Organic LETTERS

Letter

pubs.acs.org/OrgLett

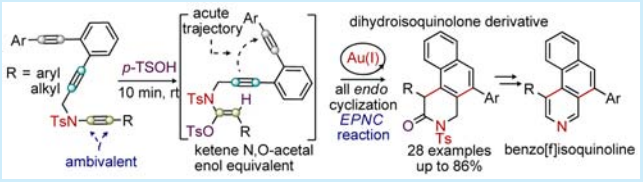
p-TsOH Promoted Au(I)-Catalyzed Consecutive Endo Cyclization of Yne-Tethered Ynamide: Access to Benzofused Dihydroisoquinolones

Sanatan Nayak, Nayan Ghosh, B. Prabagar, and Akhila K. Sahoo*

School of Chemistry, University of Hyderabad, Hyderabad-500046, India

Supporting Information

ABSTRACT: A novel synthetic route to benzo[*f*]dihydroisoquinolone through a *p*-TsOH promoted cascade cyclization of easily accessible diyne-tethered ynamides in the presence of a Au(I)-catalyst is described. This reaction unveils a broad substrate scope, constructing a wide range of benzo[*f*]dihydroisoquinolones in good yields. The diyne-tethered ynamides are synthesized from inexpensive *o*-iodoaniline through Sonogashira couplings and the Cu-mediated C−N bond formation. The role of *p*-TsOH is examined, and the reaction pathway is also deduced. The benzo[*f*]isoquinoline scaffold is constructed from benzo[*f*]dihydroisoquinolones.



Isoquinoline derivatives are potentially useful building blocks widely found in natural products and pharmaceutically active compounds (Figure 1).[1] In general, the isoquinoline frameworks

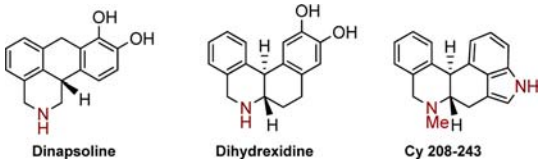
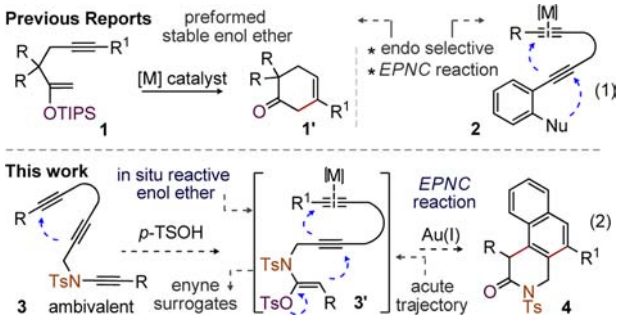


Figure 1. Isoquinoline derivatives containing natural products.

are readily manufactured from the dihydroisoquinolone motifs.[2] The benzo[*f*]isoquinolines, another class of fused N-heterocycles, structurally resemble the isoquinoline derivatives. Thus, the benzo[*f*]isoquinolines analogues, which can be easily accessed from benzo[*f*]dihydroisoquinolones, show interesting biological properties as do isoquinoline derivatives. With our current research interest in ynamides, we intend to investigate Au(I)-catalyzed cascade cyclization of diyne-tethered ynamide, which will eventually lead to the step-efficient synthesis of an unprecedented benzo[*f*]dihydroisoquinolone core (eq 2, Scheme 1).[3−5]

In general, the preformed alkyne-bearing enol-ethers **1** [alkyl/silyl enol ethers, and silyl ketene amides] are efficiently employed in Au-catalyzed cyclizations (Scheme 1).[6] In contrast, the intramolecular cyclization of an in situ generated vinyl-Au-species, formed through an *exo*/*endo*-cyclization of enol-ethers and a pendant alkyne moiety in **1**, with the tethered-yne motif, is less explored.[7] Likewise, cascade *electrophile promoted nucleophilic cyclization* (EPNC) of diyne-bearing species **2** directly constructs polyfused heterocycles in a single operation; these transformations explicitly involve 5-*endo*-dig/6-*endo*-dig cyclizations.[8] Despite this notable success, the cascade reaction of diyne-tethered ynamide is so far unprecedented (Scheme 1). We thus envisaged the formation of benzo[*f*]dihydroisoquinolone **4**

Scheme 1. Ynamide As Enol Equivalent for Cascade Cyclization/1,5-Enyne Cycloisomerization Strategy



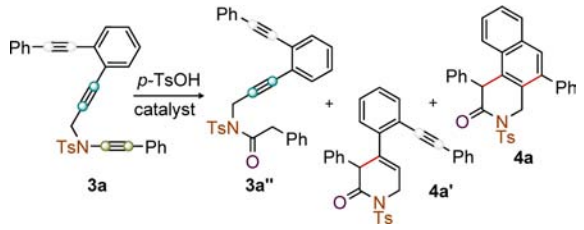
through the cascade EPNC reaction of transient enol-ether **3′** (ketene *N*,*O*-acetal), readily generated involving the facile attack of *p*-TsOH to the ambivalent ynamide **3** in situ (eq 2, Scheme 1).[9] We could foresee a 6-*endo*-dig cyclization of **3′** with the suitably substituted yne motif in the presence of a Au(I)-catalyst to form a six-membered vinyl-gold intermediate, a perfect 1,5-enyne precursor, which subsequently undergoes cyclization followed by aromatization to result **4** (eq 2, Scheme 1).[10] We herein show a convergent synthetic manifestation engendering benzo[*f*]dihydroisoquinolones from easily accessible diyne-tethered ynamides through Au-catalysis in the presence of *p*-TsOH.

To directly access the benzo[*f*]dihydroisoquinolone skeleton, investigation was initiated to examining Brønsted acid promoted Au(I)-catalyzed consecutive *endo*-cyclizations of diyne-tethered ynamide **3a**. Accordingly, compound **3a** was synthesized from the inexpensive 2-iodoaniline involving consecutive Sonogashira reactions followed by C−N bond formation in four steps with overall appreciable yield.[11] The ynamide unit is usually

Received: October 12, 2015
Published: November 2, 2015

DOI: 10.1021/acs.orglett.5b02946
Org. Lett. 2015, 17, 5662−5665

Table 1. Optimization of the Reaction Conditions[a]



entry	catalyst (mol %)[b]	solvent	yield (%)[c] 3a″	4a′	4a
1	**A** (5)	CH_3CN	–		
2	**A** (5)	dioxane	6	35	50
3	**A** (5)	dioxane	80	–	–
4	**B** (5)	dioxane	45	20	20
5	**C** (5)	dioxane	10	35	40
6	**D** (5)	dioxane	–	40	48
7	**E** (5)	dioxane	79	5	–
8	**F** (5)	dioxane	82	–	–
9	**A** (5)	DCE	trace	–	–
10	**A** (5)	dioxane/DCE	0	25	62
11[d]	**A (5)**	**dioxane/DCE**	**0**	**5**	**83**
12[d]	**B** (5)	dioxane/DCE	–	30	60
13[d]	**D** (5)	dioxane/DCE	–	30	50
14	**G** (5)	dioxane/DCE	85	–	–
15	**H** (5)	dioxane/DCE	82	–	–

[a]Reactions were carried out using **3a** (0.2 mmol), *p*-TsOH (0.3 mmol), and catalyst (5.0 mol %) in solvent (3.0 mL) at rt−80 °C for 24 h. [b]Catalyst **A**: JohnphosAu(I) (NCMe)]$^+SbF_6^-$; **B**: JohnphosAuNTf$_2$; **C**: JohnphosAuCl + $AgSbF_6$; **D**: IPrAuCl + $AgSbF_6$; **E**: Ph_3PAuCl + $AgSbF_6$; **F**: Ph_3PAuCl + $AgNTf_2$; **G**: $AgSbF_6$; **H**: $AgNTf_2$. [c]Isolated yields. [d]Reaction was conducted by stirring **3a** and *p*-TsOH in dioxane for 10 min followed by addition of catalyst in DCE and continued for 4 h at rt, and finally heating the resulting mixture for 20 h at 80 °C.

responsive to acid catalysts and H_2O; we could thus anticipate the formation of amide **3a″**, dihydropyridinone **4a′**, and the desired **4a** from **3a** (Table 1).

To validate workable conditions for the construction of **4a**, an investigation was initiated exposing **3a** to *p*-TsOH (1.5 equiv) in the presence of Echavarren's catalyst A (5.0 mol %) in CH_3CN at room temperature (rt); to our dismay, **3a** did not survive, providing a complex mixture (entry 1). Gratifyingly, **4a** (50%) was isolated along with **3a″** (6%) and **4a′** (35%), when the reaction was performed in dioxane at rt (entry 2); in contrast, reaction at 80 °C exclusively delivered **3a″** (entry 3). The use of JohnphosAuNTf$_2$ led to a poor amount of **4a** (entry 4). The use of a combination of catalysts (JohnphosAuCl/IPrAuCl with $AgSbF_6$ and Ph_3PAuCl and $AgSbF_6$/$AgNTf_2$) was inferior (entries 5−8). Catalyst **A** thus appeared to be the best (entry 2). The effect of solvents was next surveyed. The reaction of **3a** with catalyst **A** and *p*-TsOH in $ClCH_2CH_2Cl$ (DCE) provided a trace amount of **3a″** with incomplete consumption of **3a** at 80 °C (entry 9); the inadequate solubility of *p*-TsOH in DCE is presumably responsible for the poor outcome. Results from entries 2 and 9 thus inspired us to scrutinize the mixture of solvents for this study. Interestingly, the reaction in dioxane and DCE (1:2) resulted in a 62% yield of **4a**, **4a′** (25%), and **3a″** (0%) at rt (entry 10). Due to this observation, the reaction was pursued by performing it at various temperatures through sequential addition of reagents.[11] Complete consumption of **3a** surprisingly occurred, when **3a** and *p*-TsOH were stirred in dioxane at rt for 10 min; subsequently, catalyst **A** in DCE was introduced and the reaction was continued at rt until the disappearance of the intermediate species; finally, heating the resulting mixture at 80 °C for 20 h led to **4a** in 83% yield (entry 11). Under the identical conditions in entry 11, other catalysts turned moderate (entries 12 and 13). Regrettably, reaction under Ag-catalysis exclusively provided **3a″** (entries 14 and 15).

We next set out to examine the scope of Au-catalyzed cascade cyclization of diyne-tethered ynamides **3** for the construction of benzo[*f*]dihydroisoquinolone skeletons **4** and **5** (Figures 2 and 3). First, ynamide **3** having a variation of substitutions on the aryl moiety on the alkyne terminus was surveyed under the catalytic conditions shown in entry 11, Table 1 (Figure 2). The ynamide **3a** produced **4a** in 83% yield. Interestingly, cascade cyclization of ynamides **3b** and **3c** (*o*-substitution on the aryl group) provided a 1:1 mixture of two atropisomers of the corresponding **4b** and **4c**

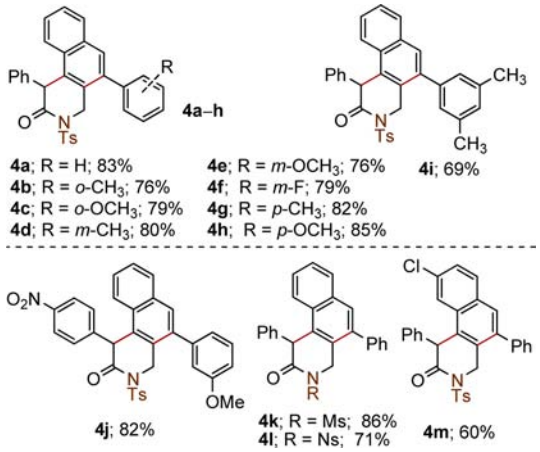


Figure 2. Substrate Scope **I**. Reactions were carried out using **3** (0.2 mmol), *p*-TsOH (0.3 mmol), catalyst **A** (5.0 mol %) in dioxane/DCE (1:2, 3.0 mL) at rt−80 °C for 24 h. Isolated yields.

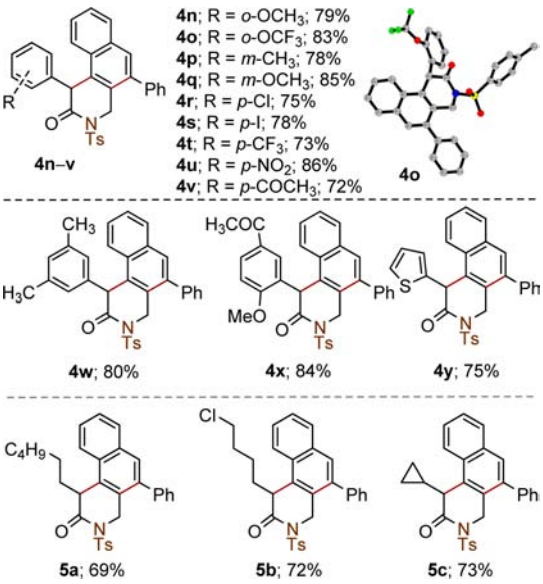


Figure 3. Substrate Scope **II**. Reactions were carried out using **3** (0.2 mmol), *p*-TsOH (0.3 mmol), catalyst **A** (5.0 mol %) in dioxane/DCE (1:2, 3.0 mL) at rt−80 °C for 24 h. Isolated yields.

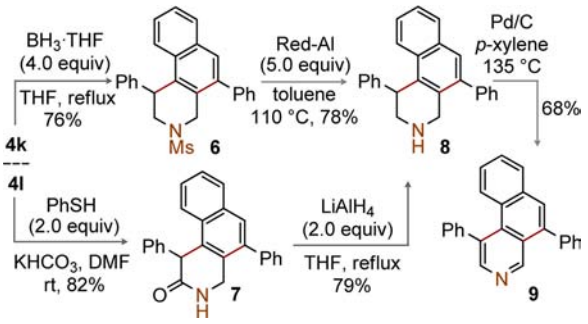
DOI: 10.1021/acs.orglett.5b02946
Org. Lett. 2015, 17, 5662−5665

in good yields. The *m*- and *p*-substitution on the aryl moiety in the alkyne terminus did not affect the reaction outcome affording **4d**–**f** (76–80%), **4g** (82%), **4h** (85%), and **4i** (69%). Ynamide **3j** [different aryl moiety on alkyne and ynamide terminus] smoothly underwent cascade cyclization to yield 82% of **4j**. The N-Ms/-Ns protecting groups were tolerated providing the desired **4k** and **4l** in good yields. Similarly, **4m** was constructed in 60% yield.

Next, the effect of substitutions on the ynamide terminus in **3** was examined for the Au-catalyzed cascade cyclization (Figure 3). The substitutions at the *o*-, *m*-, or *p*- position on the aryl moiety at the ynamide terminus in **3** did not show a pronounced effect, constructing the respective **4n**–**v** in good yields. The structure of **4o** was further confirmed by X-ray crystallographic analysis (Figure 3).[11] The modifiable functional groups $-NO_2$ and $-COCH_3$ were inert under the optimized conditions; the $-CF_3$, Cl, and I moieties did not show an adverse effect and were tolerated. Likewise, the benzo[*f*]dihydroisoquinolones **4w** (80%) and **4x** (84%) were readily accessed from **3w** and **3x** holding two-methyl or OMe and COMe substituents on the aryl moiety at the ynamide terminus. Gatifyingly, the thiophenyl bearing ynamide **3y** effectively underwent cyclization to provide **4y** in 75% yield. The effect of the aliphatic substituent at the ynamide terminus in **3** was next surveyed (Figure 3). Pleasingly, the alkyl moiety containing ynamides under the optimized conditions delivered the nonseparable mixture of rotamer of the designed products **5a**/**5a′** = 5:1 and **5b**/**5b′** = 7:1 in 69% and 72% yield, respectively.[11] The cyclopropyl group on the ynamide survived in the reaction, generating the mixture of rotamers **5c** and **5c′** = 4:1 in 73% yield.[11] Thus, the current method developed for benzo[*f*]dihydroisoquinolones synthesis from diyne-tethered ynamides proved to be general and broad (Figures 2 and 3).

We next explored the makeover of benzo[*f*]dihydroisoquinolone to benzo[*f*]isoquinoline. The B_2H_6 mediated amide reduction of **4k** followed by N-Ms deprotection of **6** with Red-Al furnished 1,5-diphenyl-1,2,3,4-tetrahydrobenzo[*f*]-isoquinoline **8** (Scheme 2). The reductive cleavage of the N-Ns

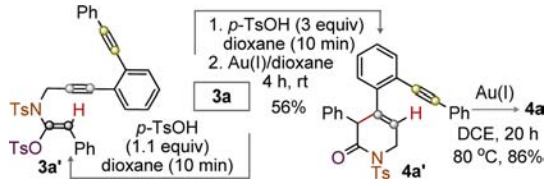
Scheme 2. Synthesis of Benzo[*f*]isoquinoline Derivative



moiety of **4l** provided **7**; subsequently $LiAlH_4$ reduction of the amide moiety of **7** directly led to **8** (Scheme 2). Finally, oxidative dehydrogenation of **8** with Pd/C delivered 1,5-diphenylbenzo-[*f*]isoquinoline **9** in 68% yield (Scheme 2).[11]

The participation of transient ketene *N*,*O*-acetal **3a′** (outlined in eq 2, Scheme 1) for the synthesis of **4** from **3** under the Au(I)-catalyzed cascade cyclization is established with the characterization of **3a′** (NMR and HRMS study), which is rapidly obtained in situ from **3a** and *p*-TsOH in dioxane at rt in 10 min (Scheme 3). Furthermore, the isolation of monocyclic species

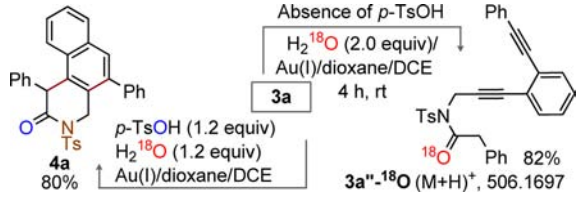
Scheme 3. Control Experiment



4a′ confirms the participation of the Au-vinyl complex (Scheme 3), when the reaction was performed with the Au-catalyst and *p*-TsOH (3.0 equiv) in dioxane for 4 h at rt. Subsequently, heating **4a′** with a Au-catalyst in DCE at 80 °C delivered **4a** (Scheme 3).[9a,b]

To further support the involvement of **3a′** and the source of oxygen in this transformation, the reaction of **3a** with a Au-catalyst in $H_2{}^{18}O$ (in the absence of *p*-TsOH) was conducted. The amide product **3a″-^{18}O** with the insertion of ^{18}O has exclusively been obtained (HRMS, Scheme 4).[11] While the

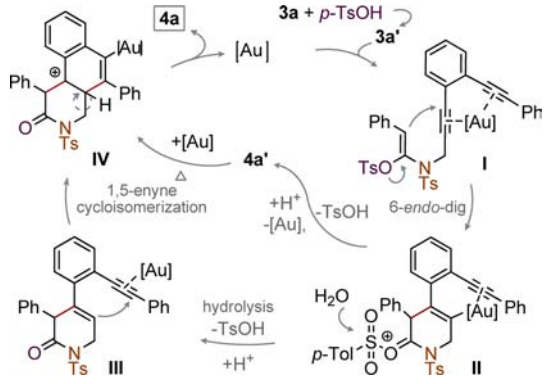
Scheme 4. Isotopic Labeling Experiment



reaction of **3a** with *p*-TsOH in $H_2{}^{18}O$ under Au-catalysis delivered **4a** (80%); the incorporation of ^{18}O is not observed (HRMS, Scheme 4).[11] It appears that the attack of *p*-TsOH to **3a** is facile over H_2O, resulting in the rapid formation of enol-ether **3a′** (Scheme 3).

On the basis of the studies shown in Schemes 3 and 4, the probable mechanistic path for the synthesis of **4** from **3** is deduced (Scheme 5).[5e] The reaction initiates with the formation

Scheme 5. Plausible Mechanistic Cycle



of ketene *N*,*O*-acetal **3a′**, which is realized through the attack of *p*-TsOH to the keteniminium intermediate of ynamide **3a**. Although both alkyne motifs undergo activation by a Au-catalyst, the stereoelectronic effect on ketene N,O-acetal **I** favors 6-*endo*-dig cyclization with the proximal Au(I) activated alkyne unit to afford monocyclic vinyl–Au species **II**.[7] The intermediate **II** undergoes hydrolysis to result **III** and simultaneously proceeds in the intramolecular cyclization of the ene moiety with the Au-activated alkyne species to attain **IV**. Finally, aromatization and

DOI: 10.1021/acs.orglett.5b02946
Org. Lett. 2015, 17, 5662–5665

protodeauration of **IV** affords the benzo[*f*]dihydroisoquinolone **4a** releasing the Au-complex for the next cycle. On the other hand, the formation of **4a′**, a 1,5-enyne surrogate, is possible with the removal of TsOH through the attack of H_2O on **II** and protodeauration, as evident in Scheme 3.[5h,10] At elevated temperature, **4a′** undergoes 6-*endo* cyclization to generate **IV** under Au-catalysis.[10]

In summary, a novel synthetic route to benzo[*f*]dihydroisoquinolone through the *p*-TsOH promoted cascade cyclization of the easily accessible diyne-tethered ynamides in the presence of a Au(I) catalyst was demonstrated. The reaction exhibited broad scope and tolerated common functional groups. Benzo[*f*]isoquinoline was realized through the peripheral modifications of benzo[*f*]dihydroisoquinolone. The reaction pathway was deduced based on the detailed studies of intermediates. Application of this method for the construction of a structurally complex framework is currently being pursued.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.5b02946.

Experimental procedures (PDF)
Compound characterization data (PDF)
Crystallographic data for **4o** (CIF)

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: akhilchemistry12@gmail.com; akssc@uohyd.ac.in.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This manuscript is dedicated to Prof. D. Basavaiah, School of Chemistry, University of Hyderabad for the development of the Baylis−Hillman−Basavaiah (BHB) reaction and for his 65th birthday. S.N, N.G., and P.B. thank CSIR, India for a fellowship. Mr. Krishna Chari, UoH is thanked for the X-ray crystallographic analysis.

■ REFERENCES

(1) (a) Chrzanowska, M.; Rozwadowska, M. D. *Chem. Rev.* **2004**, *104*, 3341. (b) Sridharan, V.; Suryavanshi, P. A.; Menéndez, J. C. *Chem. Rev.* **2011**, *111*, 2703. (c) Joule, J. A.; Mills, K. *Heterocyclic Chemistry*, 5th ed.; Wiley: Chichester, U.K., 2010. (d) Crecente-Campo, J.; Vázquez-Tato, M. P.; Seijas, J. A. *Tetrahedron* **2009**, *65*, 2655 and references cited therein. For recent examples, see: (e) Wang, C.-T.; Fan, C.-H. *Angew. Chem., Int. Ed.* **2013**, *52*, 14167. (f) Wang, S.; Onaran, M. B.; Seto, C. T. *Org. Lett.* **2010**, *12*, 2690.

(2) (a) Bembenek, M. E.; Abell, C. W.; Chrisey, L. A.; Rozwadowska, M. D.; Gessner, W.; Brossi, A. *J. Med. Chem.* **1990**, *33*, 147. (b) Kashdan, D. S.; Schwartz, J. A.; Rapoport, H. *J. Org. Chem.* **1982**, *47*, 2638.

(3) For selected reviews on alkyne and ynamide chemistry, see: (a) 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. (b) DeKorver, K. A.; Li, H.; Lohse, A. G.; Hayashi, R.; Lu, Z.; Zhang, Y.; Hsung, R. P. *Chem. Rev.* **2010**, *110*, 5064. (c) Evano, G.; Coste, A.; Jouvin, K. *Angew. Chem., Int. Ed.* **2010**, *49*, 2840. (c1) Zoellner, R. W.; Klabunde, K. J. *Chem. Rev.* **1984**, *84*, 545. (d) Mulder, J. A.; Kurtz, K. C. M.; Hsung, R. P. *Synlett* **2003**, 1379.

(4) (a) Zeiler, A.; Ziegler, M.; Rudolph, M.; Rominger, F.; Hashmi, A. S. K. *Adv. Synth. Catal.* **2015**, *357*, 1507. (b) Fujino, D.; Yorimitsu, H.; Osuka, A. *J. Am. Chem. Soc.* **2014**, *136*, 6255. (c) Jaimes, M. C. B.; Weingand, V.; Rominger, F.; Hashmi, A. S. K. *Chem. - Eur. J.* **2013**, *19*, 12504. (d) Rettenmeier, E.; Schuster, A. M.; Rudolph, M.; Rominger, F.; Gade, C. A.; Hashmi, A. S. K. *Angew. Chem., Int. Ed.* **2013**, *52*, 5880. (e) Garcia, P.; Harrak, Y.; Diab, L.; Cordier, P.; Ollivier, C.; Gandon, V.; Malacria, M.; Fensterbank, L.; Aubert, C. *Org. Lett.* **2011**, *13*, 2952. (f) Couty, S.; Meyer, C.; Cossy, J. *Angew. Chem., Int. Ed.* **2006**, *45*, 6726. (g) Dunetz, J. R.; Danheiser, R. L. *J. Am. Chem. Soc.* **2005**, *127*, 5776. (h) Zhang, Y.; Hsung, R. P.; Zhang, X.; Huang, J.; Slafer, B. W.; Davis, A. *Org. Lett.* **2005**, *7*, 1047. (i) Marion, F.; Coulomb, J.; Courillon, C.; Fensterbank, L.; Malacria, M. *Org. Lett.* **2004**, *6*, 1509.

(5) For recent reviews on gold catalysis, see: (a) Dorel, R.; Echavarren, A. M. *Chem. Rev.* **2015**, *115*, 9028. (b) Jia, M.; Bandini, M. *ACS Catal.* **2015**, *5*, 1638. (c) Friend, C. M.; Hashmi, A. S. K. *Acc. Chem. Res.* **2014**, *47*, 729. (d) Garayalde, D.; Nevado, C. *ACS Catal.* **2012**, *2*, 1462. (e) Hashmi, A. S. K. *Angew. Chem., Int. Ed.* **2010**, *49*, 5232. (f) Sohel, S. M. A.; Liu, R.-S. *Chem. Soc. Rev.* **2009**, *38*, 2269. (g) Li, Z.; Brouwer, C.; He, C. *Chem. Rev.* **2008**, *108*, 3239. (h) Michelet, V.; Toullec, P. Y.; Genêt, J.-P. *Angew. Chem., Int. Ed.* **2008**, *47*, 4268 and references cited therein. (i) Gorin, D. J.; Sherry, B. D.; Toste, F. D. *Chem. Rev.* **2008**, *108*, 3351. (j) Hashmi, A. S. K. *Chem. Rev.* **2007**, *107*, 3180. (k) Fürstner, A.; Davies, P. W. *Angew. Chem., Int. Ed.* **2007**, *46*, 3410.

(6) (a) Brown, L. E.; Dai, P.; Porco, J. A., Jr.; Schaus, S. E. *Org. Lett.* **2011**, *13*, 4228. (b) Binder, J. T.; Crone, B.; Haug, T. T.; Menz, H.; Kirsch, S. F. *Org. Lett.* **2008**, *10*, 1025. (c) Harrison, T. J.; Patrick, B. O.; Dake, G. R. *Org. Lett.* **2007**, *9*, 367. (d) Minnihan, E. C.; Colletti, S. L.; Toste, F. D.; Shen, H. C. *J. Org. Chem.* **2007**, *72*, 6287. (e) Staben, S. T.; Kennedy-Smith, J. J.; Huang, D.; Corkey, B. K.; Lalonde, R. L.; Toste, F. D. *Angew. Chem., Int. Ed.* **2006**, *45*, 5991. (f) Nevado, C.; Cárdenas, D. J.; Echavarren, A. M. *Chem. - Eur. J.* **2003**, *9*, 2627. (g) Hashmi, A. S. K.; Frost, T. M.; Bats, J. W. *J. Am. Chem. Soc.* **2000**, *122*, 11553.

(7) For selected vinyl−Au complexes, see: (a) Peng, H.; Akhmedov, N. G.; Liang, Y.-F.; Jiao, N.; Shi, X. *J. Am. Chem. Soc.* **2015**, *137*, 8912. (b) Yang, W.; Hashmi, A. S. K. *Chem. Soc. Rev.* **2014**, *43*, 2941. (c) Brown, T. J.; Weber, D.; Gagné, M. R.; Widenhoefer, R. A. *J. Am. Chem. Soc.* **2012**, *134*, 9134. (d) Hashmi, A. S. K.; Schuster, A. M.; Gaillard, S.; Cavallo, L.; Poater, A.; Nolan, S. P. *Organometallics* **2011**, *30*, 6328. (e) Seidel, I. G.; Lehmann, C. W.; Fürstner, A. *Angew. Chem., Int. Ed.* **2010**, *49*, 8466. (f) Hashmi, A. S. K. *Gold Bull.* **2009**, *42*, 275. (g) Liu, L.-P.; Xu, B.; Mashuta, M. S.; Hammond, G. B. *J. Am. Chem. Soc.* **2008**, *130*, 17642. (h) Akana, J. A.; Bhattacharyya, K. X.; Muller, P.; Sadighi, J. P. *J. Am. Chem. Soc.* **2007**, *129*, 7736.

(8) (a) Tokimizu, Y.; Wieteck, M.; Rudolph, M.; Oishi, S.; Fujii, N.; Hashmi, A. S. K.; Ohno, H. *Org. Lett.* **2015**, *17*, 604. (b) Alabugin, I. V.; Gilmore, K. *Chem. Commun.* **2013**, *49*, 11246. (c) Byers, P. M.; Rashid, I. J.; Mohamed, R. K.; Alabugin, I. V. *Org. Lett.* **2012**, *14*, 6032. (d) Naoe, S.; Suzuki, Y.; Hirano, K.; Inaba, Y.; Oishi, S.; Fujii, N.; Ohno, H. *J. Org. Chem.* **2012**, *77*, 4907. (e) Hirano, K.; Inaba, Y.; Takahashi, N.; Shimano, M.; Oishi, S.; Fujii, N.; Ohno, H. *J. Org. Chem.* **2011**, *76*, 1212.

(9) (a) Nayak, S.; Ghosh, N.; Sahoo, A. K. *Org. Lett.* **2014**, *16*, 2996. (b) Ghosh, N.; Nayak, S.; Sahoo, A. K. *Chem. - Eur. J.* **2013**, *19*, 9428. (c) Song, Y.; De Silva, H. I.; Henry, W. P.; Ye, G.; Chatterjee, S.; Pittman, C. U., Jr. *Tetrahedron Lett.* **2011**, *52*, 4507 and references cited therein.

(10) For selected examples of gold-catalyzed reaction of enynes or diynes, see: (a) Yavari, K.; Aillard, P.; Zhang, Y.; Nuter, F.; Retailleau, P.; Voituriez, A.; Marinetti, A. *Angew. Chem., Int. Ed.* **2014**, *53*, 861. (b) Hansmann, M. M.; Rudolph, M.; Rominger, F.; Hashmi, A. S. K. *Angew. Chem., Int. Ed.* **2013**, *52*, 2593. (c) Braun, I.; Asiri, A. M.; Hashmi, A. S. K. *ACS Catal.* **2013**, *3*, 1902. (d) Rao, W.; Koh, M. J.; Kothandaraman, P.; Chan, P. W. H. *J. Am. Chem. Soc.* **2012**, *134*, 10811. (e) Rao, W.; Susanti, D.; Chan, P. W. H. *J. Am. Chem. Soc.* **2011**, *133*, 15248. (f) Jiménez-Núñez, E.; Claverie, C. K.; Nieto-Oberhuber, C.; Echavarren, A. M. *Angew. Chem., Int. Ed.* **2006**, *45*, 5452.

(11) See the Supporting Information.

■ NOTE ADDED AFTER ASAP PUBLICATION

Scheme 4 was corrected on November 3, 2015.

DOI: 10.1021/acs.orglett.5b02946
Org. Lett. 2015, 17, 5662−5665