Supplementary Material For:

Synthesis of Alkylidenecyclopentenones via the Coupling of Propargyl Alcohol Derivatives with Cyclopropylcarbene-Chromium Complexes

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General Considerations. Nuclear Magnetic Resonance (^{1}H and ^{13}C NMR) spectra were recorded on a Bruker AF200 (200 MHz), Bruker AF400 (400 MHz), or Varian AF (200 MHz) spectrometer. Chemical shifts are reported in parts per million (δ) relative to an internal chloroform reference. Coupling constants (J values) are reported in hertz (Hz), and spin multiplicities are indicated by the following symbols: s (singlet), d (doublet), t (triplet), q (quartet), m (multiplet). Infrared spectra were recorded on a Nicolet 5DXC FT-IR or Perkin-Elmer model 281 spectrometer. Band positions are reported in reciprocal centimeters (cm^{-1}). Band intensities are reported relative to the most intense band and are listed as: br (broad), vs (very strong), s (strong), m (medium), w (weak); only diagnostic bands (excluding C-H strectches) above 1500 cm^{-1} are reported. Mass spectra (MS) were obtained on a VG 7070E spectrometer using electron impact (EI) or chemical ionization (CI) or on a Hewlett-Packard GC-MS 5970B with Mass Selection Detector: m/e value is reported, followed by the relative intensity in parentheses. Melting points were taken on a Fisher-Johns melting point apparatus (Model 12-144) equipped with a calibrated thermometer. Flash column chromatography was performed using thick-walled glass columns and "flash grade" silica gel (Bodman 230-400 mesh). Preparative thin layer chromatography was performed using precoated 1000 micron 20 x 20 silica gel plates purchased from Whatman. Routine thin layer chromatography (TLC) was performed using precoated 0.25mm silica gel plates purchased from Whatman. Combustion analysis results were obtained from Desert Analytics Laboratory or Galbraith Laboratories.

Tetrahydrofuran (THF), diethyl ether, and 1,4-dioxane were distilled from sodium / benzophenone ketyl. Dichloromethane, N,N-dimethylformamide (DMF) and toluene were distilled from calcium hydride before use. All reaction solvents were distilled for purity. All other reagents were obtained from commercial suppliers and used without further purification.

Preparation of Acylate Salt 10. To a solution of cyclopropyl bromide (1.20 g, 10.0 mmol) in diethyl ether (25 mL) at -78 °C under nitrogen was added t-butyllithium (9.10 mL of a 2.2M pentane solution, 20.0 mmol) via syringe pump over a period of 10 min. This solution was stirred for 20 min at -78 °C and then transferred via cannula to a suspension of chromium hexacarbonyl (2.20 g, 10.0 mmol) in diethyl ether (50 mL) at 0 °C. The reaction mixture was warmed to 25 °C and allowed to stir for 1 h. The solvent was then removed on a rotary evaporator and the residue was dissolved in a minimum amount of water and filtered through Celite. To the filtrate, 20 mL of saturated aqueous tetramethylammonium bromide solution was added, leading to immediate precipitation of the ammonium salt. The precipitate was collected by suction filtration, then dissolved in dichloromethane and dried over anhydrous sodium sulfate. The solvent was removed on a rotary evaporator to give a yellow solid (1.86 g, 55 %) identified as the acylate salt **10**. ^{1}H NMR (acetone-d_6): δ 3.44 (s, 12 H), 2.76 (m, 1 H), 0.65 (m, 2 H), 0.27 (m, 2 H).

General Procedure (I): The Synthesis of Alkyne-Containing Carbene Complexes. To a solution of acylate salt **10** (0.40 g, 1.20 mmol) in 20 mL of dichloromethane at 0 °C under nitrogen was added acetyl chloride (0.08 mL, 1.20 mmol). The reaction mixture was stirred at 0 °C for about 1 h and then warmed to 25 °C and stirred for 20 min. The solvent was removed on a rotary evaporator. Flash chromatography of the residue after evaporation using hexane as the eluent gave the pure carbene complex after solvent removal. This procedure was identical to that used by previous researchers in this group. The resulting alkyne-carbene complexes were used immediately due to mild thermal and oxidative instability. In most cases, these complexes were characterized only through NMR and infrared data.

General Procedure (II): Intramolecular Reaction of Carbene Complexes with Alkynes. To a three-neck round-bottom flask equipped with a reflux condenser and rubber septum, under nitrogen, was added toluene (50 mL) and water (0.5 mL), and the solution was heated to reflux. To this refluxing solution was added a solution of the alkyne-carbene complex in toluene (20 mL) via syringe pump over a period of 4 h. After the addition was complete, the mixture was heated at reflux for an additional 20 h and then cooled to room temperature. The resulting green mixture was filtered through Celite and the solvent was removed on a rotary evaporator. Final purification was achieved by flash chromatography on silica gel using 4:1 hexane: ethyl acetate as eluent unless otherwise noted.

General Procedure (III): Intermolecular Reaction of Methoxycarbene-Chromium Complex 1 with Propargyl Alcohol Derivatives. To a three-neck round bottom flask equipped with reflux condenser and septum, under nitrogen, was added 99:1 toluene: water (50 mL). This solution was heated to reflux. To this refluxing solution, a solution of carbene complex and propargyl alcohol derivative in toluene (20 mL) was added via syringe pump over a period of 2 h. After the addition was complete, the mixture was heated at reflux for 24 h and then cooled to room temperature. The resulting green mixture was filtered through Celite and the solvent was removed on a rotary evaporator. Final purification was achieved by flash chromatography on silica gel.

Preparation of Carbene Complex 11A. General Procedure I was followed using a solution of propargyl alcohol derivative **9A** (100 mg, 0.57 mmol) in dichloromethane (10 mL), acylate salt **10** (193 mg, 0.57 mmol), and acetyl chloride (0.042 mL, 0.S7 mmol) in dichloromethane (20 mL). After chromatographic purification, a yellow oil (130 mg, 52 %) identified as carbene complex **11A** was obtained. ^{1}H NMR ($CDCl_3$): δ 7.30 (m, 5 H), 5.12 (t, 2 H, J = 6.2), 4.80 (dd, 1 H, J = 5.0, 6.2), 3.46 (m, 1 H), 2.40 (q, 2 H, J = 6.2), 1.40 (m, 2 H), 1.15 (m, 2 H); ^{13}C NMR ($CDCl_3$): δ 223.3, 216.4, 131.4, 128.5, 128.0, 121.6, 87.9, 85.9, 76.5, 59.5, 41.2, 36.7, 17.7; IR (neat): 2059 (m), 1925 (vs).

Preparation of Carbene Complex 11B. General Procedure I was followed using the solution of propargyl alcohol derivative **9B** (170 mg, 0.65 mmol) in dichloromethane (10 mL), acylate salt **10** (264 mg, 0.78 mmol) and acetyl chloride (0.048 mL, 0.66 mmol) in

dichloromethane (20 mL). After chromatographic purification, a yellow oil (204 mg, 61 %) identified as carbene complex **11B** was obtained. ^{1}H NMR ($CDCl_3$): δ 7.30 (m, 5 H), 5.15 (t, 2 H, J = 5.8), 5.10 (br s, 1 H), 4.80 (t, H, J = 5.8), 3.65 (m, 2 H), 3.45 (m, 2 H), 2.46 (q, 1 H, J = 5.8), 1.60 (m, 6 H), 1.40-1.20 (m, 4 H); ^{13}C NMR ($CDCl_3$): δ 352.0, 223.4, 216.7, 131.7, 128.3, 128.2, 122.1, 95.4, 86.2, 76.5, 64.5, 62.1, 61.6, 41.4, 35.7, 30.1, 25.2, 18.9, 17.8; IR: (neat): 1915 (vs).

Preparation of Carbene Complex 16C. General Procedure I was followed using a solution of 2-phenoxy-4-phenyl-3-butyn-1-ol (**15C**) (98 mg, 0.41 mmol) in dichloromethane (10 mL), acylate salt **10** (139 mg, 0.41 mmol), and acetyl chloride (0.030 mL, 0.41 mmol) in dichloromethane (20 mL). After chromatographic purification using pure hexane as eluent, a yellow oil (113 mg, 57 %) identified as carbene complex **16C** was obtained. ^{1}H NMR ($CDCl_3$): δ 7.40 (m, 10 H), 5.35 (m, 3 H), 3.50 (m, 1 H), 1.58 (m, 2 H), 1.23 (m, 2 H); ^{13}C NMR ($CDCl_3$): δ 223.2, 216.4, 156.9, 131.6, 129.5, 128.6, 128.2, 122.0, 121.3, 115.9, 88.6, 82.6, 79.8, 65.9, 41.9, 18.5; IR (neat): 1916 (vs).

Preparation of Carbene Complex 22. General Procedure I was followed using a solution of the appropriate propargyl alcohol derivative (2° THP ether of 7-phenyl-6-penten-4-yne-1,3-diol, prepared similarly to **9B**) (180 mg, 0.63 mmol) in dichloromethane (10 mL), acylate salt **10** (212 mg, 0.63 mmol), and acetyl chloride (0.045 mL, 0.63 mmol) in dichloromethane (20 mL). After chromatographic purification, a yellow oil (228 mg, 68 %) identified as carbene complex **22** was obtained. ^{1}H NMR ($CDCl_3$): δ 7.35 (m, 5 H), 6.98 (d, 1 H, J = 16.2), 6.14 (dd, 1 H, J = 16.2, 1.4), 5.12 (t, 1 H, J = 6.0), 5.04 (br s, 1 H), 4.79 (t, 1 H, J = 5.6), 3.69 (m, 1 H), 3.55 (m, 1 H), 3.49 (m, 1 H), 2.39 (q, 2 H, J = 6.2), 1.60 (m, 6 H), 1.42 (m, 2 H), 1.18 (m, 2 H); ^{13}C NMR ($CDC1_3$): δ 223.8, 216.7, 142.2, 136.0, 128.7, 126.6, 126.2, 106.9, 95.4, 88.4, 85.5, 76.9, 62.2, 61.8, 41.4, 35.3, 30.2, 25.2, 18.9, 17.8; IR (neat): 1924(vs).

Thermolysis of Carbene Complex 11A. General Procedure II was followed using carbene complex **11A** (204 mg, 0.24 mmol). Purification by flash chromatography on silica gel using hexane ethyl acetate (4:1) as the eluent provided **12** as the only product.

Further purification was done by preparative thin layer chromatography (hexane: ethyl acetate = 3:2) to give 58 mg (57 %) of alkylidenecyclopentenone **12**. ^{1}NMR ($CDCl_3$): δ 7.30 (m, 5 H), 6.00 (t, 1 H, J = 4.1), 5.50 (s, 1 H), 4.40 (t, 2 H, J = 5.4), 4.05 (s, 1 H), 2.52 (td, 2 H, J = 5.4-t, 4.1-d); ^{13}C NMR ($CDCl_3$): δ 205.2, 198.3, 134.1, 129.4, 123.2, 109.4, 108.1, 68.2, 55.6, 23.7; IR (neat): 1684 (s), 1574 (vs); MS (FAB): m/e 213 (M + 1, 18), 212 (100), 184 (30); High Res. MS: Calcd for $C_{14}H_{12}O_2$: 212.0837; Found: 212.0836. The structure of **12** was further supported by decoupling experiments. Irradiation of the proton at δ 6.00: δ 2.52 (t, J = 5.4). Irradiation of the proton at δ 4.40: δ 2.52 (d, J = 4.1). Irradiation of the proton at δ 2.52: δ 6.00 (s, 1 H), 4.40 (s).

Thermolysis of Carbene Complex 11B. General Procedure II was followed using carbene complex **11B** (240 mg, 0.48 mmol). Purification by flash chromatography on silica gel using hexane: ethyl acetate (4:1) as the eluent provided alkylidenecyclopentenone **12** (65 mg, 64 %) as the only product. The spectral data were identical to those reported in the previous synthesis of alkylidenecyclopentenone **12** from complex **11A**.

Thermolysis of Carbene Complex 16C. General Procedure II was followed using carbene complex **16C** (116 mg, 0.24 mmol). Purification by flash chromatography on silica gel using hexane ethyl acetate (4:1) as the eluent provided compound **17** as the only product. Further purification was done by preparative thin layer chromatography (hexane: ethyl acetate = 3:2) to give 31.7 mg (67%) of compound **17**. ^{1}H NMR ($CDCl_3$): δ 7.23 (m, 5 H), 6.22 (br s, 1 H), 5.44 (s, 2 H), 5.27 (s, 1 H), 4.05 (s, 1 H); ^{13}C NMR ($CDCl_3$): δ 203.8, 191.5, 141.5, 128.7, 127.8, 127.4, 124.0, 111.2, 97.3, 86.1, 51.3; IR (neat): 1694 (m), 1599 (s); MS (El): m/e 198 (m, 100), 170 (15), 169 (38), HRMS: Calcd. for $C_{13}H_{10}O_2$: 198.0689, Found: 198.0687.

Thermolysis of Carbene Complex 22. General Procedure II was followed using carbene complex **22** (210 mg, 0.39 mmol). Purification by flash chromatography on silica gel using hexane ethyl acetate (4:1) as the eluent provided a mixture of compounds **23-E**, **23-Z**, and **24**. The 1:1:1 ratio of these compounds was determined by the NMR integration of the alkene peaks. Further purification was done by preparative thin layer chromatography (hexane: ethyl acetate = 3:2) and two fractions were isolated. The

compound (22.0 mg, 24 %) in the first fraction was identified as dialkylidenecyclopentenone **23-Z**. ^{1}H NMR ($CDCl_3$): δ 7.27 (m, 5 H), 6.32 (t, 1 H, J = 7.6), 6.24 (dt, 1 H, J = 4.6-t, 1.4-d), 5.55 (br s, 1 H), 4.33 (t, 2 H, J = 6.0), 4.25 (d, 2 H, J = 7.6), 2.54 (td, 2 H, J = 6.0-t, 4.6-d); ^{13}C NMR ($CDCl_3$): δ 192.8, 174.2, 139.8, 132.4, 131.1, 128.5, 126.2, 116.1, 108.5, 66.6, 33.2, 23.5; IR (neat): 1648 (s), 1572 (s); MS (EI): m/e 238 (m, 100), 167 (10), 165 (13); HRMS: Calcd. for $C_{16}H_{14}O_2$: 238.0994, Found: 238.1014. The stereochemistry of the 5-exo double bond was assigned as Z by comparing with alkylideneindanones in literature, which feature higher chemical shifts for the vinylic proton of the E-isomer, and lower chemical shifts for the exocyclic allylic protons.[2] The two compounds (40.2 mg, 43 %) in the second fraction were presumed to be the E isomer of dialkylidenecyclopentenone **23** and alkylidenecyclopentenone **24**. The chemical shift for the alkene hydrogen of dialkylidenecyclopentenone **23-E** is δ 6.86. Therefore, **23-E** was assigned as E based on its similarity to E-alkylideneindanone. A doublet at δ 6.70 and doublet of doublets at δ 6.10 are suggestive of the styryl group on compound **24**.

Coupling of Cyclopropylcarbene Complex 1 with 3-phenylpropargyl Alcohol (19A). General Procedure III was followed using carbene complex **1**[3] (182 mg, 0.65 mmol) and 3-phenylpropargyl alcohol (**19A**) (86 mg, 0.65 mmol). Toluene was used as the solvent with the addition of 1 % water. The purification was done by preparative thin layer chromatography (hexane: ethyl acetate = 2:1). A single fraction (65.2 mg, 46 %) identified as cyclopentenone **21** was obtained as a colorless oil. ^{1}H NMR ($CDCl_3$): δ 7.35 (m, 5 H), 5.38 (s, 1 H), 3.98 (dd, 1 H, J = 12.0, 3.6 Hz), 3.95 (s, 3 H), 3.86 (dd, 1 H, J = 12.0, 3.0 Hz), 3.62 (d, 1 H, J = 3.2), 3.08 (br q, 1 H, J = about 3.3), 1.80 (br s, 1 H); ^{13}C NMR ($CDCl_3$): δ 203.5, 188.7, 138.4, 128.5, 127.9, 126.6, 104.5, 61.2, 59.1, 54.5, 52.1; IR (neat): 3350 (s), 1677 (s), 1588 (vs); MS (EI): m/e 218 (37), 199 (19) 187 (100); HRMS: Calcd. for $C_{13}H_{14}O_3$: 218.0943, Found 218.0935.

Coupling of Cyclopropylcarbene Complex 1 with 3-phenylpropargyl Acetate (19B). General Procedure III was followed using carbene complex **1**[3] (136 mg, 0.49 mmol) and 3-phenylpropargyl acetate (**19B**) (85 mg, 0.49 mmol). Toluene was used as the solvent with the addition of 1 % water. The purification was done by preparative thin layer chromatography (hexane: ethyl acetate = 4:1). A single fraction (63.9

mg, 65 %) identified as alkylidenecyclopentenone **20** was obtained as a colorless oil. ^{1}H NMR ($CDCl_3$): δ 7.28 (m, 5 H), 5.77 (d, 1 H, J = 1.6), 5.57 (d, 1 H, J = 1.6), 5.13 (t, 1 H, J = 1.6), 4.13 (t, 1 H, J = 1.6), 3.96 (s, 3 H); ^{13}C NMR ($CDCl_3$): δ 200.9, 181.2, 143.3, 137.4, 128.5, 128.2, 127.0, 111.5, 105.4, 58.4, 55.4; IR (neat): 1695(s), 1574(vs); MS (El): m/e 200 (m, 100), 199 (31); HRMS: Calcd. for $C_{13}H_{12}0_2$: 200.0839, Found 200.0837. Anal: Calcd. for $C_{13}H_{12}O_2$: C 78.02%, H 6.04%; Found: C 77.85%, 6.02%.

Coupling of Cyclopropylcarbene Complex 1 with 5-phenyl-4-penten-2-ynyl Acetate (25). General Procedure III was followed using carbene complex **1**[3] (182 mg, 0.48 mmol) and 5-phenyl-4-penten-2-ynyl acetate (**25**) (95 mg, 0.48 mmol). Toluene was used as the solvent with the addition of 1 % water. The purification was done by preparative thin layer chromatography (hexane: ethyl acetate = 5:1). Two fractions were collected. The compound in the first fraction (37.2 mg, 34 %) was identified as dialkylidenecyclopentenone **26-Z**. ^{1}H NMR ($CDCl_3$): δ 7.30 (m, 5 H), 6.41 (t, 1 H, J = 7.6), 5.59 (s, 1 H), 5.47 (s, 1 H), 5.41 (s, 1 H), 4.26 (d, 2 H, J = 7.6), 3.90 (s, 3 H); ^{13}C NMR ($CDCl_3$): δ 192.8, 177.5, 139.7, 133.2, 129.8, 128.4, 127.4, 126.0, 106.7, 104.2, 57.9, 33.2; IR (neat): 1700 (s), 1601 (vs) cm^{-1}; MS (El): m/e 226 (m, 72), 70(100); HRMS: Calcd. for $C_{15}H_{14}0_2$ 226.0993, Found: 226.0990. The stereochemistry of the 5-exo double bond was determined to be Z by comparison with Z-alkylideneindanones in literature as before. The product in the second fraction (27.1 mg, 25 %) was identified as alkylidenecyclopentenone **27**, contaminated by ~10-15% of dialkylidenecyclopentenone **26**. ^{1}H NMR ($CDCl_3$): δ 7.40 (m, 5 H), 6.64 (d, 1 H, J = 16.0), 6.02 (dd, 1 H, J = 16.0, 8.0), 5.73 (s, 1 H), 5.50 (s, 1 H), 5.27 (s, 1 H), 3.74 (d, 1 H, J = 8.0), 3.92 (s, 3 H); ^{13}C NMR ($CDCl_3$): δ 201.2, 180.2, 138.8, 126.4, 133.8, 128.2, 128.0, 126.2, 124.0, 111.6, 105.8, 58.2, 53.0; IR (neat): 1696 (s), 1571 (vs).

Coupling of Cyclopropylcarbene Complex 1 with Propargyl Acetate. General Procedure III was followed using carbene complex **1**[3] (170 mg, 0.61 mmol) and propargyl acetate (60 mg, 0.61 mmol). The purification was done by preparative thin layer chromatography (hexane: ethyl acetate = 4:1). A single fraction was isolated (15.7 mg, 21%) and identified as 3-methoxy-5-methyl-2-cyclopenten-1-one (**30**) ^{1}H NMR ($CDCl_3$): δ 5.28 (s, 1 H), 3.84, s, 3 H), 2.82 (dd, 1 H, J 16.5, 7.0), 2.54 (m, 1 H), 2.21 (dd, 1

H, J = 16.5, 2.5), 1.20 (d, 3 H, J = 7.2); IR (neat): 1684 (s), 1596 (s) cm^{-1}. The spectral data were identical with a literature report.[4]

Coupling of Cyclopropylcarbene Complex 1 with 1-phenyl-2-propynyl Acetate (31A). General Procedure III was followed using carbene complex **1**[3] (200 mg, 0.72 mmol) and 1-phenyl-2-propynyl acetate (**31A**) (100 mg, 0.57 mmol). Toluene was used as the solvent with the addition of 1 % water. The purification was done by preparative thin layer chromatography (hexane: ethyl acetate = 5:1). Numerous components were present; only the major fraction was collected (49 mg, 34%) and assigned as 3-acetoxy-1-cyclopropyl-1-methoxy-4-phenyl-1,3-butadiene (**35**) ^1H NMR ($CDCl_3$): δ 7.5-7.3 (m, 5 H), 6.13 (s, 1 H),, 5.45 (s, 1 H), 3.53 (s, 3 H), 2.19 (s, 3 H), 1.91 (tt, 1 H, J = 6.8, 4.8), 0.75 (m, 2 H), 0.48 (m, 2 H); IR (neat): 1745 (s) cm^{-1}. The stereochemistry of the double bonds was suggested as that depicted in compound **35** based on comparison with a mechanistically similar reaction process.[5]

Coupling of Cyclopropylcarbene Complex 1 with 3-phenyl-3-(*t*-butyldimethylsilyloxy)-1-propyne (31B). General Procedure III was followed using carbene complex **1**[3] (570 mg, 2.06 mmol) and 1-phenyl-2-propynyl acetate (**31A**) (500 mg, 2.03 mmol). Toluene was used as the solvent. The purification was done by preparative thin layer chromatography (hexane: ethyl acetate = 2:1). A single fraction was collected (97 mg, 14%), which appeared to be a 2:1 mixture of diastereomers of **32**. ^1H NMR ($CDCl_3$), major isomer: δ 5.31 (br s, 1 H), 3.83 (s, 3 H), 2.85 (ddd, 1 H, J = 16.6, 3.0, 1.2 Hz), 2.63 (ddd, 1 H, J = 7.1, 3.0, 2.0 Hz), 2.20 (ddd, 1 H, J = 16.6, 7.1, 1.2 Hz), 0.83 (s, 9 H), -0.03 (s, 3 H), -0.18 (s, 3 H); minor isomer δ 5.04 (br s, 1 H), 3.60 (s, 3 H), 3.05 (q, 1 H, J = 5.3), 2.52 (dd, 2 H, J = 5.3, 1.2), 0.86 (s, 9 H), 0.06 (s, 3 H), -0.06 (s, 3 h); the following peaks appear to be overlapping in both isomers: 7.30 (m, 5 H), 5.38 (m, 1 H), ^{13}C NMR ($CDCl_3$): δ 205.5, 191.6, 143.8, 143.2, 128.1, 127.6, 127.1, 126.9, 126.7, 125.4, 104.3, 97.3, 73.1, 71.9, 67.0, 58.5, 58.4, 54.7, 29.4, 28.1, 25.7, 18.1, 6.8, -4.7, -5.5; MS (FAB): 333 (M+1, 3), 317 (4), 73 (100); HRMS: Calcd. for $C_{19}H_{28}O_3Si$: 332.1808, Found: 332.1815.

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