ChemComm

COMMUNICATION

View Article Online
View Journal | View Issue

Cite this: *Chem. Commun.*, 2016, 52, 8313

Received 21st April 2016,
Accepted 8th June 2016

DOI: 10.1039/c6cc03345h

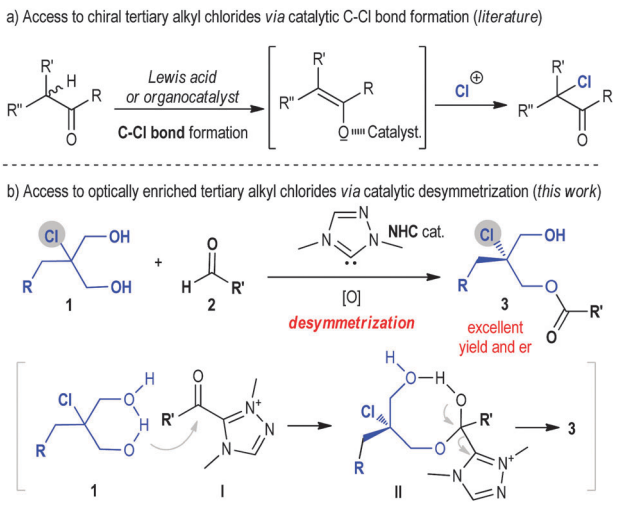
www.rsc.org/chemcomm

Carbene-catalyzed desymmetrization of 1,3-diols: access to optically enriched tertiary alkyl chlorides†

Bao-Sheng Li,‡[a] Yuhuang Wang,‡[a] Rupert S. J. Proctor,[a] Zhichao Jin[a] and Yonggui Robin Chi*[ab]

The introduction of a chlorine atom to a carbon center in an enantioselective manner *via* conventional C–Cl bond formation is difficult. Here we report a new approach to this class of tertiary alkyl chlorides with high optical purities. Instead of forming a new C–Cl bond, our approach involves carbene-catalyzed desymmetrization of 2-chloro-1,3-diols as the key step to set up the chiral carbon center with excellent enantiomeric excess.

The chlorine atom is widely found in natural products and synthetic molecules with interesting properties.[1] As such, its introduction to molecules, especially in an enantioselective fashion, has received considerable attention. In particular, it remains challenging to prepare optically enriched tertiary alkyl chlorides with the chlorine atom connected to a stereogenic carbon center. To date the dominant approach has been to form a new carbon–chlorine bond *via* asymmetric catalysis (Scheme 1a). For instance, asymmetric chlorination of carbonyl compounds (such as α-keto esters) *via* enol or enolate intermediates is the most well-established method.[2,3] Chiral Lewis acid catalysts[2] and amine[3a] or phosphoric acid[3b] organic catalysts have been explored for this type of reaction, as disclosed by, Shibata,[2a] Shibatomi,[2b,c] Bartoli,[3a] and Antilla.[3c] Our laboratory is interested in exploring carbene organic catalysts for rapid access to functional molecules.[4] Herein, we report a new approach for effective access to optically enriched tertiary alkyl chlorides *via* N-heterocyclic carbene (NHC)-catalyzed desymmetrization of 1,3-diols.[5] Our method utilizes a readily available substrate with a chlorine atom pre-installed on a pre-stereogenic carbon center (Scheme 1b). The postulated reaction pathway involves selective



Scheme 1 The synthesis of optically enriched chiral tertiary alkyl chlorides.

formation of an ester at one of the two alcohol units of substrate **1** *via* the catalytic generation of key azolium intermediate **I**.[6] The intramolecular hydrogen bonding between the two alcohol groups of the 1,3-diol substrate[7,8] likely plays an important role in this process.[9] The optically enriched alkyl chloride product **3** bears an alcohol functional group from the substrate and can readily undergo further transformations.

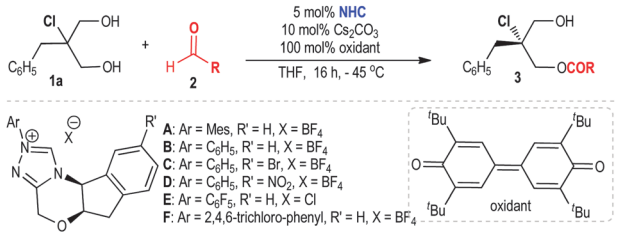
Notably, NHCs as versatile organic catalysts are most often used for new bond formations.[10] The use of NHCs for kinetic resolution has also received considerable attention in recent years.[11] In contrast, desymmetrization through NHC organocatalysis[12] has thus far received much less study. One nice work in this direction was reported by Scheidt, in which addition of an azolium enolate intermediate to one of the ketone moieties of a symmetric 1,3-diketone compound led to enantiomerically enriched products.[12a,b] Rovis[12c] and You have reported desymmetrization through a Stetter reaction, respectively.[12d] In the area of diol desymmetrization, conversion of non-chlorine-containing diols has mainly been achieved with chiral Lewis

[a] *Division of Chemistry & Biological Chemistry, School of Physical & Mathematical Sciences, Nanyang Technological University, Singapore, 637371, Singapore. E-mail: robinchi@ntu.edu.sg*
[b] *State Key Laboratory Breeding Base of Green Pesticide and Agricultural Bioengineering Ministry of Education, Guizhou University, Guiyang, 550025, China*

† Electronic supplementary information (ESI) available: Characterization data and experimental procedures. See DOI: 10.1039/c6cc03345h

‡ These authors contributed equally to this work.

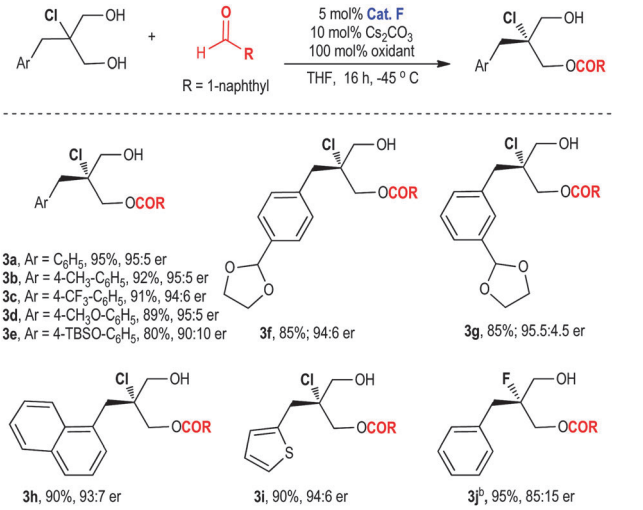
Table 1 Optimization of reaction conditions[a]



Entry	Cat.	R	3 yield[c] (%)	3 er[d]
1	**A**	C_6H_5	95	84 : 16
2	**A**	4-Cl–C_6H_5	90	80 : 20
3	**A**	4-CH_3O–C_6H_5	92	76 : 24
4	**A**	$C_6H_5CH{=}CH$	85	72 : 28
5	**A**	2-CH_3–C_6H_5	87	84 : 16
6	**A**	1-Naphthyl	93	89 : 11
7	**B**	1-Naphthyl	95	90 : 10
8	**C**	1-Naphthyl	90	77 : 23
9	**D**	1-Naphthyl	93	87 : 13
10	**E**	1-Naphthyl	94	87 : 13
11	**F**	**1-Naphthyl**	**95**	**95 : 5**
12	**F** (2 mol%)[b]	1-Naphthyl	90	95 : 5

[a] All reactions of **1a** (0.10 mmol, 20.1 mg) with aldehyde **2** (0.2 mmol, 31.2 mg) were carried out with 5 mol% **A–F** and 10 mol% Cs_2CO_3 in THF (1.0 mL) for 16 h. [b] Catalyst **F** of 2 mol% was used (48 h). [c] Isolated yield. [d] Er of **3** was determined by chiral HPLC analysis. Mes, 1,3,5-trimethylbenzene.

Table 2 Examples of Ar substituents for the diol substrates[a]



[a] Conditions as in Table 1, entry 11 unless otherwise specified; isolated yield after column chromatography. [b] The corresponding fluorine atom-containing substrate was used.

acid catalysts[13] and more recently with chiral phosphoric acid,[14] quinidine-derived[15a] or sulfide[15b] organic catalysts.

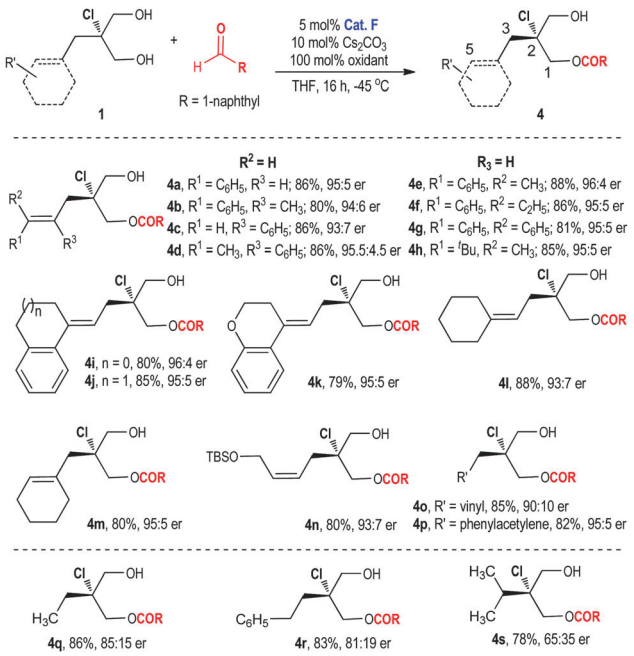
Results of our condition optimization are briefed in Table 1, using diol **1a** as the model substrate. Triazolium NHC pre-catalyst **A**, developed by Bode,[16] was first used to identify a suitable aldehyde to be the acylation agent (entries 1–12). We were very encouraged to find the formation of **3a** in 95% yield and 84 : 16 er when benzaldehyde was used (entry 1, R = Ph). Further studies of aldehyde substrates found that other aryl aldehydes and enals could effectively lead to the products **3a–3j** in good yield and a variety of enantiomeric ratios. The use of alkyl aldehydes, however, led to little formation of the desired product. Replacing the phenyl group of benzaldehyde with a naphthyl unit led to better results than with other aldehydes examined here (entry 6). We then proceeded to use naphthal as the acylation reagent to search for optimal NHC catalysts (entries 7–12), and found that the use of NHC pre-catalyst **F**, first developed by Rovis,[17] afforded **3a** with 95% yield and 95 : 5 er (entry 11). Decreasing the catalyst loading of **F** to 2 mol% led to no apparent changes in er, albeit a longer reaction time (entry 12). Increasing or decreasing the reaction temperature both led to decreased ee (see ESI†), suggesting that the hydrogen bonding might play important roles in our desymmetrization reactions.

The scope of the reaction was then examined. We first evaluated the diol substrates by replacing the phenyl group of **1a** with other (hetero) aryl substituents (Table 2). Installing various substituents on the phenyl ring **3b–3j** of the diols had no significant effect on the reaction outcomes, and the corresponding products were obtained with excellent yields and enantiomeric ratios. The phenyl unit of **1a** could also be replaced by a 1-naphthyl **3h** or 2-thiophenyl **3i** group. Furthermore, we found that when the Cl atom was replaced with an F atom, the reaction worked effectively to give **3j** with 95% yield and a somewhat lower 85 : 15 er under the same conditions without further optimization.

We next evaluated diol substrates bearing non-Ar substituents (olefins and alkynes), in order to provide rich opportunities for further functionalization. As indicated in Table 3, products **4a–4h** containing alkene units with a variety of substitution patterns could be obtained with excellent enantioselectivities and yields. Substrates with a cyclic substituent on the double bond terminus gave the corresponding products **4i–4l** with excellent yields and selectivities. For products **4i** and **4j**, containing a benzocycle, a higher enantioselectivity was achieved with the five-membered ring than with its six-membered analogue. When a benzopyran-like structure was incorporated, the product **4k** was obtained with good results as well. A cyclohexene-containing substrate was then examined and the expected product **4m** was afforded with good yield and er. Likewise, substrates with a *Z*-olefin substituent gave the desired product **4n** with similar yield and selectivity. Moreover, when the alkene moiety of the diol substrate was replaced with an alkyne, the product **4p** was formed with yield and er comparable to those of the alkene-containing products such as **4a**. However, the substrates with the alkyl sunstituent gave the monoester products (**4q–4s**) with moderate er. Our attempt to prepare 1,3-diol substrate by replacing the allylic substituent with a aryl unit was unsuccessful (as below) due to the the tertiary benzyl or allylic chloride is sensitive for reduction of 1,3-diester to 1,3-diol. The absolute configuration of the products was confirmed by optical rotation comparison of a derivative of **3j** with a known compound.[18]

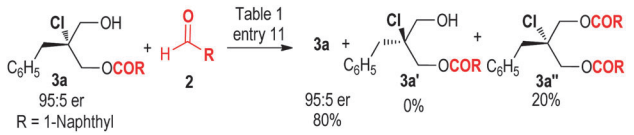
Notably, further catalytic esterification of the product **3a** under the standard condition could occur slowly to form diester adduct **3a″** (in 20% yield). This additional esterification did not lead to change of ee for **3a**. This result suggested that the second acylation reaction (to form **3a″**) was not a kinetic

Table 3 Examples of diol substrates containing alkene or alkyne substituents[a]



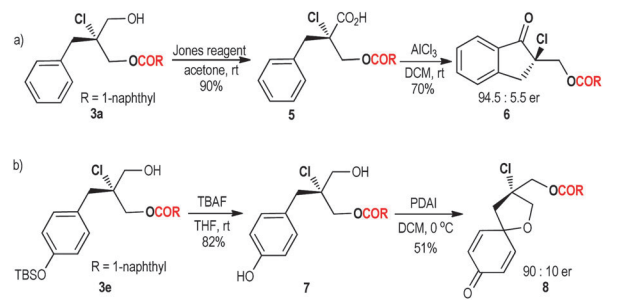
[a] Conditions as in Table 1 entry 11 unless otherwise specified; isolated yield after column chromatography.

resolution process. The enantiomeric excess of **3a** obtained in our reaction exclusively came from catalytic desymmetrization of **1a** (not from kinetic resolution of the mono-ester **3a**). Intramolecular transesterification of **3a** (to form the other enantiomer **3a′**) was not observed (eqn (1)), indicating ester **3a** is stable (no ester-exchange) under our catalytic conditions.



(1)

The optically enriched products from our reaction can readily undergo further transformations (Scheme 2). For example, oxidation of the free alcohol unit of **3a** (to form **5**) followed by intramolecular Friedel–Crafts acylation effectively afforded indanone **6**, which is a common scaffold in functional molecules. Our phenol containing product **3e** can undergo oxidation followed by intramolecular addition/dearomatization to form spirocyclic ether adduct **10** (Scheme 2b).[19]



Scheme 2 Synthetic transformations.

In summary, we have developed a new approach for effective access to tertiary alkyl chlorides with high enantiomeric excess. Instead of forming a new C–Cl bond, we obtain the sterically challenging chiral carbon center connected to a chlorine atom through carbene-catalyzed desymmetrization of 1,3-diols. The optically enriched products from our reaction can readily undergo further transformations. Since our method bypasses the difficulties in forming challenging C–Cl bonds enantioselectively, we expect a broad set of chiral alkyl chlorides to be easily obtainable by using our metal-free organic catalytic methods.

We acknowledge support from Singapore's National Research Foundation (NRF), Ministry of Education (MOE), Nanyang Technological University (NTU), and China's National Key Program for Basic Research (No. 2010CB 126105), Thousand Talent Plan, National Natural Science Foundation (No. 21132003 and 21472028), Guizhou Province Returned Oversea Student Science and Technology Activity Program, and Guizhou University.

Notes and references

1 (*a*) T. Dias, I. Brito, L. Moujir, N. Paiz, J. Darias and M. Cueto, *J. Nat. Prod.*, 2005, **68**, 1677; (*b*) A. R. Díaz-Marrero, I. Brito, J. M. de la Rosa, J. Darias and M. Cueto, *Tetrahedron*, 2008, **64**, 10821; (*c*) K. Motohashi, M. Sue, K. Furihata, S. Ito and H. Seto, *J. Nat. Prod.*, 2008, **71**, 595.

2 (*a*) N. Shibata, J. Kohno, K. Takai, T. Ishimaru, S. Nakamura, T. Toru and S. Kanemasa, *Angew. Chem., Int. Ed.*, 2005, **44**, 4204; (*b*) K. Shibatomi, A. Narayama, Y. Soga, T. Muto and S. Iwasa, *Org. Lett.*, 2011, **13**, 2944; (*c*) K. Shibatomi, Y. Soga, A. Narayama, I. Fujisawa and S. Iwasa, *J. Am. Chem. Soc.*, 2012, **134**, 9836.

3 (*a*) G. Bartoli, M. Bosco, A. Carlone, M. Locatelli, P. Melchiorre and L. Sambri, *Angew. Chem., Int. Ed.*, 2005, **44**, 6219; (*b*) W. Zheng, Z. Zhang, M. J. Kaplan and J. C. Antilla, *J. Am. Chem. Soc.*, 2011, **133**, 3339.

4 For activation of ester: (*a*) L. Hao, Y. Du, H. Lv, X. Chen, H. Jiang, Y. Shao and Y. R. Chi, *Org. Lett.*, 2012, **14**, 2154; (*b*) Z. Fu, J. Xu, T. Zhu, W. W. Y. Leong and Y. R. Chi, *Nat. Chem.*, 2013, **5**, 835; For activation of C–C bond: (*c*) B.-S. Li, Y. Wang, Z. Jin, P. Zheng, R. Ganguly and Y. R. Chi, *Nat. Commun.*, 2015, **6**, 6207; (*d*) B.-S. Li, Y. Wang, Z. Jin and Y. R. Chi, *Chem. Sci.*, 2015, **6**, 6008; For other activation: (*e*) J. Mo, X. Chen and Y. R. Chi, *J. Am. Chem. Soc.*, 2012, **134**, 8810; (*f*) J. Zhang, C. Xing, B. Tiwari and Y. R. Chi, *J. Am. Chem. Soc.*, 2013, **135**, 811; (*g*) Y. Zhang, Y. Du, Z. Huang, J. Xu, X. Wu, Y. Wang, M. Wang, S. Yang, R. D. Webster and Y. R. Chi, *J. Am. Chem. Soc.*, 2015, **137**, 2416.

5 For representive metal-catalyzed desymmetrization of 1,3-diols: (*a*) C. Roux, M. Candy, J.-M. Pons, O. Chuzel and C. Bressy, *Angew. Chem., Int. Ed.*, 2014, **53**, 766; (*b*) M. S. Hong, T. W. Kim, B. Jung and S. H. Kang, *Chem. – Eur. J.*, 2008, **14**, 3290; (*c*) B. M. Trost and T. Mino, *J. Am. Chem. Soc.*, 2003, **125**, 2410; (*d*) C. A. Lewis, B. R. Sculimbrene, Y. Xu and S. J. Miller, *Org. Lett.*, 2005, **7**, 3021; (*e*) T. Honjo, M. Nakao, S. Sano, M. Shiro, K. Yamaguchi, Y. Sei and Y. Nagao, *Org. Lett.*, 2007, **9**, 509; (*f*) S. Sano, T. Tsumura, N. Tanimoto, T. Honjo, M. Nakaoand and Y. Nagao, *Synlett*, 2010, 256; For representive Organo-catalyzed desymmetrization of 1,3-diols: (*g*) A. Sakakura, S. Umemura and K. Ishiharab, *Adv. Synth. Catal.*, 2011, **353**, 1938; (*h*) J. Merad, P. Borkar, T. B. Yenda, C. Roux, J.-M. Pons, J.-L. Parrain, O. Chuzel and C. Bressy, *Org. Lett.*, 2015, **17**, 2118; (*i*) S. Yamada, T. Misono, Y. Iwai, A. Masumizu and Y. Akiyama, *J. Org. Chem.*, 2006, **71**, 6872; (*j*) Z. Chen and J. Sun, *Angew. Chem., Int. Ed.*, 2013, **52**, 13593.

6 (*a*) B. E. Maki, A. Chan, E. M. Phillips and K. A. Scheidt, *Org. Lett.*, 2007, **9**, 371; (*b*) J. Guin, S. De Sarkar, S. Grimme and A. Studer, *Angew. Chem., Int. Ed.*, 2008, **47**, 8727; (*c*) S. De Sarkar, S. Grimme and A. Studer, *J. Am. Chem. Soc.*, 2010, **132**, 1190; (*d*) P.-C. Chiang and J. W. Bode, *Org. Lett.*, 2011, **13**, 2422; (*e*) X. Zhao, K. Z. Ruhl and T. Rovis, *Angew. Chem., Int. Ed.*, 2012, **51**, 12330; (*f*) J. Mo, X. Chen

and Y. R. Chi, *J. Am. Chem. Soc.*, 2012, **134**, 8810; (*g*) X. Chen, S. Yang, B.-A. Song and Y. R. Chi, *Angew. Chem., Int. Ed.*, 2013, **52**, 11134; (*h*) X.-Y. Chen, F. Xia, J.-T. Cheng and S. Ye, *Angew. Chem., Int. Ed.*, 2013, **52**, 10644; (*i*) M. Wang, Z. Huang, J. Xu and Y. R. Chi, *J. Am. Chem. Soc.*, 2014, **136**, 1214. For similar ammonium intermediate *via* organocatalysis: (*j*) G. Liu, M. E. Shirley, K. N. Van, R. L. McFarlin and D. Romo, *Nat. Chem.*, 2013, **5**, 1049; (*k*) S. Vellalath, K. N. Van and D. Romo, *Angew. Chem., Int. Ed.*, 2013, **52**, 13688.

7 Recent selected reviews on desymmetrization of diols, see: (*a*) C. E. Müller and P. R. Schreiner, *Angew. Chem., Int. Ed.*, 2011, **50**, 6012; (*b*) Á. Enríquez-García and E. P. Kündig, *Chem. Soc. Rev.*, 2012, **41**, 7803; (*c*) M. D. Díaz-de-Villegas, J. A. Gálvaz, R. Badorrey and M. P. López-Ram-de-Víu, *Chem. – Eur. J.*, 2012, **18**, 13920.

8 For recent reports on asymmetric desymmetrization of 2,2-disubstituted 1,3-diols, see: (*a*) B. Jung and S. H. Kang, *Proc. Natl. Acad. Sci. U. S. A.*, 2007, **104**, 1472; (*b*) B. Jung, M. S. Hong and S. H. Kang, *Angew. Chem., Int. Ed.*, 2007, **46**, 2616; (*c*) J. Y. Lee, Y. S. You and S. H. Kang, *J. Am. Chem. Soc.*, 2011, **133**, 1772; (*d*) D. W. Tay, G. Y. C. Leung and Y.-Y. Yeung, *Angew. Chem., Int. Ed.*, 2014, **53**, 5161; (*e*) Z. Ke, C. K. Tan, F. Chen and Y.-Y. Yeung, *J. Am. Chem. Soc.*, 2014, **136**, 5627; (*f*) Z. Chen and J. Sun, *Angew. Chem., Int. Ed.*, 2013, **52**, 13593; (*g*) S.-S. Meng, Y. Liang, K.-S. Cao, L. Zou, X.-B. Lin, H. Yang, K. N. Houk and W.-H. Zheng, *J. Am. Chem. Soc.*, 2014, **136**, 12249; (*h*) W. Yang, Y. Liu, S. Zhang and Q. Cai, *Angew. Chem., Int. Ed.*, 2015, **54**, 8805.

9 (*a*) J. Chen and Y. Huang, *Nat. Commun.*, 2015, **5**, 3437; (*b*) J. Chen, S. Meng, L. Wang, H. Tang and Y. Huang, *Chem. Sci.*, 2015, **6**, 4184; (*c*) L. Wang, J. Chen and Y. Huang, *Angew. Chem., Int. Ed.*, 2015, **54**, 15414.

10 For selected reviews on NHC catalysis, see: (*a*) D. Enders and T. Balensiefer, *Acc. Chem. Res.*, 2004, **37**, 534; (*b*) K. Zeitler, *Angew. Chem., Int. Ed.*, 2005, **44**, 7506; (*c*) V. Nair, S. Vellalath and B. P. Babu, *Chem. Soc. Rev.*, 2008, **37**, 2691; (*d*) T. Rovis, *Chem. Lett.*, 2008, **37**, 2; (*e*) A. T. Biju, N. Kuhl and F. Glorius, *Acc. Chem. Res.*, 2011, **44**, 1182; (*f*) D. T. Cohen and K. A. Scheidt, *Chem. Sci.*, 2012, **3**, 5336; (*g*) X. Bugaut and F. Glorius, *Chem. Soc. Rev.*, 2012, **41**, 3511; (*h*) J. Izquierdo, G. E. Hutson, D. T. Cohen and K. A. Scheidt, *Angew. Chem., Int. Ed.*, 2012, **51**, 11686; (*i*) S. D. Sarkar, A. Biswas, R. C. Samanta and A. Studer, *Chem. – Eur. J.*, 2013, **19**, 4664; (*j*) S. J. Ryan, L. Candish and D. W. Lupton, *Chem. Soc. Rev.*, 2013, **42**, 4906; (*k*) J. Douglas, G. Churchill and A. D. Smith, *Synthesis*, 2012, 2295; (*l*) J. Izquierdo, G. E. Hutson, D. T. Cohen and K. A. Scheidt, *Angew. Chem., Int. Ed.*, 2012, **51**, 11686; (*m*) M. N. Hopkinson, C. Richter, M. Schedler and F. Glorius, *Nature*, 2014, **510**, 485; (*n*) P. Chauhan and D. Enders, *Angew. Chem., Int. Ed.*, 2014, **53**, 1485; (*o*) D. M. Flanigan, F. Romanov-Michailidis, N. A. White and T. Rovis, *Chem. Rev.*, 2015, **15**, 9307.

11 For NHC catalyzed resolution of alcohol: (*a*) S. Kuwano, S. Harada, B. Kang, R. Oriez, Y. Yamaoka, K. Takasu and K.-I. Yamada, *J. Am. Chem. Soc.*, 2013, **135**, 11485; (*b*) S. Lu, S. B. Poh, W.-Y. Siau and Y. Zhao, *Angew. Chem., Int. Ed.*, 2013, **52**, 1731; (*c*) S. Lu, S. B. Poh and Y. Zhao, *Angew. Chem., Int. Ed.*, 2014, **53**, 11041; (*d*) S. Iwahana, H. Iida and E. Yashima, *Chem. – Eur. J.*, 2011, **17**, 8009.

12 (*a*) M. Wadamoto, E. M. Phillips, T. E. Reynolds and K. A. Scheidt, *J. Am. Chem. Soc.*, 2007, **129**, 10098; (*b*) B. E. Maki, A. Chan, E. M. Phillips and K. A. Scheidt, *Org. Lett.*, 2007, **9**, 371; (*c*) Q. Liu and T. Rovis, *J. Am. Chem. Soc.*, 2006, **128**, 2552; (*d*) M.-Q. Jia, C. Liu and S.-L. You, *J. Org. Chem.*, 2012, **77**, 10996.

13 (*a*) B. Jung and S. H. Kang, *Proc. Natl. Acad. Sci. U. S. A.*, 2007, **104**, 1472; (*b*) B. Jung, M. S. Hong and S. H. Kang, *Angew. Chem., Int. Ed.*, 2007, **46**, 2616; (*c*) J. Y. Lee, Y. S. You and S. H. Kang, *J. Am. Chem. Soc.*, 2011, **133**, 1772.

14 (*a*) Z. Chen and J. Sun, *Angew. Chem., Int. Ed.*, 2013, **52**, 13593; (*b*) S.-S. Meng, Y. Liang, K.-S. Cao, L. Zou, X.-B. Lin, H. Yang, K. N. Houk and W.-H. Zheng, *J. Am. Chem. Soc.*, 2014, **136**, 12249; For catalytic asymmetric desymmetrization of 1,3-diol derivatives: (*c*) Z. Chen, B. Wang, Z. Wang, G. Zhu and J. Sun, *Angew. Chem., Int. Ed.*, 2013, **52**, 2027; (*d*) Z. Wang, Z. Chen and J. Sun, *Angew. Chem., Int. Ed.*, 2013, **52**, 6685; (*e*) Z. Wang, F. K. Sheong, H. Sung, H. Y. Ian, D. Williams, Z. Lin and J. Sun, *J. Am. Chem. Soc.*, 2015, **137**, 5895.

15 (*a*) D. W. Tay, G. Y. C. Leung and Y.-Y. Yeung, *Angew. Chem., Int. Ed.*, 2014, **53**, 5161; (*b*) Z. Ke, C. K. Tan, F. Chen and Y.-Y. Yeung, *J. Am. Chem. Soc.*, 2014, **136**, 5627.

16 M. He, J. R. Struble and J. W. Bode, *J. Am. Chem. Soc.*, 2006, **128**, 8418.

17 H. U. Vora, J. R. Moncecchi, O. Epstein and T. Rovis, *J. Org. Chem.*, 2008, **73**, 9727.

18 For details, please see the ESI†.

19 (*a*) S. Nozoe, M. Morisaki, K. Tsuda, Y. Iitaka, N. Takahashi, S. Tamura, K. Ishibashi and M. Shirasaka, *J. Am. Chem. Soc.*, 1965, **87**, 4968; (*b*) M. Entzeroth, A. J. Blackman, J. S. Mynderse and R. E. Moore, *J. Org. Chem.*, 1985, **50**, 1255; (*c*) S. Aoki, Y. Watanabe, M. Sanagawa, A. Setiawan, N. Kotoku and M. Kobayashi, *J. Am. Chem. Soc.*, 2006, **128**, 3148; (*d*) I. A. Katsoulis, G. Kythreoti, A. Papakyriakou, K. Koltsida, P. Anastasopoulou, C. I. Stathakis, I. Mavridis, T. Cottin, E. Saridakis and D. Vourloumis, *ChemBioChem*, 2011, **12**, 1188.

