Reactions of (Trialkylsilyl)vinylketenes with Lithium Ynolates: A New Benzannulation Strategy

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Supporting Information

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 were 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 Merck precoated glass-backed silica gel 60 F-254 0.25 mm plates. Column chromatography was performed on Silicycle silica gel 60 (230-400 mesh), or Sorbent silica gel 60A (32-63 μm).

Materials. (Triisopropylsilyl)vinylketenes **6a** and **6b** were prepared as described previously.¹ 2-Cyclohexyl-1-(triisopropylsiloxy)ethyne (**9a**) and 3-methyl-1-(triisopropylsiloxy)-1-butyne (**9b**) were prepared from ethyl cyclohexanecarboxylate² and ethyl isobutyrate³ respectively via the one-step Kowalski reaction as reported previously. Siloxy alkynes **9d**⁴ and **9e**⁵ have been prepared from the corresponding alkynes by employing the method of Julia.⁶ Anhydrous *tert*-butyl hydroperoxide in toluene was prepared from the aqueous solution as described by Sharpless.⁷ Commercial grade reagents and solvents were used without further purification except as indicated below. Triisopropylsilyl trifluoromethanesulfonate, 1,1,1,3,3,3-hexamethyldisilazane, hexanes, benzene, and

¹ Loebach, J. L.; Bennett, D. M.; Danheiser, R. L. *J. Org. Chem.* **1998**, *63*, 8380.

² Kowalski, C. J.; Lal, G. S.; Haque, M. S. *J. Am. Chem. Soc.* **1986**, *108*, 7127.

³ Danheiser, R. L.; Helgason, A. L. *J. Am. Chem. Soc.* **1994**, *116*, 9471.

⁴ Zhang, L.; Kozmin, S. A. *J. Am. Chem. Soc.* **2004**, *126*, 10204.

⁵ Sweis, R. F.; Schramm, M. P.; Kozmin, S. A. *J. Am. Chem. Soc.* **2004**, *126*, 7442.

⁶ Julia, M.; Saint-James, V. P.; Verpeaux, J.-N. *Synlett* **1993**, 233.

⁷ Hill, J. G.; Rossiter, B. E.; Sharpless, K. B. *J. Org. Chem.* **1983**, *48*, 3607.

diisopropylethylamine were distilled under argon from calcium hydride. Dichloromethane, diethyl ether, and tetrahydrofuran were purified by pressure filtration through activated alumina. Toluene was purified by pressure filtration through activated alumina and copper(II) oxide. Methyllithium was obtained from either Aldrich Chemical Co. (1.6 M in Et₂O, 0.05 M halide content) or Alfa Aesar (1-2 M in Et₂O, “low halide”). In some cases decreased yields were observed when aged methyllithium was used in the benzannulation. Methyllithium and *n*-butyllithium were titrated according to the Watson-Eastham method using BHT in THF with 1,10-phenanthroline as an indicator.⁸

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. ¹H NMR and ¹³C NMR spectra were measured with a Varian Inova 500 MHz spectrometer or a Varian 300 MHz spectrometer. ¹H NMR chemical shifts are expressed in parts per million (δ) downfield from tetramethylsilane (with the CHCl₃ peak at 7.27 ppm or the residual benzene peak at 7.16 ppm used as a standard). ¹³C NMR spectra chemical shifts are expressed in parts per million (δ) downfield from tetramethylsilane (with the central peak of CDCl₃ at 77.23 ppm or the C₆D₆ peak at 128.06 used as a standard). High resolution mass spectra (HRMS) were measured on a Bruker Daltonics APEX II 3 tesla Fourier transform mass spectrometer or a Bruker Daltonics APEX IV 4.7 tesla Fourier transform ion cyclotron resonance mass spectrometer.

(E)-3-Methyl-3-hexen-2-one. A 250-mL, three-necked, round-bottomed flask fitted with an argon inlet adapter, rubber septum, and glass stopper was charged with a solution of *trans*-2-methyl-2-pentenoic acid (1.512 g, 13.24 mmol) in 150 mL of Et₂O and cooled at -78 °C in a dry ice-acetone bath. Methyllithium solution (1.49 M in Et₂O, 18 mL, 27 mmol) was added rapidly via syringe, and the resulting mixture was allowed to stir for 1 h. The dry ice-acetone bath was replaced with an ice-water bath, and the reaction mixture was stirred at 0 °C for 40 min and then transferred by cannula into a 500-mL, one-necked, round-bottomed flask fitted with a rubber septum containing 150 mL of 0.12 M aq HCl. The organic phase was separated and washed with two 50-mL portions of satd aq Na₂CO₃ solution and 50 mL of satd aq NaCl solution, dried over MgSO₄, filtered, and concentrated by atmospheric distillation (bath temperature 60 °C) through an 8-cm Vigreux column to ca. 2 mL. The residue was purified via bulb-to-bulb distillation at atmospheric pressure (bath temperature 150-175 °C) to yield 1.148 g (77%) of 3-methyl-3-hexen-2-one as a pale yellow oil with spectral characteristics consistent with those previously reported.⁹ IR (neat) 3047, 2969, 1670, 1641 cm⁻¹; ¹H NMR (500 MHz, CDCl₃) δ 6.59 (tq, *J* = 7.2, 1.3

⁸ (a) Watson, S. C.; Eastham, J. F. *J. Organomet. Chem.* **1967**, 9, 165. (b) Ellison, R. A.; Griffin, R.; Kotsonis, F. N. *J. Organomet. Chem.* **1972**, 36, 209.

⁹ (a) McGreer, D. E.; Chiu, N. W. K.; Vinje, M. G. *Can. J. Chem.* **1965**, 43, 1398. (b) Marr, D. H.; Stothers, J. B. *Can. J. Chem.* **1965**, 43, 596.

Hz, 1 H), 2.28 (s, 3 H), 2.24 (app quintet, $J = 7.4$ Hz, 2 H), 1.73 (s, 3 H), 1.05 (t, $J = 7.6$ Hz, 3 H); ^{13}C NMR (125 MHz, CDCl_3) δ 200.0, 145.4, 137.3, 25.5, 22.6, 13.3, 11.1.

4-Cyclohexyl-3-methyl-(*E*)-3-buten-2-one. A 250-mL, three-necked, round-bottomed flask equipped with a glass stopper, rubber septum, and argon inlet adapter was charged with a solution of 3-(triphenylphosphoranylidene)butan-2-one¹⁰ (4.316 g, 12.99 mmol) and cyclohexane carboxaldehyde (1.20 mL, 1.11 g, 9.90 mmol) in 125 mL of toluene. The rubber septum was replaced with a glass stopper and the reaction mixture was heated at reflux for 48 h. The reaction mixture was allowed to cool to room temperature and then concentrated at reduced pressure to afford 7.019 g of a tan solid.¹¹ This material was dissolved in 50 mL of EtOAc and concentrated onto 20 g of silica gel which was added to the top of a column of 150 g of silica gel and eluted with 5% EtOAc-hexanes to provide 1.017 g (62%) of 4-cyclohexyl-3-methyl-(*E*)-3-buten-2-one as a colorless oil: IR (neat) 3001, 2927, 2852, 1669, 1641, 1448, 1370, 1360, 1275, 1220, 1003, 755 cm^{-1} ; ^1H NMR (500 MHz, CDCl_3) δ 6.40 (app dd, $J = 9.2, 1.2$ Hz, 1 H), 2.30-2.41 (m, 1 H), 2.27 (s, 3 H), 1.64-1.76 (m, 7 H), 1.05-1.37 (m, 6 H); ^{13}C NMR (125 MHz, CDCl_3) δ 200.6, 149.0, 135.9, 38.4, 32.2, 26.1, 25.8, 25.6, 11.4; HRMS-ESI (m/z): $[\text{M} + \text{Na}]^+$ calcd for $\text{C}_{11}\text{H}_{18}\text{O}$, 189.1250; found, 189.1249.

General Procedure for Diazo Transfer. 1-Diazo-3-methyl-(*E*)-3-hexen-2-one (4c). A 100-mL, three-necked, round-bottomed flask equipped with a 25-mL pressure-equalizing addition funnel, rubber septum, and an argon inlet adapter was charged with a solution of HMDS (3.1 mL, 2.4 g, 15 mmol) in 30 mL of THF and then cooled at 0 °C in an ice water-bath while 6.2 mL of *n*-butyllithium solution (2.34 M in hexanes, 15 mmol) was added rapidly dropwise. After 30 min, the resulting solution was cooled at -78 °C in a dry ice-acetone bath while a solution of (*E*)-3-methyl-3-hexen-2-one (1.50 g, 13.4 mmol) in 15 mL of THF was added dropwise over 30 min (the addition funnel was rinsed with 5 mL of additional THF). The reaction mixture was stirred at -78 °C for 1.25 h, and then 2,2,2-trifluoroethyl trifluoroacetate (3.6 mL, 5.3 g, 27 mmol) was added rapidly by syringe in one portion. After 45 min, the reaction mixture was poured into a separatory funnel containing 50 mL of 5% aq HCl solution and 30 mL of Et_2O . The organic phase was washed with 50 mL of water, the combined aqueous phases were extracted with two 25-mL portions of Et_2O , and then the combined organic phases were washed with 30 mL of a saturated NaCl solution, dried over Na_2SO_4 , filtered, and concentrated at reduced pressure to give 5.353 g of a brown oil which was diluted with 30 mL of CH_3CN and transferred to a 100-mL, three-necked, round-bottomed flask equipped with a 25-mL pressure equalizing-addition funnel, rubber septum, and an argon inlet adapter. Water (0.241 mL, 0.241 g, 13.4 mmol) and Et_3N (2.8 mL, 2.0 g, 20 mmol) were added via

¹⁰ Aitken, A. R.; Atherton, J. I. *J. Chem. Soc. Perkin Trans. I* **1994**, 1281.

¹¹ The crude product contained a 92:8 mixture of *E* and *Z* enones.

syringe, and then a solution of methanesulfonyl azide (2.461 g, 20.1 mmol) in 20 mL of CH₃CN was added dropwise over 2 min (the addition funnel was rinsed with an additional 5 mL of CH₃CN). The resulting solution was stirred at room temperature for 3 h and then concentrated to a volume of ca. 15 mL. The residue was diluted with 50 mL of Et₂O and washed with four 30-mL portions of 10% aq NaOH solution and three 25-mL portions of water, and then the combined aqueous phases were extracted with 50 mL of Et₂O. The combined organic layers were washed with 30 mL of saturated NaCl solution, dried over MgSO₄, filtered, and concentrated to afford 1.808 g of yellow oil. Column chromatography on 120 g silica gel (gradient elution with 5-10% EtOAc-hexanes) provided 1.411 g (76%) of diazo ketone **4c** as a yellow oil: IR (neat) 3088, 2969, 2936, 2876, 2101, 1644, 1603, 1396, 1367, 1236, 1154, 853, 715 cm⁻¹; ¹H NMR (300 MHz, CDCl₃) δ 6.24 (tq, *J* = 7.2, 1.2 Hz, 1 H), 5.57 (s, 1 H), 2.18 (app quintet, *J* = 7.5 Hz, 2 H), 1.80 (s, 3 H), 1.02 (t, *J* = 7.5 Hz, 3 H); ¹³C NMR: (75 MHz, CDCl₃) δ 189.0, 144.1 135.1, 53.0, 22.2, 13.3, 12.2; HRMS-ESI (*m/z*): M⁺ calcd for C₇H₁₀N₂O, 138.0788; found, 138.0787.

4-Cyclohexyl-1-diazo-3-methyl-(*E*)-3-buten-2-one (4d). Reaction of 4-cyclohexyl-3-methyl-(*E*)-3-buten-2-one (1.007 g, 6.06 mmol) in 10 mL of THF with a solution of HMDS (1.50 mL, 1.15 g, 7.16 mmol) and 2.80 mL of *n*-butyllithium solution (2.34 M in hexane, 6.55 mmol) in 20 mL of THF and 2,2,2-trifluoroethyl trifluoroacetate (1.60 mL, 2.34 g, 12.0 mmol) according to the general procedure yielded 2.304 g of a brown oil which was then treated with water (0.110 mL, 0.110 g, 6.11 mmol), Et₃N (1.25 mL, 0.908 g, 8.97 mmol) and methanesulfonyl azide (1.113 g, 9.19 mmol) in 30 mL of CH₃CN at room temperature for 2.2 h to yield a yellow oil. Column chromatography on 60 g of silica gel (elution with 7.5% EtOAc-hexanes) provided 0.970 g (83%) of the diazo ketone **4d** as yellow crystals, mp 52-55 °C: IR (CHCl₃) 3019, 2929, 2853, 2107, 1643, 1602, 1358, 1337, 1216 cm⁻¹; ¹H NMR (500 MHz, CDCl₃) δ 6.09 (d, *J* = 9.3 Hz, 1 H), 5.56 (s, 1 H), 2.29-2.39 (m, 1 H), 1.62-1.86 (m, 7 H), 1.06-1.35 (m, 6 H); ¹³C NMR (125 MHz, CDCl₃) δ 189.3 143.7, 133.8, 53.1, 37.9, 32.3, 26.1, 25.8, 12.4; HRMS-ESI (*m/z*): [M + Na]⁺ calcd for C₁₁H₁₆N₂O, 215.1155; found, 215.1154.

General Procedure for the Silylation of α-Diazo Ketones. 1-Diazo-3-methyl-1-(triisopropylsilyl)-(*E*)-3-hexen-2-one (5c). 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 diazo ketone **4c** (0.145 g, 1.05 mmol) in 10 mL of 1:1 Et₂O-hexanes and *i*-Pr₂EtN (0.19 mL, 0.141 g, 1.09 mmol) was added dropwise over 1 min. After 2 min, TIPSOTf (0.28 mL, 0.319 g, 1.04 mmol) was added dropwise over 1 min, and the resulting solution was stirred at room temperature for 2.2 h. The reaction mixture was filtered through Celite with the aid of 50 mL of 1:1 Et₂O-hexanes, and the filtrate was concentrated to afford 0.343 g of an orange oil. Column chromatography on 20 g of silica gel (elution with 1% EtOAc-1% NEt₃-hexanes) provided 0.234 g (76%) of silyl diazo ketone **5c** as a yellow oil: IR (neat) 2946, 2867,

2064, 1617, 1463, 921 cm^{-1} ; ^1H NMR (300 MHz, CDCl_3) δ 5.99 (tq, $J = 7.5, 1.5$ Hz, 1 H), 2.11-2.15 (m, 2 H), 1.81 (s, 3 H), 1.35 (m, 3 H), 1.10 (d, $J = 7.3$ Hz, 18 H), 1.04 (t, $J = 7.6$ Hz, 3 H); ^{13}C NMR (125 MHz, CDCl_3) δ 190.3, 137.1, 134.6, 50.2, 21.7, 18.7, 18.0, 13.4, 11.7; HRMS-ESI (m/z): $[\text{M} + \text{Na}]^+$ calcd for $\text{C}_{16}\text{H}_{30}\text{ON}_2\text{Si}$, 317.2020; found, 317.2026.

4-Cyclohexyl-1-diazo-3-methyl-1-(triisopropylsilyl)-(E)-3-buten-2-one (5d). Reaction of diazo ketone **4d** (1.003 g, 5.22 mmol) with (*i*-Pr) $_2$ EtN (0.91 mL, 0.68 g, 5.2 mmol) and (*i*-Pr) $_3$ SiOTf (1.40 mL, 1.60 g, 5.21 mmol) in 60 mL of 1:1 Et $_2$ O-hexanes for 2.5 h according to the general procedure gave 1.870 g of an orange oil. Column chromatography on 60 g of silica gel (elution with 2% EtOAc-1% NEt $_3$ -hexanes) provided 1.458 g (80%) of silyl diazo ketone **5d** as a yellow oil: IR (neat) 2927, 2866, 2064, 1743, 1615, 1464, 1448, 882 cm^{-1} ; ^1H NMR (500 MHz, CDCl_3) δ 5.81 (app dd, $J = 9.3, 1.2$ Hz, 1 H), 2.28-2.37 (m, 1 H), 1.83 (d, $J = 1.4$ Hz, 3 H), 1.63-1.77 (m, 4 H), 1.02-1.42 (m, 27 H); ^{13}C NMR (125 MHz, CDCl_3) δ 198.0, 141.3, 133.4, 50.9, 38.0, 32.8, 26.6, 26.3, 19.2, 14.0, 12.2; HRMS-ESI (m/z): $[\text{M} + \text{Na}]^+$ calcd for $\text{C}_{20}\text{H}_{36}\text{N}_2\text{OSi}$, 371.2489; found, 371.2483.

General Procedure for Photochemical Wolff Rearrangement. 2-(1-Methyl-(E)-1-butenyl)-2-(triisopropylsilyl)ketene (6c). A 25-cm Vycor tube sealed with a rubber septum was charged with a solution of diazo ketone **5c** (0.225 g, 0.76 mmol) in 8 mL of benzene. A second rubber septum (inverted) was secured to the tube with vinyl tape to ensure a good seal, and the reaction mixture was degassed (three freeze-pump-thaw cycles at -196 $^{\circ}\text{C}$, <0.5 mmHg) and then irradiated at room temperature with 300 nm light in a Rayonet reactor for 4 h. The resulting solution was concentrated to afford 0.220 g of a yellow oil. Column chromatography on 10 g of silica gel (elution with hexanes) provided 0.150 g (74%) of ketene **6c** as a yellow oil: IR (neat) 2946, 2868, 2725, 2077, 1643, 1463, 1382, 882 cm^{-1} ; ^1H NMR (500 MHz, CDCl_3) δ 5.13 (t, $J = 7.4$ Hz, 1 H), 2.04 (app quintet, $J = 7.5$ Hz, 2 H), 1.81 (s, 3 H), 1.17-1.27 (m, 3 H), 1.10 (d, $J = 7.3$ Hz, 18 H), 0.93 (t, $J = 7.5$ Hz, 3 H); ^{13}C NMR (125 MHz, CDCl_3): δ 185.5, 128.1, 123.3, 23.4, 22.6, 19.6, 19.3, 15.0, 13.3; HRMS-ESI (m/z): $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{16}\text{H}_{30}\text{OSi}$, 267.2139; found, 267.2147.

(E)-2-(1-Methyl)-2-cyclohexylethenyl-2-(triisopropylsilyl)ketene (6d). Reaction of silyl diazo ketone **5d** (1.444 g, 4.14 mmol) in 40 mL of benzene for 4 h according to the general procedure provided a yellow oil. Column chromatography on 30 g of silica gel (elution with hexanes) provided 1.104 g (83%) of ketene **6d** as a yellow oil: IR (neat) 2925, 2867, 2077, 1642, 1464, 1382, 883 cm^{-1} ; ^1H NMR (500 MHz, CDCl_3) δ 4.98 (app dd, $J = 9.1, 1.2$ Hz, 1 H), 2.15-2.25 (m, 1 H), 1.84 (d, $J = 1.2$ Hz, 3 H), 1.58-1.72 (m, 4 H), 0.98-1.34 (m, 27 H); ^{13}C NMR (125 MHz, CDCl_3) δ 185.1, 132.1, 121.6, 37.9, 33.6, 26.3, 26.2, 23.0, 19.4, 18.9, 12.8; HRMS-ESI (m/z): $[\text{M} + \text{Na}]^+$ calcd for $\text{C}_{20}\text{H}_{36}\text{OSi}$, 343.2428; found, 343.2433.

1,1-Dibromo-4-ethoxy-2-butanone. A 250-mL, three-necked, round-bottomed flask equipped with a glass stopper, rubber septum, and argon inlet adapter was charged with a solution of dibromomethane (1.9 mL, 4.7 g, 27 mmol) and ethyl 3-ethoxypropionate (**7c**) (1.5 mL, 1.4 g, 9.7 mmol) in 50 mL THF and cooled at -78°C in a dry ice-acetone bath. A 100-mL, three-necked, round-bottomed flask equipped with a glass stopper, rubber septum, and argon inlet adapter was charged with 2,2,6,6-tetramethylpiperidine (4.5 mL, 3.8 g, 27 mmol) and 50 mL of THF and cooled at 0°C in an ice-water bath while *n*-butyllithium solution (10.0 mL, 2.34 M in hexane, 23.4 mmol) was added rapidly via syringe. The resulting solution was stirred for 5 min and then transferred via cannula over 15 min to the 250-mL flask. The reaction mixture was stirred at -78°C for 10 min, and then 75 mL of 1.2 M HCl solution was added. The aqueous phase was separated and extracted with two 50-mL portions of hexanes, and the combined organic phases were washed with 100 mL of water and 100 mL of a satd aq NaCl solution, dried over MgSO_4 , filtered and concentrated to give 2.367 g of a dark brown oil. Column chromatography on 100 g of silica gel (elution with 10% EtOAc—hexanes) afforded 1.797 g (67%) of 1,1-dibromo-4-ethoxy-2-butanone as a yellow-orange oil: IR (neat) 2976, 2931, 2871, 1724, 1112 cm^{-1} ; ^1H NMR (500 MHz, CDCl_3) δ 5.89 (s, 1 H), 3.75 (t, $J = 6.3$ Hz, 2 H), 3.52 (q, $J = 7.0$ Hz, 2 H), 3.17 (t, $J = 6.3$ Hz, 2 H), 1.20 (t, $J = 7.0$ Hz, 3 H); ^{13}C NMR (125 MHz, CDCl_3) δ 195.6, 67.4, 66.3, 44.2, 36.7, 15.8; HRMS-ESI (m/z): $[\text{M} + \text{Na}]^+$ calcd for $\text{C}_6\text{H}_{10}\text{O}_2\text{Br}_2$, 294.8940; found, 294.8948.

4-Ethoxy-1-(triisopropylsiloxy)-1-butyne (9c**).** A 250-mL, three-necked, round-bottomed flask equipped with a glass stopper, rubber septum, and argon inlet adapter was charged with a solution of 1,1-dibromo-4-ethoxy-2-butanone (1.190 g, 4.34 mmol) in 50 mL of THF and cooled at -78°C in a dry ice-acetone bath. A 100-mL, three-necked, round-bottomed flask equipped with a glass stopper, rubber septum, and argon inlet adapter was charged with a solution of HMDS (1.1 mL, 0.84 g, 5.2 mmol) in 40 mL of THF and cooled at 0°C in an ice-water bath while *n*-butyllithium solution (2.34 M in hexanes, 1.95 mL, 4.56 mmol) was added rapidly via syringe. The resulting mixture was stirred for 5 min, and then transferred via cannula over 12 min into the solution of dibromo ketone (the flask was rinsed with an additional 10 mL of THF). The resulting solution was stirred for 7 min at -78°C , and then *n*-butyllithium solution (2.34 M in hexanes, 4.1 mL, 9.6 mmol) was added dropwise over 4 min. The reaction mixture was stirred at -78°C for 8 min and then (*i*-Pr) $_3\text{SiOTf}$ (1.1 mL, 1.3 g, 4.1 mmol) was added in one portion. After 5 min, the dry ice-acetone bath was replaced with an ice-water bath and stirring was continued at 0°C for 25 min. The reaction mixture was diluted with 150 mL of hexanes, 0.1 mL of water was added, and the resulting mixture was stirred for 15 min and then dried over Na_2SO_4 . The resulting solution was filtered through a glass frit, concentrated, and the residue was taken up in ca. 5 mL of benzene, filtered through a glass frit, and concentrated to yield 1.613 g of an orange oil. Purification via bulb-to-bulb

distillation (bath temperature 90-150 °C, 0.5 mmHg) followed by column chromatography on 40 g of silica gel (elution with 2% EtOAc-hexanes) yielded 0.665 g (60%) of siloxy alkyne **9c** as a yellow oil: IR (neat) 2947, 2869, 2282, 1464, 1376, 1356, 1313, 1250, 1114, 1017, 883 cm⁻¹; ¹H NMR (500 MHz, CDCl₃) δ 3.50 (q, *J* = 7.0 Hz, 2 H), 3.48 (t, *J* = 7.3 Hz, 2 H), 2.35 (t, *J* = 7.5 Hz, 2 H), 1.25 (septet, *J* = 7.0 Hz, 3 H), 1.20 (t, *J* = 7.0 Hz, 3 H), 1.12 (d, *J* = 7.0 Hz, 18 H); ¹³C NMR (125 MHz, CDCl₃) δ 87.6, 70.4, 66.3, 27.3, 18.8, 17.6, 15.4, 12.0; HRMS-ESI (*m/z*): [M + Na]⁺ calcd for C₁₅H₃₀O₂Si 293.1907; found, 293.1898.

General Procedure for the Preparation of Siloxy Alkynes from Terminal Alkynes. 1-(*tert*-Butyldimethylsiloxy)-4-penten-1-yne (23**).** A 100-mL, three-necked, round-bottomed flask equipped with a rubber septum, glass stopper, and an argon inlet adapter was charged with a solution of 1-penten-4-yne (0.463 g, 7.00 mmol) in 20 mL of THF and cooled at -78 °C while 8.4 mL of freshly prepared LiHMDS solution (1.0 M, 8.4 mmol)¹² was added rapidly dropwise by syringe. A 100-mL, three-necked, round-bottomed flask equipped with a rubber septum, glass stopper, and an argon inlet adapter was charged with 2.3 mL of *t*-BuOOH solution (3.7 M in toluene, 8.5 mmol) and 15 mL of THF and cooled at -78 °C while 9.1 mL of freshly prepared LiHMDS solution (1.0 M, 9.1 mmol) was added rapidly dropwise via syringe. The resulting solution was then transferred via cannula over 5 min into the solution of lithium acetylide (the flask was rinsed with 5 mL of THF). The dry ice-acetone bath was replaced with an ice-water bath and the reaction mixture was stirred at 0 °C for 2.5 h. The resulting solution was cooled to -78 °C and *t*-BuMe₂SiOTf (2.1 mL, 2.4 g, 9.1 mmol) was added rapidly dropwise via syringe. The reaction mixture was stirred for 10 min at -78 °C and 30 min at 0 °C, and then was cooled at -78 °C and diluted with 75 mL of hexanes. The resulting solution was poured into 50 mL of satd aq NaHCO₃ solution, and the aqueous phase was separated and extracted with two 25-mL portions of hexanes. The combined organic phases were washed with 50 mL of water and 50 mL of brine, dried over Na₂SO₄, filtered, and concentrated under reduced pressure to afford 1.932 g of an orange oil. Purification by bulb-to-bulb distillation (50-60 °C bath temperature, 0.15-0.20 mmHg) yielded 0.653 g (48%) of siloxy alkyne **23** as a colorless oil: IR (neat) 3086, 2958, 2861, 2284, 1643, 1472, 1253 cm⁻¹; ¹H NMR (300 MHz, C₆D₆) δ 5.84 (ddt, *J* = 16.9, 10.0, 5.0 Hz, 1 H), 5.51 (app dq, *J* = 16.9, 2.0 Hz, 1 H), 5.12 (app dq, *J* = 9.9, 2.0 Hz, 1 H), 2.90 (app dt, *J* = 5.1, 1.9 Hz, 2 H), 0.95 (s, 9 H), 0.19 (s, 6 H); ¹³C NMR (75 MHz, C₆D₆) δ 135.1, 114.7, 88.8, 28.2, 25.3, 21.9, 18.3, -5.9.

¹² LiHMDS solution was prepared by the reaction of HMDS (4.2 mL, 3.2 g, 20 mmol) with 8.7 mL of *n*-BuLi solution (2.31 M in hexanes, 19 mmol) in 8.7 mL of THF.

2-(1-Cyclohexenyl)-1-(triisopropylsiloxy)ethyne (9g). Reaction of 1-ethynylcyclohexene (0.30 mL, 0.27 g, 2.6 mmol) in 20 mL of THF with LiHMDS solution¹³ (3.1 mL, 1.0 M in THF, 3.1 mmol), lithium *tert*-butyl hydroperoxide (generated from 0.83 mL of 3.7 M *t*-BuOOH solution, 3.1 mmol, and 3.3 mL of 1.0 M LiHMDS solution, 3.3 mmol), and (*i*-Pr)₃SiOTf (0.70 mL, 0.80 g, 2.6 mmol) in 20 mL of THF according to the general procedure afforded an orange oil that was filtered through 5 g of silica gel with the aid of 125 mL of hexanes. The filtrate was concentrated to yield 0.623 g (87%) of siloxy alkyne **9g** as a colorless oil: IR (neat) 2926, 2258, 1466 cm⁻¹; ¹H NMR (300 MHz, CDCl₃) δ 5.79-5.84 (m, 1 H), 1.99-2.10 (m, 4 H), 1.50-1.67 (m, 4 H), 1.20-1.34 (m, 3 H), 1.13 (d, 18 H); ¹³C NMR (75 MHz, CDCl₃) δ 129.9, 121.2, 94.8, 35.1, 30.7, 25.8, 22.9, 22.0, 17.5, 12.1.

General Procedure for Benzannulation. 2-Butyl-5, 6-dimethyl-3-(triisopropylsiloxy)phenol (15). A 25-mL, two-necked, round-bottomed flask equipped with a rubber septum and argon inlet adapter was charged with 1-(triisopropylsiloxy)-1-hexyne (**9e**) (0.314 g, 1.23 mmol) and 5 mL of THF. MeLi solution (1.53 M in Et₂O, 0.81 mL, 1.2 mmol) was added dropwise via syringe over 2 min, and the resulting solution was stirred at room temperature for 4 h. A solution of ketene **6a** (0.313 g, 1.24 mmol) in 2 mL of THF was added via cannula in one portion (the flask was rinsed with 1 mL of THF), and the resulting solution was stirred for 1 h at room temperature. The reaction mixture was poured into 10 mL of satd aq NH₄Cl solution, the aqueous phase was separated and extracted with two 10-mL portions of Et₂O, and the combined organic phases were washed with 20 mL of water and 20 mL of satd aq NaCl solution, dried over MgSO₄, filtered, and concentrated to afford 0.547 g of a yellow oil. Column chromatography on 25 g of silica gel (elution with 5% EtOAc-hexanes) provided 0.220 g (51%) of phenol **15** as a yellow oil: IR (neat) 3621, 2945, 2867, 1618, 1577, 1498, 1464, cm⁻¹; ¹H NMR (300 MHz, CDCl₃) δ 6.27 (s, 1 H), 4.66 (s, 1 H), 2.64 (t, *J* = 7.2 Hz, 2 H), 2.21 (s, 3 H), 2.11 (s, 3 H), 1.47-1.56 (m, 2 H), 1.38-1.47 (m, 2 H), 1.20-1.37 (m, 3 H), 1.15 (d, *J* = 6.9 Hz, 18 H), 0.96 (t, *J* = 7.5 Hz, 3 H); ¹³C NMR (75 MHz, CDCl₃) δ 152.5, 152.0, 134.6, 116.2, 114.2, 112.4, 32.1, 24.4, 23.6, 20.7, 18.6, 14.6, 13.6, 11.8; HRMS-ESI (*m/z*): [*M* + Na]⁺ calcd for C₂₁H₃₈O₂Si, 373.2533; found, 373.2544.

5,6-Dimethyl-2-isopropyl-3-(triisopropylsiloxy)phenol (16). Reaction of 3-methyl-1-(triisopropylsiloxy)-1-butyne (**9b**) (0.171 g, 0.711 mmol) with MeLi solution (1.42 M in Et₂O, 0.50 mL, 0.71 mmol) and ketene **6a** (0.179 g, 0.709 mmol) according to the general procedure provided 0.356 g of a yellow oil. This material was dissolved in 10 mL of CH₂Cl₂ and concentrated onto 1.5 g of silica gel which was transferred to the top of a column of 30 g of silica gel. Gradient elution with 2% EtOAc-hexanes provided 0.165 g (65%) of phenol **16** as a yellow oil: IR (neat) 3621, 3573, 2946, 1615, 1574,

¹³ LiHMDS solution was prepared by the reaction of HMDS (2.1 mL, 1.6 g, 10 mmol) with 3.9 mL of *n*-BuLi solution (2.30 M in hexanes, 9.0 mmol) in 4.0 mL of THF.

1493, 1464 cm^{-1} ; ^1H NMR (500 MHz, CDCl_3) δ 6.24 (s, 1 H), 4.68 (s, 1 H), 3.62 (septet, $J = 7.2$ Hz, 1 H), 2.18 (s, 3 H), 2.07 (s, 3 H), 1.34 (d, $J = 7.2$ Hz, 6 H), 1.32 (septet, $J = 7.2$ Hz, 3 H) 1.13 (d, $J = 7.5$ Hz, 18 H); ^{13}C NMR (125 MHz, CDCl_3) δ 153.5, 151.8, 134.5, 121.1, 114.5, 112.6, 24.7, 21.1, 20.5, 18.4, 13.4, 11.4; HRMS-ESI (m/z): $[\text{M} + \text{Na}]^+$ calcd for $\text{C}_{20}\text{H}_{36}\text{O}_2\text{Si}$, 359.2377; found, 359.2392.

2-Cyclohexyl-5,6,7,8-tetrahydro-3-(triisopropylsiloxy)-1-naphthol (17). Reaction of 2-cyclohexyl-1-(triisopropylsiloxy)-ethyne (**9a**) (0.149 g, 0.531 mmol) with MeLi solution (1.48 M in Et_2O , 0.36 mL, 0.53 mmol) and ketene **6b** (0.149 g, 0.539 mmol) according to the general procedure provided 0.290 g of a yellow oil. Column chromatography on 30 g of silica gel (elution with 1% EtOAc-hexanes) afforded 0.151 g (71%) of tetrahydronaphthol **17** as a yellow oil: IR (CH_2Cl_2) 3054, 2987, 1422 cm^{-1} ; ^1H NMR (300 MHz, CDCl_3) δ 6.19 (s, 1 H), 4.71 (s, 1 H), 3.31 (m, 1 H), 2.68 (app t, $J = 6.0$ Hz, 2 H), 2.54 (app t, $J = 6.0$ Hz, 2 H), 2.01-2.14 (m, 2 H), 1.83-1.93 (m, 4 H), 1.66-1.80 (m, 5 H) 1.31-1.46 (m, 6 H), 1.18 (d, $J = 6.9$ Hz, 18 H); ^{13}C NMR (75 MHz, CDCl_3): δ 153.3, 152.2, 135.5, 120.3, 115.4, 111.2, 35.7, 30.7, 29.8, 27.9, 26.7, 23.3, 23.2, 22.7, 18.5, 13.5; HRMS-EI (m/z): $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{25}\text{H}_{42}\text{O}_2\text{Si}$, 403.3032; found, 403.3027.

2-(2-Ethoxyethyl)-6-ethyl-5-methyl-3-(triisopropylsiloxy)phenol (18). Reaction of siloxy alkyne **9c** (0.154 g, 0.569 mmol) with MeLi solution (1.51 M in Et_2O , 0.38 mL, 0.57 mmol) in 3 mL of THF for 4 h and a solution of ketene **6c** (0.151 g, 0.567 mmol) in 2 mL of THF for 2 h according to the general procedure provided 0.216 g of a yellow oil. Column chromatography on 30 g of silica gel (gradient elution with 0-2% EtOAc-hexanes) gave 0.100 g (48%) of phenol **18** as a yellow oil: IR (neat) 3327, 2945, 2867, 1615, 1574, 1499, 1462 cm^{-1} ; ^1H NMR (500 MHz, CDCl_3) δ 8.05 (s, 1 H), 6.25 (s, 1 H), 3.68 (t, $J = 5.6$ Hz, 2 H), 3.51 (q, $J = 7.0$ Hz, 2 H), 2.99 (t, $J = 5.3$ Hz, 2 H), 2.64 (q, $J = 7.5$ Hz, 2 H) 2.24 (s, 3 H), 1.30 (septet, 3 H), 1.23 (t, $J = 6.9$ Hz, 3 H) 1.10-1.15 (m, 21 H); ^{13}C NMR (125 MHz, CDCl_3) δ 155.3, 152.1, 135.6, 124.1, 115.9, 112.4 73.2, 67.7, 25.9, 20.4, 20.1, 18.9, 15.7, 14.7, 13.8; HRMS-ESI (m/z): $[\text{M} + \text{Na}]^+$ calcd for $\text{C}_{22}\text{H}_{40}\text{O}_3\text{Si}$, 403.2639; found, 403.2658.

6-Ethyl-5-methyl-2-(3-butenyl)-3-(triisopropylsiloxy)phenol (19). Reaction of siloxy alkyne **9d** (0.150 g, 0.594 mmol) with MeLi solution (1.48 M in Et_2O , 0.40 mL, 0.59 mmol) and ketene **6c** (0.158 g, 0.593 mmol) according to the general procedure gave 0.290 g of a yellow oil. Column chromatography on 30 g of silica gel (elution with 2% EtOAc-hexanes) provided 0.145 g (68%) of phenol **19** as a yellow oil: IR (neat) 3620, 2945, 2868, 1614, 1575, 1462 cm^{-1} ; ^1H NMR (500 MHz, CDCl_3) δ 6.27 (s, 1 H), 5.95 (tdd, $J = 6.8, 10.2, 17.1$ Hz, 1 H), 5.10 (dd, $J = 17.1, 1.5$ Hz, 1 H), 5.01 (dd, $J = 10.1, 1.2$ Hz, 1 H), 4.71 (d, $J = 1.8$ Hz, 1 H), 2.73 (t, $J = 7.8$ Hz, 2 H) 2.59 (q, $J = 7.3$ Hz, 2 H), 2.30 (app q, $J = 7.9$ Hz, 2 H), 2.23 (s, 3 H), 1.32 (septet, $J = 7.2$ Hz, 3 H) 1.06-1.18 (m, 21 H); ^{13}C NMR (125 MHz,

CDCl_3) δ 152.9, 152.7, 139.6, 134.8, 121.4, 116.0, 115.6, 113.0, 34.2, 24.7, 20.24, 20.19, 18.9, 14.5, 13.8; HRMS-ESI (m/z): $[\text{M} + \text{Na}]^+$ calcd for $\text{C}_{22}\text{H}_{38}\text{O}_2\text{Si}$, 385.2553; found, 385.2542.

6-Cyclohexyl-2-(2-ethoxyethyl)-5-methyl-3-(triisopropylsiloxy)-phenol (20). Reaction of siloxy alkyne **9c** (0.149 g, 0.551 mmol) with MeLi solution (1.51 M in Et_2O , 0.37 mL, 0.56 mmol) and ketene **6d** (0.177 g, 0.552 mmol) according to the general procedure gave 0.296 g of a yellow oil. Column chromatography on 30 g of silica gel (elution with 1% EtOAc—hexanes) provided 0.109 g (46%) of phenol **20** as a yellow oil: IR (CH_2Cl_2) 3301, 3053, 2926, 2867, 1610, 1566, 1422 cm^{-1} ; ^1H NMR (500 MHz, CDCl_3): δ 7.87 (s, 1 H), 6.20 (s, 1 H), 3.65 (t, $J = 5.2$ Hz, 2 H), 3.51 (q, $J = 7.0$ Hz, 2 H), 2.93 (t, $J = 5.5$ Hz, 2 H), 2.10–2.25 (m, 4 H), 1.76–1.87 (m, 3 H), 1.66–1.73 (m, 2 H), 1.54–1.63 (m, 3 H), 1.23–1.38 (m, 5 H), 1.21 (t, $J = 7.0$ Hz, 3 H), 1.09 (d, $J = 7.5$ Hz, 18 H); ^{13}C NMR (125 MHz, CDCl_3): δ 156.4, 152.0, 135.4, 126.7, 117.0, 112.9, 73.1, 67.7, 40.3, 30.9, 28.4, 27.0, 25.9, 22.0, 18.9, 15.7, 13.7; HRMS-ESI (m/z): $[\text{M} + \text{H}]^+$ calcd for $\text{C}_{25}\text{H}_{46}\text{O}_2\text{Si}$, 435.3289; found: 435.3275.

2-(1-Cyclohexenyl)-5,6,7,8-tetrahydro-3-(triisopropylsiloxy)-1-naphthol (21). To a solution of siloxy alkyne **9g** (0.200 g, 0.718 mmol) in 3 mL of THF at 0 °C was added MeLi solution (1.47 M in Et_2O , 0.49 mL, 0.72 mmol) rapidly via syringe. The ice bath was then removed, and the resulting mixture was stirred at rt for 3.5 h. Reaction of the resulting solution with a solution of ketene **6b** (0.200 g, 0.718 mmol) in 2 mL of THF according to the general procedure gave 0.399 g of a yellow oil. Column chromatography on 30 g of silica gel (gradient elution with 10–40% EtOAc–hexanes) provided 0.125 g (43%) of phenol **21** as a yellow oil: IR (neat) 3512, 2958, 2860, 1618, 1574, 1465 cm^{-1} ; ^1H NMR (300 MHz, CDCl_3) δ 6.13 (s, 1 H), 5.73–5.78 (m, 1 H), 5.66 (s, 1 H), 2.56–2.69 (m, 4 H), 2.15–2.24 (m, 3 H), 1.65–1.85 (m, 9 H), 1.20–1.35 (m, 3 H), 1.10 (d, $J = 7.2$ Hz, 18 H); ^{13}C NMR (75 MHz, CDCl_3) δ 151.2, 150.6, 137.0, 133.9, 129.3, 118.4, 115.9, 110.3, 29.6, 28.6, 25.3, 22.84, 22.77 (2 C), 22.6, 21.8, 18.3, 13.5; HRMS-EI (m/z): $[\text{M} + \text{Na}]^+$ calcd for $\text{C}_{25}\text{H}_{40}\text{O}_2\text{Si}$, 423.2690; found, 423.2693.

2-(3-Propenyl)-5,6,7,8-tetrahydro-3-(triisopropylsiloxy)-1-naphthol (22). Reaction of siloxy alkyne **23** (0.890 g, 4.53 mmol) with MeLi solution (1.53 M in Et_2O , 3.0 mL, 4.6 mmol) in 6 mL of THF for 30 min followed by reaction with a solution of ketene **6b** (1.267 g, 4.551 mmol) in 4 mL of THF according to the general procedure gave 2.034 g of a yellow oil. Column chromatography on 100 g of silica gel (25% benzene–hexanes) provided 0.788 g (48%) of phenol **22** as a yellow oil: IR (neat) 3550, 3077, 2942, 2866, 1618, 1578, 1495, 1426 cm^{-1} ; ^1H NMR (300 MHz, CDCl_3) δ 6.23 (s, 1 H), 6.00 (ddt, $J = 17.2, 10.0, 6.2$ Hz, 1 H), 5.20 (app dq, $J = 17.3, 1.7$ Hz, 1 H), 5.12 (app dq, $J = 9.9, 1.7$ Hz, 1 H), 5.01 (s, 1 H), 3.51 (app dt, $J = 6.2, 1.6$ Hz, 2 H), 2.67 (t, $J = 6.1$ Hz, 2 H), 2.58 (t, $J = 6.1$ Hz, 2 H), 1.71–1.88 (m, 4 H), 1.32 (septet, $J = 7.3$ Hz, 3 H), 1.15 (d, 7.2 Hz, 18 H); ^{13}C NMR (75 MHz, CDCl_3) δ 153.3,

151.9, 137.0, 136.5, 116.3, 115.7, 112.5, 110.8, 31.8, 29.9, 28.6, 23.7, 22.8, 18.3, 13.3; HRMS-ESI (m/z): $[M + Na]^+$ calcd for $C_{22}H_{36}O_2Si$, 383.2377; found, 383.2380.

2-Methyl-6,7,8,9-tetrahydro-4-(triisopropylsiloxy)naphtho[1,2-b]furan (24). A 25-mL, two-necked, round-bottomed flask equipped with a rubber septum and cold-finger condenser fitted with an argon inlet adapter was charged with a solution of $PdCl_2(MeCN)_2$ (0.016 g, 0.062 mmol), LiCl (0.211 g, 4.98 mmol), and benzoquinone (0.061 g, 0.564 mmol) in 8 mL of THF. A solution of phenol **22** (0.200 g, 0.555 mmol) in 2 mL of THF was added in one portion, the rubber septum was exchanged for a glass stopper, and the resulting mixture was heated at reflux for 3.5 h and then allowed to cool to room temperature. The reaction mixture was filtered through 5 g of silica gel with the aid of 75 mL of hexanes and then concentrated to yield 0.220 g of a mixture of a black solid and orange oil. This material was diluted with 10 mL of Et_2O and concentrated onto 0.5 g of silica gel which was transferred to the top of a column of 20 g of silica gel and eluted with 25% benzene-hexanes to provide 0.119 g (60%) of tetrahydronaphthofuran **24** as a yellow oil: IR (neat) 2943, 2866, 1622, 1592, 1508, 1463, 1446 cm^{-1} ; ^1H NMR (300 MHz, $CDCl_3$) δ 6.38-6.41 (m, 2 H), 2.86-2.93 (m, 2 H), 2.77-2.84 (m, 2 H), 2.45 (d, $J = 1.1$ Hz, 3 H), 1.81-1.91 (m, 4 H), 1.27-1.41 (m, 3 H), 1.16 (d, $J = 6.9$ Hz, 18 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 154.8, 153.0, 146.3, 132.6, 119.1, 113.7, 112.5, 110.6, 29.7, 23.7, 22.9, 22.7, 18.3, 14.3, 13.1; HRMS-ESI (m/z): $[M + Na]^+$ calcd for $C_{22}H_{34}O_2Si$, 381.2220; found, 381.2236.

4c

4d

5c

6c

6d

9c

9g

23

15

17

18

19

20

21

22

24