Cycloaddition Reactions

International Edition: DOI: 10.1002/anie.201604679
German Edition: DOI: 10.1002/ange.201604679

[5+2] Cycloaddition of 2-(2-Aminoethyl)oxiranes with Alkynes via Epoxide Ring-Opening: A Facile Access to Azepines

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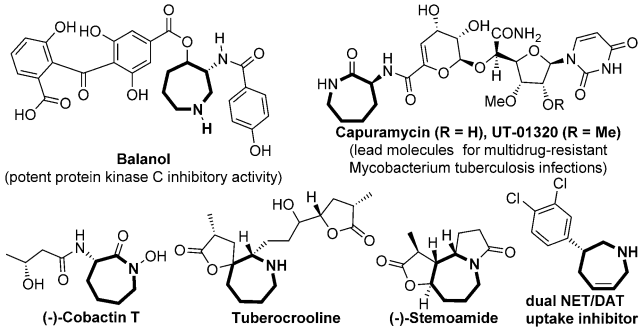
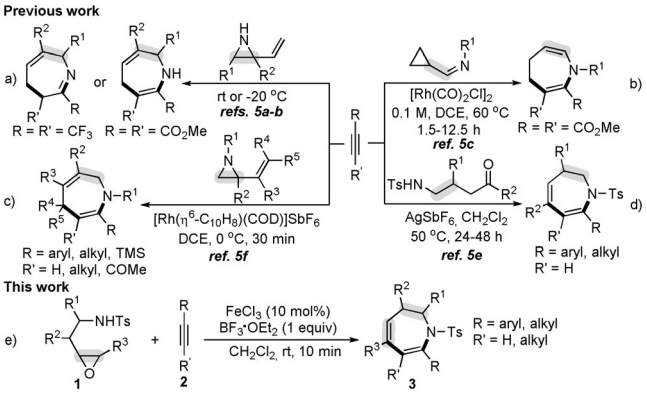
Abstract: *A new $FeCl_3$ and $BF_3{\cdot}OEt_2$ co-catalyzed tandem hetero-[5+2] cycloaddition of 2-(2-aminoethyl)oxiranes with a wide range of alkynes, including terminal alkynes and alkyl-substituted internal alkynes is presented. This is the first example of rapid and facile production of diverse 2,3-dihydro-1H-azepines through a sequence of epoxide ring-opening, annulation, and dehydroxylation with broad substrate scope and exquisite selectivity control.*

Access to seven-membered ring systems, especially seven-membered *N*-heterocyclic systems, have gained growing interest among the synthetic community owing to the continuing identification of the seven-membered-ring-containing natural products with the appealing pharmacological and pesticidal activities.[1,2] Attractive *N*-heterocyclic systems include azepine derivatives,[3] which are unique structural motifs presented in many biologically active natural products and pharmaceuticals, such as balanol,[3e,f] capuramycin and its derivatives,[3g] (−)-cobactin T,[3h–i] tuberocrooline,[3j,k] (−)-stemoamide,[3l–n] and (*S*)-3-(3,4-dichlorophenyl)-2,3,4,7-tetrahydro-1*H*-azepine[3o] (Scheme 1). Accordingly, considerable efforts has been devoted to the development of new efficient methods for assembling azepines.[4–6] Among them, cycloaddition reactions,[1,2,4] including the hetero-[5+2] cycloaddition reactions with alkynes,[5] are particularly fascinating for straightforward building the azepine frameworks. Despite the obvious synthetic utility, approaches through the hetero-[5+2] cycloaddition reactions with alkynes are less abundant and remain limited to the substrate scope with regard to both the five-atom units and the alkynes.[5] Pioneering work of the [5+2] cycloaddition reaction relied on the use of 2,3-divinylaziridine as a five-atom unit under metal-free conditions, but only two electron-poor alkynes were investigated for the synthesis of two azepines (Scheme 2a).[5a,b] To access more azepines, Wender and co-workers first developed a rhodium-catalyzed hetero-[5+2] cycloaddition of cyclopropyl imines with dimethyl acetylenedicarboxylate (Scheme 2b).[5c] Recently, we reported a new silver-catalyzed tandem [5+2] cycloaddition of γ-amino ketones with simple terminal alkynes, which provided a practical access to 2,3-dihydro-1*H*-azepines (Scheme 2d).[5e] Interestingly, Zhang and co-workers recently documented a new rhodium catalysis to extend the [5+2] cycloaddition to various vinylaziridines and alkynes leading to 2,5-dihydro-1*H*-azepines (Scheme 2c).[5f] Thus, new efficient strategies, especially involving the use of new readily available five-atom units, for the intermolecular [5+2] cycloaddition with alkynes would be warmly welcomed.



Scheme 1. Examples of important azepine derivatives.



Scheme 2. [5+2] Cycloaddition for the synthesis of azepines.

Herein, we report a new iron and $BF_3{\cdot}OEt_2$ co-catalyzed intermolecular [5+2] cycloaddition of 2-(2-aminoethyl)oxiranes with alkynes for producing diverse 2,3-dihydro-1*H*-azepines (Scheme 2e); this reaction proceeds via epoxide ring-opening by C–O bond cleavage,[7,8] annulation and dehydroxylation cascades, and represents the first example

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of utilizing oxiranes for the [5+2] intermolecular cycloaddition with alkynes.

We started our studies to explore optimal reaction conditions for the [5+2] cycloaddition between 4-methyl-*N*-(2-(oxiran-2-yl)ethyl)benzenesulfonamide (**1a**) and phenylacetylene (**2a**) (Table 1). We were pleased to find that

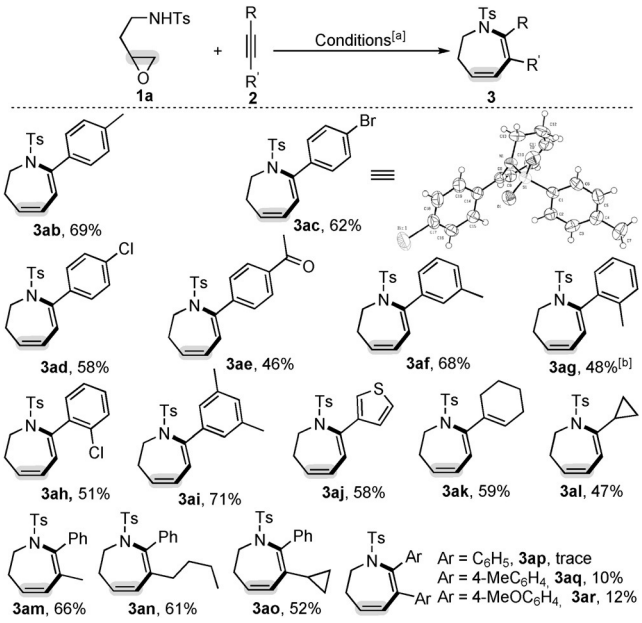
Table 1: Screening of optimal reaction conditions.[a]

Entry	Variation from the standard conditions	Yield[d] [%]
1[b]	none	74
2	without $BF_3{\cdot}OEt_2$	51
3	without $FeCl_3$	60
4	$FeCl_3$ (5 mol%)	68
5	$FeCl_3$ (15 mol%)	61
6	$BF_3{\cdot}OEt_2$ (0.8 equiv)	69
7	$BF_3{\cdot}OEt_2$ (1.2 equiv)	68
8	$FeCl_2$ instead of $FeCl_3$	57
9	$Fe(OTf)_3$ instead of $FeCl_3$	67
10	$CuCl_2$ instead of $FeCl_3$	54
11	$InCl_3$ or $YbCl_3$ instead of $FeCl_3$	49
12	at 0°C	71
13	CH_2ClCH_2Cl instead of CH_2Cl_2	70
14	MeCN instead of CH_2Cl_2	< 5
15[c]	none	60

[a] Reaction conditions: **1a** (0.1 mmol), **2a** (0.2 mmol), $FeCl_3$ (10 mol%), $BF_3{\cdot}OEt_2$ (1 equiv), CH_2Cl_2 (2 mL), room temperature, 10 min. [b] The reaction gave the same yield under air or argon atmosphere. [c] **1a** (1 mmol) and 30 min. A side-product, 2-(phenylethynyl)-1-tosylpyrrolidine (**4aa**), was obtained in 15% yield. [d] Yield of isolated product.

treatment of oxirane **1a** with alkyne **2a**, 10 mol% of $FeCl_3$ and 1 equiv of $BF_3{\cdot}OEt_2$ in CH_2Cl_2 at room temperature for 10 min was preferred to furnish the desired product **3aa** in 74% yield (entry 1). The reaction was successful when using $FeCl_3$ or $BF_3{\cdot}OEt_2$ alone, albeit giving diminishing yields (entries 2 and 3). A screen of the amount of both $FeCl_3$ and $BF_3{\cdot}OEt_2$ revealed a combination of 10 mol% of $FeCl_3$ and 1 equiv of $BF_3{\cdot}OEt_2$ as the best option (entries 1 and 4–7). A series of other Lewis acids, such as $FeCl_2$, $Fe(OTf)_3$, $CuCl_2$, $InCl_3$ and $YbCl_3$, were subsequently examined: each of which exhibited catalytic activity, but was less efficient than $FeCl_3$ (entries 1 and 8–11). A lower reaction temperature (0°C) slightly affected the reaction in terms of yield (entry 12). While CH_2ClCH_2Cl was proved to be a highly reactive medium (entry 13), MeCN had a rather lower reactivity (entry 14). Gratifyingly, the reaction scale up to 1 mmol of oxirane **1a** was successfully performed, providing **3aa** in moderate yield (entry 15).

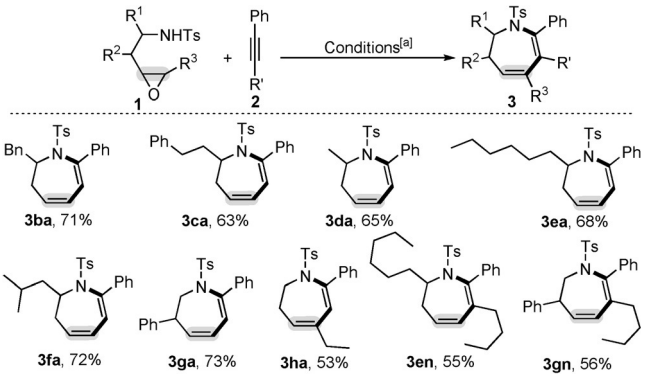
With the optimal reaction conditions in hand, we set out to investigate the scope of this intermolecular [5+2] cycloaddition protocol with respect to alkenes (**2**) (Scheme 3). Initial screening revealed that the optimal conditions were compatible with a wide range of terminal alkynes, namely arylalkynes (**2b–i**), heteroarylalkyne (**2j**), 3-enyne (**2k**) and aliphatic alkyne (**2l**). In the presence of oxirane **1a**, $FeCl_3$ and



Scheme 3. Variation of the alkynes (**2**). [a] Reaction conditions: **1** (0.2 mmol), **2** (0.4 mmol), $FeCl_3$ (10 mol%), $BF_3{\cdot}OEt_2$ (1 equiv; 0.2 mmol), CH_2Cl_2 (2 mL), room temperature and 10 min. [b] A side product, 1-(*o*-tolyl)-2-(1-tosylpyrrolidin-2-yl)ethan-1-one (**5ag**), was obtained in 23% yield.

$BF_3{\cdot}OEt_2$, several substituents, including Me, Br, Cl, and MeCO groups, on the aryl ring were well tolerated, and their nature of electron and position had an obviously effect on the yields (**3ab–ah**). While alkyne **2b** with an electron-donating Me group on the phenyl ring delivered **3ab** in 69% yield, alkyne **2e** having an electron-withdrawing MeCO group led a decrease in the yield (46%; **3ae**). Alkyne **2b** with a high active Br group was also converted to **3ab** in 62% yield.[9] In the case of methyl-substituted arylalkynes **2b**, **2f** and **2g**, the reactivity decreased from *para* to *meta* to *ortho* substitution in terms of yields (**3ab**, **3af** and **3ag**). Gratifyingly, diMe-substituted arylalkyne **2i** or 3-ethynylthiophene **2j** were viable for producing the corresponding products **3ai** and **3aj**. The optimal conditions were found to be tolerated the alkene and the cyclopropyl ring, thus giving products **3ak** and **3al** in moderate yields. Encouraged by the resulted described above, a number of internal alkynes were examined (**3am-ar**). Alkyl-substituted internal alkynes **2m–o** were viable substrates for the reaction, but 1,2-diarylalkynes **2p–r** showed lower reactivity: 1,2-Diphylalkyne **2p** had no reactivity, and other alkynes, 1,2-di-*p*-tolylethyne **2q** and 1,2-bis(4-methoxyphenyl)ethyne **2r**, delivered **3aq** and **3ar** in lower yields.

We next turned our attention to explore the generality of 2-(2-aminoethyl)oxiranes **1** in the presence of alkyne **2a**, $FeCl_3$ and $BF_3{\cdot}OEt_2$ (Scheme 4). The optimal conditions were applicable to a wide range of 2-(2-aminoethyl)oxiranes (**1**) bearing diverse substituents at the different position (**3ba-ha**). 2-Benzyl-substituted 2-(2-aminoethyl)oxirane **1b** could be smoothly converted into the desired product **3ba** in 71% yield. $PhCH_2CH_2$-substituted 2-(2-aminoethyl)oxirane **1c** and Me-substituted 2-(2-aminoethyl)oxirane **1d** were suitable for the synthesis of **3ca** and **3da** in moderate yields. Using other

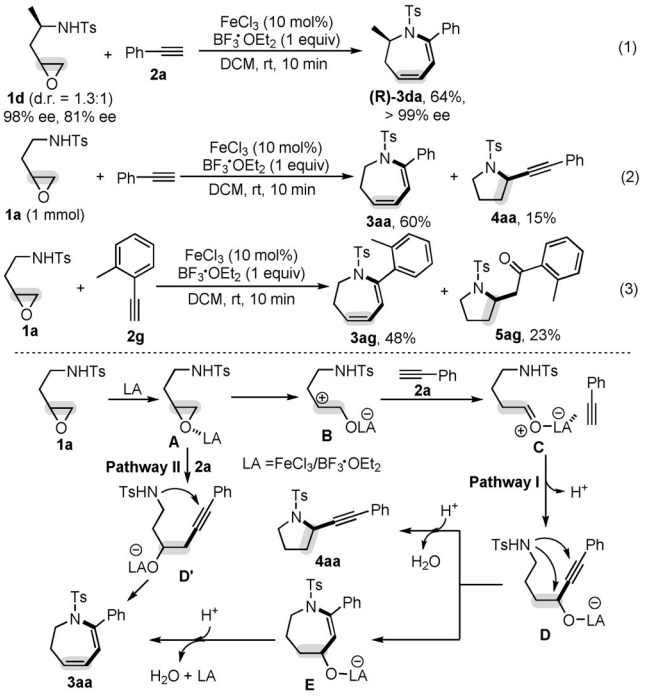


Scheme 4. Variation of the 2-(2-aminoethyl)oxiranes **1**. [a] Reaction conditions: see Table 1 and Scheme 3.

2-alkyl-substituted oxirane **1e** and **1f** successfully assembled **3ea** and **3fa**. For 2-(2-aminoethyl)oxirane **1g** having a Ph group on the 2-position of the ethyl moiety, the reaction generated **3ga** in 73% yield. Pleasingly, 2-(2-aminoethyl)oxirane **1h** with an ethyl group on the 3-position of the oxirane moiety was a suitable substrate for the cycloaddition (**3ha**). Substrates **1e** and **1g** also exhibited high reactivity with internal alkyne **1n**, thus building **3en** and **3gn** in 55% and 56% yield, respectively.

Gratifyingly, (*R*)-**1d** with 1.3:1 d.r. could be smoothly converted into the desired product (*R*)-**3da** in 64% yield with >99% *ee* [Eq. (1); Scheme 5]. Notably, two five-membered-ring side-products **4aa** [Eq. (2); Scheme 5] and **5ag** [Eq. (3); Scheme 5] were obtained (Table 1 and Scheme 3).

Consequently, the possible mechanisms outlined in Scheme 5 were proposed to understand the current tandem [5+2] cycloaddition reaction.[7,8] Both $FeCl_3$ and $BF_3{\cdot}OEt_2$ act as Lewis acids to form the carbocation intermediate **B** by coordinating with the oxygen atom in 2-(2-aminoethyl)oxirane **1a**,[8] which then undergoes ring-opening of the intermediate **B** and complex with alkyne **2a** afford the oxocarbenium ion intermediate **C** (Pathway I). Electrophilic *anti*-addition of the intermediate **C** across the C–C triple bond in alkyne **2a** selectively gives the vinyl cation intermediate **D**, followed by annulation to produce the seven-membered ring intermediate **E**, which is supported by the formation of the five-membered-ring side-products **4aa** [Eq. (2)] and **5ag** [Eq. (3)]. Finally, elimination of the intermediate **E** assembles the desired product **3aa** and releases H_2O.



Scheme 5. Control experiments and possible reaction mechanisms.

Although it is difficult to synthesize the five-membered-ring side-products **4aa** [Eq. (2)] and **5ag** [Eq. (3)] from intermediate **D′**, we cannot rule out the possible Pathway II. Notably, the results show that using a combination of $FeCl_3$ and $BF_3{\cdot}OEt_2$ as Lewis acids is necessary to offer the desired products **3** with high yields, and it might be because $FeCl_3$ can promote the ring-opening process in this tandem cycloaddition process, and a stoichiometric amount of $BF_3{\cdot}OEt_2$ can make the reaction faster and promoted the final elimination process.

In summary, we have developed a novel tandem hetero-[5+2] cycloaddition of 2-(2-aminoethyl)oxiranes with alkynes for the synthesis of 2,3-dihydro-1*H*-azepines by means of the $FeCl_3$ and $BF_3{\cdot}OEt_2$ co-catalysis. The reaction features a broad scope with respect to a wide range of both substituted 2-(2-aminoethyl)oxirane and alkynes. Importantly, the reaction employs two simple and inexpensive Lewis acids, $FeCl_3$ and $BF_3{\cdot}OEt_2$, as co-catalysts to achieve exquisite regio- and chemocontrol, thus provides a new utilization of oxiranes in the intermolecular cycloaddition reaction for the rapid and practical construction of diverse 2,3-dihydro-1*H*-azepines. Further studies on the applications of this tandem cycloaddition strategy in heterocycle synthesis are currently underway in our laboratory.

Acknowledgements

We thank the Natural Science Foundation of China (Nos. 21472039 and 21402046) and Hunan Provincial Natural Science Foundation of China (No. 13JJ2018) for financial support.

Keywords: azepines · cycloaddition · Lewis acids · oxiranes · ring opening

How to cite: *Angew. Chem. Int. Ed.* **2016**, *55*, 10423–10426
Angew. Chem. **2016**, *128*, 10579–10582

[1] For selected reviews, see: a) G. Dyker, *Angew. Chem. Int. Ed. Engl.* **1995**, *34*, 2223; *Angew. Chem.* **1995**, *107*, 2407; b) M. Harmata, *Acc. Chem. Res.* **2001**, *34*, 595; c) P. A. Wender, F. C. Bi, G. G. Gamber, F. Gosselin, R. D. Hubbard, M. J. C. Scanio, R. Sun, T. J. Williams, L. Zhang, *Pure Appl. Chem.* **2002**, *74*, 25; d) M. A. Battiste, P. M. Pelphrey, D. L. Wright, *Chem. Eur. J.* **2006**, *12*, 3438; e) H. Butenschön, *Angew. Chem. Int. Ed.* **2008**, *47*, 5287; *Angew. Chem.* **2008**, *120*, 5367; f) M. Harmata, *Chem. Commun.* **2010**, *46*, 8904; g) A. G. Lohse, R. P. Hsung, *Chem. Eur.*

J. **2011**, *17*, 3812; h) K. Tanaka, *Heterocycles* **2012**, *85*, 1017; i) C. M. Schienebeck, X. Li, X. – *z*. Shu, W. Tang, *Pure Appl. Chem.* **2014**, 86, 409; j) L. Jiao, Z.-X. Yu, *J. Org. Chem.* **2013**, *78*, 6842; k) Y. Wang, Z.-X. Yu, *Acc. Chem. Res.* **2015**, *48*, 2288; l) *Modern Rhodium-Catalyzed Organic Reactions* (Ed.: P. A. Evans), Wiley-VCH, Weinheim, **2005**.

[2] For special reviews on the [5+2] cycloaddition reaction, see: a) H. Pellissier, *Adv. Synth. Catal.* **2011**, *353*, 189; b) K. E. O. Ylijoki, J. M. Stryker, *Chem. Rev.* **2013**, *113*, 2244.

[3] For selected reviews and papers, see: a) T. Kametani, K. Fukumoto, *Heterocycles* **1975**, *3*, 931; b) B. Renfroe, C. Harrington, G. R. Proctor, *Heterocyclic Compounds: Azepines*, Wiley & Interscience, New York, **1984**; c) C. R. Ganellin, D. J. Triggle, *Dictionary of Pharmacological Agents*, Chapman & Hall/CRC, London, **1996**; d) J. J. Vaquero, A. M. Cuadro, B. Herradyn, *Modern Heterocyclic Chemistry*, Wiley-VCH, Weinheim, **2011**; balanol: e) P. Kulanthaivel, Y. F. Hallock, C. Boros, S. M. Hamilton, W. P. Janzen, L. M. Ballas, C. R. Loomis, J. B. Jiang, B. Katz, J. R. Steiner, J. Clardy, *J. Am. Chem. Soc.* **1993**, *115*, 6452; f) S. Ohshima, M. Yanagisawa, A. Katoh, T. Fujii, T. Sano, S. Matsukuma, T. Furumai, M. Fujiu, K. Watanabe, K. Yokose, M. Arisawa, T. Okuda, *J. Antibiot.* **1994**, *47*, 639; capuramycin and its derivatives: g) H. Yamaguchi, S. Sato, S. Yoshida, K. Takada, M. Itoh, H. Seto, N. Otake, *J. Antibiot.* **1986**, *39*, 1047; (−)-cobactin T: h) J. Hu, M. J. Miller, *Tetrahedron Lett.* **1995**, *36*, 6379; i) Y.-F. Song, Y. Qu, X.-P. Cao, W. Zhang, *Mar. Biotechnol.* **2011**, *13*, 868; tuberocrooline: j) R.-W. Jiang, P.-M. Hon, Y. Zhou, Y.-M. Chan, Y.-T. Xu, H.-X. Xu, H. Greger, P.-C. Shaw, P. P.-H. But, *J. Nat. Prod.* **2006**, *69*, 749; k) W.-H. Lin, H.-Z. Fu, *J. Chin. Pharm. Sci.* **1999**, *8*, 1; stemoamide: l) M. Götz, O. E. Edwards, In *The Alkaloids*, *Vol. 9* (Ed.: R. H. F. Manske), Academic Press, New York, **1967**, pp. 545 – 551; m) K. Sakata, K. Aoki, C.-F. Chang, A. Sakurai, S. Tamura, S. Murakoshi, *Agric. Biol. Chem.* **1978**, *42*, 457; n) Y. Ye, G.-W. Qin, R.-S. Xu, *Phytochemistry* **1994**, *37*, 1205; (*S*)-3-(3,4-dichlorophenyl)-2,3,4,7-tetrahydro-1*H*-azepine: o) D. G. Brown, P. R. Bernstein, Y. Wu, R. A. Urbanek, C. W. Becker, S. R. Throner, B. T. Dembofsky, G. B. Steelman, L. A. Lazor, C. W. Scott, M. W. Wood, S. S. Wesolowski, D. A. Nugiel, S. Koch, J. Yu, D. E. Pivonka, S. Li, C. Thompson, A. Zacco, C. S. Elmore, P. Schroeder, J. Liu, C. A. Hurley, S. Ward, H. J. Hunt, K. Williams, J. McLaughlin, V. Hoesch, S. Sydserff, D. Maier, D. Aharony, *ACS Med. Chem. Lett.* **2013**, *4*, 46.

[4] For representative papers on the synthesis of azepine derivatives via the cycloaddition reactions, see: a) D. J. Anderson, A. Fiassner, *J. Am. Chem. Soc.* **1971**, *93*, 4339; b) N. D. Shapiro, F. D. Toste, *J. Am. Chem. Soc.* **2008**, *130*, 9244; c) Y. Bai, J. Fang, J. Ren, Z. Wang, *Chem. Eur. J.* **2009**, *15*, 8975; d) H. Liu, X. Li, Z. Chen, W.-X. Hu, *J. Org. Chem.* **2012**, *77*, 5184; e) Y. Karibe, H. Kusama, N. Iwasawa, *Angew. Chem. Int. Ed.* **2012**, *51*, 6214; *Angew. Chem.* **2012**, *124*, 6318; f) L. Wang, J. Huang, S. Peng, H. Liu, X. Jiang, J. Wang, *Angew. Chem. Int. Ed.* **2013**, *52*, 1768; *Angew. Chem.* **2013**, *125*, 1812; g) N. Iqbal, A. Fiksdahl, *J. Org. Chem.* **2013**, *78*, 7885; h) M.-B. Zhou, R.-J. Song, J.-H. Li, *Angew. Chem. Int. Ed.* **2014**, *53*, 4196; *Angew. Chem.* **2014**, *126*, 4280; i) R. Shenje, M. C. Martin, S. France, *Angew. Chem. Int. Ed.* **2014**, *53*, 13907; *Angew. Chem.* **2014**, *126*, 14127; j) A. Seoane, N. Casanova, N. Quiñones, J. L. Mascareñas, M. Gulías, *J. Am. Chem. Soc.* **2014**, *136*, 834; k) D. J. Lee, H. S. Han, J. Shin, E. J. Yoo, *J. Am. Chem. Soc.* **2014**, *136*, 11606; l) Y. Yang, M.-B. Zhou, X.-H. Ouyang, R. Pi, R.-J. Song, J.-H. Li, *Angew. Chem. Int. Ed.* **2015**, *54*, 6595; *Angew. Chem.* **2015**, *127*, 6695; m) J.-J. Feng, T.-Y. Lin, H.-H. Wu, J. Zhang, *Angew. Chem. Int. Ed.* **2015**, *54*, 15854; *Angew. Chem.* **2015**, *127*, 16080.

[5] For special papers on the synthesis of azepine derivatives via the hetero-[5+2] cycloaddition reactions with alkynes, see: a) E. L. Stogryn, S. J. Brois, *J. Am. Chem. Soc.* **1967**, *89*, 605; b) A. Hassner, R. D'Costa, A. T. McPhail, W. Butler, *Tetrahedron Lett.* **1981**, *22*, 3691; c) P. A. Wender, T. M. Pedersen, M. J. C. Scanio, *J. Am. Chem. Soc.* **2002**, *124*, 15154; d) M. M. Montero-Campillo, E. M. Cabaleiro-Lago, J. Rodriguez-Otero, *J. Phys. Chem. A* **2008**, *112*, 9068; e) M.-B. Zhou, R.-J. Song, C.-Y. Wang, J.-H. Li, *Angew. Chem. Int. Ed.* **2013**, *52*, 10805; *Angew. Chem.* **2013**, *125*, 11005; f) J.-J. Feng, T.-Y. Lin, C.-Z. Zhu, H. Wang, H.-H. Wu, J. Zhang, *J. Am. Chem. Soc.* **2016**, *138*, 2178; g) J.-J. Feng, T.-Y. Lin, H.-H. Wu, J. Zhang, *J. Am. Chem. Soc.* **2015**, *137*, 3787; h) L. Zhu, X. Qi, Y. Lan, *Organometallics* **2016**, *35*, 771.

[6] For selected papers on the classical methods for azepine synthesis, radical: a) L. Yet, *Tetrahedron* **1999**, *55*, 9349; b) R. Guo, J. Huang, H. Huang, X. Zhao, *Org. Lett.* **2016**, *18*, 504, and references therein; ring-expansion: c) T. J. V. Bergen, R. M. Kellogg, *J. Org. Chem.* **1971**, *36*, 978; d) H. F. Motiwala, M. Charaschanya, V. W. Day, J. Aubé, *J. Org. Chem.* **2016**, *81*, 1593, and references therein; ring-closing methathesis: e) M. E. Maier, *Angew. Chem. Int. Ed.* **2000**, *39*, 2073; *Angew. Chem.* **2000**, *112*, 2153; f) P. Jakubec, A. Hawkins, W. Felzmann, D. J. Dixon, *J. Am. Chem. Soc.* **2012**, *134*, 17482; nitrene insertion or diene-conjugated nitrile ylide cyclization: g) *Comprehensive Heterocyclic Chemistry*, *Vol. 9* (Ed.: A. R. Katritzky II), Pergamon, New York, **1996**, p. 21; metal-catalyzed cyclization: h) L. F. Tietze, R. Schimpf, *Synthesis* **1993**, 876; i) H. Ohno, H. Hamaguchi, M. Ohata, S. Kosaka, T. Tanaka, *J. Am. Chem. Soc.* **2004**, *126*, 8744; j) T. O. Vieira, H. Alper, *Org. Lett.* **2008**, *10*, 485; k) I. Nakamura, M. Okamoto, Y. Sato, M. Terada, *Angew. Chem. Int. Ed.* **2012**, *51*, 10816; *Angew. Chem.* **2012**, *124*, 10974; l) Z. Shi, C. Grohmann, F. Glorius, *Angew. Chem. Int. Ed.* **2013**, *52*, 5393; *Angew. Chem.* **2013**, *125*, 5503; m) W. Zhu, L. Zhao, M.-X. Wang, *J. Org. Chem.* **2015**, *80*, 12047; n) Z. Zuo, J. Liu, J. Nan, L. Fan, W. Sun, Y. Wang, X. Luan, *Angew. Chem. Int. Ed.* **2015**, *54*, 15385; *Angew. Chem.* **2015**, *127*, 15605; o) Y.-P. Han, X.-R. Song, Y.-F. Qiu, H.-R. Zhang, L.-H. Li, D.-P. Jin, X.-Q. Sun, X.-Y. Liu, Y.-M. Liang, *Org. Lett.* **2016**, *18*, 940, and references therein; others: p) G. Yin, Y. Zhu, P. Lu, Y. Wang, *J. Org. Chem.* **2011**, *76*, 8922.

[7] For selected reviews on the epoxide ring-opening reactions, see: a) R. N. Armstrong in *Comprehensive Natural Products Chemistry*, *Vol. 5* (Ed.: D. C. Poulter), Elsevier, Amsterdam, **1999**, p. 51; b) *Aziridines and Epoxides in Organic Synthesis* (Ed.: A. K. Yudin), Wiley-VCH, Weinheim, **2006**; c) A. Gansäuer, C.-A. Fan, F. Keller, P. Karbaum, *Chem. Eur. J.* **2007**, *13*, 8084; d) I. Vilotijevic, T. F. Jamison, *Angew. Chem. Int. Ed.* **2009**, *48*, 5250; *Angew. Chem.* **2009**, *121*, 5352; e) C. J. Morten, J. A. Byers, A. R. V. Dyke, I. Vilotijevic, T. F. Jamison, *Chem. Soc. Rev.* **2009**, *38*, 3175; f) J. He, J. Ling, P. Chiu, *Chem. Rev.* **2014**, *114*, 8037; g) C. Wang, L. Luo, H. Yamamoto, *Acc. Chem. Res.* **2016**, *49*, 193.

[8] For papers on the ring-opening/annulation of epoxides with alkynes, see: a) M. Pineschi, F. Bertolini, V. Di Bussolo, P. Crotti, *Adv. Org. Synth.* **2013**, *5*, 101; b) P. Ghosh, P. Saha, S. Bondalapati, K. Indukuri, A. K. Saikia, *J. Org. Chem.* **2014**, *79*, 4119; c) J. M. Fraile, J. A. Mayoral, L. Salvatella, *J. Org. Chem.* **2014**, *79*, 5993; d) E. Hasegawa, S. Arai, E. Tayama, H. Iwamoto, *J. Org. Chem.* **2015**, *80*, 1593; e) R. Liu, M. Zhang, J. Zhang, *Chem. Commun.* **2011**, *47*, 12870; f) W. Chen, X. Fu, L. Lin, X. Yuan, W. Luo, J. Feng, X. Liu, X. Feng, *Chem. Commun.* **2014**, *50*, 11480; g) T. Boningari, A. Olmos, M. B. Reddy, J. Sommer, P. Pale, *Eur. J. Org. Chem.* **2010**, 6338.

[9] CCDC 1479587 (**3ac**) contains the supplementary crystallographic data for this paper. These data are provided free of charge by The Cambridge Crystallographic Data Centre.

Received: May 13, 2016
Revised: June 29, 2016
Published online: July 26, 2016

