Article

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Construction of Nitrogen-Containing 9-Membered Ring Epoxy Vinyl Ethers via Gold(I)-Catalyzed Intramolecular Cyclization Reactions of Acyclic 5-Aza-2,3-epoxy-7-yn-1-ols

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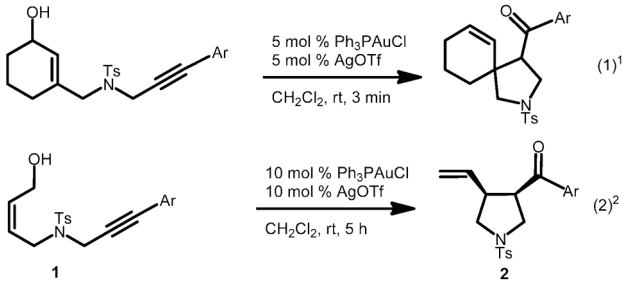
A series of substituted nitrogen-containing 9-membered epoxy vinyl ethers has been constructed from easily available 5-aza-2,3-epoxy-7-yn-1-ols. Attack of the hydroxyl group onto the gold(I)-activated alkyne gave the postulated 9-membered allylic vinyl ether gold intermediate which underwent protodeauration affording the 9-membered epoxy vinyl ethers.

Keywords: Alcohol; Alkyne; Claisen rearrangement; Epoxy; Gold; Vinyl ether.

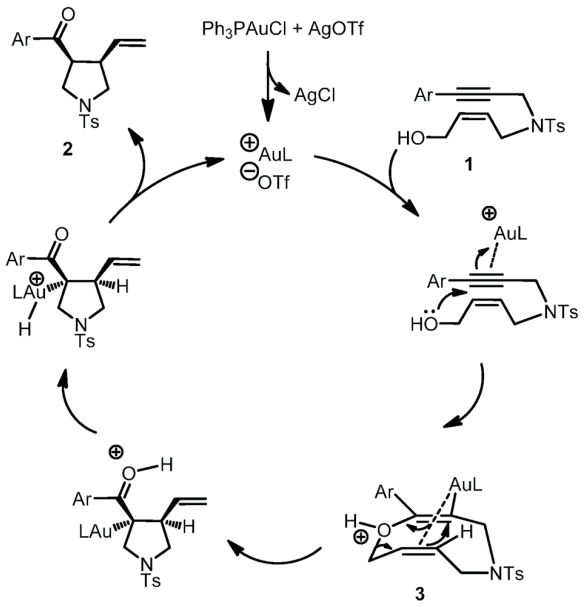
INTRODUCTION

As part of our investigation into intramolecular cyclization reactions of 2-en-7-yn-1-ols with various Lewis- and Brønted acid, we reported a gold-catalyzed Claisen-type rearrangement of cyclic 8-aryl-5-aza-2-en-7-yn-1-ols, leading to azaspirocyclic ketones (Scheme I, eq 1).[1] When acyclic analogues, (*Z*)-8-aryl-5-azaoct-2-en-7-yn-1-ol **1**, was treated with a catalytic amount of the gold cationic species, affording *cis*-3-aroyl-4-vinylpyrrolidine **2** (Scheme I, eq 2).[2] We have proposed an initial step involving an unusual 9-*endo*-*dig* attack of the hydroxyl group onto the gold-activated alkyne (Scheme II). The resulting 9-membered allylic vinyl ether gold intermediate **3** underwent a gold-assisted [3,3]-sigmatropic rearrangement to deliver the 3,4-disubstituted pyrrolidine derivative **2**. Although several vinylgold(I) intermediates have been reported and fully characterized in the literature,[3-9] we are unable to obtain the key 9-membered allylic vinyl ether gold intermediate **3**. This failure may be attributed to the facile [3.3]-sigmatropic rearrangement of the postulated reactive intermediate **3** which led to pyrrolidines. In order to confirm the key 9-*endo*-*dig* addition,[10] we envisaged that the corresponding 5-aza-2,3-epoxy-7-yn-1-ol **4** (Scheme III), generated from epoxidation of the known (*Z*)-5-aza-2-en-7-yn-1-ols **1**[2] with 1.2 molar equiv of *m*-chloroperbenzoic acid (*m*CPBA), may be a good model to offer an evidence in support of the 9-*endo*-*dig* addition hypothesis. Herein,

Scheme I Gold-catalyzed Claisen-type rearrangements of nitrogen-containing 2-en-7-yn-1-ols



Scheme II A Postulated reaction path for the formation of *cis*-3-aroyl-4-vinylpyrrolidine (**3**) from (*Z*)-8-aryl-5-azaoct-2-en-7-yn-1-ol (**1**)



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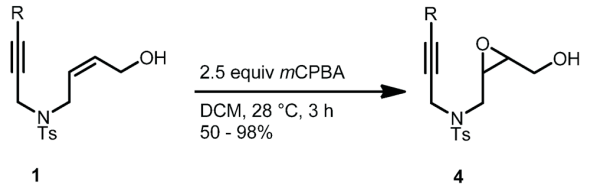
Scheme III Synthesis of 5-aza-2,3-epoxy-7-yn-1-ols **4** from (*Z*)-5-azaoct-2-en-7-yn-1-ols **3**



1 **4**

we describe a gold(I)-catalyzed intramolecular cyclization reactions of 5-aza-2,3-epoxy-7-yn-1-ols leading to 9-membered epoxy vinyl ethers. In this transformation, attack of the alcohol functionality onto the gold(I)-catalyzed alkyne produced a 9-membered vinyl ether gold intermediate which underwent protodeauration furnishing the 9-membered epoxy vinyl ether.

RESULTS AND DISCUSSION

To check the catalytic behavior of gold complexes in the intramolecular addition reaction, we first carried out the model reaction between **4a** and $AuCl_3$ (0.10 molar equiv) in dichloromethane (DCM) at ambient temperature. However, only starting substrate **4a** was recovered quantitatively after prolonged stirring for 24 h. Switching the catalyst to $NaAuCl_4{\cdot}2H_2O$ resulted in decomposition of **4a**. The use of the two-component catalytic system [Ph_3PAuCl/$AgSbF_6$] in DCM at ambient temperature for 24 h gave a trace amount of cyclized product, identified as the 9-membered ring epoxy vinyl ether **5a** (Figure 1). Changing the co-catalyst system to 0.1 molar equiv of [Ph_3PAuCl/AgOTf] in DCM, **4a** produced **5a** in 25% isolated yield after the reaction was stirred at ambient temperature for 24 h. Refluxing **5a** with [Ph_3PAuCl/AgOTf] (0.1 molar equiv) in DCM for 3 h resulted in decomposition of **5a** and gave a mixture of unidentified compounds. The investigation of various solvents in the presence of the [Ph_3PAuCl/AgOTf]] catalyst system revealed that THF, toluene and CH_3CN were ineffective. Thus, [Ph_3PAuCl/AgOTf] (0.1 molar equiv) in DCM at ambient temperature, albeit in low isolated yield, was used as the standard reaction conditions.

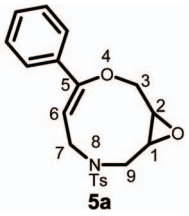
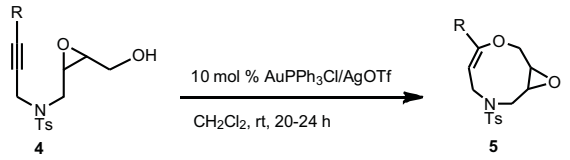


Fig. 1. Structure of **5a**.

The labile 9-membered-ring vinyl ether ring may attribute to the low isolation yield of **5a**. NMR studies provided the evidence for support of the structural assignments for **5a**. The ^1H NMR spectrum of **5a** showed two doublets centered at δ 7.77 and 7.38, respectively, and a broad multiplet, ranged from δ 7.33–7.26, assigned to seven aromatic protons; a triplet at δ 5.27, assigned to the vinyl proton at C-6 (Figure 1); a doublet of doublets, centered at δ 4.59, assigned to one of the two diastereotopic methylene protons at C-3; a doublet of doublets, centered at δ 4.29, assigned to one of the two diastereotopic methylene protons at C-9; a doublet at δ 4.21, assigned to the two protons at C-7; a multiplet, centered at δ 3.29, assigned to the proton at C-2; a doublet of doublets, centered at δ 3.25, assigned to one of the two diastereotopic methylene protons at C-3; a triplet of doublets, centered at δ 3.08, assigned to one of the two diastereotopic methylene protons at C-1; a doublet of doublets, centered at δ 2.64, assigned to one of the two diastereotopic methylene protons at C-9; and a singlet at δ 2.48, assigned to the methyl protons at the tosyl group. The ^{13}C NMR spectrum exhibited a signal at δ 106.2 assigned to the vinyl carbon at C-6.[11]

With the optimized reaction conditions in hand, we next examined the scope of the reaction using various aryl and alkyl substituted alkynes with [Ph_3PAuCl/AgOTf] in DCM. The results of the gold-catalyzed cycloisomerization reactions of 5-aza-2,3-epoxy-7-octyn-1-ols **4a–k** to produce 9-membered epoxy vinyl ethers **5a–k** are listed in Table 1. In general, cyclization of substrates with various aryl substituents at the terminal position of the acetylene, for example **4a–h**, afforded 9-membered epoxy vinyl ethers **5a–h** in 16–30% yields (Table 1, entries 1-8). It seems that the electronic effect of the substituent on the phenyl ring is rather insensitive to the yield of the reaction. The low isolated yields of **5a–h** may be due to gradual decomposition of the instable aryl vinyl ether functionality during aqueous workup and purfication on silica-gel column chromatography. Substrates **4i–k** bearing an alkyl group (methyl, *n*-butyl or allyl) at the alkyne terminus afforded higher yields of the corresponding 9-membered epoxy vinyl ethers **5i–k** (50–69%, Table 1, entries 9-11) than those analogous bearing an aryl substituent (**4a–k**). Structures of **5c** (CCDC 970660), **5h** (CCDC 970842), and **5k** (CCDC 970662) were confirmed by x-ray diffraction analysis.[11] Figure 2 shows the ORTEP structure of **5c**. The reaction path leading to 9-membered epoxy vinyl ethers **5** from 5-aza-2,3-epoxyoct-7-yn-1-ol **4** was suggested in Scheme IV. Attack

Table 1. Synthesis of 9-membered epoxy vinyl ether **5**



Entry	Substrate	R	Yield (%)[a]
1	**4a**	phenyl	25 (**5a**)
2	**4b**	4-methylphenyl	22 (**5b**)
3	**4c**	naphthalen-1-yl	16 (**5c**)
4	**4d**	4-methoxyphenyl	20 (**5d**)
5	**4e**	4-bromophenyl	34 (**5e**)
6	**4f**	2-bromophenyl	16 (**5f**)
7	**4g**	3-carbethoxyphenyl	18 (**5g**)
8	**4h**	3-nitrophenyl	30 (**5h**)
9	**4i**	methyl	69 (**5i**)
10	**4j**	*n*-butyl	50 (**5j**)
11	**4k**	allyl	55 (**5k**)

[a] Isolated yields after silica-gel column chromatography.

of the hydroxyl group onto the gold-activated alkyne gave the postulated allylic vinyl ether gold intermediate **6**, which underwent proton migration to yield the gold-hydride **7**. The transient intermediate **7** provided the 9-membered epoxy vinyl ether **5** after reductive elimination.

Interestingly, when substrate **8**, bearing a diethylester linkage at the tether, was subjected to a catalytic amount (0.1 molar equiv) of [$Ph_3PAuCl/AgOTf$] in DCM at ambient temperature for 6 h, delivering dioxabicyclo[3.2.1]octane derivative **9** in 68% isolated yield (Scheme V). A plausible reaction path for the formation of compound **9** from **8** is suggested in Scheme VI. Due to a Thorpe-Ingold effect presenting by the germinal diester group,[12-14] the oxirane may be in close proximity of the alkyne moiety and attacked at the gold-activated alkyne in a *6-exo-dig* manner

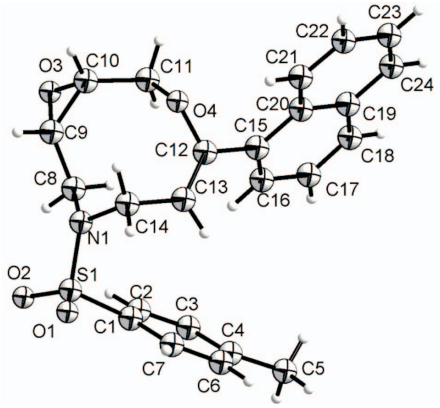
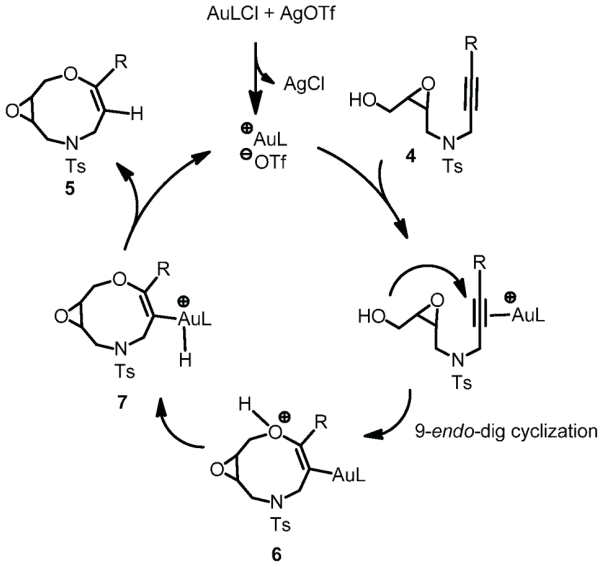
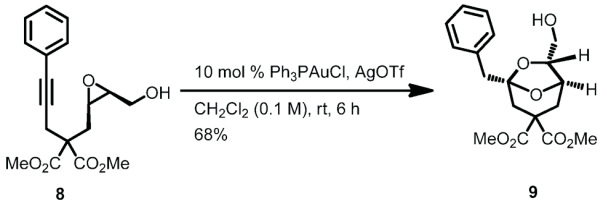


Fig. 2. ORTEP drawing of **5c**.

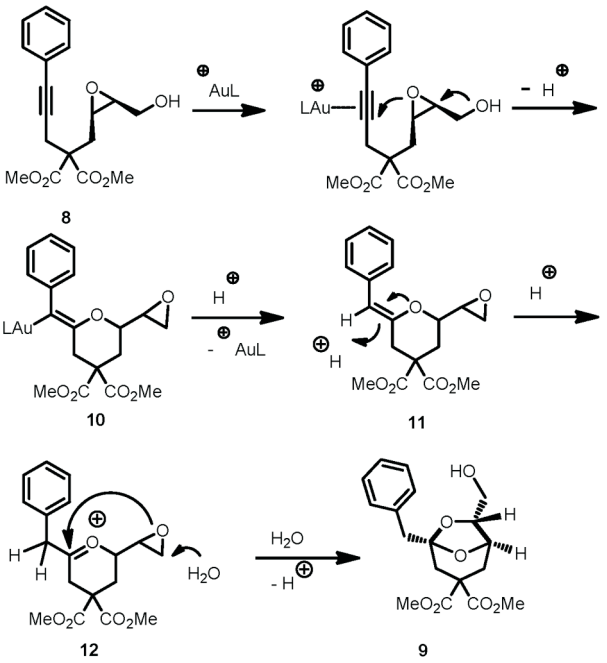
Scheme IV A plausible reaction path for the formation of **5**



Scheme V Synthesis of compound **9**



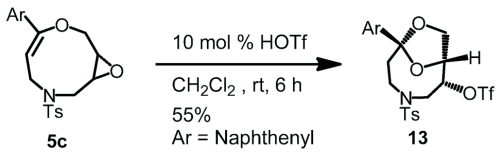
Scheme VI A proposed reaction path for the formation of **9**



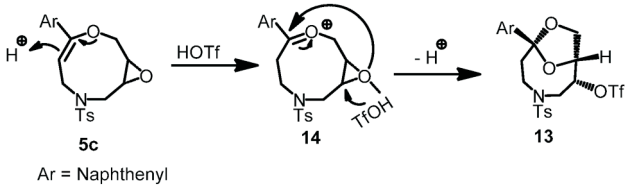
followed by ring opening of the oxirane by the pendant hydroxyl group in a concerted manner to furnish the vinyl ether gold intermediate **10**. Protodeauration of **10** led to the formation of the epoxy vinyl ether **11**. Protonation of the vinyl ether gave **12**. Addition of the oxirane at the cationic carbonyl carbon center followed by a ring opening of the oxirane with H_2O afforded dioxabicyclic compound **9**. It is worth mentioning that three stereogenic centers of compound **9** are created; however, only the single diastereomer depicted was isolated. Rigorous proof of structure of **9** (CCDC 987755) is confirmed by X-ray diffraction analysis.[11]

Due to the fact that vinyl ether derivatives are labile under acid conditions, 9-membered epoxy vinyl ether **5c** was subjected to a solution of 1.1 molar equiv of HOTf in DCM at ambient temperature. The reaction occurred spontaneously and provided the dioxabicyclo[3.2.1]octane derivative **13** as the only isomer isolated in 55% yield (Scheme VII). Scheme VIII suggested a reaction path leading to **13**. Protonation of **5c** furnished intermediate **14**. Attachment of HOTf to the oxirane via hydrogen bonding allows the ring opening by HOTF from the bottom face followed by attack of the hydroxyl group at the cationic carbonyl carbon center to provide **13**.

Scheme VII Formation of **13** from **5c**



Scheme VIII A Suggest path for the formation of **13** from **5c**



In conclusion, a gold-catalyzed synthesis of nitrogen-containing 9-membered epoxy vinyl ethers has been developed. The reaction provides an evidence for a 9-*endo*-*dig* cyclization the hydroxyl group onto the gold(I)-activated alkyne. Further synthetic applications of the 9-membered epoxy vinyl ethers are currently underway in our laboratory.

EXPERIMENTAL

General Considerations: All reactions were performed with oven-dried glassware under nitrogen atmosphere unless otherwise indicated. Anhydrous solvents or solutions were transferred via an oven-dried syringe. Tetrahydrofuran (THF), dichloromethane (DCM), acetonitrile and toluene was dried by passing through a column of Al_2O_3. Flash column chromatography was carried out with silica gel (230–400 mesh). Melting points were determined in open capillaries and are uncorrected. ^{1}H nuclear magnetic resonance (NMR) spectra were obtained with 400 and 500 MHz spectrometers. The chemical shifts are reported in parts per million with either Me_4Si (0.00 ppm) or $CDCl_3$ (7.26 ppm) as internal standard. ^{13}C NMR spectra were recorded with 100 and 125 MHz spectrometers with $CDCl_3$ as the internal standard. Infrared (IR) spectra were recorded as neat solutions. Mass spectra were determined by using a spectrometer at an ionization potential of 70 eV and were reported as mass/charge (*m*/*e*). High-resolution mass spectra were obtained with a double-focusing mass spectrometer.

General Procedure (I): Synthesis of 8-Aryl-5-aza-2,3-epoxyoct-7-yn-1-ols (4a): To a stirring solution of *cis*-2-butene-1,4-diol (4.40 g, 50 mmol) in CH_2Cl_2 (50 mL) at 0 °C were added Et_3N (1.32 g, 13 mmol), TBSCl (1.506 g, 10 mmol) and DMAP (0.124 g, 1 mmol). The reaction mixture was stirred at 30 °C for 3 h followed by quenching with 20 mL of water. The reaction mixture was extracted with CH_2Cl_2 (20 mL × 3). The combined extracts were washed with brine (5 mL × 1), dried over anhydrous $MgSO_4$ (5 g), and concentrated under reduced pressure in ice bath to give (*Z*)-4-((*tert*-butyldimethylsilyl)oxy)but-2-en-1-ol as a crude oil. The crude product was used for the following step without further purification. To a solution of triphenylphosphine (3.93 g, 15 mmol) in 75 mL of THF under nitrogen at 0 °C was added diisopropyl azodicarboxylate (DIAD, 3.00 g, 15 mmol). The reaction was allowed to stir at 0 °C for 30 min followed by addition of *N*-tosylpropargylamine (2.09 g, 10 mmol). The mixture was allowed to stir at 0 °C for 30 min and to it was added (*Z*)-4-((*tert*-butyldimethylsilyl)oxy)but-2-en-1-ol (2.03 g, 10 mmol). The reaction was stirred at 0 °C for 30 min and at ambient temperature for 2 h before being concentrated under reduced pressure to give a crude oil. The oil was purified by flash column chromatography (silica gel, ethyl acetate/hexanes 1:40) to produce (*Z*)-*N*-(4-((*tert*-butyldimethylsilyl)oxy)but-2-en-1-yl)-4-methyl-*N*-(prop-2-yn-1-yl)benzenesulfonamide (3.06 g, 7.77 mmol, 78%). In a 100-mL round-bottom flask equipped with a stirring bar were added $Pd(PPh_3)_4$ (0.39 g, 0.3 mmol), CuI (0.11 g, 0.6 mmol) and PhI (3.67 g, 18 mmol). The system was purged with N_2 and added Et_3N (30 mL). The reaction was allowed to stir at ambient temper-

ature for 20 min followed by addition of (*Z*)-*N*-(4-((*tert*-butyldimethylsilyl)oxy)but-2-en-1-yl)-4-methyl-*N*-(prop-2-yn-1-yl)-benzenesulfonamide (5.90 g, 15.0 mmol). The reaction was left at ambient temperature for 6 h. The reaction mixture was quenched with saturated $NH_4Cl_{(aq)}$. The mixture was extracted with CH_2Cl_2 (30 mL × 3). The CH_2Cl_2 solution was washed with brine, dried over $MgSO_4$, and concentrated under reduced pressure. The resulting oil was purified by flash column chromatography on silica gel, eluting with ethyl acetate/hexanes 1:20, to obtain (*Z*)-*N*-(4-((*tert*-butyldimethylsilyl)oxy)but-2-en-1-yl)-4-methyl-*N*-(3-phen-ylprop-2-yn-1-yl)benzenesulfonamide (6.09 g, 12.97 mmol, 86%). To a solution of the crude (*Z*)-*N*-(4-((*tert*-butyldimethylsilyl)oxy)but-2-en-1-yl)-4-methyl-*N*-(3-phen-ylprop-2-yn-1-yl) benzenesulfonamide (6.00 g, 12.8 mmol) in THF (60 mL) was added TBAF (4.01 g, 15.33 mol). The reaction was allowed to stir at ambient temperature for 12 h. The mixture was concentrated under reduced pressure and the residue was purified by flash column chromatography on silica gel, eluting with ethyl acetate/hexanes 1:2, to obtain (*Z*)-(3-(*N*-tosyl(3-phenylprop-2-yn-1-yl)amino)methyl)prop-2-en-1-ol (2.14 g, 6.04 mmol, 47%). To a stirring solution of (*Z*)-(3-(*N*-tosyl(3-phenylprop-2-yn-1-yl)amino)methyl)prop-2-en-1-ol (2.21 g, 4.71 mmol) in CH_2Cl_2 (50 mL) at 0 °C was added *m*-chloroperbenzoic acid (*m*CPBA, 1.22 g, 7.07 mmol). The reaction mixture was stirred at 0 °C for 2 h. The reaction was then quenched with 20 mL of saturated $K_2CO_{3(aq)}$. The reaction mixture was extracted with CH_2Cl_2 (20 mL × 3). The combined extracts were washed with brine (5 mL × 1), dried over anhydrous $MgSO_4$ (5 g), and concentrated to give a crude oil. The oil was purified by flash column chromatography (silica gel, ethyl acetate/hexanes 1:4) to produce **4a** (0.86 g, 1.766 mmol, 37%).

((3-*N*-Tosyl-*N*-(3-phenylprop-2-yn-1-yl)amino)methyl)-oxiran-2-yl)methanol (4a): A yellow oil: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.77 (d, *J* = 8.2 Hz, 2H), 7.29-7.21 (m, 5H), 7.08 (d, *J* = 7.4 Hz, 2H), 4.50 (d, *J* = 18.5 Hz, 1H), 4.40 (d, *J* = 18.5 Hz, 1H), 3.79 (s, 2H), 3.58 (dd, *J* = 14.8, 5.6 Hz, 1H), 3.45 (d, *J* = 14.6, 5.7 Hz, 1H), 3.29 (dt, *J* = 9.8, 5.2 Hz, 1H), 3.21 (dt, *J* = 9.6, 5.0 Hz, 1H), 2.63 (m, 1H), 2.32 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.9, 135.3, 131.4, 129.6, 128.5, 128.0, 127.6, 121.7, 85.9, 81.4, 59.8, 55.9, 54.9, 44.8, 38.7, 21.3; IR (CH_2Cl_2) 3520, 2923, 1594, 1347, 1159 cm^{-1}; MS (ESI) *m/e* 372.1 ([M + Na]$^+$), 354.1, 340.1, 312.1; HRMS (EI) calcd for $C_{22}H_{22}NO_4S$ [M + H]$^+$ 372.1270, found 372.1274.

Procedure (II): Synthesis of *N*-(Hex-5-en-2-yn-1-yl)-*N*-((3-(hydroxyme-thyl)oxiran-2-yl)methyl)-4-methyl-benzene-sulfonamide (4k): To a mixture of allyl bromide (0.54 g, 4.5 mmol), ((3-(*N*-tosyl-*N*-(prop-2-yn-1-yl)amino)methyl)oxiran-2-yl)methanol (0.92 g, 3.0 mmol), Na_2SO_3 (0.16 g, 1.5 mmol), CuI (3.7 mg, 0.03 mmol), K_2CO_3 (0.41 g, 3.0 mmol), and 2 drops of DBU in DMSO (3 mL) was stirred for 10 h. The mixture was extraced with 0.1 M $HCl_{(aq)}$ (10 mL) and diethyl ether (3 × 10 mL). The combined extracts were dried over anhydrous $MgSO_4$ (5 g), and concentrated to give a crude oil. The oil was purified by flash column chromatography (silica gel, ethyl acetate/hexanes 1:10) to produce **4k** (0.210 g, 0.62 mmol, 20%) as a yellow oil: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.73 (d, *J* = 8.0 Hz, 2H), 7.27 (d, *J* = 8.0 Hz, 2H), 5.63-5.53 (m, 1H), 5.07-4.98 (m, 2H), 4.26 (d, *J* = 18.2 Hz, 1H), 4.20 (d, *J* = 18.2 Hz, 1H), 3.79 (s, 2H), 3.48 (dd, *J* = 14.7, 5.6 Hz, 1H), 3.38 (dd, *J* = 14.7, 5.6 Hz, 1H), 3.43 (dd, *J* = 9.8, 5.5 Hz, 1H), 3.20 (dd, *J* = 9.5, 5.3 Hz, 1H), 2.71-2.70 (m, 3H), 2.40 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.7, 135.4, 131.6, 129.5, 127.5, 116.0, 83.1, 74.6, 59.8, 55.9, 54.8, 44.6, 38.2, 22.6, 21.3; IR (CH_2Cl_2) 3429, 2926, 2221, 1803, 1598, 1347, 1162, 1093, 1041 cm^{-1}; MS (ESI) *m/e* 358.1 ([M + Na]$^+$), 347.1, 281.3, 258.6; HRMS (ESI) calcd for $C_{17}H_{21}NO_4NaS$ [M + Na]$^+$ 358.1089, found 358.1080.

General Procedure (III): The Gold(I)-Catalyzed Cyclization of 5-Aza-2,3-epoxyoct-7-yn-1-ols 4: To an oven-dried 25 mL two-neck bottle equipped with a stirrer bar and capped with a rubber septum was added AgOTf (8 mg, 0.03 mmol). The apparatus was evacuated (oil pump) and filled with nitrogen three times. To the reaction mixture were then added PPh_3AuCl (15 mg, 0.03 mmol) and compound **4a** (111 mg, 0.32 mmol) via syringe in 3 mL of CH_2Cl_2. The resulting mixture was stirred at ambient temperature for 24 h. The resulting reaction mixture was filtered through a bed of Celite. The filtrate was concentrated in vacuo to give the crude mixture. The crude mixture obtained was purified by flash column chromatography (silica gel, ethyl acetate/hexanes 1:8) to give **5a** (30 mg, 0.081 mmol, 25%).

(*Z*)-4-Phenyl-7-tosyl-3,10-dioxa-7-azabicyclo[7.1.0]dec-4-ene (5a): A white solid: mp 132-134 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.77 (d, *J* = 6.5 Hz, 2H), 7.38 (d, *J* = 6.4 Hz, 2H), 7.33-7.31 (m, 3H), 7.28-7.26 (m, 2H), 5.27 (t, *J* = 8.4 Hz, 1H), 4.59 (dd, *J* = 11.6, 4.0 Hz, 1H), 4.29 (dd, *J* = 13.6, 2.8 Hz, 1H), 4.21 (d, *J* = 8.8 Hz, 2H), 3.29 (m, 1H), 3.25 (dd, *J* = 11.6, 7.4 Hz, 1H), 3.08 (dt, *J* = 10.8, 3.2 Hz, 1H), 2.64 (dd, *J* = 14.0, 10.8 Hz, 1H), 2.48 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 160.1, 143.7, 137.3, 134.2, 129.9, 129.2, 128.6, 127.1, 125.6, 106.2, 69.7, 53.2, 53.1, 43.2, 41.8, 21.5; IR (CH_2Cl_2) 3505, 2923, 1598, 1340, 1163 cm^{-1}; MS (ESI) *m/e* 394.1 ([M + Na]$^+$), 380.2, 372.1, 317.2; HRMS (ESI) calcd for $C_{20}H_{21}NNaO_4S$ [M + Na]$^+$ 394.1084, found 394.1089.

(*Z*)-4-(*p*-Tolyl)-7-tosyl-3,10-dioxa-7-azabicyclo-[7.1.0]dec-4-ene (5b): To a solution of AgOTf (12 mg, 0.048 mmol) and PPh_3AuCl (24 mg, 48 mmol) in 5.0 mL of CH_2Cl_2 at ambient temperature for 21 h was added 4b (184 mg, 0.48 mmol). The reaction

mixture was stirred for 24 h, and the crude mixture was purified by flash column chromatography (silica gel, ethyl acetate/hexanes 1:8) to give **5b** (37 mg, 0.096 mmol, 20%) as a colorless oil: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.75 (d, *J* = 8.0 Hz, 2H), 7.35 (d, *J* = 8.0 Hz, 2H), 7.16 (d, *J* = 8.0 Hz, 2H), 7.11 (d, *J* = 8.0 Hz, 2H), 5.19 (t, *J* = 8.4 Hz, 1H), 4.56 (dd, *J* = 11.8, 4.2 Hz, 1H), 4.25 (dd, *J* = 13.7, 2.2 Hz, 1H), 4.19 (d, *J* = 8.5 Hz, 2H), 3.29-3.18 (m, 2H), 3.06 (dt, *J* = 10.7, 3.1 Hz, 1H), 2.60 (dd, *J* = 13.4, 11.1 Hz, 1H), 2.47 (s, 3H), 2.34 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 160.2, 143.7, 138.4, 137.4, 131.4, 130.0, 129.3, 127.1, 125.6, 105.4, 69.7, 53.2, 53.1, 43.2, 42.9, 21.5, 21.2; IR (CH_2Cl_2) 3025, 2925, 1645, 1598, 1454, 1351, 1162, 1090, 1052 cm^{-1}; MS (ESI) *m/e* 408.1 ([M + Na]$^+$), 374.3, 274.1, 242.3, 233.1, 172.1, 150.1; HRMS (ESI) calcd for $C_{21}H_{23}NO_4NaS$ [M + Na]$^+$ 408.1245, found 408.1241. **(*Z*)-4-(Naphthalen-1-yl)-7-tosyl-3,10-dioxa-7-azab-icyclo[7.1.0]dec-4-ene (5c):** To a solution of AgOTf (11 mg, 0.043 mmol) and PPh_3AuCl (21 mg, 0.043 mmol) in 4.3 mL of CH_2Cl_2 at ambient temperature was added **4c** (194 mg, 0.43 mmol). The reaction mixture was stirred for 24 h, and the crude mixture was purified by flash column chromatography (silica gel, ethyl acetate/hexanes 1:15) to give 5c (66 mg, 0.147 mmol, 34%) as a white solid: mp 86-87 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.08 (d, *J*= 7.8 Hz, 1H), 7.84 (d, *J* = 8.3 Hz, 2H), 7.78 (d, *J* = 8.4 Hz, 2H), 7.51-7.44 (m, 2H), 7.40-7.35 (m, 3H), 7.27-7.25 (m, 1H), 5.31 (dd, *J* = 9.2, 7.4 Hz, 1H), 4.37 (dd, *J* = 14.1, 2.9 Hz, 1H), 4.29 (dd, *J* = 13.4, 3.4 Hz, 1H), 4.28-4.12 (m, 3H), 3.46 (dd, *J* = 12.8, 7.4 Hz, 1H), 3.27 (dd, *J* = 14.5, 3.4 Hz, 1H), 3.13-3.09 (m, 1H), 2.82 (dd, *J* = 14.1, 10.5 Hz, 1H), 2.47 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 159.9, 143.6, 137.1, 133.6, 132.1, 130.9, 130.0, 128.4, 127.7, 127.1, 126.8, 126.2, 125.2, 125.0, 111.8, 67.8, 54.1, 55.3, 46.1, 42.9, 21.5; IR (CH_2Cl_2) 3058, 2951, 1656, 1597, 1449, 1340, 1183, 1092 cm^{-1}; MS (ESI) *m/e* 444.1 ([M + Na]$^+$), 441.1, 374.1, 360.1, 319.1, 301.1; HRMS (ESI) calcd for $C_{24}H_{23}NNaO_4S$ [M + Na]$^+$ 444.1245, found 444.1240. Crystals suitable for X-ray diffraction analysis were grown from CH_2Cl_2 and hexanes. **(*Z*)-4-(4-Methoxyphenyl)-7-tosyl-3,10-dioxa-7-azabicyc-lo[7.1.0]dec-4-ene (5d):** To a solution of AgOTf (41 mg, 0.16 mmol) and PPh_3AuCl (79 mg, 0.16 mmol) in 16.0 mL of CH_2Cl_2 at ambient temperature was added **4d** (682 mg, 1.6 mmol). The reaction mixture was stirred for 24 h, and the crude mixture was purified by flash column chromatography (silica gel, ethyl acetate/hexanes 1:15) to give 5d (108 mg, 0.26 mmol, 34%) as a white solid: mp 104-105 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.76 (d, *J* = 8.3 Hz, 2H), 7.36 (d, *J* = 8.0 Hz, 2H), 7.22 (d, *J* = 2.0 Hz, 2H), 6.83 (d, *J* = 8.8 Hz, 2H), 5.13 (dd, *J* = 9.1, 7.9 Hz, 1H), 4.59 (dd, *J* = 7.4, 4.3 Hz, 1H), 4.27-4.19 (m, 2H), 3.82 (s, 3H), 3.31-3.19 (m, 1H), 3.06 (dt, *J* = 10.8, 3.3 Hz, 1H), 2.62 (dd, *J* = 13.8, 10.7 Hz, 1H), 2.48 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 160.4, 160.0, 143.6, 137.3, 129.9, 127.1, 127.0, 126.7, 114.0, 104.3, 69.6, 55.3, 53.2, 53.1, 43.1, 41.9, 21.5; IR (CH_2Cl_2) 3061, 2926, 1607, 1575, 1513, 1337, 1286, 1158, 1090 cm^{-1}; MS (ESI) *m/e* 424.1 ([M + Na]$^+$), 420.1, 291.6, 282.1, 177.1, 143.1, 121.1, 84.1; HRMS (ESI) calcd for $C_{21}H_{23}NNaO_5S$ [M + Na]$^+$ 424.1195, found 424.1196. **(*Z*)-4-(4-Bromophenyl)-7-tosyl-3,10-dioxa-7-azabicyclo[7.1.0]dec-4-ene (5e):** To a solution of AgOTf (24 mg, 0.048 mmol) and PPh_3AuCl (12 mg, 0.048 mmol) in 4.8 mL of CH_2Cl_2 at ambient temperature was added **4e** (184 mg, 0.48 mmol). The reaction mixture was stirred for 24 h, and the crude mixture was purified by flash column chromatography (silica gel, ethyl acetate/hexanes 1:15) to give **5e** (41 mg, 0.11 mmol, 22%) as a colorless oil: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.75 (d, *J* = 8.0 Hz, 2H), 7.35 (d, *J* = 8.0 Hz, 2H), 7.16 (d, *J* = 8.0 Hz, 2H), 7.11 (d, *J* = 8.0 Hz, 2H), 5.19 (t, *J* = 8.4 Hz, 1H), 4.56 (dd, *J* = 11.8, 4.2 Hz, 1H), 4.25 (dd, *J* = 13.7, 2.2 Hz, 1H), 4.20 (s, 1H), 4.18 (d, *J* = 8.5 Hz, 1H), 3.29-3.18 (m, 2H), 3.06 (dt, *J* = 10.7, 3.1 Hz, 1H), 2.60 (dd, *J* = 13.4, 11.1 Hz, 1H), 2.47 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 160.2, 143.7, 138.4, 137.4, 131.4, 130.0, 129.3, 127.1, 125.6, 105.4, 69.7, 53.2, 53.1, 43.2, 42.9, 21.5; IR (CH_2Cl_2) 3025, 2925, 1645, 1598, 1454, 1351, 1162, 1090, 1052 cm^{-1}; MS (ESI) *m/e* 408.1 ([M + Na]$^+$), 374.3, 274.1, 242.3, 233.1, 172.1, 150.1: HRMS (ESI) calcd for $C_{21}H_{23}NNaO_4S$ [M + Na]$^+$ 408.1245, found 408.1241. **(*Z*)-4-(2-Bromophenyl)-7-tosyl-3,10-dioxa-7-azabicyclo[7.1.0]dec-4-ene (5f):** To a solution of AgOTf (9 mg, 0.036 mmol) and PPh_3AuCl (18 mg, 0.036 mmol) in 3.6 mL of CH_2Cl_2 at ambient temperature was added **4f** (164 mg, 0.36 mmol). The reaction mixture was stirred for 24 h, and the crude mixture was purified by flash column chromatography (silica gel, ethyl acetate/hexanes 1:15) to give **5f** (27 mg, 0.06 mmol, 16%) as a colorless oil: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.74 (d, *J* = 8.2 Hz, 2H), 7.53 (d, *J* = 7.9 Hz, 1H), 7.33-7.15 (m, 5H), 5.19 (dd, *J* = 9.1, 7.6 Hz, 1H), 4.38 (dd, *J* = 14.1, 2.2 Hz, 1H), 4.25 (dd, *J* = 12.4, 4.9 Hz, 1H), 4.23-4.17 (m, 2H), 3.33 (dd, *J* = 12.4, 7.7 Hz, 1H), 3.21-3.19 (m, 2H), 2.82 (dd, *J* = 14.2, 10.4 Hz, 1H), 2.44 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 157.9, 143.6, 137.2, 135.7, 133.6, 130.8, 130.3, 129.9, 127.4, 127.1,121.9, 112.2, 68.2, 53.8, 53.3, 44.6, 42.1, 21.5; IR (CH_2Cl_2) 3062, 2925, 1653, 1590, 1341, 1161, 1091, 1028 cm^{-1}; MS (ESI) *m/e* 474.0, 472.0 ([M + Na]$^+$), 470.0, 395.2, 315.6, 306.0; HRMS (ESI) calcd for $C_{20}H_{20}NO_4NaSBr$ [M + Na]$^+$ 472.0194, found 472.0185. **Ethyl 3-(*Z*)-7-tosyl-3,10-dioxa-7-azabicyclo[7.1.0]dec-4-en-4-yl)benzoate (5g):** To a solution of AgOTf (15 mg, 0.056 mmol) and PPh_3AuCl (28 mg, 0.056 mmol) in 5.6 mL of CH_2Cl_2 at ambient temperature was added **4g** (250 mg, 0.56 mmol). The reaction mixture was stirred for 24 h, and the crude mixture was purified by flash column chro-

matography (silica gel, ethyl acetate/hexanes 1:15) to give **5g** (45 mg, 0.10 mmol, 18%) as a white solid: mp 164-165 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.01-7.99 (m, 2H), 7.79 (d, *J* = 8.0 Hz, 2H), 7.47 (d, *J* = 7.8 Hz, 1H), 7.41-7.37 (m, 3H), 5.39 (t, *J* = 8.0 Hz, 1H), 4.62 (dd, *J* = 11.4, 3.7 Hz, 1H), 4.41 (q, *J* = 7.1 Hz, 2H), 4.30 (dd, *J* = 13.9, 2.6 Hz), 4.21 (d, *J* = 8.4 Hz, 2H), 3.28-3.22 (m, 2H), 3.05 (dt, *J* = 10.6, 3.6 Hz, 1H), 2.64 (dd, *J* = 13.7, 10.9 Hz, 1H), 2.47 (s, 3H), 1.41 (t, *J* = 7.1 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.0, 159.2, 143.9, 137.2, 134.8, 131.2, 130.1, 130.0, 129.8, 128.7, 127.1, 126.7, 107.5, 69.8, 61.2, 53.1, 53.0, 43.3, 41.8, 21.5, 14.3; IR (CH_2Cl_2) 3055, 2924, 1719, 1454, 1353, 1287, 1162, 1089 cm^{-1}; MS (ESI) *m/e* 466.1 ([M + Na]$^+$), 463.3, 393.2, 360.3, 349.2, 242.3, 167.2; HRMS (ESI) calcd for $C_{23}H_{25}NO_6NaS$ [M + Na]$^+$ 466.1300, found 466.1294. **(*Z*)-4-(3-Nitrophenyl)-7-tosyl-3,10-dioxa-7-azabicyclo[7.1.0]dec-4-ene (5h):** To a solution of AgOTf (40 mg, 0.157 mmol) and PPh_3AuCl (78 mg, 0.157 mmol) in 15.7 mL of CH_2Cl_2 at ambient temperature was added **4h** (655 mg, 1.57 mmol). The reaction mixture was stirred for 24 h, and the crude mixture was purified by flash column chromatography (silica gel, ethyl acetate/hexanes 1:15) to give **5h** (196 mg, 0.47 mmol, 30%) as a white solid: mp 169-170 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.43 (t, *J* = 1.8 Hz, 1H), 8.05-8.04 (m, 1H), 7.79 (d, *J* = 7.84 Hz, 1H), 7.74 (d, *J* = 8.2 Hz, 2H), 7.45 (t, *J* = 8.0 Hz, 1H), 7.32 (d, *J* = 8.1 Hz, 2H), 5.37 (dd, *J* =10.0, 7.2 Hz, 1H), 4.55 (dd, *J* = 13.2, 4.1 Hz, 1H) 4.34 (dd, *J* = 13.2, 8.1 Hz, 1H), 4.18 (d, *J* = 14.7 Hz, 1H), 4.10 (dd, *J* = 14.1, 3.1 Hz, 1H), 3.84 (d, J = 14.8 Hz, 1H), 3.27-3.18 (m, 3H), 2.44 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 157.9, 148.6, 144.3, 136.4, 135.8, 134.4, 130.0, 129.0, 127.3, 123.2, 121.4, 111.7, 65.39, 52.5, 52.4, 50.4, 46.9, 21.5; IR (CH_2Cl_2) 3055, 2926, 1646, 1528, 1458, 1351, 1265, 1163, 1091 cm^{-1}; MS (ESI) *m/e* 439.1 ([M + Na]$^+$), 413.2, 393.3, 342.1, 289.6, 242.3, 220.0; HRMS (ESI) calcd for $C_{20}H_{20}N_2O_6NaS$ [M + Na]$^+$ 439.0940, found 439.0944. Crystals suitable for X-ray diffraction analysis were grown from CH_2Cl_2 and hexanes. **(*Z*)-4-Methyl-7-tosyl-3,10-dioxa-7-azabicyclo[7.1.0]dec-4-ene (5i)**: To a solution of AgOTf (17 mg, 0.065 mmol) and PPh_3AuCl (32 mg, 0.065 mmol) in 6.5 mL of CH_2Cl_2 at ambient temperature was added **4i** (200 mg, 0.65 mmol). The reaction mixture was stirred for 24 h, and the crude mixture was purified by flash column chromatography (silica gel, ethyl acetate/hexanes 1:15) to give **5i** (137 mg, 0.45 mmol, 69%) as a white solid: mp 78-79 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.70 (d, *J* = 8.6 Hz, 2H), 7.30 (d, *J* = 8.1 Hz, 2H), 4.64 (t, *J* = 8.4 Hz, 1H), 4.52-4.44 (m, 1H), 4.19 (dd, *J* = 10.7, 2.9 Hz, 1H), 3.97 (d, *J* = 8.6 Hz, 2H), 3.30-3.22 (m, 2H), 2.98 (dt, *J* = 10.7, 2.9 Hz, 1H), 2.62 (dd, *J* = 14.0, 10.8 Hz, 1H), 2.43 (s, 3H), 1.74 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 159.42, 143.4, 137.2, 130.0, 126.8, 107.0, 68.0, 53.0, 52.9, 43.1, 41.6, 21.4, 19.20; IR (CH_2Cl_2) 3025, 2948, 1677, 1338, 1187, 1158, 1097 cm^{-1}; MS (ESI) *m/e* 332.1 ([M + Na]$^+$), 328.1; HRMS (ESI) calcd for $C_{15}H_{19}NO_4NaS$ [M + Na]$^+$ 332.0932, found 332.0928. **(*Z*)-4-Butyl-7-tosyl-3,10-dioxa-7-azabicyclo[7.1.0]dec-4-ene (5j):** To a solution of AgOTf (7 mg, 0.026 mmol) and PPh_3AuCl (13 mg, 0.026 mmol) in 2.6 mL of CH_2Cl_2 at ambient temperature was added **4j** (88 mg, 0.26 mmol). The reaction mixture was stirred for 24 h, and the crude mixture was purified by flash column chromatography (silica gel, ethyl acetate/hexanes 1:15) to give **5j** (49 mg, 0.13 mmol, 50%) as a colorless oil: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.70 (d, *J* = 8.0 Hz, 2H), 7.31 (d, *J* = 8.2 Hz, 2H), 4.55 (dd, *J* = 9.6, 7.5 Hz, 1H), 4.44 (dd, *J* = 10.2, 2.5 Hz, 1H), 4.21 (dd, *J* = 13.8, 3.1 Hz, 1H), 4.05-3.95 (m, 2H), 3.27-3.19 (m, 2H), 2.97 (dt, *J* = 10.7, 3.2 Hz, 1H), 2.59 (dd, *J* = 13.8, 10.7 Hz, 1H), 2.43 (s, 3H), 2.06-1.91 (m, 2H), 1.37-1.19 (m, 4H), 0.84 (t, *J* = 7.0 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.3, 143.5, 137.3, 129.8, 127.0, 105.8, 68.5, 53.2, 53.0, 42.8, 41.5, 33.1, 28.4, 22.1, 21.5, 13.8; IR (CH_2Cl_2) 3062, 2956, 1672, 1598, 1467, 1343, 1162, 1094 cm^{-1}; MS (ESI) *m/e* 374.1 ([M + Na]$^+$), 371.1, 257.1; HRMS (ESI) calcd for $C_{18}H_{25}NO_4NaS$ [M + Na]$^+$ 374.1402, found 374.1404. **(*Z*)-4-Allyl-7-tosyl-3,10-dioxa-7-azabicyclo-[7.1.0]dec-4-ene (5k):** To a solution of AgOTf (15 mg, 0.059 mmol) and PPh_3AuCl (29 mg, 0.059 mmol) in 5.9 mL of CH_2Cl_2 at ambient temperature was added **4k** (197 mg, 0.59 mmol). The reaction mixture was stirred for 24 h, and the crude mixture was purified by flash column chromatography (silica gel, ethyl acetate/hexanes 1:15) to give **5k** (116 mg, 0.32 mmol, 55%) as a white solid: mp 68-69 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.69 (d, *J* = 8.3 Hz, 2H), 7.30 (d, *J* = 8.0 Hz, 2H), 5.66-5.59 (m, 1H), 5.07 (s, 1H), 5.04-5.02 (m, 1H), 4.60 (dd, *J* = 10.0, 7.0 Hz, 1H), 4.50-4.44 (m, 1H), 4.20 (dd, *J* = 13.8, 3.2 Hz, 1H), 4.05-3.94 (m, 2H), 3.28-3.22 (m, 2H), 2.98 (dt, *J* = 10.6, 3.2 Hz, 1H), 2.81-2.69 (m, 2H), 2.58 (dd, *J* = 13.9, 10.7 Hz, 1H), 2.43 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 161.6, 143.5, 137.2, 132.9, 129.9, 127.0, 117.9, 106.9, 68.9, 53.1, 53.0, 42.9, 41.4, 38.2, 21.5; IR (CH_2Cl_2) 3070, 2954, 1672, 1449, 1341, 1163, 914 cm^{-1}; MS (ESI) *m/e* 358.1 ([M + Na]$^+$), 355.1, 330.1, 319.2, 258.6, 249.1, 241.1; HRMS (ESI) calcd for $C_{17}H_{21}NO_4NaS$ [M + Na]$^+$ 358.1089, found 358.1098. Crystals suitable for X-ray diffraction analysis were grown from CH_2Cl_2 and hexanes. **(*1R,5S*)-Dimethyl-5-benzyl-7-(hydroxymethyl)-6,8-diox-abicyclo[3.2.1]octane-3,3-dicarboxylate (9):** To a solution of AgOTf (15 mg, 0.02 mmol) and PPh_3AuCl (11 mg, 0.02 mmol) in 5.9 mL of CH_2Cl_2 at ambient temperature was added **8** (80 mg, 0.22 mmol). The reaction mixture was stirred for 12 h, and the crude mixture was filtered through a bed of Celite and then purified by flash column chromatography (silica gel, ethyl acetate/hexanes 1:5) to give **9**

(52 mg, 0.15 mmol, 68%) as a white solid: mp 97–99 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.32–7.24 (m, 5H), 4.20 (dd, J = 4.8, 1.3 Hz, 1H), 4.10 (dd, J = 6.9, 4.6 Hz, 1H), 3.79 (s, 3H), 3.70 (s, 3H), 3.09–2.99 (m, 3H), 2.77 (ddd, J = 9.6, 5.5, 4.3 Hz, 1H), 2.72 (d, J = 11.4 Hz, 1H), 2.60 (d, J = 10.4 Hz, 1H), 2.35 (d, J = 11.4 Hz, 1H), 2.12 (dd, J = 11.5, 3.4 Hz, 1H), 0.97 (dd, J = 6.1, 4.3 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 171.6, 171.4, 134.9, 130.9, 127.9, 127.0, 106.5, 78.9, 74.2, 64.0,53.1, 51.5, 43.3, 39.6, 31.9; IR (CH_2Cl_2) 3528, 2952, 1731, 1440, 1255 cm^{-1}; HRMS (ESI) calcd for $C_{18}H_{22}O_7Na$ $[M + Na]^+$ 373.1263, found 373.1270. Crystals suitable for X-ray diffraction analysis were grown from CH_2Cl_2 and hexanes. **7-(Naphthalen-1-yl)-4-tosyl-8,10-dioxa-4-azabicyclo[5.2.1]decan-2-yl trifluoromethanesulfonate (13):** To a solution of **5c** (0.089 g, 0.2 mmol) in 4.0 mL of CH_2Cl_2 at ambient temperature was added TfOH (0.036 g, 0.24 mmol). The reaction mixture was stirred for 12 h, and the crude mixture was purified by flash column chromatography (silica gel, ethyl acetate/hexanes 1:10) to give **13** (65 mg, 0.11 mmol, 55%) as a white solid: m.p. 131-132 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.37 (d, J = 8.1 Hz, 1H), 7.87-7.81 (m, 2H), 7.74 (d, J = 8.2 Hz, 3H), 7.67 (quin, J = 7.5 Hz, 2H), 7.40 (t, J = 7.0 Hz, 1H), 7.35 (d, J = 8.0 Hz, 2H), 5.55–5.50 (m, 1H), 4.66 (t, J = 4.6 Hz, 1H), 4.37 (d, J = 9.9 Hz, 1H), 3.97-3.84 (m, 3H), 3.41 (td, J = 12.6, 2.0 Hz, 1H), 3.30 (dd, J = 14.5, 11.3 Hz, 1H), 2.76 (t, J = 12.0 Hz, 1H), 2.46 (s, 3H), 2.15 (d, J = 15.5 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.8, 137.3, 135.9, 134.5, 129.9, 129.8, 129.7, 128.8, 127.0, 126.1, 125.9, 125.6, 124.8, 112.1, 82.6, 74.3, 64.8, 50.2, 48.2, 39.7, 21.5; IR (CH_2Cl_2) 2946, 1598, 1417, 1346, 1211, 1160, 1091, 1020 cm^{-1}; MS (ESI) *m/e* 594.1 ($[M + Na]^+$), 589.1, 572.1, 566.6, 553.3, 548.1, 529.1, 523.3, 523.3, 518.5, 498.4, 491.5; HRMS (ESI) calcd for $C_{25}H_{24}NO_7NaS_2F_3$ $[M + Na]^+$ 594.0844, found 594.0845.

Supporting Information Available

Data for compounds **4b-j** and **8**, NMR Spectra for compounds **4a-k**, **5a-k**, **8**, **9** and **13**, and X-ray crystallographic information files for compounds **5c**, **5h**, **5k**, and **9** are available.

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REFERENCES

1. Yeh, M. C. P.; Pai, H. F.; Hsiow, C. Y.; Wang, Y. R. *Organometallics* **2010**, *29*, 160.
2. Yeh, M. C. P.; Lin, M. N.; Chang W. J.; Liou, J. L.; Shih, Y. F. *J. Org. Chem.* **2010**, *75*, 6031.
3. Akana, J. A.; Bhattacharyya, K. X.; Müller, P.; Sadighi, J. P. *J. Am. Chem. Soc.* **2007**, *129*, 7736.
4. Bae, H. J.; Baskar, B.; An, S. E.; Cheong, J. Y.; Thangadurai, D. T.; Hwang, I. C.; Rhee, Y. H. *Angew. Chem. Int. Ed*. **2008**, *47*, 2263-2266.
5. Hashmi, A. S. K.; Schuster, M.; Rominger, F. *Angew. Chem. Int. Ed.* **2009**, *48*, 8247.
6. Zeng, X.; Kinjo, R.; Donnadieu, B.; Bertrand, G. *Angew. Chem. Int. Ed.* **2010**, *49*, 942.
7. Chen, Y.; Wang, D.; Petersen, J. L.; Akhmedov, N. G.; Shi, X. *Chem. Commun.* **2010**, *46*, 6147.
8. Hashmi, A. S. K.; Schuster, A. M.; Rominger, F. *Adv. Synth. Catal.* **2010**, *352*, 971.
9. Zhu, Y.; Yu, B. *Angew. Chem. Int. Ed.* **2011**, *50*, 8329.
10. After our results published (ref. 2), a similar gold-catalyzed enynols cyclization was also reported in the literature. Park, Y.; Kim, S. Y.; Park, J. H.; Cho, J.; Kang, Y. K.; Chuang, Y. K. *Chem. Commun.* **2011**, *47*, 5190.
11. The structure elucidationof the compoundwas accomplished by X-ray diffraction analysis. CCDC 970660 (**5c**), CCDC 970842 (**5h**), CCDC 970662 (**5k**), and CCDC 987755 (**9**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Center via www.ccdc.cam.ac.uk/data_request/cif.
12. Beesley, R. M.; Ingold, C. K.; Thorpe, J. F. *J. Chem. Soc. Trans.* **1915**, *107*, 1080.
13. Levine, M. N.; Raines, R. T. *Chem. Sci.* **2012**, *3*, 2412.
14. Fürstner, A.; Langemann, K. *J. Org. Chem.* **1996**, *61*, 8746.

