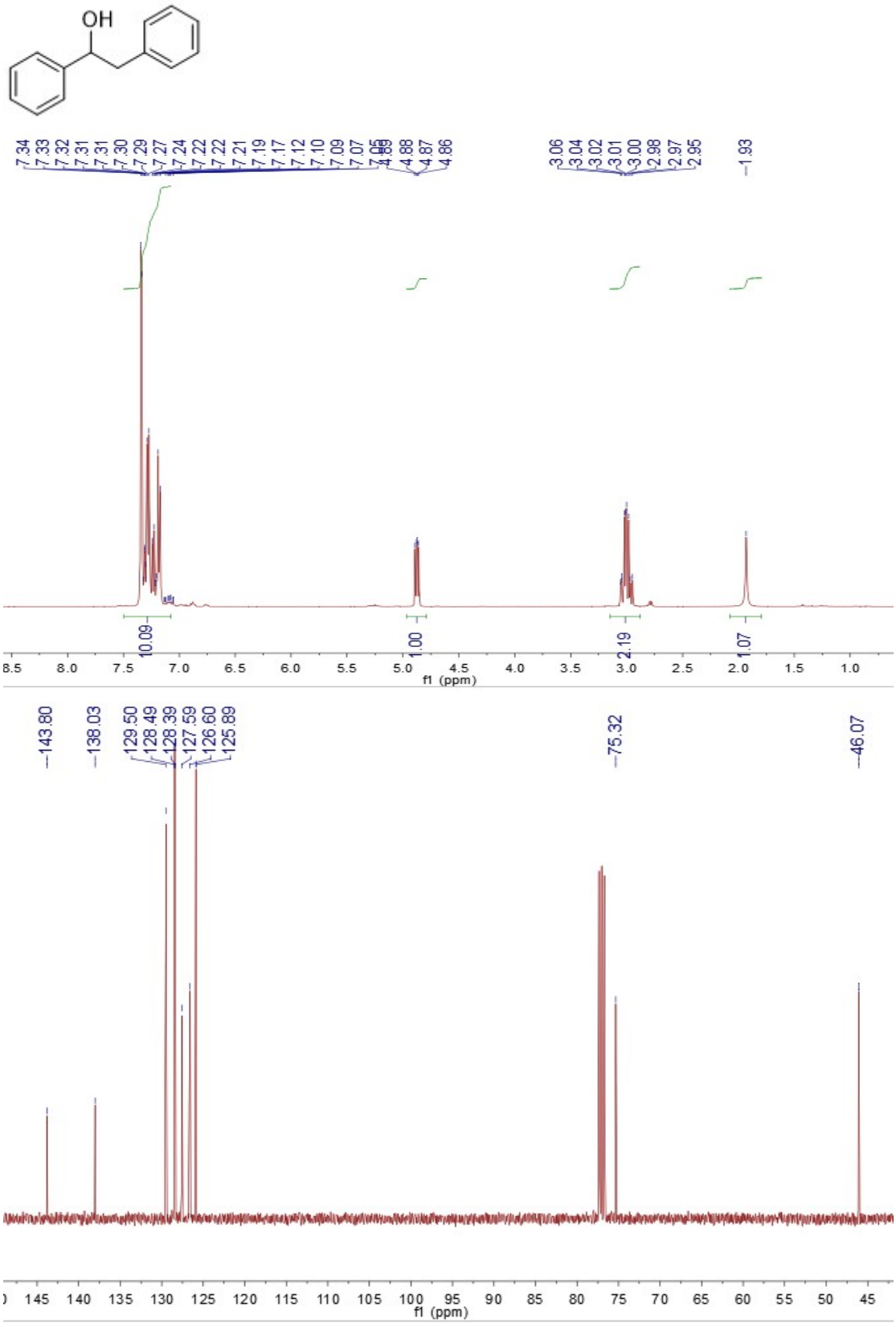


Figure S8[1]H (top) and [13]C (bottom) NMR spectra of 1,2-diphenylethan-1-ol.

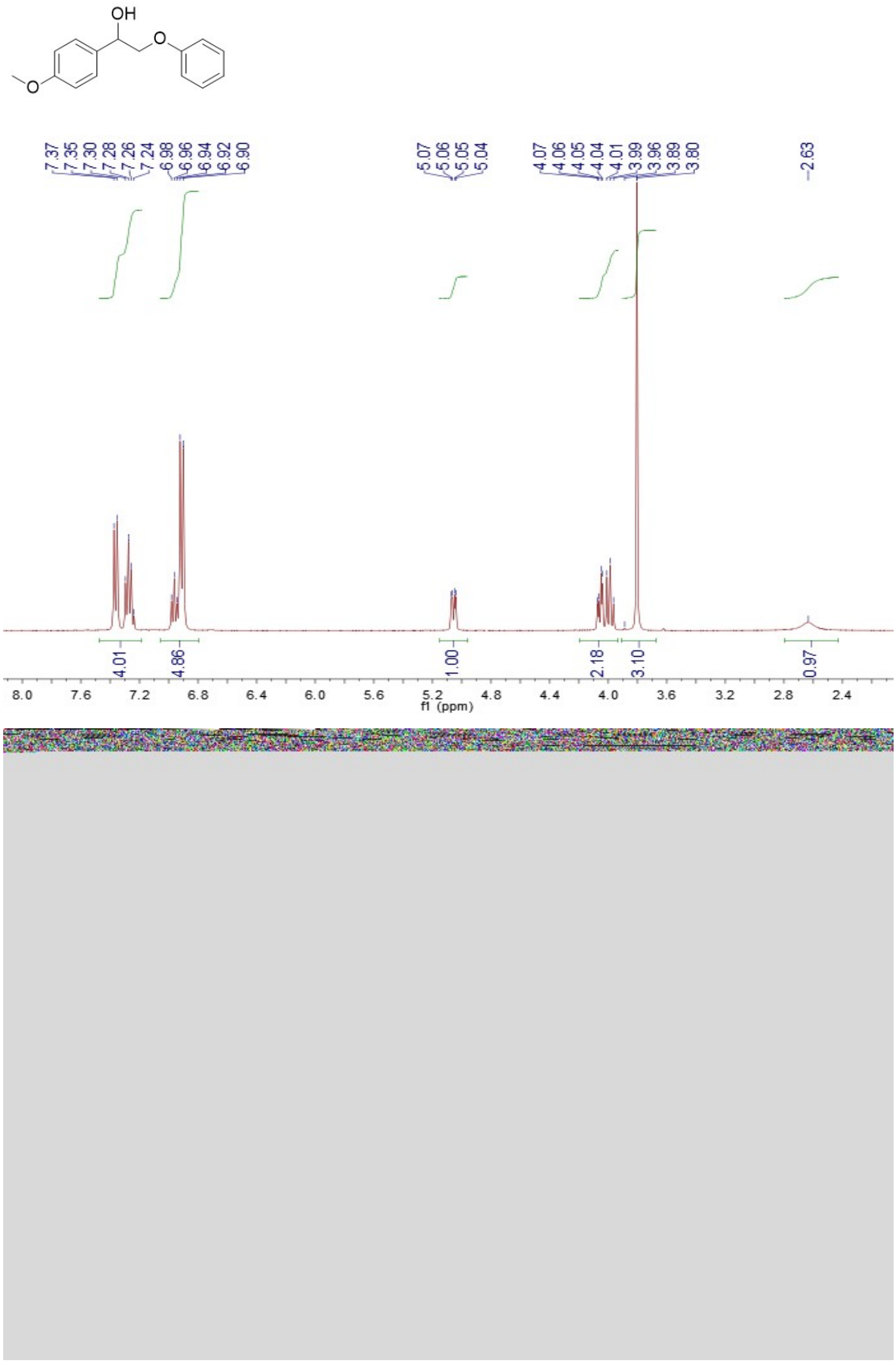


Figure S9[1]H (top) and [13]C (bottom) NMR spectra of 1-(4-methoxyphenyl)-2-phenoxyethan-1-ol.

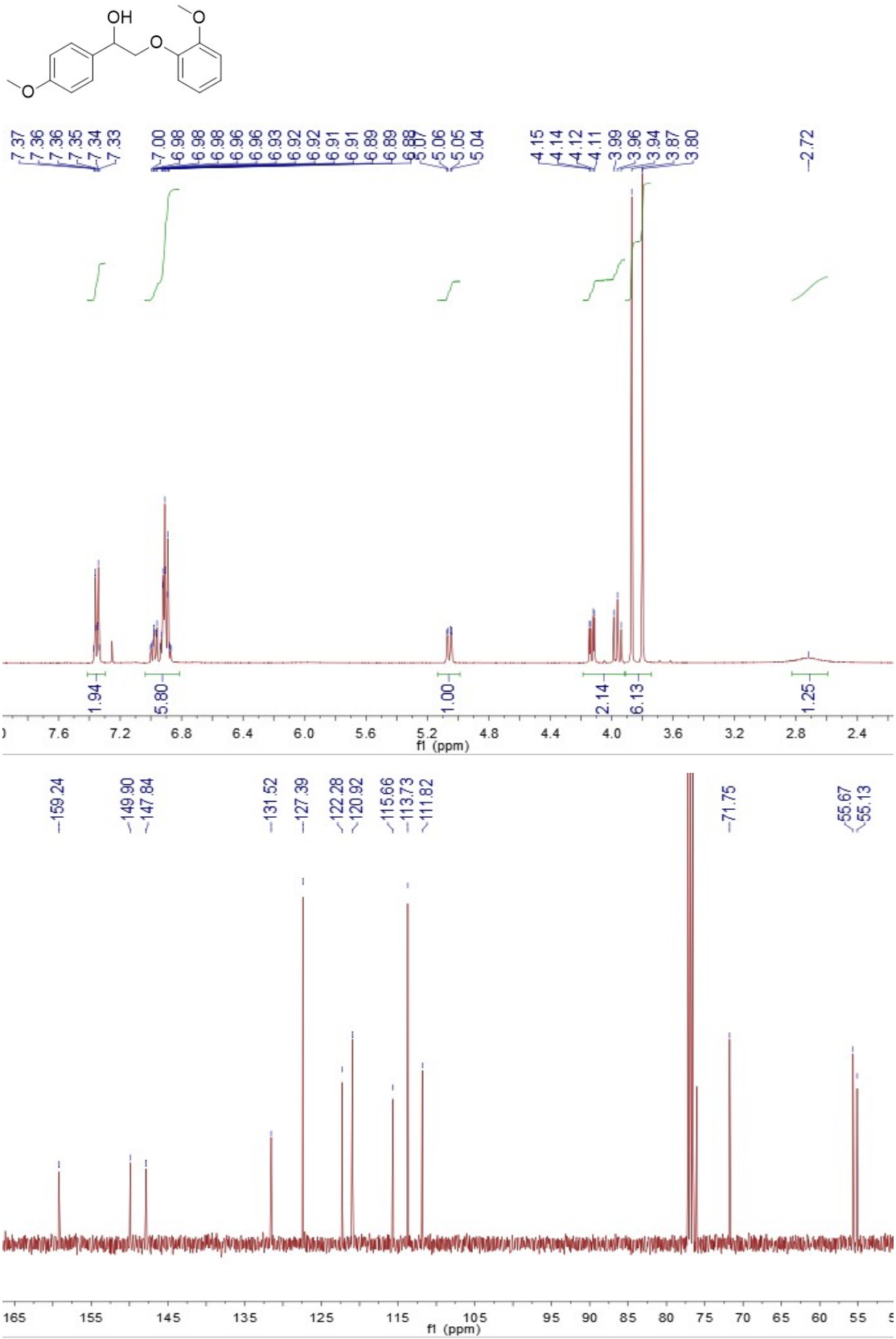


Figure S10 ^{1}H (top) and ^{13}C (bottom) NMR spectra of 2-(2-methoxyphenoxy)-1-(4-methoxyphenyl)ethan-1-ol.

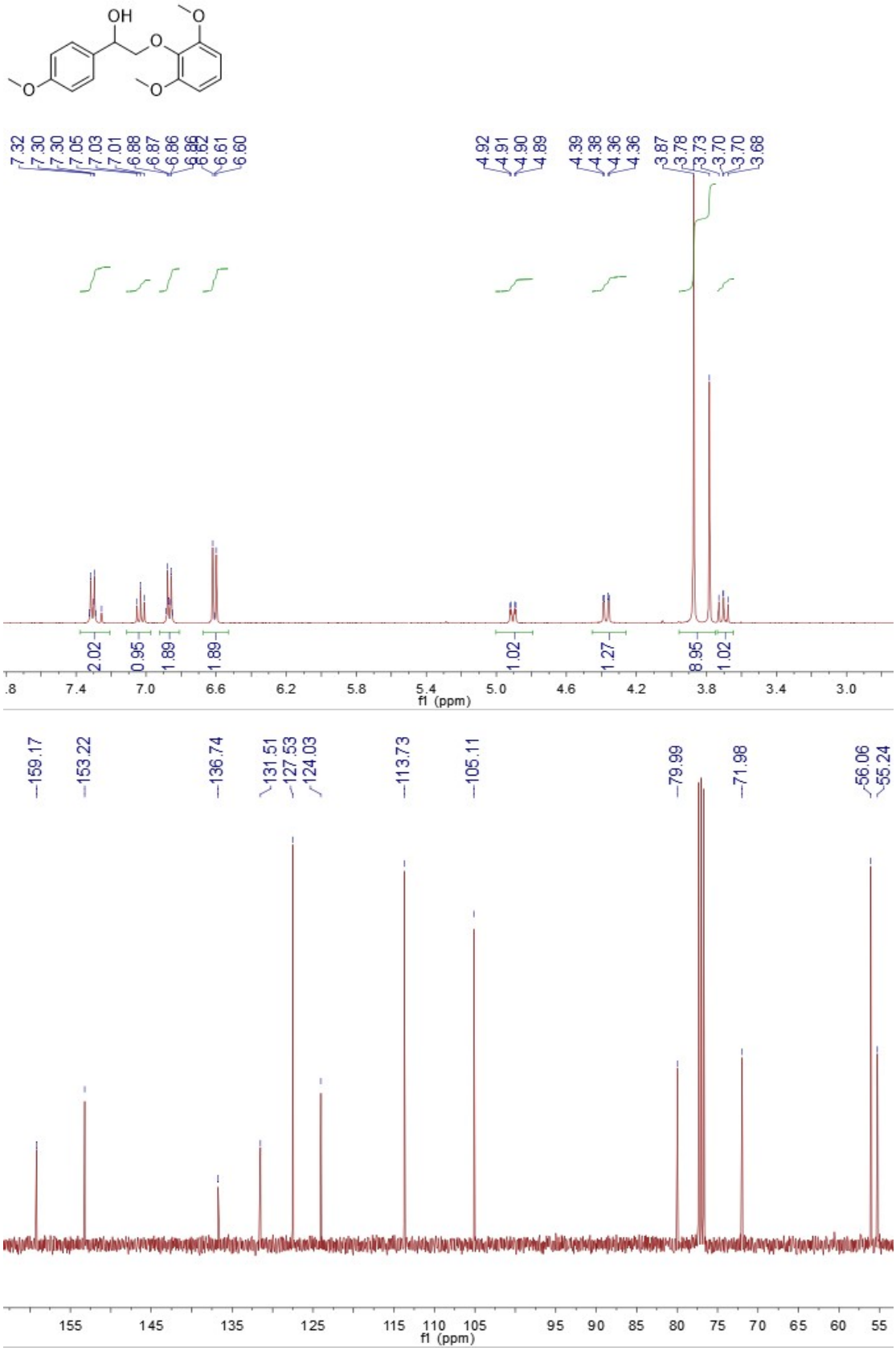


Figure S11 ^{1}H (top) and ^{13}C (bottom) NMR spectra of 2-(2,6-dimethoxyphenoxy)-1-(4-methoxyphenyl)ethan-1-ol.

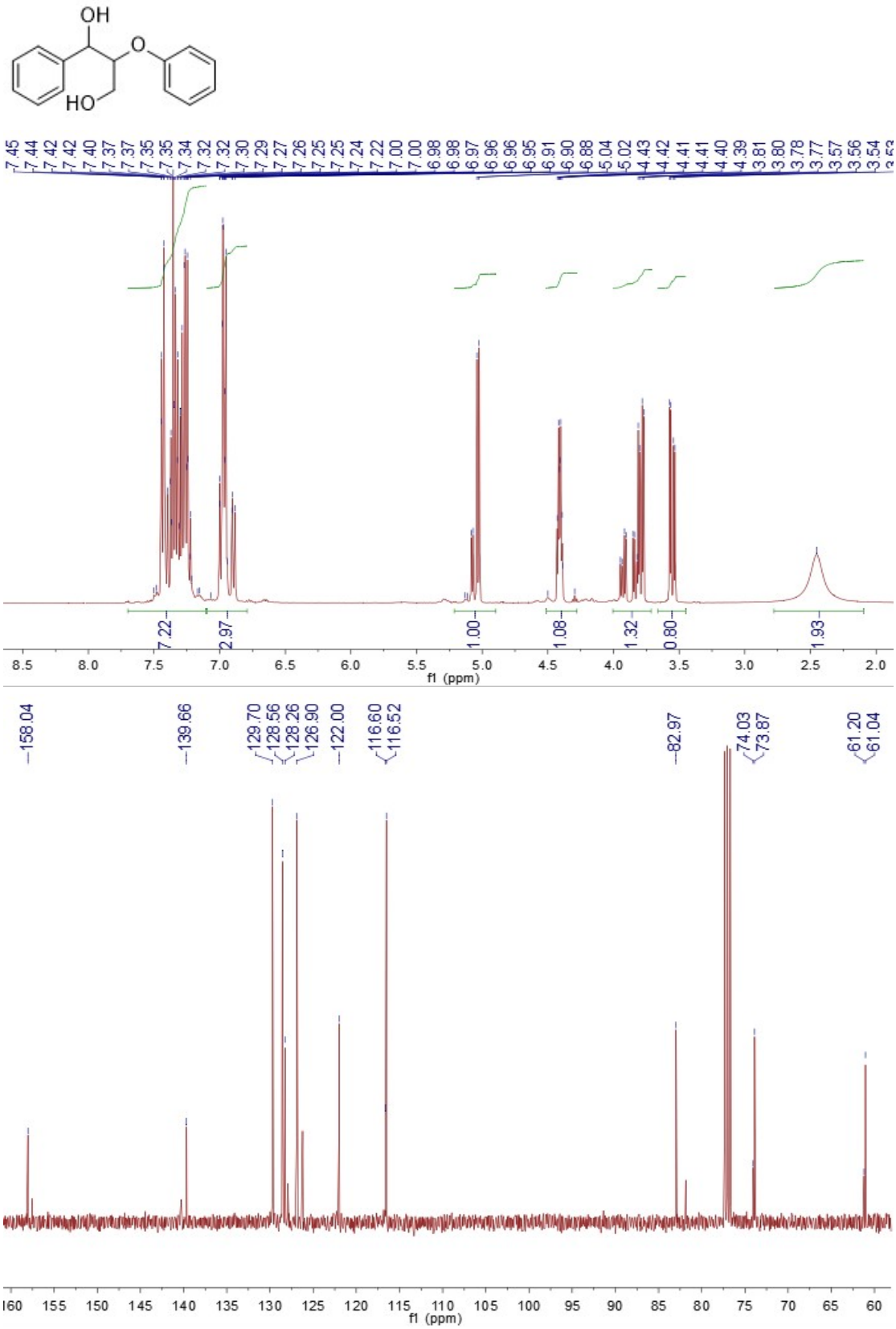


Figure S12 ^{1}H (top) and ^{13}C (bottom) NMR spectra of 2-phenoxy-1-phenylpropane-1,3-diol.

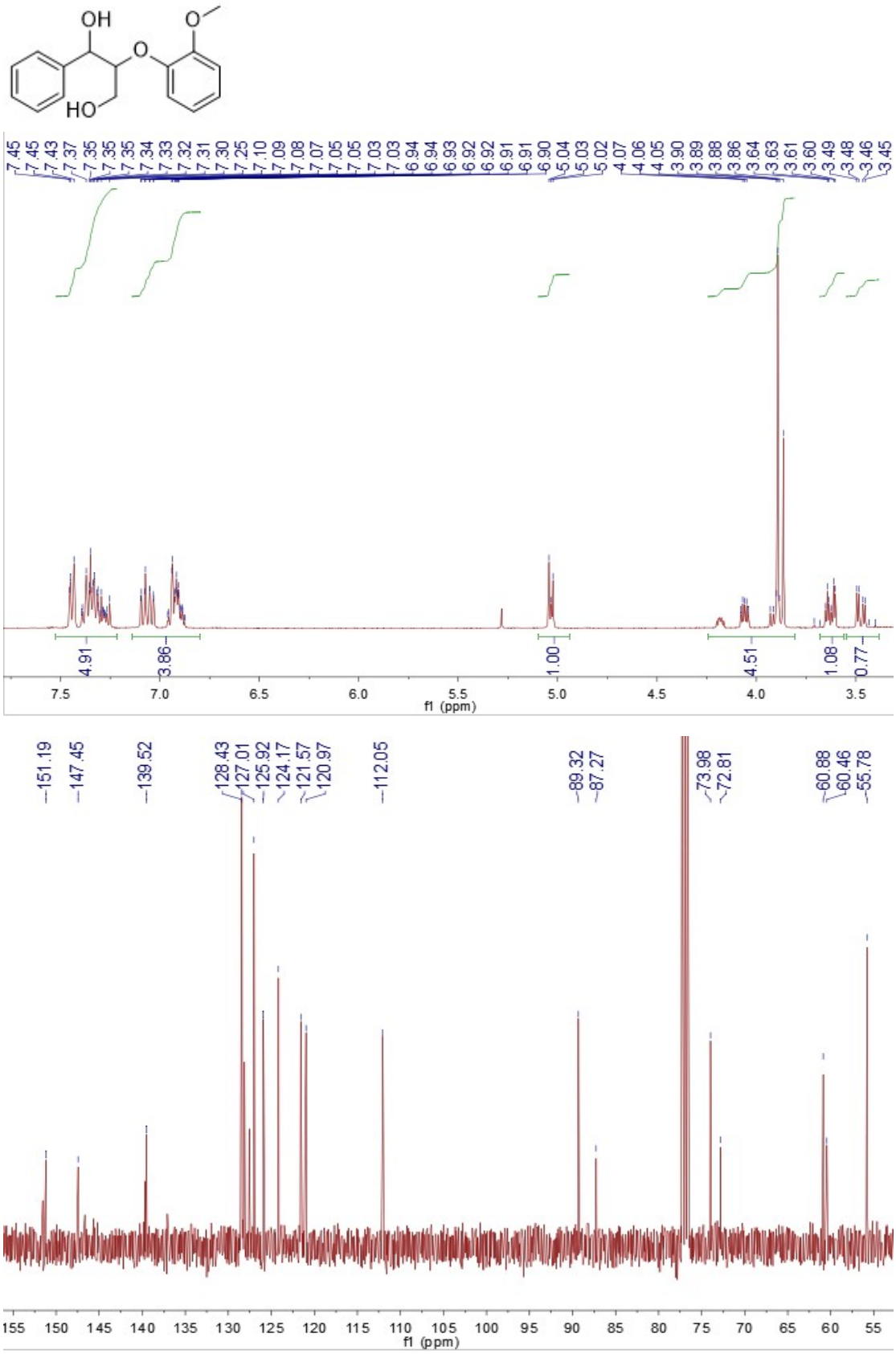


Figure S13 ^{1}H (top) and ^{13}C (bottom) NMR spectra of 2-(2-methoxyphenoxy)-1-phenylpropane-1,3-diol.

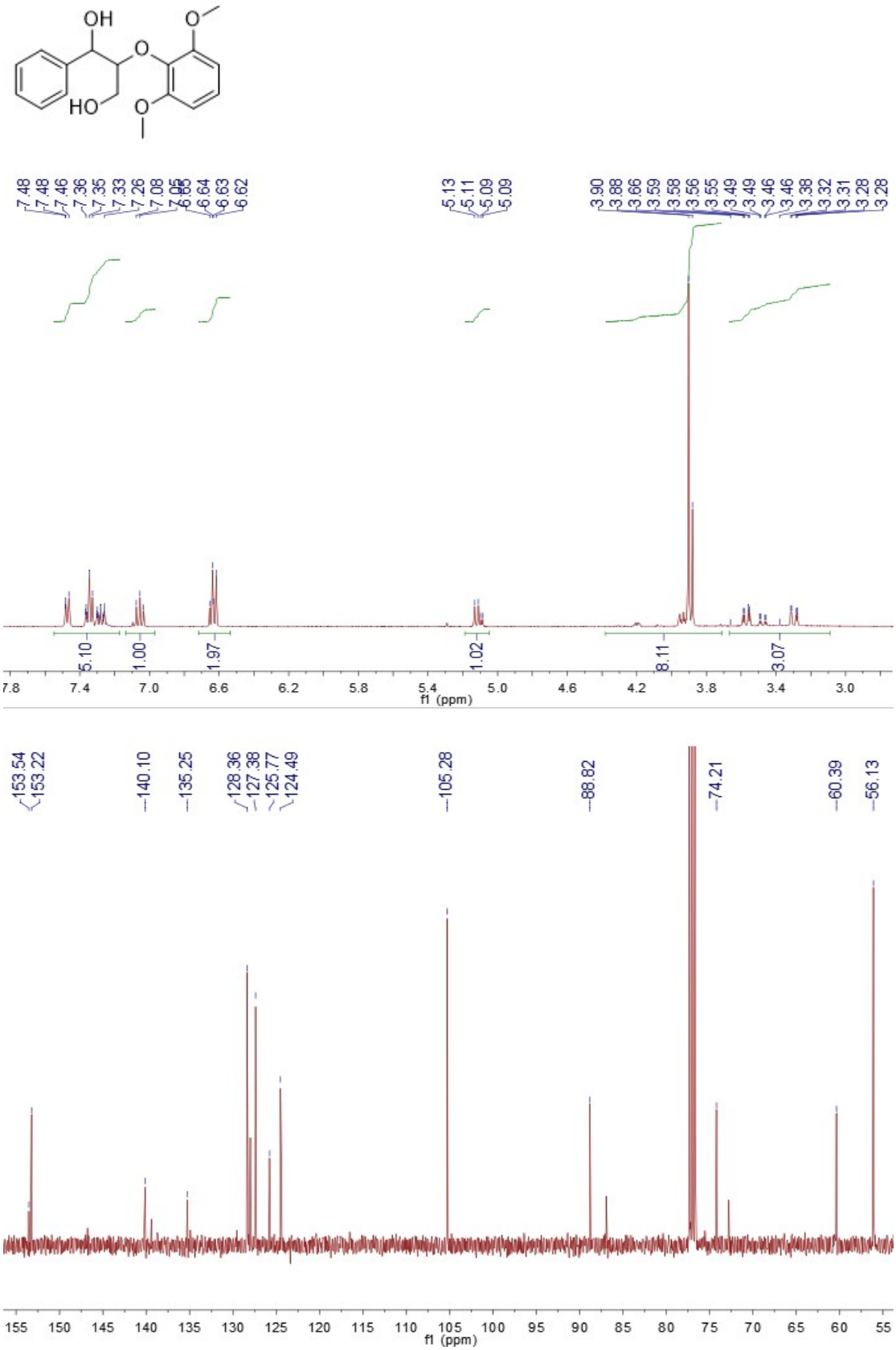


Figure S14 ^{1}H (top) and ^{13}C (bottom) NMR spectra of 2-(2,6-dimethoxyphenoxy)-1-phenylpropane-1,3-diol.

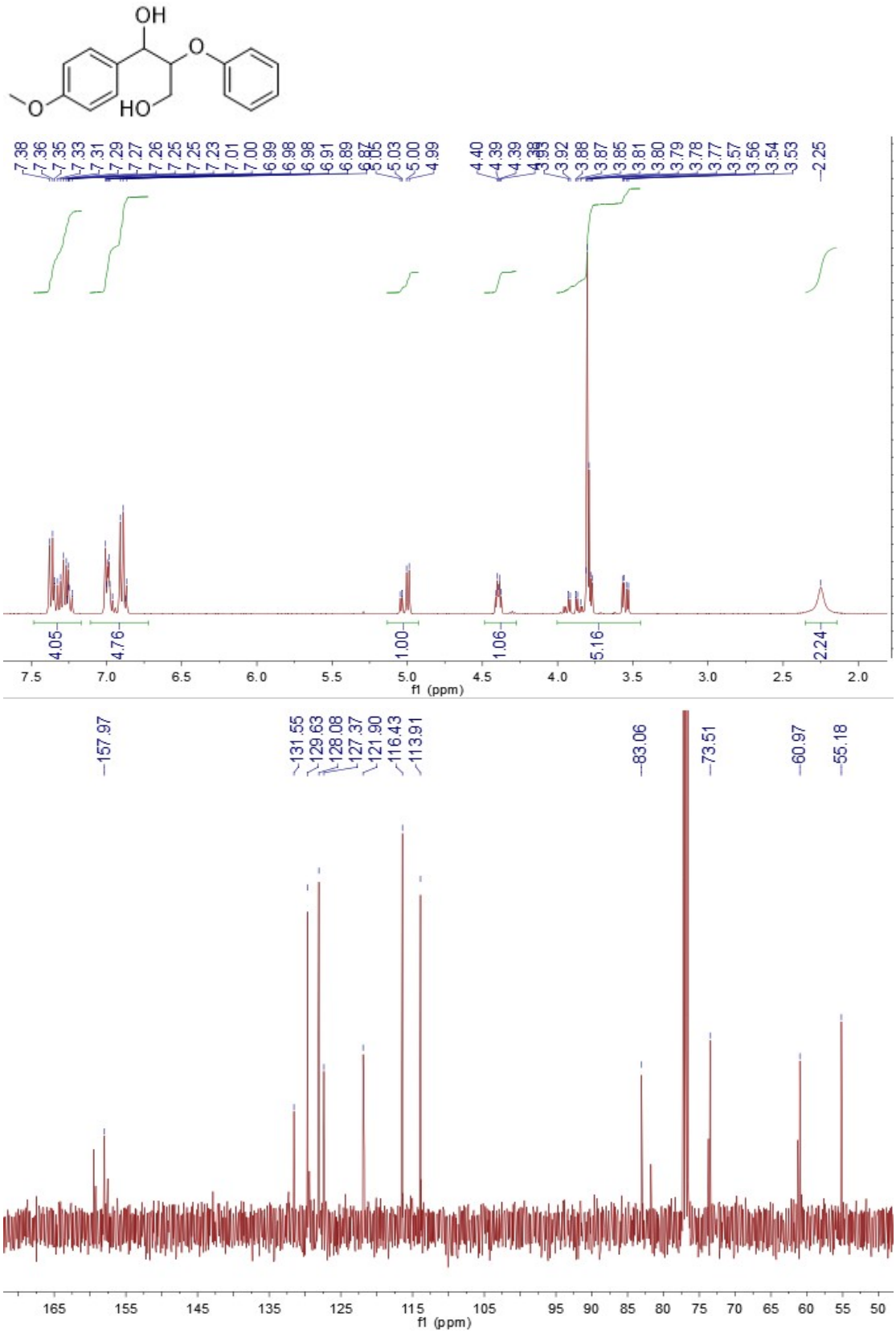


Figure S15^{1}H (top) and ^{13}C (bottom) NMR spectra of 1-(4-methoxyphenyl)-2-phenoxypropane-1,3-diol.

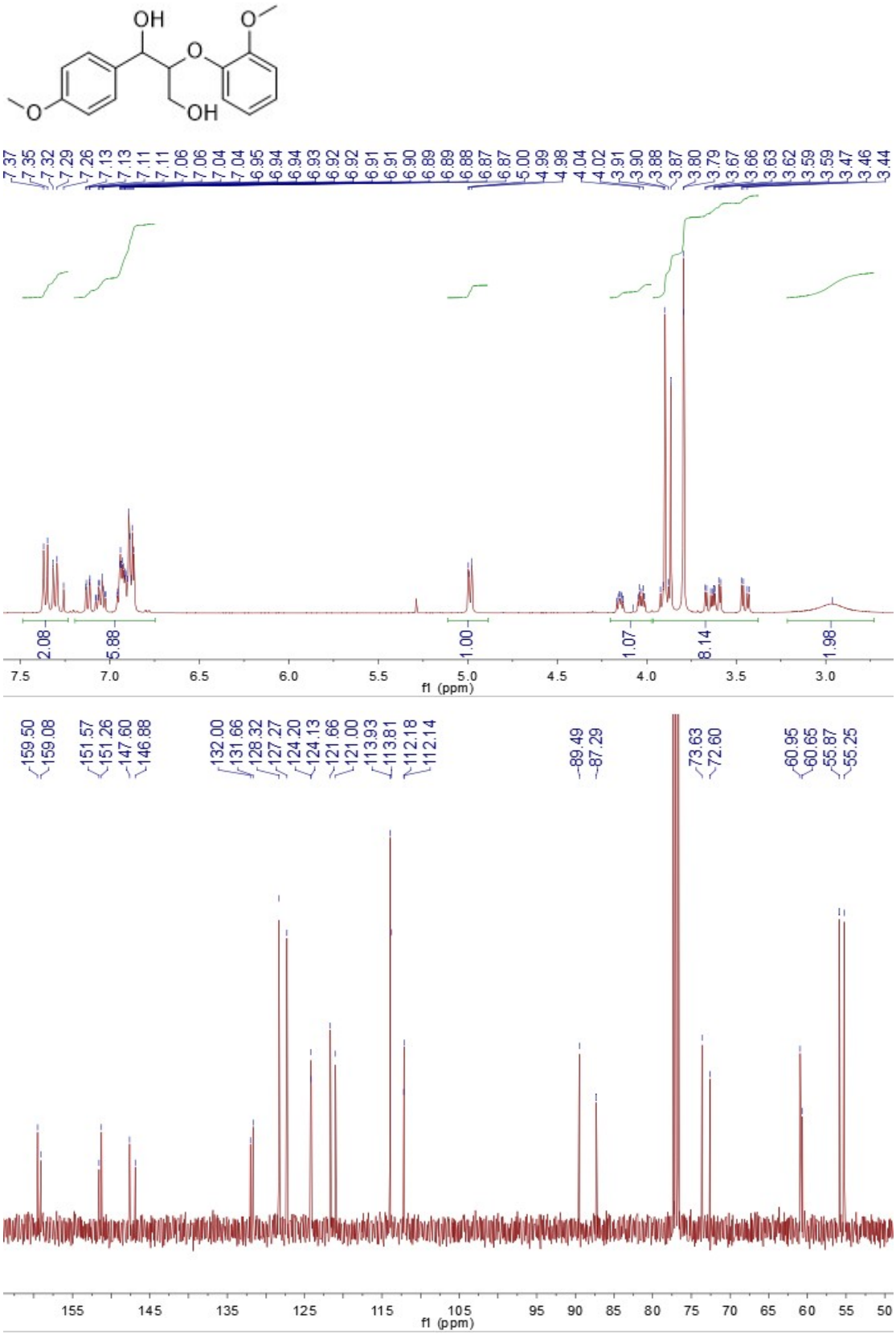


Figure S16[1]H (top) and [13]C (bottom) NMR spectra of2-(2-methoxyphenoxy)-1-(4-methoxyphenyl)propane-1,3-diol.

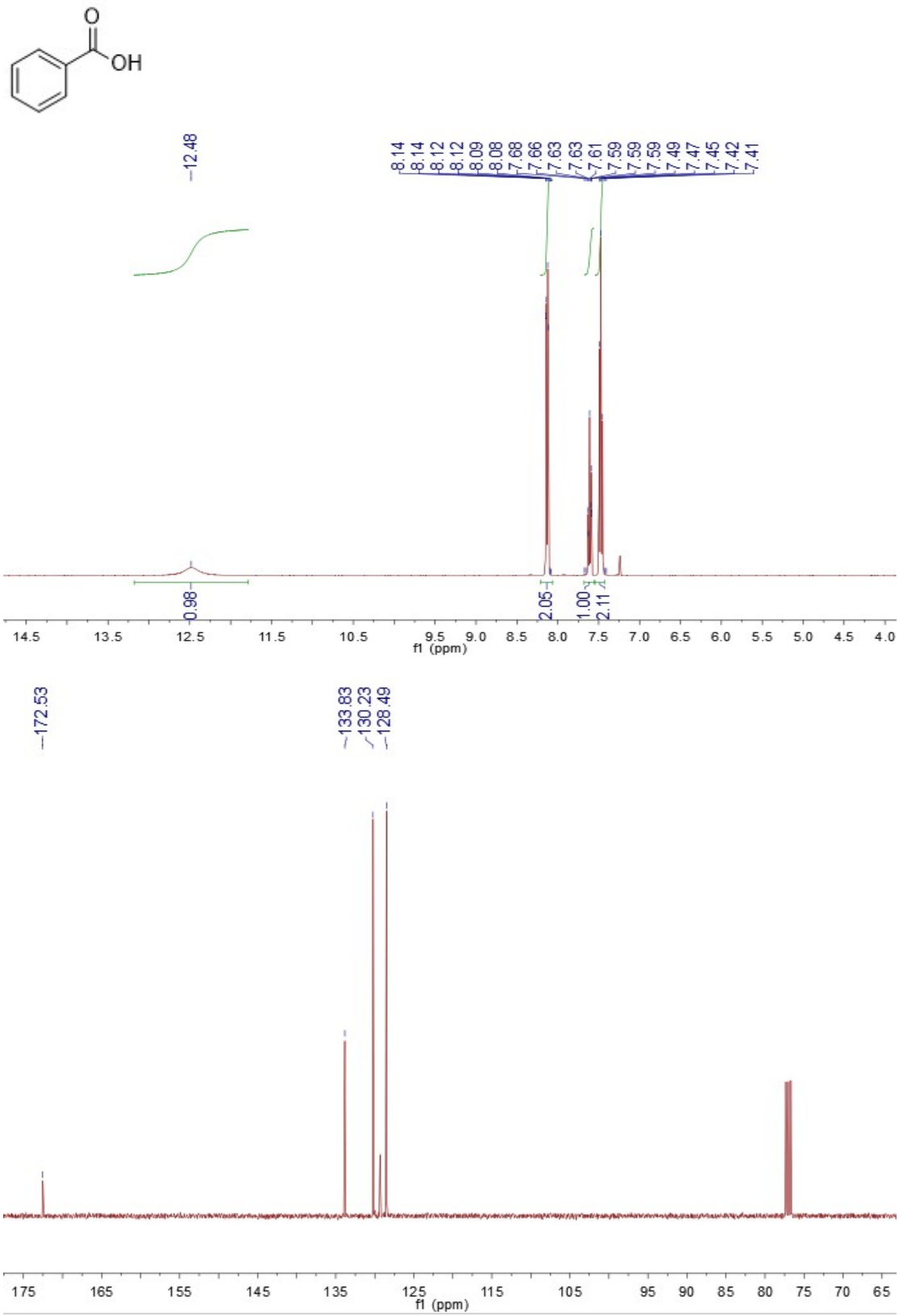


Figure S17^{1}H (top) and ^{13}C (bottom) NMR spectra ofbenzoic acid.

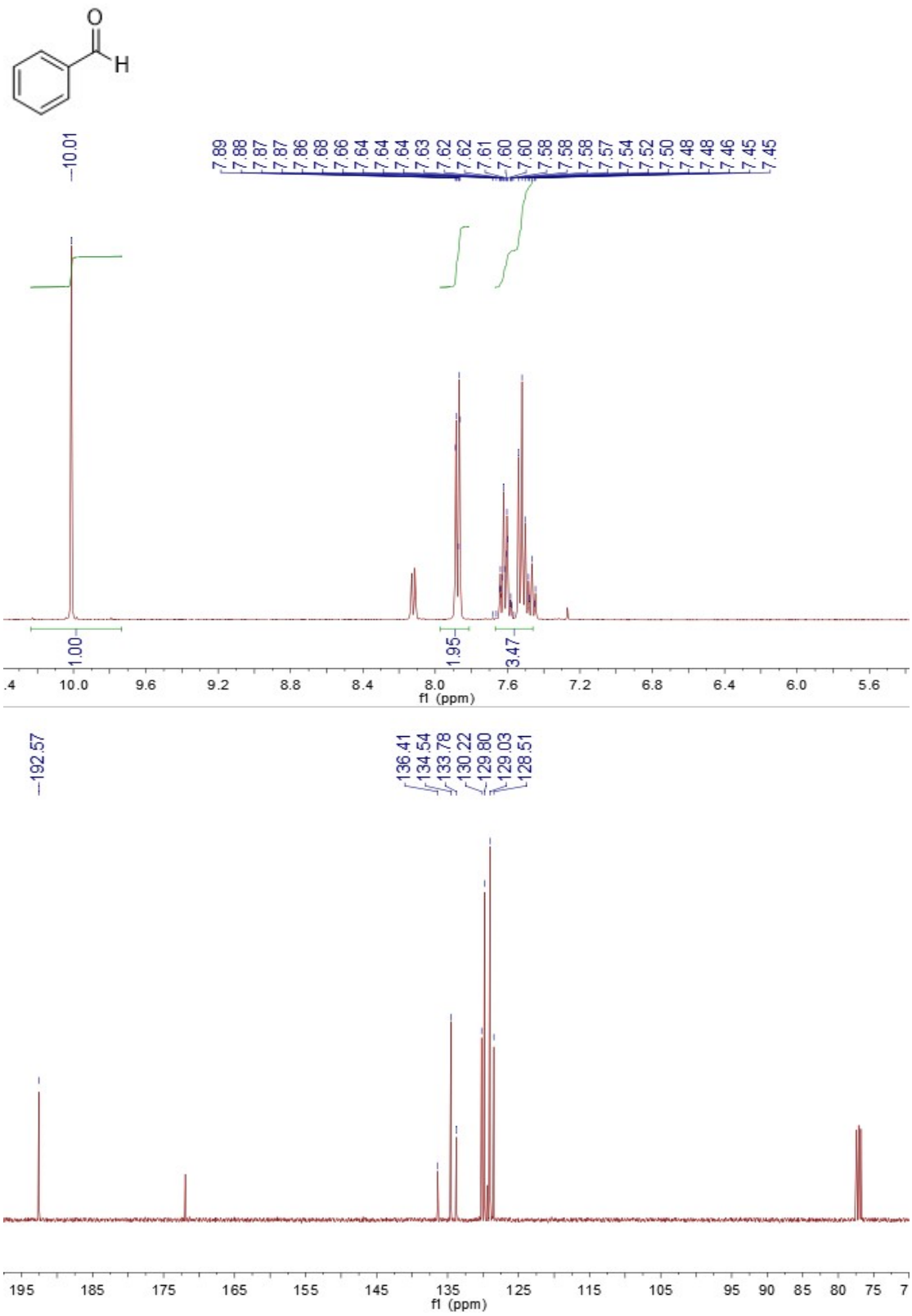


Figure S18^{1}H (top) and ^{13}C (bottom) NMR spectra ofbenzaldehyde.

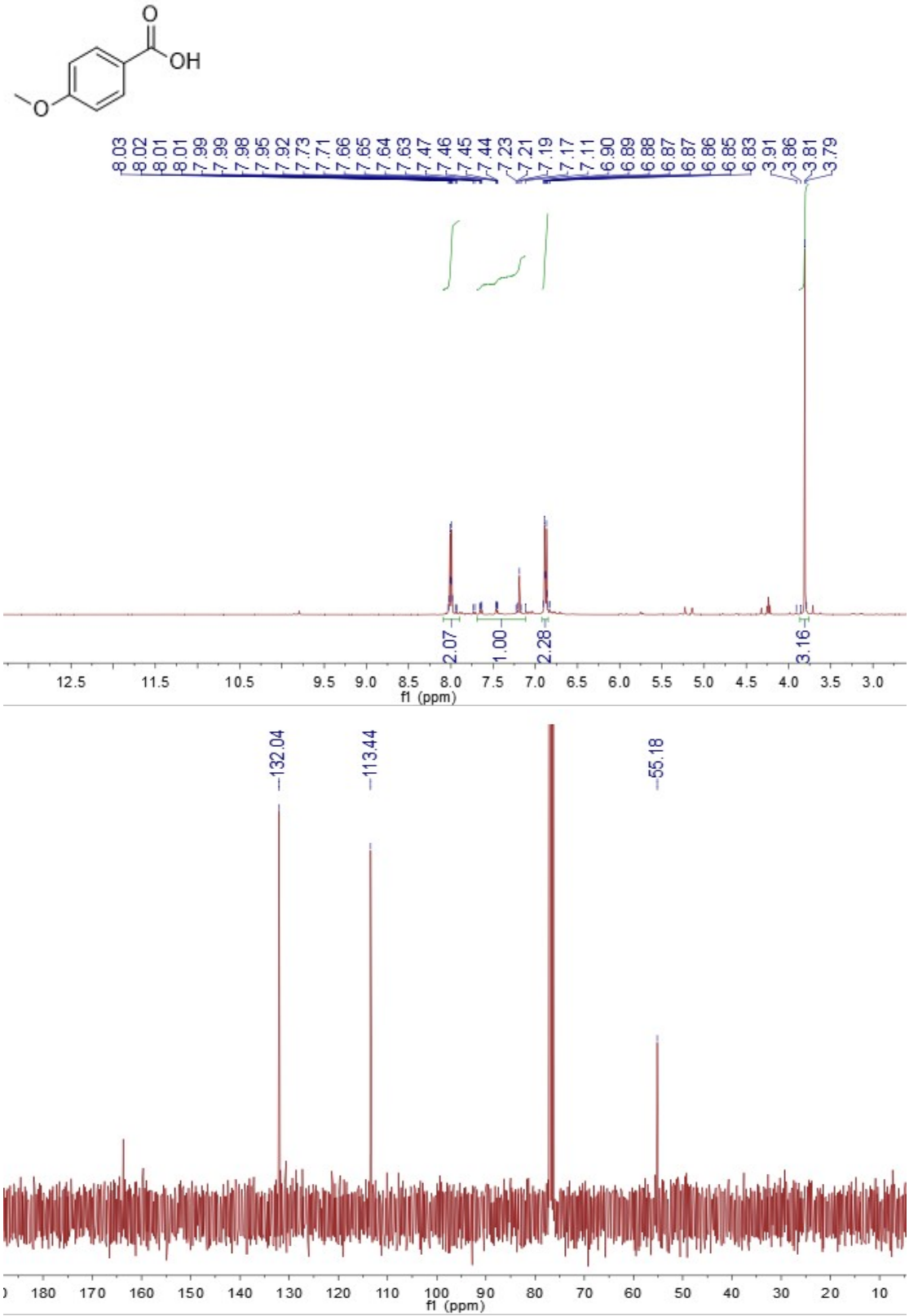


Figure S19^{1}H (top) and ^{13}C (bottom) NMR spectra of4-methoxybenzoic acid.

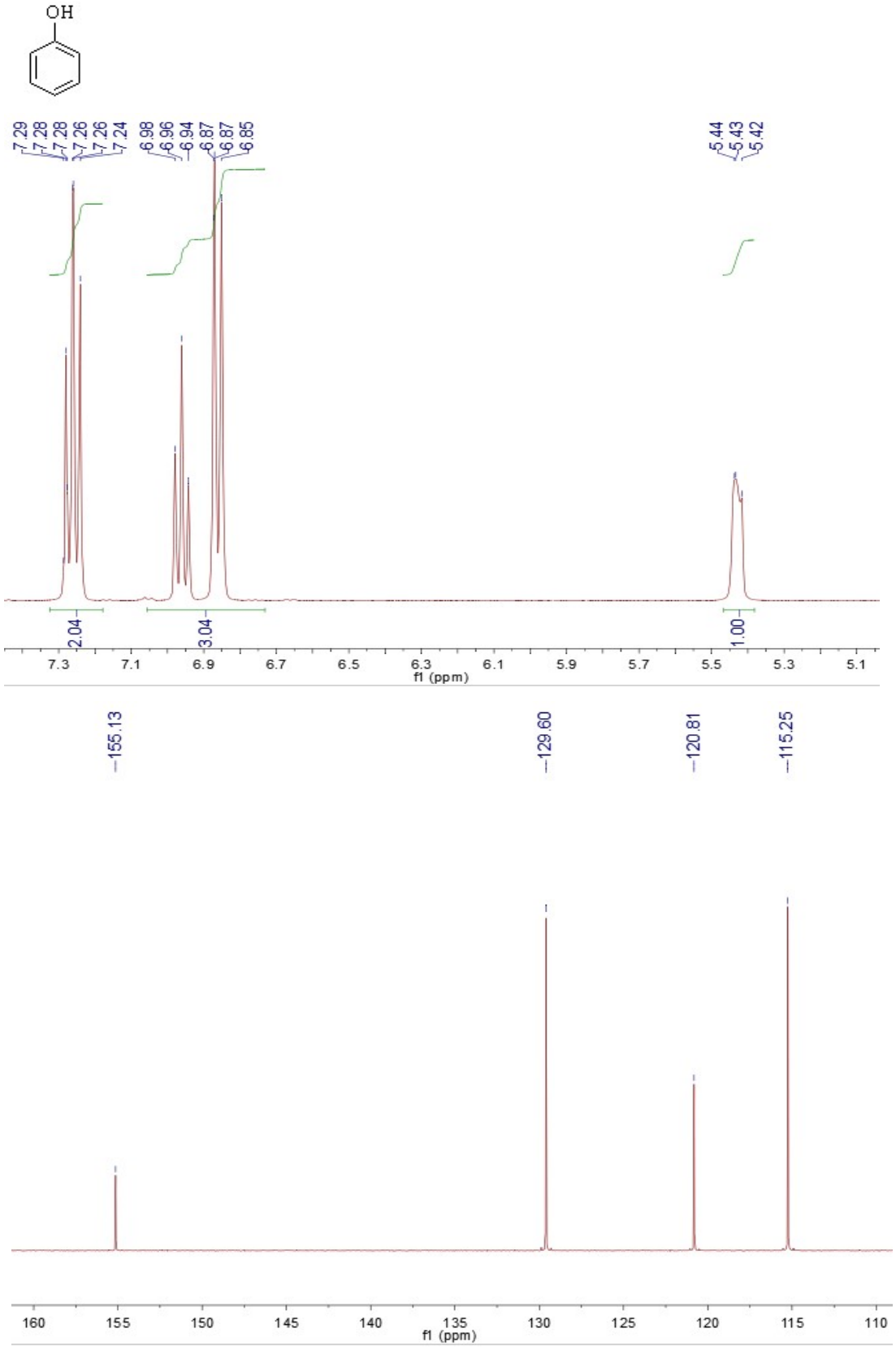


Figure S20 ^{1}H (top) and ^{13}C (bottom) NMR spectra of phenol.

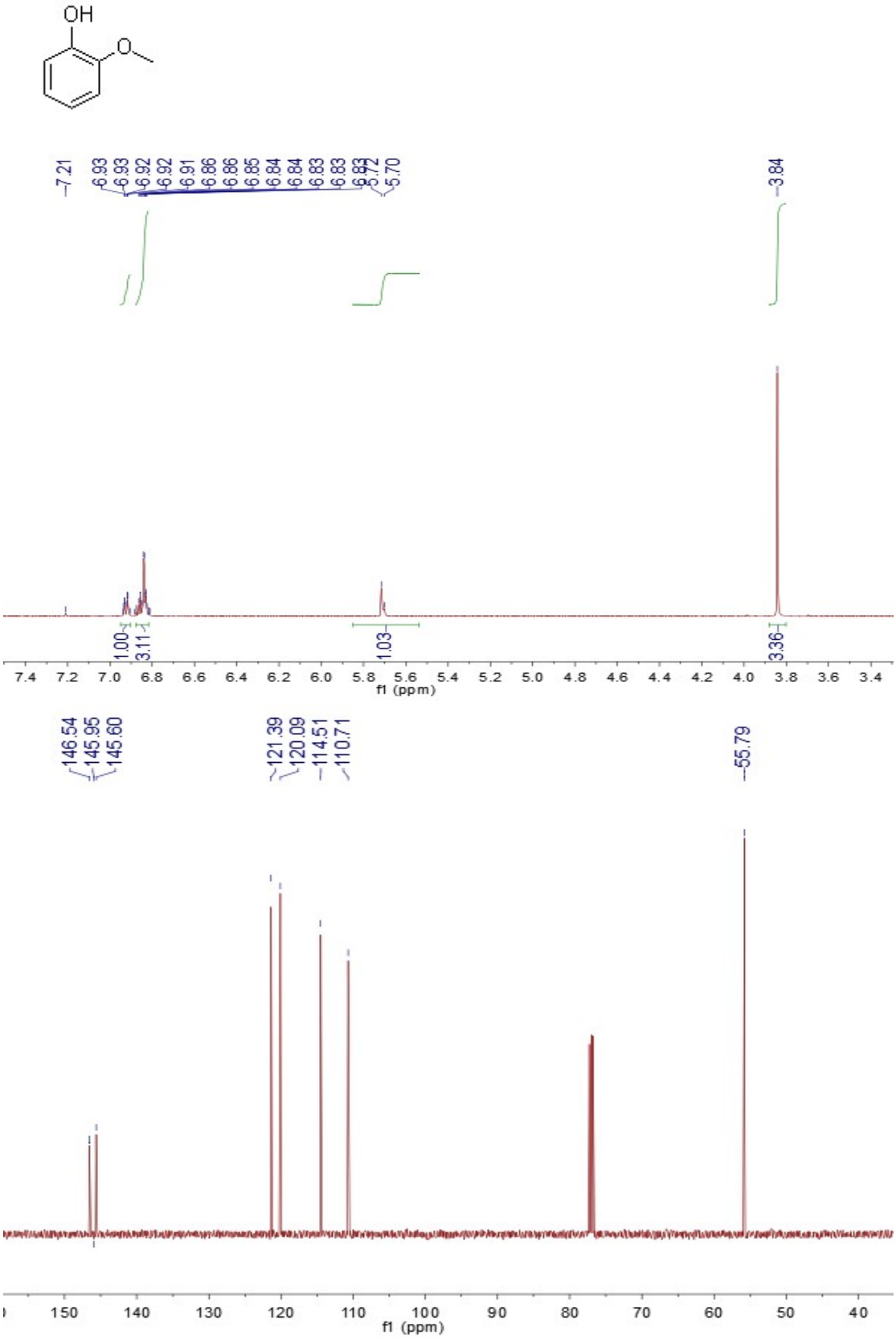


Figure S21 ^{1}H (top) and ^{13}C (bottom) NMR spectra of 2-methoxyphenol.

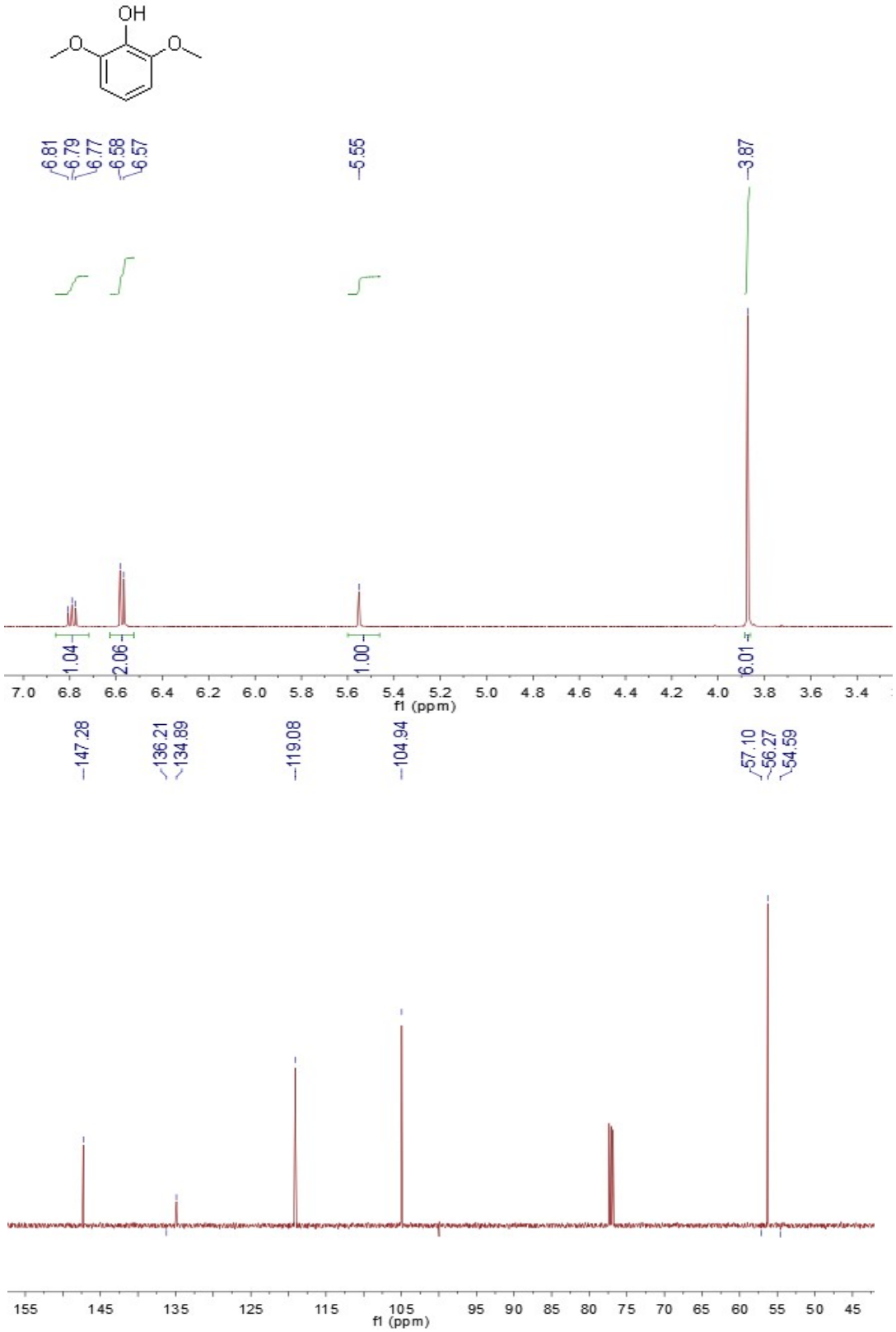


Figure S22 ^{1}H (top) and ^{13}C (bottom) NMR spectra of 2,6-dimethoxyphenol.

7.References

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