


 Cite this: *RSC Adv.*, 2019, **9**, 2799

 Received 8th January 2019
 Accepted 12th January 2019

DOI: 10.1039/c9ra00173e

rsc.li/rsc-advances

β -Hydroxy- α -amino esters and their derivatives are important structural motif in a number of biologically relevant compounds.¹ As a consequence, several elegant methods have been developed for the stereoselective² and asymmetric³ synthesis of such compounds. We speculated that the versatility of this scaffold could be expanded by the incorporation of a vinyl moiety in 3-position (e.g. 2, Scheme 1), thus allowing for additional stereoselective manipulation. For example, stereoselective epoxidation⁴ or dihydroxylation⁵ of the carbon–carbon double bond in compound 2, or cross metathesis, could furnish advanced such intermediates for the synthesis of polyhydroxylated alkaloids (Scheme 1), compounds with diverse biological activities.⁶ Compound 2, in turn, was expected to be derived through a chemoselective asymmetric transfer

Enantioselective synthesis of *anti*-3-alkenyl-2-amido-3-hydroxy esters: application to the total synthesis of (+)-alexine†

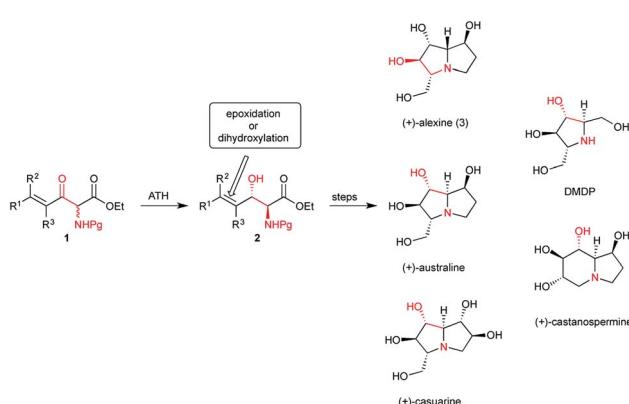
 Lu Yu  and Peter Somfai*

A straightforward synthesis of *anti*-3-alkenyl-2-amido-3-hydroxy esters from the corresponding racemic α -amino- β -keto esters by using a ATH/DKR protocol has been developed. This method gives moderate to excellent yields with high chemo-, diastereo- and enantioselectivities for a broad range of substrates. In order to highlight the versatility of the methodology it was applied in an efficient asymmetric synthesis of the polyhydroxylated pyrrolizidine alkaloid (+)-alexine (3).

hydrogenation (ATH) of α -amido- β -keto ester 1. Herein we detail our efforts towards realizing this methodology and its application to the synthesis of (+)-alexine (3).

ATH coupled with a dynamic kinetic resolution (DKR) of configurationally labile α -amido- β -keto ester has been proven to be a powerful method for the synthesis of *syn*- or *anti* β -hydroxy- α -amino esters.⁷ In such transformation two contiguous stereocenters can be constructed in high er and dr in a single operation from a racemic starting material. We have previously developed a ATH process coupled with DKR for preparation aryl, alkyl or heterocyclic *anti*- β -hydroxy- α -amido ester in organic solvents, emulsions or water system.⁸ For the present investigation it was of interest to expand the substrate scope to encompass substrates having an vinylic group in 3-position, e.g. compound 1, and to investigate the possibility of developing a chemoselective 1,2-reduction of the carbonyl group in preference of a 1,4-reduction of the enone moiety.

The investigation was initiated by examining the ATH of ester 1a using our previously optimized conditions $[(\text{RuCl}_2(\text{-benzene}))_2/(S,S)\text{-BnDPAE}]$, yielding a mixture of the desired *anti*-amino alcohol 2a, having low dr and er, and the over-reduced compound 4 in poor selectivity (Table 1, entry 1). Subjecting 2a to the reactions conditions did not afford 4 and it is believed that the latter compound is formed by an initial 1,4-reduction of the enone moiety in 1a followed by a 1,2-reduction of the resultant carbonyl group. Screening of different ligands gave 2a with increased diastereoselectivity, but in all cases the chemoselectivity remained low (entries 2–4). It was noted, however, that the use of (S,S)-DPAE resulted in the formation of 2a in high enantiomeric excess (er 95 : 5, entry 4). It was then decided to explore different ruthenium dimer catalysts together with the (S,S)-DPAE ligand (entries 5–7). The use of ruthenium(II) dichloride dimer catalyst incorporating a substituted arene moiety resulted in an improved chemoselectivity with only traces of the over reduced compound 4 being observed, the best

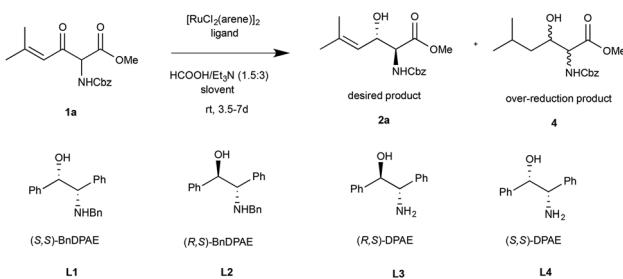


Scheme 1 Proposed route from α -amido- β -keto ester 1 to polyhydroxylated pyrrolizidine and indolizidine alkaloids.

Centre for Analysis and Synthesis, Department of Chemistry, Lund University, 22100, Lund, Sweden. E-mail: peter.somfai@chem.lu.se

† Electronic supplementary information (ESI) available. See DOI: 10.1039/c9ra00173e



Table 1 Optimization of the ATH Reaction of **1a**^a

Entry	Ru dimer	Ligand	Solvent	1a/2a/4 (%) ^b	dr (<i>anti</i> : <i>syn</i>) ^c	er (<i>anti</i>) ^d
1	Benzene	L1	CH ₂ Cl ₂	5/50/20	55 : 45	88.5 : 11.5
2	Benzene	L2	CH ₂ Cl ₂	21/41/16	89 : 11	7 : 93
3	Benzene	L3	CH ₂ Cl ₂	35/15/5	87 : 13	12.5 : 87.5
4	Benzene	L4	CH ₂ Cl ₂	<5/52/20	80 : 20	95 : 5
5	p-Cymene	L4	CH ₂ Cl ₂	33/47/<5	85 : 15	90.5 : 9.5
6	Mesitylene	L4	CH ₂ Cl ₂	20/65/<5	91.5 : 8.5	93 : 7
7	Hexamethylbenzene	L4	CH ₂ Cl ₂	34/28/<5	83 : 17	58 : 42
8	Mesitylene	L4	MeOH	49/24/<5	86 : 14	89.5 : 10.5
9	Mesitylene	L4	CH ₃ CN	26/37/<5	85 : 15	85 : 15
10	Mesitylene	L4	Dioxane	8/68/<5	93 : 7	95.5 : 4.5
11	Mesitylene	L4	CHCl ₃	13/57/<5	94.5 : 5.5	96 : 4
12 ^e	Mesitylene	L4	Dioxane	11/68/<5	93 : 7	96 : 4
13 ^f	Mesitylene	L4	Dioxane	15/60/<5	94 : 6	96 : 4
14 ^g	Mesitylene	L4	Dioxane	12/72/<5	95 : 5	96.5 : 3.5

^a Reactions preformed with [RuCl₂(arene)]₂ (0.1 eq.) and ligand (0.2 eq.) heated in 2-propanol (0.3 mL) at 80 °C for 1 h. After cooling to room temperature, the catalyst was then added to a solution of **1a** (0.2 mmol, 1 eq.) and HCO₂H/Et₃N (1.5 : 3, 1.5 eq.) in solvent (1 mL). ^b Isolated yields. ^c Determined by NMR analysis of the crude reaction mixture. ^d Determined by chiral HPLC. ^e Reaction run with 0.075 eq. of [RuCl₂(mesitylene)]₂ and 0.15 eq. of (S,S)-DPAE. ^f Reaction run with 0.05 eq. of [RuCl₂(mesitylene)]₂ and 0.1 eq. of (S,S)-DPAE. ^g Reaction run with 0.025 eq. of [RuCl₂(mesitylene)]₂ and 0.05 eq. of (S,S)-DPAE.

result being obtained with [RuCl₂(mesitylene)]₂ (entry 6). Encouraged by this result, other reaction parameters (solvent and catalyst loading) were screened in order to improve the reaction outcome. Performing the reaction in MeOH or CH₃CN did not improve the outcome (entries 8–9), while the use of dioxane or CHCl₃ afforded similar results in terms of yields and stereoselectivities as CH₂Cl₂ (entries 8–11). Since the reaction run in dioxane gave the best result this solvent was selected for the final screening of catalyst loading (entries 12–14). It was observed that similar yields but with improved diastereoselectivity could be achieved when lowering the amount of catalyst from 20 mol% to 5 mol%. The best result, 72% yield of **2a** with 95 : 5 dr and 96.5 : 3.5 er, was obtained when using 2.5 mol% of [RuCl₂(mesitylene)]₂ and 5 mol% (S,S)-DPAE (entry 14).

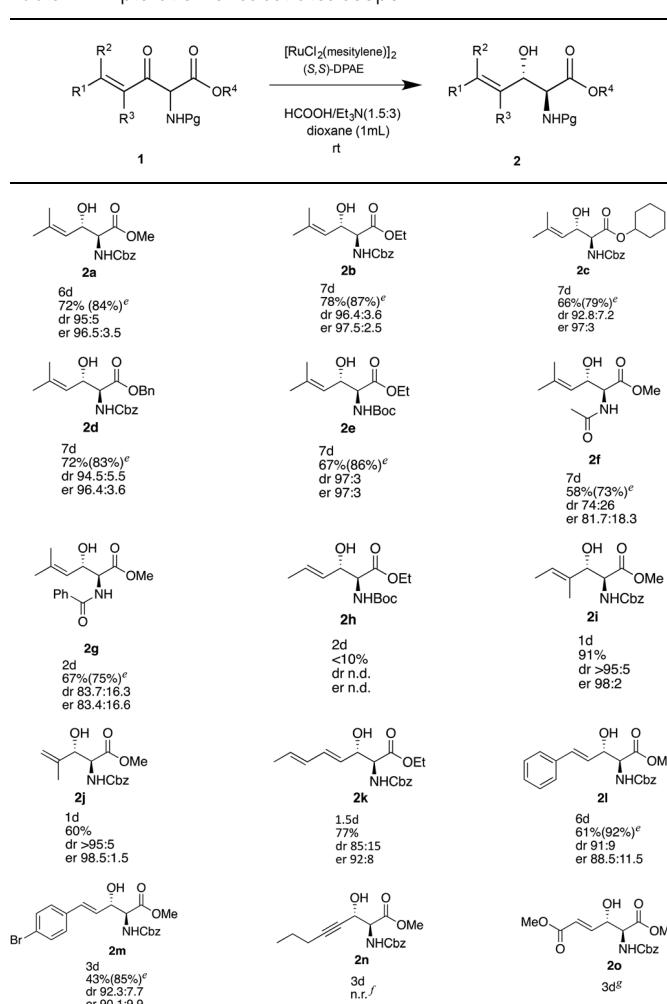
Next the scope of the ATH reaction was investigated by screening a variety of γ -alkenyl- β -keto- α -amido esters **1** and the results are summarized in Table 2. The influence of the ester moiety in the substrate was negligible as compounds **1a–d** all gave the corresponding aminoalcohols **2a–d**, respectively, in good yields and high selectivities. However, the choice of *N*-protecting group influenced the reaction outcome, with *N*-acetyl and *N*-benzoate protected substrates **1f** and **1g** furnishing the corresponding products in lower yields and selectivities compared to **1a**, while *N*-Boc protected **1e** performed equally well as **1a**. The ATH reaction proved to be sensitive to the

substitution at the olefin moiety with substrate **1h**, having a disubstituted alkene, giving mostly over-reduced products derived from both 1,4- and 1,2-reductions and only minor amounts of **2h**. Substrate **1i** and **1j**, having a trisubstituted and 1,1-disubstituted olefin moiety, respectively, performed well in the ATH reaction and deliver the corresponding products in good yields, dr and er. Similarly, substrates **1k–m**, having a conjugated olefin moiety, all performed well in the reduction, while alkynyl **1n** was unreactive under these conditions and **1o** gave a complicated mixture of products.

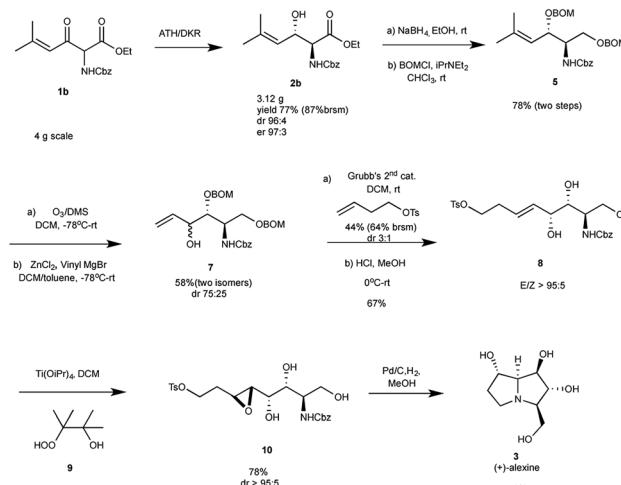
To demonstrate the applicability of the developed methodology it was decided to apply it to the total synthesis of the polyhydroxylated pyrrolizidine alkaloid (+)-alexine.⁹ Previous syntheses of this natural product has relied on carbohydrate derived strategies and relatively high steps strategies, while the present approach relies on an efficient and non-carbohydrate entry into this class of compounds. Our retrosynthetic analysis is summarized in Scheme 2 and relies on the known cyclization of amino epoxides **10** into (+)-alexine.¹⁰ Compound **10**, in turn is derived from alkene **8**, which can be derived from **2b** using standard transformations (Scheme 2).

Subjecting ester **1b** (4 g) to the ATH reaction, using the optimized conditions, furnished *anti*- α -amido- β -hydroxy ester **2b** (87% brsm) in high diastereo- and enantioselectivity (*anti*/*syn* 96 : 4, er 97 : 3), which also indicate that the ATH/DKR protocol is scalable. Reduction of **2b** with NaBH₄, followed by



Table 2 Exploration of substrates scope^{a,b,c,d}

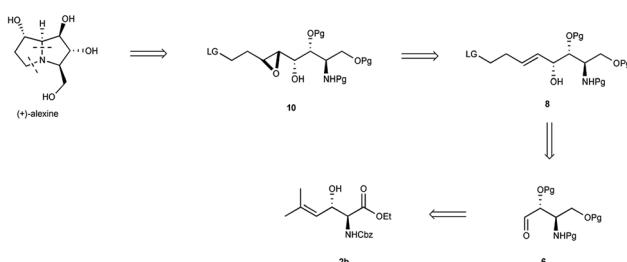
protection of the resulting 1,3-diol as the bis-BOM ether provided 5 (78%, two steps). Ozonolysis of this material followed by a chelation controlled addition of vinylmagnesium bromide afforded compound 7 (58%, dr 75 : 25).¹¹ Attempts to



Scheme 3 Total synthesis of (+)-alexine.

improve the dr of this step involved screening different solvents, Lewis acids, temperatures and hydroxyl protecting groups, but did not improve the situation.¹² The cross metathesis reaction of mixture 7 with 4-butenol *p*-tolyl-sulfonate in the presence of Grubbs' 2nd generation catalyst provided the *trans* olefin (64% brsm). After the deprotection of benzyloxymethyl group, an undesired diastereomer of compound 8 could be separated by column chromatography, and compound 8 was obtained (67%, dr > 95 : 5) as a pure form. Next the stage was set for the neighbouring group directed epoxidation of 8, which was accomplished using $\text{Ti}(\text{O}i\text{Pr})_4$ and β -hydroperoxy alcohol 9, yielding *anti* epoxide 10 (78%) as the only detectable isomer.¹³ Deprotection of 10 (Pd/C , H_2 , MeOH) followed by purification on silica gel afforded (+)-alexine (3) in 76% yield as a white solid. The $^1\text{H-NMR}$, $^{13}\text{C-NMR}$ data, melting point and the optical rotation ($\text{mp} 160\text{--}162$ °C, $[\alpha]_D^{20} = +42.1$ (c 0.3 H_2O)) were in good agreement with the published data for (+)-alexine⁹ ($\text{mp} 162\text{--}163$ °C, $[\alpha]_D^{20} = +40$ (c 0.25 in H_2O)) (Scheme 3).

In summary, we have developed an operationally straightforward synthesis of *anti*-3-alkenyl-2-amido-3-hydroxy esters from the corresponding racemic α -amino- β -keto esters by using a ATH/DKR protocol. This method gives moderate to excellent yields, diastereoselective and enantioselectivities for a broad range of substrates. In order to highlight the versatility of the methodology it was applied in an asymmetric synthesis of the polyhydroxylated pyrrolizidine alkaloid (+)-alexine (3, 8 steps and 11.5% overall yield from 2b).



Scheme 2 Retrosynthetic analysis of (+)-alexine.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This work was supported by the Swedish Research Council, the Royal Physiographic Society of Lund, the Chinese Scholarship Council, and Lund University.



Notes and references

1 (a) M. J. Miller, *Acc. Chem. Res.*, 1986, **19**, 49–56; (b) S. V. Pansare and J. C. Vederas, *J. Org. Chem.*, 1987, **52**, 4804–4810; (c) B. T. Lotz and M. J. Miller, *J. Org. Chem.*, 1993, **58**, 618–625; (d) D. Tanner, *Angew. Chem., Int. Ed. Engl.*, 1994, **33**, 599–619; (e) P. W. Ford, K. R. Gustafson, T. C. McKee, N. Shigematsu, L. K. Maurizi, L. K. Pannell, D. E. Williams, E. Dilip de Silva, P. Lassota, T. M. Allen, R. Van Soest, R. J. Andersen and M. R. Boyd, *J. Am. Chem. Soc.*, 1999, **121**, 5899–5909; (f) K. C. Nicolaou, C. N. C. Boddy, S. Bräse and N. Winssinger, *Angew. Chem., Int. Ed.*, 1999, **38**, 2096–2152; (g) J. W. Misner, J. W. Fisher, J. P. Gardner, S. W. Pedersen, K. L. Trinkle, B. G. Jackson and T. Y. Zhang, *Tetrahedron Lett.*, 2003, **44**, 5991–5993; (h) S.-J. Wen and Z.-J. Yao, *Org. Lett.*, 2004, **6**, 2721–2724; (i) K. C. Nicolaou, D. H. Dethe, G. Y. C. Leung, B. Zou and D. Y. K. Chen, *Chem.-Asian J.*, 2008, **3**, 413–429; (j) P.-G. Echeverria, S. Prévost, J. Cornil, C. Férand, S. Reymond, A. Guérinot, J. Cossy, V. Ratovelomanana-Vidal and P. Phansavath, *Org. Lett.*, 2014, **16**, 2390–2393.

2 (a) L. He, H.-S. Byun and R. Bittman, *J. Org. Chem.*, 2000, **65**, 7627–7633; (b) J. A. Bodkin, G. B. Bacska and M. D. McLeod, *Org. Biomol. Chem.*, 2008, **6**, 2544–2553; (c) J. Patel, G. Clavé, P. Y. Renard and X. Franck, *Angew. Chem., Int. Ed.*, 2008, **47**, 4224–4227; (d) T. J. Donohoe, C. K. A. Callens, A. Flores, A. R. Lacy and A. H. Rathi, *Chem.-Eur. J.*, 2011, **17**, 58–76; (e) A. C. W. Masruri and M. D. McLeod, *J. Org. Chem.*, 2012, **77**, 8480–8491; (f) Y. Singjunla, J. Baudoux and J. Rouden, *Org. Lett.*, 2013, **15**, 5770–5773; (g) P. Chaumont, J. Baudoux, J. Maddaluno, J. Rouden and A. Harrison-Marchand, *J. Org. Chem.*, 2018, **83**, 8081–8091.

3 (a) J. Kobayashi, M. Nakamura, Y. Mori, Y. Yamashita and S. Kobayashi, *J. Am. Chem. Soc.*, 2004, **126**, 9192–9193; (b) M. C. Willis, G. A. Cutting, V. J. D. Piccio, M. J. Durbin and M. P. John, *Angew. Chem., Int. Ed.*, 2005, **44**, 1543–1545; (c) T. Maeda, K. Makino, M. Iwasaki and Y. Hamada, *Chem.-Eur. J.*, 2010, **16**, 11954–11962; (d) Y. Zheng and L. Deng, *Chem. Sci.*, 2015, **6**, 6510–6514.

4 (a) K. A. Joergensen, *Chem. Rev.*, 1989, **89**, 431–458; (b) W. Adam, K. Peters and M. Renz, *Angew. Chem., Int. Ed. Engl.*, 1994, **33**, 1107–1108; (c) D. Yang, M.-K. Wong and Y.-C. Yip, *J. Org. Chem.*, 1995, **60**, 3887–3889; (d) W. Adam and C. M. Mitchell, *Angew. Chem., Int. Ed. Engl.*, 1996, **35**, 533–535; (e) K. Kamata, K. Yamaguchi, S. Hikichi and N. Mizuno, *Adv. Synth. Catal.*, 2003, **345**, 1193–1196; (f) U. M. Lindstrom, R. Ding and O. Hidestal, *Chem. Commun.*, 2005, 1773–1774.

5 (a) S. Saito, Y. Morikawa and T. Moriwake, *J. Org. Chem.*, 1990, **55**, 5424–5426; (b) J. K. Cha and N.-S. Kim, *Chem. Rev.*, 1995, **95**, 1761–1795; (c) C. J. R. Bataille and T. J. Donohoe, *Chem. Soc. Rev.*, 2011, **40**, 114–128.

6 (a) J. D. White, P. Hrnciar and A. F. T. Yokochi, *J. Am. Chem. Soc.*, 1998, **120**, 7359–7360; (b) S. E. Denmark and E. A. Martinborough, *J. Am. Chem. Soc.*, 1999, **121**, 3046–3056; (c) V. H. Lillelund, H. H. Jensen, X. Liang and M. Bols, *Chem. Rev.*, 2002, **102**, 515–554; (d) J. Cecon, A. E. Greene and J.-F. Poisson, *Org. Lett.*, 2006, **8**, 4739–4742; (e) C. Ribes, E. Falomir, M. Carda and J. A. Marco, *Org. Lett.*, 2007, **9**, 77–80; (f) E. G. Bowen and D. J. Wardrop, *Org. Lett.*, 2010, **12**, 5330–5333; (g) M. Malik, G. Witkowski and S. Jarosz, *Org. Lett.*, 2014, **16**, 3816–3819; (h) J. Robertson and K. Stevens, *Nat. Prod. Rep.*, 2014, **31**, 1721–1788; (i) Y.-X. Li, Y. Shimada, K. Sato, A. Kato, W. Zhang, Y.-M. Jia, G. W. J. Fleet, M. Xiao and C.-Y. Yu, *Org. Lett.*, 2015, **17**, 716–719.

7 (a) K. Makino, Y. Hiroki and Y. Hamada, *J. Am. Chem. Soc.*, 2005, **127**, 5784–5785; (b) K. Makino, M. Iwasaki and Y. Hamada, *Org. Lett.*, 2006, **8**, 4573–4576; (c) Y. Hamada, Y. Koseki, T. Fujii, T. Maeda, T. Hibino and K. Makino, *Chem. Commun.*, 2008, 6206–6208; (d) K. M. Steward, E. C. Gentry and J. S. Johnson, *J. Am. Chem. Soc.*, 2012, **134**, 7329–7332; (e) D. Wang and D. Astruc, *Chem. Rev.*, 2015, **115**, 6621–6686; (f) V. Bhat, E. R. Welin, X. Guo and B. M. Stoltz, *Chem. Rev.*, 2017, **117**, 4528–4561; (g) G. Sun, Z. Zhou, Z. Luo, H. Wang, L. Chen, Y. Xu, S. Li, W. Jian, J. Zeng, B. Hu, X. Han, Y. Lin and Z. Wang, *Org. Lett.*, 2017, **19**, 4339–4342; (h) L.-S. Zheng, C. Ferard, P. Phansavath and V. Ratovelomanana-Vidal, *Chem. Commun.*, 2018, **54**, 283–286.

8 (a) B. Seashore-Ludlow, P. Villo, C. Häcker and P. Somfai, *Org. Lett.*, 2010, **12**, 5274–5277; (b) B. Seashore-Ludlow, F. Saint-Dizier and P. Somfai, *Org. Lett.*, 2012, **14**, 6334–6337; (c) B. Seashore-Ludlow, P. Villo and P. Somfai, *Chem.-Eur. J.*, 2012, **18**, 7219–7223.

9 (a) G. W. J. Fleet, M. Haraldsson, R. J. Nash and L. E. Fellows, *Tetrahedron Lett.*, 1988, **29**, 5441–5444; (b) R. J. Nash, L. E. Fellows, J. V. Dring, G. W. J. Fleet, A. E. Derome, T. A. Hamor, A. M. Scofield and D. J. Watkin, *Tetrahedron Lett.*, 1988, **29**, 2487–2490; (c) H. Yoda, H. Katoh and K. Takabe, *Tetrahedron Lett.*, 2000, **41**, 7661–7665; (d) M. Dressel, P. Restorp and P. Somfai, *Chem.-Eur. J.*, 2008, **14**, 3072–3077; (e) M. Takahashi, T. Maehara, T. Sengoku, N. Fujita, K. Takabe and H. Yoda, *Tetrahedron*, 2008, **64**, 5254–5261.

10 (a) W. H. Pearson and J. V. Hines, *J. Org. Chem.*, 2000, **65**, 5785–5793; (b) D. Chikkanna, O. V. Singh, S. B. Kong and H. Han, *Tetrahedron Lett.*, 2005, **46**, 8865–8868.

11 F. Yang, L. Feng, N. Wang, X. Liu, J. Li and Y. Shen, *Tetrahedron*, 2013, **69**, 9463–9468.

12 (a) M. Carda, S. Rodríguez, F. González, E. Castillo, A. Villanueva and J. A. Marco, *Eur. J. Org. Chem.*, 2002, **2002**, 2649–2655; (b) S. G. Davies, A. L. A. Figuccia, A. M. Fletcher, P. M. Roberts and J. E. Thomson, *Org. Lett.*, 2013, **15**, 2042–2045; (c) G. E. Keck, M. B. Andrus and D. R. Romer, *J. Org. Chem.*, 1991, **56**, 417–420; (d) G. R. Stanton, C. N. Johnson and P. J. Walsh, *J. Am. Chem. Soc.*, 2010, **132**, 4399–4408.

13 W. Adam, K. Peters and M. Renz, *J. Org. Chem.*, 1997, **62**, 3183–3189.

