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A Direct Organocatalytic Entry to Selectively Protected Aldopentoses and Derivatives

Christoph Grondal[a] and Dieter Enders[a,*]

[a] Institut für Organische Chemie, RWTH Aachen University, Landoltweg 1, 52074 Aachen, Germany
Fax: (+49)-241-809-2127; e-mail: enders@rwth-aachen.de

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Dedicated to Professor Masakatsu Shibasaki on the occasion on his 60th birthday.

Abstract: The proline-catalysed aldol reaction of 2,2-dimethyl-1,3-dioxan-5-one with dimethoxyacetaldehyde is used as the key reaction according to the biomimetic C_3+C_n strategy for *de novo* carbohydrate synthesis. Based on the Whitesides inversion strategy, protected D-*erythro*-pentos-4-ulose ($de>96\%$, $ee=94\%$) was employed for a rapid and divergent entry to various selectively and partly orthogonal protected aldopentoses and derivatives, like amino sugars, thio sugars, deoxy sugars, 4-*C*-substituted (alkylated) aldopentoses and epoxy sugars.

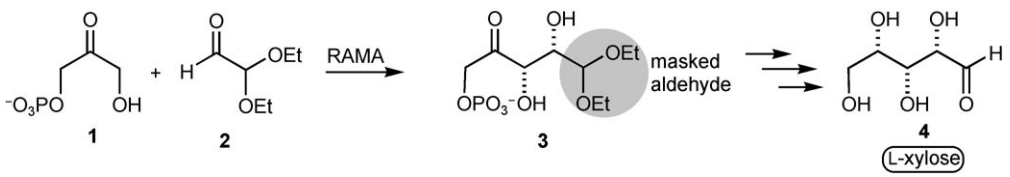
Keywords: aldol reactions; aldopentoses; asymmetric synthesis; carbohydrates; organocatalysis

Introduction

Carbohydrates are of enormous importance and constitute promising targets for drug discovery due to their interesting biological activities. Therefore, new efficient synthetic tools for the divergent-oriented synthesis of carbohydrates are highly desirable.[1] In particular, strategies for the asymmetric synthesis of selectively and orthogonal protected monosaccharide building blocks are of interest, because they can be used, for instance, in the automated synthesis of biologically active oligosaccharides[2] or employed in the synthesis of bioactive compounds containing carbohydrate motifs.[3] During our efforts regarding the development of a direct and flexible organocatalytic concept for the *de novo* synthesis of carbohydrates *via* a biomimetic $[C_3+C_n]$-strategy,[4] we envisaged to extend our concept by a divergent entry to different aldopentoses. This approach is based on the initial work on the "inversion strategy" by Whitesides et al.,[5] where dihydroxyacetone phosphate (**1**, DHAP) and diethoxyacetaldehyde (**2**) were converted to the desired aldol product **3**, catalysed by rabbit muscle aldolase (RAMA), and then reduced and deprotected to the corresponding L-xylose **4** (Scheme 1). The aldehyde moiety of **3** is protected as an acetal, while the keto function can be chemoselectively reduced to the secondary alcohol and, therefore, aldopentoses are easily available *via* this strategy.

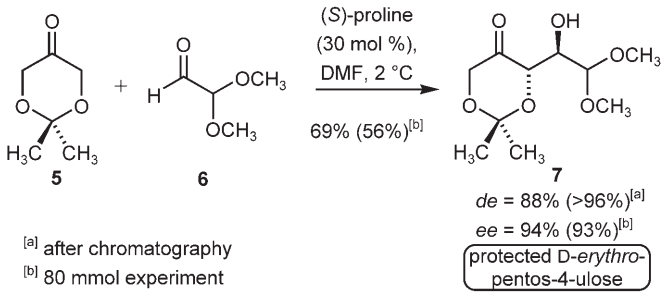
Results and Discussion

We have already reported the (*S*)-proline-catalysed aldol reaction of 2,2-dimethyl-1,3-dioxan-5-one (**5**, dioxanone)[6] and dimethoxyacetaldehyde **6** giving the corresponding aldol product **7**,[4a,c] which constitutes a viable alternative for the enzyme-catalysed synthesis of **3**. This reaction proceeded with 69% yield and high diastereo- and enantioselectivity ($de=88\%$, $ee=94\%$). At the beginning of our investigations, we have demonstrated that this reaction could be easily carried out on an 80-mmol scale to afford 11.2 g of the desired aldol product **7** with the same stereoselec-



Scheme 1. Whiteside's inversion strategy".

tivities [*de* = 88 % (≥96 % after chromatography), *ee* = 93 %], only the yield decreased from the original 69 % to 56 % (Scheme 2).

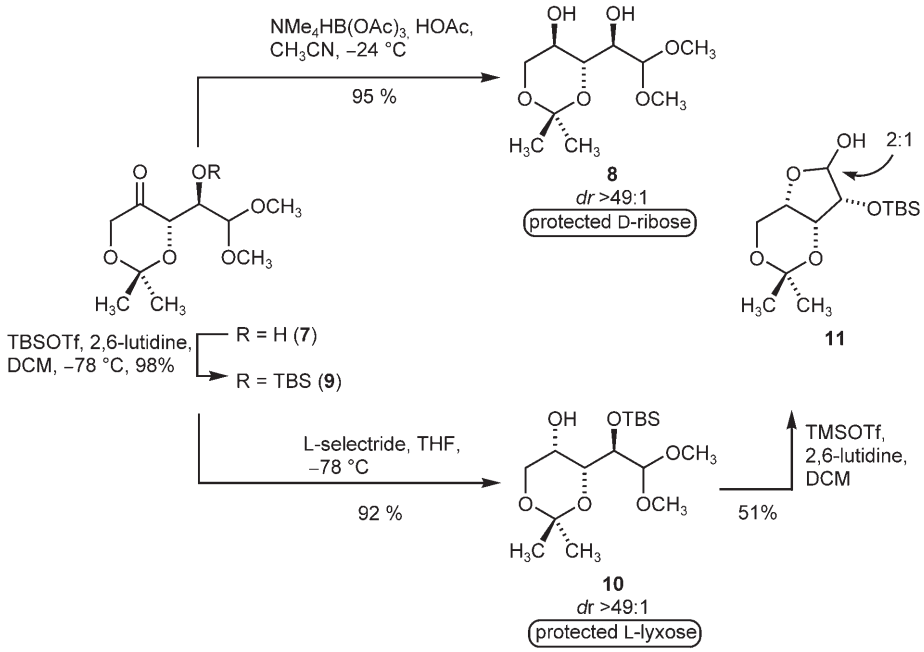


Scheme 2. (*S*)-Proline-catalysed synthesis of protected D-*erythro*-pentos-4-ulose (**7**).

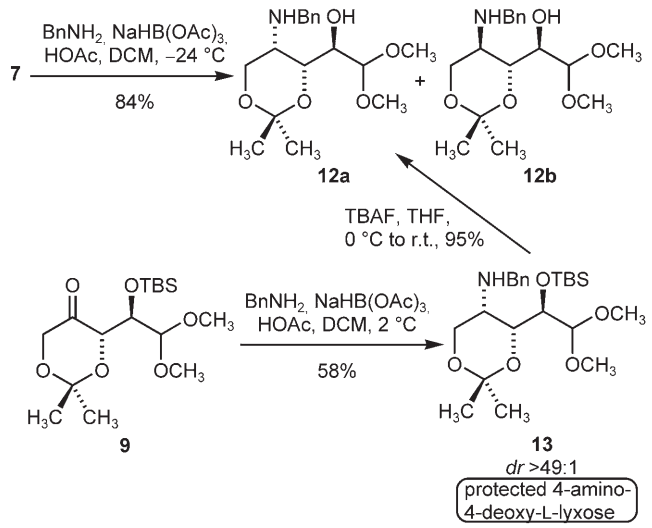
We have previously demonstrated the diastereoselective *anti*- and *syn*-1,3-selective reduction of **7** to protected D-ribose **8** and L-lyxose **10**.[4c] We have found that the *syn*-1,3-selective reduction can be performed with tetramethylammonium triacetoxyborohydride, whereas the *anti*-1,3-diol was not directly available from **7**. To circumvent this problem we have synthesised the TBS ether **9**, which can be reduced to **10** with high *anti*:*syn* ratio (≥98:2) using L-selectride. To our delight, we were able to cleave the dimethyl acetal unit of **10** chemoselectively in the presence of the acetonide acetal unit, applying Fujioka's and Kita's method[7] to obtain the protected L-lyxose lactol **11** (Scheme 3). The cleavage was performed in the presence of TMSOTf and 2,6-lutidine with 51 % yield. The resulting aldehyde cyclises to the corresponding lactol **11** spontaneously, with a ratio of 2:1 at the anomeric position.

Based on these results we have extended this concept by further transformations of the keto function of **7** and **9**, namely direct reductive amination, 1,2-addition, deoxygenation, olefination and epoxidation. The investigations towards the diastereoselective reductive amination were first concerned with the direct reductive amination and the question of whether a *syn*- and/or *anti*-1,3-diastereoselectivity can be explored. At the beginning we have employed **7** in a direct reductive amination reaction[9] with benzylamine and sodium triacetoxyborohyride in the presence of acetic acid and figured out that only little diastereocontrol could be achieved. A variation of the reaction parameters revealed a maximum ratio of 1.7:1 in favour of **12a** to **12b**. Thus, we have employed the TBS ether **9** for the direct reductive amination and to our delight we were able to obtain the same high stereocontrol and stereochemical outcome as we have observed in the L-selectride reduction of **9**. This reaction proceeds with 58 % yield and an excellent *Re* face control (*dr* >49:1) affording the protected 4-amino-4-deoxy-L-lyxose (**13**) (Scheme 4). To assign the major diastereomer of the reductive amination of **7** we have carried out the deprotection of **13** to the alcohol **12a**. This reaction proceeded in the presence of tetrabutylammonium fluoride (TBAF) with 95 % yield.

Since the corresponding *syn*-1,3-amino alcohol was not directly accessible with high stereocontrol, we have synthesised it from **10** *via* an S_N2 reaction of the



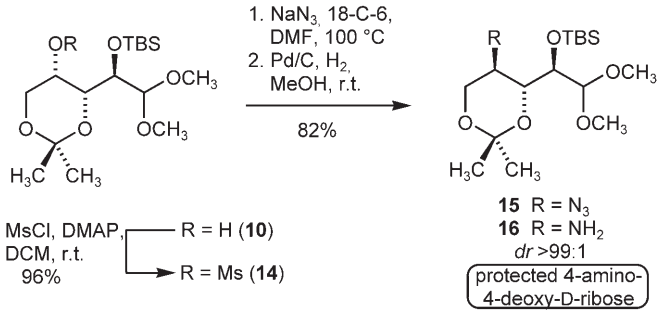
Scheme 3. Diastereoselective reduction of **7** affording protected D-ribose **8** and L-lyxose **10** and conversion to the protected L-lyxose lactol **11**.



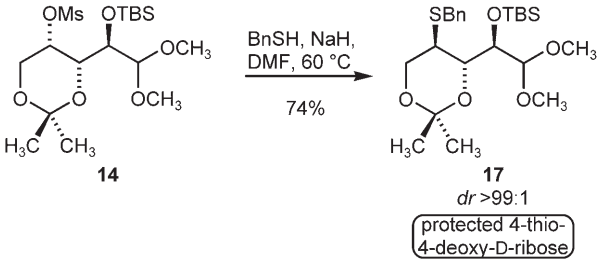
Scheme 4. Direct reductive amination of **7** and **9**.

mesylate **14** with sodium azide.[10] The substitution succeeded with complete inversion ($dr > 99{:}1$) to give the azide **15**. The following reduction to the primary amine **16** was first performed with lithium aluminium hydride, but unfortunately the TBS ether was partly cleaved. Hydrogenation on Pd/C avoided this problem and afforded the primary amine **16** with virtually quantitative yield (Scheme 5).

A substitution reaction of the mesylate **14** could also be performed with sodium benzylmercaptate affording the selectively protected 4-thio-4-deoxy-D-ribose (**17**). The substitution proceeded with complete inversion ($dr > 99{:}1$) and gave **17** in 74% yield (Scheme 6).



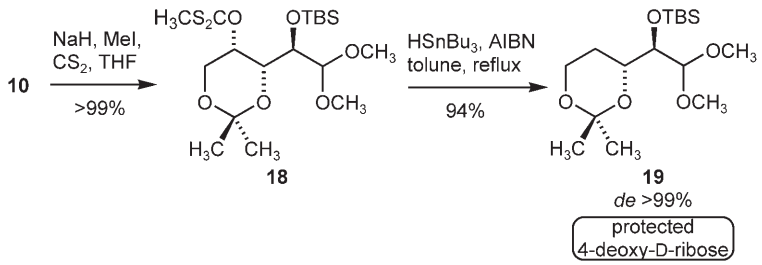
Scheme 5. Synthesis of **16** *via* S_N2-reaction with sodium azide.



Scheme 6. Synthesis of **17** *via* S_N2-reaction with sodium benzylmercaptate.

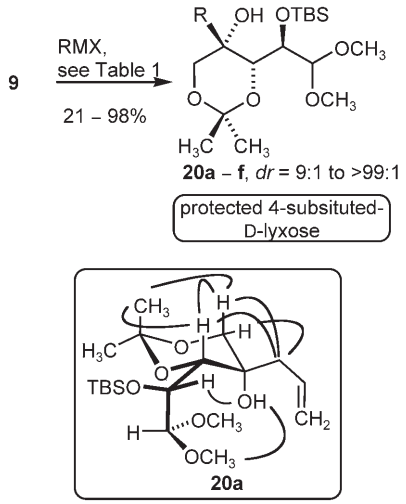
The alcohol **10** was used for the synthesis of the protected 4-deoxy-D-ribose **19** by applying the Barton-McCombie deoxygenation.[11,12] Thus, **10** was first converted with almost quantitative yield into the xanthate **18** by deprotonation of **10** with sodium hydride and quenching with carbon disulphide and methyl iodide. The xanthate **18** was then converted to **19** with 94% yield by treatment with tributyltin hydride and AIBN in refluxing toluene (Scheme 7).

The asymmetric synthesis of protected 4-*C*-substituted (alkylated) aldopentose derivatives bearing a quaternary stereocentre can be accomplished *via* a 1,2-addition with carbon nucleophiles to the keto function of **9**. Firstly, several Grignard reagents (RMgX) were used and it could demonstrated that the 1,2-addition can be performed with good yields and good to very high diastereocontrol at −78 °C, only the very reactive allylmagnesium bromide ($dr = 12{:}1$) and vinylmagnesium bromide ($dr = 9{:}1$) showed moderate diastereocontrol, while the reaction with allylmagnesium bromide was performed in the presence of zinc bromide at −100 °C to increase the selectivity. Thus, the stereoselectivity could be enhanced significantly ($dr \geq 49{:}1$). The reaction with phenylmagnesium bromide showed only traces of conversion. Therefore, we have performed this reaction with the corresponding cerium reagents, which have a stronger nucleophilicity.[13] Indeed, this procedure afforded the



Scheme 7. Deoxygenation of **10** *via* the Barton-McCombie deoxygenation.

desired product **20f** with 42% yield and high stereocontrol ($dr = 27:1$). In general, the yields of the 1,2-addition are higher utilising the cerium reagents instead of the magnesium reagents (Scheme 8, Table 1). To



Scheme 8. 1,2-Addition to **9** and representative NOE enhancements of **20a**.

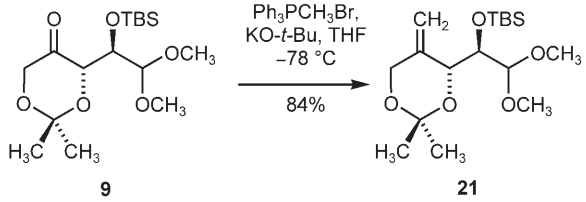
Table 1. Nucleophilic 1,2-addition of RMX to **9**.

20	R	MX/[equivs.]	T [°C]	Yield [%]	dr[a]
a	Allyl	-MgBr/2.0	−78	96	12:1
a	Allyl	-ZnBr/1.5	−100	98	≥49:1
b	Me	-MgBr/2.0	−78	76	≥49:1
b	Me	-$CeMe_xCl_y$/1.3	−78	95	50:1
c	Et	-MgBr/5.0	−78	76	>100:1
c	Et	-MgBr/3.0	−78 to 0	87	>100:1
d	*n*-Bu	-MgBr/3.0	−78	63	>100:1
d	*n*-Bu	-Ce*n*Bu_xCl_y/1.3	−78	75	>100:1
e	Vinyl	-MgBr/4.0	−78	21	9:1
f	Ph	-MgBr/5.0	−78 to 0	traces	-
f	Ph	-$CePh_xCl_y$/1.3	−78	42	27:1

[a] Determined by ^1H and ^{13}C NMR and GC.

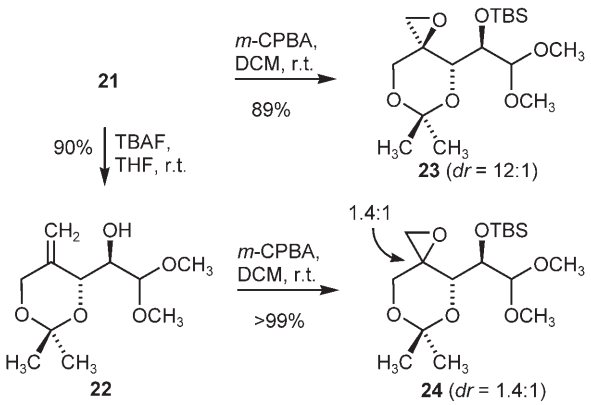
our delight, the 1,2-addition proceeds with a *Re* selective control, which is in agreement with the stereochemical outcomes of the reduction and reductive amination of **9**. The configuration of the newly created quaternary stereocentre was assigned with NOE measurements in the case of **20a**. We assume the same face selectivity for the other cases.

Moreover, we have investigated the methylenation of **9**. Unfortunately, Tebbe olefination with the commercially available Tebbe reagent[14] failed, which is probably due to the steric demand of **9**. Wittig olefination afforded the *exo*-olefin **21** with 84% yield, but it should be mentioned that the base, potassium *tert*-butoxide, is important to avoid undesired epimerisation and elimination (Scheme 9).



Scheme 9. Epimerisation-free *Wittig*-olefination of **9**.

Olefins are interesting functional groups for further transformation, for example, epoxidation, dihydroxylation, hydrogenation or aziridination. We were concerned whether the epoxidation of **21** and of the deprotected alcohol **22** could be performed with stereocontrol. We assumed that the epoxidation of **21** with *m*-CPBA should proceed with high *Re* selectivity. Indeed, this reaction proceeds with high diastereoselectivity ($dr = 12:1$) in favour of the isomer **23**. The *homo*-allyl alcohol **22**, which is available from **21** by deprotection with TBAF in 90% yield, can coordinate the *m*-CPBA *via* hydrogen bonding.[15] Therefore it should be possible to achieve a stereocontrol, at best attack from the *Si* face, like in the case of the reduction with tetramethylammonium triacetoxyborohydride of **7**. Unfortunately, the experiment revealed that the epoxidation of **22** with *m*-CPBA shows only marginal stereocontrol ($dr = 1.4:1$) (Scheme 10).



Scheme 10. Epoxidation of **21** and **22**.

Conclusions

We have developed a flexible and highly stereoselective organocatalytic entry to several selectively and partly orthogonal protected aldopentoses and derivatives, like amino sugars, thio sugars, deoxy sugars, 4-*C*-substituted (alkylated) aldopentose derivatives and epoxy sugars, based on Whiteside's original strategy for the enzymatic synthesis of aldopentoses. The scope of the method is not fully explored, for example, further transformations are possible, such as substitution of **14** with halogen nucleophiles, hydrogena-

tion or aziridination of **21**. Furthermore, we could demonstrate that the dimethyl acetal unit can be cleaved in the presence of the acetonide moiety which really expands the scope of our biomimetic C_3+C_n strategy for carbohydrate synthesis.

Experimental Section

General Remarks

Starting materials and reagents were purchased from commercial suppliers and used without further purification. THF was freshly distilled from sodium-lead alloy under argon. Dichloromethane and acetonitrile were freshly distilled from CaH_2 under argon. Acetic acid was distilled from CrO_3 under argon. Benzylamine was distilled over $MgSO_4$ and stored over 4 Å molecular sieves. Preparative column chromatography was performed on Merck silica gel 60, particle size 0.040–0.063 mm (230–240 mesh, flash). Analytical TLC: silica gel 60 F_{254} plates from Merck, Darmstadt. Visualisation of the developed chromatograms was performed by ultraviolet irradiation (254 nm) or staining using acidic ammonium molybdate. Optical rotation values were measured on a Perkin–Elmer P241 polarimeter. Microanalyses were obtained with a Vario EL element analyzer. Mass spectra were acquired on a Finnigan SSQ7000 (EI 70 eV) spectrometer. High resolution mass spectra were recorded on a Finnigan MAT95 spectrometer. IR spectra were taken on a Perkin–Elmer FT-IR 1760. ^{1}H and ^{13}C NMR spectra were recorded on Varian Mercury 300, Inova 400 or Unity 500 spectrometers with tetramethylsilane as internal standard and at ambient temperature. Analytical GC was performed on a Varian CP 3800. For the asymmetric synthesis of compounds **7--10** see ref.[4c]

Preparation of Compounds 11–19

11: To a solution of **10** (105 mg, 0.30 mmol) in dichloromethane (2 mL) was added 2,6-lutidine (0.11 mL, 0.90 mmol) and TMSOTf (0.12 mL, 0.60 mmol) at 0 °C. After being stirred for 90 min, the reaction mixture was quenched by addition of water (1 mL) and stirred for an additional 1 h. The mixture was extracted with dichloromethane (3×3 mL). The organic layer was dried over $MgSO_4$ and evaporated under reduced pressure. The crude product was purified by flash chromatography (SiO_2, *n*-pentane/diethyl ether = 1:2) affording **11** as colourless oil; yield:46 mg (51 %); $[\alpha]_D^{21}$: −19.8 (*c* 1.00, $CHCl_3$); IR ($CHCl_3$): ν = 3894, 3953, 3808, 3744, 3674, 3649, 3612, 3435, 3674, 2933, 2859, 2361, 1736, 1697, 1650, 1557, 1509, 1462, 1423, 1385, 1258, 1221, 1175, 1144, 1100, 1061, 1006, 966, 835, 777, 669, 579, 515 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): mixture of two epimers: δ = 0.11 and 0.12 (2 s, 6 H), 0.92 and 0.93 (2 s, 9 H),1.41, 1.42 and 1.44 (3 s, 6 H), 3.03 (d, *J* = 4.7 Hz, 1 H), 3.80 (q, *J* = 3.0 Hz, 1 H), 3.88 and 4.01 (dd, *J* = 12.9, 3.0 Hz), 4.05 (dd, *J* = 12.9, 3.5 Hz), 4.05–4.12 and 4.14–4.22 (complex), 5.13 (dd, *J* = 11.6, 4.6 Hz) and 5.45 (dd, *J* = 4.8, 4.7 Hz, 1 H); ^{13}C NMR (100 MHz, $CDCl_3$): mixture of two epimers: δ = −4.5, 18.4, 19.4, 19.6, 25.8, 28.7, 61,2, 61,7, 70.0, 70.4, 71.1, 71.7, 74.2, 80.4, 97.5, 97.6, 102.6; MS (EI, 70 eV): *m*/*z* = 289 (12), 247 (17), 189 (100), 171 (26), 159 (18), 143 (27), 131 (17), 129 (28), 117 (75), 101 (12), 75 (61), 73 (36), 59 (25); anal. calcd. for $C_{14}H_{28}O_5Si$ (304.17): C 56.23, H 9.27; found: C 56.39, H 9.61.

13: To a solution of freshly distilled $BnNH_2$ (80 μL, 0.72 mmol) and **9** (230 mg, 0.66 mmol) in dichloromethane (5 mL) $NaHB(OAc)_3$ (204 mg, 0.96 mmol) and anhydrous acetic acid (38 μL, 0.66 mmol) were added consecutively at 2 °C. The reaction mixture was stirred at 2 °C for 8 h and then stored at this temperature for further 48 h before it was quenched with 1 N NaOH solution (1 mL). The reaction mixture was diluted with water (2 mL) and extracted with diethyl ether (3×5 mL). The organic layer was washed with brine (3 mL) and dried over Na_2SO_4. The crude product was purified by flash chromatography (SiO_2, *n*-pentane/diethyl ether = 1:4) affording **13** as a yellow oil; yield: 171 mg (58 %); $[\alpha]_D^{23}$: +110.2 (*c* 1.01, $CHCl_3$); IR ($CHCl_3$): ν = 3970, 3940, 3919, 3825, 3818, 3767, 3760, 3733, 3646, 3590, 3559, 3496, 2286, 3335, 3299, 3268, 3237, 2932, 2856, 2775, 1461, 1375, 1252, 1200, 1145, 1085, 996, 942, 902, 834, 800, 730, 700 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$): δ = 0.11 (s, 3 H), 0.15 (s, 3 H), 0.89 (s, 9 H), 1.38 (s, 3 H), 1.46 (s, 3 H), 1.92 (br, 1 H), 2.69 (d, *J* = 1.5 Hz, 1 H), 3.35 (s, 3 H), 3.44 (s, 3 H), 3.58 (d, *J* = 12.8 Hz, 1 H), 3.87 (dd, *J* = 11.9, 1.5 Hz, 1 H), 3.97 (dd, *J* = 8.0, 1.8 Hz, 1 H), 3.99 (d, *J* = 12.8 Hz, 1 H), 4.11 (complex, 2 H), 4.15 (d, *J* = 2.5 Hz, 1 H, 7.23 (complex, 1 H), 7.32 (complex, 2 H), 7.40 (complex, 2 H); ^{13}C NMR (100 MHz, $CDCl_3$): δ = −5.0, −4.2, 18.6, 18.9, 26.3, 29.7, 50.6, 50.7, 55.9, 56.6, 61.5, 71.7, 72.5, 98.8, 104.6, 126.8, 128.2, 128.3, 141.0; MS (EI, 70 eV): *m*/*z* = 439 (15), 424 (46), 383 (12), 382 (44), 366 (14), 351 (17), 350 (60), 349 (26), 318 (41), 292 (37), 277 (12), 276 (56), 190 (17), 162 (12), 134 (13), 133 (91), 132 (36), 106 (23), 91 (100), 89 (22), 75 (49), 73 (38); anal. calcd. for $C_{23}H_{41}NO_5Si$ (439.28): C 62.86, H 9.34, N 3.19; found: C 62.42, H 9.27, N 3.52.

12a: To a solution of **13** (80 mg, 0.18 mmol) in THF (2 mL) was added a TBAF-THF-solution (1 M, 0.36 mL, 0.36 mmol) at 0 °C and then slowly warmed to room temperature and stirred until the reaction was complete (TLC control). The reaction mixture was evaporated under reduced pressure and purified by flash chromatography (SiO_2, *n*-pentane/diethyl ether = 1:4) affording **12a** as a pale yellow oil; yield: 56 mg (95 %); $[\alpha]_D^{23}$: +138.9 (*c* 0.97, $CHCl_3$); IR ($CHCl_3$): ν = 3310, 2995, 2935, 1453, 1378, 1270, 1199, 1132, 1078, 999, 913, 856, 754, 702, 666 cm^{-1}; ^{1}H NMR (300 MHz. $CDCl_3$): δ = 1.44 (s, 3 H), 1.48 (s, 3 H), 2.85 (d, *J* = 1.7 Hz, 1 H), 3.35 (s, 3 H), 3.41 (s, 3 H), 3.71 (d, *J* = 12.8 Hz, 1 H), 3.83 (dd, *J* = 4.9, 3.4 Hz, 1 H), 3.92 (complex, 2 H), 3.95 (d, *J* = 12.8 Hz, 1 H), 4.03 (dd, *J* = 3.3, 2.2 Hz, 1 H), 4.15 (d, 4.7 Hz, 1 H), 7.25–7.37 (complex, 5 H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 18.6, 29.8, 50.6, 52.5, 55.1, 56.2, 60.9, 68.9, 74.2, 99.3, 106.0, 127.5, 128.6, 128.8, 138.7; MS (EI, 70 eV): *m*/*z* = 325 (2), 310 (31), 293 (14), 250 (29), 192 (21), 190 (10), 162 (24), 149 (43), 145 (19), 133 (69), 132 (45), 106 (11), 91 (100), 75 (27); anal. calcd. for $C_{17}H_{27}NO_5$ (325.19): C 62.77, H 8.46, N 4.31; found: C 63.05, H 8.95, N 4.56.

14: To a solution of **10** (330 mg, 0.95 mmol) in dichloromethane (15 mL) DMAP (1,16 g, 9.50 mmol) and MsCl (0.36 mL, 4.70 mmol) were added at 0 °C. The reaction mixture was warmed to room temperature and stirred until the reaction was finished (TLC control, 2 h). The reaction mixture was quenched by addition of saturated $NaHCO_3$ solution (10 mL) and extracted with diethyl ehter (3×15 mL).

The organic layer was washed with brine (10 mL) and dried over $MgSO_4$. The crude product was purified by flash chromatography (SiO_2, *n*-pentane/diethyl ether = 2:1) affording **14** as a colourless oil; yield: 378 mg (93%); $[\alpha]_D^{23}$: +28.2 (*c* 1.29, $CHCl_3$); IR ($CHCl_3$): ν = 3833, 3536, 2933, 2856, 1467, 1357, 1255, 1176, 1110, 1036, 962, 881, 840, 759, 669 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$): δ = 0.14 (s, 6H), 0.89 (s, 9H), 1.44 (s, 3H), 1.48 (s, 3H), 3.14 (s, 3H), 3.43 (s, 3H), 3.48 (s, 3H), 3.91 (dd, *J* = 7.9, 2.2 Hz, 1H), 4.00 (dd, *J* = 7.9, 2.2 Hz, 1H), 4.01 (dd, *J* = 14.1, 1.3 Hz, 1H), 4.35 (dd, *J* = 14.1, 1.9 Hz, 1H), 4.36 (d, *J* = 2.2 Hz, 1H), 4.68 (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = −5.0, −4.2, 18.6, 18.8, 26.3, 29.2, 40.1, 56.2, 56.7, 62.4, 71.1, 71.2, 72.9, 99.2, 104.3; MS (EI, 70 eV): *m*/*z* = 413 (5), 267 (16), 209 (21), 185 (17), 173 (11), 171 (58), 153 (43), 143 (25), 129 (21), 89 (22), 75 (100); anal. calcd. for $C_{17}H_{36}O_8SSi$ (428.19): C 47.64, H 8.47; found: C 47.90, H 8.29.

15: To a solution of mesylate **14** (180 mg, 0.42 mmol) in DMF (6 mL) were added NaN_3 (274 mg, 4.20 mmol) and 18-crown-6 (334 mg, 1.26 mmol) and the reaction mixture was then stirred for 40 h at 100 °C. The reaction mixture was quenched with water (10 mL) and extracted with diethyl ether (3 × 15 mL). The organic layer was washed with brine (10 mL) and dried over $MgSO_4$. The crude product was purified by flash chromatography (SiO_2, *n*-pentane/diethyl ether = 6:1) affording **15** as a colourless oil; yield: 129 mg (82%); $[\alpha]_D^{23}$: −31.7 (*c* 1.00, $CHCl_3$); IR ($CHCl_3$): ν = 2934, 2858, 2240, 2107, 1466, 1379, 1324, 1257, 1225, 1200, 1150, 1076, 1024, 910, 838, 780, 734, 684 cm^{-1}; ^1H NMR (400 MHz, C_6D_6): δ = 0.19 (s, 3H), 0.23 (s, 3H), 1.06 (s, 9H), 1.18 (s, 3H), 1.31 (s, 3H), 3.22 (s, 3H), 3.23 (s. 3H), 3.53 (dd, *J* = 11.6, 9.2 Hz, 1H), 3.71 (dd, *J* = 11.6, 5.2 Hz, 1H), 3.78 (m, 1H), 3.97 (dd, *J* = 7.7, 1.1 Hz, 1H), 4.10 (dd, *J* = 9.1, 1.1 Hz, 1H), 4.44 (d, *J* = 7.7 Hz, 1H); ^{13}C NMR (100 MHz, C_6D_6): δ = −4.4, −4.2, 18.6, 19.8, 26.2, 27.8, 54.4, 54.5, 55.7, 62.4, 72.6, 75.3, 99.3, 105.6; MS (EI, 70 eV): *m*/*z* = 360 (4), 131 (34), 116 (11), 89 (19), 75 (100), 73 (15), 59 (15), 58 (11); anal. calcd. for $C_{16}H_{33}N_3O_5$ (375.24): C 52.19, H 8.79, N 11.20; found: C 52.13, H 9.11, N 11.43.

16: To a solution of azide **15** (40 mg, 0.11 mmol) in methanol (2 mL) was added Pd/C (10 mg), flushed with hydrogen (H_2 balloon, 1 bar) and stirred until the reaction was finished (TLC control, 1 h). The suspension was filtered over Celite® and Na_2CO_3. After evaporation under reduced pressure, **16** was obtained as a colorless oil; yield: 38 mg (>99%); $[\alpha]_D^{21}$: −28.3 (*c* 1.00, $CHCl_3$); IR ($CHCl_3$): ν = 3383, 2938, 2857, 1599, 1466, 1377, 1254, 1202, 1141, 1078, 1022, 838, 761, 670 cm^{-1}; ^1H NMR (300 MHz, C_6D_6): δ = 0.24 (s, 3H), 0.31 (s, 3H), 1.09 (s, 9H), 1.29 (s, 3H), 1.46 (s, 3H), 3.13–3.25 (complex, 2H), 3.20 (s, 3H), 3.24 (s, 3H), 3.64 (m, 1H), 3.76 (m, 1H), 4.02 (dd, *J* = 7.2, 1.5 Hz, 1H), 4.66 (d, *J* = 7.2 Hz, 1H); ^{13}C NMR (75 MHz, C_6D_6): δ = −4.3, −4.0, 18.8, 19.6, 26.3, 28.9, 45.5, 53.9, 55.0, 67.2, 75.8, 76.2, 98.4, 105.9; MS (EI, 70 eV): *m*/*z* = 292 (27), 260 (38), 202 (16), 186 (13), 188 (23), 186 (14), 170 (22), 131 (27), 130 (16), 100 (10), 89 (16), 75 (100), 73 (27), 72 (40), 59 (11); HR-MS (EI), *m*/*z* = 334.20497, cacld. for $C_{16}H_{33}N_3O_5-CH_3$ (M^+-CH_3): 334.20490.

17: To a solution of benzylmercaptan (0.24 mL, 2.00 mmol) in DMF (2.5 mL) NaH (60%, 64 mg, 1.60 mmol) was added and the reaction mixture was stirred for 15 min. The mesylate **14** (170 mg, 0.40 mmol), dissolved in DMF (0.5 mL), was then added and the reaction mixture was stirred for additional 18 h at 60 °C. The reaction mixture was quenched with water (5 mL) and was extracted with diethyl ether (3 × 10 mL). The organic layer was washed with brine (7 mL) and dried over $MgSO_4$. After evaporation under reduced pressure, the crude product was purified by flash chromatography (SiO_2, pentane/diethyl ether = 6:1) affording **17** as a purple oil; yield: 135 mg (74%); $[\alpha]_D^{23}$: −19.4 (*c* 1.03, $CHCl_3$); IR ($CHCl_3$): ν = 3062, 2991, 2931, 2857, 1728, 1494, 1457, 1379, 1255, 1220, 1200, 1145, 1117, 1080, 1009, 839, 759, 701, 668 cm^{-1}; ^1H NMR (400 MHz, C_6D_6): δ = 0.10 (s, 3H), 0.13 (s, 3H), 0.91 (s, 9H), 1.34 (s, 3H), 1.40 (s, 3H), 3.10 (td, *J* = 10.2, 5.8 Hz, 1H), 3.41 (s, 3H), 3.43 (s, 3H), 3.61 (d, *J* = 11.8 Hz, 1H), 3.70 (dd, *J* = 11.8, 5.8 Hz, 1H), 3.77 (s, 2H), 3.84 (dd, *J* = 7.9, 0.9 Hz, 1H), 3.88 (dd, *J* = 10.2, 0.9 Hz, 1H), 4.60 (d, *J* = 7.9 Hz, 1H), 7.08–7.36 (complex, 5H); ^{13}C NMR (100 MHz, C_6D_6): δ = −4.7, −4.2, 18.2, 19.4, 26.0, 28.8, 36.1, 38.9, 54.9, 55.7, 64.2, 74.0, 74.7, 98.4, 105.5, 126.9, 128.3, 128.4, 138.1; MS (EI, 70 eV): *m*/*z* = 441 (4), 399 (17), 341 (34), 285 (10), 179 (43), 137 (12), 131 (16), 91 (100), 75 (72), 73 (15); anal. calcd. for $C_{23}H_{40}O_5SiS$ (456.24): C 60.49, H 8.83; found: C 60.04, H 9.07.

18: To a solution of alcohol **10** (250 mg, 0.71 mmol) in THF (6 mL) was added NaH (60%, 88 mg, 2.21 mmol) in small portions at 0 °C. After 20 min CS_2 (0.15 mL, 2.49 mmol) was added and after additional 30 min MeI (0.13 mL, 2.13 mmol). After warming to room temperature, the suspension was stirred for 5 h. The reaction mixture was quenched with pH 7 buffer (5 mL) and extracted with diethyl ether (3 × 10 mL). The organic layer was washed with brine (7 mL) and dried over $MgSO_4$. The crude product was purified by flash chromatography (SiO_2, *n*-pentane/diethyl ether = 2:1) affording **18** as a yellow oil; yield: 310 mg (>99%); $[\alpha]_D^{22}$: +21.4 (*c* 1.09, $CHCl_3$); IR ($CHCl_3$): ν = 2990, 2932, 2857, 1466, 1378, 1214, 1073, 998, 961, 835, 800, 756, 682, 665 cm^{-1}; ^1H NMR (300 MHz, C_6D_6): δ = 0.05 (s, 3H), 0.11 (s, 3H), 0.85 (s, 9H), 1.41 (s, 3H), 1.47 (s, 3H), 2.57 (s, 3H), 3.46 (s, 3H), 3.50 (s, 3H), 3.94 (dd, *J* = 8.4, 2.0 Hz, 1H), 4.05 (dd, *J* = 13.4, 2.0 Hz, 1H), 4.12 (dd, *J* = 8.4, 1.5 Hz, 1H), 4.40 (d, *J* = 2.0 Hz, 1H), 4.41 (dd, *J* = 13.4, 2.1 Hz, 1H), 5.38 (m, 1H); ^{13}C NMR (75 MHz, C_6D_6): δ = −5.0, −4.1, 18.5, 18.9, 19.0, 26.3, 28.8, 56.1, 55.6, 61.8, 70.9, 71.2, 74.2, 98.8, 104.2; MS (EI, 70 eV): *m*/*z* = 425 (4), 383 (14), 325 (10), 185 (23), 165 (14), 163 (19), 131 (17), 91 (25), 75 (100), 73 (23); anal. calcd. for $C_{18}H_{36}O_5SiS_2$ (440.17): C 49.06, H 8.18; found: C 49.16, H 8.20.

19: To a refluxing solution of *n*-Bu_3SnH (.042 mL, 1.59 mmol) in toluene (10 mL) a toluene solution (2 mL) of **18** (140 mg, 0.32 mmol) and a saturated toluene solution (1 mL) of AIBN were added at the same time over 1 hour. After the addition, the solution was refluxed for a further hour. After cooling to room temperature, the solvent was carefully removed under reduced pressure and the crude product was purified by flash chromatography (SiO_2, *n*-pentane/diethyl ether = 2:1) affording **19** as a colourless oil; yield: 100 mg (94%); $[\alpha]_D^{22}$: +4.9 (*c* 0.96, $CHCl_3$); IR ($CHCl_3$): ν = 2934, 2859, 2362, 2335, 1467, 1378, 1249, 1196, 1147, 1021, 974, 945, 875, 836, 779, 668 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$): δ = 0.00 (s, 3H), 0.03 (s, 3H), 0.83 (s, 9H), 1.24 (m, 1H), 1.27 (s, 3H), 1.37 (s, 3H), 1.85 (qd, *J* = 12.5, 5.5 Hz, 1H) 3.29 (s, 3H), 3.34 (s, 3H), 3.57 (dd, *J* = 5.2, 3.3 Hz, 1H), 3.75 (m, 1H), 3.88 (td, *J* = 12.4, 2.8 Hz, 1H),

3.94 (dt, $J=11.5$, 2.8 Hz, 1H), 4.08 (d, $J=5.2$ Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=-4.5$, -4.2, 18.5, 19.4, 25.2, 26.1, 29.8, 54.9, 55.7, 59.7, 69.3, 75.2, 98.2, 105.1; MS (EI, 70 eV): $m/z=319$ (5), 187 (16), 159 (17), 131 (37), 115 (63), 89 (14), 75 (100), 73 (22), 59 (16), 57 (10); anal. calcd. for $C_{16}H_{34}O_5Si$ (334.22): C 57.47, H 10.18; found: C 57.75, H 10.18.

General Procedure (GP 1) for the Grignard Addition to 9

In a flame-dried Schlenk flask was added 1.0 equiv. of **9** dissolved in THF (1.5 mL mmol^{-1}) which was then cooled to -78 °C. Then 2.0 to 5.0 equivs. of the Grignard reagent were added dropwise with a syringe pump. The reaction mixture was stirred for 2 h at -78 °C and then warmed to room temperature overnight. After quenching with saturated $NaHCO_3$ solution the mixture was extracted three times with diethyl ether, dried over $MgSO_4$ and after evaporation under reduced pressure the crude product was purified by flash chromatography (SiO_2, *n*-pentane/diethyl ether).

General Procedure (GP 2) for the Organocerium Addition to 9

$CeCl_3 \cdot 7H_2O$ (1.3 to 3.0 equivs.) was dehydrated for 2 h at 140 °C under reduced pressure (0.1 torr) in a Schlenk flask equipped with a magnetic stirrer. It was then suspended in THF (2 mL mmol^{-1}) by sonification for 1 h and additional stirring for 2 h. The suspension was cooled to -78 °C and the organolithium reagent (1.3 to 3.0 equivs.) was added. The mixture was stirred for 1 h at this temperature giving a yellow or orange suspension. Then ketone **9** (1.0 equiv.) dissolved in THF (1.5 mL mmol^{-1}) was added dropwise at this temperature. The suspension was stirred overnight, then warmed to ambient temperature and quenched with saturated $NaHCO_3$ solution. After three times extraction with diethyl ether, the combined organic phases were dried over $MgSO_4$ and purified by flash chromatography (SiO_2, *n*-pentane/diethyl ether).

20a: According to GP 1 **9** (200 mg, 0.57 mmol) was reacted with allylMgBr (1.0 M in diethyl ether, 1.72 mL, 1.72 mmol) and $ZnBr_2$ (394 mg, 1.72 mmol) to give **20a** as a colourless oil; yield: 211 mg (95%); $[\alpha]_D^{22}$: +10.1 (*c* 1.11, $CHCl_3$); IR ($CHCl_3$): $\nu=3393$, 3009, 2935, 2859, 1378, 1253, 1219, 1112, 1075, 923, 839, 759, 668 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): $\delta=0.12$ (s, 3H), 0.15 (s, 3H), 0.91 (s, 9H), 1.35 (s, 3H), 1.41 (s, 3H), 2.28 (dd, $J=14.0$, 8.2 Hz, 1H), 2.38 (dd, $J=14.0$, 6.3 Hz, 1H), 3.44 (d, $J=11.8$ Hz, 1H), 3.47 (s, 6H), 3.60 (d, $J=11.8$ Hz, 1H), 3.84 (d, $J=2.2$ Hz, 1H), 3.98 (dd, $J=7.1$, 2.0 Hz, 1H), 4.51 (d, $J=7.1$, Hz, 1H), 4.81 (s, 1H), 5.12 (m, 1H), 5.94 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta=-4.7$, -4.4, 18.2, 21.2, 25.9, 26.7, 41.7, 55.0, 56.3, 66.9, 71.7, 74.9, 75.3, 99.3, 105.1, 118.0, 132.9; MS (EI, 70 eV): $m/z=375$ (4), 317 (21), 301 (18), 243 (18), 211 (20), 183 (18), 141 (45), 131 (21), 89 (19), 75 (100), 73 (26), 59 (22); anal. calcd. for $C_{19}H_{38}O_6Si$ (390.24): C 58.45, H 9.74; found: C 58.57, H 10.03.

20b: According to GP 2 **9** (100 mg, 0.29 mmol) was reacted with MeLi (1.64 M in hexane, 0.23 mL, 0.37 mmol) and $CeCl_3 \cdot 7H_2O$ (139 mg, 0.37 mmol) to give **20b** as a colourless oil; yield: 106 mg (95%); $[\alpha]_D^{22}$: +3.5 (*c* 0.97, $CHCl_3$); IR ($CHCl_3$): $\nu=3474$, 2935, 2859, 1466, 1378, 1255, 1226, 1089, 1014, 939, 884, 839, 758 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): $\delta=0.12$ (s, 3H), 0.15 (s, 3H), 0.92 (2, 9H), 1.17 (s, 3H), 1.39 (s, 3H), 1.44 (s, 3H), 3.45 (s, 3H), 3.48 (s, 3H), 3.51 (d, $J=6.3$ Hz, 2H), 3.84 (d, $J=2.2$ Hz, 1H), 3.95 (dd, $J=7.0$, 2.2 Hz, 1H), 4.48 (d, $J=7.0$, Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta=-4.6$, -4.4, 18.2, 19.9, 23.6, 25.9, 27.9, 54.9, 56.4, 68.9, 70.0, 75.1, 75.8, 98.9, 105.1; MS (EI, 70 eV): $m/z=349$ (4), 275 (23), 217 (26), 201 (11), 185 (22), 159 (13), 157 (20), 143 (12), 115 (53), 89 (17), 75 (100), 73 (26), 59 (28), 57 (10); anal. calcd. for $C_{17}H_{36}O_6Si$ (346.23): C 56.01, H 9.95; found: C 55.90, H 9.94.

20c: According to GP 1 **9** (220 mg, 0.63 mmol) was reacted with EtMgBr (1.0 M in THF, 1.90 mL, 1.90 mmol) to give **20c** as a colourless oil; yield: 204 mg (87%); $[\alpha]_D^{22}$: -5.3 (*c* 0.99, $CHCl_3$); IR ($CHCl_3$): $\nu=3579$, 3475, 2934, 2858, 1467, 1376, 1254, 1228, 1202, 1082, 1008, 937, 886, 838, 780, 744, 669 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): $\delta=0.10$ (s, 3H), 0.13 (s, 3H), 0.92 (s, 9H), 0.93 (t, $J=7.7$ Hz, 3H), 1.36 (s, 3H), 1.41 (s, 3H), 1.59 (q, $J=7.7$ Hz, 2H), 3.47 (s, 6H), 3.50 (d, $J=11.8$ Hz, 1H), 3.60 (d, $J=11.8$ Hz, 1H), 3.84 (d, $J=2.0$ Hz, 1H), 3.96 (dd, $J=7.2$, 2.0 Hz, 1H), 4.49 (d, $J=7.2$, Hz, 1H), 4.68 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta=-4.8$, -4.4, 18.2, 20.9, 25.9, 26.0, 27.0, 29.5, 55.2, 56.4, 66.6, 71.7, 74.8, 76.0, 99.3, 105.4; MS (EI, 70 eV): $m/z=363$ (5), 289 (29), 257 (10), 231 (30), 215 (15), 199 (31), 173 (15), 171 (21), 157 (12), 147 (12), 131 (19), 129 (81), 89 (20), 75 (100), 73 (31), 59 (25), 57 (13); anal. calcd. for $C_{18}H_{38}O_6Si$ (378.24): C 57.13, H 10.12; found: C 57.63, H 10.09.

20d: According to GP 2 **9** (214 mg, 0.61 mmol) was reacted with *n*-BuLi (2.50 M in hexane, 0.32 mL, 0.80 mmol) and $CeCl_3 \cdot 7H_2O$ (300 mg, 0.80 mmol) to give **20d** as a colourless oil; yield: 185 mg (75%); $[\alpha]_D^{22}$: -5.7 (*c* 1.08, $CHCl_3$); IR ($CHCl_3$): $\nu=3476$, 3414, 2934, 2860, 1466, 1374, 1299, 1254, 1226, 1201, 1104, 1074, 1032, 1004, 975, 939, 887, 837, 800, 674 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): $\delta=0.11$ (s, 3H), 0.14 (s, 3H), 0.91 (s, 9H), 1.30–1.56 (complex, 9H), 1.36 (s, 3H), 1.41 (s, 3H), 3.47 (s, 6H), 3.51 (d, $J=11.5$ Hz, 1H), 3.60 (d, $J=11.5$ Hz, 1H), 3.84 (d, $J=2.0$ Hz, 1H), 3.97 (dd, $J=7.0$, 2.0 Hz, 1H), 4.47 (d, $J=7.0$, Hz, 1H), 4.68 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta=-4.7$, -4.3, 14.0, 18.2, 20.8, 23.5, 24.5, 25.8, 27.0, 36.9, 55.4, 56.3, 67.1, 71.4, 74.6, 76.3, 99.2, 105.3; MS (EI, 70 eV): $m/z=391$ (3), 317 (17), 259 (14), 243 (10), 201 (11), 199 (14), 185 (10), 157 (67), 131 (18), 129 (10), 89 (16), 75 (100), 73 (32), 59 (20); anal. calcd. for $C_{20}H_{42}O_6Si$ (406.28): C 59.07, H 10.91; found: C 58.68, H 10.47.

20e: According to GP 1 **9** (150 mg, 0.43 mmol) was reacted with vinylMgBr (1.0 M in diethyl ether, 1.72 mL, 1.72 mmol) to give **20e** as a colourless oil; yield: 35 mg (21%); $[\alpha]_D^{21}$: -5.5 (*c* 1.00, $CHCl_3$); IR ($CHCl_3$): $\nu=3471$, 3091, 2990, 2934, 2857, 2833, 2777, 2362, 2335, 1468, 1378, 1331, 1254, 1198, 1133, 1072, 1043, 1001, 932, 887, 838, 813, 781, 746, 669 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=0.09$ (s, 3H), 0.15 (s, 3H), 0.93 (s, 9H), 1.43 (s, 3H), 1.49 (s, 3H), 3.37 (d, $J=12.1$ Hz, 1H), 3.69 (dd, $J=12.1$, 1.7 Hz, 1H), 3.70 (s, 6H) 3.86 (dd, $J=7.7$, 1.8 Hz, 1H), 3.98 (d, $J=1.8$ Hz, 1H), 4.42 (d, $J=7.7$ Hz, 1H), 4.96 (d, $J=1.7$ Hz, 1H), 5.27 (dd, $J=10.4$, 2.5 Hz, 1H), 5.66 (dd, $J=17.1$, 2.2 Hz, 1H), 5.81 (dd, $J=17.1$, 10.4 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=-4.6$, 18.2, 18.9, 25., 28.9, 54.5, 56.4, 68.8, 71.8, 73.1, 76.6, 98.6, 104.8, 116.2, 139.3; MS (EI,

70 eV): $m/z = 360$ (6), 156 (10), 131 (31), 116 (10), 89 (14), 75 (100), 73 (12); anal. calcd. for $C_{18}H_{36}O_6Si$ (376.22): C 57.41, H 9.64; found: C 57.48, H 9.40.

20f: According to GP 2 **9** (268 mg, 0.77 mmol) was reacted with PhLi (1.70 M in THF, 0.59 mL, 1.00 mmol) and $CeCl_3 \cdot 7H_2O$ (375 mg, 1.00 mmol) to give **20f** as a colourless oil; yield: 138 mg (42%); $[\alpha]_D^{22}$: −8.2 (*c* 0.82, $CHCl_3$); IR ($CHCl_3$): $\nu = 3442$, 3064, 2991, 2935, 2858, 2755, 1600, 1493, 1469, 1378, 1321, 1255, 1200, 1130, 1090, 1006, 969, 935, 884, 838, 813, 757, 703, 665 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$): $\delta = 0.02$ (s, 3H), 0.03 (s, 3H), 0.93 (s, 9H), 1.55 (s, 3H), 1.61 (s, 3H), 2.96 (s, 3H), 3.27 (s, 3H), 3.57 (d, $J = 12.3$ Hz, 1H), 3.58 (d, $J = 7.9$ Hz, 1H), 3.72 (dd, $J = 7.9$, 1.5 Hz, 1H), 4.41 (d, $J = 1.2$ Hz, 1H), 5.72 (d, $J = 1.5$ Hz, 1H), 7.18–7.42 (complex, 3H), 7.62 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = -5.0$, −4.6, 18.2, 19.4, 25.9, 28.7, 55.5, 57.0, 70.9, 72.8, 74.7, 76.6, 98.9, 104.8, 126.2, 127.2, 128.1, 142.6; MS (EI, 70 eV): $m/z = 411$ (4), 337 (13), 305 (20), 279 (17), 263 (29), 247 (17), 219 (19), 189 (16), 188 (31), 177 (32), 173 (13), 147 (16), 131 (27), 120 (42), 105 (19), 91 (21), 89 (21), 75 (100), 59 (17); anal. calcd. for $C_{22}H_{36}O_6Si$ (426.24): C 61.94, H 8.98; found: C 62.33, H 9.40.

21: To a suspension of PPh_3CH_3Br (3.39 g, 9.47 mmol) in THF (50 mL) was added KO-*t*-Bu (1.0 M THF solution, 8.61 mL, 8.61 mmol) at 0 °C. After 1 hour the yellow suspension was cooled to −78 °C and ketone **9** (1.00 g, 2.87 mmol dissolved in 5 mL THF) was added dropwise and and the mixture allowed to warm to room temperature overnight. After addition of H_2O (20 mL) and diethyl ether (30 mL), the mixture was extracted with diethyl ether (3 × 25 mL). The organic layer was washed with brine (20 mL) and dried over $MgSO_4$. After evaporation under reduced pressure the crude product was purified by flash chromatography (SiO_2, *n*-pentane/diethyl ether = 6:1) affording **21** as a colourless oil; yield: 819 mg (83%); $[\alpha]_D^{23}$: −55.2 (*c* 1.04, $CHCl_3$); IR ($CHCl_3$): $\nu = 2988$, 2932, 2857, 1467, 1375, 1342, 1254, 1199, 1132, 1076, 1000, 916, 889, 837, 779, 735, 674 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$): $\delta = 0.09$ (s, 3H), 0.12 (s, 3H), 0.89 (s, 9H), 1.38 (s, 3H), 1.43 (s, 3H), 3.40 (s, 3H), 3.45 (s, 3H), 3.89 (dd, $J = 6.7$, 2.8 Hz, 1H), 4.09 (d, $J = 12.4$ Hz, 1H), 4.35 (d, $J = 12.4$ Hz, 1H), 4.39 (d, $J = 6.7$ Hz, 1H), 4.54 (complex, 1H), 4.99 (d, $J = 13.1$ Hz, 2H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = -4.6$, −4.4, 18.3, 23.7, 26.0, 27.8, 54.4, 55.8, 65.5, 70.9, 71.2, 99.6, 105.3, 109.1, 142.9; MS (EI, 70 eV): $m/z = 331$ (3), 231 (12), 219 (27), 199 (37), 185 (27), 143 (11), 131 (62), 127 (88), 116 (12), 89 (26), 75 (100), 73 (38), 69 (16); anal. calcd for $C_{17}H_{34}O_5Si$ (346.22): C 58.94, H 9.82; found: C 59.01, H 9.50.

22: To a solution of olefin **21** (200 mg, 0.58 mmol) in THF (4 mL) was added TBAF (366 mg, 1.16 mmol) at room temperature and and the mixture stirred until the reaction was finished (TLC control, 16 h). The reaction mixture was quenched with pH 7 buffer (3 mL) and extracted with diethyl ether (3 × 10 mL). The organic layer was washed with brine (7 mL) and dried over $MgSO_4$. The crude product was purified by flash chromatography (SiO_2, *n*-pentane/diethyl ether = 1:1) affording **22** as a colourless oil; yield: 121 mg (90%); $[\alpha]_D^{23}$: −87.7 (*c* 1.02, $CHCl_3$); IR ($CHCl_3$): $\nu = 3484$, 2988, 2937, 2839, 1657, 1455, 1376, 1218, 1132, 1075, 980, 912, 863, 750 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$): $\delta = 1.39$ (s, 3H), 1.44 (s, 3H), 2.69 (d, $J = 4.0$, 1H), 3.45 (s, 3H), 3.52 (s, 3H), 3.88 (ddd, $J = 5.9$, 4.0, 3.7 Hz, 1H), 4.22 (d, $J = 13.3$, 1H), 4.33 (ddd, $J = 13.3$, 1.4, 1.2 Hz, 1H), 4.45 (dd, $J = 5.9$, 1.2 Hz, 1*H*), 4.52 (d, $J = 3.7$ Hz, 1H), 4.02 (d, $J = 1.4$ Hz, 1H), 5.16 (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 22.6$, 27.8, 55.1, 56.1, 64.9, 72.2, 72.7, 99.4, 103.5, 109.3, 142.2; MS (EI, 70 eV): $m/z = 272$ (3), 127 (53), 75 (100), 69 (21), 59 (17); anal. calcd. for $C_{11}H_{20}O_5$ (232.1): C 56.90, H 8.62; found: C 56.62, H 8.76.

23: To a solution of olefin **21** (100 mg, 0.29 mmol) in dichloromethane (2 mL) was added *m*-CPBA (76 mg, 0.44 mmol) at 0 °C and warmed to room temperature. The reaction was stirred until the reaction was completed (TLC control, 48 h). The reaction mixture was quenched with saturated $NaHCO_3$ solution and extracted with diethyl ether (3 × 7 mL). The organic layer was washed with brine (5 mL) and dried over $MgSO_4$. After evaporation under reduce pressure the crude product was purified by flash chromatography (SiO_2, *n*-pentane/diethyl ether = 6:1) affording **23** as a colourless oil; yield: 93 mg (89%); $[\alpha]_D^{23}$: −21.7 (*c* 0.98, $CHCl_3$); IR ($CHCl_3$): $\nu = 2936$, 2858, 1467, 1378, 1330, 1225, 1153), 1082, 841, 779, 666 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$): $\delta = 0.07$ (s, 3H), 0.10 (s, 3H), 0.89 (s, 9H), 1.40 (s, 3H), 1.48 (s, 3H), 2.65 (dd, $J = 4.4$, 1.1 Hz, 1H), 3.42 (s, 3H), 3.43 (s, 3H), 3.45 (d, $J = 4.4$ Hz, 1H), 3.65 (d, $J = 12.3$ Hz, 1H), 3.71 (dd, $J = 8.0$, 1.9 Hz, 1H), 3.74 (d, $J = 12.3$ Hz, 1H), 4.12 (d, $J = 8.0$ Hz, 1H), 4.26 (complex, 1H); ^{13}C NMR (75 MHz, $CDCl_3$ $\delta = -4.9$, −4.6, 18.2, 21.6, 25.8, 26.2, 51.9, 55.6, 55.7, 56.3, 65.5, 69.8, 74.0, 99.8, 105.2; MS (EI, 70 eV): $m/z = 347$ (4), 215 (10), 143 (26), 131 (33), 89 (23), 85 (12), 75 (100), 73 (20), 59 (11); anal. calcd. for $C_{17}H_{34}O_6Si$ (362.21): C 56.32, H 9.45; found: C 56.44, H 9.32.

24: To a suspension of olefin **22** (40 mg, 0.17 mmol) and $NaHCO_3$ (44 mg, 0.52 mmol) in dichloromethane (4 mL) was added *m*-CPBA (60 mg, 0.34 mmol) at 0 °C and the mixture stirred until the reaction was finished (TLC control, 28 h). The reaction mixture was quenched with water (3 mL) and extracted with diethyl ether (3 × 7 mL). The organic layer was washed with brine (5 mL) and dried over $MgSO_4$. After evaporation under reduce pressure the crude product was purified by flash chromatography (SiO_2, ν-pentane/diethyl ether = 1:4) affording **24** as a colourless oil and inseparable mixture of epimers; yield: 42 mg (>99%); IR ($CHCl_3$): $\nu = 3502$, 2990, 2937, 2838, 1722, 1574, 1454, 1378, 1225, 1137, 1077, 980, 936, 899, 866, 754, 705, 673, 622 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$): major epimer: $\delta = 1.43$ (s, 3H), 1.53 (s, 3H), 2.70 (dd, $J = 4.1$, 0.8 Hz, 1H), 3.40 (d, $J = 4.1$ Hz, 1H), 3.48 (s, 3H), 3.50 (s, 3H), 3.68 (d, $J = 12.3$ Hz, 1H), 3.77 (dd, $J = 6.0$, 4.5 Hz, 1H), 3.92 (d, $J = 12.3$ Hz, 1H), 4.18 (d, $J = 6.0$ Hz, 1H), 4.48 (d, $J = 4.5$ Hz, 1H); minor epimer: $\delta = 1.45$ (s, 3H), 1.51 (s, 3H), 2.60 (d, $J = 4.7$, 1H), 3.36 (d, $J = 4.7$ Hz, 1H), 3.46 (s, 3H), 3.53 (s, 3H), 3.56 (d, $J = 12.6$ Hz, 1H), 3.81 (dd, $J = 8.3$, 1.9 Hz, 1H), 4.13 (d, $J = 12.6$ Hz, 1H), 4.31 (d, $J = 8.2$ Hz, 1H), 4.49 (d, $J = 1.9$ Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): major epimer: $\delta = 22.0$, 26.4, 50.0, 55.5, 55.8, 57.2, 64.9, 69.5, 71.7, 100.2, 103.0; minor epimer: $\delta = 20.3$, 27.5, 50.0, 55.5, 55.8, 57.2, 65.0, 69.0, 69.2, 99.4, 103.8; MS (EI, 70 eV): m/z: 233 (5), 143 (9), 75 (100); anal. calcd. for $C_{11}H_{20}O_6$ (248.13): C 53.22, H 8.06; found: C 53.47, H 7.98.

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