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Synthesis of *C*-glycosyl amino acids: scope and limitations of the tandem Tebbe/Claisen approach

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Abstract—Amino acids may be used as coupling partners for esterification with 3-hydroxy glycals as substrates for the tandem Tebbe/Claisen approach to the synthesis of *C*-glycosyl amino acids. Whilst esters of substituted α-amino acids do not successfully undergo Tebbe, or other, methylenation, esters of β- or γ-amino acids are methylenated to yield vinyl ethers, which then undergo smooth thermal rearrangement to yield β-*C*-glycoside products. *tert*-Butyl esters are found to be unreactive to the Tebbe reagent, and as such *tert*-butyl protection may be used for other carboxylic acids.

1. Introduction

Naturally occurring glycoproteins, glycopeptides and peptidoglycans constitute an enormously diverse array of biologically important molecules in which carbohydrates are covalently linked to amino acids via a variety of different linkages. For example, carbohydrates are covalently linked to *N*-linked and *O*-linked glycoproteins via direct glycosidic linkages between the anomeric position of either *N*-acetyl glucosamine or *N*-acetyl galactosamine residues, and asparagine or serine/threonine side chains, respectively.[1] In contrast the carbohydrate–amino acid linkages found in peptidoglycans, which constitute major components of bacterial cell walls, generally consist of ester linkages formed between amino acid and carbohydrate hydroxyls.[2]

Significant interest has recently arisen in the synthesis of *C*-glycosyl amino acids,[3,4] in which carbohydrate and amino acid are linked via a carbon–carbon bond at the anomeric centre of the sugar, particularly as potential building blocks for the synthesis of *C*-glycopeptides as non-hydrolysable *N*- or *O*-linked glycopeptide mimetics.[5] In principle the Tebbe/Claisen approach, which as recently reported allows stereospecific access to a range of *C*-glycoside materials,[6] could be advantageously applied to the synthesis of *C*-glycosyl amino acids. This tandem approach (Fig. 1) initially involves esterification of a glycal possessing a free 3-hydroxyl with a carboxylic acid. Tebbe methylenation[7] of the resultant ester can then be followed by [3,3] sigmatropic rearrangement[8,9] yielding the *C*-glycoside product in a predictable and entirely stereoselective fashion.

The attraction of this approach is that the α-carboxylic group of any proteinogenic α-amino acid, or the β- or γ-carboxylic groups of aspartic or glutamic acids may be used for the esterification step, thus implying ready access to a wide range of *C*-glycosyl amino acid materials. Herein full details of investigations into the applicability of the tandem Tebbe/Claisen approach for the synthesis

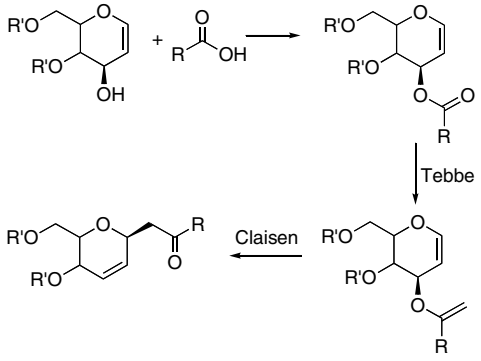

Figure 1.

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of *C*-glycosyl amino acids are provided, and delineated the scope and limitations of this methodology are given.

2. Results and discussion

2.1. Synthesis of ester substrates

The two glycals initially selected for esterification reactions were the easily accessible 4,6-*O*-di-*tert*-butylsilyl protected glucal and allal derivatives **1** and **2** (Fig. 2), which were readily accessed using published synthetic routes.[6] Previous studies had also revealed that Boc protection of nitrogen functionality was compatible with Tebbe/Claisen approach in so far as that *tert*-butyl carbamates were unreactive to the Tebbe reagent.[6] A variety of commercially available *N*-Boc protected amino acids **3a**–**e** were therefore selected as coupling partners. The D-serine derivative **3f**, which is the enantiomer of Garner's acid,[10] was accessed by base mediated hydrolysis of the corresponding known methyl ester.[11] A series of esterification reactions, mediated by dicyclohexylcarbodiimide (DCC) with catalytic dimethylamino pyridine (DMAP) in dichloromethane (DCM), then yielded the corresponding glucal (**4a**, **4b**,[6c] **4c**, **4d**, **4f**) and allal esters (**5b**, **5e**, **5f**) all in high yield (Fig. 2).

One particular aim of the programme was to investigate the effect of the length of the methylene linker between carboxylic acid and amino functions on the efficiency of the Tebbe reaction. Therefore the *N*-Boc protected β-amino and γ-amino acids **6** and **7** were also esterified with the glucal **1**, to yield the esters **8** and **9**[6c] as substrates for Tebbe methylenation (Scheme 1). Another aspect of the research programme was to investigate the feasibility the general approach using the side chain carboxylic acids of aspartic acid and glutamic acid. This strategy would require protection of the α-carboxylic acid in both cases, and it was reasoned that this could be possible by protection as the corresponding *tert*-butyl esters. In order to investigate the compatibility of *tert*-butyl ester protection with the Tebbe reaction glucal **1** was esterified with the carboxylic acid **10**, to yield the diester **11** (Scheme 1). Finally a variety of aspartic acid and glutamic acid side chain esters were also synthesised by reaction of the commercially available protected aspartic acid and glutamic acid derivatives **12** and **16** with silyl protected glucal **1**, and also with the sterically less encumbered 4,6-*O*-benzylidene protected glucal **14**,[12] to yield the esters **13**, **15** and **17** as substrates for subsequent methylenation reactions (Scheme 1).

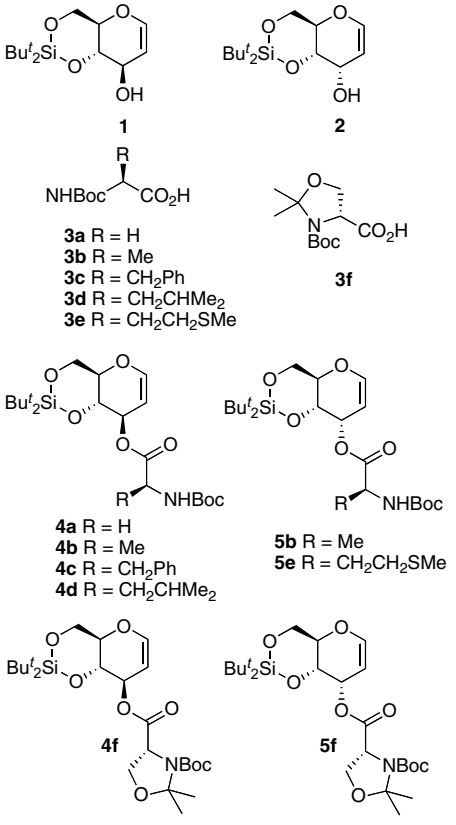
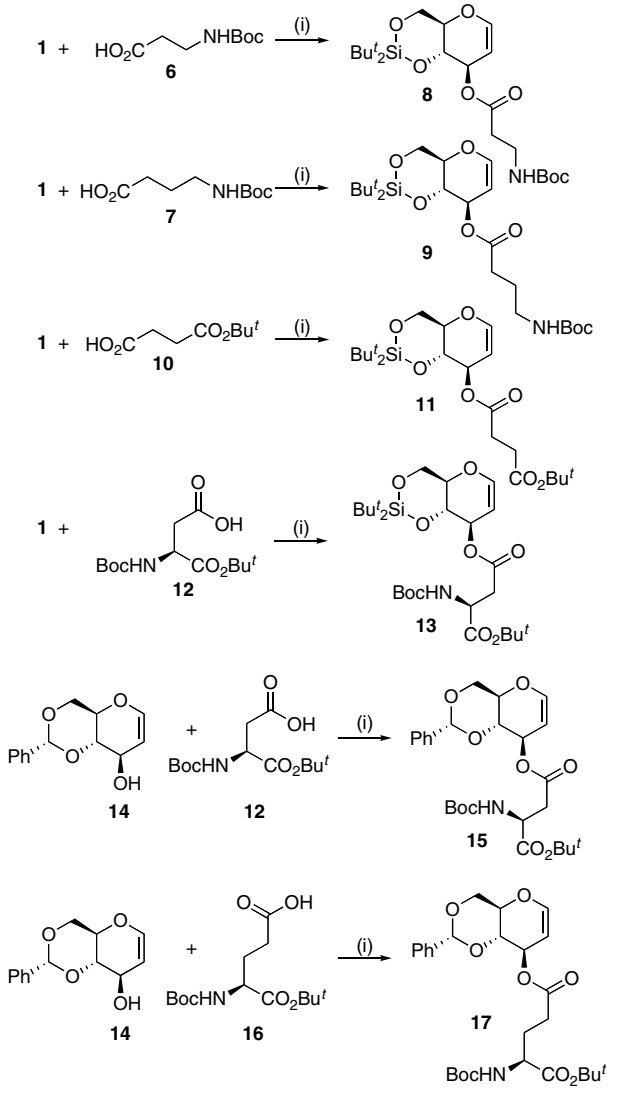


Figure 2.

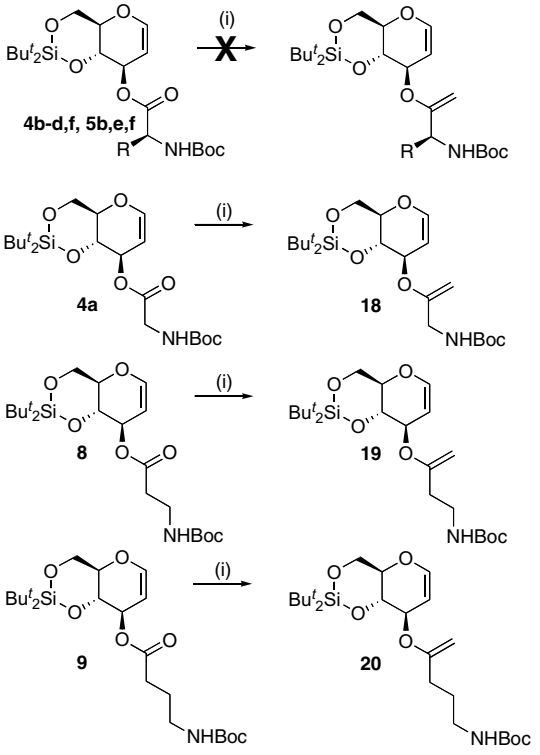


Scheme 1. Reagents and conditions: (i) DCC, DMAP, CH_2Cl_2, rt; **8**, 81%; **9**, 92%; **11**, 97%; **13**, 93%; **15**, 93%; **17**, 98%.

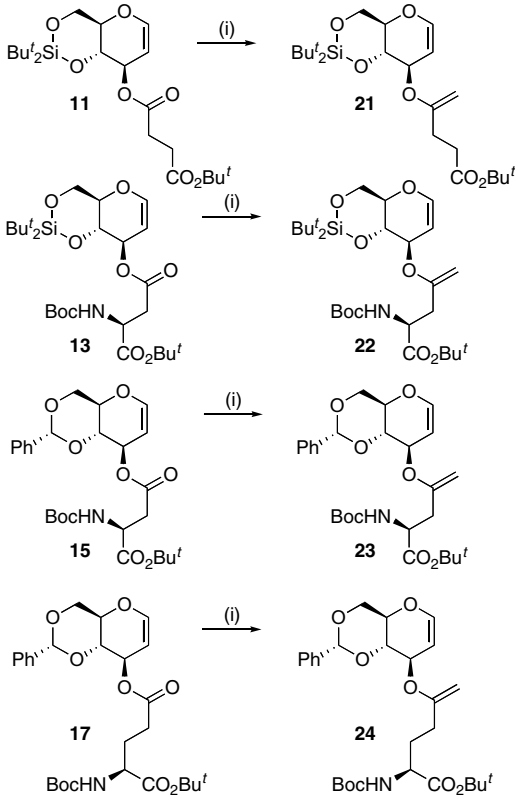
2.2. Methylenation reactions

Methylenation reactions by the Tebbe reagent were attempted on a wide selection of the esters derived from substituted α-amino acids (**4b–d,f**, **5b,e,f**). However in all cases the predominant product obtained was the glycal alcohol **1** or **2**, presumably formed by ester cleavage, rather than the desired methylenated product. In certain cases (e.g., reaction of **4b**) the methylenated product was observed, but never in more that 10% yield, making this route synthetically impractical. In light of these problems a variety of alternative reagents[13] were screened, but none were capable of methylenating any of these esters in reasonable yield.

In order to more precisely investigate the failure of these methylenation reactions, Tebbe reagent mediated methylenation was attempted on esters **4a**, **8** and **9**, all of which are derived from amino acids that are not substituted at the position α to the carbonyl, and which constitute a homologous series in which additional methylene units are incorporated between the ester and amino functional groups. In contrast to the esters derived from substituted α-amino acids successful methylenation was achieved in all three cases, yielding the desired enol ether products **18**, **19** and **20**[6c] in 44%, 80% and 82% yields, respectively (Scheme 2). It is clear from this result that increasing the number of methylene units between amine and ester from one to two or more improves the efficiency of Tebbe methylenation markedly.[14]



Scheme 2. Reagents and conditions: (i) Tebbe reagent, THF, pyridine, −40 °C to rt, 16 h; **18**, 44%; **19**, 80%; **20**, 82%.

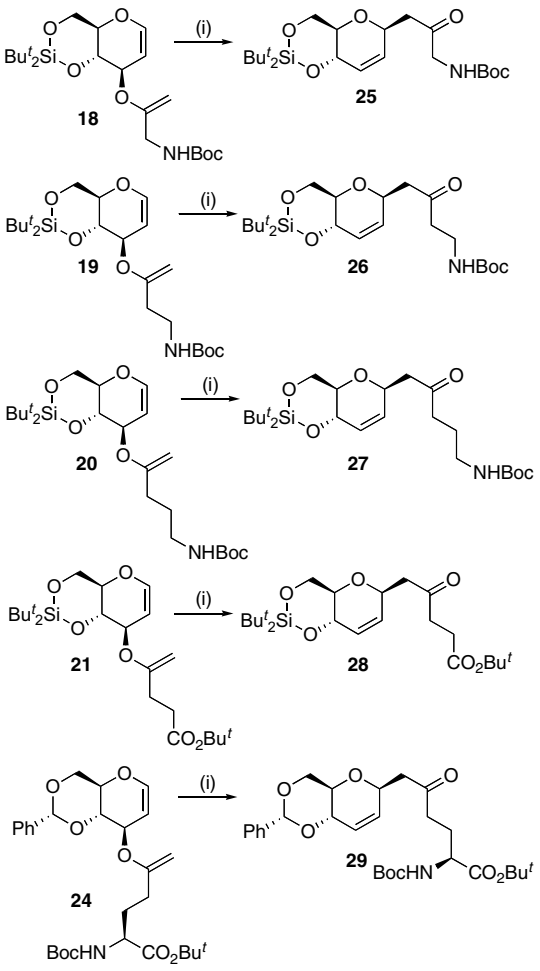


Scheme 3. Reagents and conditions: (i) Tebbe reagent, THF, pyridine, −40 °C to rt, 16 h; **21**, 83%; **22**, 6%; **23**, 22% (50% based on recovered starting material); **24**, 47%.

The lack of successful methylenation of esters derived from substituted α-amino acids indicated that the Tebbe/Claisen approach could probably only be usefully applied to esters derived from the side chains of aspartic and glutamic acids. Firstly in order to investigate if *tert*-butyl ester protection was indeed compatible with Tebbe reaction, methylenation of diester **11** was undertaken. Reaction occurred smoothly to yield the desired methylenated product **21** in 83% yield, and importantly no competitive reaction of the *tert*-butyl ester was observed (Scheme 3). Tebbe methylenation was then attempted on *tert*-butylsilyl protected aspartic acid ester **13**. Unfortunately the desired product **22** could only be isolated in extremely low yield (~6%) though in contrast to the studies on the α-amino acid esters the remainder of the mass balance was unreacted ester. It was reasoned that this lack of reactivity may be due to steric effects. Indeed when the less encumbered benzylidene protected aspartic acid ester **15** was reacted under identical conditions the methylenated product **23** was formed in an appreciably better, but still rather unsatisfactory yield (22%, 50% based on recovered starting material). However the corresponding benzylidene protected glutamic acid ester **17** did undergo satisfactory methylenation, to yield the desired product **24** (47% yield).

2.3. Claisen rearrangements

With a selection of methylenated substrates finally in hand Claisen rearrangement was undertaken (Scheme



Scheme 4. Reagents and conditions: (i) 180 °C, Bu_3N; **25**, 77%; **26**, 65%; **27**, 97%; **28**, 86%; **29**, 47%.

4). Vinyl ethers **18**, **19** and **20** all underwent smooth thermal reaction after heating to 180 °C in tributylamine, to yield the corresponding β-*C*-glycoside products **25**, **26** and **27**[6c] (77%, 65% and 77% yields, respectively, Scheme 4). Likewise vinyl ether **21** underwent rearrangement to yield the β-*C*-glycoside ester **28** in 86% yield. Finally the vinyl ether **24** derived from glutamic acid underwent successful rearrangement to yield the β-*C*-glycosyl glutamic acid derivative **29**, in a respectable 47% yield.

3. Conclusions

In conclusion it is clear that glycal esters derived from substituted α-amino acids do not undergo methylenation by the Tebbe, or other similar reagents. However glycal esters derived from β-, γ- or δ-amino acids are methylenated, though the efficiency of methylenation depends on the steric accessibility of the ester. Vinyl ethers derived from these glycal esters undergo smooth thermal Claisen rearrangement to yield a variety of *C*-glycosides in an entirely stereoselective manner. Unfortunately the limitations of the methylenation step currently mean that as far as the proteinogenic amino acids are concerned the tandem Tebbe/Claisen approach only allows the synthesis of *C*-glycosyl amino acids derived from the γ-acid of glutamic acid in reasonable yield. However *tert*-butyl esters have been demonstrated to be unreactive to the Tebbe regent, and *tert*-butyl protection allows selective methylenation of one ester in the presence of another, a process, which expands the scope of the Tebbe/Claisen approach. Further studies on the use of this tandem approach to *C*-glycoside synthesis are currently in progress, and the results will be reported in due course.

4. Experimental

4.1. General

Melting points were recorded on a Kofler hot block. Proton nuclear magnetic resonance (δ_H) spectra were recorded on Varian Gemini 200 (200 MHz), Bruker AC 200 (200 MHz), Bruker DPX 400 (400 MHz), Bruker AV 400 (400 MHz) or Bruker AMX 500 (500 MHz) spectrometers. Carbon nuclear magnetic resonance (δ_C) spectra were recorded on a Bruker DPX 400 (100.6 MHz) or a Bruker AMX 500 (125.75 MHz) spectrometer. Multiplicities were assigned using APT or DEPT sequence. All chemical shifts are quoted on the δ-scale. Infrared spectra were recorded on a Perkin–Elmer 150 Fourier transform spectrophotometer. Mass spectra were recorded on VG Micromass 30F, ZAB 1F, Masslab20–250, Micromass Platform 1 APCI or Trio-1 GCMS (DB-5 column) spectrometers, using desorption chemical ionisation (NH_3 DCI), electron impact (EI), electron spray ionisation (ESI), chemical ionisation (NH_3 CI), atmospheric pressure chemical ionisation (APCI) and fast atom bombardment (FAB) techniques as stated. Optical rotations were measured on a Perkin–Elmer 241 polarimeter with a path length of 1 dm. Concentrations are given in g/100 mL. Microanalyses were performed by the microanalytical services of the Inorganic Chemistry Laboratory, Oxford. Thin layer chromatography (TLC) was carried out on Merck glass backed sheets, pre-coated coated with $60F_{254}$ silica. Plates were developed using 0.2% w/v cerium (IV) sulfate and 5% ammonium molybdate in 2 M sulfuric acid. Flash chromatography was carried out using Sorbsil C60 40/60 silica. Solvents and available reagents were dried and purified before use according to standard procedures; dichloromethane (DCM) was distilled from calcium hydride immediately before use.

4.2. General procedure A: esterification

Glycal (1.0 equiv) and carboxylic acid (1.2–1.5 equiv) were dissolved in anhydrous DCM, and *N*,*N*′-dimethyl-4-amino pyridine (DMAP, 0.2 equiv) and then dicyclohexylcarbodiimide (DCC, 2.0 equiv) were added. The reaction mixture was stirred under an atmosphere of argon until TLC indicated the complete consumption of starting material. The reaction mixture was concentrated in vacuo, the residue taken up in ethyl acetate and the suspension filtered through Celite®. The solution was concentrated in vacuo, and the residue purified by flash column chromatography.

4.3. General procedure B: Tebbe methylenation

The enol ether (1.0 equiv) was dissolved in a 4:1 mixture of anhydrous THF and anhydrous pyridine and the solution cooled to −40 °C under an atmosphere of argon. Tebbe reagent (0.5 M in toluene, 2.0–4.0 equiv depending on age and quality) was added dropwise, and the reaction mixture allowed to warm to room temperature with stirring. After 16 h, when TLC indicated complete consumption of starting material, the reaction mixture was cooled to 0 °C and quenched by dropwise addition of sodium hydroxide (0.5 M aqueous solution) until effervescence ceased. The mixture was diluted with petrol, stirred for 30 min and sonicated for a further 10 min. The mixture was poured onto a short column of silica and eluted (petrol and ether with 2% triethylamine), concentrated in vacuo and purified by flash column chromatography (silica; petrol and ether with 2% triethylamine).

4.4. 2,2-Dimethyloxazolidine-(4*R*)-3,4-dicarboxylic acid 3-*tert*-butyl ester 3f

2,2-Dimethyloxazolidine-(4*R*)-3,4-dicarboxylic acid 3-*tert*-butyl ester 4-methyl ester[11] (2.75 g, 10.6 mmol) was dissolved in a mixture of THF (20 mL) and water (10 mL), and lithium hydroxide (713 mg, 17.0 mmol) was added. The mixture was stirred for 5 h 40 min, at which time TLC (petrol–ethyl acetate, 4:1) indicated the consumption of starting material (R_f 0.7) and the formation of a single product (R_f 0.4). The reaction mixture was concentrated in vacuo, dissolved in ethyl acetate (200 mL) and washed with sodium hydrogen sulfate (3 × 150 mL of a 1 M aqueous solution). The organic layer was extracted with sodium bicarbonate (4 × 150 mL), and the resulting aqueous layers neutralised with solid sodium hydrogen sulfate and extracted with ethyl acetate (5 × 150 mL). The organic layer was dried ($MgSO_4$), filtered and concentrated in vacuo. The resulting residue was recrystallised (petrol) to give carboxylic acid **3f** (2.58 g, 99%) as a white crystalline solid, mp 56–59 °C; $[\alpha]_D^{24} = +63.1$ (*c* 1.1, $CHCl_3$); ν_{max} (KBr disc) 2980 (br, OH), 1704 (s, acid), 1682 (s, amide) cm^{-1}; δ_H (500 MHz, $CDCl_3$, 363 K) 1.42 (9H, s, $C(CH_3)_3$), 1.45, 1.56 (6H, 2 × s, 2 × CH_3), 3.92–3.94 (1H, m, NHCHC*H*H′), 4.09–4.13 (1H, m, NHCHCH*H*′), 4.27–4.29 (1H, m, NHC*H*), 6.20 (1H, m, CO_2H); δ_C (125.7 MHz, $CDCl_3$, 363 K) 28.9 (q, 5 × CH_3), 60.4 (d, NHCH), 67.1 (t, NHCH*C*H_2), 79.9, 94.5 (2 × s, $(CH_3)_2$*C*ON, $(CH_3)_3$*C*), 152.1, 173.0 (2 × s, 2 × *C*=O); *m*/*z* (ES^-) 244 (M−H, 100%). (HRMS (ES^-) calcd for $C_{11}H_{18}NO_5$ (M−H) 244.1185. Found 244.1184).

4.5. 3-*O*-(*N*-*tert*-Butoxycarbonyl-2′-amino-ethanoyl)-4,6-*O*-di-*tert*-butylsilyldiyl-D-glucal 4a

General procedure A: glucal **1** (R_f 0.55 (petrol–ethyl acetate, 4:1), 278 mg, 0.97 mmol), *N*-*tert*-butoxycarbonyl-L-glycine **3a** (221 mg, 1.3 mmol), *N*,*N*′-dimethyl-4-amino pyridine (24 mg, 0.19 mmol), dicyclohexylcarbodiimide (400 mg, 1.94 mmol) in DCM (5 mL) gave ester **4a** (435 mg, quant.) as a colourless oil; (R_f 0.6); $[\alpha]_D^{19} = -53.4$ (*c* 0.9, $CHCl_3$); ν_{max} (thin film) 3558 (br, NH), 1740 (s, ester), 1722 (s, amide I), 1647 (m, C=C–O), 1515 (m, amide II) cm^{-1}; δ_H (400 MHz, $CDCl_3$) 0.98, 1.05 (18H, 2 × s, 2 × $SiC(CH_3)_3$), 1.46 (9H, s, $OC(CH_3)_3$), 3.88–3.93 (1H, m, H-5), 3.93–4.01 (3H, m, H-6, $C(O)CH_2$), 4.10–4.18 (1H, m, H-4), 4.17–4.21 (1H, m, H-6′), 4.73 (1H, dd, $J_{1,2}$ 6.0 Hz, $J_{2,3}$ 1.8 Hz, H-2), 5.04 (1H, br s, NH), 5.42–5.49 (1H, m, H-3), 6.33 (1H, dd, $J_{1,3}$ 1.5 Hz, H-1); δ_C (100.6 MHz, $CDCl_3$) 19.8, 22.7 (2 × s, 3 × $C(CH_3)_3$), 26.8, 27.4, 28.3 (3 × q, 3 × $C(CH_3)_3$), 42.5 (t, $NHCH_2$), 65.7 (t, C-6), 72.8, 73.3, 73.5 (3 × d, C-3, C-4, C-5), 100.0 (d, C-2), 145.4 (d, C-1), 155.5, 170.3 (2 × s, 2 × C=O); *m*/*z* (ES^+) 444 (5, $M+H^+$), 461 (18, $M+NH_4^+$), 466 (100%, $M+Na^+$). (HRMS (ES^+) calcd for $C_{21}H_{37}NO_7SiNa$ ($M+Na^+$) 466.2237. Found, 466.2237).

4.6. 3-*O*-(*N*-*tert*-Butoxycarbonyl-L-phenylalanine)-4,6-*O*-di-*tert*-butylsilanediyl-D-glucal 4c

General procedure A: glucal **1** (R_f 0.5 (petrol–ethyl acetate, 4:1), 557 mg, 1.94 mmol), *N*-*tert*-butoxycarbonyl-L-phenylalanine **3c** (640 mg, 2.53 mmol), *N*,*N*′-dimethyl-4-amino pyridine (47 mg, 0.39 mmol) and dicyclohexylcarbodiimide (802 mg, 3.89 mmol) in DCM (20 mL) gave ester **4c** (1.14 g, quant.) as a white foam; (R_f 0.7); $[\alpha]_D^{24} = -51.3$ (*c* 0.8, $CHCl_3$); ν_{max} (thin film) 3385 (br, NH), 1718 (s, ester/amide I), 1648 (m, C=C–O), 1498 (m, amide II); δ_H (400 MHz, $CDCl_3$) 0.99, 1.07 (18H, 2 × s, 2 × $SiC(CH_3)_3$), 1.43 (9H, s, $OC(CH_3)_3$), 3.05–3.17 (2H, m, $PhCH_2$), 3.88–4.02 (2H, m, H-5, H-6), 4.16–4.22 (2H, m, H-4, H-6′), 4.63–4.67 (2H, m, H-2, CH_2CH), 5.03 (1H, d, $J_{NH,CH}$ 7.6 Hz, NH), 5.37–5.39 (1H, m, H-3), 6.33 (1H, dd, $J_{1,2}$ 6.4 Hz, $J_{1,3}$ 1.4 Hz, H-1), 7.17–7.30 (5H, m, 5 × Ar-H); δ_C (100.6 MHz, $CDCl_3$) 19.8, 19.8, 22.7 (3 × s, 3 × $C(CH_3)_3$), 26.8, 27.4, 28.3 (3 × q, 3 × $C(CH_3)_3$), 38.4 (t, $PhCH_2$), 54.6 (d, $PhCH_2CH$), 65.7 (t, C-6), 72.9, 73.5, 76.7 (3 × d, C-3, C-4, C-5), 99.9 (d, C-2), 127.0, 128.4, 129.5 (3 × d, 5 × Ar-C), 135.9 (s, Ar-C), 145.3 (d, C-1), 155.0 (s, CHC=O), 171.6 (s, OC(O)N); *m*/*z* (ES^+) 592 ($M+NH_4^+$+MeCN, 100), 556 ($M+Na^+$, 40), 551 ($M+NH_4^+$, 55), 534 ($M+H^+$, 90%). (HRMS (ES^+) calcd for $C_{28}H_{47}O_7N_2Si$ ($M+NH_4^+$) 551.3153. Found 551.3149). (Found: C, 59.20; H, 9.10; N, 2.99. $C_{28}H_{43}O_7NSi$ requires C, 59.35; H, 8.92; N, 2.88).

4.7. 3-*O*-(*N*-*tert*-Butoxycarbonyl-L-leucine)-4,6-*O*-di-*tert*-butylsilanediyl-D-glucal 4d

General procedure A: glucal **1** (R_f 0.5 (petrol–ethyl acetate, 4:1), 204 mg, 0.71 mmol), *N*-*tert*-butoxycarbonyl-L-leucine **3d** (201 mg, 0.93 mmol), *N*,*N*′-dimethyl-4-amino pyridine (17 mg, 0.14 mmol) and dicyclohexylcarbodiimide (293 mg, 1.42 mmol) in DCM (20 mL) gave ester **4d** (375 mg, quant.) as a white foam; (R_f 0.6); $[\alpha]_D^{24} = -61.8$ (*c* 1.1, $CHCl_3$); ν_{max} (thin film) 3378 (br, NH), 1748 (s, ester), 1719 (s, amide I), 1648 (m, C=C–O), 1502 (m, amide II); δ_H (400 MHz, $CDCl_3$) 0.95 (3H, d, $J_{CH_3,CH}$ 6.6 Hz, CH_3), 0.95 (3H, d, $J_{CH_3',CH}$ 6.6 Hz, CH_3'), 0.98, 1.06 (18H, 2 × s, 2 × $SiC(CH_3)_3$) 1.44 (9H, s, $OC(CH_3)_3$), 1.48–1.55 (1H, m, NHCHC*H*H′), 1.60–1.66 (1H, m, NHCHCH*H*′), 1.70–

1.76 (1H, m, $(CH_3)_2CH$), 3.92–4.02 (2H, m, H-5, H-6), 4.10–4.21 (2H, m, H-4, H-6′), 4.35–4.40 (1H, m, NHC*H*), 4.37 (1H, dd, $J_{1,2}$ 6.0 Hz, $J_{2,3}$ 2.1 Hz, H-2), 4.90 (1H, d, $J_{NH,CH}$ 8.4 Hz, NH), 5.43–5.45 (1H, m, H-3), 6.32 (1H, dd, $J_{1,3}$ 1.2 Hz, H-1); δ_C (100.6 MHz, $CDCl_3$) 19.8, 22.6, 22.7 (3 × s, 3 × $C(CH_3)_3$), 22.1, 24.7, (2 × q, 2 × CH_3), 24.9 (d, $(CH_3)_2CHCH_2$), 26.8, 27.3, 28.3 (3 × q, 3 × $C(CH_3)_3$), 41.9 (t, $(CH_3)_2CHCH_2$), 52.4 (d, NHC*H*), 65.6 (t, C-6), 72.8, 72.9, 73.5 (3 × d, C-3, C-4, C-5), 100.1 (d, C-2), 145.2 (d, C-1), 155.2 (s, CHC(O)O), 172.8 (s, NC(O)O); *m/z* (ES^+) 558 ($M+NH_4^+$+MeCN, 100), 522 ($M+Na^+$, 25), 517($M+NH_4^+$, 25), 500 ($M+H^+$, 52%). (HRMS (ES^+) calcd for $C_{25}H_{46}O_7NSi$ ($M+H^+$) 500.3043. Found 500.3043). (Found: C, 59.20; H, 910; N, 2.99. $C_{25}H_{45}O_7NSi$ requires C, 59.35; H, 8.92; N, 2.88).

4.8. 2,2-Dimethyloxazolidine-(4*R*)-3,4-dicarboxylic acid 3-*tert*-butyl ester 4-(4,6-*O*-di-*tert*-butyl-silanediyl-3-*O*-yl-D-glucal) ester 4f

General procedure A: glucal **1** (R_f 0.45 (petrol–ethyl acetate, 4:1), 250.5 mg, 0.875 mmol), 2,2-dimethyloxazolidine-(4*R*)-3,4-dicarboxylic acid 3-*tert*-butyl ester **3f** (279 mg, 1.14 mmol), *N*,*N*′-dimethyl-4-amino pyridine (21 mg 0.18 mmol) and dicyclohexylcarbodiimide (361 mg, 1.75 mmol) in DCM (10 mL) gave ester **4f** (447 mg, 99%) as a colourless oil; (R_f 0.5); mixture of rotamers: major:minor, 1.6:1; $[\alpha]_D^{21} = -6.1$ (*c* 0.9, $CHCl_3$); ν_{max} (thin film) 1765 (s, ester), 1713 (s, amide), 1646 (w, C=C); δ_H (400 MHz, $CDCl_3$) major rotamer: 0.98, 1.05 (18H, 2 × s, 2 × $SiC(CH_3)_3$), 1.43, 1.50 (9H, 2 × s, $OC(CH_3)_3$), 1.55–1.69 (6H, m, $ONC(CH_3)_2$), 3.91–4.54 (7H, m, H-4, H-5, H-6, H-6′, CH_2CHCO_2, CH_2CHCO_2), 4.72 (1H, dd, $J_{1,2}$ 6.1 Hz, $J_{2,3}$ 2.0 Hz, H-2), 5.45–5.48 (1H, m, H-3), 6.34 (1H, dd, $J_{1,3}$ 1.5 Hz, H-1); minor rotamer: 0.98, 1.05 (18H, 2 × s, 2 × $SiC(CH_3)_3$), 1.43, 1.50 (9H, 2 × s, $OC(CH_3)_3$), 1.55–1.69 (6H, m, $ONC(CH_3)_2$), 3.91–4.54 (7H, m, H-4, H-5, H-6, H-6′, CH_2CHCO_2, CH_2CHCO_2), 4.77 (1H, dd, $J_{1,2}$ 6.1 Hz, $J_{2,3}$ 1.9 Hz, H-2), 5.55–5.57 (1H, m, H-3), 6.31 (1H, dd, $J_{1,3}$ 1.6 Hz, H-1); δ_C (100.6 MHz, $CDCl_3$) major rotamer: 19.8 (s, 2 × $SiC(CH_3)_3$), 22.7 (s, $OC(CH_3)_3$), 24.4, 25.0 (2 × q, $ONC(CH_3)_2$), 26.8, 27.3, 28.4 (3 × q, 3 × $C(CH_3)_3$), 59.3, 72.9, 73.4, 73.7 (4 × d, C-3, C-4, C-5, $CHCO_2$), 65.6, 66.3 (2 × t, C-6, CH_2CHCO_2), 80.3, 95.1 (2 × s, $ONC(CH_3)_2$, $(CH_3)_2C$), 100.0 (d, C-2), 145.3 (d, C-1), 151.2 (s, CHC=O), 171.0 (s, NC=O); minor rotamer: 19.8 (s, 2 × $SiC(CH_3)_3$), 22.7 (s, $OC(CH_3)_3$), 25.2, 26.0 (2 × q, $ONC(CH_3)_2$), 26.8, 27.3, 28.4 (3 × q, 3 × $C(CH_3)_3$), 60.4, 72.6, 72.8, 74.0 (4 × d, C-3, C-4, C-5, $CHCO_2$), 65.6, 66.1 (2 × t, C-6, CH_2CHCO_2), 80.8, 84.5 (2 × s, $ONC(CH_3)_2$, $(CH_3)_2C$), 100.3 (d, C-2), 145.0 (d, C-1), 151.2 (s, CHC=O), 170.5 (s, NC=O); *m/z* (ES^+) 536 ($M+Na^+$, 100), 514 ($M+H^+$, 20%). (HRMS (ES^+) calcd for $C_{25}H_{43}O_8NSiNa$ ($M+Na^+$) 536.2656. Found 536.2651).

4.9. 3-*O*-(*N*-*tert*-Butoxycarbonyl-L-alanine)-4,6-*O*-di-*tert*-butylsilanediyl-D-allal 5b

General procedure A: allal **2** (R_f 0.4 (petrol–ethyl acetate, 4:1), 688 mg, 2.33 mmol), *N*-*tert*-butoxycarbonyl-L-alanine **3b** (574 mg, 3.03 mmol), *N*,*N*′-dimethyl-4-amino pyridine (59 mg, 0.48 mmol) and dicyclohexylcarbodiimide (962 mg, 4.66 mmol) in DCM (20 mL) gave ester **5b** (1.11 g, quant.) as a colourless oil; (R_f 0.5); $[\alpha]_D^{21} = +150$ (*c* 1.1, $CHCl_3$); ν_{max} (thin film) 3378 (br, NH), 1719 (sh, ester, amide I), 1642 (m, C=C–O), 1510 (m, amide II) cm^{-1}; δ_H (400 MHz, $CDCl_3$) 1.02, 1.06 (18H, 2 × s, 2 × $SiC(CH_3)_3$), 1.42 (3H, d, $J_{CH_3,CH}$ 7.1 Hz, $CHCH_3$), 1.44 (9H, s, $OC(CH_3)_3$), 3.96 (1H, at, *J* 10.2 Hz, H-6), 4.08–4.21 (1H, m, H-5), 4.22–4.30 (2H, m, H-4, H-6′), 4.31–4.35 (1H, m, CH_3CH), 5.05 (1H, at, *J* 5.9 Hz, H-2), 5.11 (1H, d, $J_{NH,CH}$ 7.1 Hz, NH), 5.16 (1H, dd, $J_{2,3}$ 6.0 Hz, $J_{3,4}$ 3.9 Hz, H-3), 6.39 (1H, d, $J_{1,2}$ 5.9 Hz, H-1); δ_C (100.6 MHz, $CDCl_3$), 19.2 (q, CH_3CH), 20.1, 22.8 (2 × s, 2 × $SiC(CH_3)_3$), 26.9, 27.5 (2 × q, 2 × $SiC(CH_3)_3$), 27.4 (s, $OC(CH_3)_3$), 28.3 (q, $OC(CH_3)_3$), 49.4 (d, CH_3CH), 66.1 (t, C-6), 66.3 (d, C-3), 68.7 (d, C-5), 72.3 (d, C-4), 97.8 (d, C-2), 146.9 (d, C-1), 154.9 (s, CHC=O), 173.1 (s, NHC=O); *m/z* (ES^+) 480 ($M+Na^+$, 100%). (HRMS (ES^+) calcd for $C_{22}H_{39}O_7NSiNa$ ($M+Na^+$) 480.2394. Found 480.2397).

4.10. 3-*O*-(*N*-*tert*-Butoxycarbonyl-L-methionine)-4,6-*O*-di-*tert*-butylsilanediyl-D-allal 5e

General procedure A: allal **2** (R_f 0.4 (petrol–ethyl acetate, 4:1), 329 mg, 1.15 mmol), *N*-*tert*-butoxycarbonyl-L-methionine **3e** (372 mg, 1.49 mmol), *N*,*N*′-dimethyl-4-amino pyridine (28 mg 0.23 mmol) and dicyclohexylcarbodiimide (473 mg, 2.29 mmol) in DCM (15 mL) gave ester **5e** (476 mg, 80%) as a colourless oil; (R_f 0.4); mixture of rotamers: major:minor, 7:2; $[\alpha]_D^{21} = +191$ (*c* 1.0, $CHCl_3$); ν_{max} (thin film) 3370 (br, NH), 1716 (sh, ester, amide I), 1642 (m, C=C–O), 1501 (m, amide II) cm^{-1}; δ_H (400 MHz, $CDCl_3$) major rotamer: 1.03, 1.06 (18H, 2 × s, 2 × $SiC(CH_3)_3$), 1.45 (9H, s, $OC(CH_3)_3$), 1.88–1.97 (1H, m, SCH_2CHH'), 2.09 (3H, s, SCH_3), 2.13–2.24 (1H, m, SCH_2CHH'), 2.48–2.59 (2H, m, CH_3SCHH', CH_3SCHH'), 3.94–4.00 (1H, m, H-6), 4.04–4.15 (1H, m, H-5), 4.20–4.24 (1H, m, H-4), 4.23–4.30 (1H, m, H-6′), 4.37–4.45 (1H, m, NHC*H*), 5.05 (1H, at, *J* 6.1 Hz, H-2), 5.12–5.17 (1H, m, NH), 5.16–5.20 (1H, m, H-3), 6.40 (1H, d, *J* 5.9 Hz, H-1); minor rotamer: 1.03, 1.06 (18H, 2 × s, 2 × $SiC(CH_3)_3$), 1.45 (9H, s, $OC(CH_3)_3$), 1.88–1.97 (1H, m, SCH_2CHH'), 2.09 (3H, s, SCH_3), 2.13–2.24 (1H, m, SCH_2CHH'), 2.48–2.59 (2H, m, CH_3SCHH', CH_3SCHH'), 3.94–4.00 (1H, m, H-6), 4.04–4.15 (1H, m, H-5), 4.20–4.24 (1H, m, H-4), 4.23–4.30 (1H, m, H-6′), 4.37–4.45 (1H, m, NHC*H*), 4.98 (1H, at, *J* 5.9 Hz, H-2), 5.12–5.17 (1H, m, NH), 5.29–5.32 (1H, m, H-3), 6.43 (1H, d, *J* 6.0 Hz, H-1); δ_C (100.6 MHz, $CDCl_3$) 15.7 (q, SCH_3), 20.1, 22.8, 22.8 (3 × s, 3 × $C(CH_3)_3$), 26.9, 27.5, 28.3 (3 × q, 3 × $C(CH_3)_3$), 30.1, 32.8 (2 × t, SCH_2CH_2, SCH_2CH_2), 53.1 (d, CH_2CH), 66.5 (d, C-3), 66.1 (t, C-6), 68.7 (d, C-5), 72.3 (d, C-4), 97.7 (d, C-2), 147.0 (d, C-1), 178.2 (s, CHC=O); minor rotamer: 15.7 (q, SCH_3), 20.1, 22.8, 22.8 (3 × s, 3 × $C(CH_3)_3$), 26.9, 27.5, 28.3 (3 × q, 3 × $C(CH_3)_3$), 29.8, 32.7 (2 × t, SCH_2CH_2, SCH_2CH_2), 52.9 (d, CH_2CH), 65.7 (d, C-3), 66.0 (t, C-6), 68.9 (d, C-5), 72.4 (d, C-4), 97.5 (d, C-2), 147.4 (d, C-1), 171.9 (s, CHC=O); *m/z* (ES^+) 540

(M+Na$^+$, 100%), 518 (M+H$^+$, 95%). (HRMS (ES$^+$) calcd for $C_{24}H_{43}O_7NSSiNa$ (M+Na$^+$) 540.2427. Found 540.2419).

4.11. 2,2-Dimethyloxazolidine-(4*R*)-3,4-dicarboxylic acid 3-*tert*-butyl ester 4-(4,6-*O*-di-*tert*-butylsilanediyl-3-O-yl-D-allal) ester 5f

General procedure A: allal **2** (R_f 0.4 (petrol–ethyl acetate, 4:1), 207 mg, 0.91 mmol), 2,2-dimethyloxazolidine-(4*R*)-3,4-dicarboxylic acid 3-*tert*-butyl ester **3f** (290 mg, 1.18 mmol), *N*,*N*′-dimethyl-4-amino pyridine (22 mg 0.18 mmol) and dicyclohexylcarbodiimide (376 mg, 1.82 mmol) in DCM (10 mL) gave ester **5f** (367 mg, 79%) as a colourless oil; (R_f 0.5); mixture of rotamers: major:minor, 1.9:1; $[\alpha]_D^{21} = +190$ (*c* 1.0, $CHCl_3$); ν_{max} (thin film) 1755 (s, ester), 1712 (s, amide), 1641 (w, C=C–O); δ_H (400 MHz, $CDCl_3$) major rotamer: 1.02, 1.05 (18H, 2 × SiC(CH$_3$)$_3$), 1.42 (9H, s, OC(CH$_3$)$_3$), 1.55, 1.69 (6H, 2 × s, ONC(CH$_3$)$_2$), 3.94–4.53 (7H, m, H-4, H-5, H-6, H-6′, C*H*$_2$CHCO$_2$, CH$_2$C*H*CO$_2$), 5.07–5.20 (2H, m, H-2, H-3), 6.38–6.41 (1H, m, H-1); minor rotamer: 1.03, 1.04 (18H, 2 × SiC(CH$_3$)$_3$), 1.51 (9H, s, OC(CH$_3$)$_3$), 1.64, 1.67 (6H, 2 × s, ONC(CH$_3$)$_2$), 3.94–4.53 (7H, m, H-4, H-5, H-6, H-6′, C*H*$_2$CHCO$_2$, CH$_2$C*H*CO$_2$), 5.07–5.20 (2H, m, H-2, H-3), 6.38–6.41 (1H, m, H-1); major rotamer: δ_C (100.6 MHz, $CDCl_3$) 20.2, 20.3, 22.7 (3 × s, 3 × *C*(CH$_3$)$_3$), 24.4, 25.1 (2 × q, 2 × ONC(*C*H$_3$)$_2$), 27.0, 27.2, 28.3 (3 × q, 3 × C(*C*H$_3$)$_3$), 59.0, 66.3, 69.0, 72.4, (4 × d, C-3, C-4, C-5, CH$_2$*C*HCO$_2$), 65.8, 65.9 (2 × t, C-6, *C*H$_2$CHCO$_2$), 80.4, 95.1 (2 × s, ONC(*C*H$_3$)$_2$), 98.0 (d, C-2), 147.0 (d, C-1), 151.4 (s, CH*C*=O), 170.2 (s, NHC=O); minor rotamer: 20.5, 20.9, 22.7 (3 × s, 3 × *C*(CH$_3$)$_3$), 26.3, 26.7 (2 × q, 2 × ONC(*C*H$_3$)$_2$), 26.9, 27.4, 28.4 (3 × q, 3 × C(*C*H$_3$)$_3$), 59.2, 66.5, 69.0, 72.5 (4 × d, C-3, C-4, C-5, CH$_2$*C*HCO$_2$), 65.7, 65.9 (2 × t, C-6, *C*H$_2$CHCO$_2$), 80.7, 94.4 (2 × s, ONC(*C*H$_3$)$_2$), 98.1 (d, C-2), 147.0 (d, C-1), 151.4 (s, CH*C*=O), 169.7 (s, NHC=O); *m*/*z* (ES$^+$) 536 (M+Na$^+$, 100%). (HRMS (ES$^+$) calcd for $C_{25}H_{43}O_8NSiNa$ (M+Na$^+$) 536.2656. Found 536.2657).

4.12. 3-*O*-(*N*-*tert*-Butoxycarbonyl-3-amino-propanoyl)-4,6-*O*-di-*tert*-butylsilanediyl-D-glucal 8

General procedure A: glucal **1** (R_f 0.6 (petrol–ethyl acetate, 4:1), 235 mg, 0.82 mmol), *N*-β-*tert*-butoxycarbonyl-β-L-alanine **6** (201 mg, 1.06 mmol), *N*,*N*′-dimethyl-4-amino pyridine (20 mg, 0.16 mmol), dicyclohexylcarbodiimide (337 mg, 1.6 mmol) in DCM (5 mL) gave ester **8** (301 mg, 81%) as a colourless oil; (R_f 0.7); $[\alpha]_D^{19} = -48.7$ (*c* 0.8, $CHCl_3$); ν_{max} (thin film) 3460 (br, NH), 1734 (s, ester), 1721 (s, amide I), 1649 (w, C=CO), 1502 (w, amide II) cm^{-1}; δ_H (400 MHz, $CDCl_3$) 0.98, 1.05 (18H, 2 × s, 2 × SiC(CH$_3$)$_3$), 1.42 (9H, s, OC(CH$_3$)$_3$), 2.57 (2H, at, *J* 6.1 Hz, C(O)CH$_2$), 3.35–3.44 (2H, m, NHC*H*$_2$), 3.88–3.95 (1H, m, H-5), 3.94–4.10 (1H, m, H-6), 4.13–4.17 (1H, m, H-4), 4.17–4.20 (1H, m, H-6′), 4.71 (1H, dd, $J_{1,2}$ 6.1 Hz, $J_{2,3}$ 2.0 Hz, H-2), 5.01 (1H, br s, NH), 5.40–5.42 (1H, m, H-3), 6.32 (1H, dd, $J_{1,3}$ 1.9 Hz, H-1); δ_C (100.6 MHz, $CDCl_3$) 19.8, 22.7 (2 × s, 3 × *C*(CH$_3$)$_3$), 26.8, 27.4, 28.4 (3 × q, 3 × C(*C*H$_3$)$_3$), 35.0, 36.2 (2 × t, NHCH$_2$, NHCH$_2$*C*H$_2$), 65.6 (t, C-6), 72.4 (d, C-3), 72.9 (d, C-5), 73.6 (d, C-4), 100.3 (d, C-2), 145.1 (d, C-1), 155.8, 172.3 (2 × s, 2 × C=O); *m*/*z* (ES$^+$) 480 (100, M+Na$^+$). (HRMS (ES$^+$) calcd for $C_{22}H_{39}O_7NSiNa$ (M+Na$^+$) 480.2394. Found, 480.2393).

4.13. 3-*O*-(4′-*tert*-Butoxysuccinoyl)-4,6-*O*-di-*tert*-butylsilanediyl-D-glucal 11

General procedure A: glucal **1** (R_f 0.5 (petrol–ethyl acetate, 4:1), 277 mg, 0.97 mmol), 4-*tert*-butoxysuccinic acid **10** (252 mg, 1.45 mmol), *N*,*N*′-dimethyl-4-amino pyridine (24 mg, 0.19 mmol), dicyclohexylcarbodiimide (398 mg, 1.9 mmol) in DCM (10 mL) gave ester **11** (419 mg, 97%) as a colourless oil; (R_f 0.7); $[\alpha]_D^{25} = -61.1$ (*c* 1.0, $CHCl_3$); ν_{max} (thin film) 1734 (s, C=O), 1647 (w, C=C–O) cm^{-1}; δ_H (400 MHz, $CDCl_3$) 0.97, 1.05 (18H, 2 × s, 2 × SiC(CH$_3$)$_3$), 1.44 (9H, s, OC(CH$_3$)$_3$), 2.53–2.57, 2.61–2.65 (4H, m, (H$_3$C)$_3$OC(O)C*H*$_2$, (H$_3$C)$_3$OC(O)CH$_2$C*H*$_2$), 3.89–4.00 (2H, m, H-5, H-6), 4.13–4.20 (2H, m, H-4, H-6′), 4.71 (1H, dd, $J_{1,2}$ 6.1 Hz, $J_{2,3}$ 2.1 Hz, H-2), 5.38 (1H, dat, *J* 2.0, 3.7, 3.7 Hz, H-3), 6.30 (1H, dd, $J_{1,3}$ 2.0 Hz, H-1); δ_C (100.6 MHz, $CDCl_3$) 19.8, 22.7 (2 × s, 3 × *C*(CH$_3$)$_3$), 26.8, 27.4, 28.0 (3 × q, 3 × C(*C*H$_3$)$_3$), 29.5, 30.4 (2 × t, (H$_3$C)$_3$OC(O)*C*H$_2$, (H$_3$C)$_3$OC(O)CH$_2$*C*H$_2$), 65.7 (t, C-6), 72.4, 72.8, 73.6 (3 × d, C-3, C-4, C-5), 100.5 (d, C-2), 144.9 (d, C-1), 171.3, 172.4 (2 × s, 2 × C=O); *m*/*z* (ES$^+$) 465 (M+Na$^+$, 100), 460 (M+NH$_4^+$, 20), 443 (M+H$^+$, 5%). (HRMS (ES$^+$) calcd for $C_{22}H_{38}O_7NaSi$ (M+Na$^+$) 465.2285. Found, 465.2290). (Found: C, 59.67; H, 8.62. $C_{22}H_{38}O_7Si$ requires C, 59.70; H, 8.65).

4.14. 3-*O*-((*S*)-3-Amino-*N*-*tert*-butoxycarbonyl-4-*tert*-butylcarboxy-butanoyl)-4,6-*O*-di-*tert*-butylsilanediyl-D-glucal 13

General procedure A: glucal **1** (R_f 0.5, 467 mg, 1.61 mmol), *N*-butoxycarbonyl L-aspartic acid α-*tert*-butyl ester **12** (467 mg, 1.61 mmol), *N*,*N*′-dimethyl-4-amino pyridine (26 mg, 0.22 mmol), dicyclohexylcarbodiimide (444 mg, 2.15 mmol) in DCM (25 mL) gave ester **13** (558 mg, 93%) as a white crystalline solid, mp 84–85 °C (petrol); $[\alpha]_D^{22} = -30$ (*c* 1, $CHCl_3$); ν_{max} (thin film): 3426 (br, NH), 1732 (s, C=O), 1648 (m, C=C) cm^{-1}; δ_H (400 MHz, $CDCl_3$) 0.98, 1.09 (18H, 2 × s, 2 × C(CH$_3$)$_3$), 1.44, 1.45 (18H, 2 × s, 2 × CO$_2$C(CH$_3$)$_3$), 2.85 (1H, dd, $J_{CHH',CH}$ 4.6 Hz, J_{gem} 17.1 Hz, O$_2$CC*H*H′CH), 3.05 (1H, dd, $J_{CHH',CH}$ 4.1 Hz, O$_2$CCH*H*′CH), 3.90 (1H, ddd, $J_{4,5}$ 10.3 Hz, $J_{5,6}$ 10.3 Hz, $J_{5,6'}$ 4.8 Hz, H-5), 3.99 (1H, at, *J* 10.3 Hz, H-6), 4.16 (1H, dd, $J_{3,4}$ 7.6 Hz, H-4), 4.19 (1H, dd, $J_{6,6'}$ 10.1 Hz, H-6′), 4.44–4.48 (1H, m, O$_2$CCH$_2$C*H*), 4.72 (1H, dd, $J_{1,2}$ 6.1 Hz, $J_{2,3}$ 2.0 Hz, H-2), 5.36 (1H, br d, *J* 7.6 Hz, H-3), 5.45 (1H, d, $J_{CH,NH}$ 8.4 Hz, NH), 6.31 (1H, dd, $J_{1,3}$ 1.3 Hz, H-1); δ_C (100.6 MHz, $CDCl_3$) 19.8, 22.7 (2 × s, 2 × *C*(CH$_3$)$_3$), 26.9, 27.3, 27.9, 28.3 (4 × q, 4 × C(*C*H$_3$)$_3$), 37.3 (t, O$_2$CC*H*$_2$CH), 50.3 (d, O$_2$CCH$_2$*C*H), 65.6 (t, C-6), 72.9 (d, C-5), 73.0 (d, C-3), 73.3 (d, C-4), 79.8, 82.1 (2 × s, 2 × CO$_2$*C*(CH$_3$)$_3$), 100.2 (d, C-2), 145.1 (d, C-1), 155.5 (s, NH*C*O$_2$C(CH$_3$)$_3$), 169.7 (s, CH*C*O$_2$C(CH$_3$)$_3$), 170.7 (s, O$_2$*C*CH$_2$CH); *m*/*z* (FI$^+$) 557 (M, 100%). (HRMS

calcd for $C_{27}H_{47}O_9NSi$ (M) 557.3020. Found 557.3002). (Found: C, 58.27; H, 8.36; N, 2.45. $C_{27}H_{47}O_9NSi$ requires C, 58.14; H, 8.49; N, 2.51).

4.15. 3-*O*-((*S*)-3′-Amino-*N*-*tert*-butoxycarbonyl-4′-*tert*-butylcarboxy-butanoyl)-4,6-*O*-benzylidene-D-glucal 15

General procedure A: glucal **14** (R_f 0.1 (petrol–ethyl acetate, 4:1), 267 mg, 1.1 mmol), *N*-butoxycarbonyl L-aspartic acid α-*tert*-butyl ester **12** (495 mg, 1.7 mmol), *N*,*N*′-dimethyl-4-amino pyridine (28 mg, 0.23 mmol), dicyclohexylcarbodiimide (470 mg, 2.3 mmol) in DCM (25 mL) gave ester **15** (536 mg, 93%) as a white crystalline solid, mp 122–124 °C (ether/petrol); (R_f 0.2); $[\alpha]_D^{24} = -28.3$ (*c* 1.0, $CHCl_3$); ν_{max} (KBr disc) 3414 (s, NH), 1741 (s, ester), 1710 (s, amide I), 1649 (w, C=C–O), 1501 (m, amide II) cm^{-1}; δ_H (400 MHz, $CDCl_3$) 1.34, 1.41 (18H, 2 × s, 2 × $C(CH_3)_3$), 2.80 (1H, dd, ^2J 16.8 Hz, ^3J 4.9 Hz, NHCHC*H*H′), 2.98 (1H, dd, ^3J 4.2 Hz, NHCHCH*H*′), 3.81–3.86 (1H, m, H-6), 3.95–4.06 (2H, m, H-4, H-5), 4.38 (1H, dd, $J_{5,6'}$ 4.8 Hz, $J_{6,6'}$ 10.5 Hz, H-6′), 4.41–4.46 (1H, m, NHC*H*), 4.77 (1H, dd, $J_{1,2}$ 6.1 Hz, $J_{2,3}$ 2.0 Hz, H-2), 5.45 (1H, d, $J_{NH,CH}$ 8.5 Hz, NH), 5.56 (1H, dat, *J* 1.9, 1.9, 7.7 Hz, H-3), 5.59 (1H, s, $PhCHO_2$), 6.39 (1H, dd, $J_{1,3}$ 1.3 Hz, H-1), 7.28–7.50 (5H, m, 5 × Ar-H); δ_C (100.6 MHz, $CDCl_3$) 20.8, 21.0 (2 × s, 2 × $C(CH_3)_3$), 27.7, 28.3 (2 × q, 2 × $C(CH_3)_3$), 37.2 (t, NHCHCH_2), 50.4 (d, NHCH), 68.2 (t, C-6), 68.8, 69.2 (2 × d, C-3, C-5), 76.7 (d, C-4), 100.4 (d, C-2), 101.7 (d, $PhCHO_2$), 126.3, 128.2, 129.2 (3 × d, 5 × Ar-C), 136.9 (s, Ar-C), 145.6 (d, C-1), 155.4, 169.7, 170.6 (3 × s, 3 × C=O); *m*/*z* (ES^+) 1033 (2M+Na^+, 60), 528 (M+Na^+, 100%). (HRMS (ES^+) calcd for $C_{26}H_{35}O_9NNa$ (M+Na^+) 528.2210. Found, 528.2219). (Found: C, 61.55; H, 6.71; N, 2.66. $C_{26}H_{35}O_9N$ requires C, 61.77; H, 6.98; N, 2.77).

4.16. 3-*O*-((*S*)-4′-Amino-*N*-*tert*-butoxycarbonyl-5′-*tert*-butylcarboxy-pentanoyl)-4,6-*O*-benzylidene-D-glucal 17

General procedure A: glucal **14** (R_f 0.4 (petrol–ethyl acetate, 2:1), 241 mg, 1.0 mmol), *N*-butoxycarbonyl L-glutamic acid α-*tert*-butyl ester **16** (468 mg, 1.54 mmol), *N*,*N*′-dimethyl-4-amino pyridine (25 mg, 0.21 mmol), dicyclohexylcarbodiimide (425 mg, 2.1 mmol) in DCM (15 mL) gave ester **17** (526 mg, 98%) as a white foam; (R_f 0.6); $[\alpha]_D^{20} = -45.3$ (*c* 0.8, $CHCl_3$); ν_{max} (KBr disc) 3382 (br, NH), 1737 (s, ester), 1716 (s, amide I), 1642 (w, C=CO), 1503 (w, amide II) cm^{-1}; δ_H (400 MHz, $CDCl_3$) 1.44, 1.46 (18H, 2 × s, 2 × $C(CH_3)_3$), 1.90–1.99 (1H, m, NHCHCH_2C*H*H′), 2.10–2.19 (1H, m, NHCHCH_2CH*H*′), 2.35–2.43 (1H, m, NHCHC*H*H′), 2.45–2.53 (1H, m, NHCHCH*H*′), 3.87 (1H, at, *J* 10.2 Hz, H-6), 3.98–4.09 (2H, m, H-4, H-5), 4.16–4.23 (1H, m, NHC*H*), 4.41 (1H, dd, $J_{5,6'}$ 4.8 Hz, $J_{6,6'}$ 10.4 Hz, H-6′), 4.82 (1H, dd, $J_{1,2}$ 6.1 Hz, $J_{2,3}$ 2.0 Hz, H-2), 5.09 (1H, d, $J_{NH,CH}$ 8.3 Hz, NH), 5.54 (1H, dat, *J* 1.8, 1.8, 7.7 Hz, H-3), 5.62 (1H, s, $PhCHO_2$), 6.40 (1H, dd, $J_{1,3}$ 1.4 Hz, H-1), 7.34–7.52 (5H, m, 5 × Ar-H); δ_C (100.6 MHz, $CDCl_3$) 28.0, 28.3 (2 × q, 2 × $C(CH_3)_3$), 28.3, 30.6 (2 × t, NHCH$CH_2C H_2$), 53.4 (d, NHCH), 68.3 (t, C-6), 68.8, 69.1 (2 × d, C-3, C-5), 76.9 (d, C-4), 100.7 (d, C-2), 101.6 (d, $PhCHO_2$), 126.2, 128.3, 129.2 (3 × d, 5 × Ar-C), 136.9 (s, Ar-C), 145.4 (d, C-1); *m*/*z* (ES^+) 1061 (2M+Na^+, 30), 1056 (2M+NH_4^+, 15), 542 (M+Na^+, 100), 537 (M+NH_4^+, 30%). (HRMS (ES^+) calcd for $C_{27}H_{37}O_9NNa$ (M+Na^+) 542.2366. Found, 542.2377). (Found: C, 62.70; H, 7.09; N, 2.62. $C_{27}H_{37}O_9N$ requires C, 62.41; H, 7.18; N, 2.70).

4.17. 3-*O*-(3′-(*N*-*tert*-butoxycarbonylamino)-prop-1′-ene-2′-yl)-4,6-*O*-di-*tert*-butyl-silanediyl-D-glucal 18

General procedure B: ester **4a** (R_f 0.4 (petrol–ethyl acetate, 4:1), 144 mg, 0.33 mmol), Tebbe reagent (0.5 M, 2.6 mL, 1.3 mmol) in THF (4 mL) and pyridine (1 mL) gave vinyl ether **18** (63.8 mg, 44%) as a yellow oil; (R_f 0.5); ν_{max} (thin film) 3441 (br, NH), 1718 (s, ester), 1701 (s, amide I), 1653 (m, C=C–O), 1647 (m, C=CO), 1507 (m, amide II) cm^{-1}; δ_H (400 MHz, C_6D_6) 0.99, 1.04, 1.42 (27H, 3 × s, 3 × $C(CH_3)_3$), 3.66–3.86 (3H, m, H-5, NHC*H*H′, NHCH*H*′), 3.91 (1H, at, *J* 10.3 Hz, H-6), 4.01 (1H, s, C=C*H*H′), 4.10–4.13 (2H, m, H-6′, C=CH*H*′), 4.22 (1H, dd, $J_{3,4}$ 7.3 Hz, $J_{4,5}$ 10.3 Hz, H-4), 4.54–4.56 (2H, m, H-3, NH), 4.70 (1H, d, $J_{1,2}$ 6.0 Hz, H-2), 5.99 (1H, d, H-1); δ_C (100.6 MHz, C_6D_6) 20.1, 23.0 (2 × s, 3 × $C(CH_3)_3$), 27.3, 27.8, 28.6 (3 × q, 3 × $C(CH_3)_3$), 44.4 (t, NHCH_2), 66.3 (t, C-6), 73.2 (d, C-5), 75.0 (d, C-4), 75.8 (d, C-3), 78.9 (s, H_2C=*C*), 84.2 (t, H_2C=C), 100.3 (d, C-2), 144.6 (d, C-1); *m*/*z* (ES^+) 464 (M+Na^+, 100%). (HRMS (ES^+) calcd for $C_{22}H_{39}O_6NNaSi$ (M+Na^+) 464.2444. Found, 464.2439); together with hydrolysis product glucal **1** (37.3 mg, 40% R_f 0.35).

4.18. 3-*O*-(4′-(*N*-*tert*-Butoxycarbonylamino)-but-1′-ene-2′-yl)-4,6-*O*-di-*tert*-butylsilanediyl-D-glucal 19

General procedure B: ester **8** (R_f 0.5 (petrol–ethyl acetate, 4:1), 125 mg, 0.27 mmol), Tebbe reagent (0.5 M, 2.2 mL, 1.1 mmol), in THF (4 mL) pyridine (1 mL) gave vinyl ether **19** (99.5 mg, 80%) as a yellow oil; (R_f 0.6); ν_{max} (thin film) 3442 (br, NH), 1718 (sh, ester, amide I), 1646 (m, C=CO), 1510 (m, amide II) cm^{-1}; δ_H (400 MHz, C_6D_6) 1.14, 1.15, 1.57 (27H, 3 × s, 3 × $C(CH_3)_3$), 2.19–2.25 (1H, m, NHCH_2C*H*H′), 2.37–2.45 (1H, m, NHCH_2CH*H*′), 3.30–3.41 (1H, m, NHC*H*H′), 3.55–3.63 (1H, m, NHCH*H*′), 3.85–3.91 (1H, m, H-5), 4.00–4.06 (3H, m, H-6, C=C*H*H′, C=CH*H*′), 4.23 (1H, dd, $J_{5,6'}$ 5.1 Hz, $J_{6,6'}$ 10.5 Hz, H-6′), 4.32 (1H, dd, $J_{3,4}$ 7.5 Hz, $J_{4,5}$ 10.2 Hz, H-4), 4.62 (1H, d, H-3), 4.82–4.85 (2H, m, H-2, NH), 6.10 (1H, dd, $J_{1,2}$ 6.0 Hz, $J_{1,3}$ 1.1 Hz, H-1); δ_C (100.6 MHz, C_6D_6) 20.1, 23.0 (2 × s, 3 × $C(CH_3)_3$), 27.4, 27.7, 28.7 (3 × q, 3 × $C(CH_3)_3$), 35.8 (t, NHC$H_2C H_2$), 38.4 (t, NHCH_2), 66.3 (t, C-6), 73.2 (d, C-5), 75.0 (d, C-4), 75.9 (d, C-3), 78.6 (s, H_2C=*C*), 84.9 (t, H_2C=C), 100.5 (d, C-2), 144.5 (d, C-1), 160.1 (s, O_2CN); *m*/*z* (ES^+) 478 (M+Na^+, 100%). (HRMS (ES^+) calcd for $C_{23}H_{41}O_6NNaSi$ (M+Na^+) 478.2601. Found, 478.2605).

4.19. 3-*O*-(5′-*tert*-Butyl-carboxy-pent-1′-ene-2′-yl)-4,6-*O*-di-*tert*-butyl-silanediyl-D-glucal 21

General procedure B: ester **11** (R_f 0.6 (petrol–ethyl acetate, 4:1), 108 mg, 0.24 mmol), Tebbe reagent (0.5 M,

2.0 mL, 0.97 mmol) in THF (6 mL) and pyridine (1.5 mL) gave vinyl ether **21** (88.6 mg, 83%) as a colourless oil; (R_f 0.7); ν_{max} (thin film) 1732 (s, C=O), 1643 (w, C=C–O) cm^{-1}; δ_H (400 MHz, C_6D_6) 1.12, 1.15 (18H, 2 × s, 2 × $SiC(CH_3)_3$), 1.47 (9H, s, $OC(CH_3)_3$), 2.53–2.66 (4H, m, CH_2CH_2), 3.91 (1H, dat, *J* 4.9, 10.4, 10.4 Hz, H-5), 4.04 (1H, at, *J* 10.4 Hz, H-6), 4.13 (2H, br s, $C=CH_2$), 4.24 (1H, dd, $J_{5,6'}$ 5.0 Hz, $J_{6,6'}$ 10.3 Hz, H-6′), 4.37 (1H, dd, $J_{3,4}$ 7.2 Hz, $J_{4,5}$ 10.4 Hz, H-4), 4.71 (1H, dat, *J* 1.6, 1.6, 7.2 Hz, H-3), 4.92 (1H, dd, $J_{1,2}$ 6.2 Hz, $J_{2,3}$ 1.8 Hz, H-2), 6.15 (1H, dd, $J_{1,3}$ 1.5 Hz, H-1); δ_C (100.6 MHz, C_6D_6) 20.1, 23.0 (2 × s, 3 × $C(CH_3)_3$), 27.3, 27.8, 28.3 (3 × q, 3 × $C(CH_3)_3$), 31.5, 33.9 (2 × t, CH_2CH_2), 66.4 (t, C-6), 75.3 (d, C-5), 75.1 (d, C-4), 75.6 (d, C-3), 83.5 (t, $C=CH_2$), 100.6 (d, C-2), 144.5 (d, C-1), 161.4 (s, $C=CH_2$), 171.8 (s, C=O); *m*/*z* (ES^+) 463 ($M+Na^+$, 100%). (HRMS (ES^+) calcd for $C_{23}H_{40}O_6SiNa$ ($M+Na^+$) 463.2492. Found, 463.2498).

4.20. 3-*O*-((*S*)-4′-Amino-*N*-*tert*-butoxycarbonyl-5′-*tert*-butylcarboxy-pent-1′-ene-2′-yl)-4,6-*O*-di-*tert*-butylsilanediyl-D-glucal 22

General procedure B: ester **13** (R_f 0.5, 227 mg, 0.41 mmol), Tebbe reagent (0.5 M in toluene, 3.3 mL, 1.6 mmol) in THF (8 mL) and pyridine (2 mL) gave vinyl ether **22** (14.0 mg, 6%) as a pale orange oil; (R_f 0.6, petrol–ethyl acetate, 4:1); ν_{max} (thin film) 3434 (br, NH), 1718 (sh, ester, amide I), 1647 (m, C=C–O), 1498 (m, amide II) cm^{-1}; δ_H (400 MHz, C_6D_6) ratio of rotamers major:minor, 1.2:1; major rotamer: 1.03, 1.14 (18H, 2 × s, 2 × $SiC(CH_3)_3$), 1.40, 1.41 (18H, 2 × s, 2 × $OC(CH_3)_3$), 2.66 (1H, dd, ^2J 14.4 Hz, ^3J 5.3 Hz, NHCHC*H*H′), 2.79 (1H, dd, ^3J 5.3 Hz, NHCHCH*H*′), 3.80–3.97 (1H, m, H-4), 4.00–4.09 (1H, m, H-6), 4.11–4.19 (1H, m, H-6′), 4.20, 4.21 (2H, 2 × s, $C=CH_2$), 4.22–4.34 (1H, m, H-5), 4.72–4.74 (1H, m, H-3), 4.75–4.82 (1H, m, NHC*H*), 4.93–4.95 (1H, dd, $J_{1,2}$ 6.1 Hz, $J_{2,3}$ 1.4 Hz, H-2), 5.54 (1H, d, $J_{NH,CH}$ 8.6 Hz, NH), 6.15 (1H, d, H-1); minor rotamer: 1.03, 1.14 (18H, 2 × s, 2 × $SiC(CH_3)_3$), 1.43, 1.44 (18H, 2 × s, 2 × $OC(CH_3)_3$), 2.66 (1H, dd, ^2J 14.4 Hz, ^3J 5.3 Hz, NHCHC*H*H′), 2.79 (1H, dd, ^3J 5.3 Hz, NHCHCH*H*′), 3.80–3.97 (1H, m, H-4), 4.00–4.09 (1H, m, H-6), 4.11–4.19 (1H, m, H-6′), 4.20, 4.21 (2H, 2 × s, $C=CH_2$), 4.22–4.34 (1H, m, H-5), 4.36–4.41 (1H, m, H-3), 4.72–4.74 (2H, m, H-2, NHC*H*), 5.79 (1H, d, $J_{NH,CH}$ 8.5 Hz, NH), 6.06 (1H, dd, $J_{1,2}$ 6.1 Hz, $J_{1,3}$ 1.3 Hz, H-1); δ_C (100.6 MHz, C_6D_6) 27.3, 27.5, 28.5, 28.7 (4 × q, 4 × $C(CH_3)_3$), 38.9 (t, NHCHCH_2), 66.3 (t, C-6), 75.1 (d, C-3), 75.9 (d, C-4), 82.3 (s, $C=CH_2$), 86.9 (d, C-5), 87.2 (t, $C=CH_2$), 101.0 (d, NHCH), 101.3 (d, C-2), 114.3 (d, C-1); *m*/*z* (ES^+) 578 ($M+Na^+$, 100), 556 ($M+H^+$, 20%). (HRMS (ES^+) calcd for $C_{28}H_{49}NO_8SiNa$ ($M+Na^+$) 578.3125. Found, 578.3134).

4.21. 3-*O*-((*S*)-4′-Amino-*N*-*tert*-butoxycarbonyl-5′-*tert*-butylcarboxy-pent-1′-ene-2′-yl)-4,6-*O*-benzylidene-D-glucal 23

General procedure B: ester **15** (R_f 0.3 (petrol–ethyl acetate, 4:1), 119 mg, 0.24 mmol), Tebbe reagent (0.5 M, 1.9 mL, 0.94 mmol), in THF (6 mL) and pyridine (1.5 mL) gave vinyl ether (25.7 mg, 22%, 50% based on recovered starting material) as a pale orange oil; (R_f 0.4); ν_{max} (thin film) 3440 (br, NH), 1717 (sh, ester, amide I), 1640 (m, C=C–O), 1506 (m, amide II) cm^{-1}; δ_H (400 MHz, C_6D_6) ratio of rotamers major:minor, 2:1; major rotamer: 1.41, 1.49 (18H, 2 × s, 2 × $C(CH_3)_3$), 2.62–2.69 (1H, m, NHCHC*H*H′), 2.81 (1H, dd, ^2J 14.3 Hz, ^3J 5.8 Hz, NHCHCH*H*′), 3.59 (1H, at, *J* 10.3 Hz, H-6), 3.80 (1H, dat, *J* 15.3, 15.3, 5.0 Hz, H-5), 3.97–4.10 (3H, m, H-4, $C=CH_2$), 4.23 (1H, dd, $J_{5,6'}$ 5.0 Hz, $J_{6,6'}$ 10.3 Hz, H-6′), 4.37–4.82 (2H, m, H-3, NHC*H*), 4.90 (1H, dd, $J_{1,2}$ 6.8 Hz, $J_{2,3}$ 1.7 Hz, H-2), 5.53–5.60 (2H, m, NH, $PhCHO_2$), 6.13 (1H, d, H-1), 7.20–7.90 (5H, m, 5 × Ar-H); minor rotamer: 1.43, 1.48 (18H, 2 × s, 2 × $C(CH_3)_3$), 2.62–2.69 (1H, m, NHCHC*H*H′), 2.81 (1H, dd, ^2J 14.3 Hz, ^3J 5.8 Hz, NHCHCH*H*′), 3.59 (1H, at, *J* 10.3 Hz, H-6), 3.80 (1H, dat, *J* 5.0, 15.3, 15.3 Hz, H-5), 3.97–4.10 (3H, m, H-4, $C=CH_2$), 4.23 (1H, dd, $J_{5,6'}$ 5.0 Hz, $J_{6,6'}$ 10.3 Hz, H-6′), 4.37–4.82 (2H, m, H-3, NHC*H*), 4.90 (1H, dd, $J_{1,2}$ 6.7 Hz, $J_{2,3}$ 1.7 Hz, H-2), 5.53 (1H, s, $PhCHO_2$), 5.68 (1H, d, *J* 5.4 Hz, NH), 6.10 (1H, d, H-1), 7.20–7.90 (5H, m, 5 × ArH); δ_C (100.6 MHz, C_6D_6) 28.1, 28.6 (2 × q, 2 × $C(CH_3)_3$), 38.4 (t, NHCHCH_2), 52.1 (d, NHCH), 68.5 (t, C-6), 69.2 (d, C-5), 73.2 (d, C-3), 78.2 (C-4), 86.2 (t, $C=CH_2$), 100.6 (d, C-2), 101.9 (d, $PhCHO_2$), 127.0, 127.1, 128.5, 129.2 (4 × d, 5 × Ar-C), 133.0 (s, Ar-C), 140.1 (d, C-1), 160.2 (s, $C=CH_2$), 169.1, 169.2 (2 × s, 2 × C=O); *m*/*z* (ES^+) 1029 ($2M+Na^+$, 10), 526 ($M+Na^+$, 100), 521 ($M+NH_4^+$, 20), 504 ($M+H^+$, 10%). (HRMS (ES^+) calcd for $C_{27}H_{37}NO_8Na$ ($M+Na^+$) 526.2417. Found, 526.2422); and recovered starting material **15** (R_f 0.3, 78.1 mg, 66%).

4.22. 3-*O*-((*S*)-5′-Amino-*N*-*tert*-butoxycarbonyl-6′-*tert*-butylcarboxy-hex-1′-ene-2′-yl)-4,6-*O*-benzylidene-D-glucal 24

General procedure B: ester **17** (R_f 0.3 (petrol–ethyl acetate, 4:1), 129 mg, 0.25 mmol), Tebbe reagent (0.5 M, 2.0 mL, 0.99 mmol), in THF (6 mL) and pyridine (1.5 mL) gave vinyl ether **24** (60.0 mg, 47%) as a pale orange oil; (R_f 0.4); ν_{max} (thin film) 3385 (br, NH), 1716 (sh, ester, amide I), 1638 (m, C=C–O), 1507 (w, amide II) cm^{-1}; δ_H (400 MHz, C_6D_6) 1.26, 1.38 (18H, 2 × s, 2 × $C(CH_3)_3$), 1.74–1.85 (1H, m, NHCHC*H*H′), 2.07–2.19 (3H, m, NHCHCH*H*′, $NHCHCH_2CH_2$), 3.47 (1H, at, *J* 10.4 Hz, H-6), 3.69–3.76 (1H, m, H-5), 3.86–4.00 (3H, m, H-4, $C=CH_2$), 4.12 (1H, dd, $J_{5,6'}$ 5.3 Hz, $J_{6,6'}$ 10.3 Hz, H-6′), 4.46–4.49 (1H, m, NHC*H*), 4.76 (1H, d, $J_{3,4}$ 7.6 Hz, H-3), 4.83 (1H, dd, $J_{1,2}$ 6.3 Hz, $J_{2,3}$ 1.4 Hz, H-2), 5.00 (1H, d, $J_{NH,CH}$ 8.1 Hz, NH), 5.32 (1H, s, $PhCHO_2$), 6.04 (1H, d, H-1), 7.08–7.60 (5H, m, 5 × ArH); δ_C (100.6 MHz, C_6D_6) 28.0, 28.6 (2 × q, 2 × $C(CH_3)_3$), 30.9 (t, NHCHCH_2), 31.9 (t, $NHCHCH_2CH_2$), 54.3 (d, NHCH), 68.5 (t, C-6), 69.2 (d, C-5), 71.6 (d, C-3), 78.2 (d, C-4), 84.0 (t, $C=CH_2$), 100.4 (d, C-2), 101.9 (d, $PhCHO_2$), 126.9, 128.6, 129.2 (3 × d, 5 × Ar-C), 138.2 (s, $C=CH_2$), 145.0 (d, C-1), 160.6, 172.2 (2 × s, 2 × C=O); *m*/*z* (ES^+) 540 ($M+Na^+$, 100), 518 ($M+H^+$, 20%). (HRMS (ES^+) calcd for $C_{28}H_{39}O_8NNa$ ($M+Na^+$) 540.2573. Found, 540.2561).

4.23. 1-Amino-4,8-anhydro-*N*-*tert*-butoxycarbonyl-7,9-*O*-di-*tert*-butylsilanediyl-5,6-didehydro-2-oxo-1,3,5,6-tetradeoxy-D-glycero-D-gulo-nonitol 25

Vinyl ether **18** (63.8 mg, 0.144 mmol) was dissolved in anhydrous tributylamine (5 mL) and heated to 180 °C under an atmosphere of argon. After 1 h, TLC (petrol–ethyl acetate, 4:1) indicated complete consumption of starting material (R_f 0.5) and formation of a major product (R_f 0.2). The reaction mixture was diluted with ethyl acetate (50 mL), washed with hydrochloric acid (2×50 mL) and sodium bicarbonate (50 mL), dried ($MgSO_4$), filtered and concentrated in vacuo. The residue was purified by flash column chromatography (petrol–ethyl acetate, 5:1) to give β-*C*-glycoside **25** (49.4 mg, 77%) as an amorphous solid; $[\alpha]_D^{25} = +7.7$ (*c* 0.8, $CHCl_3$); ν_{max} (thin film) 3367 (br, NH), 1717 (sh, ketone, amide I), 1507 (m, amide II) cm^{-1}; δ_H (400 MHz, C_6D_6) 1.19, 1.20 (18H, $2 \times$ s, $2 \times SiC(CH_3)_3$), 1.52 (9H, s, $OC(CH_3)_3$), 1.94 (1H, dd, $J_{3,3'}$ 15.6 Hz, $J_{3,4}$ 5.1 Hz, H-3), 2.22 (1H, dd, $J_{3',4}$ 8.0 Hz, H-3′), 3.55–3.61 (1H, m, H-8), 3.70 (1H, dd, $J_{NH,1}$ 4.8 Hz, $J_{1,1'}$ 19.6 Hz, H-1), 3.81 (1H, dd, $J_{NH,1'}$ 5.3 Hz, H-1′), 3.96 (1H, at, *J* 10.2 Hz, H-9), 4.24 (1H, dd, $J_{8,9'}$ 5.0 Hz, $J_{9,9'}$ 10.3 Hz, H-9′), 4.40–4.50 (1H, m, H-4), 4.54–4.58 (1H, m, H-7), 5.10 (1H, br s, NH), 5.29 (1H, d, $J_{5,6}$ 10.4 Hz, H-6), 5.94 (1H, d, H-5); δ_C (100.6 MHz, C_6D_6) 20.4, 23.0 ($2 \times$ s, $3 \times C(CH_3)_3$), 27.5, 27.8, 28.5 ($3 \times$ q, $3 \times C(CH_3)_3$), 45.2 (t, C-3), 51.5 (t, C-1), 67.5 (t, C-9), 70.7 (d, C-7), 72.1 (d, C-4), 75.3 (d, C-8), 79.4 (s, C-2), 128.9 (d, C-6), 130.8 (d, C-5); *m/z* (ES^+) 464 ($M+Na^+$, 55), 459 ($M+NH_4^+$, 40), 442 ($M+H^+$, 20%). (HRMS (ES^+) calcd for $C_{22}H_{40}O_6NSi$ ($M+H^+$) 442.2625. Found, 442.2635).

4.24. 1-Amino-5,9-anhydro-*N*-*tert*-butoxycarbonyl-8,10-*O*-di-*tert*-butylsilanediyl-6,7-didehydro-3-oxo-1,2,4,6,7-pentadeoxy-D-glycero-D-gulo-decitol 26

Vinyl ether **19** (99.5 mg, 0.22 mmol) was dissolved in anhydrous tributylamine (5 mL) and heated to 180 °C under an atmosphere of argon. After 1 h, TLC (petrol–ethyl acetate, 4:1) indicated complete consumption of starting material (R_f 0.6) and formation of a major product (R_f 0.2). The reaction mixture was diluted with ethyl acetate (100 mL), washed with water (50 mL), hydrochloric acid (2×50 mL) and sodium bicarbonate (50 mL), dried ($MgSO_4$), filtered and concentrated in vacuo. The residue was purified by flash column chromatography (petrol–ethyl acetate, 4:1) to give *C*-glycoside **26** (65.1 mg, 65%) as a yellow oil; $[\alpha]_D^{25} = +7.2$ (*c* 0.8, $CHCl_3$); ν_{max} (thin film) 3373 (br, NH), 1700 (sh, ketone, amide I), 1507 (w, amide II) cm^{-1}; δ_H (400 MHz, C_6D_6) 1.19, 1.20 (18H, $2 \times$ s, $2 \times SiC(CH_3)_3$), 1.53 (9H, s, $OC(CH_3)_3$), 1.91–2.34 (2H, m, H-4, H-4′), 2.22–2.30 (2H, m, H-2, H-2′), 3.27–3.36 (2H, m, H-1, H-1′), 3.50–3.66 (1H, m, H-9), 3.96–4.03 (1H, m, H-10), 4.26–4.30 (1H, m, H-10′), 4.57–4.59 (2H, m, H-5, H-8), 4.90 (1H, br s, NH), 5.36 (1H, d, $J_{6,7}$ 10.2 Hz, H-7), 5.97 (1H, d, H-6); δ_C (100.6 MHz, C_6D_6) 20.4, 21.2 ($2 \times$ s, $3 \times C(CH_3)_3$), 27.5, 27.8, 28.6 ($3 \times$ q, $3 \times C(CH_3)_3$), 35.6 (t, C-1), 43.7 (t, C-2), 48.0 (t, C-4), 67.6 (t, C-10), 70.9, 72.3 ($2 \times$ d, C-5, C-8), 75.3 (d, C-9), 78.9 (s, C-3), 129.3 (d, C-7), 130.6 (d, C-6), 156.0 (s, O_2CN); *m/z* (ES^+) 478 ($M+Na^+$, 35%), 456 ($M+H^+$, 25%). (HRMS (ES^+) calcd for $C_{23}H_{42}O_6NSi$ ($M+H^+$) 456.2781. Found, 456.2783).

4.25. 6,10-Anhydro-1-*tert*-butoxycarboxy-9,11-*O*-di-*tert*-butyl-silanediyl-7,8-didehydro-4-oxo-2,3,5,7,8-pentadeoxy-D-glycero-D-gulo-undecitol 28

Vinyl ether **21** (82.7 mg, 0.19 mmol) was dissolved in anhydrous tributylamine (5 mL) and heated to 180 °C under an atmosphere of argon. After 2 h 30 min, TLC (petrol–ethyl acetate, 4:1) indicated complete consumption of starting material (R_f 0.8) and formation of a major product (R_f 0.6) and a minor product (R_f 0.2). The reaction mixture was diluted with ethyl acetate (40 mL), washed with hydrochloric acid (3×25 mL) and sodium bicarbonate (2×25 mL), dried ($MgSO_4$), filtered and concentrated in vacuo. The residue was purified by flash column chromatography (petrol–ethyl acetate, 12:1) to give β-*C*-glycoside **28** (71.0 mg, 86%) as a colourless oil; $[\alpha]_D^{24} = +16.3$ (*c* 1.2, $CHCl_3$); ν_{max} (thin film) 1726 (s, C=O); δ_H (400 MHz, C_6D_6) 1.20 (18H, s, $2 \times SiC(CH_3)_3$), 1.47 (9H, s, $OC(CH_3)_3$), 2.23 (1H, dd, $J_{5,5'}$ 16.2 Hz, $J_{5,6}$ 5.7 Hz, H-5), 2.27–2.52 (4H, m, H-2, H-2′, H-3, H-3′), 2.49–2.57 (1H, m, H-5′), 3.62–3.68 (1H, m, H-10), 4.02 (1H, at, *J* 10.1 Hz, H-11), 4.29 (1H, dd, $J_{10,11'}$ 5.1 Hz, $J_{11,11'}$ 10.0 Hz, H-11′), 4.59–4.63 (1H, m, H-9), 4.66–4.71 (1H, m, H-6), 5.48 (1H, dat, *J* 1.9, 1.9, 10.4 Hz, H-8), 5.98 (1H, d, $J_{7,8}$ 10.4 Hz, H-7); δ_C (100.6 MHz, C_6D_6) 20.4, 21.0, 23.0 ($3 \times$ s, $3 \times C(CH_3)_3$), 27.5, 27.8, 28.2 ($3 \times$ q, $3 \times C(CH_3)_3$), 29.3, 38.2 ($2 \times$ t, C-2, C-3), 48.0 (t, C-5), 67.7 (t, C-11), 70.9 (d, C-9), 72.3 (d, C-6), 75.3 (d, C-10), 80.2 (s, C-4), 129.5 (d, C-8), 130.5 (d, C-7), 171.9 (s, C-1); *m/z* (ES^+) 903 ($2M+Na^+$, 55), 463 ($M+Na^+$, 70%). (HRMS (ES^+) calcd for $C_{23}H_{44}O_6NSi$ ($M+NH_4^+$) 458.2938. Found, 458.2932).

4.26. 1-(*S*) 2-Amino-7,11-anhydro-10,12-*O*-benzylidene-*N*-*tert*-butoxycarbonyl-1-*tert*-butoxycarboxy-8,9-didehydro-2,3,4,6,8,9-hexadeoxy-5-oxo-D-glycero-D-gulo-dodecitol 29

Vinyl ether **24** (86.0 mg, 0.17 mmol) was dissolved in anhydrous tributylamine (3 mL) and heated to 180 °C under an atmosphere of argon. After 3 h, TLC (petrol–ethyl acetate, 4:1) indicated complete consumption of starting material (R_f 0.5) and formation of a major product (R_f 0.2). The reaction mixture was diluted with ethyl acetate (80 mL), washed with hydrochloric acid (5×25 mL), and sodium bicarbonate (2×25 mL), dried ($MgSO_4$), filtered and concentrated in vacuo. The residue was purified by flash column chromatography (petrol–ethyl acetate, 3:1) to give β-*C*-glycoside **29** (40.1 mg, 47%) as a colourless oil; $[\alpha]_D^{15} = +28.2$ (*c* 1.2, $CHCl_3$); ν_{max} (thin film) 3395 (br, NH), 1716 (sh, ketone, amide I), 1501 (amide II) cm^{-1}; δ_H (400 MHz, $CDCl_3$) 1.45, 1.47 (18H, $2 \times$ s, $2 \times C(CH_3)_3$), 1.80–1.88 (1H, m, H-3), 2.05–2.27 (1H, m, H-3′), 2.44–2.65 (3H, m, H-4, H-4′, H-6), 2.70 (1H, dd, $J_{6,6'}$ 15.9 Hz, $J_{6',7}$ 7.7 Hz, H-6′), 3.61 (1H, m, H-11), 3.75 (1H, at, *J* 10.2 Hz, H-12), 4.14–4.22 (2H, m, H-2, H-10), 4.29 (1H, dd, $J_{11,12'}$

4.4 Hz, $J_{12,12'}$ 10.2 Hz, H-12′), 4.77–4.80 (1H, m, H-7), 5.08 (1H, d, *J* 7.6 Hz, NH), 5.59 (1H, s, $PhCHO_2$), 5.70 (1H, dd, $J_{8,9}$ 10.3 Hz, $J_{9,10}$ 5.3 Hz, H-9), 5.98 (1H, d, H-8), 7.27–7.54 (5H, m, 5 × Ar-H); δ_C (100.6 MHz, $CDCl_3$) 20.8, 21.0 (2 × s, 2 × $C(CH_3)_3$), 28.4, 28.8 (2 × q, 2 × $C(CH_3)_3$), 28.7 (t, C-3), 41.2 (t, C-4), 48.2 (t, C-6), 54.7 (d, C-2), 69.8 (t, C-12), 71.3 (d, C-11), 72.8 (d, C-7), 75.5 (d, C-10), 82.6 (s, C-5), 102.4 (d, $PhCHO_2$), 126.7, 128.7, 129.6 (3 × d, 5 × Ar-C), 127.5 (d, C-8), 129.7 (d, C-9), 137.9 (s, Ar-C); *m/z* (ES^+) 540 ($M+Na^+$, 100%). (HRMS (ES^+) calcd for $C_{28}H_{40}NO_8$ ($M+H^+$) 518.2754. Found, 518.2754).

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14. This may indicate the operation of a through-bond inductive effect that particularly promotes ester cleavage rather than methylenation in the cases of α-amino acids.