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Gold(I)-Catalyzed Divergence in the Preparation of Bicyclic Enol Esters: From Exclusively [3C+2C]-Cycloaddition Reactions to Exclusive Formation of Vinylcyclopropanes

Ryan C. Conyers and Benjamin W. Gung*[a]

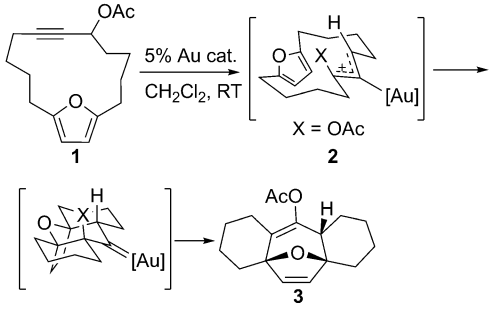
Abstract: With the use of benzonitrile-stabilized Au^I catalyst [Au(IPr)-(NCPh)]SbF_6 (**Ic**; IPr = 1,3-bis(2,6-diisopropylphenyl)imidazol-2-ylidene), a spectrum of reactivity is observed for propargyl ester **4a** with cyclic vinyl ethers, ranging from exclusively [3C+2C] cycloaddition reactions to exclusively cyclopropanation depending only on the structure of the substrate. Some initially formed cyclopropanation products rearrange into the corresponding formally [3C+2C] cycloaddition products after treatment with fresh Au^I complex at 80 °C. Vinylcyclopropanes formed from dihydrofuran and dihydropyran resisted such rearrangement, even in the presence of fresh Au^I catalyst at elevated temperature. This study addresses an important mechanistic question concerning whether the five-membered-ring products were produced by a direct [3C+2C] cycloaddition reaction or by a sequential cyclopropanation/ring-expansion reaction. A dual pathway is proposed for the Au^I-catalyzed reactions between propargyl esters and cyclic vinyl ethers. The different behavior among vinyl cyclic ethers is attributed to the difference in the polarization of the π bond. Highly polarized bonds appear to undergo the cycloaddition reaction whereas less polar π-bonds produce cyclopropanes.

Keywords: cycloaddition · cyclopropanation · gold · homogeneous catalysis · ring expansion

Introduction

Readily accessible propargylic esters are versatile substrates for Au catalysis and can undergo either 1,2-acetoxyl migration[1] or 3,3-rearrangment reactions.[2] Two competing reactive intermediates, gold vinyl carbenoids and Au-stabilized allyl cations, have been invoked in reports in which propargylic esters are employed as precursors in gold-catalyzed reactions. It is known that an allene function can be activated to generate an Au-stabilized allyl cation, which may undergo intramolecular [4C+3C]-cycloaddition reactions.[3] In 2010, we reported Au^I-catalyzed transannular [4C+3C]-cycloaddition reactions that take advantage of the allyl oxocarbenium (**2**, Scheme 1) derived from a 3,3-rearrangement of propargylic esters to provide the core structure of cortistatins (**3**).[4] In addition, we reported a study of an intermolecular version of the [4C+3C]-cycloaddition reaction,[5] in which we discussed the mechanistic possibilities of a direct [4C+3C] cycloaddition and an alternative two-step sequence of cyclopropanation followed by a Cope rearrangement.

Recent reports[6] of Au^I-catalyzed reactions between propargyl esters and olefins have prompted us to report our more recent results in this area, which involve a benzonitrile-stabilized Au^I catalyst. We have observed an interesting shift in the outcome of the reaction from exclusive intermolecular [3C+2C] cycloadditions to exclusive cyclopropanation reactions depending on the structure of the vinyl ether reagent.



Scheme 1. The Au^I-catalyzed transannular [4C+3C]-cycloaddition reaction.

Nevado and co-workers recently reported gold-catalyzed cycloadditions of olefins with propargyl esters to form five- or seven-membered rings (Scheme 2).[6a] Cyclopropane derivatives were isolated and were suggested as the precursor to the final five- and seven-membered-ring products. Subsequently, Fiksdahl et al. reported a number of gold-catalyzed cyclopropanation reactions of vinyl esters and vinyl sulfonamides with different propargyl esters (Scheme 2).[6b] In contrast to the observations of the Nevado group, ring expansion from cyclopropylvinyl esters was not successful and a

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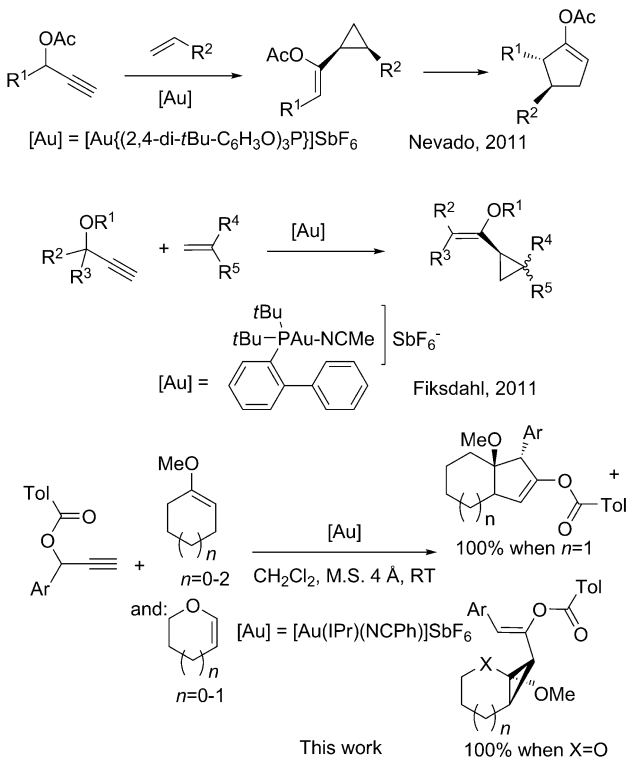


Scheme 2. The Au^I-catalyzed reactions of propargyl esters with olefins. IPr = 1,3-bis(2,6-diisopropylphenyl)imidazol-2-ylidene; Tol = tolyl; M.S. = molecular sieves.

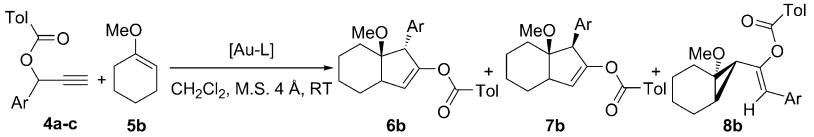
direct [3+2]-cycloaddition pathway involving a gold-stabilized 1,3-dipole was proposed. An important mechanistic question arose concerning whether the five-membered-ring products were produced by a direct [3C+2C] cycloaddition or by an initial cyclopropanation followed by a rearrangement. Only two examples of such direct cycloaddition products have been reported in the study by the Fiksdahl group.[6b] We have now observed an entire spectrum of reactivity from exclusive [3C+2C]-cycloaddition reactions to 100% cyclopropanation reactions depending only on the structure of the substrate (Scheme 2). Consistent with previous reports,[6] some cyclopropanation products rearranged to the corresponding formally [3+2]-cycloaddition products in the presence of a fresh Au^I complex at 80°C, although others resisted such rearrangement even when treated with a fresh Au^I catalyst at elevated temperature. Our results should shed some light on the divergence of the Au^I-catalyzed reactions and point to the possibility that both pathways are operating.

Results

The influence of the Au^I complex, the propargyl ester, and the vinyl ether structure on product distribution: Au^I complexes with N-heterocyclic carbene (NHC) ligands have proven to be effective catalysts in a variety of reactions.[7] Our screening for efficient Au^I–NHC catalysts concentrated on ligand structure and the use of an additional dynamic ligand that further stabilizes the active cationic Au^I catalyst.[8] The dynamic ligand we employed was benzonitrile, which made a significant difference to the reaction outcome. As shown in Table 1, when propargylic esters **4** and vinyl ether **5b** were treated with [Au(IMes)Cl] (**Ia**; IMes = 1,3-bis(2,4,6-trimethylphenyl)imidazol-2-ylidene) in the presence of $AgSbF_6$, no desired product was isolated and the cationic Au^I catalyst slowly degraded (by formation of a gold mirror).

In contrast, the employment of the same Au complex with benzonitrile-containing dynamic ligand **Ib** provided the [3C+2C]-cycloaddition products in 95% yield. The exclusive formation of the [3C+2C]-cycloaddition product at room temperature has not been reported previously by using a Au^I catalyst.[9] Near quantitative yields were obtained by employing the more stable catalyst $[Au(IPr)(NCPh)]^+SbF_6^-$ (**Ic**, Table 1, entries 3–5). Propargylic esters (**4a–c**) with different aryl groups (Ph, *p*-BrC_6H_4, or *p*-$MeOC_6H_4$) were examined briefly. The electron-withdrawing Br group (**4b**) hindered the reaction whereas the electron-donating MeO group (**4c**) allowed high yields that are comparable to those for reactions with the parent phenyl group. A small amount of the cyclopropanation product was also isolated when **4c** was employed (Table 1, entry 5).

Table 1. Au^I-catalyzed [3+2]-cycloaddition reactions with various gold(I) complexes and propargylic esters.[a]



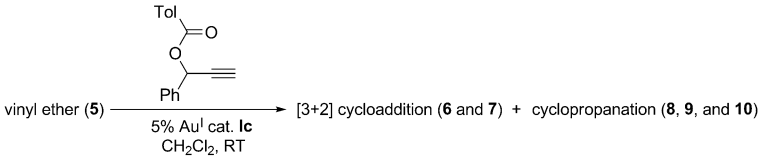
	Ar	[Au–L]	Time [h]	Yield [%][b]	Ratio (**6**+**7**)/**8**
1	Ph (**4a**)	[Au(IMes)Cl]/$AgSbF_6$ (**Ia**)	18	0[c]	n/a
2	Ph (**4a**)	$[Au(IMes)(NCPh)]^+SbF_6^-$ (**Ib**)	2	95 (55:45)	100:0
3	Ph (**4a**)	$[Au(IPr)(NCPh)]^+SbF_6^-$ (**Ic**)	2.5	99 (61:39)	100:0
4	4-Br-C_6H_4 (**4b**)	**Ic**	24	25[d] (60:40)	100:0
5	4-MeO-C_6H_4 (**4c**)	**Ic**	1	99 (50:43)	93:7

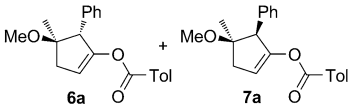
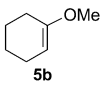
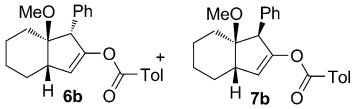
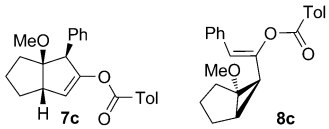
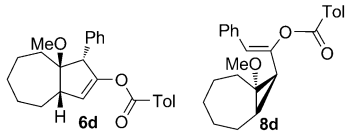
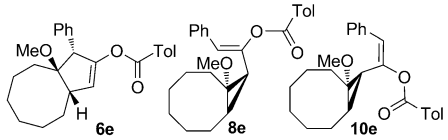
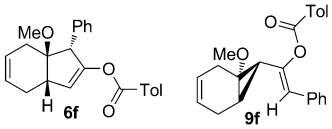
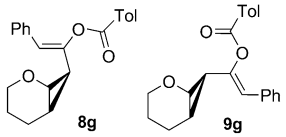
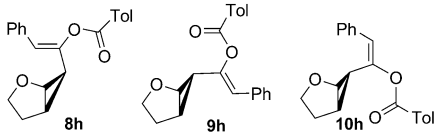
[a] Reaction conditions: **4** (1 equiv), **5b** (1.2 equiv), [Au–L] (5 mol%), 25°C, 0.05 M in CH_2Cl_2. [b] Yield of the isolated product. Ratios in parentheses are for the two diastereomers (*anti*/*syn*; (**6**:**7**)). [c] TLC indicated incomplete reaction and some formation of a gold mirror was observed. [d] Recovered 50% of **4b**.

The benzonitrile-stabilized Au^I complex **Ic** and the parent propargylic ester (**4a**) were chosen for our study into reactions with various vinyl ethers (Table 2). All reactions were performed in dichloromethane at 22°C. We observed that the vinyl ether structure plays a dominant role in the outcome of the reactions under otherwise similar conditions for all experiments.

As shown in Table 2, the acyclic vinyl ether 2-methoxypropene (**5a**), and the six-membered cyclic vinyl ether **5b**

Table 2. Au^I-catalyzed reactions of a propargylic ester with various vinyl ethers.[a]



	Vinyl ether	Products	Time [h]	Yield [%][b]	Ratio (**6**+**7**)/(**8**+**9**)
1	 **5a**	 **6a** + **7a**	1.5	99 (90:10)[c]	100:0
2	 **5b**	 **6b** + **7b**	2.5	99 (61:39)[c]	100:0
3	 **5c**	 **7c** **8c**	16	88	33:67
4	 **5d**	 **6d** **8d**	16	79	55:45
5	 **5e**	 **6e** **8e** **10e**	16	99 (76:24)[c]	28:72
6	 **5f**	 **6f** **9f**	16	79	33:67
7	 **5g**	 **8g** **9g**	2.5	89 (63:37)[c]	0:100
8	 **5h**	 **8h** **9h** **10h**	1.5	75 (52:48)[c]	0:100

[a] Reaction conditions are the same as in Table 1. Relative stereochemistry is shown. [b] Yield of the isolated product. [c] Ratios in parentheses are diastereomers (*anti*:*syn*; (**6**:**7**)) in the case of [3+2] cycloadditions and *endo*/*exo* ((**8**:**9**)) in the case of cyclopropanations.

provided exclusively the [3C+2C]-cycloaddition products, in 99% yield (Table 2, entries 1 and 2). The 5-, 7-, and eight-membered cyclic vinyl ethers **5c**, **5d**, and **5e** gave mixtures of [3C+2C]-cycloaddition and cyclopropanation products in very good combined yields (Table 2, entries 3–5). The six-membered cyclic methoxycyclohexadiene **5f** also afforded a mixture of these products, with the reaction selectively occurring at the methoxy-substituted double bond (Table 2, entry 6). When the oxygen atom is part of the ring, as in dihydropyran (**5g**) and dihydrofuran (**5h**), the cyclopropanation products formed exclusively. We will demonstrate later that these cyclopropanation products have very different propensities to undergo Au^I-catalyzed rearrangement reactions to produce the corresponding formal [3C+2C]-cycloaddition products. The evidence from our study suggests that the initial [3C+2C] products are indeed from such a mechanism, that is, the direct capture of the Au-stabilized allyl cation by the vinyl ether. Operating in parallel to the [3C+2C] cycloaddition is the cyclopropanation/rearrangement pathway. Some of the isolated vinylcyclopropane products did rearrange into cyclopentenes in the presence of fresh Au^I catalyst at higher temperatures. However, the vinylcyclopropanes formed from dihydrofuran and dihydropyran strongly resist the rearrangement reaction even when heated at 110°C in the presence of fresh Au^I catalyst (see below).

Product stereochemistry and structure determination: Diastereomers were isolated in most of the reactions in Table 2. For the [3C+2C]-cycloaddition products, the relative stereochemistry (*syn* or *anti*) with respect to the methoxy and phenyl groups was identified based on the chemical shift of the methoxy group (Table 3). In the *anti* isomer, the methoxy group has a normal chemical shift of $\delta = 3.4$ ppm whereas the methoxy group in the *syn* isomer displayed an upfield shift of $\delta = 2.9$ ppm. The significant upfield shift of the methoxy group is consistent with it being located in the region of the phenyl ring current. This difference in methoxy chemical shift holds true for other diastereomers of the [3C+2C]-cycloaddition products.

As shown in Table 3, the methoxy group has a chemical shift of $\delta = 3.4$–3.5 ppm when it is not close to a phenyl ring, such as in the cases of compounds **6**, **8**, and **9**. In the three *syn* isomers (**7a**–**c**), the chemical shift of the methoxy group has moved to approximately $\delta = 2.9$ ppm, indicating the proximity of a phenyl ring.

Table 3. Chemical shifts [ppm] for the MeO and vinyl protons in the [3+2] cycloaddition (**6** and **7**) and cyclopropanation (**8**–**10**) diastereomers.

Compound series	**6** MeO	**6** vinyl	**7** MeO	**7** vinyl	**8** MeO	**8** vinyl	**9** MeO	**9** vinyl	**10** MeO	**10** vinyl
a	3.4, 5.9		2.9, 5.7							
b	3.5, 5.8		2.9, 5.7							
c	–		2.8, 5.6		3.5, 6.1					
d	3.4, 5.9		–		3.4, 6.2					
e	3.5, 6.0		–		3.4, 6.1				3.2, 6.1	
f	3.4, 5.8						3.5, 6.2			
g					−6.0		−5.9			
h					−5.8		−6.0		−6.1	

The protons of each diastereomer in the ^{1}H NMR spectra were assigned by a combination of two-dimensional NMR methods, including COSY, HSQC, and HMBC spectroscopy. The *endo* and *exo* diastereomers in the cyclopropanation reaction products were identified by two-dimensional NOESY NMR spectroscopy. As shown in Figure 1, the vinyl

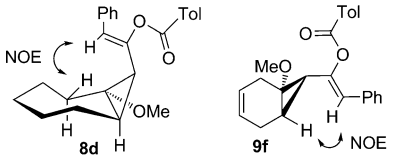
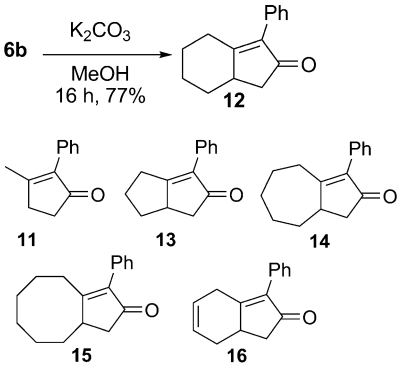


Figure 1. The stereochemistry of the *endo*- and *exo*-enol ester group relative to the ring was determined by two-dimensional NOSEY NMR spectroscopy.

proton of the enol ester group displays an NOE correlation with the ring proton adjacent to the MeO group for the *endo* diastereomer and a correlation with the cyclopropane proton for the *exo* isomer.

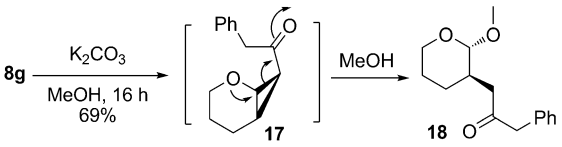
The structures of the cycloaddition products **6** and **7** were confirmed by methanolysis of the enol ester functionality by using K_2CO_3 in MeOH, as illustrated in Equation (1) by the formation of ketone **12**. Under these conditions, the methoxy group was lost through β elimination to give the corresponding cyclopentenone. The other bicyclic enol esters (**6a**–**f**) produced the corresponding ketones (**11**–**16**) under the same conditions. Compound **11** and the bicyclic enones, **12** and **13**, are known compounds,[10,11] whereas **14** and **15** have not been reported in the literature. It is worth noting that the popular Pauson–Khand[12] reaction can be employed to prepare the bicyclo[3.3.0]- and -[4.3.0]enones (**12** and **13**) and the Rautenstrauch cyclization can produce cyclopentenones,[1c,13] although the bicyclo[5.3.0]- and -[6.3.0]enones (**14** and **15**) are more difficult to obtain through these methods. Thus, for compounds similar to enones **12** and **13**, the Au^I-catalyzed cycloaddition followed by methanolysis provides an alternative preparation, whereas for structures similar to **14** and **15**, the Au^I-centered sequence provides an improved synthetic route. The structure of the [3+2]-cycloaddition product **6f**, formed from methoxycyclohexadiene (**5f**),



(1)

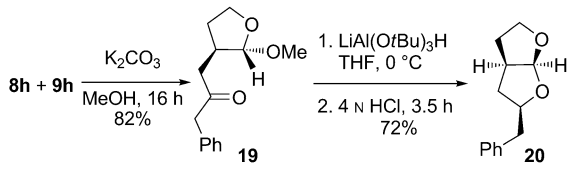
was confirmed by converting it into the bicyclic enone **12** through formation of first the methanolysis product **16** and then through selective hydrogenation.

The dihydropyran and dyhydrofuran provided exclusively the cyclopropanation products when treated with the same Au^I catalyst **Ic** and propargyl ester **4a**. Upon treatment of the cyclopropanation product **8g** (Table 2, entry 7) with K_2CO_3 in methanol overnight, the ring-opened product **18** was isolated in 69% yield [Eq. (2)]. The presumed intermediate (**17**) was not observed under the conditions employed.



(2)

Similarly, the cyclopropanation products formed from the reaction of dihydrofuran (**8h** and **9h**, Table 2, entry 8) were treated under the same conditions as **8g** to provide the ring-opened product **19** (Scheme 3). The *anti* isomer was ob-

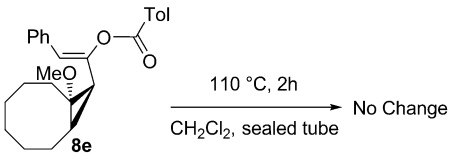


Scheme 3. Synthesis of perhydro[2,3-*b*]furofuran (**20**) through the Au^I-catalyzed cyclopropanation of dihydrofuran.

tained exclusively and the stereochemistry was determined by the absence of coupling between the anomeric proton and the proton on carbon number 2. This ketone was stereoselectively reduced with tri-*tert*-butoxy lithium aluminum hydride at 0 °C, followed by an acid-induced ring closure, to provide the bicyclic acetal **20**. This bis(perhydrofuran) is a common structural unit in a number of natural products.[14] Similar structures to **20** have been synthesized through different routes.[14–15] The efficient synthesis of the perhydro-

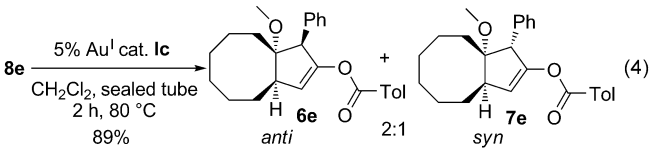
[2,3-*b*]furofuran (**20**) through the Au^I-catalyzed cyclopropanation of dihydrofuran, followed by the sequence shown in Scheme 3 demonstrates the synthetic utility of the reported reactions.

Study of the Au^I-catalyzed vinylcyclopropane/cyclopentene rearrangement reactions: No change was observed when the isolated cyclopropanation product **8e** was heated to 110 °C in a sealed Schlenk tube for 2 h [Eq. (3)]. However, in the



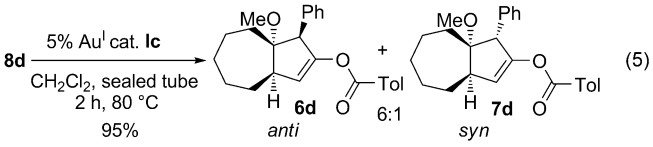
(3)

presence of fresh Au^I complex **Ic** at 80 °C in CH_2Cl_2, a mixture of two diastereomers of the ring-expansion product (**6e** and **7e**) was isolated in 89% yield in favor of the *anti* diastereomer in a 2:1 ratio [Eq. (4)].



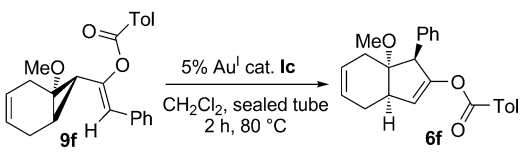
(4)

Similarly, when the isolated cyclopropanation product **8d** was treated with 5 mol% of fresh Au^I catalyst **Ic** at 80 °C for 2 h, a conversion to the [3+2]-cycloaddition products **6d** and **7d** was observed in a 6:1 ratio in favor of the *anti* diastereomer [Eq. (5)].



(5)

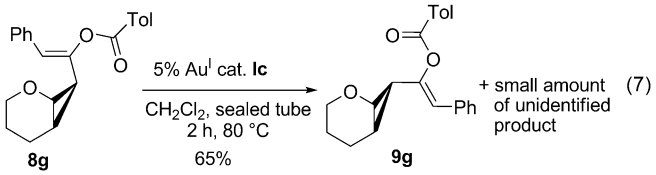
Similar behavior was also observed for vinylcyclopropane **9f** [Eq. (6)]. Since the rearrangement of the vinylcyclopropanes (**8d** and **9f**) to the cyclopentenes (**6d** and **6f**) requires heating to 80 °C in the presence of Au^I catalyst **Ic**, the initial formation of **6d** and **6f** at room temperature must have occurred through the [3C+2C] pathway by direct capture of the cationic 1,3-dipole by the vinyl enol ether.



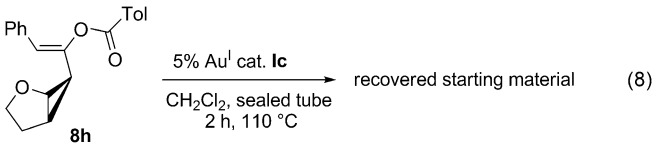
(6)

Thus the rearrangement from vinylcyclopropane derivatives to the cyclopentenes requires the presence of the Au^I catalyst and some heating. This is consistent with the recent report by Nevado et al.[6a] However, a large difference in the tendency for ring expansion/rearrangement is observed among different vinylcyclopropanes.

We also observed a strong resistance to rearrangement by some vinyl cyclopropane derivatives. This is consistent with the report by Fiksdahl et al.[6b] In this study, the vinylcyclopropanes from the reaction of dihydrofuran and dihydropyran (**8g** and **8h**) exhibit resistance to ring expansion/rearrangement. No cyclopentene derivatives were isolated despite the treatment of vinylcyclopropanes **8g** and **8h** with fresh Au^I catalyst **Ic** at elevated temperatures (110 °C). For **8g**, the treatment lead to the vinylcyclopropane with an *exo* stereochemistry (**9g**) in 65% yield, which indicates a cyclopropane ring-opening and -closing process, but no rearrangement/ring expansion product was observed [Eq. (7)]. For **8h**, only the starting material was recovered [Eq. (8)].

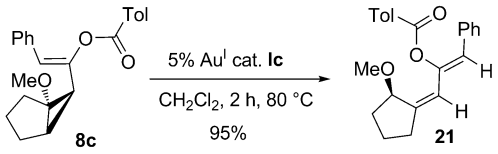


(7)

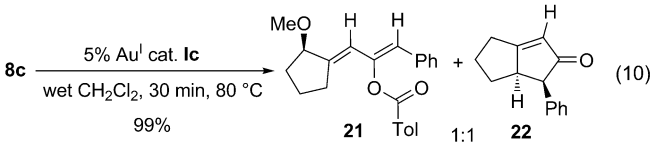


(8)

The most intriguing case of the rearrangement reaction came from the treatment of vinylcyclopropane **8c** with Au^I. Under carefully controlled conditions (with freshly distilled (over CaH_2) solvent and sealed under an inert atmosphere), diene **21** could be isolated in excellent yield [Eq. (9)] when compound **8c** was allowed to stir in the presence of fresh Au^I complex **Ic**. If the solvent was not carefully dried or if the reaction vessel was not completely sealed under an inert atmosphere, varying amounts of enone **22** were isolated along with diene **21**. When dichloromethane, directly from a commercial source, was used as the solvent without drying over CaH_2, a 50% yield of enone **22** was isolated after 30 min [Eq. (10)]. The fact that the vinyl cyclopropane **8c** does not follow the expected ring-expansion/rearrangement sequence further supports the notion that the initially



(9)



formed cyclopentene derivative **7c** (Table 2, entry 3) was a result of a direct [3C+2C]-cycloaddition reaction.

It should be pointed out that enone **22** is different from the hydrolysis product of a direct [3C+2C]-cycloaddition reaction. The direct cycloaddition product **7c** (Table 1, entry 3) yielded enone **13** upon hydrolysis of the vinyl ester. Enone **22** differs from enone **13** in the location of the phenyl group. Although the phenyl group is attached to the carbon next to the carbonyl group in both compounds, it is attached to the sp^2 carbon atom in compound **13** and to the sp^3 carbon atom in compound **22**. A discussion of possible pathways leading to enone **22** will be presented in the next section.

Discussion

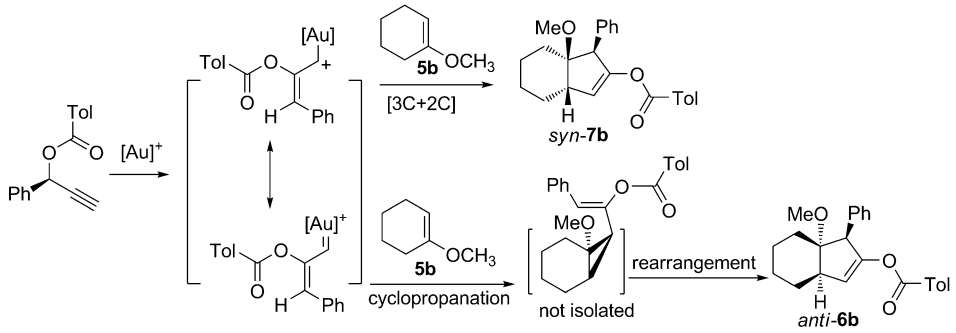
The mechanism of gold-catalyzed reactions and the characteristics of the gold–carbon bond have been elegantly examined by several leading groups.[16] The ancillary ligand attached to the gold atom plays an important role on the Au–C bonding mode of Au^I complexes. The Au–C bond in most Au^I complexes can exhibit either gold-stabilized-cation or carbene-like properties. The first gold-catalyzed cyclopropanation reaction of carbenoids derived from propargyl esters was reported by the Toste group in 2005.[17] A subsequent computational study found that the cyclopropanation reaction occurs by a process that is close to the concerted process proposed in the original report.[18] A gas-phase study in combination with computation suggested that cyclopropanation of electron-rich olefins by gold carbenes is a stepwise process as a result of the stability of the cationic intermediates.[19] More recently, in a study of the gold(I)-catalyzed intermolecular cyclopropanation of alkenes with 1,6-enynes, Echavarren et al. concluded that the cyclopropanation can occur either in a concerted or a stepwise fashion depending on the substituents present in the alkene.[20]

The divergent pathways, involving either a carbenoid or an Au-stabilized allyl oxocarbenium, in the reactions of propargylic esters have also been investigated by computational studies.[2b,16d] Furthermore, related 1,3-addition reactions have recently been reported for a vinyl metal carbenoid by Doyle et al. with rhodium[21] and previously by Toste et al. by using gold.[22] Nevado and co-workers recently reported an extensive list of gold-catalyzed cascade cyclopropanation/ring-expansion reactions of acyclic, mono-substituted olefins with a tris(2,4-di-*tert*-butylphenyl)phosphite–gold complex (Scheme 2).[6a] The mechanistic proposal for these reactions involves the initial formation of the cyclopropylvinyl esters, which undergo a subsequent ring expansion under the same gold catalysis conditions to provide the ring-expansion products with *anti* stereochemistry. In the same year, a subsequent report from Fiksdahl et al. on similar reactions[6b] suggested that a direct cycloaddition was more likely than the cyclopropanation/ring-expansion mechanism.

The current study into the reaction between cyclic vinyl ethers and propargyl esters in the presence of Au^I catalyst **Ic** shows that the capture of the Au-stabilized allyl cation or the gold carbenoid is dependent on the vinyl ether structure. Our results are more consistent with a dual reaction pathway involving both a direct [3C+2C] cycloaddition and a cascade cyclopropanation/rearrangement reaction sequence. The preference for one of the two pathways is dependent on the structure of the vinyl ether substrate. A more polarized π-bond appears to induce [3C+2C] cycloaddition, whereas a less polarized π-bond preferentially undergoes cyclopropanation reactions. Alkoxy vinyl ethers are known to be better electron donors than vinyl acetates.[23] Accordingly, the study reported by Fiksdahl et al. with vinyl acetates as reactants resulted in mainly cyclopropanation reactions (Scheme 2).[6b] In contrast, Nevado et al. studied reactions of mainly alkoxy vinyl ethers and thus obtained cycloaddition products.[6a] Under our standard conditions (Au^I catalyst **Ic** (5%), CH_2Cl_2, room temperature, ≈2 h), the reactions of vinyl ethers **5a** and **5b** gave exclusively [3C+2C]-cycloaddition products, vinyl ethers **5c**–**5f** yielded mixtures of [3C+2C]-cycloaddition and cyclopropanation products, and dihydropyran (**5g**) and dihydrofuran (**5h**) produced exclusively the cyclopropanation products (see Table 2).

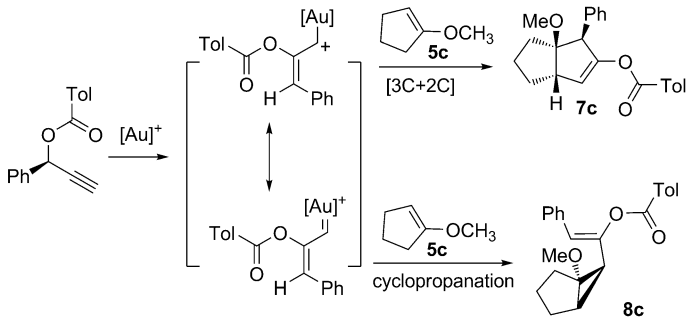
We were pleased to obtain the bicyclic enol esters under extremely mild conditions with vinyl ethers **5a** and **5b**. However, the appearance of the cyclopropanation products in varying amounts when using vinyl ethers **5c**–**5h** suggested a dual reaction pathway in the Au^I-catalyzed reactions. The stereoselective formation of the *anti*-diastereomeric five-membered rings provided supporting evidence for the proposed Au^I-catalyzed cascade cyclopropanation/rearrangement reaction sequence.[6a] The aforementioned ring-expansion/rearrangement reactions of vinylcyclopropanes **8d**, **8e**, and **9f** also gave predominantly the *anti* diastereomers. Therefore the *anti*-diastereomer **6b**, from the reaction of **5b**, might be formed from the cascading cyclopropanation/rearrangement reaction sequence, whereas the *syn*-diastereomer **7b** may arise from direct capture of the Au-stabilized allyl cation intermediate (Scheme 4).

In terms of synthetic utility, it was unfortunate that vinyl ethers **5c**–**5f** yielded mixtures of [3C+2C]-cycloaddition and cyclopropanation products at room temperature. However, in terms of understanding the mechanism of the reaction, the isolation of both products provided an opportunity to examine the two pathways. The conversion of the cyclopropanation products into the cyclopentene derivatives requires both fresh Au^I catalyst and some heating. The fact that some cyclopentene derivatives were formed at room temperature was consistent with the proposal that the initially formed cyclopentene derivatives (e.g., **7c**) were a result of



Scheme 4. Possible dual pathways leading to *syn* and *anti* diastereomers.

direct capture of the Au-stabilized allyl cation involving Au^I catalyst **Ic**. The *syn* stereochemistry of [3C+2C]-cycloaddition product **7c** further supports this reaction pathway (Scheme 5).

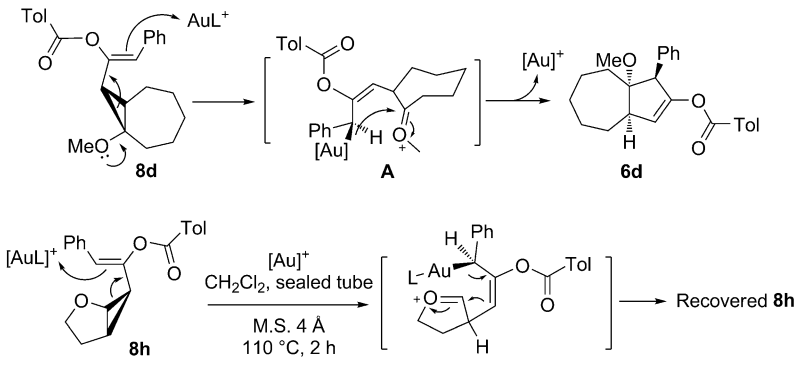


Scheme 5. Proposed dual pathways leading to the respective products **7c** and **8c**.

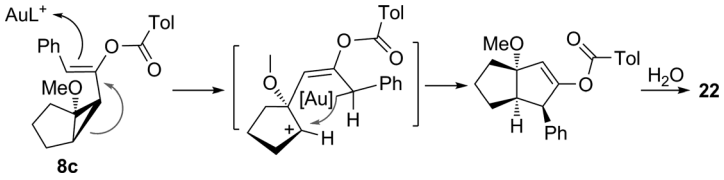
As described earlier, the outcome of the Au^I-catalyzed ring-expansion/rearrangement reaction depends on the structure of the vinylcyclopropane. However, the difference in structure for the compounds studied herein is limited to changes in the ring that is fused to the cyclopropane ring in the product (Table 2).

We attribute the difference in the behavior of the vinylcyclopropanes to a combination of stereo- and electronic properties of the fused ring on the cyclopropane. In accordance with the mechanism proposed by Nevado et al.,[6a] the initial coordination of the enol ester double bond of **8d** or **8h** to the cationic Au^I center should lead to the opening of the cyclopropane ring and the formation of an oxycarbenium ion (**A**; Scheme 6). This is a highly strained intermediate due to the *cis* configuration of the double bond. The activation of the enolate double bond by the Au^I catalyst leads to an Au–C sigma bond in intermediate **A**. Over the last a few years, stable Au–C(sp^3) bonds have been reported both in Au^I[24] and in Au^{III} complexes.[25] In the presence of protic solvents, the gold catalyst is typically regenerated by proto-deauration.[26] In this case, ring closure and deauration produce the new five-membered ring in **6d** (Scheme 6). The bicyclo[5.1.0]octane derivative **8d** and the bicyclo[4.1.0]heptane derivative **9f** have more flexible conformations than **8c** or **8h** to allow for the alignment of the involved orbitals and the formation of the new five-membered ring. In contrast, the bicyclo[3.1.0]hexane derivative **8c** and the dihydropyran and dihydrofuran derivatives (**8g** and **8h**) are more rigid and the alignment of the orbitals favors the re-closure of the three-membered ring. Subsequently, different pathways may occur depending on the substrate structure. The two most common events were 1) ring closure to form a five-membered ring and deauration (Scheme 6, top), 2) ring closure to form a three-membered ring and deauration to return to the starting material (Scheme 6, bottom), or 3) ring closure to give a vinylcyclopropane with *exo* configuration [Eq. (7)].

A third pathway in which a hydride shift leads to the formation of a diene ester was also observed [Eq. (9)] . As described earlier the Au^I-catalyzed conversion of vinylcyclopropane **8c** leads to diene **21** and enone **22**. Initially, we considered the possibility that enone **22** was formed through a rearrangement of vinylcyclopropane **8c** with the opening of the cyclopropane ring from the unexpected side, followed by hydrolysis of the enol ester (Scheme 7). However, this pathway would require opening of the cyclopropane ring from the side leading to an unstabilized secondary carbocation. This was deemed unlikely because a previous study has shown that the opening of a cyclopropane ring requires a substituent that can stabilize the developing positive charge.[27] A methoxy group is capable of stabilizing the de-



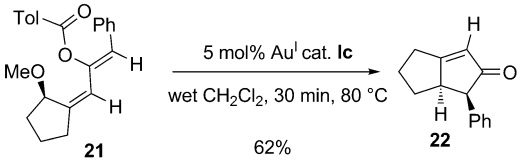
Scheme 6. Proposed Au^I-catalyzed transformation of vinylcyclopropanes.



Scheme 7. A possible, but unlikely, pathway to **22**.

veloping positive charge and the ring opening should occur on the side of the ring with the methoxy group attached. Furthermore, the hydrolysis of the enol ester requires the solvent to be either H_2O or MeOH and this reaction was performed in anhydrous CH_2Cl_2. Therefore, this pathway seems unlikely.

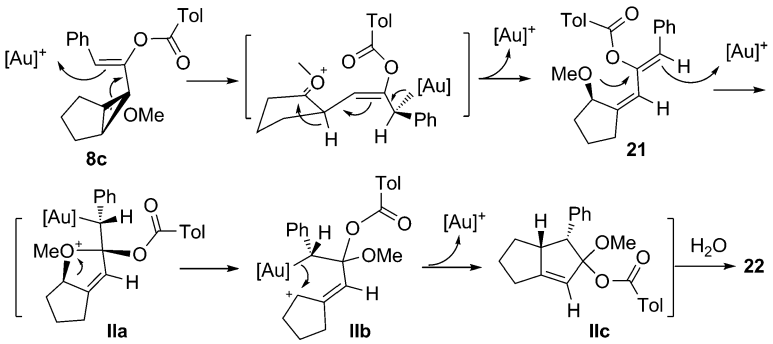
To examine the mechanism for the formation of enone **22**, two additional experiments were performed. When diene **21** was treated with fresh Au^I catalyst and heated to 80 °C for 30 min [Eq. (11)], enone **22** was isolated in 62 % yield. This experiment shows that diene **21** is an intermediate on the pathway leading to enone **22**



(11)

from the vinyl cyclopropane derivative **8c**.

A second experiment was performed in [D_8]toluene in a NMR tube. Vinylcyclopropane **8c** was stirred with 5 % Au^I catalyst **Ic** in [D_8]toluene at room temperature. The resulting mixture was filtered through a cotton plug into a high quality NMR tube. Proton NMR spectra were taken at intervals of 10 min. After each spectrum, the temperature of the NMR probe was raised by 10 °C. Diene **21** started to form at approximately 65 °C with concurrent disappearance of vinylcyclopropane **8c**. Enone **22** started to form at approximately 85 °C with simultaneous disappearance of diene **21**. Methyl toluate and a small amount of methanol were also observed in the final NMR spectrum. Based on this evidence, we propose that the formation of the diene occurs through a sequence of events involving first the $\{Au\}^+$-promoted opening of the cyclopropane ring, and then a hydride shift from the allylic carbon atom to the oxycarbenium carbon atom (Scheme 8). Once the diene has formed, it is further activated by the Au^I catalyst to form an oxygen-bridged acetal **IIa**. Similar Au^I-promoted methoxy-group transposition through a five-membered ring has previously been documented.[24,25] Methoxy-group migration occurs concurrently with the formation a new carbon–carbon bond (**IIb**) and deauration to produce the unstable acetal **IIc**. The presence of a trace amount of water can initiate the hydrolysis and methanolysis of the unstable acetal **IIc** to give enone **22**. Acetals with structures similar to **IIc** have previously been shown to spontaneously equilibrate to the corresponding ketones and esters.[28]



Scheme 8. Proposed mechanism for the formation of diene **21** and enone **22**.

Conclusion

It has been shown that the outcome of the Au^I-catalyzed reaction of propargyl esters with a cyclic vinyl ether is sensitive to substrate structure. This is consistent with several recent studies that showed the impact of alkene substituents on the mechanism of cyclopropanation. Similarly, the Au^I-catalyzed ring-expansion/rearrangement reactions of the vinylcyclopropanes also produce several different outcomes depending on the structure of the bicyclic enol esters. Based on documented mechanisms and model structures of Au^I complexes,[14,18–20] a dual reaction pathway is proposed to explain the observed divergence in the Au^I-catalyzed reactions. The preference for the [3C+2C]-cycloaddition pathway may depend on the degree of polarization of the vinyl ether double bond. A more polarized π-bond appears to induce the [3C+2C] cycloaddition, whereas a less polarized π-bond preferentially undergoes cyclopropanation reactions. However, the difference in the polarization of the π-bond does not have to be large for a change from one pathway to the other to occur. Our current effort is directed toward a better understanding of the Au^I-catalyzed ring-expansion/rearrangement reactions and our results will be reported in due course.

Experimental Section

General conditions: Unless otherwise stated, all reactions were carried out under an inert nitrogen atmosphere with anhydrous solvents. Tetrahydrofuran (THF) was distilled over sodium benzophenone, and dichloromethane (CH_2Cl_2) and benzene were distilled over calcium hydride. Re-

agents were purchased and used without further purification unless otherwise stated. Yields refer to chromatographically and spectroscopically (^{1}H NMR) homogeneous materials, unless otherwise stated. Reactions were monitored by thin-layer chromatography (TLC) carried out on Merck silica gel plates (60F-254; 0.25 mm) by using UV light as the visualizing agent and an acidic mixture of anisaldehyde, phosphomolybdic acid, ceric ammonium molybdate, or basic aqueous potassium permanganate ($KMnO_4$) and heat as developing agents. Merck silica gel (60, particle size 0.043–0.063 mm) was used for flash column chromatography. NMR spectra were recorded on Bruker Av-500 and Av-300 instruments and calibrated by using residual undeuterated solvent as an internal reference ($CHCl_3$: $\delta = 7.26$ (^{1}H), 77.0 ppm (^{13}C)). The following abbreviations (or combinations thereof) were used to explain the multiplicities: s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, br = broad. High-resolution mass spectra (HRMS) were recorded at Ohio State University.

General procedure for gold-catalyzed cycloaddition reactions: Gold catalyst **Ic** (0.009 mmol) in freshly distilled CH_2Cl_2 (1.0 mL) was added to a round-bottomed flask equipped with a stirring bar under an atmosphere of nitrogen. The propargyl ester (0.18 mmol) and vinyl ether (0.22 mmol), were both dissolved in freshly distilled CH_2Cl_2 (1.0 mL), were added dropwise to the reaction, stirred at RT, and monitored by TLC and/or ^{1}H NMR spectroscopy until completion. The reaction mixture was diluted with Et_2O, filtered through a pad of Celite, the solvent removed under reduced pressure, and the product purified by column chromatography (1–2% EtOAc/hexanes).

4-Methoxy-4-methyl-5-phenylcyclopent-1-enyl 4-methylbenzoate (***6a***): ^{1}H NMR (500 MHz, $CDCl_3$): $\delta = 0.90$ (3H, s), 2.34 (3H, s), 2.43 (1H, dd, $J = 2$, 17 Hz), 2.73 (1H, dd, $J = 2.5$, 16.5 Hz), 3.38 (3H, s), 4.21 (1H, s), 5.91 (1H, s), 7.14 (2H, d, $J = 8$ Hz), 7.19–7.22 (3H, m), 7.27–7.30 (2H, m), 7.77 ppm (2H, d, $J = 8.5$ Hz); ^{13}C NMR (125 MHz, $CDCl_3$): $\delta = 21.6$, 22.8, 40.4, 50.3, 58.8, 84.5, 112.6, 126.8, 128.3, 128.4, 128.9, 129.05, 129.09, 129.12, 129.15, 129.88, 129.92, 137.9, 144.0, 149.2, 164.2 ppm; HRMS: *m*/*z* calcd for $C_{21}H_{22}O_3$ + Na: 345.1467; found: 345.1461.

4-Methoxy-4-methyl-5-phenylcyclopent-1-enyl 4-methylbenzoate (***7a***): ^{1}H NMR (500 MHz, $CDCl_3$): $\delta = 1.61$ (3H, s), 2.36 (3H, s), 2.45 (1H, dd, $J = 3$, 15.5 Hz), 2.79 (1H, d, $J = 15.5$ Hz), 2.90 (3H, s), 3.87 (1H, s), 5.74 (1H, s), 7.16 (2H, d, $J = 8$ Hz), 7.25–7.28 (5H, m), 7.76 ppm (2H, d, $J = 8$ Hz).

1-Methoxy-9-phenylbicyclo[4.3.0]non-8-enyl 4-methylbenzoate (***6b***): ^{1}H NMR (500 MHz, $CDCl_3$): $\delta = 1.05$–1.12 (2H, m), 1.31–1.37 (2H, m), 1.45–1.50 (1H, m), 1.53–1.56 (2H, m), 1.70–1.71 (1H, m), 2.35 (3H, s), 3.03 (1H, s), 3.45 (3H, s), 4.51 (1H, s), 5.81 (1H, s), 7.15–7.27 (7H, m), 7.78 ppm (2H, d, $J = 8$ Hz); ^{13}C NMR (125 MHz, $CDCl_3$): $\delta = 19.8$, 21.7, 26.6, 28.1, 43.6, 50.2, 55.8, 86.0, 118.4, 126.5, 126.7, 127.9, 128.30, 128.33, 129.09, 129.12, 129.3, 129.5, 129.9, 130.2, 136.7, 144.0, 148.3, 164.2 ppm; HRMS: *m*/*z* calcd for $C_{24}H_{26}O_3$ + Na: 385.1780; found: 385.1770.

1-Methoxy-9-phenylbicyclo[4.3.0]non-8-enyl 4-methylbenzoate (***7b***): ^{1}H NMR (500 MHz, $CDCl_3$): $\delta = 1.45$–1.50 (2H, m), 1.50–1.55 (2H, m), 1.69–1.75 (2H, m), 1.96 (1H, dt, $J = 3.5$, 12 Hz), 2.13 (1H, d, $J = 13.5$ Hz), 2.36 (3H, s), 2.89 (3H, s), 3.15 (1H, s), 3.77 (1H, s), 5.68 (1H, s), 7.16 (2H, d, $J = 8$ Hz), 7.21–7.32 (5H, m), 7.79 ppm (2H, d, $J = 8$ Hz); ^{13}C NMR (125 MHz, $CDCl_3$): $\delta = 21.5$, 21.7, 22.0, 25.9, 30.72, 44.9, 51.2, 59.7, 83.7, 117.9, 126.7, 126.8, 128.1, 129.1, 129.4, 129.9, 136.7, 144.1, 151.7, 164.6 ppm; LCMS: *m*/*z* calcd for $C_{24}H_{26}O_3$ + Na: 385.2; found: 385.2.

1-Methoxy-8-phenylbicyclo[3.3.0]oct-7-enyl 4-methylbenzoate (***7c***): ^{1}H NMR (500 MHz, $CDCl_3$): $\delta = 1.58$–1.61 (2H, m), 1.77–1.82 (2H, m), 1.86–1.90 (1H, m), 1.99–2.04 (1H, m), 2.23–2.26 (1H, m), 2.35 (3H, s), 2.75 (3H, s), 3.25 (1H, d, $J = 8$ Hz), 4.04 (1H, s), 5.57 (1H, s), 7.15 (2H, d, $J = 8$ Hz), 7.21 (1H, d, $J = 7$ Hz), 7.27–7.32 (4H, m), 7.73 ppm (2H, d, $J = 8.5$ Hz); ^{13}C NMR (125 MHz, $CDCl_3$): $\delta = 21.7$, 24.4, 30.0, 36.9, 51.8, 52.4, 59.2, 93.7, 117.6, 126.7, 127.9, 128.0, 129.08, 129.12, 129.5, 129.6, 129.86, 129.9, 138.2, 144.1, 149.6, 164.5 ppm; LCMS: *m*/*z* calcd for $C_{23}H_{24}O_3$ + Na: 371.2; found: 371.2.

1-(1-Methoxybicyclo[3.1.0]hex-6-yl)-2-phenylvinyl 4-methylbenzoate (***8c***): ^{1}H NMR (500 MHz, $CDCl_3$): $\delta = 1.18$–1.21 (1H, m), 1.70–1.75 (2H, m), 1.80–1.83 (1H, m), 1.83 (1H, s), 1.93–1.95 (1H, m), 2.00 (1H, ddd, $J = 8.5$, 11, 12 Hz), 2.15 (1H, dd, $J = 8$, 12 Hz), 2.43 (3H, s), 3.45 (3H, s), 6.14 (1H, s), 7.11 (1H, t, $J = 7.5$ Hz), 7.19 (2H, t, $J = 7.5$ Hz), 7.28 (2H, d, $J = 8$ Hz), 7.38 (2H, d, $J = 8$ Hz), 8.03 ppm (2H, d, $J = 8$ Hz); ^{13}C NMR (125 MHz, $CDCl_3$): $\delta = 21.2$, 21.7, 26.7, 28.8, 30.0, 30.13, 30.17, 56.3, 75.7, 116.3, 126.7, 127.0, 128.3, 128.36, 128.39, 129.4, 130.2, 134.7, 144.3, 146.3, 164.3 ppm; HRMS: *m*/*z* calcd for $C_{23}H_{24}O_3$ + Na: 371.1623; found: 371.1616.

1-Methoxy-10-phenylbicyclo[5.3.0]dec-9-enyl 4-methylbenzoate (***6d***): ^{1}H NMR (500 MHz, $CDCl_3$): $\delta = 0.64$–0.73 (1H, m), 0.94–1.05 (1H, m), 1.26–1.35 (2H, m), 1.45–1.50 (2H, m), 1.59–1.65 (2H, m), 1.65–1.71 (1H, m), 1.80–1.90 (2H, m), 2.35 (3H, s), 2.76 (1H, d, $J = 11$ Hz), 3.41 (3H, s), 4.19 (1H, s), 5.92 (1H, s), 7.14 (2H, d, $J = 8$ Hz), 7.21 (2H, d, $J = 7$ Hz), 7.26–7.29 (3H, m), 7.74 ppm (2H, d, $J = 8.5$ Hz); ^{13}C NMR (125 MHz, $CDCl_3$): $\delta = 21.6$, 22.4, 30.7, 31.1, 33.2, 33.4, 49.4, 55.5, 58.5, 88.6, 119.2, 126.8, 128.3, 190.1, 129.9, 138.7, 144.0, 146.7, 164.2 ppm; LCMS: *m*/*z* calcd for $C_{25}H_{28}O_3$ + Na: 399.2; found: 399.3.

1-(1-Methoxybicyclo[5.1.0]oct-8-yl)-2-phenylvinyl 4-methylbenzoate (***8d***): ^{1}H NMR (500 MHz, $CDCl_3$): $\delta = 0.95$–1.02 (1H, m), 1.12 (1H, dd, $J = 1.5$, 13 Hz), 1.21 (1H, d, $J = 13$ Hz), 1.40–1.50 (1H, m), 1.52–1.54 (1H, m), 1.62 (1H, d, $J = 7$ Hz), 1.64–1.70 (2H, m), 1.84 (1H, d, $J = 10.5$ Hz), 2.29–2.36 (1H, m), 2.44 (3H, s), 2.63–2.65 (1H, m), 3.43 (3H, s), 6.17 (1H, s), 7.15 (1H, d, $J = 7$ Hz), 7.23 (2H, t, $J = 7.5$ Hz), 7.32 (2H, d, $J = 7.5$ Hz), 7.41 (2H, d, $J = 7.5$ Hz), 8.06 ppm (2H, d, $J = 8$ Hz); ^{13}C NMR (125 MHz, $CDCl_3$): $\delta = 21.7$, 25.6, 28.7, 30.1, 31.5, 31.6, 32.0, 38.1, 54.2, 71.5, 115.5, 126.7, 127.0, 128.3, 129.4, 129.8, 130.2, 134.8, 144.3, 144.6, 164.4 ppm; HRMS: *m*/*z* calcd for $C_{25}H_{28}O_3$ + Na: 399.1936; found: 399.1938.

1-Methoxy-11-phenylbicyclo[6.3.0]undec-10-enyl 4-methylbenzoate (***6e***): ^{1}H NMR (500 MHz, $CDCl_3$): $\delta = 0.93$ (1H, t, $J = 13.5$ Hz), 1.10 (1H, d, $J = 9$ Hz), 1.36–1.44 (2H, m), 1.61–1.68 (5H, m), 1.78 (1H, d, $J = 14.5$ Hz), 1.87–1.90 (2H, m), 2.35 (3H, s), 2.68 (1H, d, $J = 8.5$ Hz), 3.47 (3H, s), 4.16 (1H, s), 5.96 (1H, s), 7.14 (2H, d, $J = 8$ Hz), 7.21–7.28 (5H, m), 7.77 ppm (2H, d, $J = 7$ Hz); ^{13}C NMR (125 MHz, $CDCl_3$): $\delta = 21.6$, 23.9, 25.4, 26.4, 28.0, 30.6, 32.4, 50.0, 52.8, 57.4, 87.3, 120.7, 126.8, 126.9, 128.1, 129.0, 129.9, 138.6, 143.9, 147.0, 164.3 ppm; LCMS: *m*/*z* calcd for $C_{26}H_{30}O_3$ + Na: 413.2; found: 413.3.

1-(1-Methoxybicyclo[6.1.0]non-9-yl)-2-phenylvinyl 4-methylbenzoate (***8e***): ^{1}H NMR (500 MHz, $CDCl_3$): $\delta = 0.93$–0.95 (1H, m), 1.07 (1H, td, $J = 3.5$, 15.5 Hz), 1.23 (1H, d, $J = 6.5$ Hz), 1.33–1.37 (1H, m), 1.37–1.43 (1H, m), 1.43–1.45 (1H, m), 1.45–1.47 (1H, m), 1.47–1.50 (1H, m), 1.57–1.63 (1H, m), 1.63–1.64 (1H, m), 1.64–1.70 (2H, m), 2.17 (1H, dd, $J = 3.5$, 14.5 Hz), 2.44 (3H, s), 2.50 (1H, d, $J = 15.5$ Hz), 3.42 (3H, s), 6.13 (1H, s), 7.10 (1H, t, $J = 7.5$ Hz), 7.19 (2H, t, $J = 7.5$ Hz), 7.29 (2H, d, $J = 8$ Hz), 7.38 (2H, d, $J = 7.5$ Hz), 8.03 ppm (2H, d, $J = 8$ Hz); ^{13}C NMR (125 MHz, $CDCl_3$): $\delta = 21.7$, 25.1, 26.17, 26.22, 27.2, 28.4, 29.0, 31.8, 33.1, 53.9, 69.1, 114.9, 126.6, 127.1, 128.26, 128.31, 129.4, 130.2, 134.8, 144.3, 146.8, 164.4 ppm; HRMS: *m*/*z* calcd for $C_{26}H_{30}O_3$ + Na: 413.2093; found: 413.2087.

1-(1-Methoxybicyclo[6.1.0]non-9-yl)-2-phenylvinyl 4-methylbenzoate (***9e***): ^{1}H NMR (500 MHz, $CDCl_3$): $\delta = 0.87$–0.90 (2H, m), 1.32–1.45 (4H, m), 1.55–1.65 (5H, m), 1.98 (1H, d, $J = 10.5$ Hz), 2.31–2.38 (2H, m), 2.45 (3H, s), 3.20 (3H, s), 6.05 (1H, s), 7.16 (1H, d, $J = 7$ Hz), 7.21–7.30 (2H, m), 7.31 (2H, d, $J = 8$ Hz), 7.40 (2H, d, $J = 7.5$ Hz), 8.01 ppm (2H, d, $J = 8$ Hz); ^{13}C NMR (125 MHz, $CDCl_3$): $\delta = 21.7$, 24.0, 24.5, 25.2, 26.1, 28.6, 29.0, 29.7, 31.4, 31.9, 53.5, 66.7, 119.8, 120.5, 126.9, 127.2, 128.4, 128.5, 129.5, 130.1, 144.5, 145.6, 164.4 ppm; LCMS: *m*/*z* calcd for $C_{26}H_{30}O_3$ + Na: 413.2; found: 413.3.

1-Methoxy-9-phenylbicyclo[4.3.0]nona-3,7-diene-8-yl 4-methylbenzoate (***6f***): ^{1}H NMR (500 MHz, $CDCl_3$): $\delta = 1.80$ (2H, s), 1.94–1.99 (1H, m), 2.35 (3H, s), 2.44–2.47 (1H, m), 3.05–3.08 (1H, m), 3.41 (3H, s), 4.50 (1H, s), 5.53–5.56 (1H, m), 5.82–5.86 (2H, m), 7.14 (2H, d, $J = 8$ Hz), 7.19–7.27 (5H, m), 7.74 ppm (2H, d, $J = 8$ Hz); ^{13}C NMR (125 MHz, $CDCl_3$): $\delta = 21.6$, 28.7, 29.7, 30.9, 46.1, 50.2, 58.5, 88.4, 118.3, 126.7, 127.4, 127.5, 128.0, 128.3, 129.1, 129.9, 130.0, 138.1, 144.1, 144.2, 146.6, 148.1, 164.1 ppm; LCMS: *m*/*z* calcd for $C_{24}H_{24}O_3$ + Na: 383.2; found: 383.2.

1-(1-Methoxybicyclo[4.1.0]hept-3-en-7-yl)-2-phenylvinyl 4-methylbenzoate (***9f***): ^{1}H NMR (500 MHz, $CDCl_3$): $\delta = 1.67$ (1H, t, $J = 5.5$ Hz), 1.89 (1H, d, $J = 6.5$ Hz), 2.40 (1H, d, $J = 4$ Hz), 2.44 (3H, s), 2.51–2.54 (1H, m), 2.55 (1H, d, $J = 17.5$ Hz), 2.76–2.80 (1H, m), 3.46 (3H, s), 5.51 (1H, d,

J=9.5 Hz), 5.52 (1H, d, J=3 Hz), 6.17 (1H, s), 7.11 (1H, t, J=7.5 Hz), 7.20 (2H, t, J=7.5 Hz), 7.29 (2H, d, J=8 Hz), 7.39 (2H, d, J=7.5 Hz), 8.03 ppm (2H, d, J=8 Hz); ^{13}C NMR (125 MHz, $CDCl_3$): δ=21.7, 24.2, 25.0, 27.4, 29.5, 54.4, 65.7, 116.1, 123.2, 123.7, 126.7, 127.1, 128.3, 129.3, 130.2, 134.8, 144.3, 146.6, 164.3 ppm; HRMS: m/z calcd for $C_{24}H_{24}O_3$+Na: 383.1623; found: 383.1611.

*1-(2-Oxabicyclo[4.1.0]hept-7-yl)-2-phenylvinyl 4-methylbenzoate (**8g**)*: ^{1}H NMR (300 MHz, $CDCl_3$): δ=1.45–1.51 (3H, m), 1.91 (2H, dd, J=2.1, 6.9 Hz), 2.04–2.10 (1H, m), 2.44 (3H, s), 3.27–3.35 (1H, m), 3.60 (1H, d, J=10.8 Hz), 3.77 (1H, dd, J=2.1, 7.5 Hz), 5.99 (1H, s), 7.10–7.21 (3H, m), 7.25–7.35 (4H, m), 8.00 ppm (2H, d, J=8.4 Hz); ^{13}C NMR (75 MHz, $CDCl_3$): δ=18.7, 19.1, 22.1, 28.2, 58.3, 64.4, 114.9, 126.7, 126.9, 128.2, 128.4, 129.3, 130.2, 134.3, 144.4, 148.1, 164.1 ppm; LCMS: m/z calcd for $C_{22}H_{22}O_3$+Na: 357.2; found: 357.2.

*1-(2-Oxabicyclo[4.1.0]hept-7-yl)-2-phenylvinyl 4-methylbenzoate (**9g**)*: ^{1}H NMR (500 MHz, $CDCl_3$): δ=1.47–1.50 (1H, m), 1.71–1.79 (1H, m), 1.83–1.87 (2H, m), 2.36 (3H, s), 2.92 (1H, d, J=5 Hz), 3.50–3.53 (1H, m), 3.86–3.89 (1H, m), 4.01 (1H, t, J=4 Hz), 4.11 (1H, s), 5.91 (1H, s), 7.17 (2H, d, J=8 Hz), 7.19–7.22 (1H, m), 7.22–7.31 (4H, m), 7.82 ppm (2H, d, J=8 Hz); ^{13}C NMR (125 MHz, $CDCl_3$): δ=21.7, 22.2, 25.2, 38.8, 56.5, 65.0, 82.5, 116.3, 126.8, 126.9, 127.9, 128.6, 129.1, 130.0, 138.3, 144.1, 150.4, 164.1 ppm.

*1-(2-Oxabicyclo[3.1.0]hex-6-yl)-2-phenylvinyl 4-methylbenzoate (**8h**)*: ^{1}H NMR (500 MHz, $CDCl_3$): δ=1.86–1.89 (1H, m), 2.02–2.06 (1H, m), 2.36 (3H, s), 3.58–3.61 (1H, m), 3.91–3.94 (2H, m), 4.09 (1H, s), 4.43 (1H, d, J=6 Hz), 5.79 (1H, s), 7.16 (2H, d, J=8 Hz), 7.19–7.26 (4H, m), 7.29–7.32 (2H, m), 7.78 ppm (2H, d, J=8 Hz); ^{13}C NMR (125 MHz, $CDCl_3$): δ=21.7, 31.5, 45.8, 58.3, 67.1, 87.6, 115.5, 126.7, 126.8, 127.5, 128.7, 129.1, 129.9, 140.4, 144.2, 150.2, 164.0 ppm; LCMS: m/z calcd for $C_{21}H_{20}O_3$+Na: 343.1; found: 343.2.

*1-(2-Oxabicyclo[3.1.0]hex-6-yl)-2-phenylvinyl 4-methylbenzoate (**9h**)*: ^{1}H NMR (500 MHz, $CDCl_3$): δ=1.94–1.97 (1H, m), 2.02–2.42 (3H, m), 3.52 (1H, q, J=9, 17.5 Hz), 4.04 (1H, td, J=2.5, 9 Hz), 4.14 (1H, d, J=5.5 Hz), 5.95 (1H, s), 7.11 (1H, d, J=7.5 Hz), 7.18 (2H, t, J=8 Hz), 7.27 (2H, d, J=8 Hz), 7.34 (2H, d, J=8 Hz), 8.01 ppm (2H, d, J=8 Hz); ^{13}C NMR (125 MHz, $CDCl_3$): δ=21.7, 23.1, 25.8, 28.0, 65.0, 67.2, 115.4, 126.7, 127.0, 128.2, 128.4, 129.4, 130.2, 134.1, 144.5, 146.8, 164.1 ppm; HRMS: m/z calcd for $C_{21}H_{20}O_3$+Na: 343.1310; found: 343.1297.

*1-(2-Oxabicyclo[3.1.0]hex-6-yl)-2-phenylvinyl 4-methylbenzoate (**10h**)*: ^{1}H NMR (500 MHz, $CDCl_3$): δ=1.61–1.71 (1H, m), 2.19–2.26 (1H, m), 2.47 (3H, s, overlap with diastereomer **9h**), 2.63–2.70 (1H, m), 3.69–3.75 (1H, m), 3.88–4.00 (2H, m), 6.12 (1H, s), 7.12–7.39 (7H, m, overlap with diastereomer **9h**), 8.01–8.02 (2H, m, overlap with diastereomer **9h**).

General procedure for ester hydrolysis: The ester (0.06 mmol) dissolved in MeOH (3 mL) was added to a round-bottomed flask equipped with a stirring bar under an atmosphere of nitrogen. K_2CO_3 (0.15 mmol) was then added. The reaction mixture was stirred overnight at RT. TLC was performed to confirm that the ester had disappeared. The reaction was concentrated, and then diluted with EtOAc and quenched with saturated aqueous NH_4Cl. The aqueous layer was extracted three times with EtOAc. The combined organic layers were washed with brine and dried with $MgSO_4$. The solvent was removed under reduced pressure and purified by column chromatography (2–5–10% EtOAc/hexanes).

*2-Phenylbicyclo[5.3.0]dec-1-en-3-one (**14**)*: ^{1}H NMR (500 MHz, $CDCl_3$): δ=1.39–1.75 (5H, m), 1.83–1.92 (2H, m), 2.17 (1H, dd, J=2.5, 18.5 Hz), 2.72–2.78 (2H, m), 2.84 (1H, dd, J=6.5, 18.5 Hz), 3.01 (1H, s), 7.25–7.32 (3H, m), 7.39 ppm (2H, t, J=7.5 Hz); ^{13}C NMR (125 MHz, $CDCl_3$): δ= 26.1, 28.9, 30.5, 31.9, 34.8, 42.9, 43.9, 127.5, 128.2, 129.1, 132.3, 139.6, 180.5, 206.7 ppm; LCMS: m/z calcd for $C_{16}H_{18}O$+Na: 249.1; found: 249.1.

*2-Phenylbicyclo[6.3.0]undec-1-en-3-one (**15**)*: ^{1}H NMR (500 MHz, $CDCl_3$): δ=1.32–1.41 (2H, m), 1.26–1.73 (7H, m), 2.20–2.29 (1H, m), 2.34 (1H, d, J=2.5 Hz), 2.41–2.46 (1H, m), 2.69 (1H, dd, J=6.5, 18.5 Hz), 2.88–2.94 (1H, m), 3.06 (1H, s), 7.23–7.30 (2H, m), 7.31 (1H, t, J=6 Hz), 7.39 ppm (2H, t, J=8 Hz); ^{13}C NMR (125 MHz, $CDCl_3$): δ= 24.1, 26.0, 26.2, 28.8, 29.2, 29.7, 40.9, 41.9, 107.6, 127.6, 128.4, 128.6, 128.9, 132.6, 141.2, 181.1, 207.0 ppm; HRMS: m/z calcd for $C_{17}H_{20}O$+Na: 263.1412; found: 263.1398.

*2-Phenylbicyclo[4.3.0]nona-1,7-diene-3-one (**16**)*: ^{1}H NMR (500 MHz, $CDCl_3$): δ=1.59–1.63 (1H, m), 2.18–2.24 (2H, m), 2.47 (2H, d, J=2 Hz), 2.81 (1H, dd, J=7, 18.5 Hz), 2.92–2.97 (1H, m), 6.37–6.40 (1H, m), 6.78 (1H, d, J=10 Hz), 7.23 (1H, t, J=7 Hz), 7.36–7.42 ppm (4H, m); ^{13}C NMR (125 MHz, $CDCl_3$): δ=27.1, 28.9, 29.7, 36.8, 42.1, 50.5, 123.1, 127.7, 128.3, 128.7, 129.2, 129.5, 131.4, 134.8, 140.9, 166.4, 206.2 ppm; LCMS: m/z calcd for $C_{15}H_{14}O$+Na: 233.1; found: 233.1.

Hydrogenation of ketone 16: Pd/C (5 mg) and ketone **16** (0.03 mmol) dissolved in freshly distilled benzene was added to a round-bottomed flask equipped with a stirring bar under an atmosphere of hydrogen, and the resulting mixture was stirred for 45 min. The reaction mixture was diluted with Et_2O and filtered through Celite. The solvent was removed under reduced pressure and the product was purified by column chromatography (5–10% EtOAc/hexanes) to give **12** in 83% yield as a colorless oil.

*1-(2-Methoxytetrahydropyran-3-yl)-3-phenylpropan-2-one (**18**)*: ^{1}H NMR (500 MHz, $CDCl_3$): δ=1.17–1.19 (1H, m), 1.49–1.52 (2H, m), 1.87–1.89 (1H, m), 2.08–2.09 (1H, m), 2.35 (1H, dd, J=7.5, 17 Hz), 2.67 (1H, dd, J=6.5, 16.5 Hz), 3.37 (3H, s), 3.38–3.45 (1H, m), 3.70 (2H, s), 3.91–3.93 (1H, m), 4.07 (1H, d, J=6.5 Hz), 7.19 (2H, d, J=7.5 Hz), 7.26–7.28 (1H, m), 7.33 ppm (2H, d, J=7 Hz); ^{13}C NMR (125 MHz, $CDCl_3$): δ=23.8, 26.6, 36.0, 43.6, 50.2, 55.7, 64.0, 104.4, 127.0, 128.66, 128.69, 129.4, 129.5, 134.2, 206.9 ppm; LCMS: m/z calcd for $C_{15}H_{20}O_3$+Na: 271.1; found: 271.1.

*1-(2-Methoxytetrahydrofuran-3-yl)-3-phenylpropan-2-one (**19**)*: ^{1}H NMR (500 MHz, $CDCl_3$): δ=1.34–1.41 (1H, m), 2.17–2.21 (1H, m), 2.19 (1H, dd, J=6.5, 12.5 Hz), 2.56 (2H, s), 3.29 (3H, s), 3.67 (2H, s), 3.85 (2H, t, J=7.5 Hz), 4.60 (1H, s), 7.18 (2H, d, J=7 Hz), 7.24 (1H, t, J=7.5 Hz), 7.31 ppm (2H, d, J=8 Hz); ^{13}C NMR (125 MHz, $CDCl_3$): δ=29.8, 40.4, 44.5, 50.3, 54.7, 66.3, 108.8, 127.1, 128.8, 129.4, 133.9, 206.6 ppm; HRMS: m/z calcd for $C_{14}H_{18}O_3$+Na: 257.1153; found: 257.1149.

2-Benzylhexa hydro[2,3-*b*]furofuran (20): Ketone **19** (95 mg, 0.41 mmol) in freshly distilled THF (2 mL) was added to a round-bottomed flask equipped with a stirring bar under an atmosphere of nitrogen, and the resulting mixture was cooled to 0°C. Lithium tri-*tert*-butoxyaluminum hydride (0.81 mmol) was added dropwise, and the mixture was stirred for 5 h at RT. After TLC indicated that ketone **19** had disappeared, the reaction was cooled to 0°C and 4 N HCl (0.5 mL) was carefully added dropwise. The resulting mixture was stirred for 3.5 h at RT. Once the reaction was complete by TLC, the mixture was diluted with Et_2O (5 mL) and the layers were separated. The aqueous layer was extracted with Et_2O (3× 5 mL). The combined organic phases were washed with saturated aqueous $NaHCO_3$ and brine, dried over $MgSO_4$, filtered, and concentrated under reduced pressure. The residue was purified by column chromatography (10–20% EtOAc/hexanes) to give **20** (60 mg, 72%) as a colorless oil. ^{1}H NMR (500 MHz, $CDCl_3$): δ=1.27–1.29 (1H, m), 1.64 (1H, dd, J= 5, 12.5 Hz), 1.88–1.91 (1H, m), 2.10–2.12 (1H, m), 2.80 (2H, dd, J=7, 13.5 Hz), 3.03 (1H, dd, J=6, 13.5 Hz), 3.79–3.83 (1H, m), 3.92 (1H, t, J= 8 Hz), 4.01–4.04 (1H, m), 5.63 (1H, d, J=5.5 Hz), 7.20–7.29 ppm (5H, m); ^{13}C NMR (125 MHz, $CDCl_3$): δ=32.5, 36.4, 41.6, 42.9, 65.9, 79.7, 109.1, 126.3, 128.3, 129.3, 138.2 ppm; LCMS: m/z calcd for $C_{13}H_{16}O_2$+ Na: 227.1; found: 227.1.

General procedure for gold-catalyzed vinylcyclopropane/cyclopentene rearrangement reactions: Gold catalyst **Ic** (0.003 mmol) in freshly distilled CH_2Cl_2 (0.5 mL) was added to a Schlenk tube equipped with a stirring bar under an atmosphere of nitrogen. The vinylcyclopropane (0.06 mmol) was dissolved in freshly distilled CH_2Cl_2 (0.5 mL), added to the reaction mixture, and the resulting mixture was stirred at 80°C and monitored by TLC and/or ^{1}H NMR spectroscopy until completion. The reaction mixture was diluted with Et_2O, filtered through Celite, the solvent removed under reduced pressure, and residue purified by column chromatography (1–2% EtOAc/hexane).

*1-Methoxy-11-phenylbicyclo[6.3.0]undec-10-enyl 4-methylbenzoate (**7e**)*: ^{1}H NMR (500 MHz, $CDCl_3$): δ=1.48–1.65 (6H, m), 1.70–1.80 (2H, m), 1.84–1.88 (2H, m), 1.94–1.97 (1H, m), 2.34 (3H, s), 2.41 (1H, dd, J=7, 15.5 Hz), 2.47 (3H, s), 3.22 (1H, d, J=11 Hz), 4.14 (1H, s), 5.59 (1H, s),

7.11 (2H, d, $J=8$ Hz), 7.20 (1H, d, $J=7$ Hz), 7.21–7.26 (2H, m), 7.31 (2H, d, $J=7$ Hz), 7.68 ppm (2H, $J=8.5$ Hz).

*1-(2-Methoxycyclopentylidenemethyl)-2-phenylvinyl 4-methylbenzoate (**21**)*: ^{1}H NMR (500 MHz, $CDCl_3$): $\delta=1.56$–1.66 (3H, m), 1.77–1.80 (2H, m), 2.34–2.38 (1H, m), 2.46 (3H, s), 3.36 (3H, s), 4.04 (1H, s), 6.27 (1H, s), 6.30 (1H, s), 7.14 (1H, t, $J=7$ Hz), 7.20 (2H, t, $J=7.5$ Hz), 7.31 (2H, d, $J=8$ Hz), 7.42 (2H, d, $J=7.5$ Hz), 8.07 ppm (2H, d, $J=8$ Hz); ^{13}C NMR (125 MHz, $CDCl_3$): $\delta=21.8$, 22.6, 28.5, 29.7, 31.2, 56.1, 85.7, 120.7, 120.9, 126.8, 127.4, 128.5, 128.6, 128.7, 129.5, 129.8, 130.3, 143.5, 144.5, 145.2, 146.1, 163.9 ppm; LCMS: m/z calcd for $C_{23}H_{24}O_3+$Na: 371.1; found: 371.2.

*4-Phenylbicyclo[3.3.0]dec-1-en-3-one (**22**)*: ^{1}H NMR (500 MHz, $CDCl_3$): $\delta=1.26$–1.36 (1H, m), 2.00–2.06 (1H, m), 2.10–2.13 (1H, m), 2.26–2.28 (1H, m), 2.63–2.70 (2H, m), 3.00–3.05 (1H, m), 3.26 (1H, d, $J=3.5$ Hz), 5.99 (1H, s), 7.18 (2H, d, $J=7$ Hz), 7.25–7.27 (1H, m), 7.32 ppm (2H, t, $J=7$ Hz); ^{13}C NMR (125 MHz, $CDCl_3$): $\delta=25.6$, 26.4, 29.7, 30.9, 123.8, 126.9, 128.3, 128.7, 138.9, 189.2, 210.2 ppm; LCMS: m/z calcd for $C_{14}H_{14}O+$Na: 221.1; found: 221.1.

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