Tetrahedron 67 (2011) 1893–1906

Contents lists available at ScienceDirect

Tetrahedron

journal homepage: www.elsevier.com/locate/tet

Reactivity and stereoselectivity of the Diels–Alder reaction using cyclic dienophiles and siloxyaminobutadienes

Toshiyuki Ohfusa, Atsushi Nishida *

Graduate School of Pharmaceutical Sciences, Chiba University, 1-33 Yayoi-cho, Inage-ku, Chiba 263-8522, Japan

ARTICLE INFO

Article history:
Received 5 January 2011
Received in revised form 5 January 2011
Accepted 6 January 2011
Available online 13 January 2011

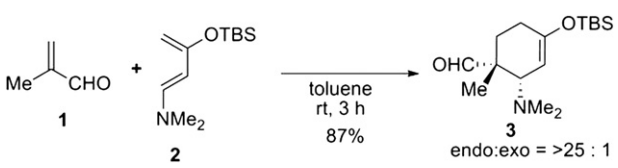
Keywords:
Diels–Alder reaction
Siloxyaminobutadiene
Cyclic dienophile
Stereoselectivity
Reactivity

ABSTRACT

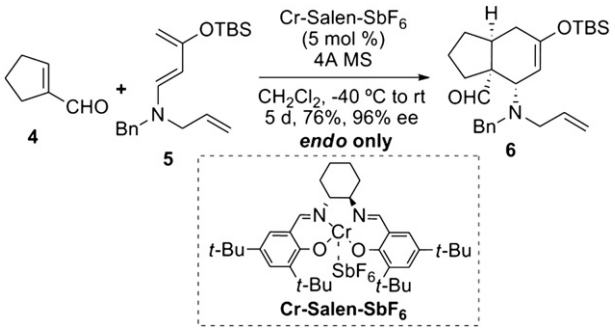
Several bicyclic compounds were synthesized by the Diels–Alder reaction using aminodiene and a cyclic dienophile. The stereochemistries of the obtained adducts were determined by X-ray crystallography or NMR analysis. The stereoselectivity of this Diels–Alder reaction was based on the interaction of molecular orbitals between the diene and dienophile. The reactivities of these Diels–Alder reactions were estimated, and the generality of this reaction is discussed.

1. Introduction

Many natural compounds contain a six-membered ring system. In the synthesis of this ring system, stereo-control is an important issue. In 1997, Rawal and Kozmin introduced 1-amino-3-siloxy-butadiene (aminodiene) as a highly reactive diene in the Diels–Alder (DA) reaction (Scheme 1).[1a] They also reported a diastereoselective DA reaction using a chiral aminodiene[1b,1c] and an enantioselective DA reaction in the presence of a chiral Cr-salen-SbF_6 catalyst.[1d–1f] These highly reactive DA reactions using aminodienes are powerful tools for constructing cyclohexene derivatives and have been applied to the synthesis of natural products.[1c,2–7] However, there are few reports of the use of aminodiene and a cyclic dienophile to construct a bicyclic system.[1d,1e,6,8] Rawal reported the DA reaction using carboxaldehyde **4** with aminodiene **5** and obtained *endo* adduct **6** (Scheme 2),[1d] although the stereochemistry of **6** was only



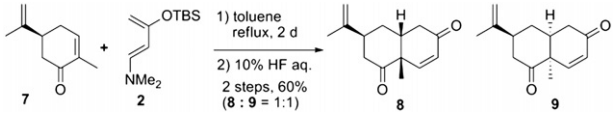
Scheme 1.



Scheme 2.

estimated based on the reaction mechanism. Furthermore, in most of these examples, an amino group is immediately removed to transform the product into an enone (Scheme 3).[9]

On the other hand, we previously reported the enantioselective DA reaction of **10** and **11** with 50 mol % of a chiral Cr-Salen-F complex, which has fluoride anion as a counter ion.[10] The reaction

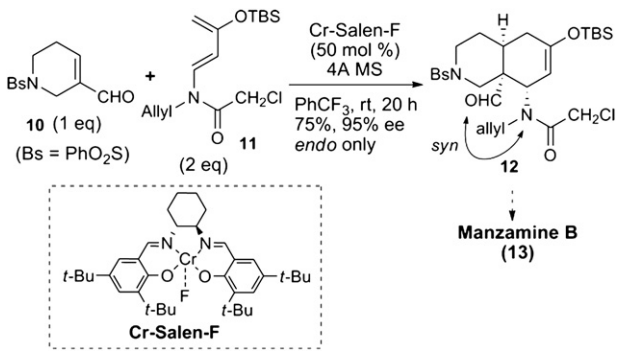


Scheme 3.

* Corresponding author. E-mail address: nishida@p.chiba-u.ac.jp (A. Nishida).

0040-4020/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tet.2011.01.019

proceeded smoothly to give a hydroisoquinoline **12** with high *endo* selectivity (Scheme 4), in which the formyl group and amino group have a *syn* stereochemistry. Isoquinoline **12** should be a potential intermediate for the total synthesis of manzamine B (**13**).

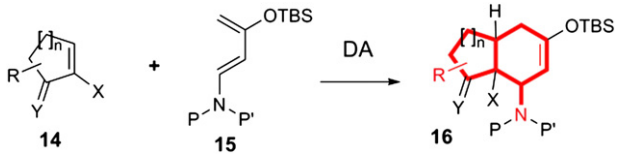


Scheme 4.

Thus, further study on the stereoselectivity of the DA reaction using aminodienes has been required. In this paper, we report a systematic study of the reactivity and stereoselectivity of the DA reaction using aminodienes and cyclic dienophiles.

2. Results and discussion

We studied DA reactions using aminodienes and cyclic dienophiles as shown in Scheme 5, with particular focus on the stereoselectivity of the amino function. If the stereoselectivity is controlled by an electron-withdrawing group X or Y on the dienophile, the reaction may be useful for constructing skeletons in natural compounds, such as **13** and **17**–**19**,[11–14] which have an amino pendant group on a bicyclic skeleton with different stereochemical requirements (Fig. 1).



Scheme 5.

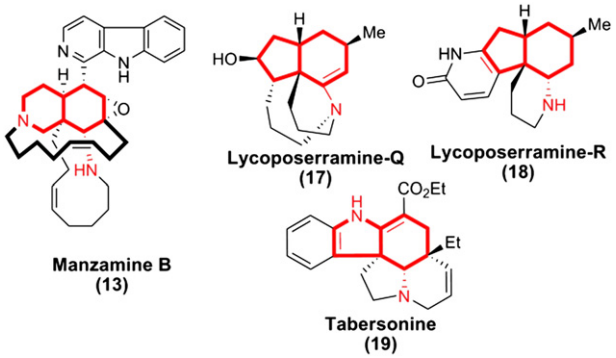


Fig. 1. Natural products possessing bicyclic system like **15**.

2.1. Synthesis of dienophiles

Carboxaldehydes **20**, **21**, and **22**, enone **23**, and doubly activated ketoesters **24** and **25** were used as dienophiles to investigate carbocyclic dienophiles (Fig. 2). Lactam dienophile **26** was also designed to compare its reactivity to that of **10** in Scheme 4. Dienophiles **20**, **24**, and **25** were synthesized by a known procedure.[15,16] Carboxaldehyde **22** was synthesized from known alcohol **33**,[17] via protection of the secondary alcohol and halogen–lithium exchange followed by formylation with DMF. The known compound **35**[18] was converted to enoen dienophile **23** by protection with a PMB group under acidic conditions. Lactam-type dienophile **26** was synthesized from *N*-benzenesulfonyl lactam **38** in 2 steps.[19] Dienes **11** and **39** were prepared by an established procedure.[10] Cyclohexenecarboxalde hyde **21** is available from Aldrich (Fig. 3).

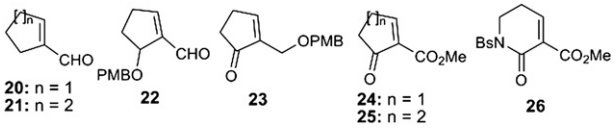


Fig. 2. Designed dienophiles.

2.2. DA reaction and determination of stereochemistry

We began to study the DA reaction using cycloalkene–carbo xaldehyde-type dienophiles **20**, **21**, and **22** under the influence of 50 mol % Cr–Salen–F complex (Table 1). These results show *endo* addition to a formyl carbonyl group. In the reaction of dienophile **22**,

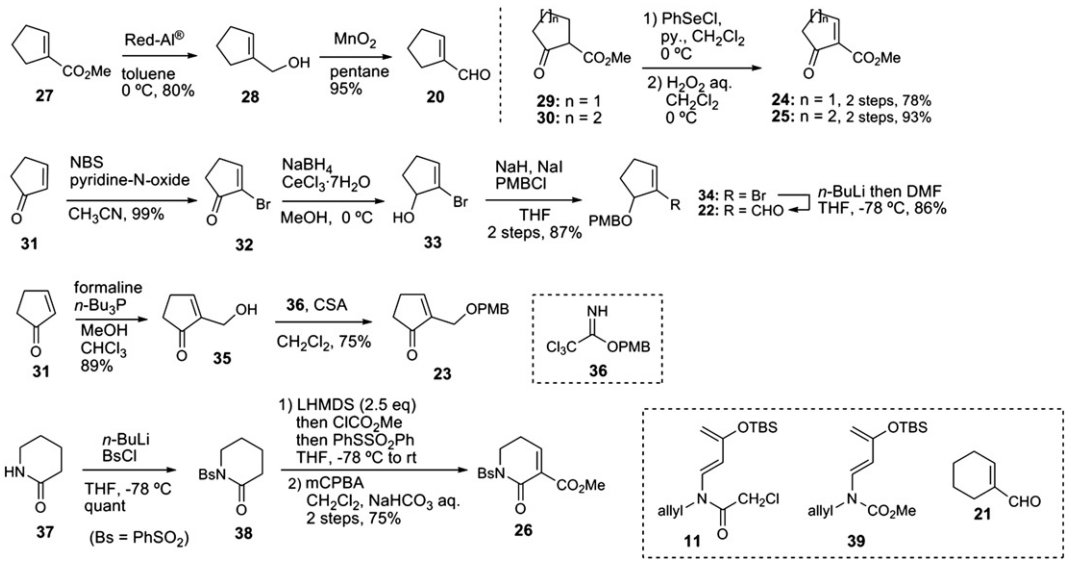
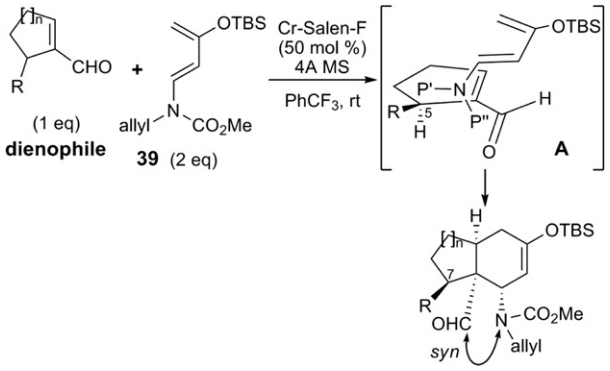


Fig. 3. Preparation of dienophile.

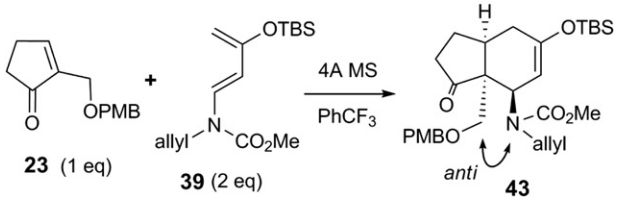
Table 1
DA reaction of carboxaldehyde-type dienophiles



Entry	Dienophile	Time (h)	Result
1	**20**: n=1, R=H	1	**40**: 86%, 79% ee
2	**21**: n=2, R=H	50	**41**: 69%, 81% ee
3	**22**: n=1, R=OPMB	5	**42**: 73%[a], 59% ee[b]

[a] Diastereomer ratio at the C7 position was 7.3:1.
[b] ee of major isomer.

Table 2
DA reaction of substituted cyclopentenone



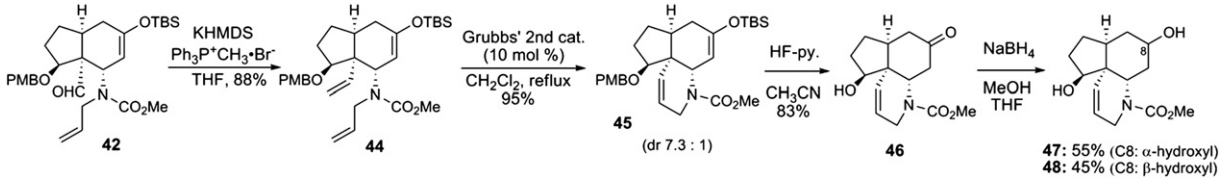
Entry	Conditions	Yield
1	Cr–Salen–F (50 mol %), 100 °C, 4 d	4%
2	Microwave (<300 W, 150 °C, <3.0 atm, 36 h)	61%

which has a stereogenic center in the cyclopentene ring, a mixture of adducts was smoothly obtained with high diastereoselectivity (7.3:1) at the C7 position. When dienophile **22** was used, C5 proton, which occupies the pseudo axial position, blocked α face in transition state as shown in **A**. Therefore, diene **39** attacked from β face. Cyclopentenecarboxaldehyde **20** was more reactive than cyclohexenecarboxaldehyde **21** and **10** (Table 1, entries 1 and 2). In all of the reactions, the face selectivity was perfectly controlled to give a *syn* adduct. On the other hand, cyclopentenone **23** was less

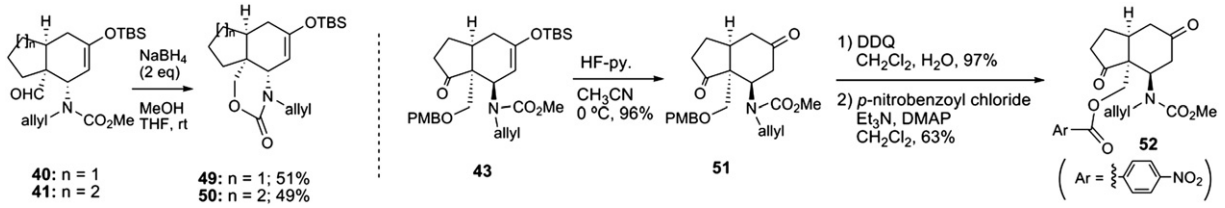
Fig. 4. X-ray crystallography of **48**.

reactive. The DA reaction of **23** and **39** gave adduct **43** in only 4% yield in the presence of 50 mol % Cr–Salen–F complex at 100 °C for 4 days (Table 2, entry 1). However, microwave irradiation accelerated the reaction to give adduct in 61% yield (Table 2, entry 2). Adduct **43** has *anti* stereochemistry, which is explained by an *endo* transition state to a ketone carbonyl group.

The DA adducts were converted into derivatives to determine their stereochemistries by X-ray crystallographic or 2D-NMR analysis and NOE correlation. Adduct **42** was converted into tricyclic compound **45** by Rawal's procedure.[2] Deprotection followed by reduction of the ketone gave a mixture of diastereomeric secondary alcohols, **47** and **48**. Separated **48** was a crystalline compound, which was suitable for X-ray analysis (Scheme 6 and Fig. 4). Adducts **40** and **41** were converted to cyclic carbamates **49** and **50** by reduction of a formyl group followed by cyclization (Scheme 7). Their stereochemistries



Scheme 6.



Scheme 7.

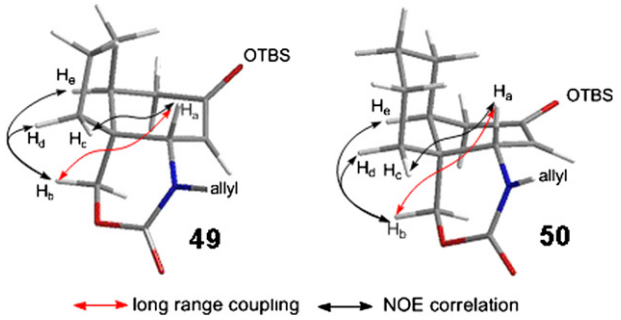


Fig. 5. Stereochemistries of **49** and **50** determined by NMR analysis.

were determined by a combination of 2D-NMR analysis and NOE experimentation (Fig. 5). DA adduct **43** was converted to crystalline compound **52** by deprotection of both the TBS enol ether and PMB group followed by acylation of a primary alcohol using *p*-nitrobenzoyl chloride. The stereochemistry of **52** was determined by X-ray analysis, and the crystal was confirmed to be a dimer (Scheme 7 and Fig. 6).

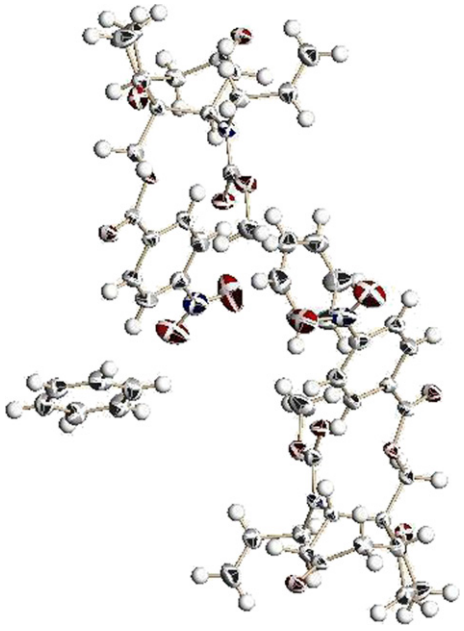
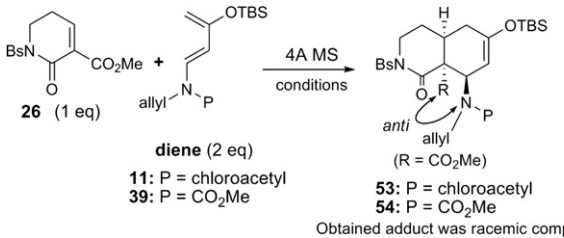


Fig. 6. X-ray crystallography of **52**.

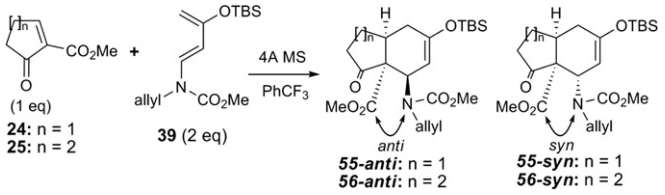
Next, we were interested in the reaction using doubly activated cyclic dienophiles. When the lactam dienophile **26** was reacted with aminodienes, *anti*-adduct **53** or **54** was obtained as a single racemic isomer (Table 3). On the other hand, both ketoester **24** and

Table 3
DA reaction using lactam-type dienophile **26**



Entry	Diene	Conditions	Result
1	**11**	Cr–Salen–F (50 mol %), $CHCl_3$, reflux, 3 d	**53**: 75%
2	**11**	Microwave (<300 W, 150 °C), 2 h	**53**: 46%
3	**39**	Cr–Salen–F (50 mol %), $CHCl_3$, reflux, 3 d	**54**: 61%
4	**39**	Microwave (<300 W, 150 °C), 2 h	**54**: 19%

Table 4
DA reaction using ketoester dienophiles **24** and **25**

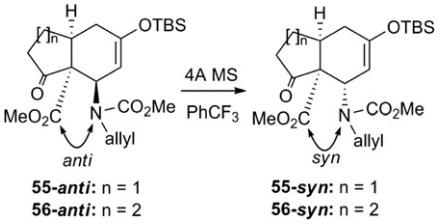


Entry	Dienophile	Conditions	Yield % (ee%)[a]	
			anti	*syn*
1	**24**	Cr–Salen–F (50 mol %), 0 °C, 4.5 h	23 (18)	24 (23)
2	**24**	Cr–Salen–F (50 mol %), rt, 2 h	38 (16)	31 (15)
3	**24**	Cr–Salen–F (50 mol %), 60 °C, 1 h	43 (16)	44 (13)
4	**24**	Microwave (<300W, 150 °C), 5 min	39	24
5	**25**	Cr–Salen–F (50 mol %), rt, 4 d	23 (48)	26 (5)
6	**25**	Cr–Salen–F (50 mol %), 60 °C, 6 h	21 (40)	25 (12)
7	**25**	Microwave (<300W, 150 °C), 2 h	35	20

[a] Absolute stereochemistry was determined from a mechanistic point of view.

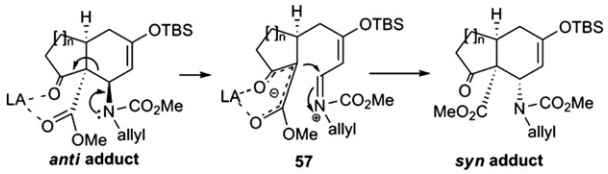
25 gave a mixture of *syn*/*anti* DA adducts with low enantioselectivity (Table 4). Although the isolated yield of both adducts is almost equal, we found that the isolated *anti* isomer isomerized to *syn* isomer under Lewis acidic conditions (Table 5). However, the isomerization did not proceed under microwave irradiation.

Table 5
Isomerization of DA adduct **55**-*anti* and **56**-*anti*



Entry	SM	Conditions	Result
1	**55**-*anti*	Cr–Salen–F (50 mol %), rt, 21 h	**55**-*syn*: quant
2	**55**-*anti*	Microwave (<300 W, 150 °C), 5 min	no reaction
3	**56**-*anti*	Cr–Salen–F (50 mol %), rt, 5 d	**56**-*anti*:**56**-*syn* ca. 1:1
4	**56**-*anti*	Microwave (<300 W, 150 °C), 2 h	no reaction

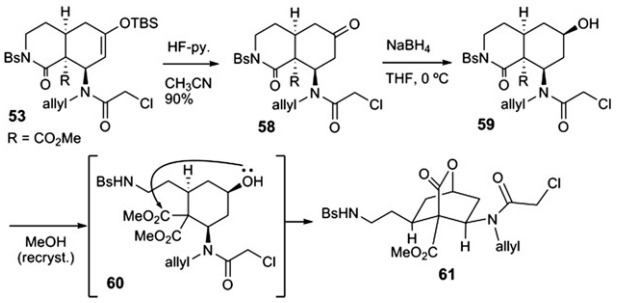
A plausible mechanism for this isomerization is shown in Scheme 8. By a retro-Mannich pathway, zwitterionic intermediate **57** is generated, which should be recyclized to the more stable *syn* adduct.[8] While the *anti* adduct was a major adduct when the dienophile **24** or **25** was irradiated by microwave with diene **39**, the selectivity was poor (Table 4, entries 4 and 7).



Scheme 8.

Silyl enol ether of **53** was converted to a ketone, which was in turn reduced to β-alcohol **59** (Scheme 9). Methanolysis of **59** followed by intramolecular lactonization (via **60**) gave crystalline compound **61**, which has an oxabicyclo[2.2.2]octanone skeleton. The structure of **61** was confirmed by X-ray crystallographic analysis (Fig. 7).

DA adducts **55**-*anti* and **55**-*syn*, synthesized from ketoester dienophile **24**, were exposed to $LiBH_4$ reduction. As a result, cyclic



Scheme 9.

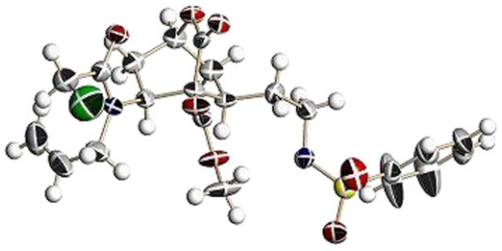
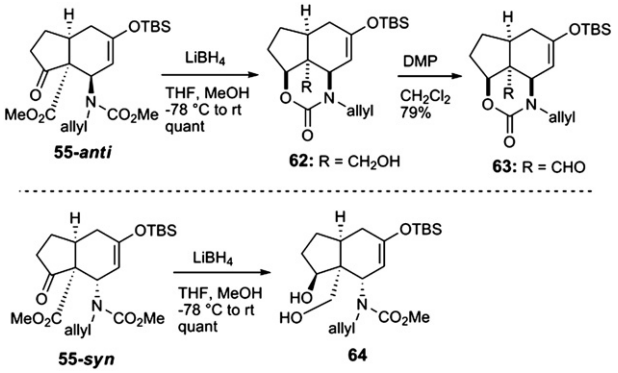


Fig. 7. X-ray crystallography of **61**.

carbamate **62** (from **55**-*anti*) and diol **64** (from **55**-*syn*) were obtained (Scheme 10). Cyclic carbamate **62** was oxidized to aldehyde **63**, and its stereochemistry was determined by 2D-NMR analysis and NOE experiments (Fig. 8). Diol **64** is a crystalline compound, and its stereochemistry was determined by X-ray analysis (Fig. 9). Although the methoxycarbonyl group at the ring-juncture was less reactive, adduct **56**-*anti* was converted to diol **66**, which was a crystalline compound suitable for X-ray analysis (Scheme 11 and Fig. 10). The crystal was determined to be a dimer.



Scheme 10.

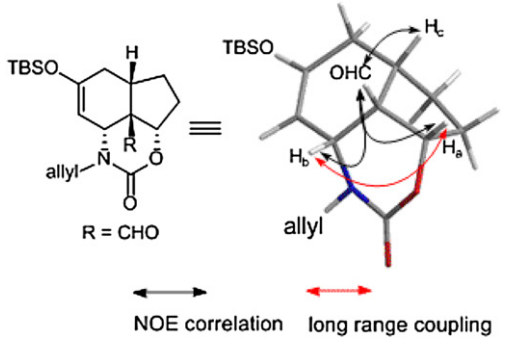


Fig. 8. Stereochemistry of **63**.

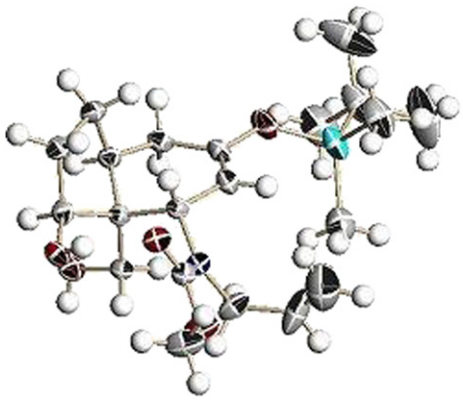
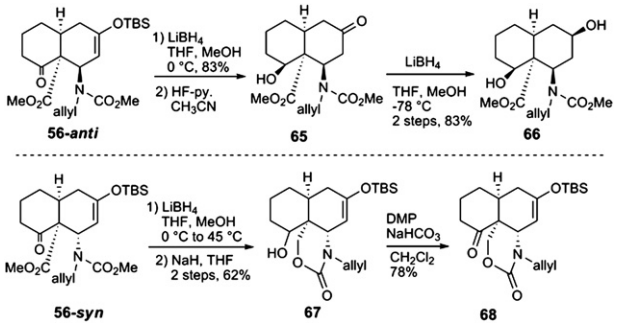


Fig. 9. X-ray crystallography of **64**.



Scheme 11.

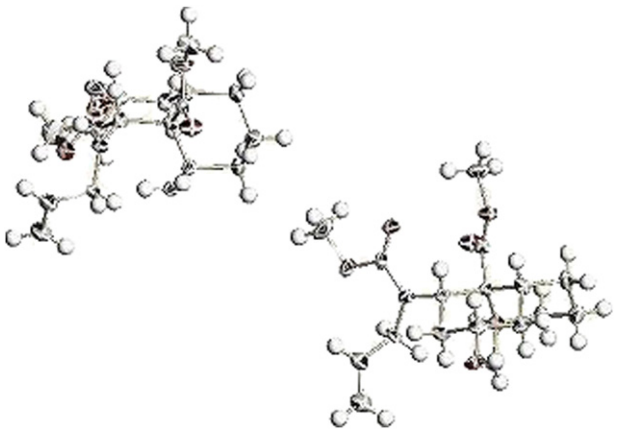


Fig. 10. X-ray crystallography of **66**.

Reduction of **56**-*syn* at 45 °C gave a diol, which was converted to cyclic carbamate **67** under basic conditions. Compound **67** was then oxidized to ketone **68** and its stereochemistry was determined by 2D-NMR analysis and NOE experiments (Scheme 11 and Fig. 11).

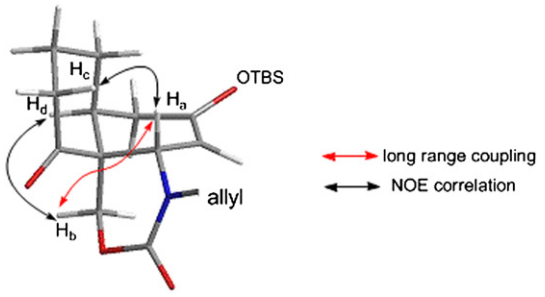


Fig. 11. Stereochemistry of **68**.

2.3. Stereoselectivity

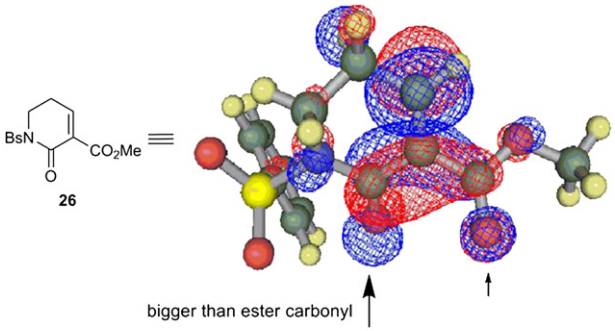
The results of the DA reaction using aminodiene and a cyclic dienophile are summarized in Table 6. These data show that the orbital interaction between a carbonyl group and diene affects the stereoselectivity to give DA adducts via an *endo* transition state to a carbonyl group. Therefore, *syn* adducts **12**, **40**, **41**, and **42** were obtained from a carboxaldehyde-type dienophile. On the other hand, enone-type dienophile **23** gave *anti* adduct **43**.

When a ketoester was used, both carbonyl groups would activate the reaction to give a *syn*/*anti* mixture. We confirmed that the *endo* adduct to a ketone, which has a larger LUMO orbital, was the major product under thermal conditions using microwave irradiation. Due to the instability of the ketoaldehyde-type dienophile, **69** could not be used for this study.

To consider the case of lactam dienophile **26**, the LUMO of dienophiles was calculated using computational chemistry. Lactam carbonyl has a larger LUMO orbital than an ester (Fig. 12). Therefore, *endo* addition to a lactam carbonyl should give *anti* adduct **53** (Table 3). However, it is unclear why the reaction of **26** showed higher selectivity than those of dienophiles **24** and **25**.

Table 6
Stereoselectivity of DA reaction using cyclic dienopile and aminodiene

Entry	Dienophile	Adduct	Stereoselectivity
1	**20:** n = 1, R = H **21:** n = 2, R = H **22:** n = 1, R = OPMB	**40:** n = 1, R = H **41:** n = 2, R = H **42:** n = 1, R = OPMB	*endo* to formyl carbonyl group
2	**23**	**43**	*endo* to ketone carbonyl group
3	**10**	**12**	*endo* to formyl carbonyl group
4	**26**	**53:** P = chloroacetyl **54:** P = CO_2Me	*endo* to lactam carbonyl group
5	**24:** n = 1 **25:** n = 1	**55-*anti*:** n = 1 **56-*anti*:** n = 2 **55-*syn*:** n = 1 **56-*syn*:** n = 2	Poor selectivity
6	**69:** X = CH_2, O, or NBs	Dienophile **69** was too unstable.	ND

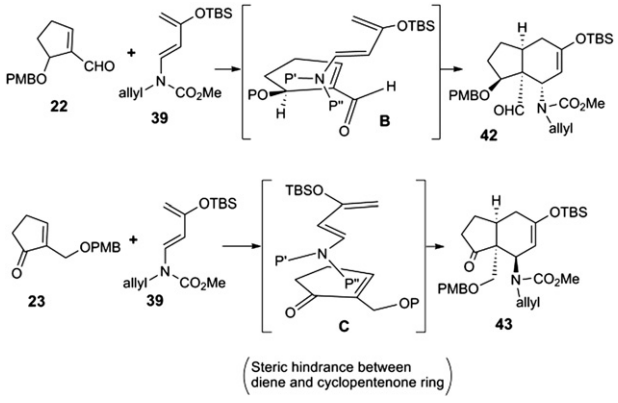


The ground-state geometry and orbitals were optimized at the B3LYP/6-31G* level using GAUSSIAN 03.

Fig. 12. Calculated LUMO of **26**.

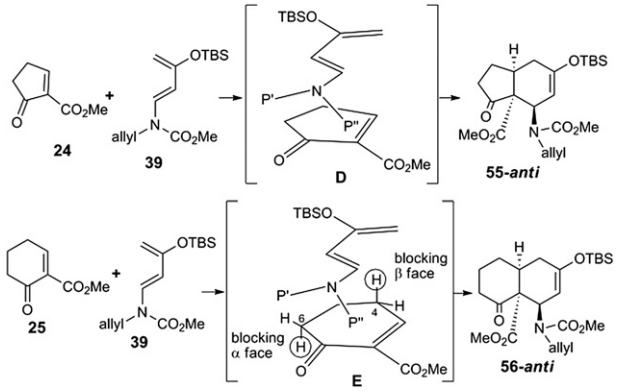
2.4. Reactivity

The structure of the dienophile clearly affected reactivity. The enone-type dienophile **23** was less reactive than cyclopentenecarboxaldehyde **22**, due to the steric hindrance between aminodiene and the cyclopentenone ring (Schemes 12). A similar difference in reactivity was observed in the reaction of **10** and **26**. While the lactam-type dienophile **26** required heating for 3 days to complete the reaction, carboxaldehyde **10** and diene **11** gave adduct **12** under rt in 20 h (Scheme 4 and Table 3, entry 1).



Scheme 12.

The ring size of the dienophile also influenced the reactivity (Scheme 13). In the case of **24** and **25**, five-membered ring dienophile **24** was more reactive than six-membered ring dienophile **25** (Table 2).[20] In a comparison of transition states, pseudo axial protons at C4 and C6 on the ring of **25** shield both faces of the dienophile (shown in **E**) and slow the reaction of **25** more than that of **24**. The reactivities of all the dienophiles are summarized in Fig. 13. Although dienophiles **22** and **24** are synthetic equivalents of each other, **24** is less effective for the DA reaction using aminodiene.



Scheme 13.

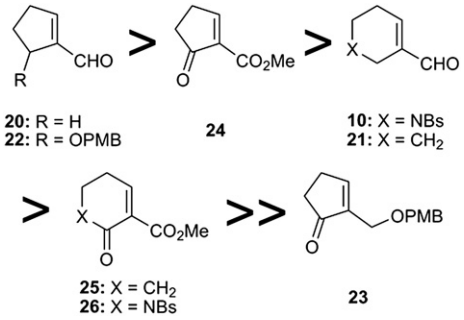
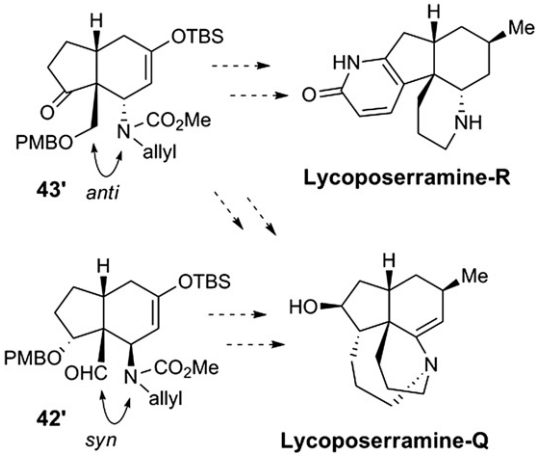


Fig. 13. Reactivity of dienophiles.

3. Conclusion

In this study, the stereoselectivity of the DA reaction using aminodienes and cyclic dienophiles was established. We have consolidated the stereoselective syntheses of bicyclic skeletons possessing an amino group.

This reaction should be useful for the synthesis of natural products. For example, DA adduct **43′**, which has *anti* stereochemistry, seems to be suitable as a building block for constructing the skeleton of lycoposerramine-R (Scheme 14).[13] In addition, as well as **43′**, *syn* adduct **42′** may be a precursor of lycoposerramine-Q.[12] We are now studying these syntheses and hope to demonstrate the efficiency of the DA reaction using aminodiene and cyclic dienophiles.



Scheme 14.

4. Experimental section

4.1. General

All reactions were performed under an argon atmosphere. Solvents and reagents were purified prior to use by the usual methods. Analytical thin-layer chromatography was performed on Merck Japan Limited silica gel 60 F_{254} plates, and on Merck DC-Platten Aluminiumoxid 60 F_{254} plates. Silica gel column chromatography was performed using Fuji Silysia Chemical Ltd silica gel PSQ 60B. Alumina column chromatography was performed using Merck Aluminiumoxid 90 aktivbasisch. Melting points were determined on a Yanagimoto micro melting point apparatus. Infrared (IR) spectra were recorded on a JASCO FT/IR-230 spectrometer. ^{1}H NMR spectra were taken on 400 or 600 MHz instruments (JEOL JNM-GSX 400α, JEOL JMN-ECP 400, JEOL JMN-ECP 600) in the indicated solvent at rt unless otherwise stated. ^{13}C NMR spectra were taken at 100 or 150 MHz in the indicated solvent. Mass spectrometry was performed on a JEOL JMS-AX500 (LRFABMS), JEOL JMS-AX505 (LRFABMS), JEOL JMS-HX100 (HRFABMS), and JEOL JMS-T100LP (HRESIMS). X-ray crystallographic analyses were performed on a BRUKER SMART APEX II. Optical rotations were measured on a JASCO P-1000 polarimeter at 589 nm. Data are reported as follows: $[\alpha]\lambda^{temp}$, concentration (*c* g/100 ml), and solvents.

Dienophile **20** was available from Aldrich. Diene **11** and **39** were prepared as described in the literature.[10] Microwave reactions were performed in a CEM Discover LabMate microwave reactor under the condition indicated.

Crystallographic data have been deposited with Cambridge Crystallographic Data Center: Deposition number CCDC-784190 for compound **48**, CCDC-784193 for compound **52**, CCDC-784189 for compound **61**, CCDC-784191 for compound **64**, and CCDC-784192 for compound **66**. Copies of the data can be obtained free of charge via http://www.ccdc.cam.ac.uk/conts/retrieving.html (or from the Cambridge Crystallographic Data Center, 12, Union Road, Cambridge, CB2 1EZ, UK; Fax: +44 1223 336033; email: deposit@ccdc.cam.ac.uk).

4.1.1. (1-Cyclopentenyl)methanol, ***28****.* To a solution of methyl-cyclopentene-1-carboxylate (0.73 mL, 5.35 mmol) in toluene (67 mL) was added dropwise Red-Al® (3.34 M in toluene, 3.6 mL, 11.7 mmol) at 0 °C. The resulting mixture was stirred for 3 h at the same temperature. Ice-cold H_2O (20 mL) was added to quench the reaction. The separated water layer was extracted with Et_2O, and the combined organic layers were dried over Na_2SO_4. After volatile material was removed under reduced pressure, the resulting residue was purified by column chromatography (SiO_2, hexane/AcOEt=9/1) to give **28** (419 mg, yield 80%) as a colorless oil. Spectral data were identical to the reported data.[21]

4.1.2. Cyclopentene-1-carboxaldehyde, ***20****.* To a solution of **28** (419 mg, 4.27 mmol) in pentane (14.2 mL) was added MnO_2 (2.1 g, 500 w/w %) at rt. The resulting mixture was stirred for 29 h at the same temperature. The mixture was filtered through a pad of Celite® and the pad was washed with Et_2O. The combined filtrates were distilled (at 35 °C, 1 atm) to remove pentane and Et_2O to give **20** (391 mg, yield 95%) as a light yellow oil. The resulting residue was used in the next step without purification. Spectral data were identical to the reported data.[22]

4.1.3. Methyl cyclopentenone-2-carboxylate, ***24****.* To a solution of PhSeCl (850 mg, 4.44 mmol) and pyridine (0.49 mL, 6.05 mmol) in CH_2Cl_2 (24 mL) was added dropwise methyl 2-cyclopentanon ecarboxylate (0.5 mL, 4.03 mmol) at 0 °C. After stirring for 1.5 h, 1 N HCl (5 mL) was added to quench the reaction. The separated organic layer was washed with saturated aqueous $NaHCO_3$ and dried over Na_2SO_4. After volatile material was removed under reduced pressure, the resulting residue was used in the next step without purification.

To a solution of crude product in CH_2Cl_2 (81 mL) was added dropwise 35% H_2O_2 aq (1.2 mL, 12.1 mmol) at 0 °C over 30 min. After stirring at the same temperature for further 2 h, the resulting mixture was washed with H_2O and saturated aqueous $NaHCO_3$ and dried over Na_2SO_4. After volatile material was removed under reduced pressure, the resulting residue was purified by Kugelrohr distillation (0.12 mmHg, 150–152 °C) to give **24** (445 mg, yield 78%, 95% purity) as a yellow oil. Spectral data were identical to the reported data.[23]

4.1.4. Methyl cyclohexanone-2-carboxylate, ***25****.* To a solution of PhSeCl (850 mg, 4.44 mmol) and pyridine (0.49 mL, 6.05 mmol) in CH_2Cl_2 (24 mL) was added dropwise methyl 2-cyclohexanon ecarboxylate (0.64 ml, 4.03 mmol) at 0 °C. After stirring for 1.5 h, 1 N HCl (5 mL) was added to quench the reaction. The separated organic layer was washed with saturated aqueous $NaHCO_3$ and dried over Na_2SO_4. After volatile material was removed under reduced pressure, the resulting residue was used in the next step without purification.

To a solution of crude product in CH_2Cl_2 (81 mL) was added dropwise 35% H_2O_2 aq (1.2 mL, 12.1 mmol) at 0 °C over 30 min. After stirring at the same temperature for further 2 h, the resulting mixture was washed with H_2O and saturated aqueous $NaHCO_3$ and dried over Na_2SO_4. After volatile material was removed under reduced pressure, the resulting residue was purified by Kugelrohr distillation (0.12 mmHg, 155–157 °C) to give **25** (575 mg, yield 93%, 95% purity) as a yellow oil. Spectral data were identical to the reported data.[18]

4.1.5. 2-Bromo-2-cyclopentenone, ***32****.* To a solution of cyclopentenone (500 mg, 6.09 mmol) and pyridine-*N*-oxide (870 mg,

9.14 mmol) in CH_3CN (30 mL) was added NBS (1.08 g, 6.09 mmol) at 0 °C. The resulting mixture was warmed to rt and stirred for 24 h. After volatile material was removed under reduced pressure, the resulting residue was purified by column chromatography (SiO_2, hexane/AcOEt=7/1) to give **32** (967 mg, yield 99%) as a brown oil. Spectral data were identical to the reported data.[24]

4.1.6. 1-((2-Bromocyclopent-2-enyloxy)methyl)-4-methoxybenzene, ***34****.* To a solution of **32** (100 mg, 0.62 mmol) and $CeCl_3\cdot 7H_2O$ (278 mg, 0.75 mmol) in MeOH (6.2 mL) was added $NaBH_4$ (35 mg, 0.93 mmol) at 0 °C. The resulting mixture was stirred for 20 min at the same temperature. Saturated aqueous NH_4Cl (3 mL) was added to quench the reaction. The separated water layer was extracted with AcOEt, and the combined organic layers were washed with brine and dried over Na_2SO_4. After volatile material was removed under reduced pressure, the resulting residue was used in the next step without purification.

To a solution of crude product and NaI (138 mg, 0.92 mmol) in THF (6.1 mL) was added NaH (60% in oil, 37 mg, 0.92 mmol) at 0 °C. After stirring for 10 min, PMBCl (0.12 mL, 0.92 mmol) was added dropwise at 0 °C and the resulting mixture was warmed to rt and stirred for 8 h. Saturated aqueous NH_4Cl (4 mL) was added to quench the reaction. The separated water layer was extracted with AcOEt, and the combined organic layers were washed with brine and dried over Na_2SO_4. After volatile material was removed under reduced pressure, the resulting residue was purified by column chromatography (SiO_2, hexane/AcOEt=5/1) to give **34** (151 mg, yield 87%) as a brown oil: ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.92–2.00 (m, 1H), 2.17–2.29 (m, 2H), 2.39–2.49 (m, 1H), 3.80 (s, 3H), 4.49–4.54 (m, 1H), 4.56 (s, 2H), 6.10 (dt, J=0.6, 1.2 Hz, 1H), 6.88 (dt, J=2.0, 7.2 Hz, 2H), 7.30–7.34 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 29.3, 30.5, 55.1, 70.3, 85.2, 113.6, 122.4, 129.2, 130.3, 135.2, 159.0; IR (ATR): ν 2934, 2852, 1612, 1585 cm^{-1}; LRMS (FAB) m/z 321 (M+K); HRMS (FAB) m/z calcd for $C_{13}H_{15}O_2BrK$ (M+K) 320.9892, found 320.9986.

4.1.7. 5-(4-Methoxybenzyloxy)cyclopent-1-enecarbaldehyde, ***22****.* To a solution of **34** (20 mg, 0.071 mmol) in THF (0.71 mL) was added dropwise *n*-BuLi (1.65 M, in hexane) at −78 °C. After stirring for 30 min, dropwise DMF (7.8 mg, 0.106 mmol) in THF (0.1 mL) was added at −78 °C and the resulting mixture was stirred for 1.5 h at the same temperature. Saturated aqueous NH_4Cl (2 mL) was added to quench the reaction. The separated water layer was extracted with AcOEt, and the combined organic layers were washed with brine and dried over Na_2SO_4. After volatile material was removed under reduced pressure, the resulting residue was purified by column chromatography (SiO_2, hexane/AcOEt=1/1) to give **22** (14.2 mg, yield 86%) as a colorless solid: ^{1}H NMR (400 MHz, $CDCl_3$): δ 2.00–2.18 (m, 2H), 2.46 (ddt, J=2.8, 8.4, 19.6 Hz, 1H), 2.70–2.80 (m, 1H), 3.76 (s, 3H), 4.55 (s, 2H), 4.83 (d, J=7.2 Hz, 1H), 6.85 (d, J=8.8 Hz, 2H), 7.02–7.05 (m, 1H), 7.28 (d, J=8.8 Hz, 2H), 9.82 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 30.8, 31.4, 55.0, 71.4, 79.3, 113.5, 129.1, 130.5, 147.2, 156.2, 158.8, 189.0; IR (ATR): ν 2936, 2834, 1679, 1612 cm^{-1}; LRMS (FAB) m/z 271 (M+K); HRMS (FAB) m/z calcd for $C_{14}H_{16}O_3K$ (M+K) 271.0737, found 271.0735.

4.1.8. 2-(Hydroxymethyl)cyclopent-2-enone, ***35****.* To a solution of cyclopentenone (1 g, 12.2 mmol) in $CHCl_3$ (14.6 mL) and MeOH (9.8 mL) was added dropwise 37% HCHO aq (1.2 mL, 14.6 mmol) and *n*-Bu_3P (0.15 mL, 0.61 mmol) at rt. The resulting mixture was stirred for 1 h. After volatile material was removed under reduced pressure, the resulting residue was purified by column chromatography (SiO_2, hexane/AcOEt=1/3) to give **35** (1.10 g, yield 89%) as a colorless oil. Spectral data were identical to the reported data.[18]

4.1.9. 2-((4-Methoxybenzyloxy)methyl)cyclopentenone, ***23****.* To a solution of **35** (1.0 g, 8.92 mmol) and 4-methoxybenzyl 2,2,2-trichloroacetimidate **36** (6.85 g, 24.4 mmol) in CH_2Cl_2 (30 mL) was added dropwise a solution of CSA (207 mg, 0.892 mmol) in CH_2Cl_2 (6 mL) at 0 °C. After stirring for 10 min, the resulting mixture was warmed to rt and stirred for 3 h. Saturated aqueous $NaHCO_3$ (10 mL) was added to quench the reaction. The separated water layer was extracted with AcOEt, and the combined organic layers were washed with brine and dried over Na_2SO_4. After volatile material was removed under reduced pressure, the resulting residue was purified by column chromatography (SiO_2, hexane/AcOEt=3/1) to give **23** (1.55 g, yield 75%) as a colorless oil: ^{1}H NMR (400 MHz, $CDCl_3$): δ 2.43 (ddd, J=2.4, 2.4, 4.8 Hz, 2H), 2.62 (ddt, J=2.4, 2.4, 4.8 Hz, 2H), 3.80 (s, 3H), 4.17 (dd, J=2.4, 8.0 Hz, 2H), 4.51 (s, 2H), 6.89–90 (m, 2H), 7.26–7.31 (m, 2H), 7.61 (tt, J=1.6, 2.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 26.7, 34.7, 55.1, 63.6, 72.6, 113.6, 128.3, 129.2, 143.2, 159.1, 159.6, 208.3; IR (ATR): ν 2931, 2857, 2836, 1690, 1612 cm^{-1}; LRMS (EI) m/z 232 (M); HRMS (EI) m/z calcd for $C_{14}H_{16}O_3$ (M) 232.1099, found 232.1095.

4.1.10. (1-Benzensulfonyl)piperidin-2-one, ***38****.* To a solution of piperidin-2-one (5.0 g, 50.4 mmol) in THF (250 mL) was added *n*-BuLi (1.6 M in hexane, 37.8 mL, 60.5 mmol) at −78 °C. After stirring for 1 h at the same temperature, benzenesulfonyl chloride (9.7 mL, 75.7 mmol) was added dropwise at −78 °C and the resulting mixture was stirred for 4 h at the same temperature. Saturated aqueous NH_4Cl (30 mL) was added to quench the reaction. The separated water layer was extracted with AcOEt, and the combined organic layers were washed with brine and dried over Na_2SO_4. After volatile material was removed under reduced pressure, the resulting residue was purified by column chromatography (SiO_2, hexane/AcOEt/CH_2Cl_2=1/1/1) to give **38** (12.05 g, yield quant) as a colorless oil. Spectral data were identical to the reported data.[19]

4.1.11. Methyl 1-(benzensulfonyl)-2-oxo-1,2,5,6-tetrahydropyridine-3-carboxylate, ***26****.* To a solution of **38** (7.0 g, 29.25 mmol) in THF (250 mL) was added LHMDS (1.0 M in THF, 73.1 mL, 73.1 mmol) at −78 °C. After stirring for 30 min at the same temperature, methyl chloroformate (2.5 mL, 32.2 mmol) was added dropwise at −78 °C. After stirring for 1 h at the same temperature, a solution of $PhSSO_2Ph$ (8.06 g, 32.2 mmol) in THF (10 mL) was added dropwise at −78 °C and the mixture was warmed to rt and stirred for 17.5 h. Saturated aqueous NH_4Cl (30 mL) was added to quench the reaction. The separated water layer was extracted with AcOEt, and the combined organic layers were washed with brine and dried over Na_2SO_4. After volatile material was removed under reduced pressure, the resulting residue was used in the next step without purification.

To a solution of *m*CPBA (10.82 g, 43.8 mmol) in CH_2Cl_2 (192 mL) and saturated aqueous $NaHCO_3$ (292 mL) was added dropwise a solution of crude product in CH_2Cl_2 (100 mL) at 0 °C over 30 min. The resulting mixture was warmed to rt and stirred vigorously for 15 h. Saturated aqueous sodium thiosulfate (50 mL) was added at 0 °C and the mixture was stirred at rt for 30 min. The separated water layer was extracted with AcOEt, and the combined organic layers were washed with brine and dried over Na_2SO_4. After volatile material was removed under reduced pressure, the resulting residue was purified by column chromatography (SiO_2, hexane/AcOEt=1/2) to give **26** (6.10 g, yield 75%, in two steps) as a colorless oil: ^{1}H NMR (400 MHz, $CDCl_3$): δ 2.68 (dt, J=4.4, 6.4 Hz, 2H), 3.76 (s, 3H), 4.12 (t, J=6.4 Hz, 2H), 7.50–7.56 (m, 2H), 7.59–7.66 (m, 2H), 8.05 (dd, J=1.2, 8.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 25.4, 43.3, 52.4, 128.5, 128.74, 128.78, 133.8, 138.5, 151.3, 159.4, 163.4; IR (ATR): ν 2952, 1738, 1687 cm^{-1}; HRMS (ESI) m/z calcd for $C_{13}H_{13}NO_5SNa$ (M+Na) 318.0412, found 318.0431.

4.2. General procedure for the Diels–Alder reaction using Salen–Cr–F complex (1 mmol-scale experiments)[10]

After a mixture of Salen–Cr–F complex (50 mol %, based on dienophile) and oven-dried powdered 4Å MS (0.8 g) was dried

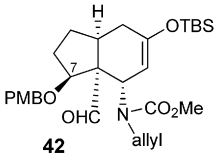
under vacuum for 20 min, a solution of dienophile (1 mmol) in $PhCF_3$ (5 ml) was added and the mixture was stirred for 30 min at rt. To this mixture was added aminodiene (2 mmol), and the resulting mixture was stirred at the temperature indicated. The reaction mixture was then filtered through a pad of Celite®, the pad was washed with CH_2Cl_2, and volatile material was removed under reduced pressure. The resulting residue was purified by column chromatography (SiO_2, hexane/AcOEt=7/1) to give Diels–Alder adduct.

4.3. General procedure for the Diels–Alder reaction using microwave irradiation (1 mmol-scale experiments)

Oven-dried powdered 4A MS (0.8 g) was added to a solution of dienophile (1 mmol) in $PhCF_3$ (5 mL) and the mixture was stirred for 5 min at rt. To this mixture was added aminodiene (2 mmol), and the resulting mixture was irradiated by microwave (<300 W, 150 °C, in a sealed tube) in a CEM. Discover LabMate microwave reactor. The reaction mixture was then filtered through a pad of Celite®, the pad was washed with CH_2Cl_2, and volatile material was removed under reduced pressure. The resulting residue was purified by column chromatography (SiO_2, hexane/AcOEt=7/1) to give Diels–Alder adduct.

4.3.1. DA adduct ***40***. ^{1}H NMR ($CDCl_3$, 400 MHz, 55 °C): δ 0.14 (s, 6H), 0.92 (s, 9H), 1.41–1.56 (m, 2H), 1.67–1.79 (m, 4H), 2.11 (t, J=10.0 Hz, 1H), 2.31 (dd, J=8.0, 18.0 Hz, 1H), 2.57–2.64 (m, 1H), 3.53–3.64 (m, 1H), 3.67 (s, 3H), 3.74 (dd, J=5.6, 16.0 Hz, 1H), 4.66 (d, J=4.8 Hz, 1H), 5.03 (d, J=8.4, 17.6 Hz, 1H), 5.05 (d, J=9.6 Hz, 1H), 5.09 (br s, 1H), 5.73 (ddd, J=5.6, 10.4, 23.2 Hz, 1H), 9.51 (s, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz, 55 °C): δ −4.51, −4.28, 17.9, 19.4, 25.6, 31.1, 32.1, 32.3, 34.7, 46.9, 52.5, 54.8, 60.1, 100.3, 115.8, 135.4, 153.3, 157.2, 203.3; IR (ATR): ν 2953, 2930, 2883, 2857, 1726, 1697, 1671 cm^{-1}; HRMS (ESI) m/z calcd for $C_{42}H_{70}N_2O_8Si_2Na$ (2M+Na) 809.4568, found 809.4545; HPLC: DAICEL CHIRALCEL OD-H, 210 nm, flow rate 1.0 mL/min, hexane/*i*-PrOH=99:1, retention time: 6.4 min and 7.1 min; $[\alpha]_D^{25}$ 36.4 (c 1.00, $CHCl_3$, 79% ee).

4.3.2. DA adduct ***41***. ^{1}H NMR (C_6D_6, 400 MHz, 75 °C): δ 0.21 (s, 6H), 1.06 (s, 9H), 1.27 (br s, 4H), 1.51–1.84 (m, 4H), 2.07 (br d, J=18.0 Hz, 1H), 2.23 (br d, J=18.0 Hz, 1H), 2.48 (br s, 1H), 3.57 (br s, 3H), 3.74 (br d, J=16.0 Hz, 1H), 3.96 (br d, J=16.0 Hz, 1H), 4.81 (br s, 1H), 5.11 (br d, J=18.0 Hz, 3H), 5.80–5.97 (m, 1H), 9.80 (br s, 1H); ^{13}C NMR (C_6D_6, 100 MHz, 75 °C): δ −4.29, −4.13, 18.1, 21.4, 22.7, 25.8, 27.6, 28.6, 30.9, 31.6, 47.8, 52.3, 53.3, 57.3, 101.2, 115.2, 136.6, 153.5, 157.3, 204.0; IR (ATR): ν 2928, 2857, 1723, 1695, 1674 cm^{-1}; HRMS (ESI) m/z calcd for $C_{22}H_{37}NO_4SiNa$ (M+Na) 430.2389, found 430.2408; HPLC: DAICEL CHIRALCEL OD-H, 210 nm, flow rate 1.0 mL/min, hexane/*i*-PrOH=99:1, retention time: 6.1 min and 7.1 min; $[\alpha]_D^{25}$ 43.7 (c 0.83, $CHCl_3$, 81% ee).



42
(dr 7.3: 1)

4.3.3. DA adduct ***42***. Adduct **42** was obtained as inseparable diastereomixtures at C7 position. Good ^{1}H and ^{13}C NMR spectra were difficult to obtain due to the presence of rotamers and diastereomers, even at elevated temperatures. The structure of **42** was determined after it was converted to **48** or **70** via **45**.

4.3.4. DA adduct ***43***. ^{1}H NMR (C_6D_6, 400 MHz, 75 °C): δ 0.15 (s, 3H), 0.16 (s, 3H), 0.98 (s, 9H), 1.63–1.72 (m, 1H), 1.77 (br s, 1H), 1.94 (dt, J=9.2, 19.2 Hz, 1H), 1.99 (br d, J=17.6 Hz, 1H), 2.26 (dd, J=7.6, 17.6 Hz, 1H), 2.45 (ddt, J=2.4, 6.8, 16.4 Hz, 1H), 2.60 (ddt, J=2.4, 6.8, 13.2 Hz, 1H), 3.41 (s, 3H), 3.55 (s, 3H), 3.58 (dd, J=8.4, 17.6 Hz, 2H), 3.64 (br s, 1H), 3.79 (br d, J=8.8 Hz, 1H), 3.89 (br d, J=12.4 Hz, 1H), 4.34 (dd, J=11.6, 20.4 Hz, 1H), 4.66 (br s, 1H), 4.90 (t, J=2.4 Hz, 1H), 5.01 (dd, J=1.2, 10.4 Hz, 1H), 5.08 (dd, J=1.2, 17.2 Hz, 1H), 5.85 (ddt, J=5.2, 5.2, 22.0 Hz, 1H), 6.80 (d, J=8.4 Hz, 2H), 7.16 (dd, J=8.4 Hz, 2H); ^{13}C NMR (C_6D_6, 100 MHz, 75 °C): δ −4.16, −4.14, 18.2, 25.9, 26.5, 32.1, 38.0, 38.3, 45.5, 52.1, 54.9, 56.1, 56.9, 73.6, 75.2, 114.3, 115.4, 128.5, 129.4, 131.1, 136.4, 151.6, 156.9, 160.0, 216.0; IR (ATR): ν 2929, 1736, 1702 cm^{-1}; LRMS (FAB) m/z 552 (M+Na); HRMS (FAB) m/z calcd for $C_{29}H_{43}NO_6SiNa$ (M+Na) 552.2757, found 552.2737.

4.3.5. DA adduct ***53***. ^{1}H NMR (400 MHz, $CDCl_3$): δ −0.01 (s, 3H), 0.04 (s, 3H), 0.85 (s, 9H), 1.71–1.85 (m, 2H), 2.02 (dd, J=4.8, 17.6 Hz, 1H), 2.20–2.27 (m, 1H), 2.92 (br td, J=5.6, 11.6 Hz, 1H), 3.30 (br td, J=8.8, 14.4 Hz, 1H), 3.55 (s, 3H), 3.88 (d, J=12.8 Hz, 1H), 4.03 (d, J=12.8 Hz, 1H), 4.12 (br d, J=19.6 Hz, 1H), 4.39 (ddd, J=2.0, 8.8, 13.6 Hz, 1H), 4.47 (br d, J=2.0 Hz, 1H), 4.61 (br s, 1H), 5.02 (d, J=17.2 Hz, 1H), 5.19 (d, J=10.4 Hz, 1H), 5.85 (ddt, J=3.6, 9.6, 16.8 Hz, 1H), 7.52 (t, J=7.6 Hz, 2H), 7.62 (t, J=7.6 Hz, 2H), 7.97 (d, J=7.6 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$): δ −4.8, −4.5, 14.2, 17.8, 21.0, 33.6, 34.5, 41.9, 42.2, 49.5, 53.6, 56.5, 59.2, 60.4, 100.2, 115.3, 128.4, 128.6, 133.7, 136.7, 138.4, 151.0, 166.9, 166.9, 168.7, 169.3; IR (ATR): ν 2991, 1754, 1724, 1698 cm^{-1}; LRMS (FAB) m/z 649 (M+K); HRMS (FAB) m/z calcd for $C_{28}H_{39}ClN_2O_7SSiK$ (M+K) 649.1573, found 649.1588.

4.3.6. DA adduct ***54***. ^{1}H NMR (400 MHz, $CDCl_3$, 55 °C): δ 0.01 (s, 3H), 0.06 (s, 3H), 0.86 (s, 9H), 1.74–1.94 (m, 2H), 2.02 (dd, J=6.4, 18.0 Hz, 1H), 2.15 (dt, J=3.2, 14.0 Hz, 1H), 2.84 (ddd, J=4.0, 6.4, 10.4 Hz, 1H), 3.40 (ddd, J=6.8, 9.2, 13.6 Hz, 1H), 3.56 (s, 3H), 3.61 (s, 3H), 3.94–3.99 (m, 1H), 4.33 (ddd, J=3.6, 8.4, 13.6 Hz, 1H), 4.70 (br s, 1H), 4.97 (br d, J=17.2 Hz, 1H), 5.00 (br d, J=10.4 Hz, 1H), 5.29 (d, J=2.0 Hz, 1H), 5.72 (ddd, J=5.2, 10.4, 17.2 Hz, 1H), 7.50 (t, J=7.6 Hz, 2H), 7.60 (t, J=7.6 Hz, 2H), 7.98 (d, J=7.6 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$, 55 °C): δ −4.7, −4.5, 17.9, 25.4, 25.6, 33.8, 34.2, 42.5, 49.2, 52.4, 53.1, 57.9, 60.2, 102.0, 114.2, 128.55, 128.60, 133.5, 136.9, 139.1, 149.7, 160.8, 166.7, 169.8; IR (ATR): ν 2950, 1745, 1711, 1697 cm^{-1}; HRMS (ESI) m/z calcd for $C_{28}H_{40}N_2O_8SSiNa$ (M+Na) 615.2172, found 615.2162.

4.3.7. DA adduct ***55****-anti*. ^{1}H NMR (400 MHz, $CDCl_3$, 55 °C): δ 0.14 (s, 6H), 0.91 (s, 9H), 1.94–2.02 (m, 3H), 2.22–2.25 (m, 0.5H), 2.27–2.30 (m, 0.5H), 2.31–2.40 (m, 2H), 2.94–3.01 (m, 1H), 3.61 (s, 3H), 3.73 (s, 3H), 3.79–3.93 (m, 2H), 4.77 (d, J=1.6 Hz, 1H), 5.10 (dd, J=1.6, 5.6 Hz, 1H), 5.13 (dt, J=1.6, 13.2 Hz, 1H), 5.19 (br s, 1H), 5.76 (ddd, J=5.6, 10.4, 22.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$, 55 °C): δ −4.36, 18.0, 25.6, 26.0, 31.1, 37.6, 41.3, 50.0, 52.2, 52.9, 55.7, 62.4, 103.6, 115.8, 135.3, 149.7, 156.6, 172.8, 211.4; IR (ATR): ν 2952, 2930, 2857, 1734, 1701, 1678 cm^{-1}; HRMS (ESI) m/z calcd for $C_{44}H_{70}N_2O_{12}Si_2Na$ (2M+Na) 897.4365, found 897.4339; HPLC: DAICEL CHIRALPAK IA, 210 nm, flow rate 0.5 mL/min, hexane/*i*-PrOH=95:5, retention time: 12.2 min and 13.3 min; $[\alpha]_D^{25}$ 9.6 (c 1.00, $CHCl_3$, 16% ee).

4.3.8. DA adduct ***55****-syn*. ^{1}H NMR ($CDCl_3$, 400 MHz, 55 °C): δ 0.09 (s, 3H), 0.10 (s, 3H), 0.87 (s, 9H), 1.50–1.73 (m, 2H), 1.96–2.09 (m, 1H), 2.18 (dt, J=9.6, 19.2 Hz, 1H), 2.37 (dt, J=9.6, 19.2 Hz, 2H), 3.27 (dd, J=8.4, 14.4 Hz, 1H), 3.60–3.66 (m, 1H), 3.64 (s, 3H), 3.67 (s, 3H), 3.78 (dd, J=6.0, 16.0 Hz, 1H), 4.69 (dd, J=1.2, 4.8 Hz, 1H), 5.06 (br d, J=8.8 Hz, 1H), 5.09 (br d, J=16.4 Hz, 1H), 5.36 (br s, 1H), 5.76 (ddd, J=6.0, 11.2, 22.4 Hz, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz, 55 °C): δ −4.58, −4.33, 17.9, 25.6, 25.9, 31.0, 32.2, 35.0, 48.3, 52.4, 52.5, 54.0, 64.8, 101.8, 115.8, 135.32, 151.9, 156.5, 168.6, 208.7; IR (ATR): ν 2949, 2932, 2857, 1750, 1728, 1695, 1677 cm^{-1}; HRMS (ESI) m/z calcd for $C_{22}H_{35}NO_6SiNa$ (M+Na) 460.2131, found 460.2142; HPLC: DAICEL CHIRALPAK IA, 210 nm, flow rate 0.5 mL/min, hexane/*i*-

PrOH=95:5, retention time: 14.1 min and 17.3 min; $[\alpha]_D^{26}$ −28.4 (*c* 1.00, $CHCl_3$, 15% ee).

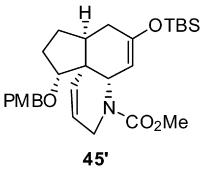
*4.3.9. DA adduct **56**-anti.* ^{1}H NMR ($CDCl_3$, 400 MHz, 55 °C): δ 0.117 (s, 3H), 0.126 (s, 3H), 0.90 (s, 9H), 1.54 (br d, *J*=9.6 Hz, 1H), 1.80–2.05 (m, 5H), 2.26 (br d, *J*=13.6 Hz, 1H), 2.55–2.63 (m, 1H), 2.96–3.04 (m, 1H), 3.60 (s, 3H), 3.75 (s, 3H), 4.10 (br d, *J*=17.6 Hz, 1H), 4.32 (dd, *J*=3.2, 17.6 Hz, 1H), 4.78 (br s, 1H), 5.00 (br d, *J*=16.0 Hz, 1H), 5.04 (br d, *J*=10.0 Hz, 1H), 5.21 (br s, 1H), 5.76 (ddd, *J*=4.8, 10.0, 22.4 Hz, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz, 55 °C): δ −4.65, −4.38, 17.9, 23.4, 25.6, 26.6, 30.5, 39.8, 41.1, 48.4, 52.4, 52.6, 58.1, 64.8, 101.7, 113.8, 137.4, 149.8, 157.8, 171.7, 205.6; IR (ATR): ν 2950, 2930, 2858, 1743, 1717, 1682 cm^{-1}; HRMS (ESI) *m*/*z* calcd for $C_{46}H_{74}N_2O_{12}Si_2Na$ (2M+Na) 925.4678, found 925.4674; HPLC: DAICEL CHIRALPAK IA, 210 nm, flow rate 0.5 mL/min, hexane/*i*-PrOH=95:5, retention time: 13.6 min and 18.4 min; $[\alpha]_D^{25}$ 59.9 (*c* 0.60, $CHCl_3$, 48% ee).

*4.3.10. DA adduct **56**-syn.* ^{1}H NMR ($CDCl_3$, 400 MHz, 55 °C): δ 0.13 (s, 6H), 0.91 (s, 9H), 1.57 (br d, *J*=14.0 Hz, 1H), 1.85–1.97 (m, 4H), 2.08–2.19 (m, 1H), 2.37–2.44 (m, 2H), 3.13 (br s, 1H), 3.64 (s, 3H), 3.65 (br s, 1H), 3.66 (s, 3H), 3.79 (br s, 1H), 4.71 (d, *J*=4.4 Hz, 1H), 5.05 (br d, *J*=10.4 Hz, 1H), 5.05 (br d, *J*=16.4 Hz, 1H), 5.67–5.80 (m, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz, 55 °C): δ −4.59, −4.24, 17.9, 22.7, 25.6, 26.4, 30.1, 40.2, 47.8, 52.2, 52.4, 53.4, 64.8, 101.8, 115.6, 135.6, 151.5, 156.5, 170.3, 204.0; IR (ATR): ν 2950, 2929, 2898, 2857, 1745, 1717, 1682 cm^{-1}; HRMS (ESI) *m*/*z* calcd for $C_{23}H_{37}NO_6SiNa$ (M+Na) 474.2288, found 474.2306; HPLC: DAICEL CHIRALPAK IA, 210 nm, flow rate 0.5 mL/min, hexane/*i*-PrOH=95:5, retention time: 14.3 min and 25.3 min; $[\alpha]_D^{25}$ 52.5 (*c* 0.615, $CHCl_3$, 12% ee).

*4.3.11. Diene **44**.* To a solution of $Ph_3P^+CH_3 \cdot Br^-$ (2.02 g, 5.66 mmol) in THF (10 mL) was added KHMDS (0.5 M in toluene, 11.3 mL, 5.66 mmol) at 0 °C. After stirring for 1 h at rt, a solution of **42** (1.0 g, 1.89 mmol) in THF (9 mL) was added dropwise to the mixture at 0 °C and the mixture was stirred for 1.5 h at rt. Saturated NH_4Cl (10 mL) were added to quench the reaction at 0 °C. The separated water layer was extracted with AcOEt, and the combined organic layers were washed with brine and dried over Na_2SO_4. Volatile material was removed under reduced pressure. The resulting residue was purified by column chromatography (SiO_2, hexane/AcOEt=5/1) to give inseparable mixture of **44** (874 mg, yield 88%) and its stereoisomer as a colorless oil, which was used in the next step without purification.

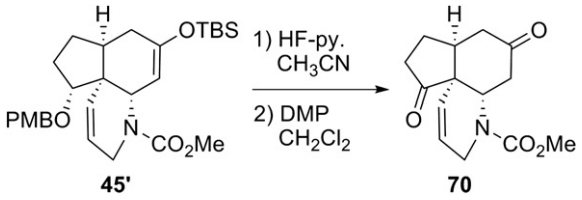
*4.3.12. RCM of **44**.* To a solution of **44** (691 mg, 1.31 mmol) in CH_2Cl_2 (131 mL) was added Grubbs' second cat. (111 mg, 0.131 mmol) at rt. The resulting mixture was warmed to reflux temperature and stirred for 6 h. The mixture was filtered through a pad of Celite® and volatile material was removed under reduced pressure. The resulting residue was purified by column chromatography (SiO_2, hexane/AcOEt=7/1) to give **45** (545 mg, yield 84%) and **45′** (<75 mg, yield 11%, with impurities derived from Grubbs' second cat.).

Compound **45** (mixture of rotamers): ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.08 (s, 3H), 0.10 (s, 3H), 0.88 (s, 9H), 1.59–1.75 (m, 3H), 1.75–1.95 (m, 2H), 2.04–2.2.20 (m, 2H), 3.50–3.56 (m, 1H), 3.57 (s, 3H), 3.74 (s, 3H), 3.74–3.83 (m, 1H), 4.19–4.36 (m, 1H), 4.38–4.53 (m, 3H), 5.07 (br s, 0.5H), 5.24 (br s, 0.5H), 5.38 (t, *J*=9.6 Hz, 1H), 5.73 (ddd, *J*=1.6, 4.0, 10.0 Hz, 0.5H), 5.81 (ddd, *J*=1.6, 4.0, 10.0 Hz, 0.5H), 6.78–6.83 (m, 2H), 7.12–7.16 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$, 55 °C): δ −4.6, −4.3, 18.0, 25.7, 25.9, 28.1, 28.4, 29.4, 39.6, 42.8, 45.4, 47.2, 47.5, 52.2, 53.4, 55.2, 71.7, 72.1, 86.5, 86.7, 104.1, 113.7, 125.2, 125.7, 128.5, 128.9, 131.2, 131.4, 131.6, 150.6, 159.1; IR (ATR): ν 2952, 2931, 1699, 1671, 1512, 1445, 1324, 1246 cm^{-1}; LRMS (FAB) *m*/*z* 522 (M+Na); HRMS (FAB) *m*/*z* calcd for $C_{28}H_{41}NO_5SiNa$ (M+Na) 522.2652, found 522.2639; HPLC: DAICEL CHIRALPAK IB, 254 nm, flow rate 1.0 mL/min, hexane/*i*-PrOH=97:3, retention time: 5.9 min and 6.3 min.



45′

Good ^{1}H and ^{13}C NMR spectra were difficult to obtain due to the presence of rotamers and inseparable impurity. The structure of **45′** was determined after it was converted to diketone **70** (Scheme 15).



Scheme 15.

*4.3.13. Diketone **70**.* To a solution of **45′** (25 mg, <50 μmol, impure) in CH_3CN (0.5 mL) was added HF·Py (20 μL, 0.75 mmol) at 0 °C. The resulting mixture was warmed to rt and stirred for 19 h at the same temperature. Saturated aqueous $NaHCO_3$ (1 mL) was added to quench the reaction at 0 °C. The separated water layer was extracted with AcOEt, and the combined organic layers were dried over Na_2SO_4. Volatile material was removed under reduced pressure, and the resulting residue was used in the next step without purification.

To a solution of crude product in CH_2Cl_2 (0.5 mL) was added Dess–Martin periodinane (69 mg, 0.15 mmol) at 0 °C. The resulting mixture was warmed to rt and stirred for 18 h at the same temperature. Saturated aqueous $NaHCO_3$ (1 mL) and sodium thiosulfate (1 mL) were added and the mixture stirred for 30 min to quench the reaction. The separated water layer was extracted with AcOEt, and the combined organic layers were washed with brine and dried over Na_2SO_4. Volatile material was removed under reduced pressure. The resulting residue was purified by column chromatography (SiO_2, hexane/AcOEt=1/3) to give **70** (7 mg, yield 54%, in two steps) as a colorless foam: ^{1}H NMR (400 MHz, C_6D_6, 75 °C): δ 1.19–1.33 (m, 1H), 1.34–1.48 (m, 1H), 1.77–1.92 (m, 2H), 2.02–2.18 (m, 2H), 2.19–2.37 (m, 3H), 3.30 (ddd, *J*=2.4, 4.8, 19.2 Hz, 1H), 3.54 (s, 3H), 4.44 (br s, 1H), 4.72 (br s, 1H), 5.06 (br d, *J*=10.0 Hz, 1H), 5.72 (dd, *J*=2.4, 10.0 Hz, 1H); ^{13}C NMR (100 MHz, C_6D_6, 75 °C): δ 24.4, 35.8, 40.5, 40.9, 42.4, 43.5, 48.7, 52.5, 53.2, 124.5, 128.5, 138.3, 204.8, 211.1; IR (ATR): ν 3365, 2922, 2851, 1735, 1682, 1457, 1363 cm^{-1}; LRMS (FAB) *m*/*z* 268 (M+H); HRMS (ESI) *m*/*z* calcd for $C_{28}H_{34}N_2O_8Na$ (2M+Na) 549.2213, found 549.2239.

Compound **45** (103 mg, 0.206 mmol) was also converted to **70** (44 mg, yield 81%, in two steps) by the same method as shown above.

*4.3.14. Secondary alcohol **46**.* To a solution of **45** (1.20 g, 2.4 mmol) in CH_3CN (24 mL) was added HF·Py (0.31 mL, 7.2 mmol) at 0 °C. The resulting mixture was warmed to rt and stirred for 17.5 h at the same temperature. Saturated aqueous $NaHCO_3$ (1 mL) was added to quench the reaction at 0 °C. The separated water layer was extracted with AcOEt, and combined organic layers were dried over Na_2SO_4. Volatile material was removed under reduced pressure, and the resulting residue was purified by column chromatography (SiO_2, hexane/AcOEt=1/4) to give **46** (529 mg, yield 85%) as

a colorless oil: ^{1}H NMR (400 MHz, $CDCl_3$, 55 °C): δ 1.67 (br s, 1H), 1.80–1.90 (m, 1H), 1.90–1.99 (m, 1H), 2.04 (br s, 2H), 2.31 (dd, J=4.4, 16.4 Hz, 1H), 2.35–2.42 (m, 1H), 2.45 (dd, J=4.8, 15.2 Hz, 1H), 2.55 (dd, J=13.2, 16.0 Hz, 1H), 3.18 (br s, 1H), 3.55 (t, J=2.0 Hz, 0.5H), 3.60 (t, J=2.0 Hz, 0.5H), 3.75 (s, 3H), 3.94 (br s, 1H), 4.32 (br d, J=18.8 Hz, 1H), 4.98 (br d, J=10.4 Hz 1H), 5.48 (ddd, J=2.0, 3.6, 10.0 Hz, 1H), 5.75 (br s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$, 55 °C): δ 29.0, 31.2, 40.1, 40.4, 41.7, 44.4, 47.0, 49.9, 53.0, 79.6, 123.4, 131.3, 156.4, 209.0; IR (ATR): ν 3442, 2953, 1699, 1681, 1448, 1239 cm^{-1}; LRMS (FAB) m/z 266 (M+H); HRMS (FAB) m/z calcd for $C_{14}H_{20}NO_4$ (M+H) 266.1392, found 266.1394.

*4.3.15. Reduction of **46**.* To a solution of **46** (50 mg, 0.188 mmol) in THF (24 mL) were added MeOH (1 drop) and $NaBH_4$ (29 mg, 0.754 mmol) at 0 °C. The resulting mixture was warmed to rt and stirred for 3.5 h at the same temperature. Then reaction mixture was added $NaBH_4$ (29 mg, 0.745 mmol) again at 0 °C and stirred 1.5 h at rt H_2O (10 mL) was added to quench the reaction at 0 °C. The separated water layer was extracted with AcOEt, and combined organic layers were dried over Na_2SO_4. Volatile material was removed under reduced pressure, and the resulting residue was purified by column chromatography (SiO_2, AcOEt) to give **47** (27 mg, yield 55%) as a colorless solid and **48** (23 mg, yield 45%) as a colorless foam. Then **48** was recrystallized from i-Pr_2O. The stereochemistry of **48** was determined by X-ray crystallography.

*4.3.16. Diol **47** (a mixture of rotamers).* ^{1}H NMR (400 MHz, $CDCl_3$, 55 °C): δ 1.59 (dt, J=3.6, 14.0 Hz, 1H), 1.61 (dt, J=3.6, 14.0 Hz, 1H), 1.69 (t, J=4.8 Hz, 3H), 1.81–1.92 (m, 4H), 1.92–2.00 (m, 1H), 2.08–2.16 (m, 1H), 3.52 (t, J=2.4 Hz, 0.5H), 3.57 (t, J=2.4 Hz, 0.5H), 3.73 (s, 3H), 3.83 (t, J=6.4 Hz, 1H), 4.12–4.17 (m, 1H), 4.25 (dt, J=2.4, 18.8 Hz, 1H), 4.82 (dd, J=3.6, 12.0 Hz, 1H), 5.39 (ddd, J=2.0, 3.6, 10.0 Hz, 1H), 5.73 (br d, J=4.8 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$, 55 °C): δ 27.5, 31.0, 33.6, 33.8, 40.4, 42.0, 44.1, 47.0, 48.8, 52.9, 67.3, 80.7, 123.7, 131.9, 156.6; IR (ATR): ν 3393, 3015, 2969, 2938, 2921, 2886, 2857, 1738, 1661 cm^{-1}; HRMS (ESI) m/z calcd for $C_{28}H_{43}N_2O_8$ (2M+H) 535.3019, found 535.3044.

*4.3.17. Diol **48**.* ^{1}H NMR (400 MHz, $CDCl_3$, 55 °C): δ 1.35 (ddd, J=5.2, 10.8, 24.0 Hz, 2H), 1.48–189 (m, 8H), 1.99–2.09 (m, 1H), 2.10–2.20 (m, 1H), 3.54 (t, J=2.0 Hz, 0.5H), 3.59 (t, J=2.0 Hz, 0.5H), 3.73 (s, 3H), 3.87 (t, J=8.8 Hz, 1H), 3.97 (tt, J=4.8, 10.8, 21.6 Hz, 1H), 4.26 (br d, J=2.4, 18.0 Hz, 1H), 4.45 (br d, J=11.6 Hz, 1H), 5.39 (dd, J=1.6, 10.4 Hz, 1H), 5.86 (br d, J=8.8 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$, 55 °C): δ 24.4, 30.3, 34.5, 36.3, 40.1, 43.0, 46.9, 47.1, 52.8, 80.6, 125.5, 130.8, 156.4; IR (ATR): ν 3365, 2922, 2851, 1735, 1682, 1457, 1363 cm^{-1}; LRMS (FAB) m/z 268 (M+H); HRMS (FAB) m/z calcd for $C_{14}H_{22}NO_4$ (M+H) 268.1549, found 268.1543; mp: 70–71.5 °C (from i-Pr_2O).

*4.3.18. Cyclic carbamate **49**.* To a solution of **40** (40 mg, 0.102 mmol) in THF (1.0 mL) were added MeOH (1 drop) and $NaBH_4$ (7.7 mg, 0.203 mmol) at 0 °C. The resulting mixture was warmed to rt and stirred for 14 h at the same temperature. Saturated aqueous NH_4Cl (1 mL) was added to quench the reaction at rt. The separated water layer was extracted with AcOEt, and combined organic layers were washed with brine and dried over Na_2SO_4. Volatile material was removed under reduced pressure, and the resulting residue was purified by column chromatography (SiO_2, hexane/AcOEt=3/1) to give **49** (19 mg, yield 51%) as a colorless foam: ^{1}H NMR ($CDCl_3$, 600 MHz): δ 0.14 (s, 3H), 0.15 (s, 3H), 0.92 (s, 9H), 1.43 (dt, J=9.6, 19.2 Hz, 1H), 1.59–1.65 (m, 1H), 1.66–1.77 (m, 2H), 1.78–1.82 (m, 1H), 1.86–1.96 (m, 2H), 1.95 (d, J=19.2 Hz, 1H), 2.16 (dd, J=7.2, 17.4 Hz, 1H), 3.59 (dd, J=7.8, 15.0 Hz, 1H), 3.62 (br s, 1H), 3.69 (dd, J=1.8, 10.2 Hz, 1H), 4.21 (d, J=10.2 Hz, 1H), 4.32 (dd, J=4.8, 15.0 Hz, 1H), 4.88 (br s, 1H), 5.21 (d, J=5.4 Hz, 1H), 5.22 (d, J=16.2 Hz, 1H), 5.87 (ddd, J=5.4, 9.6, 16.2 Hz, 1H); ^{13}C NMR ($CDCl_3$, 150 MHz): δ −4.51, −4.35, 18.0, 20.8, 25.5, 30.6, 31.3, 34.0, 39.5, 41.5, 50.3, 56.4, 71.5, 101.9, 118.2, 133.0, 150.6, 153.5; IR (ATR): ν 2952, 2928, 2857, 1695, 1666 cm^{-1}; HRMS (ESI) m/z calcd for $C_{20}H_{33}NO_3SiNa$ (M+Na) 386.2127, found 386.2142.

*4.3.19. Cyclic carbamate **50**.* To a solution of **41** (40 mg, 98.1 μmol) in THF (0.98 mL) were added MeOH (1 drop) and $NaBH_4$ (7.4 mg, 0.196 mmol) at 0 °C. The resulting mixture was warmed to rt and stirred for 14 h at the same temperature. Saturated aqueous NH_4Cl (1 mL) was added to quench the reaction at rt. The separated water layer was extracted with AcOEt, and the combined organic layers were washed with brine and dried over Na_2SO_4. Volatile material was removed under reduced pressure, and the resulting residue was purified by column chromatography (SiO_2, hexane/AcOEt=3/1) to give **50** (18 mg, yield 49%) as a colorless foam: ^{1}H NMR ($CDCl_3$, 600 MHz): δ 0.14 (s, 3H), 0.15 (s, 3H), 0.92 (s, 9H), 1.10–1.15 (m, 1H), 1.25–1.39 (m, 3H), 1.46–1.53 (m, 1H), 1.59–1.69 (m, 3H), 1.72–1.79 (m, 1H), 2.00 (d, J=9.6 Hz, 1H), 2.31 (dt, J=3.0, 18.0 Hz, 1H), 3.56 (dd, J=7.2, 15.0 Hz, 1H), 3.60 (dd, J=1.8, 10.8 Hz, 1H), 3.97 (br s, 1H), 4.35–4.40 (m, 2H), 4.89 (br s, 1H), 5.21 (d, J=9.6 Hz, 1H), 5.22 (d, J=16.2 Hz, 1H), 5.86 (ddd, J=5.4, 9.6, 16.2 Hz, 1H); ^{13}C NMR ($CDCl_3$, 150 MHz): δ −4.46, −4.29, 18.0, 20.9, 25.6, 25.6, 29.4, 30.2, 33.5, 33.7, 36.3, 50.1, 52.7, 72.2, 101.1, 118.2, 133.3, 149.8, 153.1; IR (ATR): ν 2927, 2856, 1693, 1667 cm^{-1}; HRMS (ESI) m/z calcd for $C_{21}H_{35}NO_3SiNa$ (M+Na) 400.2284, found 400.2274.

*4.3.20. Diketone **51**.* To a solution of **43** (200 mg, 0.378 mmol) in CH_3CN (3.8 mL) was added HF·Py (29 μL, 1.13 mmol) at 0 °C. The resulting mixture was warmed to rt and stirred for 4 h at the same temperature. Saturated aqueous $NaHCO_3$ (1 mL) was added to quench the reaction at 0 °C. The separated water layer was extracted with AcOEt, and the combined organic layers were dried over Na_2SO_4. Volatile material was removed under reduced pressure, and the resulting residue was purified by column chromatography (SiO_2, hexane/AcOEt=3/2) to give 5**1** (152 mg, yield 96%) as a colorless oil: ^{1}H NMR (C_6D_6, 400 MHz, 75 °C): δ 1.53 (br s, 1H), 1.65–1.74 (m, 1H), 1.98 (dt, J=9.6, 16.4 Hz, 1H), 2.38 (dd, J=2.4, 17.2 Hz, 1H), 2.43–2.58 (m, 3H), 2.65 (dd, J=5.2, 17.2 Hz, 1H), 3.43 (m, 2H), 3.45 (s, 3H), 3.49 (s, 3H), 3.68 (d, J=9.2 Hz, 1H), 3.71 (br s, 1H), 4.00 (br s, 2H), 4.35 (s, 2H), 5.01 (dq, J=1.6, 10.4 Hz, 1H), 5.06 (dq, J=1.6, 17.2 Hz, 1H), 5.76 (ddt, J=5.6, 10.4, 17.2 Hz, 1H), 6.88 (dt, J=2.4, 8.8 Hz, 2H), 7.20 (dt, J=2.4, 8.8H, 2H); ^{13}C NMR (C_6D_6, 100 MHz, 75 °C): δ 27.2, 38.1, 40.2, 41.5, 42.9, 52.1, 52.9, 54.8, 55.0, 56.3, 73.7, 75.1, 114.5, 116.6, 129.6, 130.6, 135.4, 156.7, 160.3, 207.4, 215.7; IR (ATR): ν 2952, 1692, 1611 cm^{-1}; LRMS (FAB) m/z 438 (M+Na); HRMS (FAB) m/z calcd for $C_{23}H_{29}NO_6Na$ (M+Na) 438.1893, found 438.1903.

*4.3.21. p-Nitorobenzoate **52**.* To a solution of **51** (152 mg, 0.366 mmol) in CH_2Cl_2 (5.9 mL) and H_2O (1.5 mL) was added DDQ (166 mg, 0.732 mmol) at 0 °C. The resulting mixture was warmed to rt and stirred for 1 h at the same temperature. Saturated aqueous sodium thiosulfate (3 mL) was added and the resulting mixture was stirred for 30 min at rt. The separated water layer was extracted with CH_2Cl_2, and the combined organic layers were dried over Na_2SO_4. Volatile material was removed under reduced pressure, and the resulting residue was purified by column chromatography (SiO_2, hexane/AcOEt=1/3) to give deprotected alcohol (105 mg, yield 97%) as a colorless oil: ^{1}H NMR (C_6D_6, 400 MHz, 75 °C): δ 1.24 (br s, 1H), 1.69 (br s, 1H), 1.82–1.94 (m, 1H), 2.12 (br d, J=15.6 Hz, 2H), 2.35–2.47 (m, 2H), 2.55 (br s, 1H), 2.68 (br s, 1H), 3.34 (br s, 1H), 3.48 (s, 3H), 3.65 (br d, J=10.8 Hz, 2H), 3.80 (br d, J=15.6 Hz, 1H), 4.04 (br d, J=16.4 Hz, 1H), 4.40 (br s, 1H), 5.00 (br d, J=12.0 Hz, 2H), 5.62–5.76 (m, 1H); ^{13}C NMR (C_6D_6, 100 MHz, 75 °C): δ 26.5, 37.6, 38.0, 42.4, 49.9, 50.9, 52.6, 54.4, 57.9, 65.2, 116.1, 135.8, 158.2, 206.4,

217.5; IR (ATR): ν 3430, 2953, 1712, 1691 cm^{-1}; HRMS (ESI) m/z calcd for $C_{30}H_{42}N_2O_{10}Na$ (2M+Na) 613.2737, found 613.2728.

To a solution of the alcohol (105 mg, 0.356 mmol) in CH_2Cl_2 (3.6 mL) was added Et_3N (0.15 mL, 1.07 mmol) at rt. After stirring for 5 min, *p*-nitrobenzoyl chloride (79 mg, 0.427 mmol) and DMAP (4.4 mg, 35.6 μmol) were added at 0 °C. The resulting mixture was warmed to rt and stirred for 1.5 h at the same temperature. Saturated aqueous NH_4Cl (2 mL) was added to quench the reaction. The separated water layer was extracted with AcOEt, and the combined organic layers were dried over Na_2SO_4. Volatile material was removed under reduced pressure, and the resulting residue was purified by column chromatography (SiO_2, hexane/AcOEt/CH_2Cl_2=1/1/1) to give **52** (100 mg, yield 63%) as a colorless solid. Then **52** was recrystallized from benzene. The Stereochemistry of **52** was determined by X-ray crystallography: ^1H NMR (C_6D_6, 400 MHz, 75 °C): δ 1.54 (br s, 1H), 1.62–1.74 (m, 1H), 1.98 (dt, J=9.2, 18.8 Hz, 1H), 2.23–2.34 (m, 2H), 2.37 (d, J=6.0 Hz, 1H), 2.40–2.44 (m, 1H), 2.52 (br s, 1H), 3.18–3.51 (br s, 1H), 3.48 (s, 3H), 3.88 (m, 3H), 4.49 (dd, J=11.2, 20.0 Hz, 2H), 5.01 (d, J=3.2 Hz, 2H), 5.04 (d, J=11.2 Hz, 1H), 5.74 (ddd, J=5.6, 10.8, 22.4 Hz, 1H), 7.27–7.31 (m, 2H), 7.84 (dd, J=8.8, 12.8 Hz, 2H); ^{13}C NMR (C_6D_6, 100 MHz, 75 °C): δ 26.9, 37.9, 38.0, 38.9, 40.9, 42.5, 52.3, 54.2, 56.6, 68.7, 116.9, 123.7, 128.5, 135.0, 135.1, 151.1, 156.8, 164.4, 206.2, 212.2; IR (ATR): ν 2958, 1727, 1706, 1694 cm^{-1}; HRMS (ESI) m/z calcd for $C_{22}H_{24}N_2O_8Na$ (M+Na) 467.1430, found 467.1446; mp 137.5–139.5 °C (benzene).

*4.3.22. Ketone **58**.* To a solution of **53** (26 mg, 42.5 μmol) in CH_3CN (0.5 mL) was added HF·Py (2 mg, 98.2 μmol) at 0 °C. After stirring for 10 min, the resulting mixture was warmed to rt and stirred for 13 h. Saturated aqueous $NaHCO_3$ (10 mL) was added to quench the reaction. The separated water layer was extracted with AcOEt, and the combined organic layers were washed with brine and dried over Na_2SO_4. Volatile material was removed under reduced pressure. The resulting residue was purified by column chromatography (SiO_2, hexane/AcOEt=1/3) to give **58** (19 mg, yield 90%) as a colorless foam: ^1H NMR (C_6D_6, 400 MHz, 75 °C): δ 1.42 (br s, 1H), 1.74 (br s, 1H), 1.92 (br t, J=14.0 Hz, 1H), 2.07 (br d, J=15.2 Hz, 1H), 2.38 (br d, J=15.2 Hz, 1H), 2.58 (br s, 1H), 3.03 (br t, J=14.0 Hz, 1H), 3.33 (br s, 1H), 3.43 (s, 3H), 3.69 (br d, J=12.4 Hz, 1H), 3.79 (br d, J=12.4 Hz, 1H), 3.84–3.96 (m, 1H), 4.11–4.30 (m, 2H), 4.88 (br t, J=9.2 Hz, 2H), 5.08 (br s, 1H), 5.43 (br s, 1H), 7.14 (br s, 3H), 8.05 (br d, J=5.2 Hz, 2H); ^{13}C NMR (100 MHz, C_6D_6, 75 °C): δ 26.5, 35.5, 41.6, 42.2, 43.0, 44.3, 48.8, 53.2, 55.9, 61.7, 116.3, 128.6, 128.9, 133.4, 135.6, 139.7, 167.7, 168.3, 169.4, 202.4; IR (ATR): ν 2924, 1710, 1661 cm^{-1}; LRMS (FAB) m/z 535 (M+K); HRMS (FAB) m/z calcd for $C_{22}H_{25}ClN_2O_7SK$ (M+K) 535.0708, found 535.0715.

*4.3.23. Oxabicyclo[2.2.2]octanone **61**.* To a solution of **58** (14 mg, 28.2 μmol) in THF (0.3 mL) was added $NaBH_4$ (2 mg, 56.3 μmol) at 0 °C. After stirring for 35 min at the same temperature, water (1 mL) was added to quench the reaction. The separated water layer was extracted with AcOEt, and the combined organic layers were washed with brine and dried over Na_2SO_4. Volatile material was removed under reduced pressure. Crude **59** was dissolved in MeOH for 2 days to give **61** (10 mg, yield 71%) as a colorless crystal. The stereochemistry of **61** was determined by X-ray crystallography: ^1H NMR (400 MHz, $CDCl_3$): δ 1.04 (dd, J=13.2, 24.8 Hz, 1H), 1.66 (dddt, J=2.4, 7.2, 9.6, 12.0 Hz, 1H), 1.83 (dd, J=12.0, 24.0 Hz, 1H), 1.88–2.01 (m, 3H), 2.28–2.38 (m, 1H), 2.72–2.2.82 (m, 1H), 3.33 (ddd, J=6.4, 9.6, 14.4 Hz, 1H), 3.53 (s, 3H), 3.77 (tt, J=4.0, 15.2 Hz, 1H), 3.98 (d, J=13.2 Hz, 1H), 4.04 (d, J=13.2 Hz, 1H), 4.16 (dt, J=2.0, 18.8 Hz, 1H), 4.27 (ddd, J=4.0, 7.6, 14.0 Hz, 1H), 4.55 (dd, J=4.8, 19.2 Hz, 1H), 4.75 (dd, J=3.2, 13.2 Hz, 1H), 5.03 (d, J=17.2 Hz, 1H), 5.09 (d, J=10.4 Hz, 1H), 5.65 (ddd, J=4.8, 10.4, 17.2 Hz, 1H), 7.56 (t, J=8.0 Hz, 2.6H), 7.67 (t, J=7.2 Hz, 1.4H), 7.97 (d, J=7.2 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 27.1, 34.4, 34.9, 40.0, 42.1, 42.2, 47.7, 53.6, 55.0, 61.4, 68.0, 115.6, 128.4, 128.6, 133.8, 136.3, 138.2, 168.0, 168.5, 169.0; IR (ATR): ν 3447, 2928, 1707, 1652 cm^{-1}; LRMS (FAB) m/z 499 (M+H); HRMS (FAB) m/z calcd for $C_{22}H_{28}ClN_2O_7S$ (M+H) 499.1306, found 499.1281; mp 157.5–159 °C (MeOH).

*4.3.24. Cyclic carbamate **62**.* To a solution of **55**-*anti* (20 mg, 45.7 μmol) in THF (0.46 mL) was added $LiBH_4$ (2.0 M in THF, 23 μL, 46.0 μmol) at −78 °C. After stirring for 30 min at the same temperature, MeOH (1 drop) was added and the mixture was warmed to rt and then stirred for 1 h. After addition of water (3 mL) at 0 °C, the separated water layer was extracted with AcOEt, and the combined organic layers were washed with brine and dried over Na_2SO_4. Volatile material was removed under reduced pressure. The resulting residue was purified by column chromatography (SiO_2, hexane/AcOEt=1/3) to give **62** (16 mg, yield quant) as a colorless oil: ^1H NMR ($CDCl_3$, 600 MHz): δ 0.14 (s, 6H), 0.91 (s, 9H), 1.67–1.73 (m, 1H), 1.82–1.93 (m, 3H), 2.00–2.05 (m, 1H), 2.04 (dd, J=4.0, 10.4 Hz, 1H), 2.17 (dd, J=4.4, 6.6 Hz, 1H), 2.24 (dt, J=4.4, 9.6 Hz, 1H), 3.45 (d, J=6.4 Hz, 1H), 3.53 (d, J=6.4 Hz, 1H), 3.59 (dd, J=5.2, 10.0 Hz, 1H), 3.86 (d, J=1.2 Hz, 1H), 4.28–4.35 (m, 2H), 4.78 (d, J=2.4 Hz, 1H), 5.23 (d, J=6.8 Hz, 1H), 5.26 (d, J=11.6 Hz, 1H), 5.85 (dddd, J=4.0, 5.2, 6.8, 18.0 Hz, 1H); ^{13}C NMR ($CDCl_3$, 150 MHz): δ −4.35, −4.21, 18.1, 25.6, 25.7, 31.0, 31.3, 33.0, 41.1, 49.5, 52.5, 54.5, 66.9, 84.9, 101.5, 118.7, 133.5, 154.5, 157.4; IR (ATR): ν 3409, 2951, 2928, 2888, 2859, 1708, 1665 cm^{-1}; HRMS (ESI) m/z calcd for $C_{40}H_{67}N_2O_8Si_2$ (2M+H) 759.4436, found 759.4424.

*4.3.25. Aldehyde **63**.* To a solution of **62** (14 mg, 36.9 μmol) in CH_2Cl_2 (0.4 mL) was added Dess–Martin periodinane (34 mg, 79 μmol) at 0 °C. After stirring for 10 min, the resulting mixture was warmed to rt and stirred for 1.5 h. Saturated aqueous $NaHCO_3$ (2 mL) and aqueous sodium thiosulfate (2 mL) were added and the mixture was stirred for 30 min. The separated water layer was extracted with AcOEt, and the combined organic layers were washed with brine and dried over Na_2SO_4. Volatile material was removed under reduced pressure. The resulting residue was purified by column chromatography (SiO_2, hexane/AcOEt=2/1) to give **63** (11 mg, yield 79%) as a colorless oil: ^1H NMR ($CDCl_3$, 600 MHz): δ 0.15 (s, 6H), 0.92 (s, 9H), 1.78 (dt, J=7.8, 13.2 Hz, 2H), 2.00–2.07 (m, 1.5H), 2.08–2.14 (m, 1.5H), 2.16 (dt, J=6.6, 16.8 Hz, 1H), 2.59 (dt, J=6.6, 13.2 Hz, 1H), 3.60 (dd, J=7.2, 15.0 Hz, 1H), 4.25 (d, J=3.6 Hz, 1H), 4.30 (ddt, J=1.8, 5.4, 15.6 Hz, 1H), 4.80 (dd, J=3.0, 6.6 Hz, 1H), 4.86 (d, J=3.6 Hz, 1H), 5.25 (d, J=17.4 Hz, 1H), 5.26 (dd, J=0.6, 8.4 Hz, 1H), 5.80 (ddd, J=4.8, 8.4, 17.4 Hz, 1H), 9.52 (s, 1H); ^{13}C NMR ($CDCl_3$, 150 MHz): δ −4.52, −4.36, 18.0, 25.5, 30.5, 31.3, 31.9, 39.4, 49.2, 51.8, 61.7, 81.9, 100.2, 118.8, 133.0, 154.5, 156.5, 198.7; IR (ATR): ν 2930, 2857, 1716, 1665 cm^{-1}; HRMS (ESI) m/z calcd for $C_{20}H_{31}NO_4SiNa$ (M+Na) 400.1920, found 400.1939.

*4.3.26. Diol **64**.* To a solution of **55**-*syn* (151 mg, 0.345 mmol) in THF (3.5 mL) was added $LiBH_4$ (2.0 M in THF, 0.35 mL, 0.70 mmol) at −78 °C. After stirring for 1 h at the same temperature, MeOH (1 drop) was added and the mixture was warmed to rt and stirred for 2 h. Saturated aqueous NH_4Cl (3 mL) was added to quench the reaction at 0 °C. The separated water layer was extracted with AcOEt, and the combined organic layers were dried over Na_2SO_4. Volatile material was removed under reduced pressure. The resulting residue was purified by column chromatography (SiO_2, hexane/AcOEt=1/2) to give **64** (121 mg, yield 85%) as a colorless solid. Then **64** was recrystallized from AcOEt/hexane. The stereochemistry of **64** was determined by X-ray crystallography: ^1H NMR ($CDCl_3$, 400 MHz): δ 0.13 (s, 3H), 0.14 (s, 3H), 0.91 (s, 9H), 1.50–1.62 (m, 1H), 1.62–1.86 (m, 3H), 1.94–2.09 (m, 1H), 2.15 (ddd, J=4.4, 9.6, 18.4 Hz, 1H), 2.21–2.38 (m, 1H), 2.78 (br s, 1H), 3.51–3.62 (m, 2H), 3.65–3.85 (m, 2H), 3.73 (s, 3H), 3.99 (dd, J=4.8, 15.2 Hz, 1H), 4.33 (br s, 1H), 4.74 (tt, J=2.4, 14.0 Hz, 1H), 5.03–5.19 (m, 3H), 5.85 (ddt, J=5.2, 10.0, 16.8 Hz, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ −4.46, 17.9, 25.5, 26.0, 29.2, 30.5, 37.2, 47.8, 48.9, 53.1, 53.2, 64.4, 77.9, 102.3,

115.3, 135.8, 152.1, 159.2; IR (ATR): ν 3396, 2956, 2928, 2857, 1736, 1660 cm^{-1}; HRMS (ESI) m/z calcd for $C_{42}H_{74}N_2O_{10}Si_2Na$ (2M+Na) 845.4780, found 845.4762; mp 116–118.5 °C (AcOEt/*n*-hexane).

4.3.27. Diol ***66****.* To a solution of **56**-*anti* (93 mg, 0.206 mmol) in THF (3.5 mL) was added $LiBH_4$ (2.0 M in THF, 0.10 mL, 0.20 mmol) at 0 °C. After stirring for 1 h at the same temperature, ice-cold H_2O (3 mL) was added to quench the reaction at 0 °C. The separated water layer was extracted with AcOEt, and the combined organic layers were dried over Na_2SO_4. Volatile material was removed under reduced pressure. The resulting residue was purified by column chromatography (SiO_2, hexane/AcOEt=4/1) to give secondary alcohol (77 mg, yield 83%) as a colorless oil: ^1H NMR (C_6D_6, 400 MHz, 75 °C): δ 0.36 (s, 6H), 1.11 (s, 9H), 1.27–1.59 (m, 2.8H), 1.59–1.74 (d, 1.2H), 1.80–2.10 (m, 3H), 2.18 (br s, 1H), 2.87 (br s, 1.3H), 3.10 (br s, 1.7H), 3.50 (br s, 7H), 4.31 (br d, J=16.0 Hz, 1H), 4.69 (br s, 1H), 5.00–5.16 (m, 3H), 5.80 (br s, 1H); ^{13}C NMR (C_6D_6, 100 MHz, 75 °C): δ −4.2, −4.0, 15.6, 18.2, 26.0, 28.6, 31.8, 33.5, 34.4, 51.4, 52.5, 52.9, 65.6, 67.9, 104.3, 116.2, 134.8, 152.3, 157.4, 175.6; IR (ATR): ν 3447, 2929, 2856, 1727, 1702 cm^{-1}; HRMS (ESI) m/z calcd for $C_{46}H_{78}N_2O_{12}Si_2Na$ (2M+Na) 929.4991, found 929.4973. Broad peaks were observed in ^{13}C NMR spectra due to the presence of rotamers, even at elevated temperatures. Three carbons were not observed separately.

To a solution of the alcohol (70 mg, 0.154 mmol) in CH_3CN (1.5 mL) was added HF·Py (20 μL, 0.772 mmol) at 0 °C. After stirring for 10 min, the resulting mixture was warmed to rt and stirred for 16 h. Saturated aqueous $NaHCO_3$ (2 mL) was added to quench the reaction at 0 °C. The separated water layer was extracted with AcOEt, and the combined organic layers were dried over Na_2SO_4. Volatile material was removed under reduced pressure to give crude **65**, which was used in the next step without purification.

To a solution of crude **65** in THF (1.5 mL) was added MeOH (1 drop) and $LiBH_4$ (2.0 M in THF, 0.15 mL, 0.30 mmol) at −78 °C. After stirring for 1 h at the same temperature, ice-cold H_2O (3 mL) was added at −78 °C. The resulting mixture was slowly warmed to rt to quench the reaction. The separated water layer was extracted with AcOEt, and the combined organic layers were dried over Na_2SO_4. Volatile material was removed under reduced pressure and the resulting residue was purified by column chromatography (SiO_2, hexane/AcOEt=2/3) to give **66** (24 mg, yield 52%, in two steps) as a colorless solid. Then **66** was recrystallized from AcOEt/*i*-PrOH. The stereochemistry of **66** was determined by X-ray crystallography: ^1H NMR (DMSO-d_6, 400 MHz, 100 °C): δ 1.33 (dt, J=3.2, 12.8 Hz, 1H), 1.41–1.65 (m, 4H), 1.74–1.84 (m, 2H), 1.93 (ddt, J=4.4, 13.2, 26.4 Hz, 2H), 2.36 (t, J=7.6 Hz, 1H), 2.59 (dd, J=11.2, 24.4 Hz, 1H), 3.41 (br s, 2H), 3.66 (s, 3H), 3.67 (s, 3H), 3.67–3.77 (m, 1H), 4.15 (dd, J=4.0, 15.6 Hz, 1H), 4.30 (dd, J=4.0, 15.6 Hz, 1H), 4.47 (dd, J=5.6, 16.4 Hz, 1H), 4.55 (br s, 1H), 5.15 (dd, J=1.6, 7.6 Hz, 1H), 5.19 (dd, J=1.6, 14.4 Hz, 1H), 5.94 (ddt, J=5.6, 10.4, 17.6 Hz, 1H); ^{13}C NMR (DMSO-d_6, 100 MHz, 100 °C): δ 14.1, 28.8, 31.5, 33.7, 35.7, 36.5, 45.7, 51.0, 51.6, 52.3, 58.9, 67.0, 67.9, 114.2, 136.4, 155.8, 173.7; IR (ATR): ν 3437, 3324, 2926, 2860, 1695 cm^{-1}; HRMS (ESI) m/z calcd for $C_{17}H_{27}NO_6Na$ (M+Na) 364.1736, found 364.1751; mp 174–175.5 °C (from AcOEt/*i*-PrOH).

4.3.28. Secondary alcohol ***67****.* To a solution of mixture of **56**-*syn* (69 mg, 0.153 mmol) in THF (1.5 mL) were added MeOH (1 drop) and $LiBH_4$ (2.0 M in THF, 0.23 mL, 0.46 mmol) at 0 °C. After stirring for 1 h at the same temperature, the resulting mixture was warmed to 45 °C and stirred for 1.5 h. Saturated aqueous NH_4Cl (2 mL) was added at rt. The separated water layer was extracted with AcOEt, and the combined organic layers were dried over Na_2SO_4. Volatile material was removed under reduced pressure, and the resulting residue was used in the next step without purification.

To a solution of crude product in THF (1.5 mL) was added NaH (60% in oil, 6.7 mg, 0.168 mmol) at rt. After stirring for 10 min at the same temperature, saturated aqueous NH_4Cl (2 mL) was added to quench the reaction at 0 °C. The separated water layer was extracted with AcOEt, and the combined organic layers were dried over Na_2SO_4. Volatile material was removed under reduced pressure and the resulting residue was purified by column chromatography (SiO_2, hexane/AcOEt=2/3) to give **67** (37 mg, yield 62%, in two steps) colorless oil: ^1H NMR ($CDCl_3$, 400 MHz): δ 0.14 (s, 3H), 0.15 (s, 3H), 0.91 (s, 9H), 1.22–1.39 (m, 2H), 1.41–1.55 (m, 2H), 1.56–1.66 (m, 1H), 1.65 (d, J=18.0 Hz, 1H), 1.70–1.82 (m, 2H), 2.02–2.14 (m, 1H), 2.15–2.27 (m, 1H), 3.06 (br s, 1H), 3.54 (dd, J=8.0, 15.2 Hz, 1H), 3.91 (br s, 1H), 3.94 (br s, 1H), 4.16 (d, J=10.4 Hz, 1H), 4.27 (d, J=10.4 Hz, 1H), 4.34 (dt, J=1.2, 4.8 Hz, 1H), 4.87 (t, J=1.6 Hz, 1H), 5.20–5.27 (m, 1H), 5.83 (dtt, J=4.8, 9.6, 11.2 Hz, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ −4.44, −4.29, 17.9, 19.3, 25.5, 28.6, 28.9, 30.3, 33.3, 37.7, 50.0, 53.8, 63.8, 66.9, 101.0, 118.4, 133.0, 150.5, 153.9; IR (ATR): ν 3404, 2932, 2857, 1734, 1654 cm^{-1}; HRMS (ESI) m/z calcd for $C_{21}H_{35}NO_4SiNa$ (M+Na) 416.2233, found 416.2242.

4.3.29. Ketone ***68****.* To a solution of **67** (30 mg, 76.2 μmol) in CH_2Cl_2 (0.76 mL) was added $NaHCO_3$ (13 mg, 0.152 mmol) and Dess–Martin periodinane (65 mg, 0.152 mmol) at 0 °C. After stirring for 10 min, the resulting mixture was warmed to rt and stirred for 5.5 h. Saturated aqueous sodium thiosulfate (2 mL) was added and the mixture was stirred for 30 min. The separated water layer was extracted with AcOEt, and the combined organic layers were washed with brine and dried over Na_2SO_4. Volatile material was removed under reduced pressure. The resulting residue was purified by column chromatography (SiO_2, hexane/AcOEt=1/1) to give **68** (21 mg, yield 78%) as a colorless oil: ^1H NMR (CD_3CN, 600 MHz): δ 0.18 (s, 3H), 0.19 (s, 3H), 0.94 (s, 9H), 1.66–1.75 (m, 2H), 1.77–1.87 (m, 2H), 2.03–2.09 (m, 2H), 2.25 (br d, J=9.6 Hz, 1H), 2.33 (ddt, J=2.0, 4.4, 12.4 Hz, 1H), 2.71 (dt, J=4.4, 17.2 Hz, 1H), 3.61 (dd, J=4.4, 10.4 Hz, 1H), 4.13 (d, J=7.6 Hz, 2H), 4.17 (ddt, J=0.8, 3.2, 14.0 Hz, 1H), 4.33 (dd, J=0.8, 7.6 Hz, 1H), 4.45 (br s, 1H), 5.00 (dt, J=0.8, 1.2 Hz, 1H), 5.17 (dd, J=1.2, 3.2 Hz, 1H), 5.19 (ddd, J=0.8, 1.6, 7.6 Hz, 1H); ^{13}C NMR (CD_3CN, 150 MHz): δ −4.5, −4.3, 18.5, 25.8, 26.3, 28.4, 33.0, 38.3, 38.6, 49.9, 50.7, 54.4, 67.0, 102.9, 118.17, 134.4, 150.8, 152.7, 210.8; IR (ATR): ν 2928, 2856, 1697, 1660 cm^{-1}; HRMS (ESI) m/z calcd for $C_{42}H_{66}N_2O_8Si_2Na$ (2M+Na) 805.4255, found 805.4223.

Acknowledgements

This work was supported by a Grant-in-Aid for Scientific Research (B) from MEXT, Japan (project number; 21390002).

Supplementary data

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.tet.2011.01.019.

References and notes

1. (a) Kozmin, S. A.; Rawal, V. H. *J. Org. Chem.* **1997**, *62*, 5252; (b) Kozmin, S. A.; Rawal, V. H. *J. Am. Chem. Soc.* **1997**, *119*, 7165; (c) Kozmin, S. A.; Rawal, V. H. *J. Am. Chem. Soc.* **1999**, *121*, 9562; (d) Huang, Y.; Iwama, T.; Rawal, V. H. *J. Am. Chem. Soc.* **2000**, *122*, 7843; (e) Huang, Y.; Iwama, T.; Rawal, V. H. *J. Am. Chem. Soc.* **2002**, *124*, 5950; (f) Huang, Y.; Iwama, T.; Rawal, V. H. *Org. Lett.* **2002**, *4*, 1163.
2. Kozmin, S. A.; Iwama, T.; Huang, Y.; Rawal, V. H. *J. Am. Chem. Soc.* **2002**, *124*, 4628.
3. (a) Gagnon, A.; Danishefsky, S. J. *Angew. Chem., Int. Ed.* **2002**, *41*, 1581; (b) Yun, H.; Gagnon, A.; Danishefsky, S. J. *Tetrahedron Lett.* **2006**, *47*, 5311.
4. (a) Smith, A. B., III; Basu, K.; Bosanac, T. *J. Am. Chem. Soc.* **2007**, *129*, 14872; (b) Smith, A. B., III; Bosanac, T.; Basu, K. *J. Am. Chem. Soc.* **2009**, *131*, 2348.
5. Nicolaou, K. C.; Tria, G. S.; Edmonds, D. J. *Angew. Chem., Int. Ed.* **2008**, *47*, 1780.
6. Kita, Y.; Toma, T.; Kan, T.; Fukuyama, T. *Org. Lett.* **2008**, *10*, 3251.
7. Martin, D. B. C.; Vanderwal, C. D. *J. Am. Chem. Soc.* **2009**, *131*, 3472.
8. (a) Seth, P. P.; Totah, N. I. *Org. Lett.* **1999**, *1*, 1411; (b) Seth, P. P.; Chen, D.; Wang, J.; Gao, X.; Totah, N. I. *Tetrahedron* **2000**, *56*, 10185.
9. Kozmin, S. A.; Janey, J. M.; Rawal, V. H. *J. Org. Chem.* **1999**, *64*, 3039.
10. (a) Matsumura, T.; Akiba, M.; Arai, S.; Nakagawa, M.; Nishida, A. *Tetrahedron Lett.* **2007**, *48*, 1265; (b) Mihara, Y.; Matsumura, T.; Terauchi, Y.; Akiba, M.; Arai, S.; Nishida, A. *Bull. Chem. Soc. Jpn.* **2009**, *82*, 1520.

11. Manzamine B (13): Sakai, R.; Kohmoto, S.; Higa, T.; Jefford, C. W.; Bernardinelli, G. *Tetrahedron Lett.* **1987**, *28*, 5493.
12. Lycoposerramine Q (17): Takayama, H.; Katakawa, K.; Kitajima, M.; Yamaguchi, K.; Aimi, N. *Tetrahedron Lett.* **2002**, *43*, 8307.
13. Lycoposerramine R (18): Katakawa, K.; Kogure, N.; Kitajima, M.; Takayama, H. *Helv. Chim. Acta* **2009**, *92*, 445.
14. Tabersonine (19): Janot, M.-M.; Pourrat, H.; Le Men, J. *Bull. Soc. Chim. Fr.* **1954**, 707.
15. Starkenmann, C.; Mayenzet, F.; Brauchli, R.; Wunsche, L.; Vial, C. *J. Agric. Food Chem.* **2007**, *55*, 10902.
16. Liotta, D.; Barnum, C.; Puleo, R.; Zima, G.; Bayer, C.; Kezar, H. S., III. *J. Org. Chem.* **1981**, *46*, 2920.
17. Schinzer, D.; Bärmann, H. *Tetrahedron Lett.* **2007**, *48*, 8607.
18. Ito, H.; Takenaka, Y.; Fukunishi, S.; Iguchi, K. *Synthesis* **2005**, *18*, 3035.
19. Nakagawa, M.; Uchida, H.; Ono, K.; Kimura, Y.; Yamabe, M.; Watanabe, T.; Tsuji, R.; Akiba, M.; Terada, Y.; Nagaki, D.; Ban, S.; Miyashita, N.; Kano, T.; Theeraladanon, C.; Hatakeyama, K.; Arisawa, M.; Nishida, A. *Heterocycles* **2003**, *59*, 721.
20. da Silva Filho, L. C.; Lacerda, V., Jr.; Constantino, M. G.; da Silva, G. V. J.; Invernize, P. R. *Beilstein J. Org. Chem.* **2005**, *1*.
21. Kapat, A.; Nyfeler, E.; Giuffredi, T. G.; Renaud, P. *J. Am. Chem. Soc.* **2009**, *131*, 17746.
22. Kozikowski, A. P.; Tuckmantel, W. *J. Org. Chem.* **1991**, *56*, 2826.
23. Ley, S. V.; Murray, P. J.; Palmer, B. D. *Tetrahedron* **1985**, *41*, 4765.
24. Smith, A. B., III; Branca, S. J.; Guaciaro, M. A.; Wovkulich, P. M.; Korn, A. *Org. Synth.* **1983**, *61*, 65.