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Stereoselective Synthesis of Highly Substituted Cyclopentenones via [4 + 1] Annulation Reactions of (Trialkylsilyl)vinylketenes with α-Benzotriazolyl Organolithium Compounds

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General Procedures. All reactions were performed in flame-dried or oven-dried glassware under a positive pressure of argon. Reaction mixtures were stirred magnetically unless otherwise indicated. Air- and moisture-sensitive liquids and solutions were transferred by syringe or cannula and introduced into reaction vessels through rubber septa. Reaction product solutions and chromatography fractions were concentrated by rotary evaporation at ca. 20 mmHg and then at ca. 0.1 mmHg (vacuum pump) unless otherwise indicated. Thin layer chromatography was performed on EMD (Merck) precoated glass-backed silica gel 60 F-254 0.25 mm plates. Preparative-scale thin layer chromatography was performed on Analtech precoated glass-backed silica gel GF 2000 μm plates. Column chromatography was performed on Silicycle silica gel 60 (230-400 mesh) or Sorbent Technologies silica gel 60 (230-450 mesh).

Materials. Commercial grade reagents and solvents were used without further purification except as indicated below. Dichloromethane was purified by pressure filtration through activated alumnia. Tetrahydrofuran was distilled under argon from sodium benzophenone ketyl or dianion or purified by pressure filtration through activated alumina. Toluene was purified by pressure filtration through activated alumina and Cu(II) oxide. Iodine monochloride (Aldrich, 1.0 M in CH_2Cl_2) was used as received. Diisopropylamine was distilled under argon from calcium hydride. Tributyltin hydride and methyl iodide were distilled under argon. Copper(I) iodide was extracted with THF for 24 h in a Soxhlet extractor and then dried under vacuum (0.1 mmHg). Palladium(II) chloride (bis)triphenylphosphine was recrystallized from boiling chloroform. *n*-BuLi was titrated according to the Watson-Eastham method using BHT in THF or toluene at 0 °C with 1,10-phenanthroline as an indicator.[1] Benzotriazole derivatives **2a**,[2] **2d**,[3] **2e**,[4] **2f**,[5] **2g**,[6] and **2i**[3] were prepared according to previously reported procedures. Solid benzotriazole derivatives **2a** and **2d-g** were dried overnight in a vacuum dessicator (ca. 0.2 mmHg) over P_2O_5 before use in [4 + 1] annulations. Other benzotriazole derivatives (**2b**, **2c**, **2h**, and **2i**) were dried by azeotropic removal of water with toluene immediately before use (vide infra). $ZnBr_2$ (Alfa Aesar, 99.9%) was ground into a fine powder (in a glove box) and dried under vacuum (≤ 0.25 mmHg) at 200-240 °C for ca. 20 h before use.

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[1] a) S. C. Watson, J. F. Eastham, *J. Organomet. Chem.* **1967,** *9,* 165; b) R. A. Ellison, R. Griffin, F. N. Kotsonis, *J. Organomet. Chem.* **1972,** *36,* 209.
[2] A. R. Katritzky, Z. Luo, Y. Fang, P. J. Steel, *J. Org. Chem.* **2001,** *66,* 2858.
[3] A. R. Katritzky, S. Rachwal, K. C. Caster, F. Mahni, K. W. Law, O. Rubio, *J. Chem. Soc. Perkin Trans. 1* **1987,** 781.
[4] For an experimental procedure, see: A. R. Katritzky, Z. Yang, D. J. Cundy, *Synth. Commun.* **1993,** *23,* 3061. For spectral data, see: A. R. Katritzky, S. Rachwal, B. Rachwal, *J. Org. Chem.* **1989,** *54,* 6022.
[5] A. R. Katritzky, Z. Yang, J. N. Lam, *J. Org. Chem.* **1991,** *56,* 2143.
[6] For an experimental procedure, see: Y. H. Kang, K. Kim, *J. Heterocycl. Chem.* **1997,** *34,* 1741. For spectral data, see: A. R. Katritzky, X. Lan, J. N. Lam, *Chem. Ber.* **1991,** *124,* 1819.

Instrumentation. Melting points were determined with a Fisher-Johns melting point apparatus and are uncorrected. Infrared spectra were obtained using a Perkin Elmer 2000 FT-IR spectrophotometer. ^{1}H NMR spectra were recorded on Varian XL-300 (300 MHz), Varian Unity 300 (300 MHz), and Varian Inova 500 (500 MHz) spectrometers. ^{13}C NMR spectra were recorded on Varian XL-300 (75 MHz) and Varian Inova 500 (125 MHz) spectrometers. ^{1}H NMR chemical shifts and ^{13}C NMR chemical shifts are expressed in parts per million (δ) downfield from tetramethylsilane. High resolution mass spectra (HRMS) were measured on a Bruker Daltonics APEXII 3 telsa Fourier transform mass spectrometer. Elemental analyses were performed by E&R Microanalytical Laboratory, Inc. of Parsippany, NJ.

Part I. Experimental Procedures for Preparation of Benzotriazoles

3-(Benzotriazol-1-yl)-3-ethoxy-1-propene (2b).[7] A 10-mL, one-necked, round-bottomed flask equipped with a rubber septum and argon inlet needle was charged with benzotriazole (0.415 g, 3.48 mmol), 3 mL of toluene, and then 3,3-diethoxy-1-propene (0.35 mL, 0.30 g, 2.3 mmol). The rubber septum was replaced with a reflux condenser and the heterogeneous reaction mixture was heated at reflux for 24 h. The resulting homogeneous pale yellow mixture was allowed to cool to rt and then diluted with 30 mL of Et_2O and washed with two 15-mL portions of saturated aq Na_2CO_3, 15 mL of H_2O, dried over Na_2SO_4, filtered, and concentrated to afford 0.442 g of a yellow oil. This material was dissolved in CH_2Cl_2 and concentrated onto 1 g of silica gel which was transferred to the top of a column of 15 g of silica gel. Elution with 1% Et_3N-10% EtOAc-hexanes provided 0.280 g (59%) of benzotriazole **2b** as a pale yellow oil, 0.024 g (5%) of 3-(Benzotriazol-2-yl)-3-ethoxy-1-propene (**25**) as a pale yellow, and 0.105 g (22%) of a mixture of **2b** and **25** (88:12 by ^{1}H NMR analysis) as a pale yellow oil. Spectral characteristics for **2b** are consistent with those previously reported.[8]

4-(Benzotriazol-1-yl)-4-ethoxy-2-butyne (2c). A 25-mL, one-necked, round-bottomed flask equipped with a rubber septum and argon inlet needle was charged with benzotriazole (1.114 g, 9.351 mmol), 5 mL of toluene, and then 1,1-diethoxy-2-butyne (0.99 mL, 0.89 g, 6.3 mmol). The rubber septum was replaced with a reflux condenser and the heterogeneous reaction mixture was heated at reflux for 14 h. The resulting homogeneous orange mixture was allowed to cool to rt and then diluted with 30

[7] This procedure is a modification of a procedure in which **2b** is prepared by the reaction of benzotriazole with 3,3-diethoxy-1-propene in refluxing hexanes, see: A. R. Katritzky, D. Feng, H. Lang, *J. Org. Chem.* **1997,** *62,* 4131.
[8] A. R. Katritzky, G. Zhang, J. Jiang, *J. Org. Chem.* **1995,** *60,* 7589.

mL of Et_2O and washed with two 15-mL portions of saturated aq Na_2CO_3, 15 mL of saturated NaCl solution, dried over $MgSO_4$, filtered, and concentrated to afford 1.512 g of an orange oil. This material was dissolved in CH_2Cl_2 and concentrated onto 3 g of silica gel which was transferred to the top of a column of 53 g of silica gel. Elution with 1% Et_3N-10% EtOAc-hexanes provided 1.065 g (79%) of benzotriazole **2c** as a pale yellow oil, 0.051 g (4%) of 4-(Benzotriazol-2-yl)-4-ethoxy-2-butyne (**26**) as a colorless oil, and 0.094g (7%) of a mixture of **2c** and **26** (91:9 by ^1H NMR analysis) as a pale yellow oil. For **2c**: IR (film) 2979, 2922, 2251, 1614, 1493, 1450, 1334, 1277 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$): δ 8.07 (d, *J* = 8.4 Hz, 1 H), 7.96 (d, *J* = 8.4 Hz, 1 H), 7.52 (app t, *J* = 7.7 Hz, 1 H), 7.40 (app t, *J* = 7.7 Hz, 1 H), 6.76 (q, *J* = 2.1 Hz, 1 H), 3.56-3.63 (m, 1 H), 3.30-3.38 (m, 1 H), 1.92 (d, *J* = 2.1 Hz, 3 H), 1.14 (t, *J* = 7.1 Hz, 3 H); ^{13}C NMR (125 MHz, $CDCl_3$): δ 146.9, 131.3, 127.9, 124.6, 120.1, 111.8, 85.7, 78.9, 72.5, 64.5, 14.8, 3.8. HRMS (ESI) Calcd for $C_{12}H_{13}N_3O$ $(M+H)^+$: 216.1131. Found: 216.1141.

1-(Benzotriazol-1-yl)ethyl phenyl ether (2h).[9] A 100-mL, one-necked, round-bottomed flask equipped with a rubber septum and argon inlet needle was charged with a solution of 1-(phenoxymethyl)benzotriazole[10] (1.075 g, 4.772 mmol) in 48 mL of THF and then cooled at -78 °C while *n*-BuLi solution (2.45 M in hexane, 2.14 mL, 5.24 mmol) was added dropwise over 2 min. The resulting deep green solution was stirred at -78 °C for 30 min and then a solution of MeI (0.33 mL, 0.75 g, 5.3 mmol) in 5 mL of THF was added dropwise via cannula over 3 min. The resulting dark brown solution was allowed to slowly warm to rt over 15 h. The reaction mixture was then diluted with 50 mL of water and the aqueous phase was separated and extracted with three 50-mL portions of ether. The combined organic layers were washed with 50 mL of half-saturated aq $Na_2S_2O_3$ solution and 50 mL of saturated NaCl solution, dried over Na_2SO_4, filtered, and concentrated to afford 1.174 g of a brown oil. This material was dissolved in CH_2Cl_2 and concentrated onto 2.4 g of silica gel which was transferred to the top of a column of 120 g of silica gel. Gradient elution with 20-30% EtOAc-hexanes provided 0.981 g (86%) of benzotriazole **2h** as an off-white solid:[11] mp 66-68 ºC (lit.[11] mp 60-62 ºC); IR (film) 3064, 2996, 1590, 1492 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$): δ 8.02 (app dt, *J* = 8.4, 0.9 Hz, 1 H), 7.81 (app dt, *J* = 8.4, 0.9 Hz, 1 H), 7.44-7.48 (m, 1 H), 7.33-7.37 (m, 1 H), 7.16-7.20 (m, 2 H), 7.05 (q, *J* = 6.2 Hz, 1 H),

[9] This procedure is a modification of a procedure in which **2h** is prepared and used in a subsequent step without purification, see: A. R. Katritzky, L. Serdyuk, L. Xie, *J. Chem. Soc. Perkin Trans. 1* **1998,** 1059.
[10] Prepared according to the procedure reported in reference [9].
[11] For previously reported melting point and spectral data, see: A. R. Katritzky, D. Feng, M. Qi, *J. Org. Chem.* **1998,** *63,* 1473.

6.92-6.98 (m, 3 H), 2.07 (d, J = 6.1 Hz, 3 H); ^{13}C NMR (125 MHz, $CDCl_3$): δ 155.8, 146.7, 131.0, 129.7, 127.7, 124.3, 122.9, 120.2, 116.2, 111.1, 84.6, 21.3. Anal. Calcd for $C_{14}H_{13}N_3O$: C, 70.28; H, 5.48; N, 17.56. Found: C, 70.53; H, 5.47; N, 17.45.

Part II. Experimental Procedures for [4 + 1] Annulations

***trans*-5-(*N*-benzyl-*N*-*tert*-butoxycarbonyl)amino-3,4-dimethyl-2-(triisopropylsilyl)cyclopent-2-enone (4a).** A 25-mL, two-necked, round-bottomed flask equipped with a rubber septum and argon inlet adapter was charged with a solution of the benzotriazole **2a** (0.149 g, 0.440 mmol) in 4.4 mL of THF and then cooled at -78 °C while *n*-BuLi solution (2.35 M in hexane, 0.19 mL, 0.45 mmol) was added dropwise over 1 min. The resulting orange-yellow solution was stirred at -78 °C for 30 min and then a solution of silylketene **1a** (0.105 g, 0.416 mmol) in 1.4 mL of THF was added dropwise via cannula over 1 min. The resulting orange-yellow solution was stirred at -78 °C for 2 h. The cooling bath was then removed and the reaction mixture was stirred for 2.5 h. The resulting mixture was diluted with 30 mL of Et_2O and washed with 15 mL of water, and the aqueous phase was backextracted with 10 mL of Et_2O. The combined organic layers were washed with 15 mL of saturated NaCl solution, dried over $MgSO_4$, filtered, and concentrated to afford 0.221 g of a viscous yellow oil. Column chromatography on 16 g of silica gel (elution with 1-5% EtOAc-hexanes) provided 0.143 g (73%) of *trans*-cyclopentenone **4a** as a colorless oil (96% pure by ^{1}H NMR analysis; contains 4% of an impurity which is tentatively assigned as the *cis* isomer): IR (film) 2944, 2866, 1697, 1570, 1456 cm^{-1}; ^{1}H NMR (500 MHz, DMSO-d_6, 135 °C): δ 7.26-7.31 (m, 4 H), 7.19-7.23 (m, 1 H), 4.41 (d, J = 15.7 Hz, 1 H), 4.35 (d, J = 15.6 Hz, 1 H), 3.61 (d, J = 4.5 Hz, 1 H), 2.84-2.90 (m, 1 H), 2.07 (s, 3 H), 1.46 (sept, J = 7.5 Hz, 3 H), 1.34 (s, 9 H), 1.00-1.06 (m, 21 H); ^{13}C NMR (125 MHz, DMSO-d_6, 135 °C): δ 205.5, 185.2, 154.1, 138.4, 133.3, 127.3, 126.7, 126.1, 78.9, 69.3, 51.0, 44.2, 27.3, 17.9, 17.8, 17.4, 15.7, 10.6. HRMS (ESI) Calcd for $C_{28}H_{45}NO_3Si$ $(M+Na)^+$: 494.3061. Found: 494.3073.

***trans*-7-(*N*-benzyl-*N*-*tert*-butoxycarbonyl)amino-9-(triisopropylsilyl)bicyclo[4.3.0]non-1(9)-en-8-one (5a).** A 25-mL, two-necked, round-bottomed flask equipped with a rubber septum and argon inlet adapter was charged with a solution of the benzotriazole **2a** (0.153 g, 0.452 mmol) in 4.5 mL of THF and then cooled at -78 °C while *n*-BuLi solution (2.40 M in hexane, 0.19 mL, 0.45 mmol) was added dropwise over 1 min. The resulting orange-yellow solution was stirred at -78 °C for 30 min and then a

solution of silylketene **1b** (0.118 g, 0.424 mmol) in 1.4 mL of THF was added dropwise via cannula over 2 min. The resulting orange-yellow solution was stirred at -78 °C for 1 h. The cooling bath was then removed and the reaction mixture was stirred for 2.5 h. The reaction mixture was diluted with 30 mL of Et_2O and washed with 15 mL of water, and the aqueous phase was backextracted with 10 mL of Et_2O. The combined organic layers were washed with 15 mL of saturated NaCl solution, dried over $MgSO_4$, filtered, and concentrated to afford 0.242 g of a yellow oil. This material was dissolved in CH_2Cl_2 and concentrated onto 0.6 g of silica gel which was transferred to the top of a column of 19 g of silica gel. Gradient elution with 1-5% EtOAc-hexanes provided 0.141 g (67%) of cyclopentenone **5a** (≥99:1 *trans*:*cis* by ^{1}H NMR analysis) as a viscous, pale orange oil: IR (film) 2939, 2864, 1701, 1569, 1456 cm^{-1}; ^{1}H NMR (500 MHz, DMSO-d_6, 130 °C): δ 7.27-7.30 (m, 4 H), 7.19-7.24 (m, 1 H), 4.43 (d, J = 15.6 Hz, 1 H), 4.31 (d, J = 15.7 Hz, 1 H), 3.57 (d, J = 4.3 Hz, 1 H), 2.88 (d, J = 14.7 Hz, 1 H), 2.69-2.75 (m, 1 H), 2.18-2.26 (m, 1 H), 1.82-1.95 (m, 2 H), 1.65-1.72 (m, 1 H), 1.44 (sept, J = 7.5 Hz, 3 H), 1.33 (s, 9 H), 1.27-1.49 (m, 3 H), 1.04 (d, J = 7.5 Hz, 9 H), 1.02 (d, J = 7.4 Hz, 9 H); ^{13}C NMR (125 MHz, DMSO-d_6, 130 °C): δ 205.9, 186.9, 154.1, 138.4, 127.4, 126.7, 126.2, 98.7, 78.9, 68.4, 51.1, 46.8, 32.5, 31.4, 27.4, 25.7, 23.8, 17.93, 17.86, 10.6. HRMS (ESI) Calcd for $C_{30}H_{47}NO_3Si$ $(M+H)^+$: 498.3398. Found: 498.3386.

***trans*-5-Ethoxy-3,4-dimethyl-2-triisopropylsilyl-5-(vinyl)cyclopent-2-enone (6a)** and ***cis*-5-Ethoxy-3,4-dimethyl-2-triisopropylsilyl-5-(vinyl)cyclopent-2-enone (6b).** An oven-dried, 25-mL, one-necked, round-bottomed flask equipped with a three-way stopcock adapter (fitted with a rubber septum and connected to a vacuum/Ar manifold) was charged with the benzotriazole derivative **2b** (0.125 g, 0.615 mmol). Toluene (5 mL) was added and the resulting solution was concentrated at 0.2 mmHg with vigorous stirring. This process was repeated twice, and the residue was then dissolved in 6.2 mL of THF and cooled at -78 °C while *n*-BuLi solution (2.39 M in hexane, 0.25 mL, 0.60 mmol) was added dropwise over 1 min. The resulting deep green solution was stirred at -78 °C for 4 min and then a solution of silylketene **1a** (0.141 g, 0.558 mmol) in 1.9 mL of THF was added dropwise via cannula over 2 min. The resulting orange-yellow solution was allowed to slowly warm to rt over 15 h. The reaction mixture was then diluted with 30 mL of Et_2O and washed with 15 mL of water, and the aqueous phase was backextracted with 20 mL of Et_2O. The combined organic layers were washed with 15 mL of saturated NaCl solution, dried over $MgSO_4$, filtered, and concentrated to afford 0.218 g of an orange oil. This material was dissolved in CH_2Cl_2 and concentrated onto 0.5 g of silica gel which was transferred to the

top of a column of 20 g of silica gel. Gradient elution with 0-2.5% EtOAc-hexanes provided 0.131 g (70%) of *trans*-cyclopentenone **6a** and *cis*-isomer **6b** (76:24 by ^{1}H NMR analysis) as a pale yellow oil. A pure sample of **6a** and an enriched sample of **6b** (77:23 **6b**:**6a** by ^{1}H NMR analysis) were obtained by preparative TLC (elution with 4% EtOAc-hexanes). For **6a** and **6b**: IR (film) 2944, 2866, 1698, 1574, 1463 cm^{-1}; ^{1}H NMR (500 MHz, C_6D_6) for **6a**: δ 5.69 (dd, *J* = 17.5, 10.7 Hz, 1 H), 5.60 (dd, *J* = 17.4, 2.1 Hz, 1 H), 5.27 (dd, *J* = 10.7, 2.1 Hz, 1 H), 3.59-3.71 (m, 2 H), 2.74 (q, *J* = 7.4 Hz, 1 H), 1.75 (s, 3 H), 1.57 (sept, *J* = 7.6 Hz, 3 H), 1.14 (app d, *J* = 7.6 Hz, 18 H), 1.12-1.17 (m, 3 H), 0.84 (d, *J* = 7.6 Hz, 3 H); for **6b**: δ 5.85 (dd, *J* = 17.5, 10.9 Hz, 1 H), 5.31 (dd, *J* = 17.7, 1.2 Hz, 1 H), 5.12 (dd, *J* = 10.7, 1.2 Hz, 1 H), 3.85-3.92 (m, 1 H), 3.59-3.66 (m, 1 H), 2.43 (q, *J* = 7.2 Hz, 1 H), 1.76 (s, 3 H), 1.57 (sept, *J* = 7.6 Hz, 3 H), 1.13 (app d, *J* = 7.5 Hz, 18 H), 1.12-1.17 (m, 3 H), 1.09 (d, *J* = 7.2 Hz, 3 H); ^{13}C NMR (125 MHz, $CDCl_3$): for **6a** and **6b**: δ 209.2, 209.0, 187.8, 187.7, 138.0, 134.9, 134.1, 132.3, 118.0, 116.8, 87.0, 86.3, 60.7, 60.1, 51.2, 50.5, 19.8, 19.3, 19.02, 18.98, 18.95, 18.93, 16.0, 15.9, 15.1, 14.5, 11.92, 11.87. HRMS (ESI) Calcd for $C_{20}H_{36}O_2Si$ $(M+Na)^+$: 359.2377. Found: 359.2382.

***trans*-5-Ethoxy-3,4-dimethyl-5-prop-1-ynyl-2-(triisopropylsilyl)cyclopent-2-enone (7a).** An oven-dried, 25-mL, one-necked, round-bottomed flask equipped with a three-way stopcock adapter (fitted with a rubber septum and connected to a vacuum/Ar manifold) was charged with the benzotriazole derivative **4c** (0.140 g, 0.650 mmol). Toluene (5 mL) was added and the resulting solution was concentrated at 0.2 mmHg with vigorous stirring. This process was repeated twice, and the residue was then dissolved in 6.5 mL of THF and cooled at -78 °C while *n*-BuLi solution (2.39 M in hexane, 0.26 mL, 0.62 mmol) was added dropwise over 1 min. The resulting deep blue solution was stirred at -78 °C for 5 min and then a solution of silylketene **1a** (0.149 g, 0.590 mmol) in 2.0 mL of THF was added dropwise via cannula over 2 min. The resulting red-brown solution was allowed to slowly warm to rt over 15 h. The reaction mixture was then diluted with 30 mL of Et_2O and washed with 15 mL of water, and the aqueous phase was backextracted with 10 mL of Et_2O. The combined organic layers were washed with 15 mL of saturated NaCl solution, dried over $MgSO_4$, filtered, and concentrated to afford 0.255 g of a brown oil. This material was dissolved in CH_2Cl_2 and concentrated onto 0.7 g of silica gel which was transferred to the top of a column of 25 g of silica gel. Gradient elution with 0-2.5% EtOAc-hexanes provided 0.111 g (54%) of cyclopentenone **7a** (97:3 mixture of *trans*:*cis* isomers by ^{1}H NMR analysis) as a yellow oil. For *trans*-cyclopentenone **7a**: IR (film) 2944, 2866, 2245, 1705, 1580, 1463 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$): δ 3.69-3.83 (m, 2 H), 2.72, (q, *J* = 7.4 Hz, 1 H), 2.16 (s, 3 H), 1.91 (s, 3 H), 1.50

(sept, J = 7.5 Hz, 3 H), 1.26 (d, J = 7.4 Hz, 3 H), 1.16 (app t, J = 7.05 Hz, 3 H), 1.06 (d, J = 7.3 Hz, 9 H), 1.05 (d, J = 7.3 Hz, 9 H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 205.8, 187.3, 131.5, 86.9, 82.2, 74.4, 61.2, 52.8, 19.5, 18.94, 18.92, 16.5, 15.7, 11.9, 4.0. HRMS (ESI) Calcd for $C_{21}H_{36}O_2Si$ $(M+H)^+$: 349.2557. Found: 349.2559.

***trans*-3,4-Dimethyl-5-phenylthio-2-(triisopropylsilyl)cyclopent-2-enone (9a).** A 25-mL, two-necked, round-bottomed flask equipped with a rubber septum and argon inlet adapter was charged with a solution of 1-(phenylthiomethyl)benzotriazole (**2d**) (0.086 g, 0.356 mmol) in 3.6 mL of THF and then cooled at -78 °C while *n*-BuLi solution (2.39 M in hexane, 0.149 mL, 0.356 mmol) was added dropwise over 1 min. The resulting orange-brown mixture was stirred at -78 °C for 1 h and then a solution of silylketene **1a** (0.087 g, 0.345 mmol) in 1.1 mL of THF was added dropwise via cannula over 1 min. After 1 h, a solution of $ZnBr_2$ (1.00 M in THF, 1.02 mL, 1.02 mmol) was added dropwise over 2 min and the resulting bright yellow mixture was allowed to slowly warm to rt over 18.5 h. The reaction mixture was then filtered through Celite with the aid of 30 mL of Et_2O and the filtrate was washed with 15 mL of 1 N aq HCl solution. The aqueous phase was extracted with 10 mL of Et_2O, and the combined organic phases were washed with 15 mL of saturated NaCl solution, dried over $MgSO_4$, filtered, and concentrated to afford 0.199 g of a yellow oil. This material was dissolved in CH_2Cl_2 and concentrated onto 0.5 g of silica gel which was transferred to the top of a column of 20 g of silica gel. Gradient elution with 0-5% EtOAc-hexanes provided 0.089 g (69%) of cyclopentenone **9a** (98:2 mixture of *trans*:*cis* isomers by ^{1}H NMR and GC analysis) as a colorless oil which partially solidified on standing: IR (film) 2944, 2865, 1696, 1574, 1463, 1248 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$): for *trans* isomer: δ 7.44-7.48 (m, 2 H), 7.20-7.28 (m, 3 H), 3.28 (d, J = 3.1 Hz, 1 H), 2.72 (qd, J = 7.1, 3.1 Hz, 1 H), 2.12 (s, 3 H), 1.52 (sept, J = 7.6 Hz, 3 H), 1.25 (d, J = 7.3 Hz, 3 H), 1.04 (app dd, J = 7.8, 2.5 Hz, 18 H); for *cis* isomer (partial): δ 4.16 (d, J = 6.8 Hz, 1 H), 3.09 (app quint, J = 7.1 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$): δ 208.2, 188.8, 134.8, 134.2, 132.4, 129.0, 127.5, 57.7, 49.4, 19.1, 18.95, 18.93, 18.8, 11.8. Anal. Calcd for $C_{22}H_{34}OSSi$: C, 70.53; H, 9.15. Found: C, 70.37; H, 9.10.

***trans*-7-Phenylthio-9-(triisopropylsilyl)bicyclo[4.3.0]non-1(9)-en-8-one (10a).** A 25-mL, two-necked, round-bottomed flask equipped with a rubber septum and argon inlet adapter was charged with a solution of 1-(phenylthiomethyl)benzotriazole (**2d**) (0.098 g, 0.406 mmol) in 4.1 mL of THF and then cooled at -78 °C while *n*-BuLi solution (2.34 M in hexane, 0.174 mL, 0.406 mmol) was added dropwise over 1 min. The resulting orange-brown mixture was stirred at -78 °C for 1 h and then a solution of

silylketene **1b** (0.109 g, 0.391 mmol) in 1.3 mL of THF was added dropwise via cannula over 1 min. After 1 h, a solution of $ZnBr_2$ (1.00 M in THF, 1.16 mL, 1.16 mmol) was added dropwise over 2 min and the resulting bright yellow mixture was allowed to slowly warm to rt over 20 h. The reaction mixture was diluted with 30 mL of Et_2O and washed with 15 mL of 1 N aq HCl solution. The aqueous phase was extracted with 10 mL of Et_2O, and the combined organic phases were washed with 15 mL of saturated NaCl solution, dried over $MgSO_4$, filtered, and concentrated to afford 0.193 g of a yellow oil. This material was dissolved in CH_2Cl_2 and concentrated onto 0.4 g of silica gel which was transferred to the top of a column of 19 g of silica gel. Gradient elution with 0-5% EtOAc-hexanes provided 0.080 g (51%) of cyclopentenone **10a** (≥98:2 mixture of *trans*:*cis* isomers by ^{1}H NMR analysis) as a colorless oil: IR (film) 2941, 2864, 1696, 1573, 1463 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$): for *trans* isomer: δ 7.44-7.49 (m, 2 H), 7.20-7.28 (m, 3 H), 3.27 (d, *J* = 3.3 Hz, 1 H), 2.98 (d, *J* = 13.8 Hz, 1 H), 2.60 (ddd, *J* = 12.3, 5.4, 3.3 Hz, 1 H), 2.21-2.28 (m, 1 H), 2.18 (td, *J* = 13.4, 5.4 Hz, 1 H), 1.96-2.03 (m, 1 H), 1.83 (d, *J* = 13.2 Hz, 1 H), 1.50 (sept, *J* = 7.5 Hz, 3 H), 1.08-1.47 (m, 3 H), 1.03 (app t, *J* = 7.6 Hz, 18 H); for *cis* isomer (partial): δ 4.07 (d, *J* = 7.2 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$): δ 208.2, 190.7, 134.4, 132.24, 132.18, 129.0, 127.5, 56.3, 51.9, 34.8, 32.7, 27.5, 25.4, 18.98, 18.96, 11.8. HRMS (ESI) Calcd for $C_{24}H_{36}OSSi$ $(M+Na)^+$: 423.2148. Found: 423.2145.

***trans*-5-Methoxy-3,4-dimethyl-2-(triisopropylsilyl)cyclopent-2-enone (11a).** A 50-mL, three-necked, round-bottomed flask equipped with a glass stopper, rubber septum and argon inlet adapter was charged with a solution of 1-(methoxymethyl)benzotriazole (**2e**) (0.330 g, 2.02 mmol) in 10 mL of THF and then cooled at -78 °C while *n*-BuLi solution (2.31 M in hexane, 0.86 mL, 2.0 mmol) was added dropwise over 2 min. The resulting emerald green mixture was stirred at -78 °C for 1 h and then a solution of silylketene **1a** (0.477 g, 1.89 mmol) in 3.5 mL of THF was added dropwise via cannula over 4 min. After 1h, a solution of $ZnBr_2$ (1.0 M in THF, 5.7 mL, 5.7 mmol) was added dropwise over 9 min and the resulting yellow-brown solution was allowed to slowly warm to rt over 15 h, during which time a white precipitate formed. The reaction mixture was diluted with 50 mL of Et_2O and filtered though a fritted glass funnel containing Celite. The filtrate was washed with 30 mL of 1 N aq HCl solution, and the aqueous phase was backextracted with 15 mL of Et_2O. The combined organic layers were washed with 30 mL of saturated NaCl solution, dried over $MgSO_4$, filtered, and concentrated to afford 0.660 g of an orange-yellow oil. This material was dissolved in CH_2Cl_2 and concentrated onto 1.3 g of silica gel which was transferred to the top of a column of 65 g of silica gel. Gradient elution with 0-8% EtOAc-

hexanes provided 0.459 g (82%) of cyclopentenone **11a** (≥99:1 mixture of *trans*:*cis* isomers by ^{1}H NMR analysis) as a colorless oil which solidified upon standing: mp 47-49 °C; IR (film) 2944, 2866, 1699, 1574, 1463 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$): for *trans* isomer: δ 3.59 (s, 3 H), 3.41 (d, *J* = 3.4 Hz, 1 H), 2.68 (qdd, *J* = 7.2, 3.5, 0.9 Hz, 1 H), 2.15 (d, *J* = 0.8 Hz, 3 H), 1.51 (sept, *J* = 7.5 Hz, 3 H), 1.30 (d, *J* = 7.3 Hz, 3 H), 1.04 (app dd, *J* = 7.5, 1.8 Hz, 18 H); for *cis* isomer (partial): δ 3.88 (d, *J* = 6.7 Hz, 1 H), 2.89 (app quint, *J* = 6.9 Hz, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$): δ 210.2, 186.6, 134.2, 87.8, 58.6, 47.0, 19.04, 18.96, 18.89, 17.5, 11.8. HRMS (ESI) Calcd for $C_{17}H_{32}O_2Si$ $(M+H)^+$: 297.2244. Found: 297.2239.

***trans*-5-Methoxy-3,4-dimethyl-2-(triethylsilyl)cyclopent-2-enone (12a).** A 50-mL, three-necked, round-bottomed flask equipped with a rubber septum, glass stopper, and argon inlet adapter was charged with a solution of 1-(methoxymethyl)benzotriazole (**4e**) (0.329 g, 2.02 mmol) in 20 mL of THF and then cooled at -78 °C while *n*-BuLi solution (2.42 M in hexane, 0.82 mL, 2.0 mmol) was added dropwise over 2 min. The resulting emerald green solution was stirred at -78 °C for 1 h and then a solution of silylketene **1c** (0.399 g, 1.90 mmol) in 6.3 mL of THF was added dropwise via cannula over 5 min. After 1 h, a solution of $ZnBr_2$ (1.0 M in THF, 5.7 mL, 5.7 mmol) was added dropwise over 4 min and the resulting yellow-orange solution was allowed to slowly warm to rt over 19 h, during which time a white precipitate formed. The reaction mixture was then diluted with 50 mL of Et_2O and filtered though a fritted glass funnel containing Celite. The filtrate was washed with 30 mL of 1 N aq HCl solution, and the aqueous phase was backextracted with 15 mL of Et_2O. The combined organic layers were washed with 30 mL of saturated NaCl solution, dried over $MgSO_4$, filtered, and concentrated to afford 0.588 g of a yellow-orange oil. This material was dissolved in CH_2Cl_2 and concentrated onto 1.2 g of silica gel which was transferred to the top of a column of 60 g of silica gel. Gradient elution with 0-8% EtOAc-hexanes provided 0.336 g (70%) of cyclopentenone **12a** (≥99:1 *trans*:*cis* by ^{1}H NMR analysis) as a pale yellow oil. For the *trans* isomer **12a**: IR (film) 2955, 2875, 2826, 1698, 1582, 1457, 1376 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$): δ 3.60 (s, 3 H), 3.40 (d, *J* = 3.3 Hz, 1 H), 2.64-2.70 (m, 1 H), 2.11 (d, *J* = 1.0 Hz, 3 H), 1.29 (d, *J* = 7.3 Hz, 3 H), 0.91 (app t, *J* = 7.9 Hz, 9 H), 0.75-0.80 (m, 6 H); ^{13}C NMR (125 MHz, $CDCl_3$): δ 210.1, 186.3, 135.5, 87.8, 58.7, 46.9, 18.3, 17.3, 7.6, 3.6. HRMS (ESI) Calcd for $C_{14}H_{26}O_2Si$ $(M+Na)^+$: 277.1594. Found: 277.1583.

***trans*-5-(Carbazol-9-yl)-3,4-dimethyl-2-(triisopropylsilyl)cyclopent-2-enone (13a)** and ***cis*-5-(Carbazol-9-yl)-3,4-dimethyl-2-(triisopropylsilyl)cyclopent-2-enone (13b).** A 25-mL, two-necked,

round-bottomed flask equipped with a rubber septum and argon inlet adapter was charged with a solution of 1-(carbazol-9-ylmethyl)benzotriazole (**2f**) (0.129 g, 0.432 mmol) in 4.3 mL of THF and then cooled at -78 °C while *n*-BuLi solution (2.45 M in hexane, 0.177 mL, 0.434 mmol) was added dropwise over 1.5 min. The resulting orange solution was stirred at -78 °C for 1 h and then a solution of silylketene **1a** (0.104 g, 0.412 mmol) in 1.4 mL of THF was added dropwise via cannula over 2 min. After 1 h, a solution of $ZnBr_2$ (1.0 M in THF, 1.2 mL, 1.2 mmol) was added dropwise over 2 min and the resulting yellow mixture was allowed to slowly warm to rt over 17 h, during which time a white precipitate formed. The reaction mixture was diluted with 30 mL of Et_2O and filtered though a fritted glass funnel containing Celite. The filtrate was washed with 15 mL of 1 N aq HCl solution, and the aqueous phase was backextracted with 15 mL of Et_2O. The combined organic layers were washed with 15 mL of saturated NaCl solution, dried over $MgSO_4$, filtered, and concentrated to afford 0.202 g of a pale violet solid. This material was dissolved in CH_2Cl_2 and concentrated onto 0.5 g of silica gel which was transferred to the top of a column of 20 g of silica gel. Gradient elution with 0-5% EtOAc-hexanes provided 0.160 g of a pale violet solid. This material was dissolved in 25 mL of CH_2Cl_2, stirred with 0.3 g of decolorizing charcoal for several minutes, filtered, and concentrated to afford 0.152 g (85%) of a mixture of *trans*-cyclopentenone **13a** and *cis*-isomer **13b** (74:26 by ^{1}H NMR analysis) as a white solid. A pure sample of the major isomer was obtained by preparative TLC (elution with 5% EtOAc-hexanes and then with 2.5% EtOAc-hexanes). For **13a**: mp 164-167 ºC; IR (film) 2943, 2865, 1703, 1563, 1455 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$): δ 8.10 (d, *J* = 7.9 Hz, 2 H), 7.25-7.54 (m, 4 H), 7.23 (t, *J* = 7.6 Hz, 1 H), 6.82 (br s, 1 H), 4.84 (d, *J* = 4.9 Hz, 1 H), 3.32-3.38 (m, 1 H), 2.34 (s, 3 H), 1.62 (sept, *J* = 7.5 Hz, 3 H), 1.43 (d, *J* = 7.0 Hz, 3 H), 1.16 (d, *J* = 7.5 Hz, 9 H), 1.16 (d, *J* = 7.5 Hz, 9 H); ^{13}C NMR (125 MHz, $CDCl_3$): δ 206.2, 187.2, 136.3, 125.7 (2 C), 120.7 (2 C), 119.5, 109.0, 66.1, 45.6, 19.19, 19.17, 19.06, 17.9, 12.0. HRMS (ESI) Calcd for $C_{28}H_{37}NOSi$ $(M+H)^+$: 432.2717. Found: 432.2705. For **13b** (partial): ^{1}H NMR (500 MHz, $CDCl_3$): δ 6.93-6.99 (m, 1 H), 5.30 (d, *J* = 7.5 Hz, 1 H), 3.40 (app quint, *J* = 7.5 Hz, 1 H), 2.32 (s, 3 H), 1.18 (d, *J* = 7.5 Hz, 9 H), 0.81 (d, *J* = 7.5 Hz, 3 H).

***trans*-5-(4′-Methoxy-phenyl)-3,4-dimethyl-2-(triisopropylsilyl)cyclopent-2-enone (14a).** A 25-mL, two-necked, round-bottomed flask equipped with a rubber septum and argon inlet adapter was charged with a solution of 1-[(4′-methoxy-phenyl)methyl]benzotriazole (**2g**) (0.102 g, 0.426 mmol) in 4.3 mL of THF and then cooled at -78 °C while *n*-BuLi solution (2.33 M in hexane, 0.183 mL, 0.426 mmol) was added dropwise over 1 min. The resulting deep green mixture was stirred at -78 °C for 1 h and then a

solution of silylketene **1a** (0.103 g, 0.406 mmol) in 1.4 mL of THF was added dropwise via cannula over 2 min. After 1 h, a solution of $ZnBr_2$ (1.00 M in THF, 1.22 mL, 1.22 mmol) was added dropwise over 2 min. The resulting bright yellow mixture was allowed to slowly warm to rt over 10 h, after which time the reaction flask was equipped with a reflux condenser and the mixture was heated at reflux for 4 h. After cooling, the reaction mixture was diluted with 25 mL of Et_2O and washed with 10 mL of 1 N aq HCl solution, 10 mL of saturated NaCl solution, dried over $MgSO_4$, filtered, and concentrated to afford 0.252 g of an orange oil. This material was dissolved in CH_2Cl_2 and concentrated onto 0.5 g of silica gel which was transferred to the top of a column of 20 g of silica gel. Gradient elution with 0-8% EtOAc-hexanes provided 0.052 g (34%) of cyclopentenone **14a** (≥99:1 *trans*:*cis* by ^{1}H NMR analysis) as a pale yellow oil: IR (film) 2943, 2865, 1692, 1576, 1513, 1463, 1249 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.02 (d, *J* = 8.7 Hz, 2 H), 6.85 (d, *J* = 8.7 Hz, 2 H), 3.78 (s, 3 H), 3.06 (d, *J* = 3.2 Hz, 1 H), 2.81 (qd, *J* = 7.2, 3.3 Hz, 1 H), 2.26 (s, 3 H), 1.54 (sept, *J* = 7.5 Hz, 3 H), 1.31 (d, *J* = 7.1 Hz, 3 H), 1.08 (d, *J* = 7.5 Hz, 9 H), 1.05 (d, *J* = 7.5 Hz, 9 H); ^{13}C NMR (125 MHz, C_6D_6): δ 211.2, 188.8, 159.3, 135.4, 133.0, 129.5, 114.8, 61.6, 55.1, 51.9, 19.54, 19.50, 19.1, 18.9, 12.4. HRMS (ESI) Calcd for $C_{23}H_{36}O_2Si$ $(M+Na)^+$: 395.2377. Found: 395.2377.

***trans*-3,4,5-Trimethyl-5-phenoxy-2-(triisopropylsilyl)cyclopent-2-enone (15a) and *cis*-3,4,5-Trimethyl-5-phenoxy-2-(triisopropylsilyl)cyclopent-2-enone (15b).** A 25-mL, two-necked, round-bottomed flask equipped with a rubber septum and argon inlet adapter was charged with a solution of the substituted benzotriazole **4h** (0.081 g, 0.339 mmol) in 3.4 mL of THF and then cooled at -78 °C while *n*-BuLi solution (2.39 M in hexane, 0.14 mL, 0.33 mmol) was added dropwise over 1 min. The resulting deep red solution was stirred at -78 °C for 5 min[12] and then a solution of silylketene **1a** (0.081 g, 0.321 mmol) in 1.1 mL of THF was added dropwise via cannula over 2 min. After 2 h, a solution of $ZnBr_2$ (1.0 M in THF, 0.97 mL, 0.97 mmol) was added dropwise over 2 min and the resulting yellow solution was allowed to slowly warm to rt over 14 h, during which time a white precipitate formed. The reaction mixture was then diluted with 30 mL of Et_2O and filtered though a fritted glass funnel containing Celite. The filtrate was washed with 15 mL of 1 N aq HCl solution, 15 mL of saturated NaCl solution, dried over $MgSO_4$, filtered, and concentrated to afford 0.166 g of a yellow oil. This material was dissolved in CH_2Cl_2 and concentrated onto 0.5 g of silica gel which was transferred to the top of a column of 17 g of

[12] In this case some decomposition of the lithiated benzotriazole derivative was observed when metallation was allowed to proceed for longer than 5 min.

silica gel. Gradient elution with 0-5% EtOAc-hexanes provided 0.078 g (65%) of a mixture of *trans*-cyclopentenone **15a** and *cis*-cyclopentenone **15b** (75:25 by ^{1}H NMR analysis) as a colorless oil. Pure samples of each isomer were obtained by preparative TLC (elution with 5% EtOAc-hexanes). The *trans* isomer **15a** was obtained as a colorless oil which partially solidified upon standing: IR (film) 2943, 2865, 1706, 1567, 1493 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.15-7.20 (m, 2 H), 6.94 (tt, *J* = 7.4, 1.0 Hz, 1 H), 6.74-6.78 (m, 2 H), 3.22 (qd, *J* = 7.4, 1.0 Hz, 1 H), 2.17 (d, *J* = 1.1 Hz, 3 H), 1.55 (sept, *J* = 7.5, 3 H), 1.33 (s, 3 H), 1.18 (d, *J* = 7.4 Hz, 3 H), 1.07 (d, *J* = 7.5 Hz, 9 H), 1.06 (d, *J* = 7.5 Hz, 9 H); ^{13}C NMR (125 MHz, $CDCl_3$): δ 210.7, 186.4, 155.5, 134.1, 129.4, 122.2, 119.4, 85.8, 46.2, 21.1, 19.2, 19.04, 18.97, 12.4, 12.0. HRMS (ESI) Calcd for $C_{23}H_{36}O_2Si$ $(M+H)^+$: 373.2557. Found: 373.2556. The *cis* isomer **15b** was obtained as a colorless oil: IR (film) 2942, 2865, 1705, 1578, 1493, 1230 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.23-7.27 (m, 2 H), 7.03-7.07 (m, 2 H), 6.99 (tt, *J* = 7.3, 1.0 Hz, 1 H), 2.85 (q, *J* = 7.1 Hz, 1 H), 2.23(s, 3 H), 1.54 (sept, *J* = 7.5, 3 H), 1.39 (s, 3 H), 1.27 (d, *J* = 7.1 Hz, 3 H), 1.07 (app t, *J* = 7.5 Hz, 18 H); ^{13}C NMR (125 MHz, $CDCl_3$): δ 210.7, 187.4, 155.8, 131.5, 129.2, 122.1, 120.3, 85.2, 54.3, 22.1, 20.1, 19.02, 18.99, 16.3, 11.9.

***trans*-3,4,5-Trimethyl-5-phenylthio-2-(triisopropylsilyl)cyclopent-2-enone (16a).** An oven-dried, 25-mL, one-necked, round-bottomed flask equipped with a three-way stopcock adapter (fitted with a rubber septum and connected to a vacuum/Ar manifold) was charged with the benzotriazole derivative **4i** (0.121 g, 0.474 mmol). Toluene (5 mL) was added and the resulting solution was concentrated at 0.2 mmHg with vigorous stirring. This process was repeated twice, and the residue was then dissolved in 4.7 mL of THF and cooled at -78 °C while *n*-BuLi solution (2.45 M in hexane, 0.18 mL, 0.44 mmol) was added dropwise over 1 min. The resulting deep purple solution was stirred at -78 °C for 1 h and then a solution of silylketene **1a** (0.108 g, 0.428 mmol) in 1.4 mL of THF was added dropwise via cannula over 2 min. After 1 h, a solution of $ZnBr_2$ (1.0 M in THF, 1.3 mL, 1.3 mmol) was added dropwise over 2 min and the resulting bright yellow solution was allowed to slowly warm to rt over 15 h, during which time a white precipitate formed. The reaction mixture was diluted with 30 mL of Et_2O and filtered through a fritted glass funnel containing Celite. The filtrate was washed with 15 mL of 1 N aq HCl solution, and the aqueous phase was backextracted with 15 mL of Et_2O. The combined organic layers were washed with 15 mL of saturated NaCl solution, dried over $MgSO_4$, filtered, and concentrated to afford 0.208 g of a yellow oil. This material was dissolved in CH_2Cl_2 and concentrated onto 0.5 g of silica gel which was transferred to the top of a column of 21 g of silica gel. Gradient elution with 0-2.5% EtOAc-hexanes

provided 0.107 g (64%) of cyclopentenone **16a** (97:3 mixture of *trans*:*cis* isomers by ^{1}H NMR analysis) as a colorless oil which partially solidified upon standing. For *trans*-cyclopentenone **16a**: IR (film) 2943, 2865, 1694, 1580, 1464, 1254 cm^{-1}; ^{1}H NMR (500 MHz, C_6D_6): δ 7.63-7.67 (m, 2 H), 6.97-7.06 (m, 3 H), 2.69 (q, *J* = 7.3 Hz, 1 H), 1.68 (s, 3 H), 1.60 (sept, *J* = 7.5 Hz, 3 H), 1.26 (s, 3 H), 1.15 (app t, *J* = 7.5 Hz, 18 H), 0.77 (d, *J* = 7.4 Hz, 3 H); ^{13}C NMR (125 MHz, C_6D_6): δ 210.0, 186.4, 137.1, 133.1, 132.8, 129.2, 129.1, 58.5, 52.5, 19.9, 19.50, 19.48, 19.0, 15.1, 12.5. HRMS (ESI) Calcd for $C_{23}H_{36}OSSi$ $(M+Na)^+$: 411.2148. Found: 411.2164.

Part III. Experimental Procedures for Transformations of Annulation Products

***trans*-5-Ethoxy-3,4-dimethyl-5-propyl-2-(triisopropylsilyl)cyclopent-2-enone (8a).** A 50-mL, one-necked, round-bottomed flask equipped with a rubber septum and argon inlet needle was charged with a solution of (triisopropylsilyl)cyclopentenone **7a** (0.030 g, 0.086 mmol) in 8.6 mL of EtOH. Palladium on carbon (5 wt%, 0.018 g, 0.008 mmol) was added, and the rubber septum was replaced with a Claisen adapter (fitted with a gas outlet adapter and a thermometer adapter). A balloon filled with H_2 was attached to a disposable glass pipette, and the pipette was inserted through the thermometer adapter so that the tip of the pipette was submerged into the reaction mixture. The stopcock on the gas outlet adapter was carefully opened to obtain a modest rate of H_2 bubbling, and the reaction mixture was stirred at rt for 4 h (the H_2 balloon was refilled as necessary). The reaction mixture was then filtered through a fritted glass funnel containing Celite with the aid of ca. 20 mL of EtOH, and the filtrate was concentrated to afford 0.033 g of a colorless oil. Column chromatography on 5 g of silica gel (elution with 3% EtOAc-hexanes) provided 0.030 g (100%) of cyclopentenone **8a** (96:4 mixture of *trans*:*cis* isomers by ^{1}H NMR analysis) as a colorless oil which partially solidified upon standing. For *trans*-cyclopentenone **8a**: IR (film) 2962, 2867, 1698, 1577, 1463 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$): δ 3.24-3.38 (m, 2 H), 2.83 (q, *J* = 7.3 Hz, 1 H), 2.16 (s, 3 H), 1.24-1.61(m, 7 H), 1.11-1.15 (m, 6 H), 1.04 (app d, *J* = 7.5 Hz, 18 H), 0.90 (t, *J* = 7.3 Hz, 3 H); ^{13}C NMR (125 MHz, $CDCl_3$): δ 211.0, 187.6, 133.3, 86.0, 59.3, 48.8, 33.2, 19.5, 19.00, 18.99, 16.5, 15.9, 14.8, 13.6, 11.9. HRMS (ESI) Calcd for $C_{21}H_{40}O_2Si$ $(M+Na)^+$: 375.2690. Found: 375.2697.

***trans*-2-Iodo-5-methoxy-3,4-dimethylcyclopent-2-enone (22).** A 25-mL, two-necked, round-bottomed flask equipped with a rubber septum and argon inlet adapter was charged with a solution of

(triisopropylsilyl)cyclopentenone **11a** (0.324 g, 1.09 mmol) in 3 mL of CH_2Cl_2 and then cooled at 0 °C while a solution of ICl (1.0 M in CH_2Cl_2, 2.2 mL, 2.2 mmol) was added dropwise over 4 min. The resulting deep red solution was stirred at 0 °C in the dark for 2 h and then a second portion of ICl (1.0 M in CH_2Cl_2, 1.1 mL, 1.1 mmol) was added dropwise over 1 min. After 2 h, a third portion of ICl (1.0 M in CH_2Cl_2, 0.55 mL, 0.55 mmol) was added dropwise over 1 min. The deep red reaction mixture was stirred for an additional hour at 0 °C and then was diluted with 50 mL of CH_2Cl_2 and washed with 40 mL of saturated $Na_2S_2O_3$ solution. The aqueous phase was backextracted with three 15-mL portions of CH_2Cl_2, and the combined organic layers were washed with 40 mL of saturated NaCl solution, dried over $MgSO_4$, filtered, and concentrated to afford 0.512 g of an oily, yellow-green solid. Column chromatography on 50 g of silica gel (elution with 10% EtOAc-hexanes) provided 0.234 g of iodocyclopentenone **22** (≥99:1 *trans*:*cis* by ^{1}H NMR analysis) as a pale yellow oil: IR (film) 2966, 2931, 2829, 1724, 1597, 1452 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$): δ 3.61 (s, 3 H), 3.56 (d, *J* = 2.8 Hz, 1 H), 2.80-2.86 (m, 1 H), 2.18 (d, *J* = 1.2 Hz, 3 H), 1.34 (d, *J* = 7.3 Hz, 3 H); ^{13}C NMR (125 MHz, $CDCl_3$): δ 200.5, 180.5, 100.8, 84.9, 58.8, 47.2, 20.4, 17.0. HRMS (ESI) Calcd for $C_8H_{11}IO_2$ $(M+Na)^+$: 288.9696. Found: 288.9695.

***trans*-2-Iodo-5-methoxy-3,4-dimethylcyclopent-2-enone (22).** A 25-mL, two-necked, round-bottomed flask equipped with a rubber septum and argon inlet adapter was charged with a solution of (triethylsilyl)cyclopentenone **12a** (0.215 g, 0.845 mmol) in 3 mL of CH_2Cl_2 and then cooled at 0 °C while a solution of ICl (1.0 M in CH_2Cl_2, 1.0 mL, 1.0 mmol) was added dropwise over 1 min. The resulting deep red solution was stirred at 0 °C in the dark for 2.5 h. The reaction mixture was then diluted with 30 mL of CH_2Cl_2 and washed with 25 mL of saturated $Na_2S_2O_3$ solution. The aqueous phase was extracted with two 10-mL portions of CH_2Cl_2, and the combined organic layers were washed with 25 mL of saturated NaCl solution, dried over $MgSO_4$, filtered, and concentrated to afford 0.311 g of a yellow oil mixed with some white solid. Column chromatography on 23 g of silica gel (elution with 10% EtOAc-hexanes) provided 0.200 g of iodocyclopentenone **22** (≥99:1 *trans*:*cis* by ^{1}H NMR analysis) as a pale yellow oil.

***trans*-5-Methoxy-3,4-dimethylcyclopent-2-enone (23).** A 25-mL, one-necked, round-bottomed flask equipped with a rubber septum and argon inlet needle was charged with iodocyclopentenone **22** (0.141 g, 0.530 mmol). The reaction flask was purged with argon for 10 min, and then 2.5 mL of THF, Bu_3SnH (0.428 mL, 0.463 g, 1.59 mmol), and AIBN (0.50 M in THF, 0.11 mL, 0.06 mmol) were added. The rubber septum was replaced with a reflux condenser and the reaction mixture was heated at 55 °C for

1 h. The reaction mixture was allowed to cool to rt and then concentrated by rotary evaporation at ca. 20 mmHg (bath temperature 0-10 °C) to afford 0.492 g of a pale yellow liquid. Column chromatography on 12 g of silica gel (elution with 0-20% EtOAc-hexanes) provided 0.078 g of a pale yellow liquid. This material was dissolved in 15 mL of CH_3CN and washed with three 10-mL portions of hexanes to remove the last traces of tributyltin-containing impurities.[13] Concentration of the CH_3CN phase at 20 mmHg and 0-10 °C provided 0.065 g (88%) of cyclopentenone **23** (≥99:1 *trans*:*cis* by ^{1}H NMR analysis) as a pale yellow oil: IR (film) 2968, 2828, 1710, 1618, 1438 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$): δ 5.88 (s, 1 H), 3.59 (s, 3 H), 3.47 (d, *J* = 2.8 Hz, 1 H), 2.68-2.74 (m, 1 H), 2.08 (s, 3 H), 1.31 (d, J = 7.4 Hz, 3 H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 205.6, 178.9, 128.4, 87.4, 58.6, 45.0, 17.5, 16.8. HRMS (ESI) Calcd for $C_8H_{12}O_2$ $(M+Na)^+$: 163.0730. Found: 163.0725.

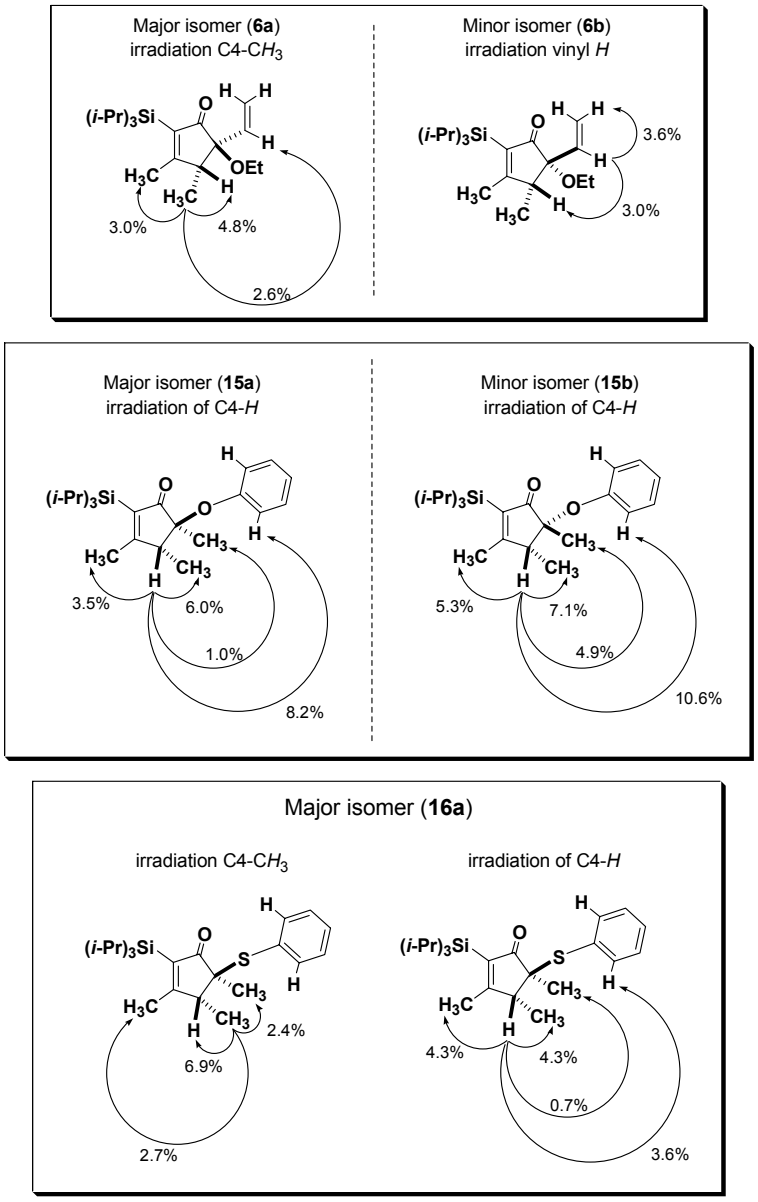
***trans*-5-Methoxy-3,4-dimethyl-2-(2-trimethylsilylethynyl)cyclopent-2-enone (24).** A 10-mL, two-necked, round-bottomed flask equipped with a rubber septum and argon inlet adapter was charged with $(Ph_3P)_2PdCl_2$ (0.012 g, 0.017 mmol), CuI (0.002 g, 0.011 mmol), and a solution of iodocyclopentenone **22** (0.075 g, 0.282 mmol) in 2 mL of THF. Trimethylsilylacetylene (0.0.060 mL, 0.042 g, 0.428 mmol) was added, followed by *i*-Pr_2NH (0.395 mL, 0.285 g, 2.82 mmol), and the resulting mixture was stirred at rt for 3 h. The dark brown reaction mixture was diluted with 5 mL of Et_2O and filtered through a plug of 1 g of silica gel with the aid of 50 mL of Et_2O. The filtrate was washed with 25 mL of saturated $Na_2S_2O_3$ solution, and the aqueous phase was backextracted with 25 mL of Et_2O. The combined organic layers were washed with 25 mL of saturated NaCl solution, dried over $MgSO_4$, filtered, and concentrated to afford 0.100 g of a yellow-brown oil. Column chromatography on 14 g of silica gel (elution with 10% EtOAc-hexanes) provided 0.065 g (97%) of cyclopentenone **24** (≥99:1 *trans*:*cis* by ^{1}H NMR analysis) as a pale orange solid: mp 43-45 ºC; IR (film) 2963, 2829, 2158, 1721, 1608, 1380 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$): δ 3.58 (s, 3 H), 3.46 (d, *J* = 3.1 Hz, 1 H), 2.68-2.75 (m, 1 H), 2.19 (d, *J* = 1.2 Hz, 3 H), 1.30 (d, *J* = 7.3 Hz, 3 H), 0.22 (s, 9 H); ^{13}C NMR (125 MHz, $CDCl_3$): δ 201.7, 181.0, 124.1, 103.9, 94.7, 86.6, 58.6, 44.1, 17.0, 16.8, 0.1. HRMS (ESI) Calcd for $C_{13}H_{20}O_2Si$ $(M+Na)^+$: 259.1125. Found: 259.1113.

[13] For a discussion of the removal of organotin impurities by this extraction procedure see: J. M. Berge, S. M. Roberts, *Synthesis* **1979,** 471.

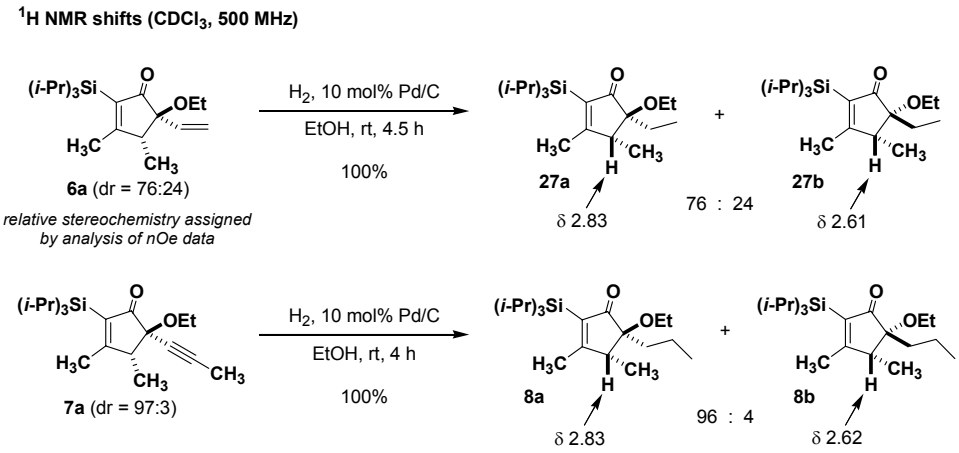
Part IV. Assignment of Stereochemistry for Cyclopentenone Products

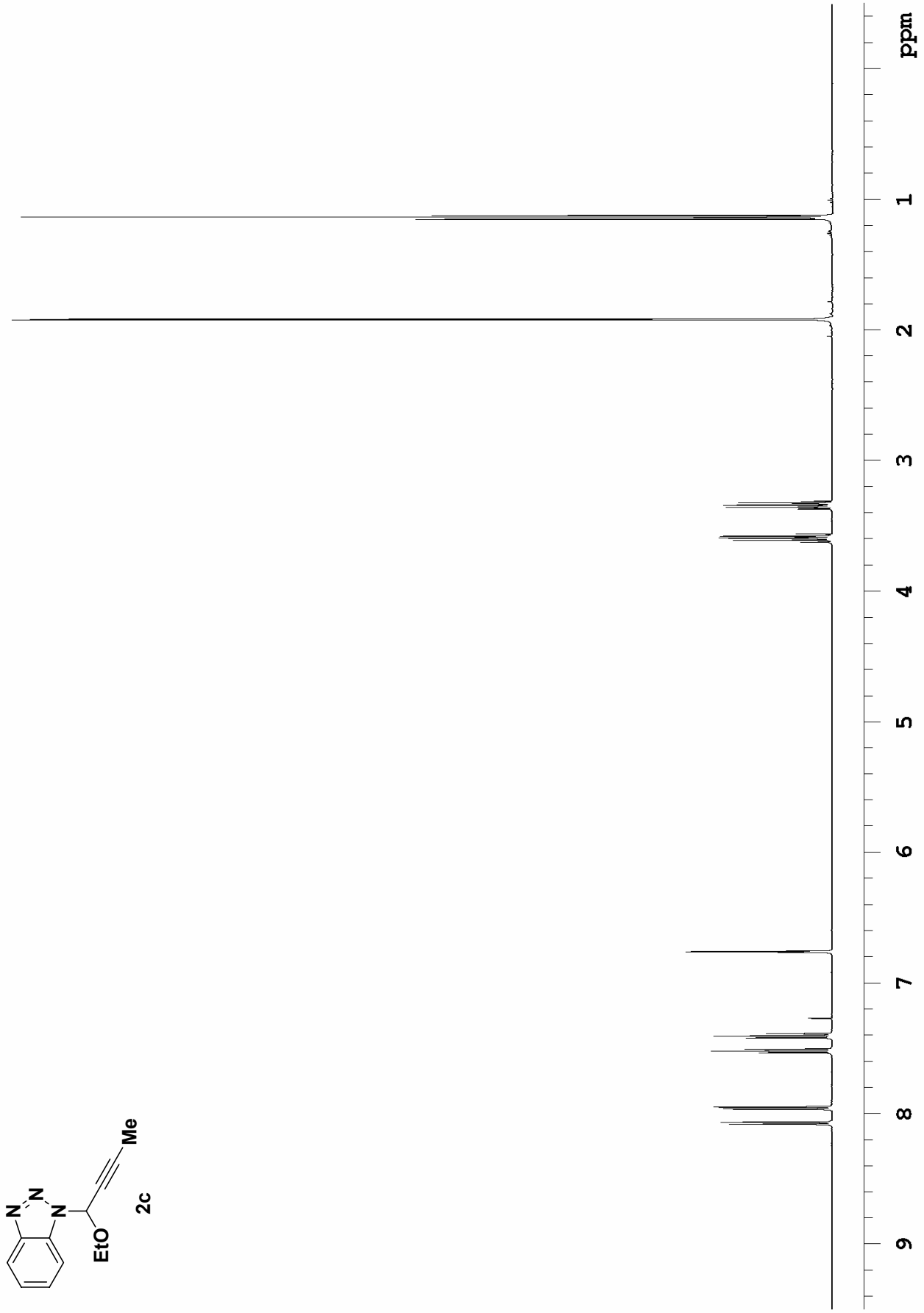
The relative stereochemistry of cyclopentenones **9a-14a** was assigned based on analysis of ^{1}H NMR coupling constants. Stereochemical assignments for cyclopentenones **4a** and **5a** are based on analysis of ^{1}H NMR coupling constants of the corresponding secondary amines after cleavage of the BOC group.

The relative stereochemistry of cyclopentenones **6**, **15**, and **16** was assigned based on nOe experiments as summarized below.



The relative stereochemistry of cyclopentenone **7** was assigned by comparison of ^{1}H NMR chemical shift data for its hydrogenation products **8a** and **8b** with that of cyclopentenones **27a** and **27b** (derived from **6a** and **6b** whose stereochemistry had been determined from nOe studies).

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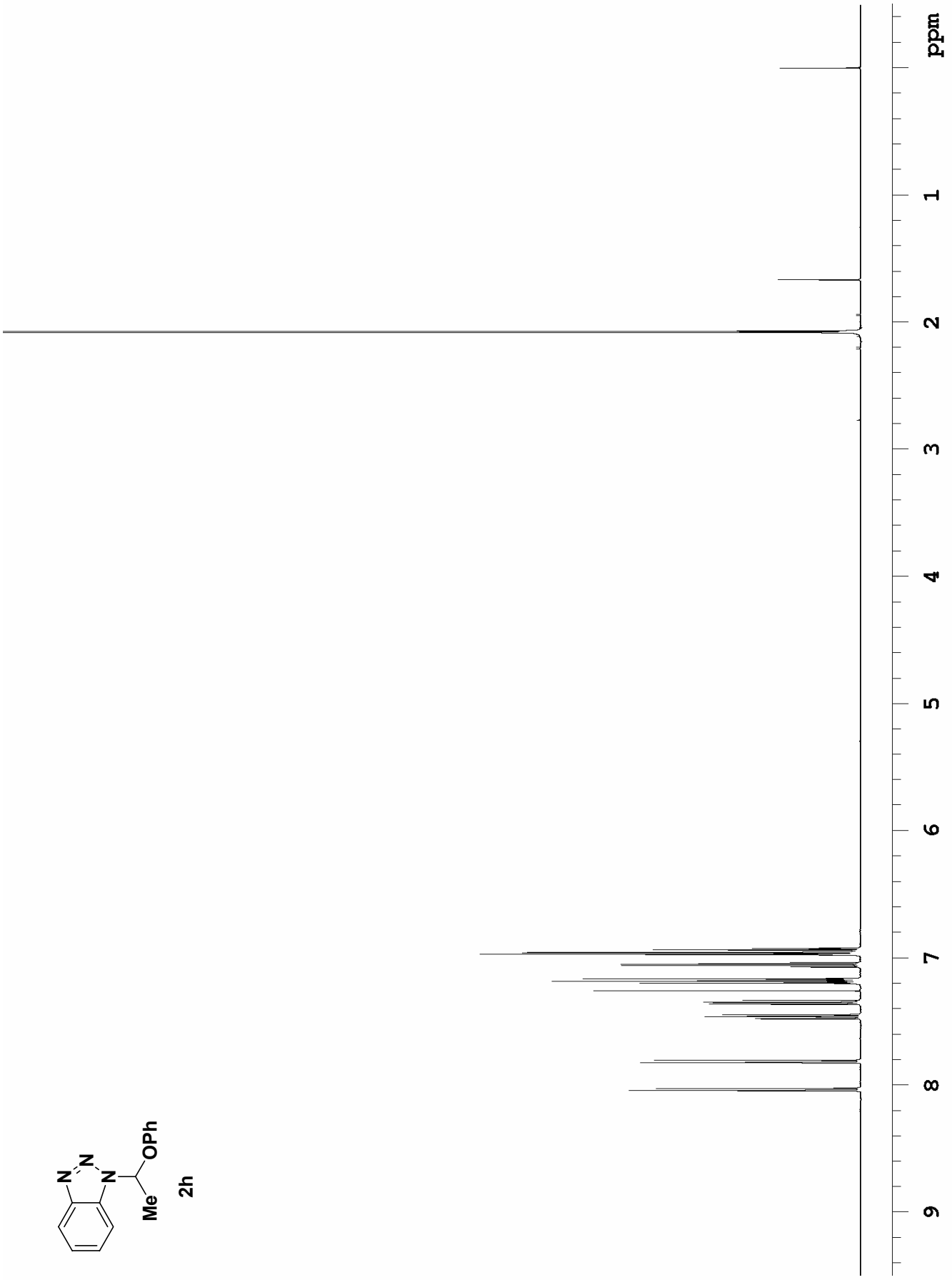
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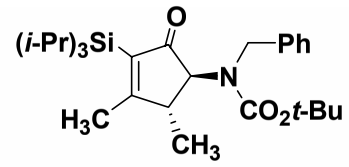
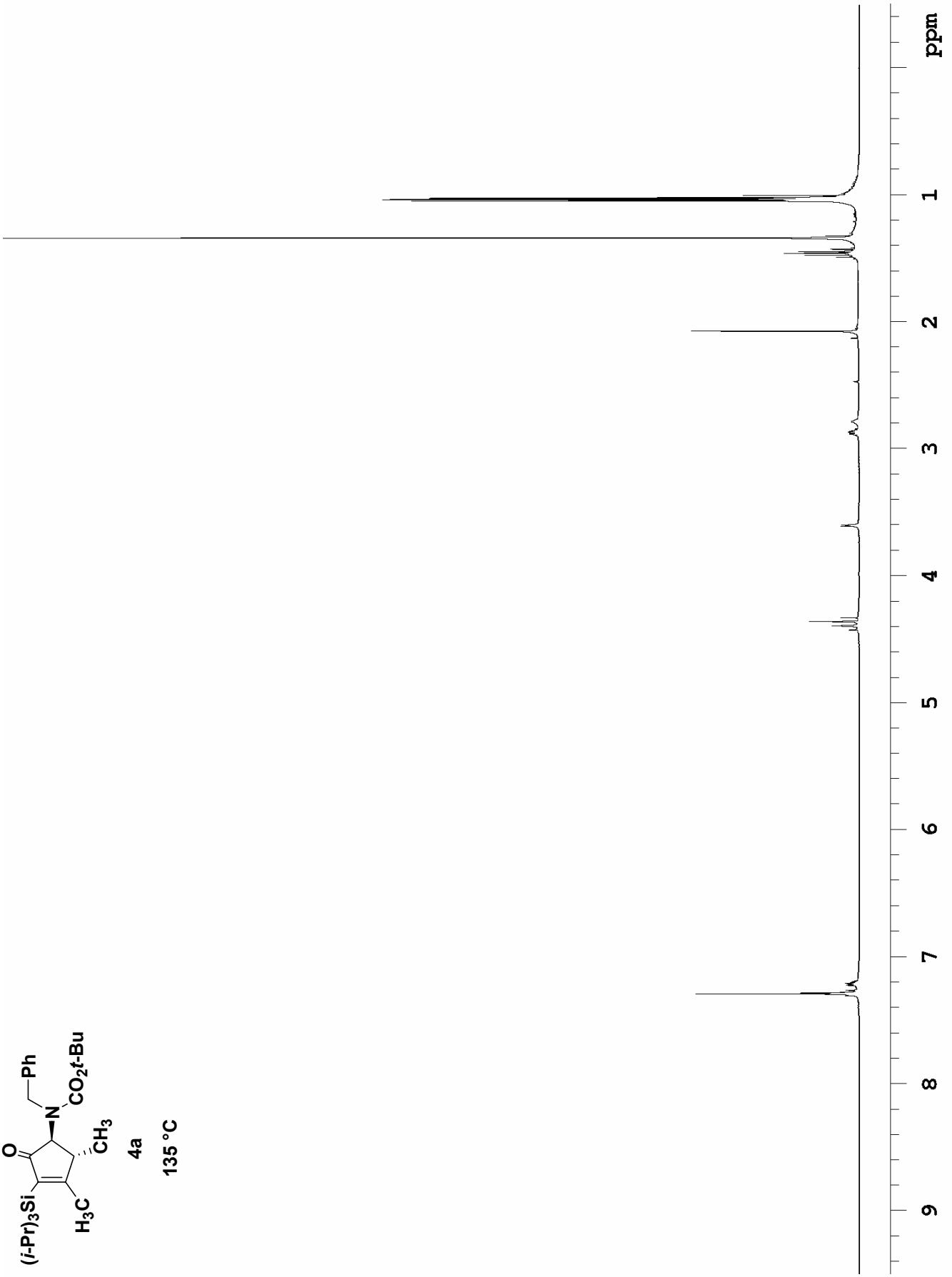


4a

20 °C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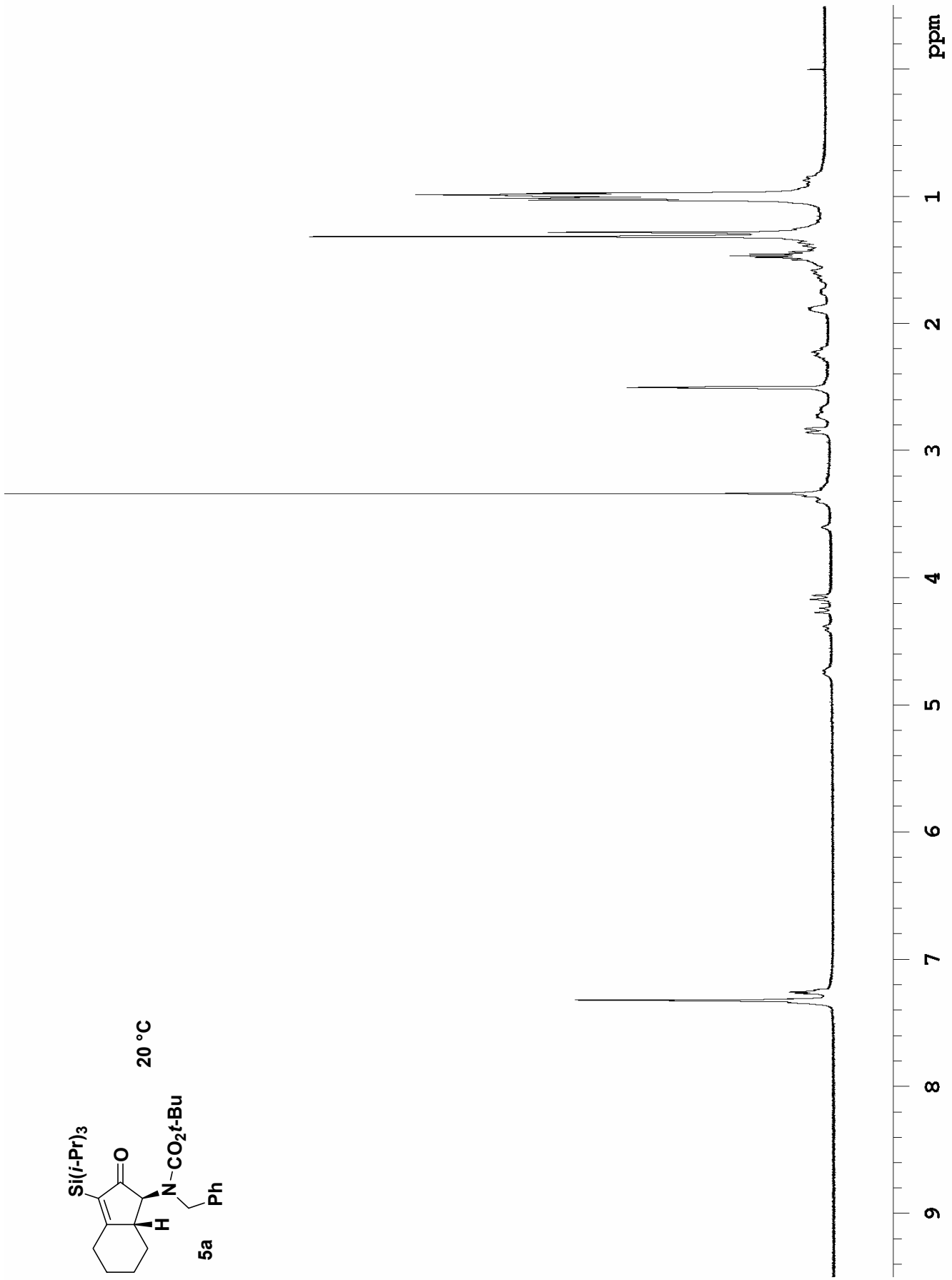
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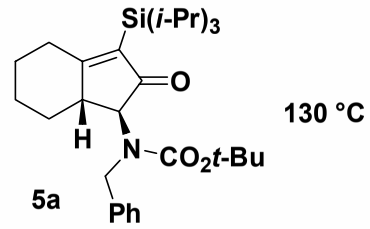
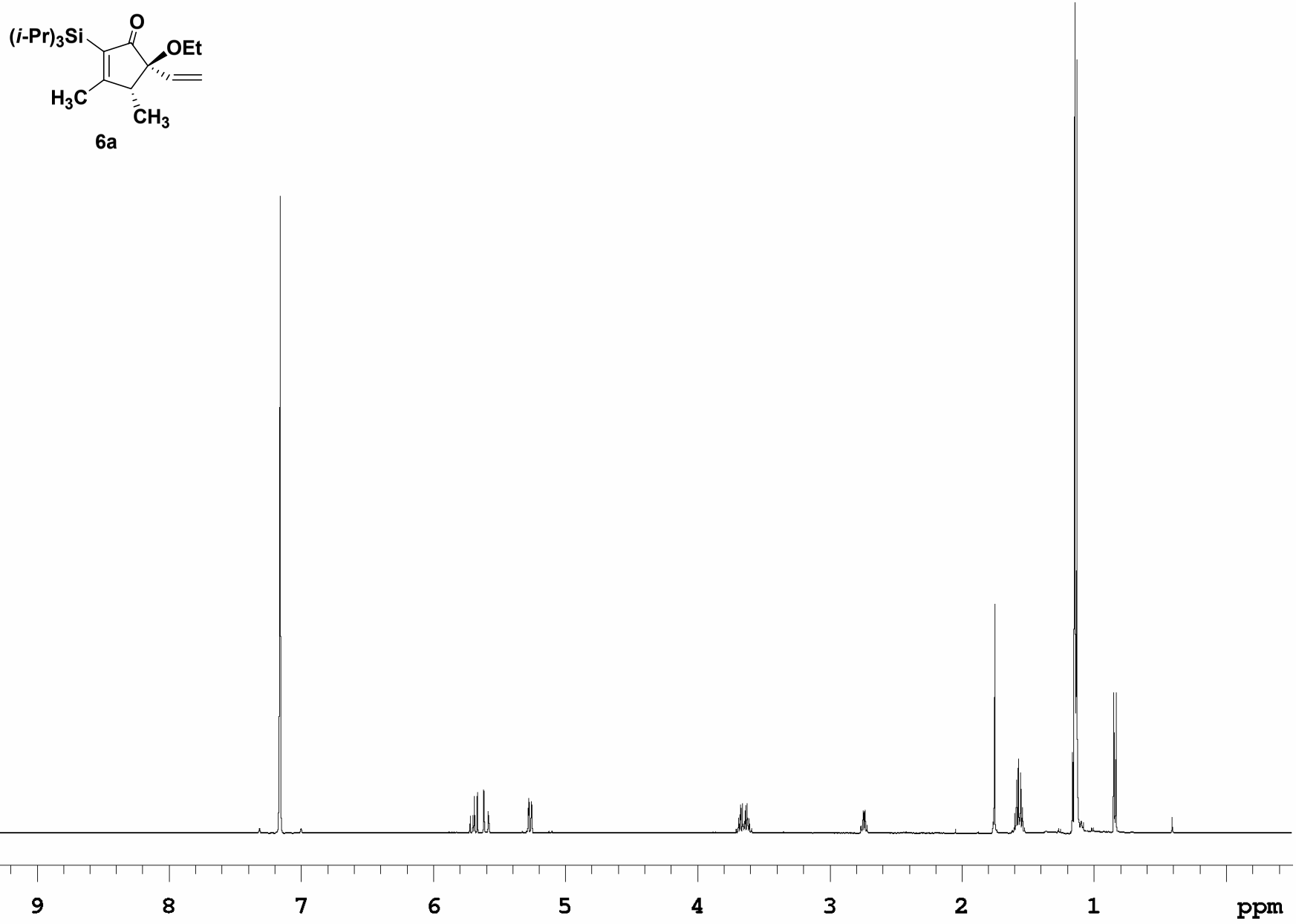


5a

130 °C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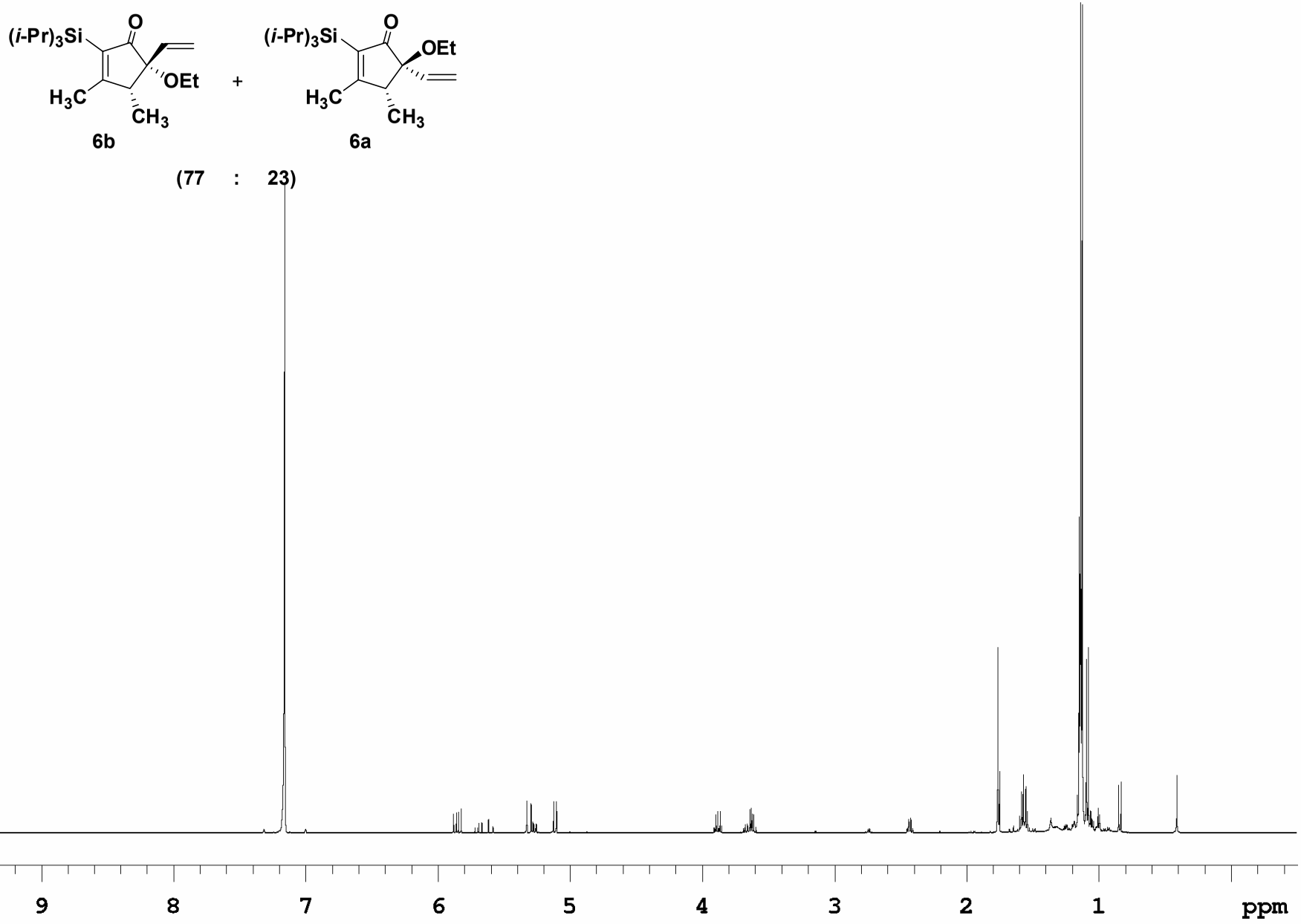
ppm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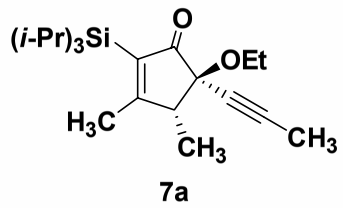
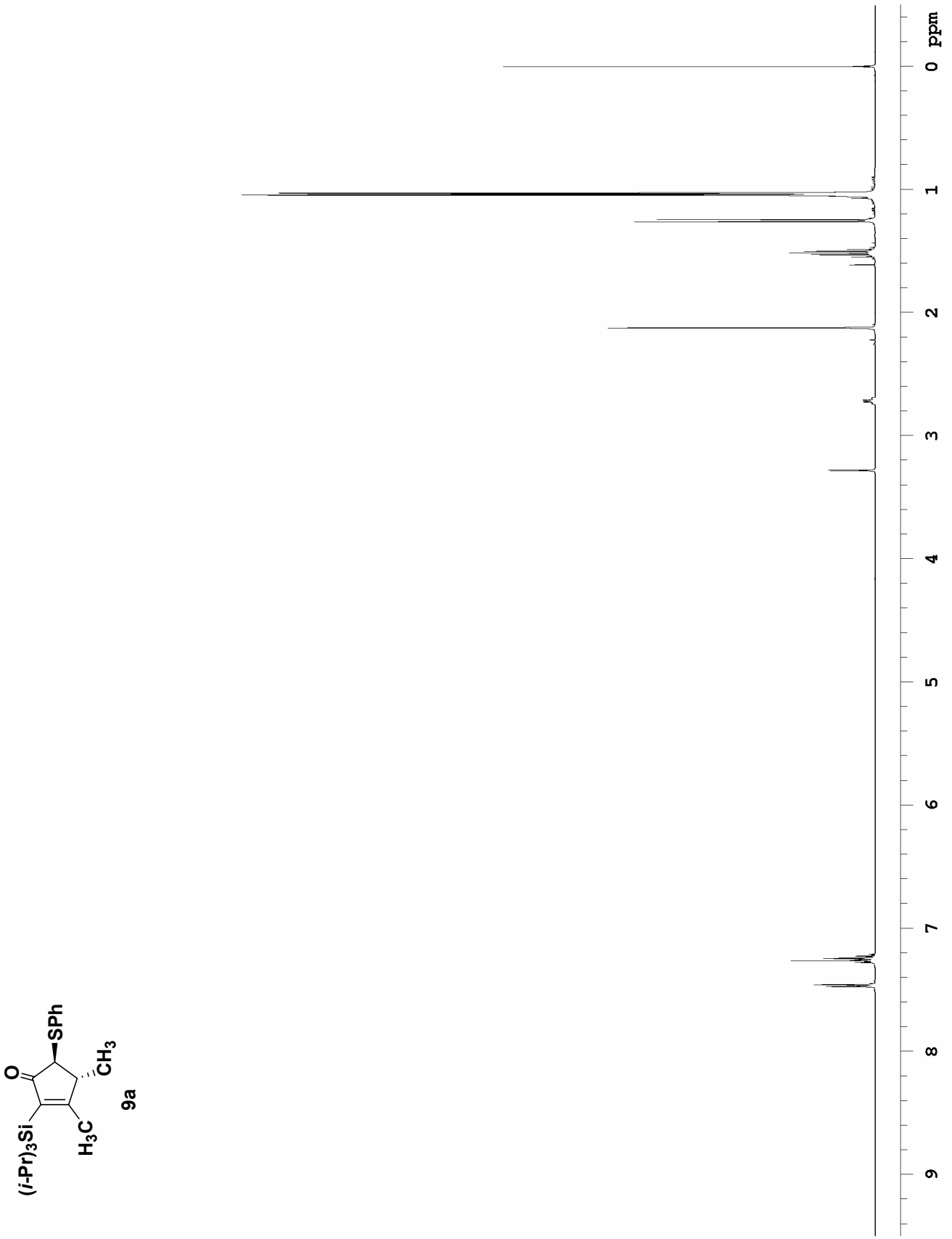


7a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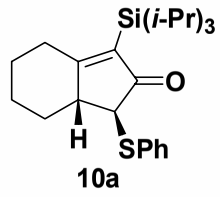
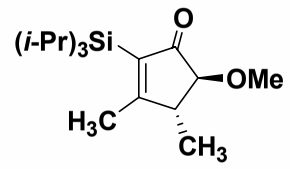
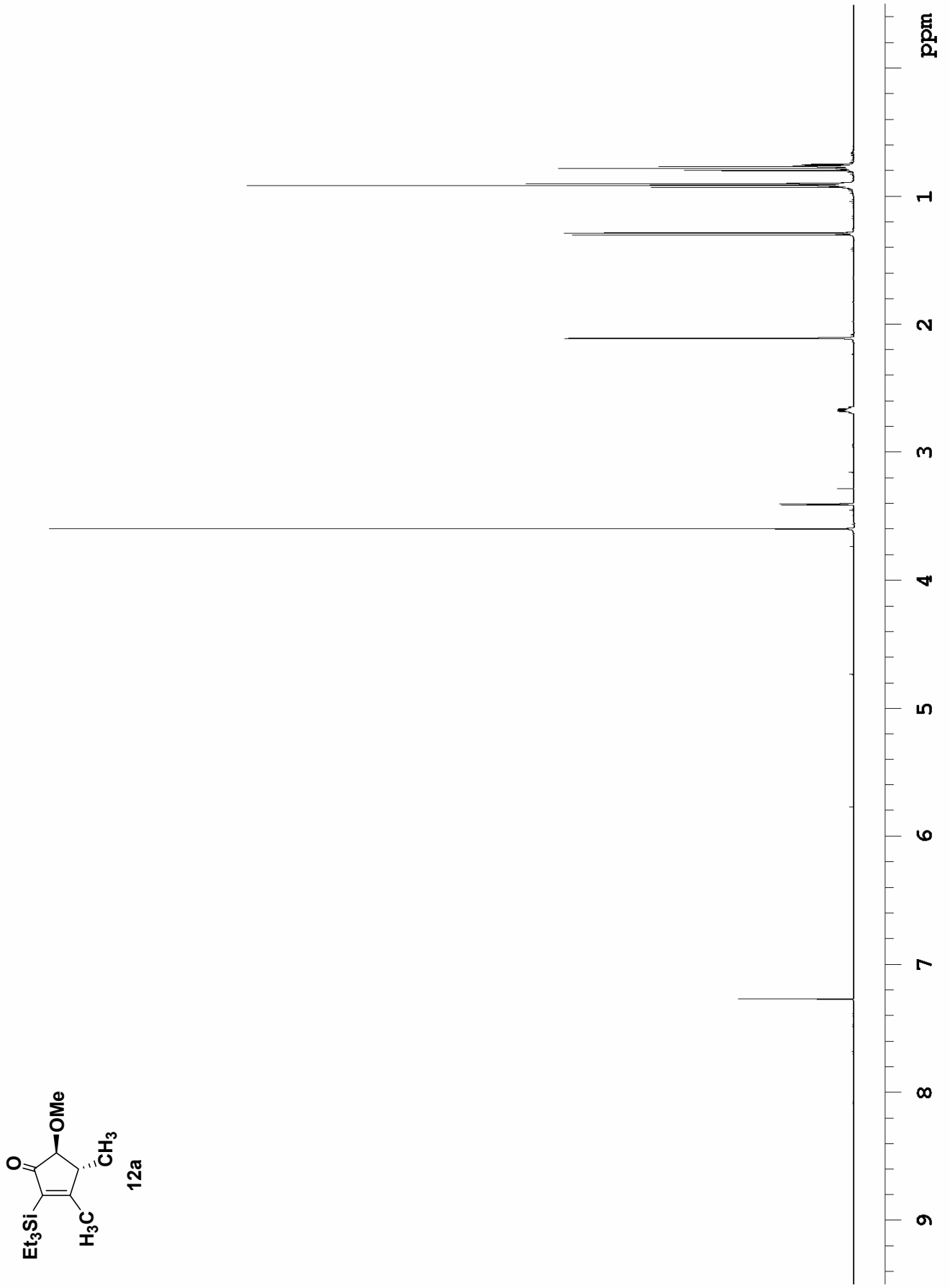


10a



11a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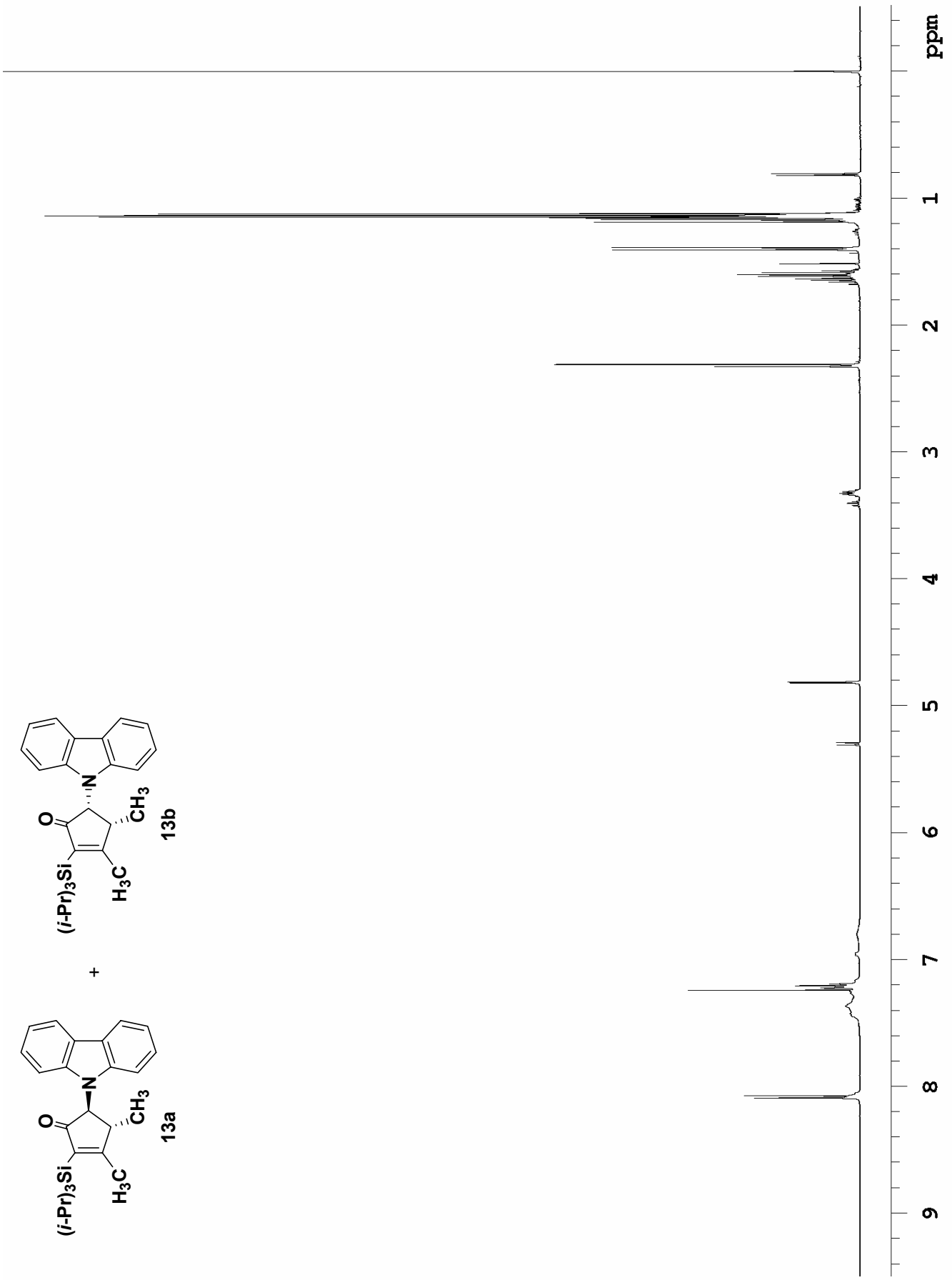
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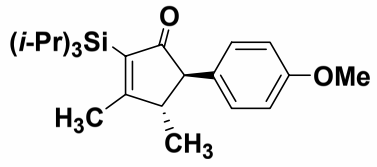

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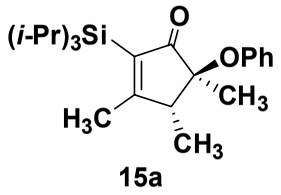

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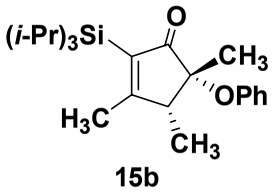

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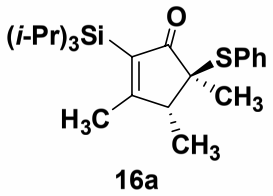
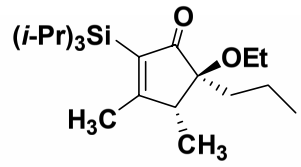
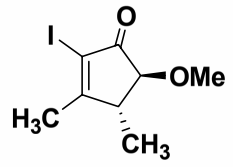


16a



8a



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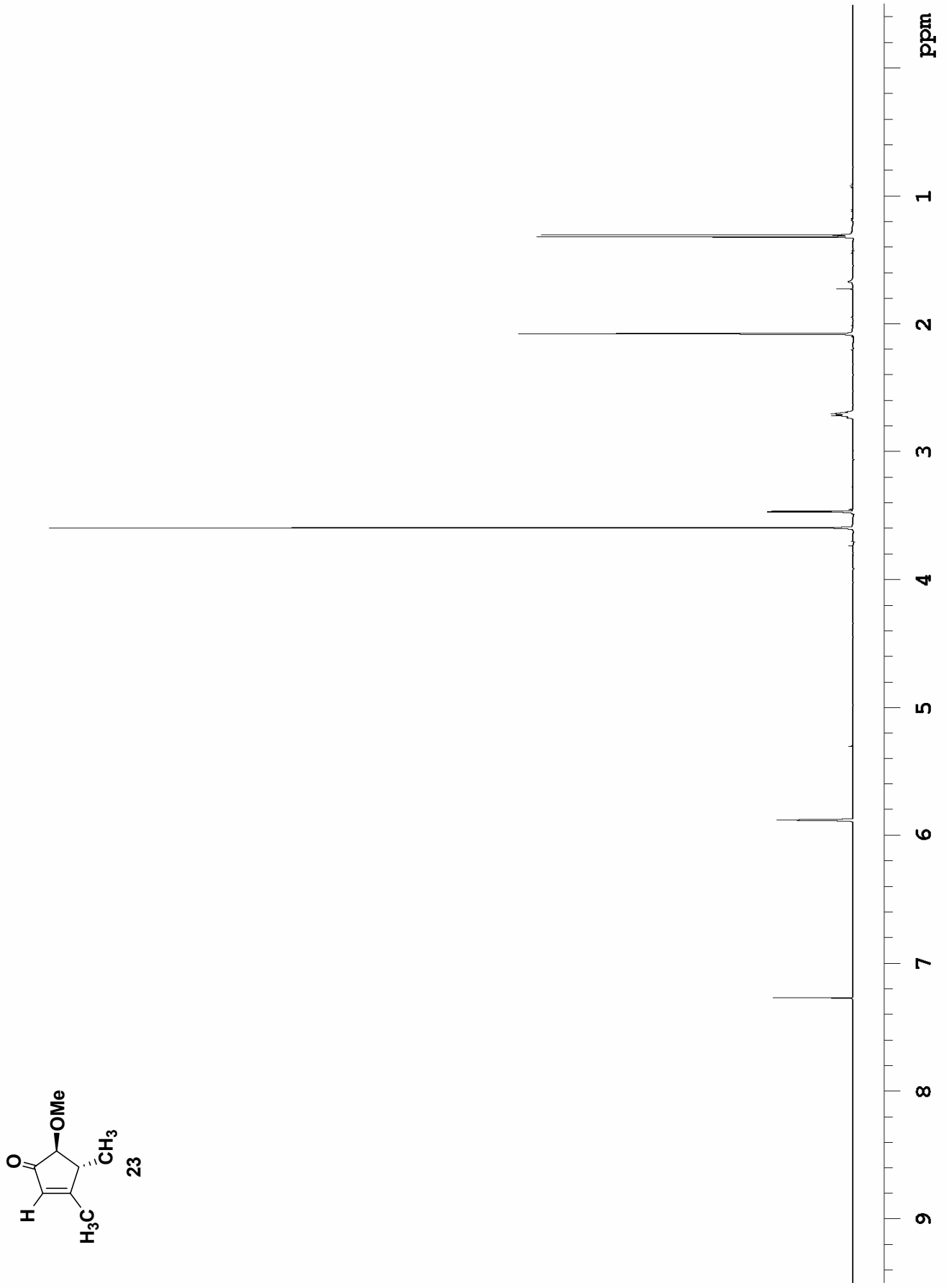
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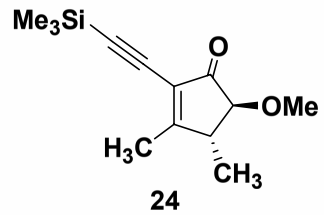

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