



Cite this: *RSC Adv.*, 2018, 8, 18308

Facile synthesis of α -alkoxyl amides *via* scandium-catalyzed oxidative reaction between ynamides and alcohols†

Zhi-Xin Zhang,^a Bo-Han Zhu,^a Pei-Xi Xie,^a Jia-Qi Tang,^a Xin-Ling Li,^a Chunyin Zhu,^b Ying-Wu Yin^{*a} and Long-Wu Ye^{†ac}

Received 4th May 2018
 Accepted 11th May 2018

DOI: 10.1039/c8ra03842b

rsc.li/rsc-advances

A novel and efficient scandium-catalyzed oxidative reaction between ynamides and alcohols for the facile synthesis of various α -alkoxyl amides is reported in this paper. The reaction avoids the need for the use of α -diazo carbonyls which are unstable and may cause some safety concerns. Instead, by using alkynes as the starting materials, this protocol features readily available substrates, compatibility with a broad range of functional groups, simple procedure, mild reaction conditions, and high chemoselectivity.

Introduction

α -Alkoxyl carbonyls are a class of privileged motifs prevalent in many important natural products, pharmaceuticals, and agrochemicals (Fig. 1).¹ Accordingly, significant efforts have been devoted to their synthesis. In this context, α -functionalization of carbonyl compounds such as the transition metal-catalyzed insertion of α -diazo carbonyl into O–H bond (Scheme 1a),^{2,3} has been established as one of the most important methods to construct these structures. However, those reactions involving α -diazo carbonyls generally suffer from the problems of inaccessible precursors, limitations on the substrate scope, and multistep synthesis.² Moreover, the preparation of α -alkoxyl amides has been less explored and documented than that of α -alkoxyl ketones and esters.⁴ Thus, to develop highly efficient strategies to access valuable α -alkoxyl amides is of great importance.

Alkynes have been recognized as one type of the most fundamental synthons due to their ample availability and divergent reactivity. As a consequence, alkynes have been reported to undergo numerous useful transformations, among which the gold-catalyzed intermolecular *N*-oxide oxidation of alkynes *via* a presumable α -oxo gold carbene pathway has attracted significant research attention.⁵ This protocol renders readily available and safer alkynes as the replacement for

hazardous, inaccessible, and potentially explosive α -diazo carbonyls for the generation of α -oxo gold carbenes that can react with different nucleophiles for various functionalizations. Therefore, many elegant studies have been published for synthetic applications of this chemistry over the last several years.^{6,7} However, the intermolecular oxidative reaction of alkynes with external nucleophiles is still challenging and successful examples are rather limited.⁷ There are at least two competing reactions. One is the background reaction of external nucleophiles with the activated alkynes, which produces the corresponding olefins, and another is the over-oxidation of the generated electrophilic carbene center,⁸ which affords diketone byproducts.

In our recent study on ynamide chemistry,^{9,10} we found that this kind of intermolecular oxidation of alkynes could occur efficiently by employing zinc as catalyst, thus leading to the facile synthesis of α -azido, α -thiocyanate, α -halide and α -aryloxy amides.¹¹ It is important to note that this oxidative zinc catalysis could significantly prohibit the overoxidation reaction. Motivated by these results, we envisioned that judicious choice of a metal catalyst would enable the construction of α -alkoxyl amides *via* such an oxidative reaction of ynamides with alcohols (Scheme 1b). We report herein the realization of the scandium-

^aState Key Laboratory of Physical Chemistry of Solid Surfaces, Key Laboratory for Chemical Biology of Fujian Province, College of Chemistry and Chemical Engineering, Xiamen University, Xiamen 361005, China. E-mail: longwuye@xmu.edu.cn

^bSchool of Chemistry and Chemical Engineering, Jiangsu University, Zhenjiang 212013, China. E-mail: zhucygn@gmail.com

^cState Key Laboratory of Organometallic Chemistry, Shanghai Institute of Organic Chemistry, Chinese Academy of Sciences, Shanghai 200032, China

† Electronic supplementary information (ESI) available. See DOI: 10.1039/c8ra03842b

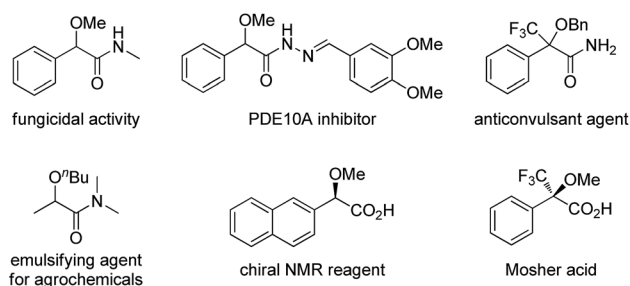
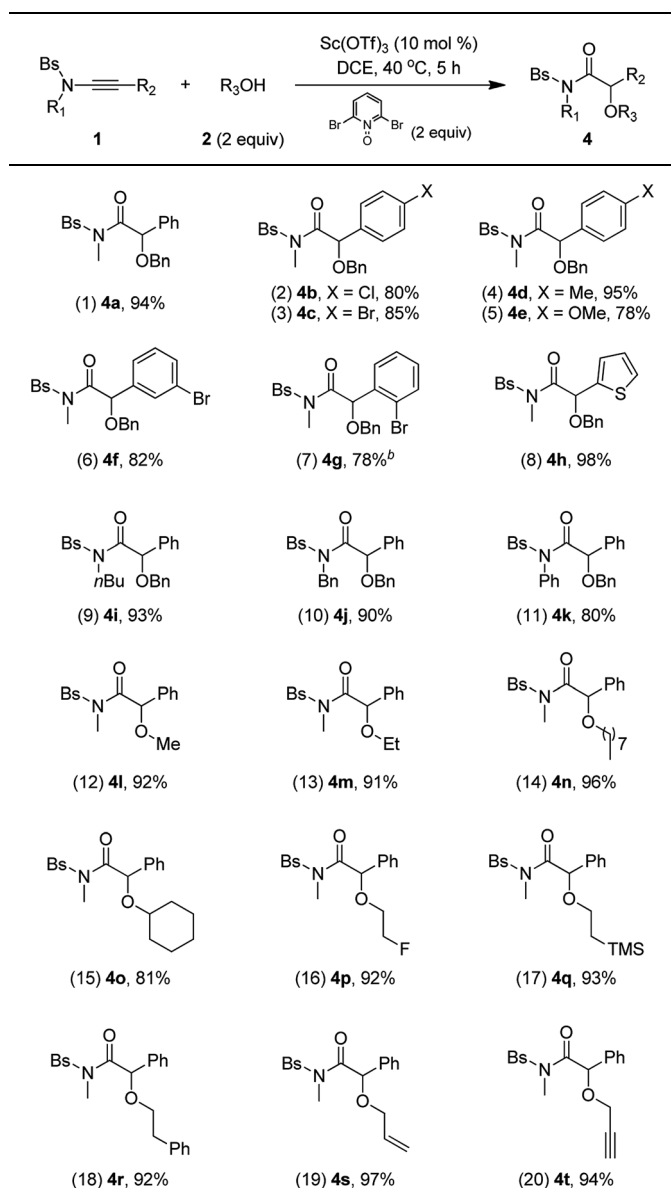
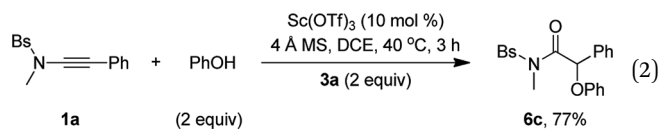


Fig. 1 Selected examples of bioactive α -alkoxyl carbonyls.

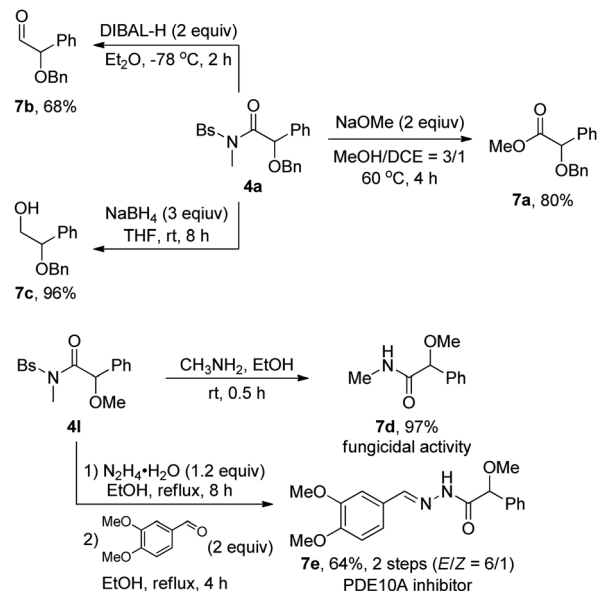
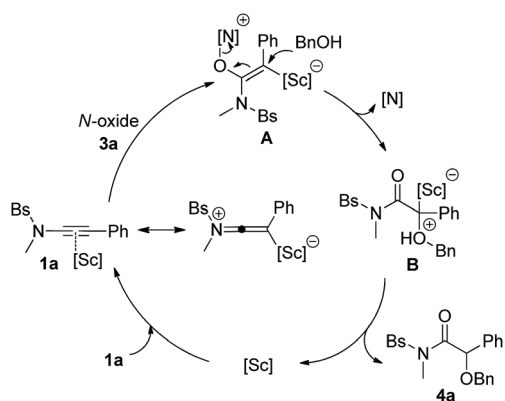


Table 2 Reaction scope study^a

^a Reactions run in vials; [1] = 0.05 M; isolated yields are reported. ^b 3 equiv. of **3a** was employed.



The utility of this methodology was also showcased by the transformation of the as-synthesized α -alkoxy amides **4**, as outlined in Scheme 2. The amide **4a** could be readily converted into the corresponding synthetically useful α -alkoxy ester **7a** in 80% yield, α -alkoxy aldehyde **7b** in 68% yield and β -alkoxy alcohol **7c** in 96% yield, respectively. Moreover, the synthesis of α -methoxyl amide **7d** with fungicidal activity¹⁸ and PDE10A

Scheme 2 Transformation of selected α -alkoxy amides.Scheme 3 Mechanistic rationale for the synthesis of α -alkoxy amide **4a**.

inhibitor¹⁸ **7e** could be readily achieved by starting from the corresponding α -alkoxy amide **4l**.

Based on the obtained results and our previous reports,¹¹ we propose the following mechanism with ynamide **1a** and benzyl alcohol **2a** as the substrates (Scheme 3). Initially, the pyridine N -oxide **3a** attacks the Sc(III)-activated substrate **1a** to deliver the vinyl Sc(III) intermediate **A**. The resulting **A** then undergoes an intermolecular $\text{S}_{\text{N}}2'$ pathway and subsequent protodemetalation, leading to the final α -alkoxy amide **4a** and regenerating the scandium catalyst. In contrast, trapping of the intermediate **A** by another N -oxide leads to the formation of diketone **4aa**. It is noteworthy that the activation of alkynes by scandium has relatively seldom been explored.¹⁴

Conclusions

In conclusion, we have presented a novel scandium-catalyzed oxidative reaction between ynamides and alcohols, leading to the facile synthesis of valuable α -alkoxy amides in good to



excellent yields. This reaction avoids the need for the use of α -diazo carbonyls which are unstable and may cause some safety concerns. Instead, by using alkynes as the starting material, this protocol features readily available substrates, compatibility with a broad range of functional groups, a simple procedure, mild reaction conditions, and high chemoselectivity. Additional exploration on the asymmetric version of this oxidative reaction and further synthetic applications of this chemistry are currently underway in our group.

Experimental section

General information

Ethyl acetate (ACS grade), hexanes (ACS grade) and anhydrous 1,2-dichloroethane (ACS grade) were obtained commercially and used without further purification. Methanol, tetrahydrofuran and diethyl ether were purified according to standard methods unless otherwise noted. Commercially available reagents were used without further purification. High-resolution mass spectra were obtained using electrospray ionization using an ICR analyzer (ESI-MS). ^1H NMR spectra were recorded in chloroform- d_3 . Chemical shifts are reported in ppm with the internal TMS signal at 0.0 ppm as a standard. The data are being reported as (s = singlet, d = doublet, t = triplet, m = multiplet or unresolved, brs = broad singlet, coupling constant(s) in Hz, integration). ^{13}C NMR spectra were recorded in chloroform- d_3 . Chemical shifts are reported in ppm with the internal chloroform signal at 77.0 ppm as a standard.

Ynamides **1** were prepared according to the known procedure.¹⁵ The data of the ynamides **1a–1h**, **1j** and **1k** were reported in our previous work.¹¹

4-Bromo-*N*-butyl-*N*-(phenylethynyl)benzenesulfonamide

(**1i**). Pale yellow oil (80%). ^1H NMR (400 MHz, CDCl_3) δ 7.81 (d, J = 8.8 Hz, 2H), 7.70 (d, J = 8.8 Hz, 2H), 7.42–7.36 (m, 2H), 7.35–7.20 (m, 3H), 3.41 (t, J = 7.2 Hz, 2H), 1.76–1.63 (m, 2H), 1.47–1.31 (m, 2H), 0.93 (t, J = 7.2 Hz, 3H); ^{13}C NMR (100 MHz, CDCl_3) δ 136.5, 132.4, 131.4, 129.0, 128.7, 128.3, 128.0, 122.5, 81.8, 70.9, 51.5, 29.9, 19.4, 13.5; IR (neat): 3054, 2930, 2235, 1358, 958, 724; HRESIMS calcd for $[\text{C}_{18}\text{H}_{18}\text{BrNNaO}_2\text{S}]^+$ ($\text{M} + \text{Na}^+$) 414.0134, found 414.0135.

General procedure for the scandium-catalyzed synthesis of α -alkoxyl amide **4**

2,6-Dibromopyridine *N*-oxide (151.7 mg, 0.60 mmol) and $\text{Sc}(\text{OTf})_3$ (14.7 mg, 0.03 mmol) were added in this order to a mixture of the ynamide **1** (0.30 mmol) and alcohol **2** (0.60 mmol) in DCE (6.0 mL) at room temperature. The reaction mixture was stirred at 40 °C and the progress of the reaction was monitored by TLC. The reaction typically took 5 h. Upon completion, the mixture was then concentrated and the residue was purified by chromatography on silica gel (eluent: hexanes/ethyl acetate) to afford the desired α -alkoxyl amide **4**.

2-(Benzyloxy)-*N*-((4-bromophenyl)sulfonyl)-*N*-methyl-2-phenylacetamide (4a). Pale yellow oil (133.8 mg, 94%). ^1H NMR (400 MHz, CDCl_3) δ 7.56 (s, 4H), 7.44–7.19 (m, 10H), 5.50 (s, 1H), 4.62–4.48 (m, 2H), 3.15 (s, 3H); ^{13}C NMR (125 MHz, CDCl_3)

δ 170.4, 137.2, 136.7, 134.6, 132.1, 129.5, 129.0, 128.8, 128.5, 128.1, 128.0, 127.8, 80.6, 71.6, 32.9; IR (neat): 2924, 1770 (s), 1345, 1240, 1158, 743; HRESIMS calcd for $[\text{C}_{22}\text{H}_{20}\text{BrNNaO}_4\text{S}]^+$ ($\text{M} + \text{Na}^+$) 496.0189, found 496.0195.

***N*-((4-Bromophenyl)sulfonyl)-*N*-methyl-2-oxo-2-phenylacetamide (4aa)**. Pale yellow oil. ^1H NMR (400 MHz, CDCl_3) δ 7.94 (d, J = 7.2 Hz, 2H), 7.88 (d, J = 8.8 Hz, 2H), 7.76 (d, J = 8.8 Hz, 2H), 7.66 (t, J = 7.6 Hz, 1H), 7.54 (t, J = 7.6 Hz, 2H), 3.26 (s, 3H); ^{13}C NMR (125 MHz, CDCl_3) δ 188.0, 167.0, 135.5, 134.7, 132.9, 132.5, 130.2, 129.8, 129.7, 128.9, 30.9; IR (neat): 2924, 1770 (s), 1345, 1240, 1158, 743; HRESIMS calcd for $[\text{C}_{15}\text{-H}_{12}\text{BrNNaO}_4\text{S}]^+$ ($\text{M} + \text{Na}^+$) 403.9563, found 403.9565.

***N*-((4-Bromophenyl)sulfonyl)-*N*-methyl-2-oxo-2-phenylacetamide (4ab)**. Pale yellow oil. ^1H NMR (400 MHz, CDCl_3) δ 7.74–7.54 (m, 4H), 7.40–7.20 (m, 3H), 7.20–7.06 (m, 2H), 3.99 (s, 2H), 3.29 (s, 3H); ^{13}C NMR (125 MHz, CDCl_3) δ 171.0, 137.7, 132.9, 132.4, 129.2, 129.1, 129.0, 128.7, 127.3, 43.1, 33.4; IR (neat): 2924, 1770 (s), 1345, 1240, 1158, 743; HRESIMS calcd for $[\text{C}_{15}\text{H}_{14}\text{BrNNaO}_3\text{S}]^+$ ($\text{M} + \text{Na}^+$) 389.9770, found 389.9772.

2-(Benzyloxy)-*N*-((4-bromophenyl)sulfonyl)-2-(4-chlorophenyl)-*N*-methylacetamide (4b). Pale yellow oil (122.1 mg, 80%). ^1H NMR (400 MHz, CDCl_3) δ 7.57 (s, 4H), 7.37–7.24 (m, 9H), 5.53 (s, 1H), 4.61–4.40 (m, 2H), 3.14 (s, 3H); ^{13}C NMR (100 MHz, CDCl_3) δ 170.2, 137.2, 136.5, 135.1, 133.3, 132.3, 129.4, 129.2, 129.1, 129.0, 128.6, 128.3, 128.2, 79.9, 71.7, 33.0; IR (neat): 3054, 2937, 1596 (s), 1349, 1164, 1090, 744; HRESIMS calcd for $[\text{C}_{22}\text{H}_{19}\text{BrClNNaO}_4\text{S}]^+$ ($\text{M} + \text{Na}^+$) 529.9799, found 529.9797.

2-(Benzyloxy)-2-(4-bromophenyl)-*N*-((4-bromophenyl)sulfonyl)-*N*-methylacetamide (4c). Pale yellow oil (141.1 mg, 85%). ^1H NMR (400 MHz, CDCl_3) δ 7.57 (s, 4H), 7.53–7.40 (m, 2H), 7.39–7.31 (m, 3H), 7.31–7.26 (m, 2H), 7.24–7.15 (m, 2H), 5.51 (s, 1H), 4.55–4.48 (m, 2H), 3.14 (s, 3H); ^{13}C NMR (100 MHz, CDCl_3) δ 170.1, 137.2, 136.5, 133.9, 132.3, 132.0, 129.5, 129.3, 129.1, 128.6, 128.2, 128.1, 123.3, 80.0, 71.7, 33.0; IR (neat): 3054, 2920, 1353, 1261, 1164, 784; HRESIMS calcd for $[\text{C}_{22}\text{H}_{19}\text{Br}_2\text{-NNaO}_4\text{S}]^+$ ($\text{M} + \text{H}^+$) 573.9294, found 573.9296.

2-(Benzyloxy)-*N*-((4-bromophenyl)sulfonyl)-*N*-methyl-2-(*p*-tolyl)acetamide (4d). Pale yellow oil (139.2 mg, 95%). ^1H NMR (400 MHz, CDCl_3) δ 7.60–7.53 (m, 4H), 7.35–7.26 (m, 5H), 7.18–7.12 (m, 4H), 5.43 (s, 1H), 4.56–4.49 (m, 2H), 3.15 (s, 3H), 2.35 (s, 3H); ^{13}C NMR (100 MHz, CDCl_3) δ 170.6, 139.0, 137.4, 136.9, 132.1, 131.5, 129.5, 129.4, 128.9, 128.5, 128.1, 128.0, 127.8, 80.4, 71.5, 32.9, 21.2; IR (neat): 3022, 2926, 1614 (s), 1345, 1158, 742; HRESIMS calcd for $[\text{C}_{23}\text{H}_{22}\text{BrNNaO}_4\text{S}]^+$ ($\text{M} + \text{Na}^+$) 510.0345, found 510.0348.

2-(Benzyloxy)-*N*-((4-bromophenyl)sulfonyl)-2-(4-methoxyphenyl)-*N*-methylacetamide (4e). Colorless oil (118.0 mg, 78%). ^1H NMR (400 MHz, CDCl_3) δ 7.59–7.51 (m, 4H), 7.37–7.28 (m, 5H), 7.21–7.16 (m, 2H), 6.88–6.83 (m, 2H), 5.43 (s, 1H), 4.51 (s, 2H), 3.81 (s, 3H), 3.14 (s, 3H); ^{13}C NMR (100 MHz, CDCl_3) δ 170.6, 160.2, 137.3, 136.9, 132.1, 129.5, 129.4, 128.9, 128.5, 128.2, 128.0, 126.5, 114.2, 79.8, 71.3, 55.3, 32.9; IR (neat): 3089, 2924, 1709 (s), 1512, 1361; 1250, 1173, 1068, 827, 750; HRESIMS calcd for $[\text{C}_{23}\text{H}_{22}\text{BrNNaO}_5\text{S}]^+$ ($\text{M} + \text{Na}^+$) 526.0294, found 526.0298.



2-(Benzyloxy)-2-(3-bromophenyl)-N-((4-bromophenyl)sulfonyl)-N-methylacetamide (4f). Pale yellow oil (131.2 mg, 82%). ^1H NMR (400 MHz, CDCl_3) δ 7.59 (s, 4H), 7.51–7.46 (m, 1H), 7.40–7.28 (m, 6H), 7.25–7.19 (m, 2H), 5.50 (s, 1H), 4.59–4.49 (m, 2H), 3.16 (s, 3H); ^{13}C NMR (100 MHz, CDCl_3) δ 170.0, 137.2, 137.1, 136.4, 132.4, 132.1, 130.6, 130.4, 129.3, 129.2, 128.6, 128.3(0), 128.2(7), 126.4, 122.9, 80.1, 72.0, 33.0; IR (neat): 2920, 1766 (s), 1358, 1258, 1172, 764; HRESIMS calcd for $[\text{C}_{22}\text{H}_{19}\text{Br}_2\text{NNaO}_4\text{S}]^+$ ($\text{M} + \text{Na}^+$) 573.9294, found 573.9298.

2-(Benzyloxy)-2-(2-bromophenyl)-N-((4-bromophenyl)sulfonyl)-N-methylacetamide (4g). Pale yellow oil (124.8 mg, 78%). ^1H NMR (500 MHz, CDCl_3) δ 7.72 (d, $J = 8.5$ Hz, 2H), 7.59–7.53 (m, 3H), 7.33–7.19 (m, 8H), 5.83 (s, 1H), 4.60 (d, $J = 11.0$ Hz, 1H), 4.54 (d, $J = 11.0$ Hz, 1H), 3.16 (s, 3H); ^{13}C NMR (125 MHz, CDCl_3) δ 169.2, 137.2, 136.4, 134.4, 133.0, 132.1, 130.5, 129.6, 129.2, 128.9, 128.4, 128.1, 127.9, 124.5, 79.3, 72.4, 32.8; IR (neat): 2921, 1768 (s), 1356, 1241, 1172, 764; HRESIMS calcd for $[\text{C}_{22}\text{H}_{19}\text{Br}_2\text{NNaO}_4\text{S}]^+$ ($\text{M} + \text{Na}^+$) 573.9294, found 573.9294.

2-(Benzyloxy)-N-((4-bromophenyl)sulfonyl)-N-methyl-2-(thiophen-2-yl)acetamide (4h). Colorless oil (141.2 mg, 98%). ^1H NMR (400 MHz, CDCl_3) δ 7.59–7.53 (m, 4H), 7.39–7.29 (m, 6H), 6.99–6.96 (m, 2H), 5.85 (s, 1H), 4.55 (dd, $J = 17.2$, 11.6 Hz, 2H), 3.18 (s, 3H); ^{13}C NMR (100 MHz, CDCl_3) δ 169.6, 137.3, 137.1, 136.5, 132.3, 129.3, 129.1, 128.5, 128.3, 128.2, 127.9, 127.6, 126.8, 75.7, 71.3, 33.1; IR (neat): 3089, 3031, 2922, 1707 (s), 1573, 1390, 1361, 1170, 1068, 742; HRESIMS calcd for $[\text{C}_{20}\text{H}_{18}\text{BrNNaO}_4\text{S}_2]^+$ ($\text{M} + \text{Na}^+$) 501.9753, found 501.9756.

2-(Benzyloxy)-N-((4-bromophenyl)sulfonyl)-N-butyl-2-phenylacetamide (4i). Pale yellow oil (144.1 mg, 93%). ^1H NMR (400 MHz, CDCl_3) δ 7.62–7.53 (m, 4H), 7.42–7.24 (m, 10H), 5.40 (s, 1H), 4.57–4.49 (m, 2H), 3.58–3.50 (m, 2H), 1.50–1.35 (m, 1H), 1.34–1.22 (m, 1H), 1.21–1.08 (m, 2H), 0.77 (t, $J = 7.2$ Hz, 3H); ^{13}C NMR (125 MHz, CDCl_3) δ 170.2, 137.9, 136.8, 134.7, 132.1, 129.7, 129.1, 128.9, 128.8, 128.5, 128.2, 128.1, 127.9, 80.1, 71.5, 46.4, 31.8, 19.8, 13.4; IR (neat): 2929, 1641 (s), 1347, 1193, 1158, 742; HRESIMS calcd for $[\text{C}_{25}\text{H}_{26}\text{BrNNaO}_4\text{S}]^+$ ($\text{M} + \text{Na}^+$) 538.0658, found 538.0658.

N-Benzyl-2-(benzyloxy)-N-((4-bromophenyl)sulfonyl)-2-phenylacetamide (4j). Pale yellow oil (148.6 mg, 90%). ^1H NMR (400 MHz, CDCl_3) δ 7.53 (s, 4H), 7.36–7.24 (m, 10H), 7.18–7.05 (m, 5H), 5.25 (s, 1H), 4.90 (dd, $J = 48.5$, 15.8 Hz, 2H), 4.37 (dd, $J = 34.0$, 12.0 Hz, 2H); ^{13}C NMR (125 MHz, CDCl_3) δ 170.7, 137.6, 136.6, 135.7, 134.3, 132.0, 130.0, 129.3, 129.0, 128.9, 128.8, 128.4, 128.2, 128.1, 128.0, 127.9, 126.9, 79.7, 71.3, 49.2; IR (neat): 2927, 1607 (s), 1435, 1246, 1158, 947; HRESIMS calcd for $[\text{C}_{28}\text{H}_{24}\text{BrNNaO}_4\text{S}]^+$ ($\text{M} + \text{Na}^+$) 572.0502, found 572.0504.

2-(Benzyloxy)-N-((4-bromophenyl)sulfonyl)-N,2-diphenylacetamide (4k). Pale yellow oil (128.7 mg, 80%). ^1H NMR (400 MHz, CDCl_3) δ 7.87 (d, $J = 6.8$ Hz, 2H), 7.69 (d, $J = 6.8$ Hz, 2H), 7.41 (t, $J = 7.6$ Hz, 1H), 7.33–7.20 (m, 8H), 7.19–7.09 (m, 2H), 6.94–6.88 (m, 2H), 6.79 (d, $J = 7.2$ Hz, 2H), 4.58 (s, 1H), 4.35 (dd, $J = 40.4$, 12.0 Hz, 2H); ^{13}C NMR (125 MHz, CDCl_3) δ 169.8, 137.5, 136.7, 134.2, 132.0, 130.8, 130.5, 130.2, 129.4, 129.3, 129.2, 128.6, 128.5, 128.4, 128.1, 128.0, 126.9, 78.8, 70.8; IR (neat): 2927, 1607 (s), 1435, 1246, 1158, 947; HRESIMS

calcd for $[\text{C}_{27}\text{H}_{22}\text{BrNNaO}_4\text{S}]^+$ ($\text{M} + \text{Na}^+$) 558.0345, found 558.0349.

N-((4-Bromophenyl)sulfonyl)-2-methoxy-N-methyl-2-phenylacetamide (4l). Pale yellow oil (109.9 mg, 92%). ^1H NMR (500 MHz, CDCl_3) δ 7.61–7.55 (m, 4H), 7.38–7.33 (m, 3H), 7.30–7.26 (m, 2H), 5.33 (s, 1H), 3.38 (s, 3H), 3.18 (s, 3H); ^{13}C NMR (125 MHz, CDCl_3) δ 170.5, 137.3, 134.4, 132.2, 129.5, 129.1, 129.0, 128.9, 127.8, 83.4, 57.6, 32.9; IR (neat): 3022, 2926, 1614 (s), 1345, 1158, 742; HRESIMS calcd for $[\text{C}_{16}\text{H}_{16}\text{BrNNaO}_4\text{S}]^+$ ($\text{M} + \text{Na}^+$) 419.9876, found 419.9875.

N-((4-Bromophenyl)sulfonyl)-2-ethoxy-N-methyl-2-phenylacetamide (4m). Pale yellow oil (112.6 mg, 91%). ^1H NMR (500 MHz, CDCl_3) δ 7.60 (s, 4H), 7.36–7.31 (m, 3H), 7.28–7.24 (m, 2H), 5.39 (s, 1H), 3.60–3.50 (m, 2H), 3.20 (s, 3H), 1.24 (t, $J = 7.2$ Hz, 3H); ^{13}C NMR (125 MHz, CDCl_3) δ 170.8, 137.3, 134.9, 132.2, 129.6, 129.0, 128.9, 128.8, 127.5, 82.2, 65.8, 32.9, 15.1; IR (neat): 3055, 2930, 1603 (s), 1347, 1159, 949; HRESIMS calcd for $[\text{C}_{17}\text{H}_{18}\text{BrNNaO}_4\text{S}]^+$ ($\text{M} + \text{H}^+$) 434.0032, found 434.0030.

N-((4-Bromophenyl)sulfonyl)-2-ethoxy-N-methyl-2-phenylacetamide (4n). Pale yellow oil (143.0 mg, 96%). ^1H NMR (400 MHz, CDCl_3) δ 7.64–7.58 (m, 4H), 7.35–7.30 (m, 3H), 7.27–7.24 (m, 2H), 5.35 (s, 1H), 3.52–3.41 (m, 2H), 3.20 (s, 3H), 1.62–1.55 (m, 2H), 1.47–1.20 (m, 10H), 0.88 (t, $J = 6.4$ Hz, 3H); ^{13}C NMR (100 MHz, CDCl_3) δ 170.8, 137.5, 135.0, 132.1, 129.6, 128.9, 128.8, 127.2, 82.5, 70.6, 32.8, 31.8, 29.7, 29.3, 29.2, 26.0, 22.6, 14.0; IR (neat): 2924, 1347, 1193, 1158, 743; HRESIMS calcd for $[\text{C}_{23}\text{H}_{30}\text{BrNNaO}_4\text{S}]^+$ ($\text{M} + \text{Na}^+$) 518.0971, found 518.0970.

N-((4-Bromophenyl)sulfonyl)-2-(cyclohexyloxy)-N-methyl-2-phenylacetamide (4o). Pale yellow oil (113.3 mg, 81%). ^1H NMR (500 MHz, CDCl_3) δ 7.66–7.60 (m, 4H), 7.33–7.21 (m, 5H), 5.44 (s, 1H), 3.40–3.32 (m, 1H), 3.22 (s, 3H), 1.91–1.84 (m, 2H), 1.75–1.63 (m, 2H), 1.45–1.31 (m, 2H), 1.29–1.19 (m, 4H); ^{13}C NMR (125 MHz, CDCl_3) δ 171.5, 137.3, 135.4, 132.0, 129.7, 128.9, 128.8, 128.5, 126.5, 80.5, 78.1, 32.9, 32.4, 25.5, 23.9; IR (neat): 2931, 1614 (s), 1346, 1158, 743; HRESIMS calcd for $[\text{C}_{21}\text{H}_{24}\text{BrNNaO}_4\text{S}]^+$ ($\text{M} + \text{Na}^+$) 488.0502, found 488.0502.

N-((4-Bromophenyl)sulfonyl)-2-(2-fluoroethoxy)-N-methyl-2-phenylacetamide (4p). Pale yellow oil (118.8 mg, 92%). ^1H NMR (500 MHz, CDCl_3) δ 7.61 (s, 4H), 7.40–7.33 (m, 3H), 7.32–7.27 (m, 2H), 5.56 (s, 1H), 4.65–4.49 (m, 2H), 3.81–3.68 (m, 2H), 3.19 (s, 3H); ^{13}C NMR (125 MHz, CDCl_3) δ 170.3, 137.1, 134.2, 132.2, 129.6, 129.2, 129.1, 129.0, 127.9, 83.6, 82.2, 69.0 (d, $J = 19.5$ Hz), 32.9; IR (neat): 2932, 1488, 1345, 1193, 1132, 783; HRESIMS calcd for $[\text{C}_{17}\text{H}_{17}\text{BrFNNaO}_4\text{S}]^+$ ($\text{M} + \text{Na}^+$) 451.9938, found 451.9939.

N-((4-Bromophenyl)sulfonyl)-N-methyl-2-phenyl-2-(2-(trimethylsilyl)ethoxy)acetamide (4q). Pale yellow oil (135.2 mg, 93%). ^1H NMR (400 MHz, CDCl_3) δ 7.61 (s, 4H), 7.40–7.31 (m, 3H), 7.30–7.25 (m, 2H), 5.39 (s, 1H), 3.65–3.48 (m, 2H), 3.22 (s, 3H), 1.05–0.96 (m, 2H), 0.00 (s, 9H); ^{13}C NMR (125 MHz, CDCl_3) δ 170.9, 137.4, 134.9, 132.1, 129.6, 129.0, 128.8, 128.7, 127.3, 82.0, 67.9, 32.9, 18.3, –1.5; IR (neat): 2926, 2855, 1694 (s), 1682, 1450, 1330, 1193, 1151, 784; HRESIMS calcd for $[\text{C}_{20}\text{H}_{26}\text{BrNNaO}_4\text{SSi}]^+$ ($\text{M} + \text{Na}^+$) 506.0427, found 506.0429.

N-((4-Bromophenyl)sulfonyl)-N-methyl-2-phenethoxy-2-phenylacetamide (4r). Pale yellow oil (134.8 mg, 92%). ^1H NMR (500 MHz, CDCl_3) δ 7.58 (s, 4H), 7.34–7.27 (m, 5H), 7.25–7.16



(m, 5H), 5.33 (s, 1H), 3.72–3.66 (m, 2H), 3.05 (s, 3H), 3.00–2.85 (m, 2H); ^{13}C NMR (125 MHz, CDCl_3) δ 170.6, 138.4, 137.4, 134.6, 132.1, 129.6, 129.0, 128.9, 128.9, 128.8, 128.4, 127.2, 126.4, 82.6, 71.2, 36.2, 32.7; IR (neat): 2930, 1732 (s), 1343, 1244, 1157, 745; HRESIMS calcd for $[\text{C}_{23}\text{H}_{22}\text{BrNNaO}_4\text{S}]^+$ ($\text{M} + \text{Na}^+$) 510.0345, found 510.0348.

2-(Allyloxy)-*N*-((4-bromophenyl)sulfonyl)-*N*-methyl-2-phenylacetamide (4s). Pale yellow oil (123.5 mg, 97%). ^1H NMR (500 MHz, CDCl_3) δ 7.59 (s, 4H), 7.38–7.30 (m, 3H), 7.29–7.24 (m, 2H), 5.94–5.85 (m, 1H), 5.47 (s, 1H), 5.35–5.22 (m, 2H), 4.10–3.97 (m, 2H), 3.19 (s, 3H); ^{13}C NMR (125 MHz, CDCl_3) δ 170.5, 137.2, 134.5, 133.5, 132.2, 129.6, 129.1, 129.0, 128.9, 127.7, 118.5, 80.9, 70.8, 32.9; IR (neat): 2920, 1731 (s), 1346, 1244, 1159, 1014, 739; HRESIMS calcd for $[\text{C}_{18}\text{H}_{18}\text{BrNNaO}_4\text{S}]^+$ ($\text{M} + \text{Na}^+$) 446.0032, found 446.0039.

***N*-((4-Bromophenyl)sulfonyl)-*N*-methyl-2-phenyl-2-(prop-2-yn-1-yloxy)acetamide (4t).** Pale yellow oil (119.1 mg, 94%). ^1H NMR (400 MHz, CDCl_3) δ 7.60 (s, 4H), 7.40–7.33 (m, 3H), 7.32–7.28 (m, 2H), 5.78 (s, 1H), 4.28–4.08 (m, 2H), 3.21 (s, 3H), 2.51 (t, $J = 2.4$ Hz, 1H); ^{13}C NMR (125 MHz, CDCl_3) δ 169.9, 137.1, 133.7, 132.2, 129.6, 129.4, 129.1, 129.0, 128.4, 79.2, 78.4, 76.1, 56.5, 33.0; IR (neat): 2934, 1620 (s), 1467, 1157, 746; HRESIMS calcd for $[\text{C}_{18}\text{H}_{16}\text{BrNNaO}_4\text{S}]^+$ ($\text{M} + \text{Na}^+$) 443.9876, found 389.1062.

General procedure for the scandium-catalyzed synthesis of α -alkylthio amide 6

2,6-Dibromopyridine *N*-oxide (151.7 mg, 0.60 mmol) and $\text{Sc}(\text{OTf})_3$ (14.7 mg, 0.03 mmol) were added in this order to a mixture of the ynamide **1** (0.30 mmol) and thiol **5** or phenol (0.60 mmol) in DCE (6.0 mL) at room temperature. The reaction mixture was stirred at 40 °C and the progress of the reaction was monitored by TLC. The reaction typically took 3 h. Upon completion, the mixture was then concentrated and the residue was purified by chromatography on silica gel (eluent: hexanes/ethyl acetate) to afford the desired α -alkylthio amide **6**.

***N*-((4-Bromophenyl)sulfonyl)-2-(ethylthio)-*N*-methyl-2-phenylacetamide (6a).** Colorless oil (75.8 mg, 61%). ^1H NMR (400 MHz, CDCl_3) δ 7.65–7.54 (m, 4H), 7.37–7.28 (m, 5H), 5.37 (s, 1H), 3.25 (s, 3H), 2.52–2.36 (m, 2H), 1.16 (t, $J = 7.6$ Hz, 3H); ^{13}C NMR (100 MHz, CDCl_3) δ 170.3, 137.4, 135.3, 132.3, 129.3, 129.0, 128.8, 128.6, 128.2, 52.4, 33.5, 25.5, 14.0; IR (neat): 2920, 2849, 2359, 2341, 1694 (s), 1573, 1359, 1171, 1069, 745; HRESIMS calcd for $[\text{C}_{17}\text{H}_{18}\text{BrNNaO}_3\text{S}_2]^+$ ($\text{M} + \text{Na}^+$) 449.9804, found 449.9807.

2-(Benzylthio)-*N*-((4-bromophenyl)sulfonyl)-*N*-methyl-2-phenylacetamide (6b). Pale yellow oil (88.7 mg, 69%). ^1H NMR (400 MHz, CDCl_3) δ 7.59–7.51 (m, 4H), 7.36–7.21 (m, 10H), 5.03 (s, 1H), 3.62 (dd, $J = 66.8, 13.2$ Hz, 2H), 3.06 (s, 3H); ^{13}C NMR (100 MHz, CDCl_3) δ 169.8, 137.4, 137.1, 134.7, 132.3, 129.4, 129.1, 129.0, 128.9, 128.9, 128.7, 128.4, 127.4, 51.7, 36.0, 33.2; IR (neat): 2919, 2849, 1699 (s), 1574, 1454, 1360, 1170, 1069, 745, 699; HRESIMS calcd for $[\text{C}_{22}\text{H}_{20}\text{BrNNaO}_3\text{S}_2]^+$ ($\text{M} + \text{Na}^+$) 511.9960, found 511.9963.

***N*-((4-Bromophenyl)sulfonyl)-*N*-methyl-2-phenoxy-2-phenylacetamide (6c).** Pale yellow oil (106.3 mg, 77%). This compound is known and the spectroscopic data match those reported in our previous work.^{11a} ^1H NMR (400 MHz, CDCl_3)

δ 7.52 (d, $J = 8.4$ Hz, 2H), 7.48–7.37 (m, 7H), 7.23 (d, $J = 7.6$ Hz, 2H), 7.03–6.97 (m, 1H), 6.87 (d, $J = 8.4$ Hz, 2H), 6.32 (s, 1H), 3.24 (s, 3H).

Methyl 2-(benzyloxy)-2-phenylacetate (7a). Compound **7a** was prepared in 80% yield according to the known procedure.^{11a} Colorless oil. ^1H NMR (400 MHz, CDCl_3) δ 7.48–7.29 (m, 10H), 4.94 (s, 1H), 4.58 (dd, $J = 15.2, 11.6$ Hz, 2H), 3.70 (s, 3H); ^{13}C NMR (125 MHz, CDCl_3) δ 171.2, 137.1, 136.2, 128.7, 128.6, 128.4, 128.0, 127.9, 127.4, 79.6, 71.1, 52.2; IR (neat): 3030, 2921, 1749 (s), 1454, 1259, 1209, 1172, 1100, 734, 697; HRESIMS calcd for $[\text{C}_{16}\text{H}_{16}\text{NaO}_3]^+$ ($\text{M} + \text{Na}^+$) 279.0992, found 279.0995.

2-(Benzyloxy)-2-phenylacetaldehyde (7b). Compound **7b** was prepared in 68% yield according to the known procedure.¹⁶ This compound is known and the spectroscopic data match those reported.¹⁷ ^1H NMR (400 MHz, CDCl_3) δ 9.62 (d, $J = 1.6$ Hz, 1H), 7.42–7.31 (m, 10H), 4.80 (d, $J = 1.6$ Hz, 1H), 4.67 (d, $J = 12.0$ Hz, 1H), 4.54 (d, $J = 12.0$ Hz, 1H); ^{13}C NMR (100 MHz, CDCl_3) δ 198.3, 137.0, 134.0, 129.0, 128.9, 128.5, 128.0(4), 128.0(0), 127.5, 85.5, 71.1.

2-(Benzyloxy)-2-phenylethan-1-ol (7c). Compound **7c** was prepared in 96% yield according to the known procedure.^{11a} Colorless oil. ^1H NMR (500 MHz, CDCl_3) δ 7.41–7.28 (m, 10H), 4.57–4.52 (m, 2H), 4.34 (d, $J = 11.5$ Hz, 1H), 3.76–3.71 (m, 1H), 3.69–3.57 (m, 1H), 2.32 (s, 1H); ^{13}C NMR (100 MHz, CDCl_3) δ 138.4, 137.9, 128.6, 128.4, 128.2, 127.9, 127.8, 127.0, 82.3, 70.7, 67.4; IR (neat): 3356 (br), 2920, 2851, 1492, 1453, 1010, 1065, 1026, 736, 699; HRESIMS calcd for $[\text{C}_{15}\text{H}_{16}\text{NaO}_2]^+$ ($\text{M} + \text{Na}^+$) 251.1043, found 251.1047.

2-Methoxy-*N*-methyl-2-phenylacetamide (7d). Compound **7d** was prepared according to the known procedures.^{1a} This compound is known and the spectroscopic data match those reported.^{1a,18} ^1H NMR (400 MHz, CDCl_3) δ 7.42–7.28 (m, 5H), 6.79 (s, 1H), 4.61 (s, 1H), 3.35 (s, 3H), 2.82 (d, $J = 4.8$ Hz, 3H); ^{13}C NMR (100 MHz, CDCl_3) δ 171.1, 137.0, 128.4, 128.3, 126.9, 83.8, 57.1, 25.6.

(*E*)-*N*-(3,4-Dimethoxybenzylidene)-2-methoxy-2-phenylacetohydrazide (7e). Compound **7e** was prepared according to the known procedures.^{1a} This compound is known and the spectroscopic data match those reported.^{1a} ^1H NMR (400 MHz, CDCl_3) δ 9.58 (s, 1H), 8.18 (s, 1H), 7.50–7.44 (m, 3H), 7.40–7.25 (m, 3H), 7.10–7.06 (m, 1H), 6.85 (d, $J = 8.4$ Hz, 1H), 4.80 (s, 1H), 3.92 (s, 3H), 3.91 (s, 3H), 3.44 (s, 3H); ^{13}C NMR (100 MHz, CDCl_3) δ 166.5, 151.4, 149.4, 136.3, 128.6, 128.5, 128.0, 127.1, 126.5, 122.8, 110.5, 108.4, 83.6, 57.4, 56.0, 55.9.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

We are grateful for financial support from the NNSFC (21572186 and 21622204), NSFFJ for Distinguished Young Scholars (No. 2015J06003), the President Research Funds from Xiamen University (20720180036), NFFTBS (No. J1310024), Qing Lan Project of Jiangsu Province and PCSIRT.



Notes and references

- 1 For recent selected examples, see:(a) N. S. Cutshall, R. Onrust, A. Rohde, S. Gragerov, L. Hamilton, K. Harbol, H. R. Shen, S. McKee, C. Zuta, G. Gragerova, V. Florio, T. N. Wheeler and J. L. Gage, *Bioorg. Med. Chem. Lett.*, 2012, **22**, 5595; (b) J. Nie, H.-C. Guo, D. Cahard and J.-A. Ma, *Chem. Rev.*, 2011, **111**, 455; (c) T. Vidal, M. Guglieri, and O. Jentzer, PCT Int. Appl. WO 2011048314A1, 2011; (d) L.-W. Ye, S.-B. Wang, Q.-G. Wang, X.-L. Sun, Y. Tang and Y.-G. Zhou, *Chem. Commun.*, 2009, 3092; (e) H. A. Schenck, P. W. Lenkowski, I. Choudhury-Mukhejee, S.-H. Ko, J. P. Stables, M. K. Patel and M. L. Brown, *Bioorg. Med. Chem.*, 2004, **12**, 979; (f) M. Kimura, A. Kuboki and T. Sugai, *Tetrahedron: Asymmetry*, 2002, **13**, 1059; (g) T. Ichiba, T. Murashi, S. Suzuki, T. Ohtsuka and M. Masuko, *J. Pestic. Sci.*, 2002, **27**, 223.
- 2 For recent selected reviews, see:(a) L. Liu and J. Zhang, *Chem. Soc. Rev.*, 2016, **45**, 506; (b) A. Ford, H. Miel, A. Ring, C. N. Slattery, A. R. Maguire and M. A. McKerverey, *Chem. Rev.*, 2015, **115**, 9981; (c) F. Wei, C. Song, Y. Ma, L. Zhou, C.-H. Tung and Z. Xu, *Sci. Bull.*, 2015, **60**, 1479; (d) D. Gillingham and N. Fei, *Chem. Soc. Rev.*, 2013, **42**, 4918; (e) X. Guo and W. Hu, *Acc. Chem. Res.*, 2013, **46**, 2427; (f) S.-F. Zhu and Q.-L. Zhou, *Acc. Chem. Res.*, 2012, **45**, 1365; (g) Z. Zhang and J. Wang, *Tetrahedron*, 2008, **64**, 6577.
- 3 For recent selected examples, see:(a) X. Gao, B. Wu, W.-X. Huang, M.-W. Chen and Y.-G. Zhou, *Angew. Chem., Int. Ed.*, 2015, **54**, 11956; (b) K. J. Kilpin, U. S. D. Paul, A.-L. Lee and J. D. Crowley, *Chem. Commun.*, 2011, **47**, 328; (c) S.-F. Zhu, Y. Cai, H.-X. Mao, J.-H. Xie and Q.-L. Zhou, *Nat. Chem.*, 2010, **2**, 546; (d) S.-F. Zhu, X.-G. Song, Y. Li, Y. Cai and Q.-L. Zhou, *J. Am. Chem. Soc.*, 2010, **132**, 16374; (e) Y. Liang, H. Zhou and Z.-X. Yu, *J. Am. Chem. Soc.*, 2009, **131**, 17783; (f) T. C. Maier and G. C. Fu, *J. Am. Chem. Soc.*, 2006, **128**, 4594.
- 4 For recent selected examples, see:(a) S. Yamazaki, T. Naito, M. Niina and K. Kakiuchi, *J. Org. Chem.*, 2017, **82**, 6748; (b) M. Keita, M. Vandamme and J.-F. Paquin, *Synthesis*, 2015, **47**, 3758; (c) V. Leiro, J. M. Seco, E. Quiñoá and R. Riguera, *Chem.-Asian J.*, 2010, **5**, 2106; (d) T. Maki, K. Ishihara and H. Yamamoto, *Org. Lett.*, 2005, **7**, 5043.
- 5 For reviews on the generation of α -oxo gold carbenes via gold-catalyzed alkyne oxidation, see:(a) Z. Zheng, Z. Wang, Y. Wang and L. Zhang, *Chem. Soc. Rev.*, 2016, **45**, 4448; (b) H.-S. Yeom and S. Shin, *Acc. Chem. Res.*, 2014, **47**, 966; (c) L. Zhang, *Acc. Chem. Res.*, 2014, **47**, 877; (d) J. Xiao and X. Li, *Angew. Chem., Int. Ed.*, 2011, **50**, 7226.
- 6 For recent selected examples, see:(a) M. J. Barrett, G. F. Khan, P. W. Davies and R. S. Grainger, *Chem. Commun.*, 2017, **53**, 5733; (b) X. Zeng, S. Liu, Z. Shi, G. Liu and B. Xu, *Angew. Chem., Int. Ed.*, 2016, **55**, 10032; (c) Y. Zhang, Y. Xue, G. Li, H. Yuan and T. Luo, *Chem. Sci.*, 2016, **7**, 5530; (d) Y. Wang, Z. Zheng and L. Zhang, *J. Am. Chem. Soc.*, 2015, **137**, 5316; (e) H. Chen and L. Zhang, *Angew. Chem., Int. Ed.*, 2015, **54**, 11775; (f) K. Ji, Z. Zheng, Z. Wang and L. Zhang, *Angew. Chem., Int. Ed.*, 2015, **54**, 1245; (g) Z. Zheng and L. Zhang, *Org. Chem. Front.*, 2015, **2**, 1556; (h) S. N. Karad and R.-S. Liu, *Angew. Chem., Int. Ed.*, 2014, **53**, 5444; (i) T. Wang, S. Shi, M. M. Hansmann, E. Rettenmeier, M. Rudolph and A. S. K. Hashmi, *Angew. Chem., Int. Ed.*, 2014, **53**, 3715; (j) F. Pan, S. Liu, C. Shu, R.-K. Lin, Y.-F. Yu, J.-M. Zhou and L.-W. Ye, *Chem. Commun.*, 2014, **50**, 10726; (k) C. Shu, L. Li, Y.-F. Yu, S. Jiang and L.-W. Ye, *Chem. Commun.*, 2014, **50**, 2522.
- 7 For examples on the strategy by employing P,N- or P,S-bidentate ligands and slow addition of oxidants via a syringe pump, see:(a) J. Li, K. Ji, R. Zheng, J. Nelson and L. Zhang, *Chem. Commun.*, 2014, **50**, 4130; (b) K. Ji, Y. Zhao and L. Zhang, *Angew. Chem., Int. Ed.*, 2013, **52**, 6508; (c) Y. Luo, K. Ji, Y. Li and L. Zhang, *J. Am. Chem. Soc.*, 2012, **134**, 17412; for other examples, see:(d) V. A. Rassadin, V. P. Boyarskiy and V. Y. Kukushkin, *Org. Lett.*, 2015, **17**, 3502; (e) M. D. Santos and P. W. Davies, *Chem. Commun.*, 2014, **50**, 6001; (f) W. He, C. Li and L. Zhang, *J. Am. Chem. Soc.*, 2011, **133**, 8482.
- 8 (a) P. Nösel, L. N. dos Santos Comprido, T. Lauterbach, M. Rudolph, F. Rominger and A. S. K. Hashmi, *J. Am. Chem. Soc.*, 2013, **135**, 15662; (b) K.-B. Wang, R.-Q. Ran, S.-D. Xiu and C.-Y. Li, *Org. Lett.*, 2013, **15**, 2374; (c) L.-Q. Yang, K.-B. Wang and C.-Y. Li, *Eur. J. Org. Chem.*, 2013, 2775; (d) R. B. Dateer, K. Pati and R.-S. Liu, *Chem. Commun.*, 2012, **48**, 7200; (e) A. Mukherjee, R. B. Dateer, R. Chaudhuri, S. Bhunia, S. N. Karad and R.-S. Liu, *J. Am. Chem. Soc.*, 2011, **133**, 15372; (f) D. Vasu, H.-H. Hung, S. Bhunia, S. A. Gawade, A. Das and R.-S. Liu, *Angew. Chem., Int. Ed.*, 2011, **50**, 6911.
- 9 For recent reviews on ynamide reactivity, see:(a) F. Pan, C. Shu and L.-W. Ye, *Org. Biomol. Chem.*, 2016, **14**, 9456; (b) G. Evano, C. Theunissen and M. Lecomte, *Aldrichimica Acta*, 2015, **48**, 59; (c) X.-N. Wang, H.-S. Yeom, L.-C. Fang, S. He, Z.-X. Ma, B. L. Kedrowski and R. P. Hsung, *Acc. Chem. Res.*, 2014, **47**, 560; (d) K. A. DeKorver, H. Li, A. G. Lohse, R. Hayashi, Z. Lu, Y. Zhang and R. P. Hsung, *Chem. Rev.*, 2010, **110**, 5064; (e) G. Evano, A. Coste and K. Jouvin, *Angew. Chem., Int. Ed.*, 2010, **49**, 2840.
- 10 For recent selected examples, see:(a) W.-B. Shen, Q. Sun, L. Li, X. Liu, B. Zhou, J.-Z. Yan, X. Lu and L.-W. Ye, *Nat. Commun.*, 2017, **8**, 1748; (b) B. Zhou, L. Li, X.-Q. Zhu, J.-Z. Yan, Y.-L. Guo and L.-W. Ye, *Angew. Chem., Int. Ed.*, 2017, **56**, 4015; (c) W.-B. Shen, X.-Y. Xiao, Q. Sun, B. Zhou, X.-Q. Zhu, J.-Z. Yan, X. Lu and L.-W. Ye, *Angew. Chem., Int. Ed.*, 2017, **56**, 605; (d) C. Shu, Y.-H. Wang, C.-H. Shen, P.-P. Ruan, X. Lu and L.-W. Ye, *Org. Lett.*, 2016, **18**, 3254; (e) Y. Pan, G.-W. Chen, C.-H. Shen, W. He and L.-W. Ye, *Org. Chem. Front.*, 2016, **3**, 491; (f) C. Shu, Y.-H. Wang, B. Zhou, X.-L. Li, Y.-F. Ping, X. Lu and L.-W. Ye, *J. Am. Chem. Soc.*, 2015, **137**, 9567; (g) A.-H. Zhou, Q. He, C. Shu, Y.-F. Yu, S. Liu, T. Zhao, W. Zhang, X. Lu and L.-W. Ye, *Chem. Sci.*, 2015, **6**, 1265.
- 11 (a) P.-P. Ruan, C.-H. Shen, L. Li, C.-Y. Liu and L.-W. Ye, *Org. Chem. Front.*, 2016, **3**, 989; (b) F. Pan, X.-L. Li, X.-M. Chen,



- C. Shu, P.-P. Ruan, C.-H. Shen, X. Lu and L.-W. Ye, *ACS Catal.*, 2016, **6**, 6055; (c) B. Zhou, L. Li and L.-W. Ye, *Synlett*, 2016, 493; (d) L. Li, B. Zhou, Y.-H. Wang, C. Shu, Y.-F. Pan, X. Lu and L.-W. Ye, *Angew. Chem., Int. Ed.*, 2015, **54**, 8245.
- 12 F. Pan, C. Shu, Y.-F. Ping, Y.-F. Pan, P.-P. Ruan, Q.-R. Fei and L.-W. Ye, *J. Org. Chem.*, 2015, **80**, 10009.
- 13 (a) *Sulfur Compounds: Advances in Research and Application*, ed. A. Q. Acton, Scholarly Editions, Atlanta, 2012; (b) *For the medicinal use of sulfur: Archaeo-Mineralogy*, ed. G. R. Rapp, Springer, Berlin, 2009; (c) E. A. Ilardi, E. Vitaku and J. T. Njardarson, *J. Med. Chem.*, 2014, **57**, 2832.
- 14 For a review on scandium triflate in organic synthesis, see: S. Kobayashi, *Eur. J. Org. Chem.*, 1999, 15.
- 15 (a) R. B. Dateer, B. S. Shaibu and R.-S. Liu, *Angew. Chem., Int. Ed.*, 2012, **51**, 113; (b) B.-B. Yao, Z.-J. Liang, T.-M. Niu and Y.-H. Zhang, *J. Org. Chem.*, 2009, **74**, 4630.
- 16 M. Mukherjee, Y. Zhou, Y. Dai, A. K. Gupta, V. R. Pulgam, R. J. Staples and W. D. Wulff, *Chem.-Eur. J.*, 2017, **23**, 2552.
- 17 B. Hu, Y. Li, Z. Li and X. Meng, *Org. Biomol. Chem.*, 2013, **11**, 4138.
- 18 R. V. Hoffman and N. K. Nayyar, *J. Org. Chem.*, 1995, **60**, 7043.

