HOKKAIDO UNIVERSITY

Title	Synthesis of γ,δ-Unsaturated Esters and Amides via Au(I)-Catalyzed Reactions of Aryl Ynol Ethers or Ynamides with Allylic Alcohols
Author(s)	Misawa, Souta; Miyairi, Asaki; Oonishi, Yoshihiro et al.
Citation	Synthesis-stuttgart, 53(24), 4644-4653 https://doi.org/10.1055/a-1559-3020
Issue Date	2021-09-29
Doc URL	https://hdl.handle.net/2115/86987
Rights	This is an Accepted Manuscript of an article published by Thieme Publishing Group in Journal Title on Publication Date, available online at https://www.thieme-connect.de/products/ejournals/abstract/10.1055/a-1559-3020
Type	journal article
File Information	Sato_manuscript_revise.pdf

Hokkaido University Collection of Scholarly and Academic Papers : HUSCAP

Synthesis of γ,δ-Unsaturated Esters and Amides via Au(I)-Catalyzed Reactions of Aryl Ynol Ethers or Ynamides with Allylic Alcohols

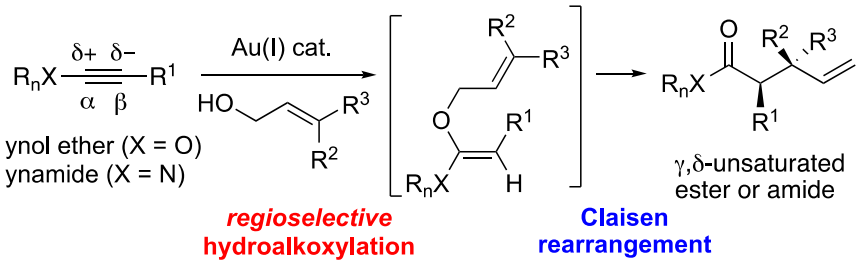
Souta Misawa[a,†]
Asaki Miyairi[a,†]
Yoshihiro Oonishi*[a]
Steven P. Nolan[b]
Yoshihiro Sato*[a]

[a] Faculty of Pharmaceutical Sciences Hokkaido University, Sapporo 060-0812, Japan

[b] Department of Chemistry and Centre for Sustainable Chemistry Ghent University, Krijgslaan 281, S-3, 9000, Belgium

[†] These authors contributed equally to this work.

biyo@pharm.hokudai.ac.jp.

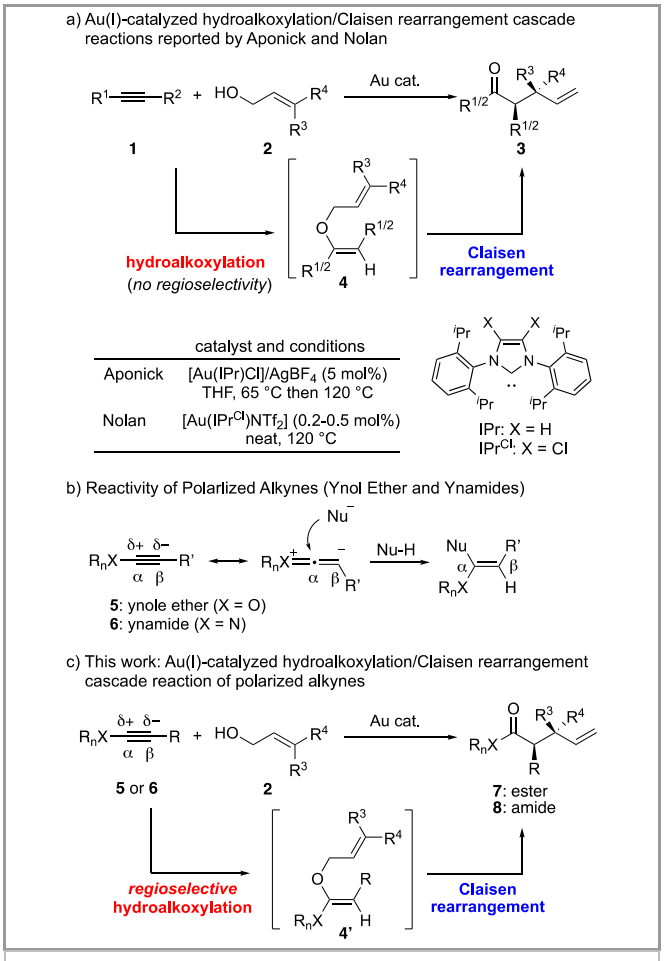


Received:
Accepted:
Published online:
DOI:

Abstract Polarized alkynes such as ynol ethers and ynamides have attracted much attention due to their inherent unique reactivity. Herein, we report Au(I)-catalyzed hydroalkoxylation/Claisen rearrangement cascade reactions of aryl ynol ethers and ynamides with allylic alcohols. At the first stage (hydroalkoxylation) of this cascade reaction, attack of allylic alcohols to aryl ynol ethers or ynamides occurs at the α-position of the polarized alkynes in an entirely regioselective manner. Claisen rearrangement of the resulting adducts subsequentially takes place to give γ,δ-unsaturated esters or amides, respectively. The [Au(IPr)NTf$_2$] catalyst is most effective for this reaction, and the reaction proceeds under mild conditions (in the case of aryl ynol ether: in THF, 60 °C; in the case of ynamides: in toluene, 80 °C) in an atom-economical way.

Key words gold, ynol, ynamide, hydroalkoxylation, Claisen rearrangement, ester, amide

Addition of nucleophiles to alkynes through activation of the C-C triple bond by transition metal complexes is a straightforward and atom-economical methodology for synthesis of functionalized alkenes.[1] Au(I) complexes are widely used for this purpose in a process in which Au(I) activates the alkyne due to its π-Lewis acidity. A number of reactions of alkynes with nucleophiles (especially, heteroatom nucleophiles) using such catalyst have been reported.[2] Among these, the Au(I)-catalyzed reaction of alkynes with allyl alcohols is of great interest because [3,3]-sigmatropic rearrangement sequentially occurs after hydroalkoxylation of the alkyne to afford γ,δ-unsaturated ketones in a one-pot reaction.[3-5] For instance, Aponick[3] and Nolan[4] independently reported the synthesis of γ,δ-unsaturated ketones via a Au(I)-catalyzed hydroalkoxylation/Claisen rearrangement cascade starting from alkynes and allyl alcohols (Scheme 1a). In both reactions however, the regioselectivity of the addition of the allyl alcohol to the alkynes, when unsymmetrical internal alkynes were employed, was difficult to control, resulting in a mixture of isomers. Of note, polarized alkynes such as ynol ethers and ynamides have unique properties due to the delocalization of a lone electron pair of oxygen and nitrogen, and it is well known that addition of a nucleophile to ynol ethers or ynamides usually occurs at the α-position of the alkynes (Scheme 1b).[6]

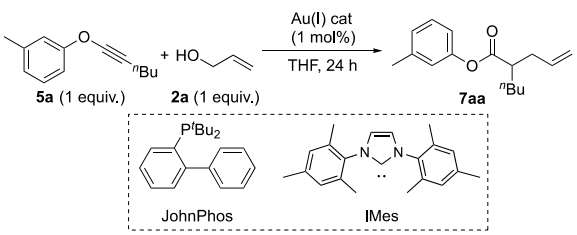


Background of Au(I)-catalyzed hydroxylation/Claisen rearrangement cascade reactions of alkynes.

In the context of our continued interest in the reactivity of ynol ethers and ynamides,[7] we envisaged utilization of these polarized alkynes in the Au(I)-catalyzed hydroalkoxylation/Claisen rearrangement cascade (Scheme 1c). Our hypothesis, in this case, was that the hydroalkoxylation by allyl alcohols would regioselectively occur at the α-position, followed by Claisen rearrangement, giving γ,δ-unsaturated esters or amides. Although there has been one report disclosing Au(I)-catalyzed hydroalkoxylation/Claisen rearrangement cascade reaction of polarized alkynes,[8] a comprehensive exploration of this fascinating transformation has not been carried out, and the scope and limitations of this reaction still remain unclear. In this paper, we report Au(I)-catalyzed hydroalkoxylation/Claisen rearrangement cascade reactions of aryl ynol ethers and ynamides with allylic alcohols.[9]

Initially, we investigated the reaction of aryl ynol ether **5a** with allyl alcohol (**2a**) in THF (a solvent selected based on the basis of conditions reported by Aponick[3]) in the presence of various Au(I) catalysts, and key results are summarized in Table 1. Reactions using Au(I) catalysts bearing the phosphine ligands PPh_3 and JohnPhos gave the desired product **7aa** in 16% and 34% yields, respectively (Entries 1 and 2). *N*-heterocyclic carbene (NHC) ligands appear to be more effective than phosphines (Entries 3-5), and the reaction using 1 mol% Au(IPr)NTf_2 afforded **5a** in 57% yield. The use of an isolated [Au(IPr)NTf_2][10,11] catalyst showed almost the same result (Entry 6) as that in entry 5 using a catalyst formed by mixing [Au(IPr)Cl] (1 mol%) and $AgNTf_2$ (1 mol%) prepared just prior to use. When we carefully examined and identified by-products formed during the reactions, we noticed the formation of *m*-cresol. Thus, the reactions were carried out at lower temperature to possibly get rid of this side-product. In spite of the milder reaction conditions, the yield of **7aa** was not improved (Entries 7 and 8). We speculated that an excess of allyl alcohol could operate as a proton source in the presence of a trace amount of Tf_2NH derived from the catalyst, resulting in decomposition of the intermediate **4'**. We therefore proceeded with slow addition of a THF solution of **2a** to the mixture of **5a** and with the [Au(IPr)NTf_2] catalyst. In this manner, the yield of **7aa** was greatly improved to 86% (Entry 9).

Table 1 Screening of conditions for reaction of **5a** with **2a**.



Entry	Au(I) catalyst	Temp. (°C)	**7aa** (%)[a]
1[b]	[Au(PPh_3)Cl]/$AgNTf_2$[c]	80	16
2[b]	[Au(JohnPhos)Cl]/$AgNTf_2$[c]	80	34
3[b]	[Au(IMes)Cl]/$AgNTf_2$[c]	80	42
4[b]	[Au(IPr^{Cl})Cl]/$AgNTf_2$[c]	80	45
5[b]	[Au(IPr)Cl]/$AgNTf_2$[c]	80	57
6[b]	[Au(IPr)NTf_2]	80	56
7[b]	[Au(IPr)NTf_2]	60	59
8[b]	[Au(IPr)NTf_2]	40	45
9[d]	[Au(IPr)NTf_2]	60	86 (82)

[a] Yields were determined by ^{1}H-NMR using 1,3,5-trimethoxybenzene as an internal standard. Isolated yield is given in parentheses. [b] The mixture of **5a**, **2a**, and Au(I) catalyst was stirred at the indicated temperature for 24 h. [c] The Au(I) catalyst was prepared from [Au(ligand)Cl] (1 mol%) and $AgNTf_2$ (1 mol%) prior to use. [d] A solution of **2a** in THF was slowly added (ca. 10 min) to the mixture of **5a** and [Au(IPr)NTf_2] at 60 °C, and then the mixture was stirred at the same temperature for 24 h.

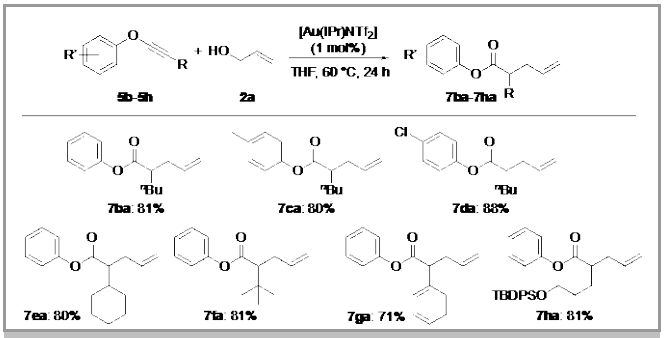
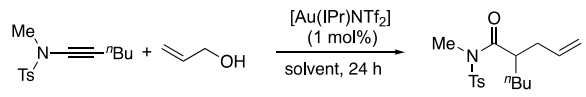


Figure 1 Scope of the reaction of aryl ynol ethers and allyl alcohol.

Next, we examined the reaction of ynamide **6a** with allyl alcohol (**2a**). When the reaction of **6a** with **2a** was carried out under the above-mentioned optimal conditions, the desired product **8aa** was obtained in a modest yield, 56% (Table 2, Entry 1). Thus, we rescreened conditions in order to improve the yield, and representative results are summarized in Table 2. When the reaction was carried out at 80 °C, the yield of **8aa** was improved to 77% yield (Entry 2). Solvent screening revealed that toluene is suitable in this reaction (Entries 3-6). The use of a [Au(IPr)NTf_2] catalyst prepared from [Au(IPr)Cl] (1 mol%) and $AgNTf_2$ (1 mol%) prior to use showed the same reactivity as that of the isolated catalyst (Entry 7). In this reaction, the catalyst loading can be reduced to 0.1 mol% without any loss of reactivity, giving **8aa** in 86% yield (Entry 8). It is noteworthy that the slow addition of **2a** is not necessary in this reaction, and the mixture of **5a**, **2a**, and the catalyst in toluene can be simply heated to 80 °C. This is surely due to the increased stability of ynamides as well as the intermediate derived from ynamides compared to ynol ethers.

Table 2 Re-screening of conditions for reaction of **6a** with **2a**.



Entry	Temp. (°C)	solvent	**8aa** (%)[a]
1	60	THF	56
2	80	THF	77
3	80	DMF	73
4	80	CH_3CN	51
5	80	Dichloroethane	65

6	80	Toluene	89
7[b]	80	Toluene	92
8[c]	80	Toluene	86[d]

[a] Yields were determined by ^{1}H-NMR using 1,3,5-trimethoxybenzene as an internal standard. [b] The Au(I) catalyst was prepared from [Au(ligand)Cl] (1 mol%) and $AgNTf_2$ (1 mol%) prior to use. [c] 0.1 mol% of $[Au(IPr)NTf_2]$ was used. [d] Isolated yield.

We applied the optimized conditions for ynamides to the reaction of various ynamides with allyl alcohol (**2a**) (Figure 2). The reaction of ynamides **6b**-**6d**, having an aromatic ring with various substituents at the *para*-position, under the optimal conditions gave the corresponding products **8ba**-**8da** in good yields. In the case of ynamide **6e** bearing a terminal bulky substituent (*tert*-butyl group), the yield of **8ea** was modest, while other alkyl group such as methyl, phenethyl, and *tert*-butyldimethylsilyloxy-ethyl groups (**6f**-**6h**) are tolerated to give products **8fa**-**8ha** in good yields. The ynamide **6i**, having a cyclic carbamate moiety, also afforded amide **8ia** in good yield, while acyclic carbamate **6j** gave no desired product at all, although the differences of the reactivity depending on the structure of ynamide are not clear.

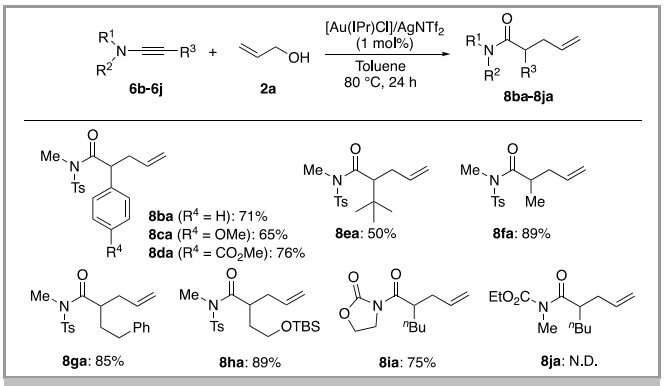


Figure 2 Scope of the reaction of various ynamides and allyl alcohol (**2a**).

The scope of the allylic alcohol was next investigated in the reaction of ynamide **6a** (Figure 3). In the reaction of **6a** with allyl alcohol **2b** or **2c**, having a substituent at the C2-position, the desired products **8ab** and **8ac** were obtained in good yields. Interestingly, the reaction with **2d** also proceeded to give γ,δ,ε,ζ-unsaturated amide **8ad** in 81% yield as a single isomer.

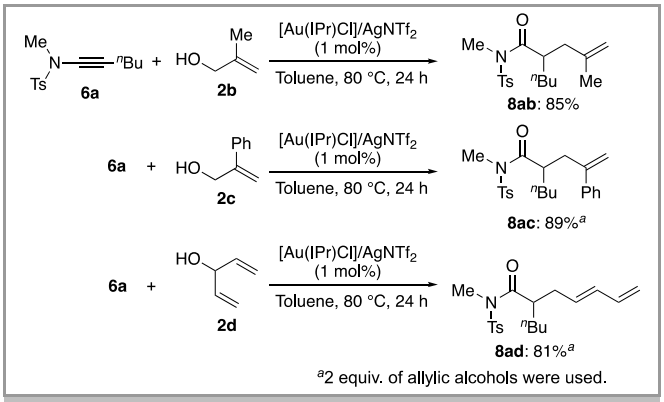


Figure 3 Scope of the reaction of ynamide **6a** with various allylic alcohols.

In the case of the reaction using allyl alcohol having a substituent at the C3-position, the product possesses two chiral carbon centers, in which the diastereoselectivity is of interest. Thus, the reaction of ynamides with *E*- or *Z*-crotyl alcohol (**2e**) was investigated (Figure 4). The reaction of **6a** with (*E*)-**2e** under the optimized conditions produced *anti*-**8ae** as a major isomer in 65% yield as a 30:70 mixture of diastereomers. On the other hand, in the reaction with (*Z*)-**2e** under the same conditions, *syn*-**8ae** was formed as a major isomer in comparable yield to that of the reaction with (*E*)-**2e** but with higher diastereoselectivity. The reaction of **6f** with (*E*)- or (*Z*)-**2e** showed the same trend as that for **6a**, in which *anti*-**8fe** or *syn*-**8fe** was formed as a major isomer from (*E*)-**2e** or (*Z*)-**2e**, respectively. The diastereoselectivity found for the reaction using (*Z*)-**2e** was quite low compared to that of **6a** and (*Z*)-**2e**. The relative configuration of **8fe** was determined as follows (Figure 5); a diastereo-mixture of **8fe** (78:22), which was obtained in the reaction of **6f** and (*E*)-**2e**, was converted to the carboxylic acid **9** by hydrolysis. The spectral data of both *syn*-**9** and *anti*-**9** have been reported in the literature.[12] By a comparison of ^{1}H-NMR of a mixture of **9** with the reported data, we unambiguously determined that *anti*-**8fe** was formed as the major isomer in the reaction of **6f** and (*E*)-**2e**. The relative configuration of **8ae** was inferred by analogy to the spectral data of **8fe**.

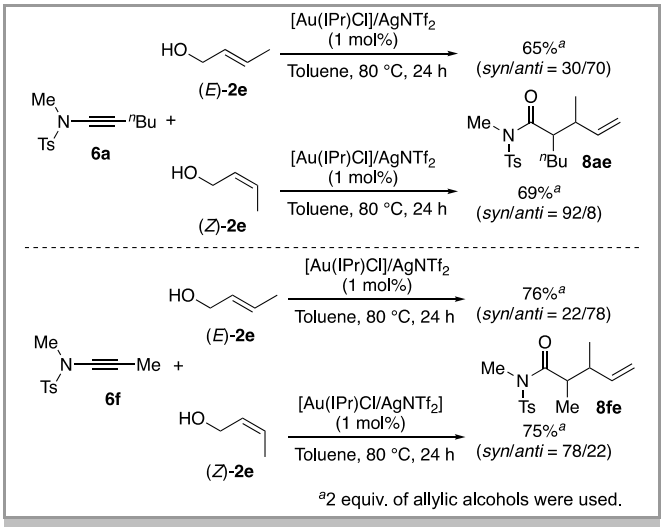


Figure 4 Reaction of ynamides **6a** and **6f** with *E*- or *Z*-crotyl alcohol.

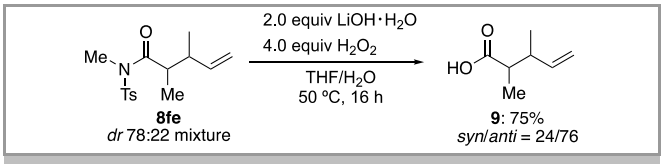


Figure 5 Determination of the relative configuration of **8fe**.

The origin of the diastereoselectivity in the Claisen rearrangement has been well documented.[13] Also, it is well known that nucleophilic addition to activated alkynes via Au(I) catalysis usually occurs from the opposite side to Au (i.e. **10** in eq. 1, Figure 7), giving an *anti*-**11** adduct (Figure 7).[2] The results shown in Figure 4 are therefore consistent with those of a traditional Claisen rearrangement as well as those previously reported by Aponick[3] and Nolan[4] in a Au(I)-catalyzed hydroalkoxylation/Claisen rearrangement cascade starting from simple alkynes. Thus, it is thought that the reaction of ynamide **6a** or **6f** with (*E*)-**2e** produced (*E*)-**4ae** or (*E*)-**4fe**, and *anti*-**8ae** or *anti*-**8fe** is obtained as the major diastereomer via transition state **C-1**. Conversely, in the reaction with (*Z*)-**2e**, *syn*-**8ae** or *syn*-

8fe was preferentially produced as the major diastereomer via transition state **C-2** from (*Z*)-**4ae** or (*Z*)-**4fe** (Figure 6).

However, we wondered if the diastereoselectivity shown in Figure 4 was lower than that of previously reported cases[3,4], especially in the reaction of **6f** with (*Z*)-**2e**. We therefore explored the selectivity at the stage of the nucleophilic attack of alcohol to activated ynamide by the Au(I) complex by using ynamide **6f** and MeOH as the nucleophile under the optimized conditions and examining the temperature as a variable (Figure 7). The expected product (*Z*)-**13** was obtained in 29% yield as the minor isomer, while (*E*)-**13** was formed in 46% yield as the major isomer. This result indicates that hydroalkoxylation of ynamides is not very stereoselective compared to that of simple alkynes. It is well known that a keteniminium species like **14** is formed from ynamides through activation by a Au(I) complex,[2] in which **14** has two perpendicular planes. In this case, nucleophilic attack of MeOH both from the Au side (i.e., according to the blue dotted arrow) and from the Me side (i.e., according to the red arrow) is possible, which would then definitely affect the diastereoselectivity of the final products.

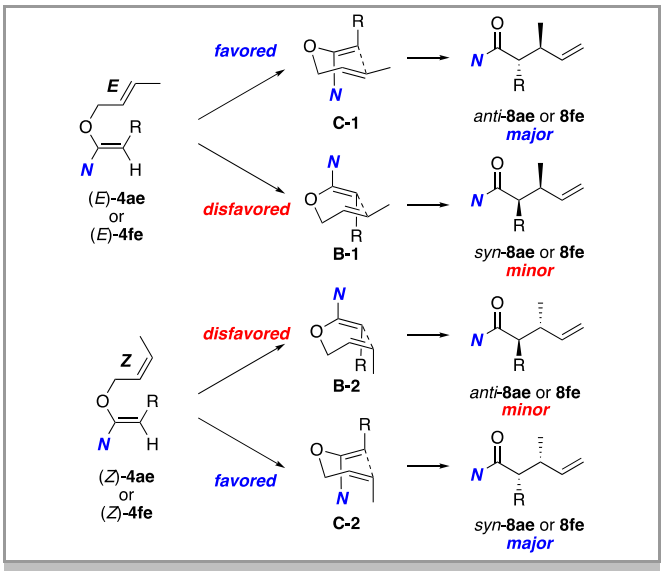


Figure 6 Transition state of Claisen rearrangement of (*E*)- or (*Z*)-**4ae** and **4fe**.

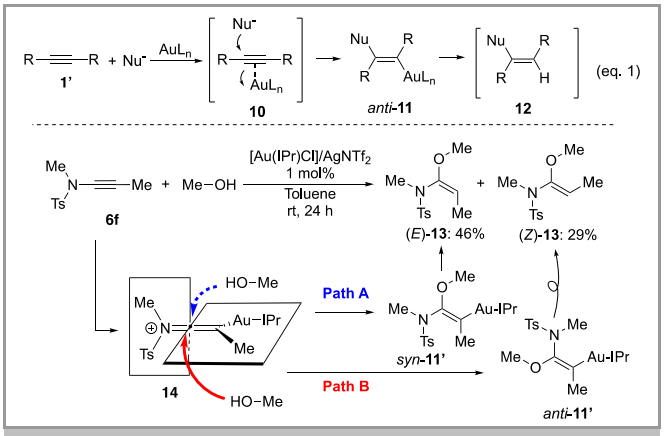


Figure 7 Stereoselectivity in the addition of MeOH to ynamide **6f**.

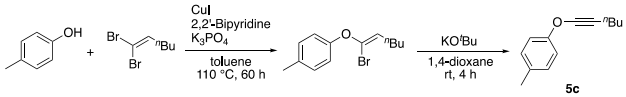
In conclusion, we have developed Au(I)-catalyzed hydroalkoxylation/Claisen rearrangement cascade reactions involving aryl ynol ethers and ynamides with allylic alcohols, giving γ,δ-unsaturated esters and amides, respectively. In this reaction, attack of allylic alcohols occurs in a perfectly regio-selective manner due to the inherent property of polarized alkynes. The use of a [Au(IPr)NTf$_2$] catalyst is most effective, and the reaction proceeds under mild conditions. This reaction is an atom-economical methodology for synthesis of γ,δ-unsaturated esters or amides, and further studies including application to the synthesis of natural products are currently underway making use of alternative catalysts possibly rendering even more user-friendly.

Solvents were purified under N_2 using The Ultimate Solvent System (Glass Counter Inc.) (for THF, Toluene, DMF, CH_3CN) or distilled under an N_2 atmosphere from CaH_2 ($ClCH_2CH_2Cl$). All other solvents and reagents were used without purification or purified when necessary by standard procedures. Column chromatography was performed on silica gel (Wakogel® FC-40). TLC and PTLC were performed on Wako Silicagel 70 F254. IR spectra were obtained on a JASCO FT/IR 460Plus spectrometer. ^{1}H NMR and ^{13}C-NMR spectra were recorded on JEOL ECX400P (^{1}H:400 MHz, ^{13}C:100 MHz), JEOL ECS400 (^{1}H:400 MHz, ^{13}C:100 MHz), JEOL ECP400 (^{1}H:400 MHz, ^{13}C:100 MHz), and JEOL ECA500 (^{1}H:500 MHz, ^{13}C:125 MHz) NMR spectrometers. Chemical shifts are reported in ppm from the solvent as the internal standard ($CDCl_3$: δ = 7.26 ppm for ^{1}H, 77.16 ppm for ^{13}C). Mass spectra were obtained on JEOL JMS-T100LP and JMS-T100GCV and JEOL JMS-FAB mate mass spectrometers and on a Thermo Scientific Q Exactive mass spectrometer.

Preparation of Aryl Ynol Ethers

Aryl ynol ethers, used as a substrate, were synthesized according to the reported methods, see; For **5a**, **5b**, and **5d**[14]; For **5e**, **5f**, **5g**, and **5h**[7b].

1-(Hex-1-yn-1-yloxy)-4-methylbenzene (5c).



According to the procedures reported by Evano[15], a 30 mL test tube with screw cap was charged with *p*-cresol (454 mg, 4.20 mmol), CuI (397 mg 2.08 mmol), 2,2'-bipyridine (651 mg, 4.17 mmol) and K_3PO_4 (3.98 g, 18.7 mmol). The tube was evacuated under high vacuum and backfilled with argon. A solution of the 1,1- dibromo-1-alkene (1.52 g, 6.30 mmol) in dry and degassed toluene (12.5 mL) was next added. The test tube was sealed by screw cap and the heterogeneous mixture was heated at 110 °C for 60 hours. The reaction mixture was then cooled to room temperature, filtered over a plug of silica gel (washed with AcOEt), and concentrated in vacuo. The crude residue was purified by flash chromatography on silica gel (hexane). The resulting 1-bromoenol ether (*Z*:*E*≈10:1) was dissolved in 1,4-dioxane (12.5 mL) and added KO^{t}Bu (1.18 g, 10.5 mmol). After stirring 4 hours at room temperature, the reaction was quenched with sat. NH_4Cl aq., and the aqueous layer was extracted with hexane. The organic layer was dried over Na_2SO_4 and concentrated in vacuo. The crude residue was purified by flash column chromatography on silica gel (hexane) followed by gel permeation chromatography (eluent: $CHCl_3$).

IR (neat): 2962, 2931, 2276, 1609, 1503, 1246 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.18-7.13 (m, 4H), 2.50 (s, 3H), 2.30 (t, *J* = 7.2 Hz, 2H), 1.61-1.44 (m, 4H), 0.97 (t, *J* = 7.2 Hz, 3H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 154.5, 133.4, 130.1, 114.7, 83.8, 44.3, 31.7, 22.1, 20.7, 17.1, 13.8.

HRMS (EI): *m/z* [(M- Me)$^+$] calcd for $C_{12}H_{13}O$: 173.0966; found: 173,0967.

General Procedure for the Reaction of Aryl Ynol Ethers with Allyl Alcohol

A solution of allyl alcohol (0.3 mmol) in THF (0.3 mL) was added dropwise over 10 min to a solution of [Au(IPr)NTf$_2$] (0.003 mmol) and aryl ynol ether (0.3 mmol) in THF (0.3 mL) with stirring at 60 °C. The mixture was stirred at this temperature for 24 h. After removal of volatiles under vacuum, the residue was purified by column chromatography on silica gel to give the product.

***m*-Tolyl 2-allylhexanoate (7aa) (Table 1, Entry 9).** According to the General Procedure for the Reaction of Aryl Ynol Ethers with Allyl Alcohol, a crude material was obtained from the reaction of **5a** (55.4 mg, 0.294 mmol), **2a** (20.0 μL, 0.294 mmol), and [Au(IPr)NTf_2] (2.5 mg, 0.003 mmol), from which the yield of **7aa** was determined to be 86% by ^{1}H-NMR by using 1,3,5-trimethoxybenzene as an internal standard. The product **7aa** (59.3 mg, 82%) was isolated from the crude material by column chromatography (*n*-hexane: diethyl ether=20:1) as a colorless oil.

IR (neat): 2930, 2860, 1757, 1642, 1613, 1588 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.25 (t, *J* = 7.2 Hz, 1H), 7.02 (d, *J* = 7.2 Hz, 1H), 6.86 (s, 1H), 6.85 (d, *J* = 7.2 Hz, 1H), 5.91-5.81 (m, 1H), 5.18-5.08 (m, 2H), 2.70-2.63 (m, 1H), 2.54-2.33 (m, 5H), 1.78-1.59 (m, 2H), 1.42-1.35 (m, 4H), 0.95-0.91 (t, *J* = 7.0 Hz, 3H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 174.5, 150.8, 139.7, 135.5, 129.2, 126.7, 122.3, 118.7, 117.2, 45.5, 36.6, 31.8, 29.7, 22,7, 21.5, 14.1.

HRMS (ESI): *m/z* [(M+Na)$^+$] calcd for $C_{16}H_{22}NaO_2$: 269.1512; found: 269.1511.

Phenyl 2-allylhexanote (7ba) (Figure 1). According to the General Procedure, **7ba** (55.0 mg, 81%) was obtained as a colorless oil from the reaction of **5b** (51.1 mg, 0.293 mmol), **2a** (20.0 μL, 0.294 mmol), and [Au(IPr)NTf_2] (2.5 mg, 0.003 mmol) after purification by column chromatography (*n*-hexane: diethyl ether=20:1).

IR (neat): 3077, 2931, 2860, 1757, 1642, 1593 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.39-7.35 (m, 2H), 7.24-7.20 (m, 1H), 7.06-7.04 (m, 2H), 5.90-5.83 (m, 1H), 5.19-5.09 (m, 2H), 2.70-2.66 (m, 1H), 2.54-2.46 (m, 1H), 2.41-2.34 (m, 1H), 1.81-1.74 (m, 1H), 1.66-1.58 (m, 1H), 1.43-1.35 (m, 4H), 0.93 (t, *J* = 7.2 Hz, 3H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 174.4, 150.9, 135.4, 129.5, 125.8, 121.8, 117.2, 45.5, 36.8, 31.8, 29.7, 22.7, 14.1.

HRMS (ESI): *m/z* [(M+Na)$^+$] calcd for $C_{15}H_{20}NaO_2$: 255.1356; found: 255.1357.

***o*-Tolyl 2-allylhezanoate (7ca) (Figure 1).** According to the General Procedure, **7ca** (58.3 mg, 80%) was obtained as a colorless oil from the reaction of **5c** (55.5 mg, 0.295 mmol), **2a** (20.0 μL, 0.294 mmol), and [Au(IPr)NTf_2] (2.5 mg, 0.003 mmol) after purification by column chromatography (*n*-hexane: diethyl ether=20:1).

IR (neat): 2930, 2860, 1755, 1642, 1594, 1508 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.16 (d, *J* = 8.4 Hz, 2H), 6.92 (d, *J* = 8.4 Hz, 2H), 5.90-5.80 (m, 1H), 5.17-5.08 (m, 2H), 2.70-2.62 (m, 1H), 2.53-2.34 (m, 5H), 1.78-1.58 (m, 2H) , 1.41-1.35 (m, 4H), 0.94-0.90 (t, *J* = 7.2 Hz, 3H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 174.5, 148.6, 135.45, 135.43, 130.0, 121.4, 117.2, 45.5, 36.7, 31.8, 29.6, 22.7, 21.0, 14.1.

HRMS (ESI): *m/z* [(M+Na)$^+$] calcd for $C_{16}H_{22}NaO_2$: 269.1512; found: 269.1514.

4-Chlorophenyl 2-allylhexanote (7da) (Figure 1). According to the General Procedure, **7da** (69.3 mg, 88%) was obtained as a colorless oil from the reaction of **5d** (61.6 mg, 0.295 mmol), **2a** (20.0 μL, 0.294 mmol), and [Au(IPr)NTf_2] (2.5 mg, 0.003 mmol) after purification by column chromatography (*n*-hexane: diethyl ether=20:1).

IR (neat): 2931, 2859, 1757, 1642 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.35 (d, *J* = 8.8 Hz, 2H), 7.00 (d, *J* = 8.8 Hz, 2H), 5.89-5.79 (m, 1H), 5.17-5.08 (m, 2H), 2.71-2.63 (m, 1H), 2.52-2.37 (m, 1H), 2.35-2.33 (m, 1H), 1.77-1.72 (m, 1H), 1.63-1.58 (m, 1H), 1.40-1.36 (m, 4H), 0.92 (t, *J* = 7.0 Hz, 3H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 174.1, 149.3, 135.3, 131.2, 129.6, 123.1, 117.3, 45.5, 36.7, 31.7, 29.6, 22.7, 14.1.

HRMS (ESI): *m/z* [(M+H)$^+$] calcd for $C_{15}H_{19}O_2Cl$: 267.1146; found: 267.1150.

Phenyl 2-cyclohexyl-4-pentenonate (7ea) (Figure 1). According to the General Procedure, **7ea** (60.8 mg, 80%) was obtained as a colorless oil from the reaction of **5e** (59.1 mg, 0.295 mmol), **2a** (20.0 μL, 0.294 mmol), and [Au(IPr)NTf_2] (2.5 mg, 0.003 mmol) after purification by column chromatography (*n*-hexane: diethyl ether=10:1).

IR (neat): 3076, 2926, 2852, 1755, 1642, 1592 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.36 (dd, *J* = 7.5, 7.5 Hz, 2H), 7.23-7.21 (t, *J* = 7.5 Hz, 1H), 7.05 (d, *J* = 7.5 Hz, 2H), 5.92-5.82 (m, 1H), 5.19-5.07 (m, 2H), 2.52-2.42 (m, 3H), 1.92-1.68 (m, 6H), 1.33-1.04 (m, 5H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 173.7, 150.9, 135.9, 129.5, 125.8, 121.8, 117.0, 51.8, 40.1, 34.0, 31.1, 30.8, 26.5, 26.39, 26.37.

HRMS (ESI): *m/z* [(M+Na)$^+$] calcd for $C_{17}H_{22}NaO_2$: 281.1512; found: 281.1513.

Phenyl 2-*tert*-butyl-4-pentenonate (7fa) (Figure 1). According to the General Procedure, **7fa** (55.4 mg, 81%) was obtained as a colorless oil from the reaction of **5f** (51.4 mg, 0.295 mmol), **2a** (20.0 μL, 0.294 mmol), and [Au(IPr)NTf_2] (2.5 mg, 0.003 mmol) after purification by column chromatography (*n*-hexane: diethyl ether=20:1).

IR (neat): 3077, 2963, 1754, 1642, 1593 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.35 (dd, *J* = 7.7, 7.7 Hz, 2H), 7.22 (t, *J* = 7.7 Hz, 1H), 7.05-7.03 (m, 2H), 5.92-5.81 (m, 1H), 5.18 (d, *J* = 17.2 Hz, 1H), 5.10 (d, *J* = 10.4 Hz, 1H), 2.53-2.44 (m, 2H), 2.41-2.34 (m, 1H), 1.10 (s, 9H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 173.3, 150.8, 136.2, 129.5, 125.8, 121.9, 116.9, 55.9, 33.3, 32.4, 28.0.

HRMS (ESI): *m/z* [(M+Na)$^+$] calcd for $C_{15}H_{20}NaO_2$: 255.1356; found: 255.1357.

Phenyl 2-phenyl-4-pentenonate (7ga) (Figure 1). According to the General Procedure, **7ga** (35.2 mg, 71%) was obtained as a colorless oil from the reaction of **5g** (38.2 mg, 0.197 mmol), **2a** (13.3 μL, 0.196 mmol), and [Au(IPr)NTf_2] (1.7 mg, 0.002 mmol) after purification by column chromatography (*n*-hexane: diethyl ether=10:1).

IR (neat): 3065, 3030, 2919, 1756, 1642, 1592 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.43-7.29 (m, 7H), 7.21-7.18 (t, *J* = 7.6 Hz, 1H), 6.998 (d, *J* = 7.6 Hz, 2H), 5.88-5.78 (m, 1H), 5.19-5.15 (m, 1H), 5.08 (d, *J* = 10.4 Hz, 1H), 3.89 (dd, *J* = 9.0, 6.6 Hz, 1H), 2.99-2.91 (m, 1H), 2.66-2.59 (m, 1H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ = 172.1, 150.8, 138.2, 135.1, 129.5, 128.9, 128.1, 127.7, 126.0, 121.6, 117.5, 51.6, 37.8.

HRMS (ESI): *m/z* [(M + Na)$^+$] calcd for $C_{17}H_{16}NaO_2$: 275.1043; found: 275.1044.

Phenyl 2-allyl-5-(*tert*-butyldimethylsilyl)oxypentanoate (7ha) (Figure 1). According to the General Procedure, **7ha** (113.2 mg, 81%) was obtained as a colorless oil from the reaction of **5h** (122.2 mg, 0.296 mmol), **2a** (20.0 μL, 0.294 mmol), and [Au(IPr)NTf_2] (2.5 mg, 0.003 mmol) after purification by column chromatography (*n*-hexane: diethyl ether=10:1).

IR (neat): 3071, 2931, 2857, 1757, 1591 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$) : δ = 7.67 (d, *J* = 7.2 Hz, 4H), 7.44-7.34 (m, 8H), 7.21 (t, *J* = 7.6 Hz, 1H), 7.03 (d, *J* = 7.6 Hz, 2H), 5.88-5.81 (m, 1H), 5.18-5.13 (m, 1H), 5.12 (d, *J* = 10.0 Hz, 1H), 3.72-3.69 (m, 2H), 2.73-2.66 (m, 1H), 2.54-2.47 (m, 1H), 2.40-2.33 (m, 1H), 1.86-1.64 (m, 4H), 1.05 (s, 9H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 174.1, 150.8, 135.7, 135.29, 135.27, 134.00, 133.98, 129.7, 129.5, 127.8, 125.9, 121.8, 117.3, 63.6, 45.1, 36.7, 30.3, 28.4, 27.0, 19.4.

HRMS (ESI): *m/z* [(M+Na)$^+$] calcd for $C_{30}H_{36}NaO_3Si$: 495.2326; found: 495.2330.

Preparation of Ynamides

Ynamides, used as a substrate, were synthesized according to the reported methods.[7d,7g,16-18]

General Procedure for the Reaction of Ynamides with Allylic Alcohols

A solution of ynamide (0.6 mmol) and allylic alcohol (0.6 mmol) in toluene (0.6 mL) was added to a mixture of [Au(ligand)Cl] (0.006 mmol, 1 mol% to a substrate) and $AgNTf_2$ (0.006 mmol, 1 mol% to a substrate) in toluene (0.6 mL) under N_2. The mixture was stirred at 80 °C for 24 h. After removal of the volatiles under vacuum, the residue was purified by column chromatography on silica gel to give the product.

2-Allyl-*N*-methyl-*N*-tosylhexanamide (8aa) (Table 2, Entry 7). According to the General Procedure for the Reaction of Ynamides with Allylic Alcohols, a crude material was obtained from the reaction of **6a** (158.9 mg, 0.60 mmol), **2a** (0.60 mL of 1.0 M solution in toluene, 0.60 mmol), [Au(IPr)Cl] (3.7 mg, 0.006 mmol), and $AgNTf_2$ (2.4 mg, 0.006 mmol), from which the yield of **8aa** was determined to be 92% by ^{1}H-NMR by using 1,3,5-trimethoxybenzene as an internal standard.

IR (neat): 2930, 1697, 1641, 1597 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.76 (d, *J* = 7.7 Hz, 2H), 7.33 (d, *J* = 7.7 Hz, 2H), 5.58-5.48 (m, 1H), 4.96-4.88 (m, 2H), 3.34 (s, 3H), 3.19-3.15 (m, 1H), 2.44 (s, 3H), 2.31-2.24 (m, 1H), 2.17-2.09 (m, 1H), 1.59-1.52 (m, 1H), 1.40-1.35 (m, 1H), 1.22-1.13 (m, 2H), 1.06-1.01 (m, 2H), 0.80 (t, J = 7.2 Hz, 3H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 176.6, 144.8, 137.0, 135.2, 129.8, 127.6, 117.2, 45.1, 37.0, 33.3, 32.2, 29.3, 22.8, 21.7, 14.0.

HRMS (ESI): *m/z* [(M+Na)$^+$] calcd for $C_{17}H_{25}NNaO_3S$: 346.1447; found: 346.1443.

2-Allyl-*N*-methyl-*N*-tosylhexanamide (8aa) (Table 2, Entry 8, Gram scale reaction). A solution of **6a** (1.58 g, 5.95 mmol) and **2a** (6.0 mL of 1.0 M solution in toluene, 6.0 mmol), in toluene (6.0 mL) was added to a mixture of $[Au(IPr)NTf_2]$ (0.006 mmol, 0.1 mol% to a substrate) in toluene (6.0 mL) under N_2. The mixture was stirred at 80 °C for 24 h. After removal of the volatiles under vacuum, the residue was purified by column chromatography on silica gel to give **8aa** (1.65 g, 86% yield) as a colorless liquid.

***N*-Methyl-2-phenyl-*N*-tosylpent-4-enamide (8ba) (Figure 2).** According to the General Procedure, a crude product, which was prepared from ynamide **6b** (170.2 mg, 0.596 mmol), **2a** (0.60 mL of 1.0 M solution in toluene, 0.60 mmol), [Au(IPr)Cl] (0.006 mmol, 1 mol%), and $AgNTf_2$ (0.006 mmol, 1 mol%) in toluene (1.2 mL) at 80 °C for 24 h, was purified by column chromatography on silica gel (*n*-hexane/EtOAc = 8/1) to give **8ba** (146.2 mg, 71% yield) as a colorless liquid.

IR (neat): 1698, 1598, 1455, 1358 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.48 (d, *J* = 8.6 Hz, 2H), 7.19-7.14 (m, 5H), 7.06-7.03 (m, 2H), 5.55-5.45 (m, 1H), 4.89-4.81 (m, 2H), 4.23 (t, *J* = 7.5 Hz, 1H), 3.12 (s, 3H), 2.67-2.60 (m, 1H), 2.33-2.26 (m, 4H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 173.2, 144.7, 137.7, 136.1, 135.2, 129.6, 128.8, 128.2, 127.8, 127.5, 117.2, 51.4, 39.3, 33.2, 21.6.

HRMS (ESI): *m/z* [(M+H)$^+$] calcd for $C_{19}H_{22}NO_3S$: 344.1315; found: 344.1312.

2-(4-Methoxyphenyl)-*N*-methyl-*N*-tosylpent-4-enamide (8ca) (Figure 2). According to the General Procedure, a crude product, which was prepared from ynamide **6c** (189.5 mg, 0.601 mmol), **2a** (0.60 mL of 1.0 M solution in toluene, 0.60 mmol), [Au(IPr)Cl] (0.006 mmol, 1 mol%), and $AgNTf_2$ (0.006 mmol, 1 mol% to a substrate) in toluene (1.2 mL) at 80 °C for 24 h, was purified by column chromatography on silica gel (*n*-hexane/EtOAc = 10/1) to give **8ca** (145.5 mg, 65% yield) as a yellow liquid.

IR (neat): 2954, 1696, 1609, 1511 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.59 (d, *J* = 8.5 Hz, 2H), 7.25 (d, *J* = 8.5 Hz, 2H), 7.06-7.02 (m, 2H), 6.81-6.77 (m, 2H), 5.62-5.51 (m, 1H), 4.97-4.90 (m, 2H), 4.24 (t, *J* = 7.4 Hz, 1H), 3.79 (s, 3H), 3.21 (s, 3H), 2.71-2.64 (m, 1H), 2.46-2.31 (m, 4H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 173.5, 158.9, 144.7, 136.1, 135.2, 129.6, 129.5, 129.3, 127.8, 117.2, 114.2, 55.3, 50.5, 39.2, 33.2, 21.7.

HRMS (ESI): *m/z* [(M+H)$^+$] calcd for $C_{20}H_{24}NO_4S$: 374.1421; found: 374.1420.

Methyl 4-(1-((*N*,4-dimethylphenyl)sulfonamido)-1-oxopent-4-en-2-yl)benzoate (8da) (Figure 2). According to the General Procedure, a crude product, which was prepared from ynamide **6d** (204.5 mg, 0.596 mmol), **2a** (0.60 mL of 1.0 M solution in toluene, 0.60 mmol), [Au(IPr)Cl] (0.006 mmol, 1 mol%), and $AgNTf_2$ (0.006 mmol, 1 mol% to a substrate) in toluene (1.2 mL) at 80 °C for 24 h, was purified by column chromatography on silica gel (*n*-hexane/EtOAc = 10/1) to give **8da** (182.0 mg, 76% yield) as a colorless liquid.

IR (neat): 2952, 1719, 1610 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.92 (d, *J* = 8.5 Hz, 2H), 7.56 (d, *J* = 8.5 Hz, 2H), 7.26-7.21 (m, 4H), 5.60-5.49 (m, 1H), 4.97-4.91 (m, 2H), 4.45 (t, *J* = 7.4 Hz, 1H), 3.92 (s, 3H), 3.21 (s, 3H), 2.76-2.69 (m, 1H), 2.42-2.35 (m, 4H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 172.8, 166.8, 145.0, 142.9, 136.0, 134.6, 130.0, 129.8, 129.4, 128.4, 127.6, 117.7, 52.2, 51.4, 39.2, 33.3, 21.7.

HRMS (ESI): *m/z* [(M+H)$^+$] calcd for $C_{21}H_{24}NO_5S$: 402.1370; found: 402.1366.

2-(*tert*-Butyl)-*N*-methyl-*N*-tosylpent-4-enamide (8ea) (Figure 2). According to the General Procedure, a crude product, which was prepared from ynamide **6e** (158.6 mg, 0.598 mmol), **2a** (0.60 mL of 1.0 M solution in toluene, 0.60 mmol), [Au(IPr)Cl] (0.006 mmol, 1 mol%), and $AgNTf_2$ (0.006 mmol, 1 mol% to a substrate) in toluene (1.2 mL) at 80 °C for 24 h, was purified by column chromatography on silica gel (*n*-hexane/EtOAc = 20/1) to give **8ea** (97.0 mg, 50% yield) as a colorless liquid.

IR (neat): 2960, 1694, 1597, 1353 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ =7.79 (d, *J* =2.1 Hz, 2H), 7.30 (d, *J* = 8.1 Hz, 2H), 5.52-5.41 (m, 1H), 4.86-4.78 (m, 2H), 3.29 (s, 3H), 3.10-2.99 (m, 1H), 2.42 (s, 3H), 2.40-2.29 (m, 1H), 2.21-2.15 (m, 1H), 0.94 (s, 9H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 146.6, 143.143.136.7, 135.8, 129.5, 128.1, 117.2, 53.4, 34.5, 33.7, 33.5, 27.8, 21.7.

HRMS (ESI): *m/z* [(M+Na)$^+$] calcd for $C_{17}H_{25}NNaO_3S$: 346.1447; found: 346.1444.

***N*,2-Dimethyl-*N*-tosylpent-4-enamide (8fa) (Figure 2).** According to the General Procedure, a crude product, which was prepared from ynamide **6f** (100.0 mg, 0.447 mmol), **2a** (0.45 mL of 1.0 M solution in toluene, 0.45 mmol), [Au(IPr)Cl] (0.0045 mmol, 1 mol%), and $AgNTf_2$ (0.0045 mmol, 1 mol% to a substrate) in toluene (0.9 mL) at 80 °C for 24 h, was purified by column chromatography on silica gel (*n*-hexane/EtOAc = 10/1) to give **8fa** (111.4 mg, 89% yield) as a colorless solid.

IR (CH_2Cl_2): 3056, 2979, 1697, 1641, 1598, 1495 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.75 (d, *J* = 8.2 Hz, 2H), 7.33 (d, *J* = 8.2 Hz, 2H), 5.56-5.45 (m, 1H), 4.97-4.88 (m, 2H), 3.32-3.25 (m, 4H), 2.44 (s, 3H), 2.36-2.29 (m, 1H), 2.09-2.02 (m, 1H), 1.07 (d, *J* = 6.8 Hz, 3H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 177.2, 145.0, 136.8, 135.1, 130.0, 127.5, 117.3, 39.7, 38.5, 33.3, 21.8, 17.5.

HRMS (ESI): *m/z* [(M+Na)$^+$] calcd for $C_{14}H_{19}NNaO_3S$: 304.0978; found: 304.0982.

***N*-Methyl-2-phenethyl-*N*-tosylpent-4-enamide (8ga) (Figure 2).** According to the General Procedure, a crude product, which was prepared from ynamide **6g** (188.1 mg, 0.600 mmol), **2a** (0.60 mL of 1.0 M solution in toluene, 0.6 mmol), [Au(IPr)Cl] (0.006 mmol, 1 mol%), and $AgNTf_2$ (0.006 mmol, 1 mol% to a substrate) in toluene (1.2 mL) at 80 °C for 24 h, was purified by column chromatography on silica gel (*n*-hexane/EtOAc = 40/1) to give **8ga** (188.4 mg, 85% yield) as a colorless liquid.

IR (neat): 2925, 1736, 1697, 1640, 1598 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.67 (d, *J* = 8.1 Hz, 2H), 7.25 (d, *J* = 8.1 Hz, 2H), 7.20-7.16 (m, 2H), 7.12-7.09 (m, 1H), 7.00 (d, *J* = 6.6 Hz, 2H), 5.48-5.40 (m, 1H), 4.89-4.82 (m, 2H), 3.19 (s, 3H), 3.15-3.10 (m, 1H), 2.38-2.21 (m, 6H), 2.13-2.09 (m, 1H), 1.88-1.84 (m, 1H), 1.70-1.65 (m, 1H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 176.0, 144.9, 141.3, 136.7, 134.6, 129.8, 128.4, 128.3, 127.6, 126.0, 117.4, 44.2, 36.8, 33.7, 33.1, 33.0, 21.6.

HRMS (ESI): *m/z* [(M+Na)$^+$] calcd for $C_{21}H_{25}NNaO_3S$: 394.1447; found: 394.1443.

2-(2-((*tert*-Butyldimethylsilyl)oxy)ethyl)-*N*-methyl-*N*-tosylpent-4-enamide (8ha) (Figure 2). According to the General Procedure, a crude product, which was prepared from ynamide **6h** (220.1 mg, 0.599 mmol), **2a** (0.60 mL of 1.0 M solution in toluene, 0.6 mmol), [Au(IPr)Cl] (0.006 mmol, 1 mol%), and $AgNTf_2$ (0.006 mmol, 1 mol% to a substrate) in toluene (1.2 mL) at 80 °C for 24 h, was purified by column chromatography on silica gel (*n*-hexane/EtOAc = 30/1) to give **8ha** (228.0 mg, 89% yield) as a colorless liquid.

IR (neat): 2929, 1697, 1598, 1471 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ =7.80 (d, *J* = 8.4 Hz, 2H), 7.31 (d, *J* = 8.4 Hz, 2H), 5.60-5.54 (m, 1H), 4.96-4.90 (m, 2H), 3.54-3.49 (m, 1H), 3.44-3.38 (m, 1H), 3.36-3.33 (m, 4H), 2.43 (s, 3H), 2.33-2.26 (m, 1H), 2.20-2.14 (m, 1H), 1.86-1.80 (m, 1H), 1.63-1.57 (m, 1H), 0.87 (s, 9H), 0.01 (s, 6H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 176.3, 144.7, 136.8, 134.8, 129.7, 127.9, 117.4, 60.5, 41.2, 36.9, 35.1, 33.3, 26.0, 21.7, 18.4, -5.3.

HRMS (ESI): *m/z* [(M+Na)$^+$] calcd for $C_{21}H_{35}NNaO_4SSi$: 448.1948; found: 448.1943.

3-(2-Allylhexanoyl)oxazolidin-2-one (8ia) (Figure 2). According to the General Procedure, a crude product, which was prepared from ynamide **6i** (99.7 mg, 0.596 mmol), **2a** (0.60 mL of 1.0 M solution in toluene, 0.6 mmol), [Au(IPr)Cl] (0.006 mmol, 1 mol%), and $AgNTf_2$ (0.006 mmol, 1 mol% to a substrate) in toluene (1.2 mL) at 80 °C for 24 h, was purified by column chromatography on silica gel (*n*-hexane/EtOAc = 8/1) to give **8ia** (100.9 mg, 75% yield) as a colorless liquid.

IR (neat): 2930, 2860, 1779, 1697, 1641, 1480 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.82-5.72 (m, 1H), 5.07-4.98 (m, 2H), 4.41-4.36 (m, 2H), 4.06-3.98 (m, 2H), 3.94-3.87 (m, 1H), 2.44-2.36 (m, 1H), 2.29-2.22 (m, 1H), 1.73-1.67 (m, 1H), 1.58-1.46 (m, 1H), 1.31-1.25 (m, 4H), 0.87 (t, *J* = 7.0 Hz, 3H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 176.4, 153.4, 135.6, 116.9, 61.7, 42.8, 42.3, 36.5, 31.5, 29.3, 22.8, 14.0.

HRMS (EI): *m/z* [(M-H)$^+$] calcd for $C_{12}H_{19}NO_3$: 225.1365; found: 225.1366.

***N*-Methyl-2-(2-methylallyl)-*N*-tosylhexanamide (8ab) (Figure 3).** According to the General Procedure, a crude product, which was prepared from ynamide **6a** (157.2 mg, 0.592 mmol), allylic alcohol **2b** (0.60 mL of 1.0 M solution in toluene, 0.6 mmol), [Au(IPr)Cl] (0.006 mmol, 1 mol%), and $AgNTf_2$ (0.006 mmol, 1 mol% to a substrate) in toluene (1.2 mL) at 80 °C for 24 h, was purified by column chromatography on silica gel (*n*-hexane/EtOAc = 8/1) to give **8ab** (172.0 mg, 85% yield) as a colorless liquid.

IR (neat): 2931, 1698, 1597, 1456 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.76 (d, *J* = 8.5 Hz, 2H), 7.32 (d, *J* = 8.5 Hz, 2H), 4.69 (s, 1H), 4.57 (s, 1H), 3.34-3.21 (m, 4H), 2.44 (s, 3H), 2.33 (dd, *J* = 13.7, 7.0 Hz, 1H), 2.04 (dd, *J* = 13.7, 7.4 Hz, 1H), 1.63 (s, 3H), 1.56-1.48 (m, 1H), 1.41-1.31 (m, 1H), 1.21-1.11 (m, 2H), 1.06-0.90 (m, 2H), 0.78 (t, *J* = 7.4 Hz, 3H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 176.9, 144.8, 142.7, 136.8, 129.8, 127.5, 112.8, 43.6, 40.7, 33.4, 32.1, 29.3, 22.8, 22.4, 21.7, 14.0.

HRMS (ESI): *m/z* [(M+H)$^+$] calcd for $C_{18}H_{28}NO_3S$: 338.1784; found: 338.1785.

***N*-Methyl-2-(2-phenylallyl)-*N*-tosylhexanamide (8ac) (Figure 3).** According to the General Procedure, a crude product, which was prepared from ynamide **6a** (161.5 mg, 0.608 mmol), allylic alcohol **2c** (1.2 mL of 1.0 M solution in toluene, 1.2 mmol), [Au(IPr)Cl] (0.006 mmol, 1 mol%), and $AgNTf_2$ (0.006 mmol, 1 mol% to a substrate) in toluene (1.2 mL) at 80 °C for 24 h, was purified by column chromatography on silica gel (*n*-hexane/EtOAc = 15/1) to give **8ac** (217.7 mg, 89% yield) as a colorless liquid.

IR (neat): 2956, 1696, 1598, 1495, 1455, 1357 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.56 (d, *J* = 8.5 Hz, 2H), 7.30-7.15 (m, 7H), 5.09 (s, 1H), 4.86 (s, 1H), 3.07-2.98 (m, 4H), 2.81-2.75 (m, 1H), 2.55-2.49 (m, 1H), 2.34 (s, 3H), 1.50-1.45 (m, 1H), 1.35-1.29 (m, 1H), 1.07-1.00 (m, 2H), 0.95-0.86 (m, 1H), 0.81-0.72 (m, 1H), 0.68 (t, *J* = 7.2 Hz, 3H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 176.6, 145.4, 144.6, 140.4, 136.7, 129.6, 128.5, 127.8, 127.7, 126.4, 115.2, 43.7, 38.3, 33.1, 32.6, 29.1, 22.8, 21.7, 13.9.

HRMS (ESI): *m/z* [(M+H)$^+$] calcd for $C_{23}H_{30}NO_3S$: 400.1941; found: 400.1937.

2-Butyl-*N*-methyl-*N*-tosylhepta-4,6-dienamide (8ad) (Figure 3). According to the General Procedure, a crude product, which was prepared from ynamide **6a** (158.0 mg, 0.595 mmol), allylic alcohol **2d** (1.2 mmol), [Au(IPr)Cl] (0.006 mmol, 1 mol%), and $AgNTf_2$ (0.006 mmol, 1 mol% to a substrate) in toluene (1.2 mL) at 80 °C for 24 h, was purified by column chromatography on silica gel (*n*-hexane/EtOAc = 10/1) to give **8ad** (168.7 mg, 81% yield) as a colorless liquid.

IR (neat): 2957, 1697, 1598, 1357, 1163 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.74 (d, *J* = 8.1 Hz, 2H), 7.32 (d, *J* = 8.1 Hz, 2H), 6.20-6.12 (m, 1H), 5.97-5.90 (m, 1H), 5.38-5.30 (m, 1H), 5.09-4.96 (m, 2H), 3.31 (s, 3H), 3.23-3.16 (m, 1H), 2.44 (s, 3H), 2.35-2.27 (m, 1H), 2.18-2.10 (m, 1H), 1.63-1.54 (m, 1H), 1.45-1.35 (m, 1H), 1.22-1.15 (m, 2H), 1.09-1.02 (m, 2H), 0.81 (t, *J* = 7.2 Hz, 3H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 176.7, 144.9, 137.0, 136.9, 133.4, 131.2, 130.0, 127.6, 116.0, 45.5, 35.8, 33.4, 32.5, 29.4, 22.9, 21.8, 14.0.

HRMS (ESI): *m/z* [(M+H)$^+$] calcd for $C_{19}H_{28}NO_3S$: 350.1784; found: 350.1781.

Diastereoselective Reaction of Ynamides with Allylic Alcohols (Figure 4)

2-(1-Methyl-2-propenyl)-*N*-methyl-*N*-tosylhexanamide (8ae). According to the General Procedure, the reaction of ynamide **6a** (157.8 mg, 0.595 mmol), allylic alcohol (*E*)-**2e** (1.2 mL of 1.0 M solution in toluene, 1.2 mmol), [Au(IPr)Cl] (0.006 mmol, 1 mol%), and $AgNTf_2$ (0.006 mmol, 1 mol% to a substrate) was carried out in toluene (1.2 mL) at 80 °C for 24 h, from which **8ae** (130.1 mg, 65% yield) was obtained as a colorless liquid as a mixture of diastereomers (*syn*/*anti* = 30/70)) after purification by column chromatography on silica gel (*n*-hexane/EtOAc = 40/1).

In a similar manner, the reaction of ynamide **6a** (158.4 mg, 0.597 mmol), allylic alcohol (*Z*)-**2e** (1.2 mL of 1.0 M solution in toluene, 1.2 mmol), [Au(IPr)Cl] (0.006 mmol, 1 mol%), and $AgNTf_2$ (0.006 mmol, 1 mol% to a substrate) in toluene (1.2 mL) at 80 °C for 24 h gave **8ae** (139.3 mg, 69% yield, a mixture of diastereomers (*syn*/*anti* = 92/8)) as a colorless liquid.

Spectral data of **8ae** (a mixture of diastereomers)

IR (neat): 2959, 1695, 1597, 1465, 1358 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.77 (d, *J* = 8.1 Hz, 2H), 7.32 (d, *J* = 8.1 Hz, 2H), 5.62-5.52 (m, 1H), 4.98-4.92 (m, 2H, *anti*), 4.88-4.82 (m, 2H, *syn*), 3.37 (s, 3H, *anti*), 3.31 (s, 3H, *syn*), 3.04-2.98 (m, 1H), 2.44-2.34 (m, 4H), 1.58-1.36 (m, 2H), 1.21-1.08 (m, 2H), 0.96-0.89 (m, 5H), 0.80-0.73 (m, 3H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 176.4 (*anti*), 176.1 (*syn*), 144.8 (*syn*), 144.7 (*anti*), 141.2 (*syn*), 140.9 (*anti*), 137.0 (*syn*), 136.9 (*anti*), 129.7, 127.9 (*syn*), 127.8 (*anti*), 115.2 (*anti*), 114.6 (*syn*), 50.1 (*syn*), 49.8 (*anti*), 41.5 (*anti*), 40.4 (*syn*), 33.5 (*syn*), 33.3 (*anti*), 30.6 (*anti*), 29.4 (*syn*), 29.3 (*anti*), 29.2 (*syn*), 22.9, 21.7, 18.4 (*anti*), 16.1 (*syn*), 13.9.

HRMS (ESI): *m/z* [(M+H)$^+$] calcd for $C_{18}H_{28}NO_3S$: 338.1784; found: 338.1784.

***N*,2,3-Trimethyl-*N*-tosylpent-4-enamide (8fe).** According to the General Procedure, the reaction of ynamide **6f** (130.0 mg, 0.58 mmol), allylic alcohol (*E*)-**2e** (1.2 mL of 1.0 M solution in toluene, 1.2 mmol), [Au(IPr)Cl] (0.006 mmol, 1 mol%), and $AgNTf_2$ (0.006 mmol, 1 mol% to a substrate) was carried out in toluene (1.2 mL) at 80 °C for 24 h, from which **8fe** (130.8 mg, 76% yield) was obtained as a colorless liquid as a mixture of diastereomers (*syn*/*anti* = 22/78)) after purification by column chromatography on silica gel (*n*-hexane/EtOAc = 40/1).

In a similar manner, the reaction of ynamide **6f** (131.04 mg, 0.58 mmol), allylic alcohol (*Z*)-**2e** (1.2 mL of 1.0 M solution in toluene, 1.2 mmol), [Au(IPr)Cl] (0.006 mmol, 1 mol%), and $AgNTf_2$ (0.006 mmol, 1 mol% to a substrate) in toluene (1.2 mL) at 80 °C for 24 h gave **8fe** (129.9 mg, 75% yield, a mixture of diastereomers (*syn*/*anti* = 78/22)) as a colorless liquid.

Spectral data of **8fe** (a mixture of diastereomers)

IR (neat): 2971, 1967, 1597, 1455, 1357, 1308 cm^{-1}.

^1H NMR (400 MHz, $CDCl_3$): δ = 7.76 (d, *J* = 8.3 Hz, 2H), 7.33 (d, *J* = 8.3 Hz, 2H), 5.57-5.47 (m, 1H, *anti*), 5.42-5.33 (m, 1H, *syn*), 4.99-4.94 (m, 2H, *anti*), 4.87-4.75 (m, 2H, *syn*), 3.34 (s, 3H, *anti*), 3.28 (s, 3H, *syn*), 3.15-3.06 (m, 1H, *syn*), 3.06-3.00 (m, 1H, *anti*), 2.44-2.32 (m, 4H), 1.01 (d, *J* = 6.6 Hz, 3H, *syn*),

0.96 (d, *J* = 6.6 Hz, 3H, *anti*), 0.91 (d, *J* = 6.6 Hz, 3H, *syn*), 0.73 (d, *J* = 6.6 Hz, 3H, *anti*).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 177.3 (*anti*), 176.9 (*syn*), 144.9, 141.3 (*syn*), 140.7 (*anti*), 137.0, 129.9 (*anti*), 129.8 (*syn*), 127.6 (*anti*), 127.5 (*syn*), 115.6 (*anti*), 114.6 (*syn*), 44.9 (*syn*), 44.6 (*anti*), 42.1 (*anti*), 41.2 (*syn*), 33.2, 21.7, 18.6 (*anti*), 16.2, 14.7 (*syn*).

HRMS (ESI): *m/z* [(M+Na)$^+$] calcd for $C_{15}H_{21}NNaO_3S$: 318.1134; found: 318.1139.

Determination of Relative Configuration of 8fe (Figure 5). 2,3-Dimethylpent-4-enoic acid (9). A solution of **8fe** (*dr* = 78:22, 87.5 mg, 0.30 mmol), which was obtained from the reaction of **6f** and (*E*)-**2e**, in THF (0.3 mL) was added to a cooled solution of LiOH·H_2O (27.7 mg, 0.6 mmol) and H_2O_2 (30% (v/v) aqueous solution, 0.3 mL, 1.2 mmol), and the mixture was stirred at 50 °C for 16 h. The solution was washed with CH_2Cl_2 (3 × 15 mL), then the aqueous phase was acidified and extracted with CH_2Cl_2 (3 × 15 mL). The combined organic extracts were washed with brine and dried over $MgSO_4$. After removal of the solvent, the crude material was obtained as an enough quality for comparison with ^{1}H-NMR of known compounds in the literature. By comparison, we found that *anti*-**8fe** was formed as the major product in reaction of **6f** and (*E*)-**2e**.

Spectral data of **9**: a mixture of diastereomers (*syn*/*anti* = 24/76)

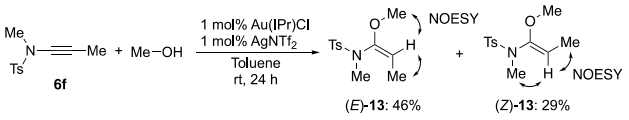
IR (neat): 3080, 2976, 1707, 1460, 1291 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 11.35 (brs, 1H), 5.84-5.73 (m, 1H, *syn*), 5.70-5.61 (m, 1H, *anti*), 5.09-5.00 (m, 2H), 2.55-2.31 (m, 2H), 1.14-1.00 (m, 6H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 141.3, 140.6, 115.5, 114.8, 45.0, 44.6, 40.9, 40.2, 18.5, 16.1, 14.5, 13.3.

HRMS (ESI): *m/z* [(M-H)$^-$] calcd for $C_7H_{11}O_2$: 127.0765; found: 127.0761.

Reaction of 6f with MeOH (Figure 7, eq.1). According to the General Procedure, a crude product, which was obtained from ynamide **6f** (100.0 mg, 0.447 mmol), MeOH (0.45 mmol), [Au(IPr)Cl] (0.0045 mmol, 1 mol%), and $AgNTf_2$ (0.0045 mmol, 1 mol% to a substrate) in toluene (0.9 mL) at 80 °C for 24 h, was purified by column chromatography on silica gel (*n*-hexane/EtOAc = 10/1) to give (*E*)-**13** (52.0 mg, 46% yield) and (*Z*)-**13** (33.2 mg, 29% yield) as a colorless liquid, respectively. The geometry of the olefin in (*E*)-**13** and (*Z*)-**13** was determined by the NOESY spectrum of each compound, as shown in the below Figure.



(*E*)-*N*-(1-Methoxyprop-1-en-1-yl)-*N*,4-dimethylbenzenesulfonamide ((*E*)-13).

IR (CH_2Cl_2): 2942, 1681, 1599, 1453. 1349, 1272 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.74 (d, *J* = 8.6 Hz, 2H), 7.28 (d, *J* = 8.6 Hz, 2H), 4.61 (q, *J* = 6.6 Hz, 1H), 3.44 (s, 3H), 2.88 (s, 3H), 2.42 (s, 3H), 1.73 (d, *J* = 6.8 Hz, 3H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 150.0, 143.4, 136.1, 129.4, 128.2, 95.4, 55.3, 35.7, 21.7, 12.0.

HRMS (ESI): *m/z* [(M+Na)$^+$] calcd for $C_{12}H_{17}NNaO_3S$: 278.0821; found: 278.0825.

(*Z*)-*N*-(1-Methoxyprop-1-en-1-yl)-*N*,4-dimethylbenzenesulfonamide ((*Z*)-13).

IR (CH_2Cl_2): 2941, 1680, 1599, 1453, 1349, 1273 cm^{-1}.

^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.71 (d, *J* = 8.2 Hz, 2H), 7.31 (d, *J* = 8.2 Hz, 2H), 4.23 (q, *J* = 6.9 Hz, 1H), 3.57 (s, 3H), 2.96 (s, 3H), 2.43 (s, 3H), 1.55 (d, *J* = 6.8 Hz, 3H).

^{13}C NMR (100 MHz, $CDCl_3$): δ = 148.6, 143.8, 135.0, 129.6, 128.0, 102.6, 56.2, 37.8, 21.7, 10.6.

HRMS (ESI): *m/z* [(M+Na)$^+$] calcd for $C_{12}H_{17}NNaO_3S$: 278.0821; found: 278.0819.

Acknowledgment

This work was financially supported in part by Grants-in Aid for Scientific Research (B) (No. 20H0360) and Scientific Research (C) (No. 20K06960) from the Japan Society of the Promotion of Science (JSPS). The Nagase Science and Technology Foundation (for YS) and the Akiyama Life Science Foundation (for YO) are also acknowledged for financial support. SPN thanks the UGent BOF for starting and advanced grants.

Supporting Information

Is there **Supporting Information** to be published? Click here to indicate YES or NO (text and links will be updated prior to publication).

Conflict of Interest

There are no conflicts to declare.

References

(1) For selected reviews, see: (a) Alonso, F.; Beletskaya, I. P.; Yus, M. *Chem. Rev.* **2004**, *104*, 3079. (b) Evano, G.; Gaumont, A. C.; Alayrac, C.; Wrona, I. E.; Giguere, J. R.; Delacroix, O.; Bayle, A.; Jouvin, K.; Theunissen, C.; Gatignol, J.; Silvanus, A. C. *Tetrahedron* **2014**, *70*, 1529.

(2) For selected reviews, see: (a) Hashmi, A. S. K. *Gold Bull.* **2004**, *37*, 51. (b) Hashmi, A. S. K.; Hutchings, G. J. *Angew. Chem., Int. Ed.* **2006**, *45*, 7896. (c) Marion, N.; Nolan, S. P. *Chem. Soc. Rev.* **2008**, *37*, 1776. (d) Krause, N.; Winter, C. *Chem. Rev.* **2011**, *111*, 1994. (e) Goodwin, J. A.; Aponick, A. *Chem. Commun.* **2015**, *51*, 8730. (f) Dorel, R.; Echavarren, A. M. *Chem. Rev.* **2015**, *115*, 9028. (g) Hu, Y.-C.; Zhao, Y.; Wan, B.; Chen, Q.-A. *Chem. Soc. Rev.* **2021**, *50*, 2582. (h) Campeau, D.; Leoń, D. F. R.; Mansour, A.; Muratov, K.; Gagosz, F. DOI: 10.1021/acs.chemrev.0c00788.

(3) Ketcham, J. M.; Biannic, B.; Aponick, A. *Chem. Commun.* **2013**, *49*, 4157.

(4) Gomez-Suárez, A.; Gasperini, D.; Vummaleti, S. V. C.; Poater, A.; Cavallo, L.; Nolan, S. P. *ACS Catal.* **2014**, *4*, 2701.

(5) For selected examples of gold-catalyzed nucleophilic addition of oxygen atom to alkyne followed by [3,3]-rearrangement, see: (a) 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. (b) Ueda, M.; Sato, A.; Ikeda, Y.; Miyoshi, T.; Naito, T.; Miyata, O. *Org. Lett.* **2010**, *12*, 2594. (c) Istrate, F. M.; Gagosz, F. Beilstein *J. Org. Chem.* **2011**, *7*, 878. (d) Park, S. R.; Kim, C.; Kim, D.-G.; Thrimurtulu, N.; Yeom, H.-S.; Jun, J.; Shin, S.; Rhee, Y. H. *Org. Lett.* **2013**, *15*, 1166. (e) Wu, H.; Zi, W.; Li, G.; Lu, H.; Toste, F. D. *Angew. Chem., Int. Ed.* **2015**, *54*, 8529.

(6) For a recent review on the chemistry of ynol ethers, see: Gray, V. J.; Wilden, J. D. *Org. Biomol. Chem.* **2016**, *14*, 9695. For recent reviews on the chemistry of ynamides, see: (b) Evano, G.; Coste, A.; Jouvin, K. *Angew. Chem. Int. Ed.* **2010**, *49*, 2840. (c) DeKorver, K. A.; Li, H.; Lohse, A. G.; Hayashi, R.; Lu, Z.; Zhang, Y.; Hsung, R. P. *Chem. Rev.* **2010**, *110*, 5064. (d) Wang, X.-N.; Yeom, H.-S.; Fang, L.-C.; He, S.; Ma, Z.-X.; Kedrowski, B. L.; Hsung, R. P. *Acc. Chem. Res.* **2014**, *47*, 560.

(7) For our report on transition metal catalysis utilizing ynol ethers as a platform, see: (a) Saito, N.; Sun, Z.; Sato, Y. *Chem. Asian J.* **2015**, *10*, 1170. For our reports on transition metal catalysis utilizing ynamide as a platform, see: (b) Saito, N.; Katayama, T.; Sato, Y. *Org. Lett.* **2008**, *10*, 3829. (c) Saito, N.; Katayama, T.; Sato, Y. *Heterocycles* **2011**, *82*, 1181. (d) Saito, N.; Saito, K.; Shiro, M.; Sato, Y. *Org. Lett.* **2011**, *13*, 2718. (e) Saito, N.; Ichimaru, T.; Sato, Y. *Org. Lett.* **2012**, *14*, 1914. (f) Saito, N.; Saito, K.; Sato, H.; Sato, Y. *Adv. Synth. Catal.* **2013**, *355*, 853. (g) Saito, N.; Abdullah, I.; Hayashi, K.; Hamada, K.; Koyama, M.; Sato, Y. *Org. Biomol. Chem.* **2016**, *14*, 10080. (h) Doi, R.; Abdullah, I.; Taniguchi, T.; Saito, N.; Sato, Y. *Chem. Commun.* **2017**, *53*, 7720. (i) Doi, R.; Okano, T.; Abdullah, I.; Sato, Y. *Synlett* **2019**, *30*, 1048.

(8) Liu et al. reported that γ,δ-unsaturated amides were produced as undesired products in some cases in their study on Au(I)-catalyzed

1,4-carbooxygenation of 3-ene-1-ynamide with allylic alcohol, see: Giri, S.S.; Lin. L.-H.; Jadhav, P. D.; Liu, R.-S. *Adv. Synth. Catal.* **2017**, *359*, 590.

(9) Other examples of hydroalkoxylation/Claisen rearrangement cascades of ynamides and/or aryl ynol ether with allylic alcohol; Brønsted acid-catalyzed reaction: (a) Mulder, J. A.; Hsung, R. P.; Frederick, M. O.; Tracey, M. R.; Zificsak, C. A. *Org. Lett.* **2002**, *4*, 1383. (b) Frederick, M. O.; Hsung, R. P.; Lambeth, R. H.; Mulder, J. A.; Tracey, M. R. *Org. Lett.* **2003**, *5*, 2663. Zn- or Sc-catalyzed reaction: (c) Grimster, N. P.; Wilton, D. A. A.; Chan, L. K. M.; Godfrey, C. R. A.; Green, C.; Owen, D. R.; Gaunt, M. J. *Tetrahedron* **2010**, *66*, 6429. Yttrium-catalyzed intramolecular reaction: (d) Zhou, B.; Li, L.; Zhu, X.-Q.; Yan, J.-Z.; Guo, Y.-L.; Ye, L.-W. *Angew. Chem. Int. Ed.* **2017**, *56*, 4015. Yttrium-catalyzed intermolecular reaction: (e) Zhou, B.; Li, L.; Liu, X.; Tan, T.-D.; Lin, J.; Ye, L.-W. *J. Org. Chem.* **2017**, *82*, 10149.

(10) Ricard, L.; Gagosz, F. *Organometallics* **2007**, *26*, 4704.

(11) For recent examples for the reaction using [Au(IPr)NTf_2] as a catalyst, see: (a) Pirovano, V.; Brambilla, E.; Rizzato, S.; Abbiati, G.; Bozzi, M.; Rossi, E. *J. Org. Chem.* **2019**, *84*, 5150. (b) Virumbrales, C.; Solas, M.; Suárez-Pantiga, S.; Fernández-Rodríguez, M. A.; Marín-Luna, M.; Silva López, C.; Sanz, R. *Org. Biomol. Chem.* **2019**, *17*, 9924. (c) Dubovtsev, A. Y.; Shcherbakov, N. V.; Dar'in, D. V.; Kukushkin, V. Y. *Adv. Synth. Catal.* **2020,** *362*, 2672. (d) Gómez-Herrera, A.; Hashim, I. I.; Porré, M.; Nahra, F.; Cazin, C. S. J. *Eur. J. Org. Chem.* **2020**, 6790. (e) Zimin, D. P.; Dar'in, D. V.; Kukushkin, V. Y.; Dubovtsev, A. Y. *J. Org. Chem.* **2021**, *86*, 1748 and references therein.

(12) Metz, P.; Hungerhoff, B. *J. Org. Chem.* **1997**, *62*, 4442.

(13) For a representative report, see: Vance, R. L.; Rondan, N. G.; Houk, K. N.; Jensen, F.; Borden, W. T.; Komornicki, A.; Wimmer, E. *J. Am. Chem. Soc.* **1988**, *110*, 2314.

(14) Hu, L.; Gui, Q.; Chan, X.; Tan, Z.; Zhu, G. *J. Org. Chem.* **2016**, *81*, 4861.

(15) Jouvin, K.; Bayle, A.; Legrand, F.; Evano, G. *Org. Lett.* **2012**, *14*, 1652.

(16) Zhang, Y.; Hsung, R. P.; Tracey, M. R.; Kurtz, K. C. M.; Vera, E. L. *Org. Lett.* **2004**, *6*, 1151.

(17) Hamada, T.; Ye, X.; Stahl, S. S. *J. Am. Chem. Soc*. **2008**, *130*, 833.

(18) Yasui, H.; Yorimitsu, H.; Oshima, K. *Chem. Lett.* **2008**, *37*, 40.