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Unexpected Cycloisomerizations of Nonclassical Carbocation Intermediates in Gold(I)-Catalyzed Homo-Rautenstrauch Cyclizations

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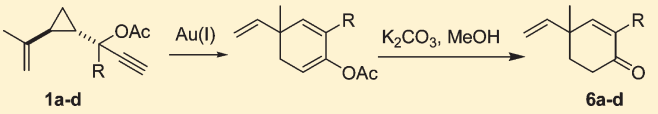
Supporting Information

ABSTRACT: An unexpected gold(I)-catalyzed homo-Rautenstrauch rearrangement of 1-cyclopropyl propargylic esters to cyclohexenones is disclosed. This rearrangement represents new evidence for the recently discussed gold-stabilized nonclassical carbocation character of intermediates in gold catalysis. A mechanistic study proved partial chirality transfer from optically active propargyl acetates.

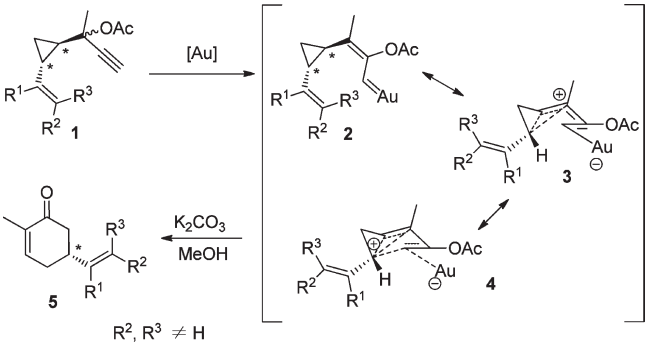


Due to its strong relativistic effects, gold's unique reactivity to activate unsaturated moieties has made homogeneous gold catalysis one of the most rapidly growing research fields in recent years.[1] In contrast to the impressive advances made in preparative applications, comprehension of the nature of the involved organogold intermediates of many reactions is still a matter of debate. One controversially discussed topic is the dichotomy of the carbene versus carbocation character of gold−carbon bonds formed during homogeneous gold catalysis.[2] Recently, we developed a new Au-catalyzed homo-Rautenstrauch rearrangement of stabilized 1-cyclopropyl propargylic esters to give five-, six- and seven-membered carbocycles under mild conditions (Scheme 1).[3] A chirality transfer study in these reactions suggested that gold-stabilized nonclassical carbocations with a certain configurational stability might be involved. A vinyl substituent at the cyclopropyl ring in substrate **1** capable of stabilizing the positive charge in proposed intermediates **3** and **4** >was found to be a key factor for the successful progression of this transformation to cyclohexenones **5**. In this paper, we describe the surprising finding that a change in the substitution pattern of this vinyl group led to the selective formation of completely different cyclohexenones: instead of the expected homo-Rautenstrauch[4] rearrangement products **5** reported earlier, substituents R^1 (R^1 = alkyl, $R^2 = R^3 = H$) led to compounds **6** (Scheme 2). These results represent a convincing proof of the concept that nonclassical carbocations are intermediates in gold catalysis.[5]

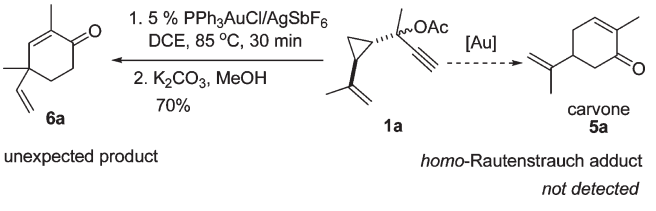
The novel transformation was discovered during our attempts to synthesize naturally occurring odorants, i.e. carvone (**5a**) and cryptomerione, by utilizing the Au-catalyzed homo-Rautenstrauch rearrangement sequence (Scheme 2).[6] Under standard Au-catalyzed homo-Rautenstrauch rearrangement conditions,[3a] the functionalized cyclopropyl propargylic ester **1a** did not cyclize to the expected product carvone but instead generated cyclohexenone **6a** at elevated temperature after methanolysis.

To understand and further explore the scope of this unexpected cycloisomerization reaction, several other isopropenyl-substituted

Scheme 1. Au(I)-Catalyzed Homo-Rautenstrauch Rearrangement of 1-Cyclopropyl Propargylic Acetates



Scheme 2. Unexpected Cycloisomerization of 1a in Gold(I)-Catalyzed Homo-Rautenstrauch Cyclizations



1-cyclopropyl propargylic esters, **1b**−**d**, were synthesized. As shown in Scheme 3, ethyl 5-methylhex-4-enoate (**8**) was first prepared from 2-methylbut-3-en-2-ol and triethyl orthoacetate via a Johnson−Claisen rearrangement according to the literature method.[7] After three classical transformations, successive treatment of ketones **11a**−**d** with *N*-bromosuccinimide and potassium

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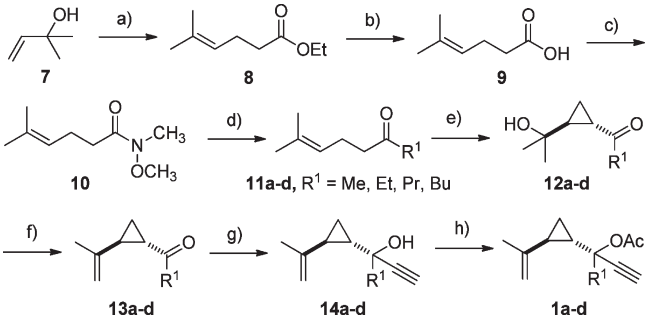
Scheme 3. Synthesis of Cyclopropyl Alkynyl Acetates 1[a]



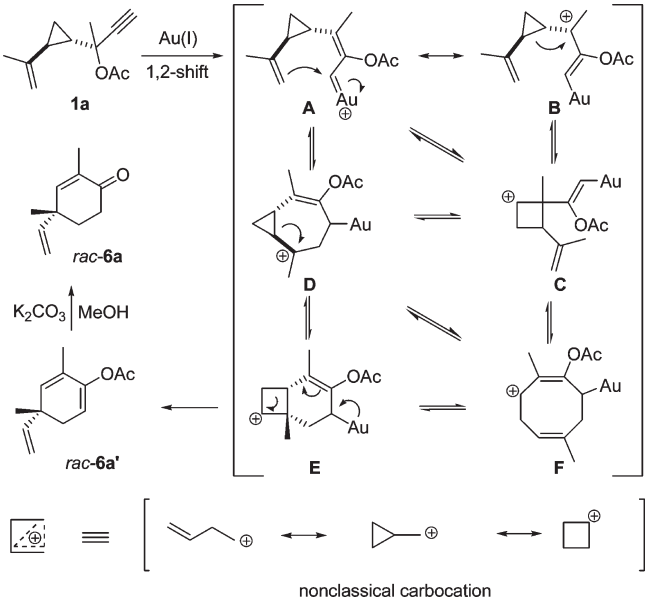
[a] Conditions: (a) 1,1,1-triethyl orthoacetate, oxalic acid, 145 °C, 24 h, 78%; (b) 50% NaOH (aq), EtOH, reflux, 12 h, 92%; (c) *N*,*O*-dimethylhydroxylamine, DCC, Et_3N, $CHCl_3$, 4 h, 83%; (d) R^1MgBr, THF, 3 h, 93−88%; (e) NBS, KOH, DMSO, H_2O, 80−85%; (f) *N*-(triethylammoniumsulfonyl)carbamate, 80−87%; (g) *t*-BuOK, HC≡CH, THF, 83−87%; (h) Ac_2O, Et_3N, DMAP; 89−92%.

hydroxide in DMSO afforded the 2-(1-hydroxy-1-methylethyl)cyclopropyl ketones **12a**−**d**.[8] The relative configuration of **12** was assigned to be completely trans; their spectra were in accordance with those reported by Cossy and Meyer,[9] who revised initially incorrect assignments.[8] Selective dehydration of **12** by methyl *N*-(triethylammoniumsulfonyl)carbamate (Burgess reagent) afforded isopropenylcyclopropyl ketones **13a**−**d** in high yields.[10] The 1-cyclopropyl propargylic esters **1a**−**d** were obtained after acetylene addition and consecutive esterification.

The gold-catalyzed rearrangement of **1** was then investigated by applying different conditions. As shown in Table 1, different gold complexes, counteranions, and various alkyl substituents at the propargylic positions were tolerated. The reactions were complete after 120 min at room temperature (entry 1). At elevated reaction temperatures, substrates were converted in 30 min (entries 2−4) and the cyclohexenone products **6a**−**c** were obtained in good yields after in situ methanolysis. Through the elaboration of Table 1 we experienced that a substantial variation of the reaction conditions was necessary to perform the individual reactions successfully. There was no single set of reaction parameters that worked equally well for all substrates, even if small changes of substituent R^1 appeared to be trivial. Thus, while the reaction of substrates with a methyl or ethyl substituent proceeded similarly well to afford cyclohexenone **6a** or **6b** by using $Ph_3PAuCl/AgSbF_6$, substrate **1c**, bearing a propyl substituent, did not result in product **6c** using the same cationic gold(I) complex as catalyst even after a substantially prolonged reaction time (entry 5). Switching to the NHC-derived catalyst **B** and increasing the catalyst dosage to 10 mol % gave only a very low yield after 120 min (entry 6). Finally, application of 20 mol % of catalyst **C** allowed us to isolate product **6c** in 80% yield (entry 4). To our surprise, compound **1d** bearing an *n*-butyl substituent worked again well using the NHC complex **B** (entry 7). Similarly subtle structure−reactivity relationships were also observed by Zhang et al. in a homogeneous gold-catalyzed cycloisomerization of 1,5-enynes.[11] In order to prove that the reactions were not simply catalyzed by protons, a control experiment using a catalytic amount of triflic acid was performed which expectedly led to the cyclopropane opening product **6f** (entry 9).[12]

In general terms, the stabilization of positive charge by an appropriate substitution pattern at the cyclopropane unit is essential for a smooth conversion of **1** into the cyclization products **6**. In light of

Scheme 4. Postulate of the Reaction Mechanism



the recently discussed nonclassical carbocationic nature of carbenoid-like intermediates of gold-catalyzed enyne cyclizations,[1a] a mechanism accounting for the formation of unexpected enol acetates *rac*-**6a**′ is proposed in Scheme 4. The cycle begins with a gold-promoted 1,2-acyloxy migration[13] of propargylic ester *rac*-**1a**, leading to the formation of the Au-carbenoid **A**. This Au-carbenoid can also be interpreted as the resonant gold-stabilized cyclopropylmethyl cation **B**.[1a,2e] Theoretical studies have revealed that the $C_4H_7^+$ cation undergoes facial interconversions of cyclopropylcarbinyl, cyclobutyl, and homoallyl derivatives.[14] The nonclassical character of carbocation **B** had been embodied previously to explain the formation of the homo-Rautenstrauch type cycloisomerization product **5** (structures **3** and **4**, Scheme 1).[3] In the present case, intramolecular cyclization and isomerization of intermediates **A**/**B** would finally result into a new nonclassical cation with isomeric structures **C**−**F**, triggered by low steric hindrance at the distal methylene group and stabilization of the localized cation **D**. From there, only the involvement of cyclobutyl cation **E** as part of the new nonclassical assembly can illustrate the rearrangement of intermediates into the observed product *rac*-**6a**′. Further evidence for this mechanistic scenario comes from the conversion of deuterated compound **1e**, which afforded the expected cyclohexenone **6e** in high yield (Table 1, entry 8). The acidic alkyne deuterium atom does not become part of the nonclassical carbocation, and hence no D shifts occur during the reaction.

The extent of chirality transfer in potentially cationic processes reveals valuable information regarding the mechanistic proposal. Therefore, optically active 1-cyclopropyl propargylic ester (1*S*,2*S*)-**20** (ee = 90%) was prepared by kinetic resolution from *rac-trans*-carboxylic acid **16** according to Scheme 5[15,16] to further study the nature of our nonclassical carbonium ions.

A series of gold complexes were utilized to optimize the cycloisomerization of **20** (Table 2). The best case using $IPrAuCl/AgNTf_2$ (10 mol %) catalyst afforded, after methanolysis, (*S*)-cyclohexenone **21** in 56% yield and 37% ee. Other catalytic systems and lower temperatures only decreased the yield without significantly improving the ee value (Table 2, entries 2−6). Interestingly, the achiral octa-2,6-dienone **22** was also isolated, albeit in only 30% yield (Table 2), which constitutes

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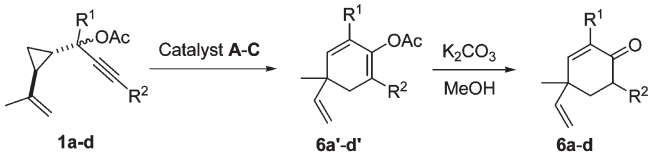
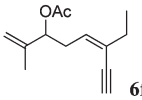
Table 1. Au(I)-Catalyzed Cycloisomerization of Cyclopropyl Alkynyl Acetates[a]



A = $PPh_3AuCl/AgSbF_6$ (5 mol%)
B = $IPrAuCl/AgNTf_2$ (10 mol%)
C = $PPh_3AuCl/AgNTf_2$ (20 mol%)

entry	substrate	product	cat.	time (min)	temp. (°C)	yield (%)
1	**1a** R^1 = Me, R^2 = H	**6a**	**B**	120	R.T.	73
2	**1a**	**6a**	**A**	30	85	70
3	**1b** R^1 = Et, R^2 = H	**6b**	**A**	30	85	86
4	**1c** R^1 = Pr, R^2 = H	**6c**	**C**	30	85	80
5	**1c**	**6c**	**A**	120	85	-[b]
6	**1c**	**6c**	**B**	120	85	11
7	**1d** R^1 = Bu, R^2 = H	**6d**	**B**	30	85	88
8	**1e** R^1 = Bu, R^2 = D	**6e**	**B**	30	85	85
9	**1b**	 **6f**	HOTf[c]	30	85	65

[a] Conditions: compound **1** (0.68 mmol) and a catalyst in CH_2ClCH_2Cl (2 mL) under an argon atmosphere were stirred for 30 min at 85 °C. Then K_2CO_3 (1.36 mmol) and MeOH (2 mL) were added at room temperature. The mixture was stirred for a further 2 h. [b] The starting material disappeared, but **6c** could not be detected by GC-MS. [c] 10 mol % of triflic acid used.

additional evidence for the mechanism depicted in Scheme 4: compound **22** was brought about by a species analogous to nonclassical cyclopropylcarbinyl cations **D** or the homo-allyl cations **F**. In comparison to derivative **1a**, vicinal strain entailed by the additional methyl group at the cyclopropane unit of **20** accounts for this result. The absolute configurations of compound **16** (90% ee) and compound **21** (47% ee) were unequivocally determined by electronic circular dichroism (ECD) measurements.[17] In an elegant stereoselective synthesis of sesquiterpene (−)-cubebol based on a Pt-, Au-, or Cu-catalyzed cycloisomerization, Fehr and co-workers have reported that the cycloisomerization reaction of enantioenriched propargyl pivalates occurs with substantial chirality transfer.[18] The mechanistic hypothesis is also consistent with a related study by Toste, who proposed a mechanism involving cyclization and ring expansion for gold(I)-catalyzed cycloisomerization of enynes containing an embedded cyclopropane unit.[19]

In summary, we have developed an unprecedented gold(I)-catalyzed cycloisomerization of 1-cyclopropyl propargylic acetates which instructively complements the gold-catalyzed homo-Rautenstrauch rearrangement previously reported by our group. From a mechanistic point of view, the unique feature of the present cycloisomerization is the gold-stabilized nonclassical carbocationic nature of organo-gold species, especially the occurrence of nonclassical cyclobutyl cations involved in the transformation. Partial chirality transfer in the reaction also reveals the intrinsically stereospecific nature of these transformations.

EXPERIMENTAL SECTION

$IPrAuNTf_2$ was prepared according to the reported procedure.[20] The Weinreb amide **10** was prepared by following the literature method, starting from 2-methylbut-3-en-2-ol (**7**).[8] The γ,δ-unsaturated ketones **11** were obtained by reacting **10** with the corresponding Grignard reagent

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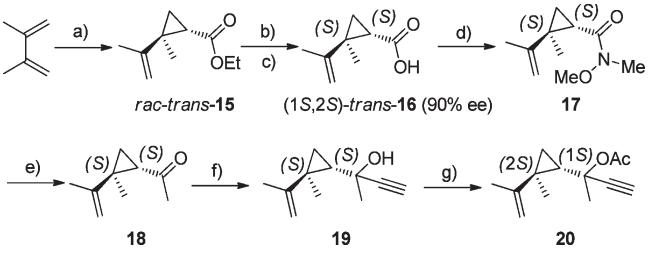
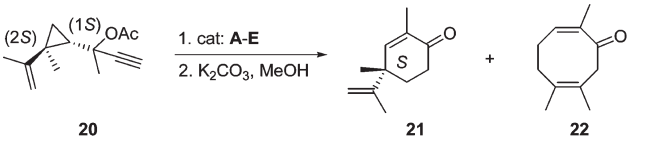
Scheme 5. Synthesis of 2-((1*S*,2*S*)-2-Methyl-2-(1-methylethenyl)cyclopropyl)but-3-yn-2-yl Acetate[a]



[a] Conditions: (a) ethyl 2-diazoacetate, catalyst $Rh_2(OAc)_4$, CH_2Cl_2, overnight, yield 43%; (b) 50% NaOH (aq), EtOH, reflux, 12 h, yield 95%; (c) (+)-MTDP, isopropyl ether, yield 80%, ee = 90%; (d) *N,O*-dimethylhydroxylamine, DCC, Et_3N, $CHCl_3$, 5 h, yield 89%, ee = 90%; (e) CH_3MgBr, THF, 3 h, yield 85%, ee = 90%; (f) *n*-BuLi, HC≡CH, THF, yield 90%; (g) Ac_2O, Et_3N, DMAP, yield 87%.

Table 2. Au(I)-Catalyzed Chirality Transfer in the Conversion of Compound 20



entry	cat.	time	temp (°C)	product (ratio)	yield (%)	ee (%)
1	**A**	30 min	85	**21**/**22** (7/3)	56	37
2	**B**	2 h	room temp	**21** (100%)	56	42
3	**C**	3 h	room temp	**21**/**22** (8/2)	30	20
4	**D**	2 d	room temp	**21** (100%)	28	47
5	**A**	2 d	0	n.r.		
6	**E**	3 h	85	complex[a]		

[a] The starting material disappeared, but neither **21** nor **22** could be detected by GC-MS.

R^1MgBr in dry THF by Woerpel's procedure.[21] Hydroxy ketones **12a**–**d** were prepared according to the method of Dechoux.[8]

***trans*-1-[2-(1-Hydroxy-1-methylethyl)cyclopropyl]ethanone (12a).** Analytical data were reported.[10b]

***trans*-1-[2-(1-Hydroxy-1-methylethyl)cyclopropyl]propanone (12b).** Colorless oil; 83% yield. ^{1}H NMR (300 MHz, $CDCl_3$): δ 2.60 (q, J = 7.3 Hz, 2H), 2.05–1.99 (m, 1H), 1.59–1.52 (m, 2H), 1.41–1.21 (m, 6H), 1.17–1.01 (m, 5H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 211.2 (s), 68.4 (s), 36.7 (t), 35.6 (d), 29.5 (q), 29.2 (q), 23.9 (d), 13.3 (t), 8.1 (q) ppm. HRMS (ESI): m/z calcd for $C_9H_{16}O_2$ $(M + H)^+$ 157.1229, found 157.1221.

***trans*-1-[2-(1-Hydroxy-1-methylethyl)cyclopropyl]butanone (12c).** Colorless oil; 80% yield. ^{1}H NMR (300 MHz, $CDCl_3$): δ 2.53 (t, J = 7.2 Hz, 2H), 2.06–2.00 (m, 1H), 1.69–1.51 (m, 4H), 1.43–1.21 (m, 6H), 1.18–1.12 (m, 1H), 1.04–0.91 (m, 4H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 210.9 (s), 68.5 (s), 45.6 (t), 35.7 (d), 29.5 (q), 29.2 (q), 24.2 (d), 17.6 (t), 13.8 (q), 13.4 (t) ppm. EI-MS (m/z, relative intensity): 170 (M^+, 0.4), 43 (100).

***trans*-1-[2-(1-Hydroxy-1-methylethyl)cyclopropyl]pentanone (12d).** Colorless oil; 85% yield. ^{1}H NMR (300 MHz, $CDCl_3$): δ 2.54 (t, J = 7.2 Hz, 2H), 2.06–1.84 (m, 2H), 1.65–1.51 (m, 3H), 1.37–1.25 (m, 8H), 1.17–1.11 (m, 1H), 1.04–0.98 (m, 1H), 0.91 (t, J = 7.3 Hz, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 211.1 (s), 68.5 (s), 43.4 (t), 35.7 (d), 29.5 (q), 29.2 (q), 26.2 (t), 24.2 (d), 22.3 (t), 13.8 (q), 13.4 (t) ppm. HRMS (ESI): m/z calcd for $C_{11}H_{20}O_2$ $(M + H)^+$ 185.1542, found 185.1537.

Cyclopropyl ketone **13a** was synthesized by dehydration of **12a** using Burgess' protocol.[10b] Compounds **13b**,**c** were prepared using the same method.

***trans*-1-[2-(1-Methylethenyl)cyclopropyl]propanone (13b).** Colorless oil; 80% yield. ^{1}H NMR (300 MHz, $CDCl_3$): δ 4.77 (s, 2H), 2.61 (q, J = 7.4 Hz, 2H), 2.00 (t, J = 7.0 Hz, 2H), 1.66 (s, 3H), 1.38–1.31 (m, 1H), 1.14–1.07 (m, 4H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 210.0 (s), 143.3 (s), 110.4 (t), 36.8 (t), 30.9 (d), 28.0 (d), 23.0 (q), 16.0 (t), 7.9 (q) ppm. HRMS (ESI): m/z calcd for $C_9H_{14}O$ $(M + H)^+$ 139.1123, found 139.1132.

***trans*-1-[2-(1-Methylethenyl)cyclopropyl]butanone (13c).** Colorless oil; 84% yield. ^{1}H NMR (300 MHz, $CDCl_3$): δ 4.77 (bs, 2H), 2.54 (t, J = 7.2 Hz, 2H), 2.00 (t, J = 7.4 Hz, 2H), 1.69–1.61 (m, 5H), 1.38–1.32 (m, 1H), 1.14–1.10 (m, 1H), 0.93 (t, J = 7.4 Hz, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 209.7 (s), 143.3 (s), 110.5 (t), 45.7 (t), 31.0 (d), 28.3 (d), 20.4 (q), 17.5 (t), 16.0 (t), 13.7 (q) ppm. HRMS (ESI) m/z calcd for $C_{10}H_{16}O$ $(M + Na)^+$ 175.1099, found 175.1105.

***trans*-1-[2-(1-Methylethenyl)cyclopropyl]pentanone (13d).** Colorless oil; 87% yield. ^{1}H NMR (300 MHz, $CDCl_3$): δ 4.90–4.76 (m, 2H), 2.56 (t, J = 7.2 Hz, 2H), 2.02–1.97 (m, 2H), 1.66–1.58 (m, 5H), 1.38–1.30 (m, 3H), 1.14–1.08 (m, 1H), 0.92 (t, J = 7.3 Hz, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 209.8 (s), 143.3 (s), 110.5 (t), 43.6 (t), 31.0 (d), 28.3 (d), 26.2 (t), 22.3 (t), 20.4 (q), 16.0 (t), 13.8 (q) ppm. HRMS (ESI): m/z calcd for $C_{11}H_{18}O$ $(M + H)^+$ 167.1436, found 167.1444.

General Procedure for the Synthesis of Alcohols 14a–d. In a 250 mL flask, *t*-BuOK (9.74 g, 87.0 mmol) was dissolved in 100 mL of dry THF. Acetylene was slowly bubbled through the solution for 30 min at 25 °C. Then bubbling was stopped. The unsaturated cyclopropyl ketone (72.5 mmol) **13** was added dropwise. The reaction mixture was stirred for an additional 3 h, quenched by the addition of H_2O (100 mL), and then extracted with MTBE (3 × 50 mL). The combined extracts were dried over $MgSO_4$ and concentrated under reduced pressure. The residue was subjected to bulb-to-bulb distillation to give the acetylenic alcohols **14a**–**d**.

trans-2-[2-(1-Methylethenyl)cyclopropyl]but-3-yn-2-ol (***14a***). Colorless oil; 87% yield. ^{1}H NMR (300 MHz, $CDCl_3$): δ 4.78–4.70 (m, 2H), 2.41 (s, 1H), 2.25–2.15 (m, 1H), 1.76–1.64 (m, 4H), 1.59–1.50 (m, 3H), 1.29–1.18 (m, 1H), 0.98–0.70 (m, 1H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$; major isomer): δ 145.0 (s), 108.9 (t), 85.2 (s), 71.9 (s), 69.2 (d), 29.8 (q), 29.6 (d), 21.9 (d), 20.9 (q), 9.6 (t) ppm. HRMS (ESI): m/z calcd for $C_{10}H_{14}O$ $(M + Na)^+$ 173.0942, found 173.0938.

trans-3-[2-(1-Methylethenyl)cyclopropyl]pent-1-yn-3-ol (***14b***). Colorless oil; 83% yield. ^{1}H NMR (300 MHz, $CDCl_3$): δ 4.71 (bs, 2H), 2.41 (s, 1H), 2.26–2.12 (m, 1H), 1.92–1.76 (m, 2H), 1.68 (bs, 3H), 1.60–1.53 (m, 1H), 1.21–1.05 (m, 4H), 0.97–0.67 (m, 2H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$; major isomer): δ 144.8 (s), 108.9 (t), 83.8 (s), 73.2 (d), 73.1 (s), 35.6 (t), 28.0 (d), 23.0 (d), 20.8 (q), 8.7 (q), 8.1(t) ppm. EI-MS (m/z, relative intensity) 164 (M^+, 2.2), 96 (100).

trans-3-[2-(1-Methylethenyl)cyclopropyl]hex-1-yn-3-ol (***14c***). Colorless oil; 87% yield. ^{1}H NMR (300 MHz, $CDCl_3$): δ 4.89–4.63 (m, 2H), 2.41 (s, 1H), 2.10–1.55 (m, 9H), 1.39–0.71 (m, 6H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$; major isomer): δ 144.8 (s), 108.9 (t), 84.0 (s),73.1 (d), 72.6 (s), 45.0 (t), 28.4 (d), 23.0 (d), 20.9 (q), 17.6 (t), 14.2 (q), 8.2 (t) ppm. HRMS (ESI): m/z calcd for $C_{12}H_{18}O$ $(M + Na)^+$ 201.1255, found 201.1256.

trans-3-[2-(1-Methylethenyl)cyclopropyl]hept-1-yn-3-ol (***14d***). Colorless oil; 86% yield. ^{1}H NMR (300 MHz, $CDCl_3$): δ 4.84–4.66

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(m, 2H), 2.41 (s, 1H), 2.13−1.01 (m, 1H), 1.82−1.74 (m, 2H), 1.68 (s, 3H), 1.58−1.48 (m, 3H), 1.43−1.32 (m, 2H), 1.25−1.16 (m, 1H), 1.02−0.66 (m, 5H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$; major isomer): δ 144.8 (s), 108.9 (t), 84.1 (s), 73.1 (d), 72.6 (s), 42.5 (t), 28.4 (d), 26.4 (t), 23.0 (d), 22.8 (t), 20.9 (q), 14.0 (q), 8.2 (t) ppm. HRMS (ESI): m/z calcd for $C_{13}H_{20}O$ $(M + H)^+$ 193.1592, found 193.1593.

Method A: General Procedure for the Synthesis of Cyclopropyl Propargyl Acetates 1a−e. A mixture consisting of cyclopropyl propargyl alcohol **14** (48.78 mmol), Ac_2O (14.92 g, 146.3 mmol), Et_3N (24.63 g, 243.9 mmol), and DMAP (0.30 g, 2.44 mmol) was stirred overnight and quenched by the addition of H_2O (100 mL). The mixture was extracted with MTBE (3 × 50 mL). The combined organic phases were washed with saturated aqueous $NaHCO_3$, dried over $MgSO_4$, filtered, and concentrated under reduced pressure. The residue was subjected to bulb-to-bulb distillation to furnish pure substrates **1a**−**d**.

*trans-2-[2-(1-Methylethenyl)cyclopropyl]but-3-yn-2-yl Acetate (**1a**).* Colorless oil; 90% yield. dr = 45:55. ^{1}H NMR (300 MHz, $CDCl_3$): δ 4.85−4.62 (m, 2H), 2.52 (s, 1H), 2.04 (s, 3H), 1.84−1.66 (m, 6H), 1.63−1.55 (m, 1H), 1.46−1.38 (m, 1H), 1.12−0.76 (m, 2H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$; major isomer): δ 169.2 (s), 144.6 (s), 108.8 (t), 81.2 (s), 76.6 (s), 73.9 (d), 27.8 (d), 27.0 (q), 22.4 (d), 21.9 (q), 21.2 (q), 10.2 (t) ppm. HRMS (ESI): m/z calcd for $C_{12}H_{16}O_2$ $(M + Na)^+$ 215.1048, found 215.1055.

*trans-3-[2-(1-Methylethenyl)cyclopropyl]pent-1-yn-3-yl Acetate (**1b**).* Colorless oil; 92% yield. dr = 24:76. ^{1}H NMR (300 MHz, $CDCl_3$): δ 4.89−4.66 (m, 2H), 2.53 (s, 1H), 2.31−1.96 (m, 5H), 1.85−1.75 (m, 1H), 1.74−1.63 (m, 3H), 1.63−1.57 (m, 1H), 1.47−1.40 (m, 1H), 1.17−1.09 (m, 1H), 1.04 (t, J = 7.4 Hz, 3H), 0.90−0.78 (m, 1H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$; major isomer): δ 169.2 (s), 144.6 (s), 109.2 (t), 81.3 (s), 79.9 (s), 75.1 (d), 33.1 (t), 25.1 (d), 23.1 (d), 21.9 (q), 20.7 (q), 10.1 (t), 8.5 (q) ppm. HRMS (ESI): m/z calcd for $C_{13}H_{18}O_2$ $(M + H)^+$ 207.1385, found 207.1366.

*trans-3-[2-(1-Methylethenyl)cyclopropyl]hex-1-yn-3-yl Acetate (**1c**).* Colorless oil; 89% yield. dr = 35:65. ^{1}H NMR (300 MHz, $CDCl_3$): δ 4.71 (s, 1H), 4.68 (s, 1H), 2.52 (s, 1H), 2.22−1.68 (m, 5H), 1.66−1.40 (m, 7H), 1.16−1.10 (m, 1H), 0.97 −0.77 (m, 4H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$; major isomer): δ 169.2 (s), 144.6 (s), 109.2 (t), 80.8 (s), 80.1 (s), 75.0 (d), 42.1 (t), 25.5 (d), 23.1 (d), 22.0 (q), 20.7 (q), 17.5 (t), 14.0 (q), 10.2 (t) ppm. HRMS (ESI): m/z calcd for $C_{14}H_{20}O_2$ $(M + Na)^+$ 243.1361, found 243.1356.

*trans-3-[2-(1-Methylethenyl)cyclopropyl]hept-1-yn-3-yl Acetate (**1d**).* Colorless oil; 92% yield. dr = 32:68. ^{1}H NMR (300 MHz, $CDCl_3$): δ 4.79−4.46 (m, 2H), 2.46 (s, 1H), 2.30−2.05 (m, 2H), 1.96−1.90 (m, 3H), 1.75−1.16 (m, 9H), 1.09−1.02 (m, 1H), 0.97−0.79 (m, 3H), 0.78−0.72 (m, 1H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$; major isomer): δ 169.1 (s), 144.5 (s), 109.1 (t), 80.8 (s), 80.1 (s), 75.0 (d), 39.7 (t), 26.2 (t), 25.5 (d), 23.1 (d), 22.6 (t), 21.9 (q), 20.7 (q), 13.9 (q), 10.1 (t) ppm. HRMS (ESI): m/z calcd for $C_{15}H_{22}O_2$ $(M + H)^+$ 235.1698, found 235.1679.

*trans-1-Deuterium-3-[2-(1-methylethenyl)cyclopropyl]hept-1-yn-3-yl Acetate (**1e**).* To a solution of **1d** (150 mg, 0.64 mmol) in dry THF (1 mL) at −78 °C was added dropwise a 1.6 mol/L solution of *n*-BuLi in hexanes (0.5 mL, 0.72 mmol). The reaction mixture was stirred for 1 h at the same temperature and quenched by the addition of D_2O (5 mL). The mixture was extracted with Et_2O (3 × 2 mL). The organic phases were dried over $MgSO_4$ and concentrated under reduced pressure. Product **1e** was purified by bulb-to-bulb distillation. Colorless oil; 93% yield. D incorporation: 68%. ^{1}H NMR (300 MHz, $CDCl_3$): δ 4.79−4.63 (m, 2H), 2.30−1.98 (m, 2H), 2.05−2.01 (m, 3H), 1.79−1.28 (m, 9H), 0.98−0.73 (m, 5H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$; major isomer): δ 169.3 (s), 145.1 (s), 108.7 (t), 81.1 (s), 80.8 (s), 75.0 (d), 39.7 (t), 26.3 (t), 25.6 (d), 22.6 (d), 22.0 (t), 21.2 (q), 20.8 (q), 14.0 (q), 10.2 (t) ppm. HRMS (ESI): m/z calcd for $C_{15}H_{21}DO_2$ $(M + Na)^+$ 258.1580, found 258.1588.

Method B: General Experimental Procedure for the Preparation of Compounds 6a−f. A 0.25 M Au(I) catalyst was prepared as follows: in a flame-dried 50 mL flask, the Au catalyst (5 mmol) and Ag catalyst (5 mmol) or TfOH (as shown in Table 1) were added to dry CH_2ClCH_2Cl (20 mL) under an argon atmosphere. To the preprepared catalyst solution (10 mmol % or as specified in Table 1) was added a solution of substrate **1** (2 mL, 0.34 M) in CH_2ClCH_2Cl. The reaction mixture was stirred at room temperature or heated to 85 °C (as specified in Table 1) until complete. The reaction was monitored by GC-MS. After completion, the reaction mixture was loaded directly onto a silica gel column and eluted with 100/1 hexanes/ethyl acetate to afford the enol acetates **6′**, which were directly subjected to methanolysis by adding a mixture of K_2CO_3 (2.0 equiv) and MeOH (5 mL) at room temperature for 2 h. Dilute HCl (20 mL) was added, and the mixture was extracted by MTBE (3 × 10 mL), dried ($MgSO_4$), and concentrated under reduced pressure. Ketones **6** and acetate **6f** were purified by flash chromatography or bulb-to-bulb distillation.

*2,4-Dimethyl-4-vinylcyclohex-2-enone (**6a**).* Colorless oil; 70% yield. ^{1}H NMR (300 MHz, $CDCl_3$): δ 6.39 (s, 1H), 5.80 (dd, J = 10.5, 17.4 Hz, 1H), 5.10 (d, J = 10.5 Hz, 1H), 5.02 (d, J = 17.4 Hz, 1H), 2.49−2.34 (m, 2H), 1.93−1.89 (m, 2H), 1.80 (s, 3H), 1.22 (s, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 199.8 (s), 151.1 (d), 143.3 (d), 134.4 (s), 113.8 (t), 39.6 (s), 35.0 (t), 34.3 (t), 27.3 (q), 16.0 (q) ppm. HRMS (ESI): m/z calcd for $C_{10}H_{14}O$ $(M + Na)^+$ 173.0942, found 173.0936.

*2-Ethyl-4-methyl-4-vinylcyclohex-2-enone (**6b**).* Colorless oil. ^{1}H NMR (300 MHz, $CDCl_3$): δ 6.33 (s, 1H), 5.81 (dd, J = 10.5, 17.4 Hz, 1H), 5.10 (d, J = 10.5 Hz, 1H), 5.02 (d, J = 17.4 Hz, 1H), 2.51−2.38 (m, 2H), 2.38−2.20 (m, 2H), 1.92−1.88 (m, 2H), 1.23 (s, 3H), 1.03 (t, J = 7.5 Hz, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 198.4 (s), 148.5 (d), 142.4 (d), 139.0 (s), 112.7 (t), 38.4 (s), 33.8 (t), 33.6 (t), 26.5 (q), 21.4 (t), 12.0 (q) ppm. HRMS (ESI): m/z calcd for $C_{11}H_{16}O$ $(M + H)^+$ 165.1279, found 165.1286.

*4-Methyl-2-propyl-4-vinylcyclohex-2-enone (**6c**).* Colorless oil. ^{1}H NMR (300 MHz, $CDCl_3$): δ 6.33 (s, 1H), 5.84 (dd, J = 10.5, 17.4 Hz, 1H), 5.10 (dd, J = 0.9, 10.5 Hz, 1H), 5.02 (dd, J = 0.9, 17.4 Hz, 1H), 2.52−2.31 (m, 2H), 2.20−2.14 (m, 2H), 1.92−1.87 (m, 2H), 1.47−1.40 (q, J = 7.5 Hz, 2H), 1.22 (s, 3H), 0.90 (t, J = 7.3 Hz, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 199.4 (s), 150.6 (d), 143.4 (d), 138.4 (s), 113.8 (t), 39.5 (s), 34.9 (t), 34.6 (t), 31.5(t), 27.5 (q), 21.8 (t), 13.8 (q) ppm. HRMS (ESI): m/z calcd for $C_{12}H_{18}O$ $(M + Na)^+$ 201.1255, found 201.1254.

*6-Butyl-4-methyl-4-vinylcyclohexa-1,5-dienyl Acetate (**6d′**).* This compound was prepared according to the general procedure without applying the in situ methanolysis. Colorless oil; 90% yield. ^{1}H NMR (300 MHz, $CDCl_3$): δ 5.87 (dd, J = 10.5, 17.4 Hz, 1H), 5.32−5.30 (m, 2H), 5.07 (dd, J = 1.3, 17.4 Hz, 1H), 4.97 (dd, J = 1.3, 10.5 Hz, 1H), 2.29 (dd, J = 5.0, 9.2 Hz, 2H), 2.16 (s, 3H), 1.96 (t, J = 6.4 Hz, 2H), 1.43−1.27 (m, 4H), 1.14 (s, 3H), 0.90 (t, J = 7.1 Hz, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 169.5 (s), 146.5 (s), 144.7 (d), 132.6 (s), 132.1 (d), 111.3 (d), 111.3 (t), 37.6 (s), 35.1 (t), 30.6 (t), 30.4 (t), 25.3 (q), 22.4 (t), 20.8 (q), 13.9 (q) ppm. HRMS (ESI): m/z calcd for $C_{15}H_{22}O_2$ $(M + Na)^+$ 257.1518, found 257.1517.

*2-Butyl-4-methyl-4-vinylcyclohex-2-enone (**6d**).* Colorless oil. ^{1}H NMR (300 MHz, $CDCl_3$): δ 6.33 (s, 1 H), 5.80 (dd, J = 10.5, 17.4 Hz, 1H), 5.10 (d, J = 10.5 Hz, 1H), 5.02 (d, J = 17.4 Hz, 1H), 2.57−2.31 (m, 2H), 2.29−2.12 (m, 2H), 2.02−1.83 (m, 2H), 1.58−1.14 (m, 7H), 1.07−0.76 (m, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 199.4 (s), 150.4 (d), 143.4 (d), 138.6 (s), 113.7 (t), 39.5 (s), 34.9 (t), 34.6 (t), 30.9 (t), 29.2 (t), 27.5 (q), 22.5 (t), 13.9 (q) ppm. HRMS (ESI): m/z calcd for $C_{13}H_{20}O$ $(M + Na)^+$ 215.1412, found 215.1412.

*2-Butyl-6-deuterium-4-methyl-4-vinylcyclohex-2-enone (**6e**).* Colorless oil. D incorporation: 68%. ^{1}H NMR (300 MHz, $CDCl_3$): δ 6.33 (s, 1H), 5.80 (dd, J = 10.5, 17.4 Hz, 1H), 5.06 (d, J = 10.5 Hz, 1H), 5.96 (d, J = 17.4 Hz, 1H), 2.45−2.32 (m, 1H), 2.25−2.16 (m, 2H),

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1.92−1.87 (m, 2H), 1.42−1.2 (m, 4H), 1.22 (s, 3H), 0.90 (t, J = 7.0 Hz, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 198.5 (s), 149.4 (d), 142.5 (d), 137.6 (s), 112.8 (t), 38.5 (s), 33.9 (t), 33.6 (t), 29.9 (t), 28.2 (t), 26.4 (q), 21.5 (t), 12.9 (q) ppm. HRMS (ESI): m/z calcd for $C_{13}H_{19}DO$ $(M + Na)^+$ 216.1475, found 216.1470.

*(5Z)-6-Ethyl-2-methylocta-1,5-dien-7-yn-3-yl Acetate (**6f**).* Colorless oil. ^{1}H NMR (300 MHz, $CDCl_3$): δ 5.67 (t, J = 7.2 Hz, 1H), 5.24 (t, J = 6.5 Hz, 1H), 4.95 (s, 1H), 4.90 (s, 1H), 3.13 (s, 1H), 2.46 (t, J = 6.9 Hz, 2H), 2.18−2.06 (m, 5H), 1.75 (s, 3H), 1.07 (t, J = 7.4 Hz, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 170.2, 142.7, 132.3, 126.4, 112.7, 81.9, 81.7, 76.1, 33.8, 30.1, 21.1, 18.4, 13.1 ppm. HRMS (ESI): m/z calcd for $C_{13}H_{18}O_2$ $(M + Na)^+$ 229.1204, found 229.1218.

Preparation of (1*S*,2*S*)-2-Methyl-2-(1-methylethenyl)cyclopropanecarboxylic Acid (16)[15]. To a solution of 2,3-dimethylbuta-1,3-diene (24.27 g, 296.0 mmol) and $Rh_2(OAc)_4$ (0.70 g, 1.47 mmol) in CH_2Cl_2 (200 mL) was added dropwise at room temperature ethyl 2-diazoacetate (16.87 g, 148.0 mmol) over a period of 1 h. The mixture was stirred further for 3 h and filtered through a pad of silica gel at reduced pressure. The residue was washed repeatedly with CH_2Cl_2, and the filtrate was collected. The solvent was evaporated to give a residue that was subjected to flash column chromatography (PE/MTBE, 50/1) to give *trans*-**15** as a colorless oil. Yield: 10.70 g (43%).

To a solution of **15** (17.49 g, 104.1 mmol) in THF (90 mL) and MeOH (45 mL) was added NaOH (20.82 g, 520.5 mmol) in H_2O (45 mL). The mixture was stirred for 2 days and then diluted by H_2O (100 mL) and washed with isohexane (3 × 30 mL). The aqueous phase was neutralized by HCl to pH 5, extracted with CH_2Cl_2 (3 × 30 mL), and dried over $MgSO_4$. The solvent was removed under reduced pressure to give the racemic acid *trans*-**16**.

A three-necked 250 mL flask, equipped with a mechanical stirrer and a reflux condenser, was charged with 50 mL of isopropyl ether and the resolving agent (1*S*,2*S*)-(+)-2-(dimethylamino)-1-[4-(methylthio) phenyl]propane-1,3-diol ((1*S*,2*S*)-(+)-MTDP; 9.48 g, 39.3 mmol).[16] The suspension was heated under reflux until the materials were completely dissolved. A solution of the racemic acid *trans*-**16** (10.01 g, 71.4 mmol) dissolved in 20 mL of isopropyl ether was added. The mixture was heated under reflux and stirred for an additional 30 min. After the mixture was cooled to room temperature, the precipitated salt was separated by filtration. The salt was then washed three times with 10 mL of isopropyl ether and dried at 25 °C/24 mbar to furnish the crude (+)-salt. The acid was extracted by toluene after acidifying with 1 M HCl to give a yellow oil, which was resolved once again with the chiral amine (1*S*,2*S*)-(+)-MTDP to improve the ee value up to 90%. The absolute configuration was assigned to be 1*S*,2*S* by means of a theoretical simulation of its electronic circular dicroism spectra (ECD; see also the Supporting Information).

Yellow oil; 4.01 g (yield 80%). ^{1}H NMR (300 MHz, $CDCl_3$): δ 4.98−4.70 (m, 2H), 2.00−1.69 (m, 4H), 1.53−1.22 (m, 5H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 178.9 (s), 148.0 (s), 111.1 (t), 33.3 (s), 26.0 (d), 20.8 (t), 20.1 (q), 16.9 (q) ppm. HRMS (ESI): m/z calcd for $C_8H_{12}O_2$ $(M + Na)^+$ 163.0735, found 163.0740.

Preparation of (1*S*,2*S*)-*N*-Methoxy-*N*,2-dimethyl-2-(1-methylethenyl)cyclopropanecarboxamide (17). To a solution of **16** (5.00 g, 35.70 mmol), *N*,*O*-dimethylhydroxyamine hydrochloride (3.48 g, 35.70 mmol), and Et_3N (5.41 g, 53.60 mmol) in CH_2Cl_2 (100 mL) was added DCC (7.37 g, 35.70 mmol) slowly with ice−water cooling. The mixture was stirred overnight, diluted with H_2O (200 mL), and extracted with CH_2Cl_2 (3 × 30 mL). The combined organic extract was dried over $MgSO_4$. The solvent was removed under reduced pressure, and the residual mass was purified by flash chromatography (silica gel, PE-EA, 25/1) to give the Weinreb amide **17**. Colorless oil; 5.81 g (yield: 89%). ^{1}H NMR (300 MHz, $CDCl_3$): δ 4.86 (s, 1H), 4.80 (s, 1H), 3.71 (s, 3H), 3.23 (s, 3H), 2.33−2.16 (m, 1H), 1.88−1.76 (m, 3H), 1.30−1.24 (m, 4H), 1.13−1.09 (m, 1H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 172.2, 148.6, 110.4, 61.4, 32.7, 30.8, 24.4, 20.0, 18.1, 16.8 ppm. HRMS (ESI): m/z calcd for $C_{10}H_{17}NO_2$ $(M + Na)^+$ 206.1157, found 206.1157.

Preparation of 1-[(1*S*,2*S*)-2-Methyl-2-(1-methylethenyl)-cyclopropyl]ethanone (18). To a solution of **17** (6.12 g, 33.42 mmol) in THF (50 mL) at 0 °C was added methylmagnesium bromide (freshly prepared, 66.84 mmol) dropwise under an argon atmosphere. The reaction mixture was stirred for 2 h, quenched by the addition of 1 M HCl, and extracted with MTBE (3 × 30 mL). The organic extracts were dried over $MgSO_4$, filtered, and concentrated in vacuo. The crude residue was purified by bulb-to-bulb distillation to give the pure ketone **18**. Colorless oil; 4.62 g (yield: 85%). ee = 90%. ^{1}H NMR (300 MHz, $CDCl_3$): δ 4.84−4.74 (m, 2H), 2.27 (bs, 3H), 2.07 (t, J = 6.2 Hz, 1H), 1.78 (bs, 3H), 1.35−1.15 (m, 5H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 205.9 (s), 148.4 (s), 110.8 (t), 35.1 (s), 34.6 (d), 32.0 (q), 20.5 (t), 20.2 (q), 16.1 (q) ppm. HRMS (ESI): m/z calcd for $C_9H_{14}O$ $(M + Na)^+$ 161.0942, found 161.0954. $[\alpha]^{20}_D$ = +269.84° (c 1.0, MeOH).

Preparation of 2-[(1*S*,2*S*)-2-Methyl-2-(1-methylethenyl)-cyclopropyl]but-3-yn-2-ol (19). In a flame-dried 250 mL flask, acetylene was bubbled into the flask slowly and dissolved in dry THF (15 mL) for 5 min. A 1.6 mol/L solution of *n*-BuLi in hexanes (28.1 mL, 45.00 mmol) was added dropwise into the flask at −78 °C. The reaction was stirred for a further 25 min. Then bubbling was stopped, and ketone **18** (4.14 g, 30 mmol) was added dropwise with stirring. The reaction mixture was stirred further for 3 h and quenched by careful addition of H_2O (70 mL). The mixture was extracted with MTBE (3 × 20 mL). The organic layer was separated, dried over $MgSO_4$, filtered, and concentrated under reduced pressure. The crude residue was purified by bulb-to-bulb distillation to afford the propargyl alcohol **19**. Colorless oil; 4.43 g (yield: 90%). ^{1}H NMR (300 MHz, $CDCl_3$): δ 4.60 (bs, 1H), 4.55 (bs, 1H), 2.41 (s, 1H), 1.94 (bs, 1H), 1.63 (bs, 3H), 1.54 (bs, 3H), 1.35 (bs, 3H), 1.05−1.00 (m, 1H), 0.89−0.84 (m, 1H), 0.73−0.69 (m, 1H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 150.6 (s), 109.3 (t), 87.5 (s), 73.0 (s), 68.5 (d), 34.6 (d), 31.8 (q), 27.5 (s), 20.1 (q), 17.1 (q), 16.8 (t) ppm. HRMS (ESI): m/z calcd for $C_{11}H_{16}O$ $(M + Na)^+$ 187.1099, found 187.1085.

2-((1*S*,2*S*)-2-Methyl-2-[(1-methylethenyl)cyclopropyl]-but-3-yn-2-yl Acetate (20; Method A). Colorless oil; 4.52 g (yield 87%). ^{1}H NMR (300 MHz, $CDCl_3$): δ 4.73 (s, 1H), 4.68 (s, 1H), 2.68 (s, 1H), 2.04 (s, 3H), 1.93 (s, 3H), 1.74 (bs, 3H), 1.52−1.37 (m, 4H), 1.06−0.96 (m, 2H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 169.3 (s), 150.5 (s), 109.4 (t), 83.3 (s), 77.5 (s), 75.7 (d), 33.0 (d), 29.0 (d), 27.9 (s), 22.0 (q), 20.0 (q), 17.6 (t), 17.2 (q) ppm. HRMS (ESI): m/z calcd for $C_{13}H_{18}O_2$ $(M + Na)^+$ 229.1205, found 229.1204.

(*S*)-2,4-Dimethyl-4-(1-methylethenyl)cyclohex-2-enone (21; Method B). Colorless oil. ee = 37%. ^{1}H NMR (300 MHz, $CDCl_3$): δ 6.61 (s, 1H), 4.80 (s, 1H), 4.72 (s, 1H), 2.68−2.48 (m, 2H), 2.42−2.36 (m, 1H), 2.33−2.22 (m, 1H), 1.77 (s, 3H), 1.72 (s, 3H), 1.13 (s, 3H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 199.6 (s), 149.6 (s), 142.6 (d), 135.1 (s), 110.7 (t), 49.4 (t) 42.2 (s), 37.1 (t), 25.9 (q), 19.3 (q), 15.5 (q) ppm. HRMS (ESI): m/z calcd for $C_{11}H_{16}O$ $(M + Na)^+$ 187.1099, found 187.1099.

2,6,7-Trimethylcycloocta-2,6-dienone (22). Colorless oil; 19 mg (yield: 24%). ^{1}H NMR (300 MHz, $CDCl_3$): δ 6.03 (t, J = 6.1 Hz, 1H), 2.91 (d, J = 5.9 Hz, 2H), 2.77 (t, J = 6.9 Hz, 2H), 2.40 (t, J = 6.9 Hz, 2H), 1.80 (s, 3H), 1.65 (s, 6H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ 208.6 (s), 137.6 (s), 132.3 (d), 130.0 (s), 128.2 (s), 43.3 (t), 35.6 (t), 30.0 (t), 21.3 (q), 21.0 (q), 19.4 (q) ppm. EI-MS (m/z, relative intensity): 164 (M^+, 52.8), 93 (100). HRMS (ESI): m/z calcd for $C_{11}H_{16}O$ $(M + H)^+$ 165.1279, found 165.1267.

■ ASSOCIATED CONTENT

Supporting Information. Figures and text giving ^{1}H and ^{13}C NMR spectra for **1a**−**d**, **6a**−**f**, **12b**−**d**, **13b**−**d**, **14a**−**d**, and

16−**22**, details of the ECD study on chiral molecules **16** and **21**, and chiral GC spectra of **16** and **21**. This material is available free of charge via the Internet at http://pubs.acs.org.

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