Articles

Stereoselective Palladium Catalyzed Cyclizations of Enediyne Compounds

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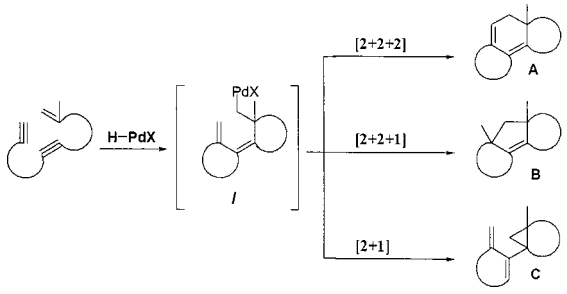
Hydropalladium carboxylates, formed from π-allylpalladium chloride dimer plus carboxylic acids, have been shown to catalyze cyclization of structurally diverse enediynes to form the corresponding six- or five-membered rings depending upon the reaction conditions. Some enediynes having an oxygen linker in an appropriate position under the similar condition yielded the corresponding cyclopropanation products in highly stereoselective manner. A study using deuterated formic acid has proven that the alkylpalladium intermediates formed in our conditions were reduced by the pendant formate ligand. The dienediyne **10** yielded only the tricyclic product **12** in 67% yield, although it was expected to form the cyclic product **11**. All these cyclizations seemed to occur *via* the corresponding alkylpalladium intermediates ***I***, which could proceed to the corresponding cyclic products depending on the reaction conditions and the substrates. The study using deuterated formic acid could provide an important information to understand the present cyclization mechanism. Overall the present study could play an important role in developing new synthetic methodologies for constructing complex polycyclic compounds.

Introduction

Palladium catalyzed reactions have long been widely studied for invention of new organic reactions and also for syntheses of complex natural products because palladium compounds offer more possibilities of carbon-carbon bond formation than any other metal compounds.[1] Among the substrates, polyunsaturated compounds such as enediynes and enynes have been subjects for organic synthetic chemists mainly due to their possibilities for constructing polycyclic compounds in a convenient and efficient one step reaction. Terminal or activated triple bonds are known to undergo facile hydropalladation with HPdX species to form the corresponding vinylpalladium species.[2] Trost disclosed such idea to invent palladium catalyzed [2+2+2] cyclizations starting from enediynes.[3] Negishi and his coworkers also studied similar cyclizations starting of dienyne substrates.[4] They employed terminal iodoolefins pending a triple bond and another double bond. Oxidative addition of palladium (0) compounds to iodoolefins could lead to the vinylpalladium species, the same type of intermediates formed in Trost enediyne cyclization. One other variation developed by de Meijere was bromoene-yne-ene cyclization.[5] Negishi and de Meijere employed dienyne substrates, which should eventually form the corresponding neopentyl type alkylpalladium intermediates. Both groups have shown that neopentyl type alkylpalladium intermediates formed cyclopropane ring systems. Grigg reported the first [2+2+2] palladium catalyzed cyclization of aryl iodides with enynes, where the neopentyl type alkylpalladium intermediates have been proposed.[5] Trost also proposed that the neopentyl type alkylpalladium intermediate formed from enediyne cyclization underwent cyclopropanation as a major route.[5]



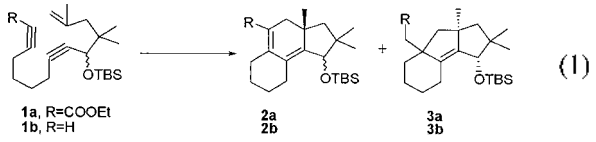
Scheme 1

We have long been studied alkylpalladium intermediates in the following reasons. First, are these alkylpalladium intermediates really formed? Second, could we alter the next pathways of these alkylpalladium intermediates? Our interest in palladium catalyzed enediyne cyclizations has required the substrates which should form neopentyl-type alkylpalladium intermediates as shown in Scheme 1. The neopentyl-type alkylpalladium intermediates (***I***) having a conjugated diene unit were expected to undergo three different types of cyclization to form the corresponding six (**A**), five (**B**), and three membered ring (**C**) depending on reaction conditions and substrates (Scheme 1).[8] Due to the complexity of these reactions, little attention has been devoted to clarify which factors govern each of these cyclization pathways. We have reported an important clue to change those reaction pathways to form chemoselectively either the six-membered ring **A** or the five-membered ring **B**.[9] We also reported that some oxygen-containing enediynes could undergo cyclopropanation as a major route.[10] In this full article, we wish to report the scope and limitations of the present enediyne cyclizations including the experimental details and the mechanistic aspects obtained by use of deu-

terated formic acid.

Results and Discussion

Enediyne **1a** and **1b** served as our initial substrates shown in eq 1. When a dimethylformamide solution of substrate **1a**, π-allylpalladium chloride dimer (7 mol %),[11] triphenylphosphine (14 mol %) and acetic acid (7 mol %) was stirred for 6 h at 90 °C, the reaction was completed to give the corresponding cyclized product **2a** in 86% yield (entry 1). Note that a neopentyl type alkylpalladium intermediate has been successfully cyclized to form |6,6,5|-tricyclic compounds.[4a,12] When the substrate **1b** under the similar condition was stirred for 4 h at 100 °C, the reaction was sluggish to give the corresponding cyclized product **2b** in 10-20% as a mixture of diastereomers (entry 2).



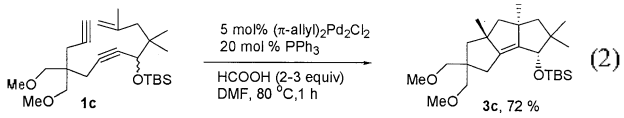
(1)

Attempts to cyclize the substrate **1b** using other palladium catalysts such as palladium chloride, palladium acetate, and tetrakis(triphenylphosphine)palladium in DMF have not been successful because the dimeric product was readily formed by C-C coupling between the terminal acetylene groups of two substrates.[13]

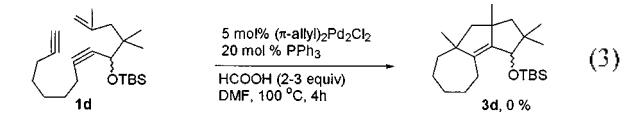
Use of formic acid instead of acetic acid has altered the reaction pathway dramatically. For example, when a dimethylformamide solution of substrate **1b**, π-allylpalladium chloride dimer (5 mol %), triphenylphosphine (10 mol %), and formic acid (20 mol %) was stirred for 4 h at 80 °C, the reaction afforded the corresponding |6,6,5|-tricyclic product **2b** and the |6,5,5|-tricyclic product **3b** in 57 and 17% yields, respectively (entry 3). This implies that formic acid has participated in this reaction as a reagent. When we used two equivalents of formic acid based on the enediyne **1b**, we could isolate the |6,5,5|-tricyclic product **3b** as a single isomer in 82% yield (entry 4). Likewise, the substrate **1a** at 90 °C for 6 h under the similar condition also cleanly underwent cyclization to form the corresponding product **3a** in 87% yield (entry 5). These preliminary results prompted us study unprecedented [2+2+1] cyclizations which could provide diverse types of tricyclic |m,5,n|-tricyclic compounds from the corresponding acyclic enediynes and study mechanistic details in which the present cyclization could occur *via* a direct carbopalladation of the resultant alkylpalladium intermediate. Under these standard conditions, enediyne **1c** was exclusively transformed to the |5,5,5|-tricyclic product **3c** in 72% yield (eq 2). Endiyne **1d**, however, did not undergo cyclization under the similar condition even at 120 °C (eq 3).

Table 1. Palladium Catalyzed Reactions of Enediynes **1a** and **1b** in DMF

entry	enediynes	catalysts and conditions	products (%)
1	**1a**	7 mol % (π-C_3H_5)$_2$$Pd_2Cl_2$, 14 mol % PPh_3, 7 mol % AcOH, 90 °C, 6 h	**2a** (86%)
2	**1b**	5 mol % (π-C_3H_5)$_2$$Pd_2Cl_2$, 10 mol % PPh_3, 5 mol % CH_3COOH, 100 °C, 4 h	**2b**(10-20%)
3	**1b**	5 mol % (π-C_3H_5)$_2$$Pd_2Cl_2$, 10 mol % PPh_3, 20 mol % HCOOH, 80 °C, 4 h	**2b** (57%) **3b** (17%)
4	**1b**	7 mol % (π-C_3H_5)$_2$$Pd_2Cl_2$, 14 mol % PPh_3, 200 mol % HCOOH, 60 °C, 4 h	**3b** (82%)
5	**1a**	7 mol % (π-C_3H_5)$_2$$Pd_2Cl_2$, 14 mol % PPh_3, 200 mol % HCOOH, 90 °C, 6 h	**3a** (87%)

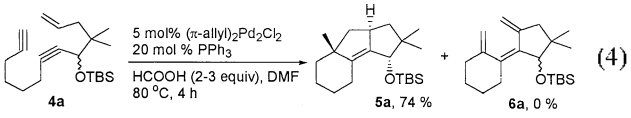


(2)

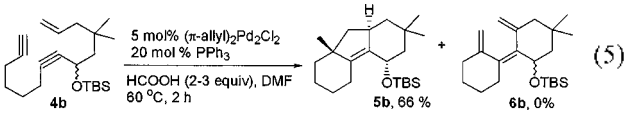


(3)

Note that these palladium-catalyzed reactions afforded the corresponding tricyclic carbocycles in highly stereoselective manners determined by NMR spectra. We have chosen the product **3b** and confirmed its relative stereochemistry by two-dimensional NOE (NOESY). In order to gain more insight into the mechanism for these reactions, we have studied the enediynes **4a** and **4b**, whose structures are different from the enediyne **1a-d** in their olefin region. The enediynes **4a** and **4b** would form the corresponding alkylpalladium intermediates that were expected to undergo β-elimination to the corresponding 1,3,5-trienes more readily than any other pathways. Surprisingly, the substrates **4a** and **4b** under our conditions cleanly underwent cyclization to afford the corresponding 5-membered rings **5a** and **5b** without formation of the corresponding 1,3,5-trienes **6a** and **6b**, respectively (eq 4, 5).

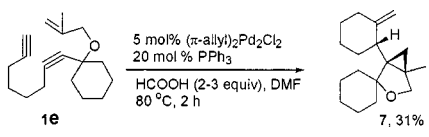


(4)



(5)

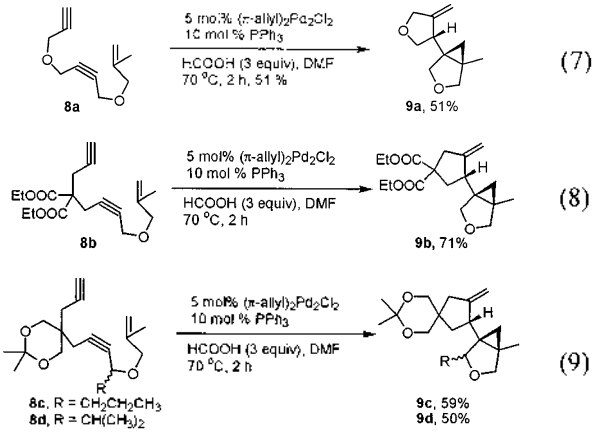
While working on enediyne cyclization, we found a limitation of this present methodology, that a substrate **1e** gave an unexpected product 7 along with the desired tricyclic product (eq 6).



(6)

Our study showed that the substrates **8a-d** possessing an etheral oxygen in the appropriate position afforded the corre-

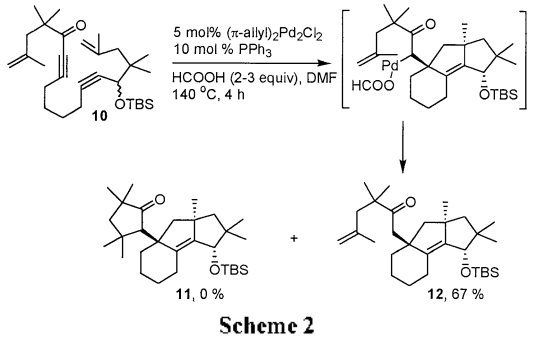
sponding cyclopropanation products in moderate to high yields summarized in eq 7-9. We should note that these products **9a-d** were stereochemically pure when analyzed by ^{1}H NMR and ^{13}C NMR spectra.



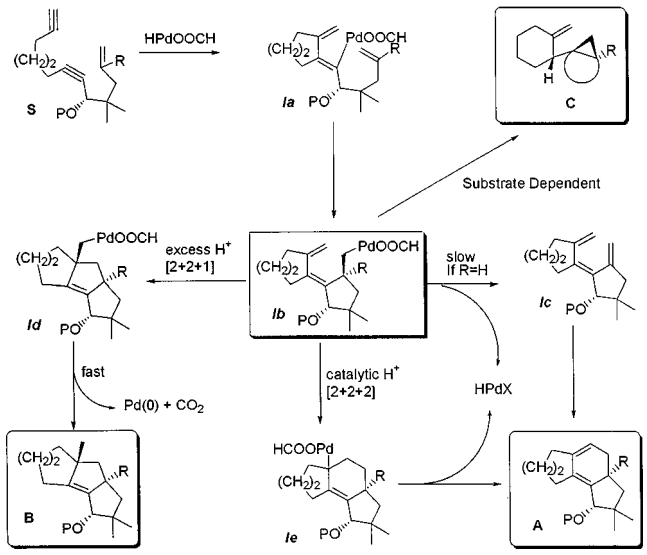
We have further studied our cyclization method in order to apply to construction of the more complex carbocycles like **11**. Thus, when the readily available dienediyne **10** under the similar condition was heated at 140 °C for 4 h in DMF as shown in Scheme 2, the reactions chemo- and stereoselectively afforded the corresponding [6,5,5]-tricyclic compound **12** in 67% yield.

These results could be understood in terms of our previously proposed mechanism as shown in Scheme 3. The activated triple bond in substrate **S** regioselectively reacts with the HPdX and then with the internal triple bond to form the vinylpalladium intermediate ***Ia***, which then further reacts with a pendant double bond stereoselectively to form the (neopentyl type) alkylpalladium intermediate ***Ib***. Although β-elimination was known to be a major route for some cases, we could not detect any such products. Under these mild conditions, carbopalladation should compete over β-elimination (to ***Ic***) to form the next alkylpalladium intermediates ***Id*** or ***Ie*** depending upon the reaction conditions.

In the presence of only a catalytic amount of acids, the intermediate ***Ib*** can irreversibly cyclize to form the [6,6,5]-tricyclic product **A** *via* the intermediate ***Ie***. In the presence of excess formic acid, however, the intermediate ***Ib*** may form the unstable intermediate ***Id*** which reductively cleaves to form the stable product **B** and palladium(0) which can reform HPdX with formic acid.

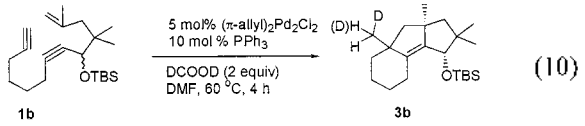


Scheme 2

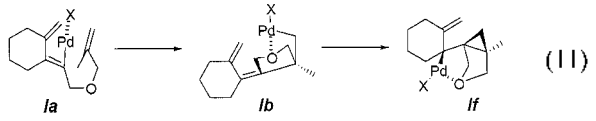


Scheme 3

In order to gain more insight in the present cyclization, we prepared deuterated product **3b** by employing deuterated formic acid (DCOOD, 90% deuterium content) (eq 10). As expected, about 1.3 deuterium per the product **3b** was found by analyzing mass spectral analysis of the molecular ion peaks. This revealed that our proposed mechanism would be operating.[14]



In the case of enediynes possessing an ether oxygen, the intermediate ***Ib*** might chelate with the etheral oxygen, so that subsequent carbopalladation could form the intermediate ***If***. In the presence of formic acid, the intermediate ***If*** could reductively cleave to form the cyclopropanation product **C** and palladium(0), which can reform HPdX with formic acid as shown in eq 11.



In conclusion, the present cyclizations seemed to occur *via* the corresponding alkylpalladium intermediates ***I***, which could proceed to the corresponding cyclic products depending on the reaction conditions and the substrates. The study using deuterated formic acid provided an important information to understand the present cyclization mechanism. Overall the present study could play an important role in developing new synthetic methodologies for constructing complex polycyclic compounds.

Experimental Section

General procedure for the [2+2+2] cyclization of

enediynes. In a 5 mL test tube were placed enediyne **1a** (77.8 mg, 0.19 mmol), triphenyl phosphine (7.0 mg, 0.026 mmol), allylpalladium chloride (2.4 mg, 0.013 mmol) and dry N,N-dimethylformamide (1.0 mL). The resulting mixture was treated with acetic acid (7.5 μL, 0.013 mmol) under argon atmosphere. The mixture was stirred for 10 min at room temperature and for 6 h at 90 °C preheated oil bath. Then, the reaction mixture was concentrated under reduced pressure and separated on silica gel chromatography using a 5:95 mixture of ethyl acetate and hexane to give the cyclized product **2a** (66.7 mg, 86%) as a colorless oil. **2a**: ^{1}H NMR (300 MHz, $CDCl_3$) δ For major isomer 4.41 (d, *J* 2.0 Hz, 1H), 4.22-4.08 (m, 2H), 3.30-3.04 (m, 1H), 2.45-2.2.20 (m, 3H), 2.20-2.02 (m, 1H), 1.80-0.82 (m, 7H), 1.28 (t, *J* 7.2 Hz, 3H), 1.09 (s, 3H), 1.03 (s, 3H), 0.98 (s, 3H), 0.94 (s, 9H), 0.10 (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 169.40, 150.11, 147.65, 147.49, 145.12, 127.52, 127.35, 120.93, 119.33, 82.17, 79.83, 59.74, 59.65, 51.93, 50.24, 43.71, 42.72, 40.26, 39.68, 38.76, 34.95, 28.31, 28.05, 27.80, 27.73, 27.50, 25.97, 25.78, 25.72, 24.39, 24.15, 23.65, 23.36, 22.85, 22.71, 22.03, 18.20, 18.00, 14.23, 13.96, -3.97, -4.10, -4.12, -4.68; IR (neat, cm^{-1}) 2905, 1696, 1562, 1440, 1358, 1238.

2b: ^{1}H NMR (300 MHz, $CDCl_3$) δ For major 5.40-5.17 (m, 1H), 3.83 (s, 1H), 2.42-2.22 (m, 1H), 2.22-2.07 (m, 1H), 2.06-1.65 (m, 3 H), 1.64-1.45 (m, 2H), 1.30-1.18 (m, 4H), 1.04 (s, 3H), 0.94 (s, 3H), 0.90 (s, 9H), 0.88 (s, 3H), 0.95-0.82 (m, 2H), 0.06 (s, 3H), 0.02 (s, 3H).

General procedure for the [2+2+1] cyclization of enediynes. In a 5 mL test tube were placed enediyne **1a** (88.8 mg, 0.21 mmol), triphenyl phosphine (7.7 mg, 0.029 mmol), allylpalladium chloride (2.7 mg, 0.015 mmol), and dry N,N-dimethylformamide (1.0 mL). The resulting mixture was treated with formic acid (0.025 mL, 0.4 mmol) under argon atmosphere. The mixture was stirred for 10 min at room temperature and for 6 h at 90 °C preheated oil bath. Then, the reaction mixture was concentrated under reduced pressure and separated on silica gel chromatography using a 5 : 95 mixture of ethyl acetate and hexane to give the cyclized product **3a** (77.3 mg, 87%) as a colorless oil.

3a: ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.21-4.08 (m, 2H), 3.79 (s, 1H), 2.75 (d, *J* 13.2 Hz, 1H), 2.44-2.32 (m, 2H), 2.25 (d, *J* 13.2 Hz, 1H), 2.16-2.07 (m, 1H), 2.04-1.75 (m, 2H), 1.72-1.48 (m, 5H), 1.29 (s, 3H), 1.25 (t, *J* 7.0 Hz, 3H), 1.32-1.24 (m, 1H), 1.04 (s, 3H), 0.98-0.86 (m, 1H), 0.87 (s, 9H), 0.84 (s, 3H), 0.04 (s, 3H), -0.03 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 172.59, 146.67, 138.25, 76.61, 59.84, 54.87, 54.40, 51.69, 51.63, 45.30, 40.48, 39.89, 31.53, 30.01, 27.38, 25.76, 24.83, 24.71, 22.03, 18.10, 14.18, -4.57, -5.33; IR (neat, cm^{-1}) 2910, 2845, 1721, 1450, 1248, 1164, 1084.

3b: ^{1}H NMR (300 MHz, $CDCl_3$) δ 3.79 (s, 1H), 2.34 (ddd, *J* 12.6, 6.0, 1.8 Hz, 1H), 1.93 (ddd, *J* 12.6, 11.8, 6.0 Hz, 1H), 1.84-1.70 (m, 1H), 1.76 (d, *J* 12.6 Hz, 1H), 1.62 (d, *J* 12.6 Hz, 1H), 1.57-1.48 (m, 1H), 1.52 (d, *J* 12.9 Hz, 1H), 1.32-1.16 (m, 2H), 1.30 (s, 3H), 1.26 (d, *J* 12.9 Hz, 1H), 1.21 (s, 3H), 1.05 (s, 3H), 0.96-0.86 (m, 2H), 0.89 (s, 9H), 0.84 (s, 3H), 0.06 (s, 3H), -0.00 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 145.01, 139.72, 76.58, 59.69, 54.34, 51.41, 49.16, 45.41, 44.34, 31.95, 29.92, 27.77, 25.81, 24.91, 24.81, 24.31, 22.45, 18.14, -4.54, -5.33; FT-IR ($CHCl_3$, cm^{-1}) 2955, 2928, 2858, 1463, 1371, 1254, 1084, 1069, 1043; HRMS calcd for $C_{22}H_{40}OSi$ (M^+) 348.2848, found 348.2838.

3c: ^{1}H NMR (300 MHz, $CDCl_3$) δ 3.69 (s, 1H), 3.36 (s, 3H), 3.36-3.28 (m, 2H), 3.30 (s, 3H), 3.13 (Abq, *J* 9.0 Hz, =7.8 Hz, 2H), 2.05 (Abq, *J* 15.9 Hz, =25.2 Hz, 2H), 1.83 (Abq, *J* 12.3 Hz, =14.7 Hz, 2H), 1.50 (Abq, *J* 13.2 Hz, =13.2 Hz, 2H), 1.35 (s, 3H), 1.27 (s, 3H), 1.23 (Abq, *J* 13.5 Hz, =22.5Hz, 2H), 1.04 (s, 3H), 0.94 (s, 3H), 0.87 (s, 9H), 0.04 (s, 3H), 0.00 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 145.37, 144.61, 77.79, 77.33, 77.24, 61.24, 59.18, 59.06, 58.66, 57.44, 54.43, 49.15, 48.07, 45.48, 31.28, 30.08, 29.84, 27.45, 25.77, 24.80, 18.13, -4.41, -5.38; IR (neat, cm^{-1}) 2920, 2845, 1450, 1245, 1105.

5a: ^{1}H NMR (300 MHz, $CDCl_3$) δ 3.74 (s, 1H), 3.19 (m, 1H), 2.36 (m, 1H), 2.01 (dd, *J* 11.7, 7.5 Hz, 1H), 1.97-1.84 (m, 1H), 1.80 (dd, *J* 11.7, 10.5 Hz, 1H), 1.82-1.68 (m, 2H), 1.55-1.40 (m, 1H), 1.31-1.15 (m, 3H), 1.07 (s, 3H), 1.02 (s, 3H), 0.99-0.82 (m, 2H), 0.86 (s, 9H), 0.83 (s, 3H), 0.02 (s, 3H), -0.05 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 142.96, 138.80, 75.88, 51.95, 50.60, 46.23, 43.42, 43.05, 42.94, 29.27, 27.31, 25.71, 25.02, 23.95, 22.54, 21.91, 18.08, -4.62, -5.31; IR (neat, cm^{-1}) 2975, 2900, 1480, 1280, 1100, 1035.

5b: ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.54 (t, *J* 3.0 Hz, 1H), 3.95 (m, 1H), 2.36 (m, 1H), 1.93 (dd, *J* 12.6, 7.8 Hz, 1H), 1.91-1.80 (m, 1H), 1.78-1.50 (m, 7H), 1.28-1.20 (m, 2H), 1.14 (s, 3H), 1.12-1.03 (m, 1H), 1.01 (s, 3H), 0.88-0.80 (m, 1H), 0.87 (s, 3H), 0.84 (s, 9H), 0.01 (s, 3H), -0.06 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 140.09, 134.46, 64.56, 50.20, 47.98, 47.04, 46.35, 42.54, 36.52, 33.91, 31.38, 27.47, 27.23, 25.68, 23.60, 23.39, 22.84, 17.82, -4.62, -5.17.

General procedure for cyclopropanation of enediynes. In a 5 mL test tube were placed enediyne **8a** (79.5 mg, 0.45 mmol), triphenyl phosphine (11.8 mg, 0.045 mmol), allylpalladium chloride (4.1 mg, 0.022 mmol), and dry N,N-dimethylformamide (1.0 mL). The resulting mixture was treated with formic acid (0.050 mL, 1.4 mmol) under argon atmosphere. The mixture was stirred for 10 min at room temperature and for 2 h at 70 °C preheated oil bath. Then, the reaction mixture was concentrated under reduced pressure and separated on silica gel chromatography using a 5 : 95 mixture of ethyl acetate and hexane to give the cyclized product **9a** (40.9 mg, 51%) as a colorless oil.

9a: ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.09 (dd, *J* 4.4, 2.1 Hz, 1H), 4.92 (dd, *J* 4.4, 2.4 Hz, 1H), 4.36 (d, *J* 13.8 Hz, 1H), 4.29 (dq, *J* 13.8, 2.4 Hz, 1H), 4.03 (dd, *J* 8.7, 7.2 Hz, 1H), 3.79 (d, *J* 7.8 Hz, 1H), 3.76 (d, *J* 9.9 Hz, 1H), 3.71 (t, *J* 7.8 Hz, 2H), 3.53 (d, *J* 7.8 Hz, 1H), 2.56 (t, *J* 6.9 Hz, 1H), 1.29 (s, 3H), 0.72 (d, *J* 4.5 Hz, 1H), 0.30 (d, *J* 4.5 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 148.63, 105.65, 74.82, 73.24, 72.26, 69.80, 45.01, 32.51, 27.58, 18.27, 14.55; IR (neat, cm^{-1}) 2910, 2840, 1650, 1440, 1065.

9b: ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.10 (bs, 1H), 4.77 (bs, 1H), 4.20 (m, 4H), 3.81 (d, *J* 8.1 Hz, 1H), 3.80 (d, *J* 7.8

Hz, 1H), 3.66 (d, *J* 7.8 Hz, 1H), 3.57 (d, *J* 8.1 Hz, 1H), 3.06 (bd, *J* 16.8 Hz, 1H), 2.92 (dq, *J* 16.8, 2.4 Hz, 1H), 2.60 (m, 1H), 2.43 (m, 1H), 1.95 (dd, *J* 12.6, 11.7 Hz, 1H), 1.26 (t, *J* 7.2 Hz, 6H), 1.22 (s, 3H), 0.72 (d, *J* 4.2 Hz, 1H), 0.30 (d, *J* 4.2 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 171.79, 171.55, 147.69, 108.57, 75.23, 69.53, 61.54, 61.49, 58.07, 43.73, 41.14, 39.08, 32.57, 27.74, 18.41, 14.53, 13.91; IR (neat, cm^{-1}) 2910, 2840, 1725, 1640, 1450.

9c: ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.09 (s, 1H), 4.76 (bs, 1H), 4.02 (d, *J* 6.3 Hz, 1H), 3.73 (d, *J* 8.1 Hz, 1H), 3.67 (Abq, *J* 11.4 Hz, =9.3 Hz, 2H), 3.59 (Abq, *J* 11.7 Hz, =1.8 Hz, 2H), 3.49 (d, *J* 8.1 Hz, 1H), 2.48-2.38 (m, 2H), 2.19-2.04 (m, 2H), 1.60-1.25 (m, 5H), 1.43 (s, 6H), 1.17 (s, 3H), 0.91 (t, *J* 6.6 Hz, 3H), 0.72 (d, *J* 4.5 Hz, 1H), 0.20 (d, 4.5 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 149.24, 109.68, 98.01, 79.20, 73.82, 69.54, 67.09, 41.61, 41.34, 39.97, 37.49, 35.46, 35.19, 28.05, 24.15, 23.21, 19.73, 15.64, 14.59, 14.25; IR (neat, cm^{-1}) 2900, 1645, 1450.

9d: ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.10 (s, 1H), 4.76 (bs, 1H), 3.91 (d, *J* 3.0 Hz, 1H), 3.70 (d, *J* 8.1 Hz, 1H), 3.66 (Abq, *J* 11.4 Hz, =6.6 Hz, 2H), 3.58 (Abq, *J* 11.7 Hz, =2.4 Hz, 2H), 3.44 (d, *J* 8.1 Hz, 1H), 2.47 (m, 1H), 2.41 (m, 1H), 2.19-2.06 (m, 2H), 1.82 (m, 1H), 1.52 (dd, *J* 12.9, 11.4 Hz, 1H), 1.43 (s, 6H), 1.15 (s, 3H), 1.01 (d, *J* 6.9 Hz, 3H), 0.93 (d, *J* 6.9 Hz, 3H), 0.88 (d, *J* 4.8 Hz, 1H), 0.25 (d, *J* 4.8 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 148.93, 109.98, 98.02, 82.66, 73.50, 69.55, 66.93, 41.68, 41.59, 40.01, 37.40, 33.20, 31.14, 26.37, 24.14, 23.22, 21.18, 16.43, 16.09, 14.62; IR (neat, cm^{-1}) 2925, 1850, 1650, 1455, 1385, 1370, 1200.

12: ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.81 (s, 1H), 4.62 (s, 1H), 3.80 (s, 1H), 3.13 (d, *J* 18.9 Hz, 1H), 2.54 (d, *J* 18.9 Hz, 1H), 2.39 (m, 3H), 2.30 (s, 3H), 2.16 (d, *J* 13.2 Hz, 1H), 2.10 (m, 1H), 1.90 (m, 1H), 1.77 (m, 1H), 1.64-1.46 (m, 4H), 1.33-1.20 (m, 2H), 1.28 (d, *J* 13.2 Hz, 1H), 1.19 (s, 3H), 1.14 (s, 6H), 1.04 (s, 3H), 0.88 (s, 9H), 0.84 (s, 3H), 0.05 (s, 3H), 0.00 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 214.65, 146.40, 142.70, 139.16, 114.05, 79.13, 55.41, 54.27, 51.70, 50.89, 47.44, 47.10, 45.31, 40.85, 39.21, 32.18, 29.98, 27.41, 25.80, 25.31, 25.27, 25.08, 24.83, 24.34, 22.40, 18.12, -4.49, -5.28; IR (neat, cm^{-1}) 2900, 2825, 1695, 1440, 1240, 1060.

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References

1. (a) Tsuji, J. *Palladium Reagents and Catalysts*; Wiley: Chichester, England, 1995. (b) Ojima, I.; Tzamarioudaka, M.; Li, Z.; Donovan, R. J. *Chem. Rev.* **1996**, *96*, 683. (c) Trost, B. M. *Science* **1991**, *254*, 1471. (d) Abelman, M. M.; Overman, L. E. *J. Am. Chem. Soc.* **1988**, *110*, 2328. (e) Grigg, R.; Dorrity, M. J.; Malone, J. F.; Sridharan, V.; Sukirthalingam, S. *Tetrahedron Lett.* **1990**, *31*, 1343.
2. For reviews, see (a) Trost, B. M. *Science* **1991**, *254*, 1471. (b) Trost, B. M. *Acc. Chem. Res.* **1990**, *23*, 34.
3. Trost, B. M.; Shi, Y. *J. Am. Chem. Soc.* **1992**, *114*, 791.
4. (a) Zhang, Y.; Negishi, E.-I. *J. Am. Chem. Soc.* **1989**, *111*, 3454. (b) Negishi, E.-I.; Harring, L. S.; Owczarczyk, Z.; Mohamud, M. M.; Ay, M. *Tetrahedron Lett.* **1992**, *33*, 3253. (c) Owczarczyk, Z.; Lamaty, F.; Vawter, E. J.; Negishi, E.-I. *J. Am. Chem. Soc.* **1992**, *114*, 10091.
5. (a) Grigg, R.; Dorrity, M. J.; Malone, J. F.; Sridharan, V.; Sukirthalingam, S. *Tetrahedron Lett.* **1990**, *31*, 1343. (b) Grigg, R.; Sridharan, V.; Sukirthalingam, S. *Tetrahedron Lett.* **1991**, *32*, 3855. (c) Meyer, F. E.; Parsons, P. J.; de Meijere, A. *J. Org. Chem.* **1991**, *56*, 6487.
6. Brown, S.; Clarkson, S.; Grigg, R.; Sridharan, V. *Tetrahedron Lett.* **1993**, *34*, 157.
7. (a) Trost, B. M.; Lautens, M.; Chan, C.; Jebaratnam, D. J.; Mueller, T. *J. Am. Chem. Soc.* **1991**, *113*, 636. (b) Trost, B. M.; Grese, T. A. *J. Am. Chem. Soc.* **1991**, *113*, 7363.
8. (a) Meyer, F. E.; Parsons, P. J.; de Meijere, A. *J. Org. Chem.* **1991**, *56*, 6487. (b) Meyer, F. E.; de Meijere, A. *Synlett* **1991**, 777. (c) Meyer, F. E.; Brandenburg, J.; Parsons, P. J.; de Meijere, A. *J. Chem. Soc., Chem. Commun.* **1992**, 390. (d) Negishi, E.-I.; Hawing, S. L.; Owczarczyk, Z.; Mohamud, M. M.; Ay, M. *Tetrahedron Lett.* **1992**, *33*, 3253. (e) Owczarczyk, Z.; Lamaty, F.; Vawter, E. J.; Negishi, E.-I. *J. Am. Chem. Soc.* **1992**, *114*, 10091.
9. (a) Oh, C. H.; Kim, A.; Rhim, C. Y.; Kang, J. H.; Park, B. S. *Bull. Korean Chem. Soc.* **1996**, *17*, 879. (b) Oh, C. H.; Rhim, C. Y.; Kang, J. H.; Kim, A.; Park, B. S.; Seo, Y. *Tetrahedron Lett.* **1996**, *37*, 8875.
10. Oh, C. H.; Kang, J. H.; Rhim, C. Y.; Kim, J. H. *Chem. Lett.* **1998**, 375.
11. Allylpalladium chloride dimer was prepared according to the literature procedure. Tatsuno, Y.; Yoshida, T.; Otsuka, S. *Inorg. Synth.* **1981**, *28*, 342.
12. Trost, B. M.; Shi, Y. *J. Am. Chem. Soc.* **1993**, *115*, 12491.
13. The ^{1}H chemical shifts and coupling constants of the dimeric product were almost identical to those of the starting material **1b** except disappearance of the acetylenic proton peak and its related couplings.
14. The intensity ratio at 350 ($C_{22}D_2H_{38}OSi$), 349 ($C_{22}DH_{39}OSi$), and 348 ($C_{22}H_{40}OSi$) was 50 : 100 : 0, indicating that deuterium content from formic acid would be at least 1.3 per product molecule.