61. C_{45}- and C_{50}-Carotenoids

Part 7[1])

Total Synthesis of (all-*E*,2*R*,6*R*,2′*R*,6′*R*)- and (all-*E*,2*R*,6*S*,2′*R*,6′*S*)-2,2′-Bis(4-hydroxy-3-methylbut-2-enyl)-γ,γ-carotene (Sarcinaxanthin)

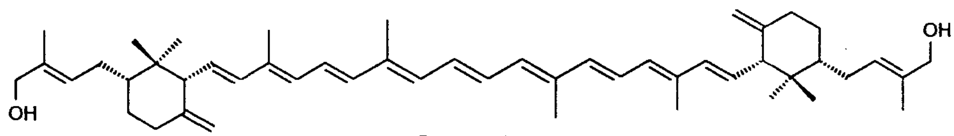
by **Marc Lanz**[2]), **Birgit Bartels**[3]), and **Hanspeter Pfander***

Departement für Chemie und Biochemie, Universität Bern, Freiestr. 3, CH-3012 Bern

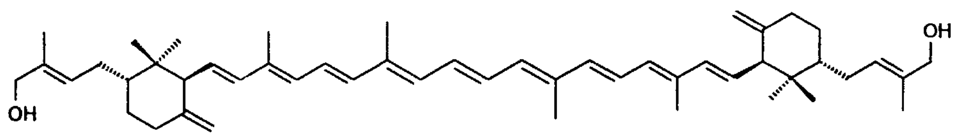
(25.XI.96)

The synthesis of sarcinaxanthin ((2*R*,6*R*,2′*R*,6′*R*)-**1**), a symmetrical C_{50}-carotenoid with two γ-end groups, isolated from *Sarcina lutea* and from *Cellulomonas biazotea* as major pigment, was based on the strategy $C_{20} + C_{10} + C_{20} = C_{50}$ using camphoric acid as starting material for the C_{20}-end group **3**. The key step of the synthesis is a ring enlargement of the cyclopentane derivative **10** with 2,4,4,6-tetrabromocyclohexa-2,5-dien-1-one (TBCO) to give the cyclohexane derivative **11** (*Scheme 1*). The spectroscopic data of the synthetic compound are in full agreement with the data of the isolated product and give the final proof for the (2*R*,6*R*,2′*R*,6′*R*) chirality of natural sarcinaxanthin.

1. Introduction. – Sarcinaxanthin (**1**) was for the first time isolated by *Hertzberg* and *Jensen* from *Sarcina lutea* and identified as (all-*E*,2*R*,6*R*,2′*R*,6′*R*)-2,2′-bis(4-hydroxy-3-methylbut-2-enyl)-γ,γ-carotene based on UV/VIS, CD, ^{1}H-NMR and mass spectra [2]. The same pigment was isolated by *Weeks* as major carotenoid in *Cellulomonas biazotea* [3].



(all-*E*,2*R*,6*R*,2′*R*,6′*R*)-**1**



(all-*E*,2*R*,6*S*,2′*R*,6′*S*)-**1**

The synthesis of racemic sarcinaxanthin (**1**), with the correct relative configuration at the γ-ring end group, using the sulfone method as coupling reaction, has been reported

1) Part 6: [1].

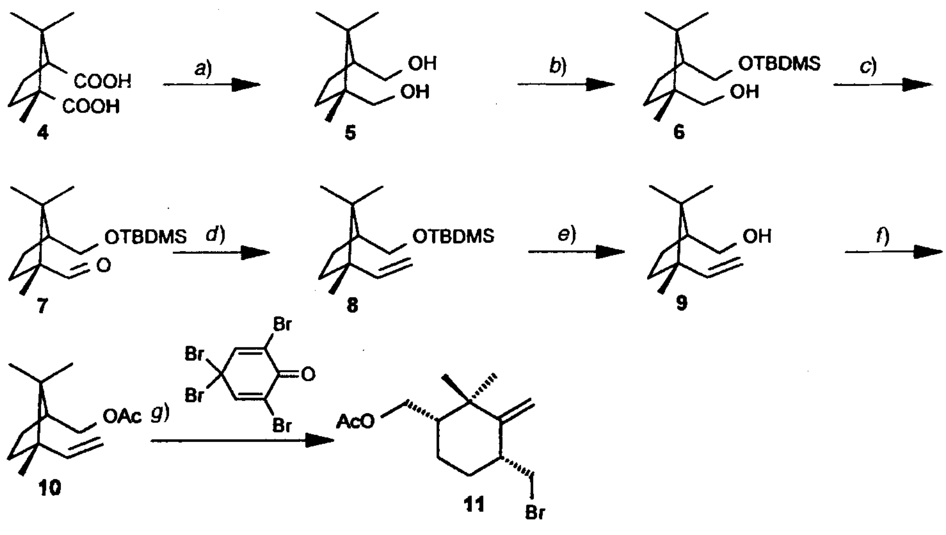
2) Part of the planned Ph. D. thesis of *M. L.*

3) Present address: Department of Chemistry, Faculty of Science, University of Natal, Pietermaritzburg, 3209 South Africa.

previously [4]. In the course of our investigations of the synthesis of cyclic C_{50}-carotenoids, we have so far reported on the synthesis of *C.p. 450* [5] and *C.p. 473* [6], both containing a *β*-end group, as well as of decaprenoxanthin [1] with the ε-end group. In view of the elucidation of the configuration of natural **1**, we report in the present paper the synthesis of (all-*E*,2*R*,6*R*,2′*R*,6′*R*)- and (all-*E*,2*R*,6*S*,2′*R*,6′*S*)-sarcinaxanthin ((all-*E*,2*R*,6*R*,2′*R*,6′*R*)- and (all-*E*,2*R*,6*S*,2′*R*, 6′*S*)-**1**, resp.).

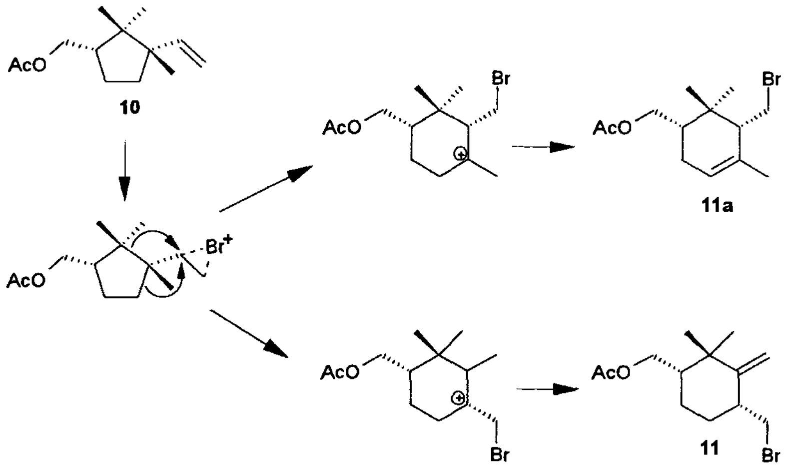
2. Results and Discussion. – As strategy for the synthesis of **1**, the well-known approach $C_{20} + C_{10} + C_{20} = C_{50}$ was applied, using C_{10}-dialdehyde **2** as central building block. As starting material for the synthesis of the optically active C_{20}-phosphonium salts (2*R*,6*R*)- and (2*R*,6*S*)-**3**, (+)-camphoric acid **4** was selected (*Scheme 1*). The reduction of **4** with $NaBH_4$ and $BF_3 \cdot OEt_2$ gave the diol **5** which was transformed into **6** by reaction with (*tert*-butyl)dimethylsilyl chloride ((*t*-Bu)Me_2SiCl). *Swern* oxidation of **6** afforded aldehyde **7** which was transformed by a *Wittig* reaction with $MePPh_3Br$ into olefin **8**. Deprotection of **8** with tetrabutylammonium fluoride (Bu_4NF) gave **9**, and the reaction with Ac_2O afforded acetate **10** in 73% yield with respect to the starting material **4** [7] [8]. The key step of the synthesis of the optically active end group **3** is the ring enlargement of acetate **10** to the bromocyclohexane derivative **11**. According to the mechanism shown in *Scheme 2*, the reaction of **10** with TBCO (2,4,4,6-tetrabromocyclohexa-2,5-dienone) gave a mixture of **11** and **11a** (ratio 1:1.45) in a yield of 34% [9]. Attempts to separate **11** and **11a** on a preparative scale were unsuccessful and, therefore, the mixture was directly used for the next steps. In addition, 52% of unreacted **10** was separated from the reaction mixture by flash chromatography and recycled. Although many experiments were carried out to optimize this reaction no improvement was achieved.

Scheme 1



a) $NaBH_4$, $BF_3 \cdot OEt_2$, THF; 94%. *b*) (*t*-Bu)Me_2SiCl (TBDMSCl), imid., CH_2Cl_2; 83%. *c*) $(COCl)_2$, DMSO, Et_3N, CH_2Cl_2. *d*) Ph_3PMeBr, BuLi, THF; 94% rel. to 6. *e*) Bu_4NF, THF; 100%. *f*) Ac_2O, Py; 99.5%. *g*) THF; AcOH, Zn; 10%.

Scheme 2

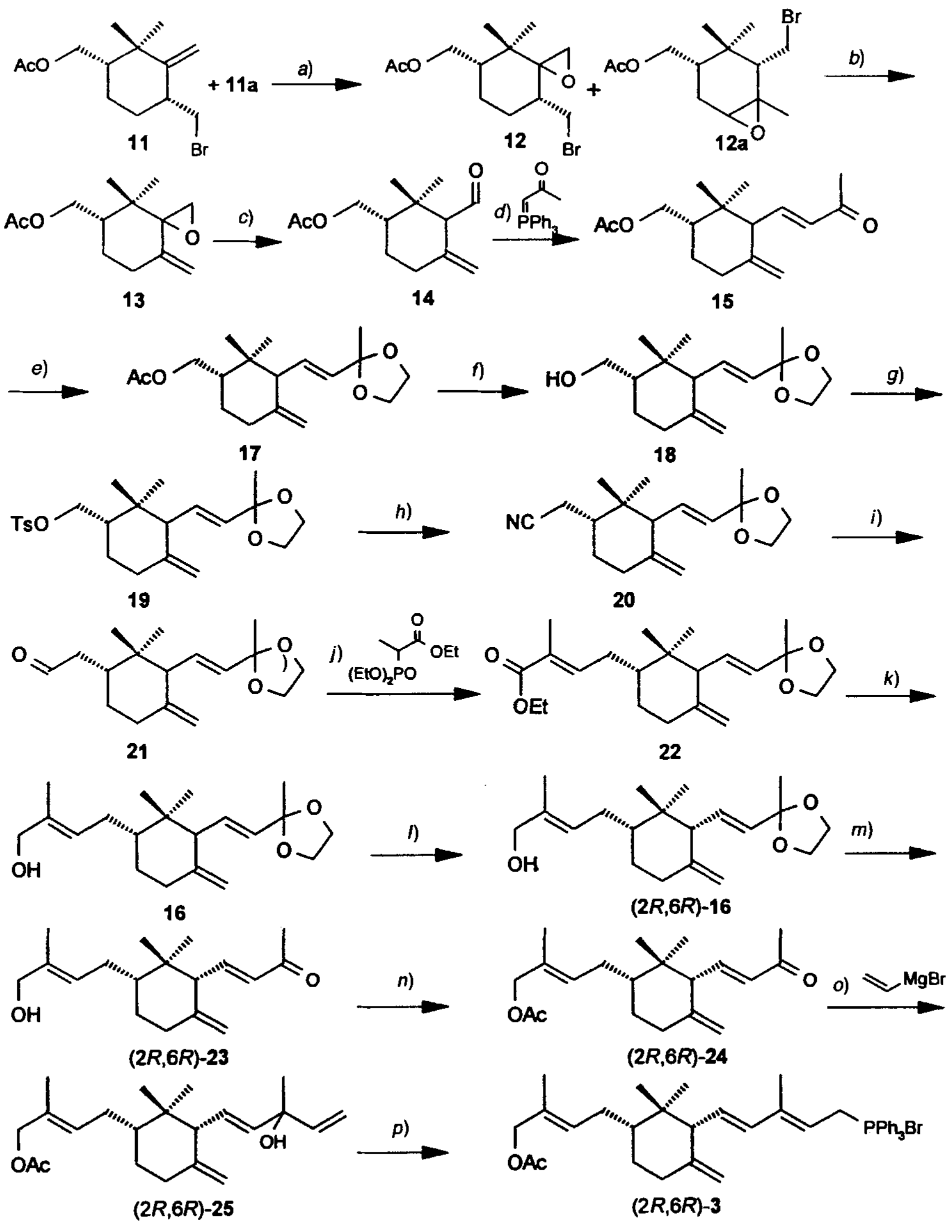


The mixture **11/11a** was epoxidized with 3-chloroperbenzoic acid to give **12/12a** in 95% yield, which was directly used for the next step of the synthesis. The dehydrohalogenation with sodium 1,1-dimethylpropoxide gave, after FC, the diastereoisomeric cyclohexane derivatives **13** with the exocyclic double bond at the C(8) position [10] in an overall yield of 9% with respect to **10**. The epoxide mixture **13** was opened to aldehydes **14** with MgBr · OEt_2 [11] [12] and without further purification reacted with (acetonylidene)(triphenyl)phosphorane to the α,β-unsaturated ketones **15** (61.4% yield from **13**). For characterization, the two diastereoisomers (2*S*,6*R*)- and (2*S*,6*S*)-**15** were separated by FC, and the subsequent steps were also carried out separately for both diastereoisomers.

For the synthesis of **1**, the separation of the diastereoisomeric compounds was performed only after conversion of the mixture **15** to the C_{18}-alcohol **16** as shown in *Scheme 3*. Protection of **15** with ethylene glycol in boiling benzene gave the ketal **17** in 99% yield [13]. After hydrolysis of the AcO group of **17**, alcohol **18** was treated with TsCl to give **19** in 92% yield with respect to **17** [14]. The reaction of **19** with NaCN yielded nitrile **20** which was treated with DIBAH to give aldehyde **21** (89% yield rel. to **19**) [15]. The *Horner-Emmons* reaction with ethyl 2-(diethylphosphinyl)propanoate gave the α,β-unsaturated ester **22** which was reduced with DIBAH to the diastereoisomeric alcohols **16** (95% yield rel. to **21**). The two diastereoisomers of **16** were separated by flash chromatography. The optically pure hydroxy ketal (2*R*,6*R*)-**16** was deprotected giving (2*R*,6*R*)-**23** in quantitative yield. *Grignard* reaction with vinylmagnesium bromide led to diol (2*R*,6*R*)-**24** in 60% yield [14] which was acetylated to the hydroxy acetate (2*R*,6*R*)-**25** (98% yield). Then, (2*R*,6*R*)-**25** was treated with PPh_3 · HBr to give the phosphonium salt (2*R*,6*R*)-**3** in 95% yield [16] (*Scheme 3*).

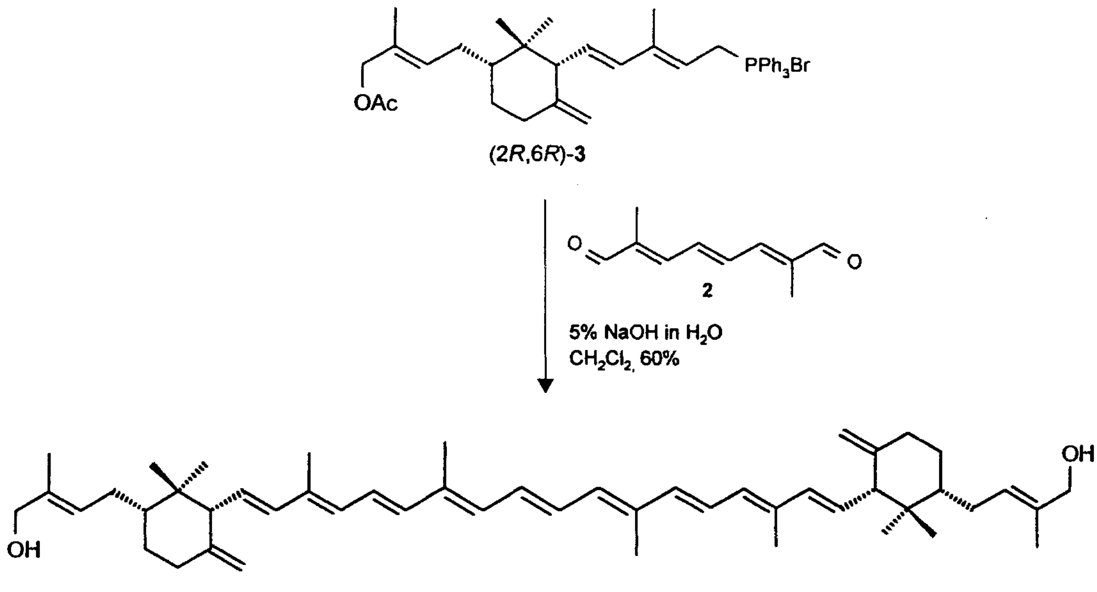
In a two-phase reaction in CH_2Cl_2 and 5% NaOH/H_2O, the phosphonium salt (2*R*,6*R*)-**3** reacted with C_{10}-dial **2** directly to the deprotected crystalline carotenoid (2*R*,6*R*,2'*R*,6'*R*)-sarcinaxanthin ((2*R*,6*R*,2'*R*,6'*R*)-**1**) in 60% yield. Recrystallization from (hexane/AcOEt) afforded (all-*E*,2*R*,6*R*,2'*R*,6'*R*)-sarcinaxanthin ((all-*E*,2*R*,6*R*,2'*R*,6'*R*)-**1**) (*Scheme 4*).

Scheme 3



a) 3-$ClC_6H_4CO_3H$, CH_2Cl_2; 90%. *b*) *t*-AmONa, THF/DMSO; 95%. *c*) $MgBr_2 \cdot OEt_2$, THF. *d*) Toluene, 62% rel. to 13. *e*) $(CH_2OH)_2$, benzene; 96%. *f*) 10% KOH in MeOH; 95%. *g*) TsCl, Py, THF; 96%. *h*) NaCN, DMF; 98%. *i*) DIBAH, hexane; 91%. *j*) NaH; 96%. *k*) DIBAH, hexane; 95%. *l*) Separation. *m*) Pyridinium toluene-4-sulfonate, acetone, H_2O; 99%. *n*) Et_2O; 60%. *o*) Ac_2O, Py, THF; 98%. *p*) $PPh_3 \cdot HBr$, MeOH; 95%.

Scheme 4



(all-*E*,2*R*,6*R*,2′*R*,6′*R*)-1

Using (2*R*,6*S*)-**16** and applying the same pathway *via* (2*R*,6*S*)-**3**, also (all-*E*,2*R*,6*S*, 2′*R*,6′*S*)-2,2′-bis(4-hydroxy-3-methylbut-2-enyl)-γ,γ-carotene ((all-*E*,2*R*,6*S*,2′*R*,6′*S*)-**1**) was synthesized.

3. Spectroscopic Studies and Conclusions. – The ^{1}H-NMR, UV/VIS, and MS data of (all-*E*,2*R*,6*R*,2′*R*,6′*R*)- and (all-*E*,2*R*,6*S*,2′*R*,6′*S*)-**1** are in full agreement with the data previously reported. Using 400 MHz ^{1}H- and ^{13}C-NMR, DEPT, COSY, T-ROESY, and inverse HMQC experiments, all protons and C-atoms of the two diastereoisomers were unambiguously assigned (*Table*). Because of the different configuration of the ring of the two compounds, all ^{1}H- and ^{13}C-signals of the ring atoms of the two diastereoisomers are different. Especially the signals of the exocyclic methylidene group (CH_2(18)) are influenced. Since in the (2*R*,6*R*)-configuration, the polyene chain is in close vicinity to the methylidene group, the two protons show significantly different signals.

The CD spectrum of (all-*E*,2*R*,6*R*,2′*R*,6′*R*)-**1** (*Fig.*) with maxima and minima at 200(+), 205(−), 267.5(−), 332(+), 449(−), 466(+), 483(−) and 491(+) nm, when compared to the natural product (267(−), 335(+) nm), finally establishes the (all-*E*,2*R*,6*R*,2′*R*,6′*R*)-configuration of the natural compound.

The authors are grateful to the *Swiss National Science Foundation* for financial support, to *F. Hoffmann-La Roche Ltd.*, Basel, for financial support and providing chemicals, and to Mrs. Kohler (*F. Hoffmann-La Roche Ltd.*, Basel) for measuring the CD spectra.

Table. *[1]H- and [13]C-NMR Data* (400 and 100.6 MHz, resp., $CDCl_3$) *of (2R,6R,2′R,6′R)- and (2R,6S,2′R,6′S)-*1

	^{1}H-NMR (δ[ppm], J[Hz])		^{13}C-NMR (δ[ppm])	
	(2*R*,6*R*,2′*R*,6′*R*)-1	(2*R*,6*S*,2′*R*,6′*S*)-1	(2*R*,6*R*,2′*R*,6′*R*)-1	(2*R*,6*S*,2′*R*,6′*S*)-1
C(1)	–	–	39.21	37.78
CH(2)	1.28 (*tm*, J = 12.0)	1.50 (*tm*, J = 11.2)	48.43	42.83
CH_2(3)	1.18 (*qd*, J = 12.4, 4.0, H_{ax})	1.22 (*qd*, J = 12.4, 4.0, H_{ax})	28.86	28.28
	1.71 (*m*, H_{eq})	1.73 (*dq*, J = 12.8, 4.0, H_{eq})		
CH_2(4)	2.03 (*td*, J = 12.8, 4.0, H_{ax})	2.17 (*m*)	36.30	31.40
	2.35 (*dq*, J = 12.8, 1.0, H_{eq})			
C(5)	–	–	150.33	149.90
CH(6)	2.47 (*d*, J = 10.0)	2.55 (*d*, J = 8.8)	58.43	60.64
CH(7)	5.82 (*dd*, J = 15.6, 10.0)	5.98 (*dd*, J = 15.4, 8.8)	128.34	128.79
CH(8)	6.12 (*d*, J = 15.6)	6.14 (*d*, J = 15.4)	137.51	136.09
C(9)	–	–	135.36	135.41
CH(10)	6.11 (*d*, J = 12.8)	6.11 (*d*, J = 12.8)	130.63	130.82
CH(11)	6.62 ('*t*', J = 13)	6.61 ('*t*', J = 12.8)	124.87	124.90
CH(12)	6.34 (*d*, J = 14.8)	6.32 (*d*, J = 14.8)	137.31	137.28
C(13)	–	–	136.37	136.36
CH(14)	6.24 (*d*, J = 8.0)	6.26 (*d*, J = 11.4)	132.40	132.42
CH(15)	6.62 ('*t*', J = 8.0)	6.62 ('*t*', J = 11)	129.95	130.11
Me(16)	0.95 (*s*)	0.91 (*s*)	27.62	27.21
Me(17)	0.73 (*s*)	0.84 (*s*)	15.21	22.36
CH_2(18)	4.53 (*s*, H *cis* to C(6))	4.64 (*s*, H *cis* to C(6))	108.09	108.56
	4.76 (*s*, H *trans* to C(6))	4.67 (*s*, H *trans* to C(6))		
Me(19)	1.97 (*s*)	1.92 (*s*)	13.16	12.78
Me(20)	1.96 (*s*)	1.96 (*s*)	12.78	13.10
CH_2(1″)	1.71 (*m*)	1.75 (*dm*, J = 4.1)	28.41	27.81
	2.24 (*dd*, J = 14.7, 5.4)	2.21 (*m*)		
CH(2″)	5.42 (*tm*, J = 6.8)	5.43 (*tm*, J = 6.3)	126.11	125.91
C(3″)	–	–	135.22	135.19
CH_2(4″)	4.02 (*s*)	4.01 (*s*)	69.04	68.90
Me–C(3″)	1.66 (*s*)	1.65 (*s*)	13.79	13.81
OH	1.58 (br. *s*)	1.59 (br. *s*)		

Experimental Part

1. *General.* All experiments were carried out under N_2 or Ar. Solvents were distilled or purchased in HPLC quality. Most reactions were worked up according to the following procedure (= usual workup): Extraction with (*t*-Bu)OMe or AcOEt, followed by washing with sat. aq. $NaHCO_3$ soln. and brine. The combined aq. phase was re-extracted, the combined org. phase dried ($MgSO_4$), and the solvent evaporated under reduced pressure. TLC: silica gel KG *60* F_{254} (*Merck*). FC: silica gel *60* (*Baker*, 0.040–0.063 mm). M.p.: *Büchi 510*; not corrected. UV Spectra: *Perkin-Elmer 554*; λ_{max} in nm. IR Spectra: *Perkin-Elmer 782* spectrometer, ν in cm^{-1}. ^{1}H- and ^{13}C-NMR Spectra: *Bruker AC 300* (300 and 75.5 MHz, resp.), *Bruker AM 400* (400 and 100.6 MHz, resp.); in $CDCl_3$; chemical shift δ in ppm rel. to $SiMe_4$ using $CDCl_3$ (δ = 7.27 as reference, J in Hz). Mass spectra: *Varian MAT CH-7A*; *m*/*z* (rel. intensity in %), ionization energy 70 eV.

2. *(1*R*,3*S*)-1,2,2-Trimethylcyclopentane-1,3-dimethanol* (**5**). To a soln. of (+)-camphoric acid (50 g, 250 mmol; **4**) in THF (500 ml), $NaBH_4$ (36.5 g, 970 mmol) was slowly added at −10°. The white slurry was stirred for 1 h, and then $BF_3 \cdot OEt_2$ (150 ml, 580 mmol) was added dropwise. After 1 h, the slurry was poured onto ice/H_2O and the white residue carefully dissolved with H_2O and the slurry then poured onto ice/H_2O. The mixture was worked up as usual. FC (hexane/AcOEt 65:35) and subsequent crystallization (AcOEt/hexane) afforded 39.94 g (94%) of **5**. M.p. 131.5–133°. IR (KBr): 3621*s*, 2941*s*, 2878*s*, 1464*m*, 1372*m*, 1020*s*. ^{1}H-NMR (300 MHz, $CDCl_3$): 0.79 (*s*, Me–C(2)); 1.01 (*s*, Me–C(1)); 1.02 (s, Me–C(2)); 1.36 (*m*, H_{exo}–C(5), H_{exo}–C(4));

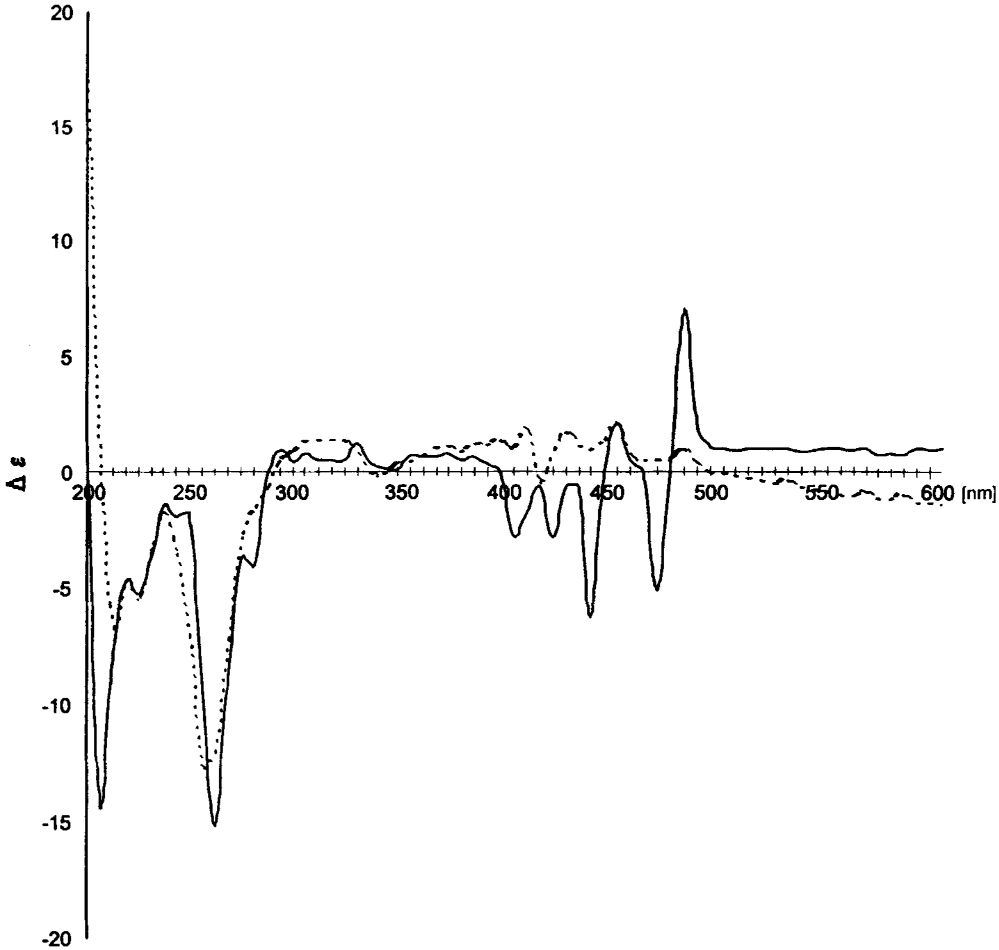


Figure. *CD Spectra of (all-*E*,2*R*,6*R*,2′*R*,6′*R*)-1 at −180°* (—) *and at 20°* (· · · ·)

1.60 (*dt*, J = 12.5, 6.0, H−C(3)); 1.95 (*m*, H$_{\text{'endo'}}$−C(5)); 2.04 (*m*, H$_{\text{'endo'}}$−C(4)); 3.47 (*d*, J = 11, 1 H, CH_2−C(1)); 3.51 (*dd*, J = 10.2, 8.1, 1 H, CH_2−C(3)); 3.58 (*d*, J = 11, 1H, CH_2−C(1)); 3.73 (*dd*, J = 10.2, 5.5, 1 H, CH_2−C(3)). ^{13}C-NMR (75.5 MHz, $CDCl_3$): 18.49 (*Me*−C(1)); 20.14 (*Me*−C(2)); 24.18 (*Me*−C(2)); 25.53 (C(5)); 33.74 (C(4)); 43.96 (C(2)); 48.80 (C(1)); 50.49 (C(3)); 64.90 (CH_2−C(3)); 69.15 (CH_2−C(1)). MS: 154 (7, $[M - H_2O]^+$), 139 (64), 123 (100), 109 (24), 95 (23), 85 (45), 81 (66), 69 (56), 55 (41), 43 (63).

3. *(1*R*,3*S*)-3-{[(*tert*-Butyl)dimethylsilyloxy]methyl}-1,2,2-trimethylcyclopentane-1-methanol* (**6**). At 0°, **5** (74.6 g, 434 mmol) was dissolved in CH_2Cl_2 (500 ml) and (*t*-Bu)Me_2SiCl (71.84 g, 477 mmol) in CH_2Cl_2 (300 ml) was added dropwise within 1½ h. The mixture was worked up as usual. FC (hexane/AcOEt 94:6) gave 104.84 g (83%) of **6**. IR ($CDCl_3$): 3630*s*, 2947*s*, 2928*s*, 2859*s*, 1470*m*, 1372*m*, 1104*s*, 837*s*. ^{1}H-NMR (300 MHz, $CDCl_3$): 0.05 (*s*, Me_2Si); 0.79 (*s*, Me−C(2)); 0.90 (*s*, *t*-Bu); 1.00 (*s*, Me−C(1)); 1.01 (*s*, Me−C(2)); 1.36 (*m*, H$_{\text{'exo'}}$−C(5)); 1.40 (*m*, H$_{\text{'exo'}}$−C(4)); 1.49 (br. *s*, OH); 1.57 (*dt*, J = 12.5, 6.0, H−C(3)); 1.87 (*m*, H$_{\text{'endo'}}$−C(5)); 2.08 (*m*, H$_{\text{'endo'}}$−C(4)); 3.47 (*d*, J = 11, 1H, CH_2−C(1)); 3.50 (*dd*, J = 10.2, 8.1, 1H, CH_2−C(3)); 3.57 (*d*, J = 11, 1H, CH_2−C(1)); 3.66 (*dd*, J = 10.2, 5.5, 1H, CH_2−C(3)). ^{13}C-NMR (75.5 MHz, $CDCl_3$): −5.40 (*Me*$_2$Si); 18.26 (Me_3*C*); 18.35 (*Me*−C(1)); 20.40 (*Me*−C(2)); 24.40 (*Me*−C(2)); 25.29 (C(5)); 25.94 (*Me*$_3$C); 33.68 (C(4)); 43.86 (C(2)); 48.90 (C(1)); 50.10 (C(3)); 64.69 (CH_2−C(3); 69.31 (CH_2−C(1)). MS: 271 (1, $[M - Me]^+$), 229 (6), 211 (7), 199 (5), 155 (5), 137 (100), 105 (75), 95 (67), 89 (34), 81 (61), 75 (86).

4. *(1*R*,3*S*)-3-{[(*tert*-Butyl)dimethylsilyloxy]methyl}-1,2,2-trimethylcyclopentane-1-carbaldehyde* (**7**). At $-78°$, $(COCl)_2$ (31.9 ml, 371 mmol) and DMSO (62.3 ml, 878 mmol) were dissolved in CH_2Cl_2 (450 ml) and stirred for 30 min. Afterwards, **6** (96.9 g, 338 mmol) in CH_2Cl_2 (300 ml) was added and the soln. stirred for 1 h. Then, Et_3N (165 ml, 1.18 mol) was added and the soln. stirred for 20 min, allowed to warm up to r.t., and then stirred for 1 additional h. Sat. NH_4Cl soln. was added to the white slurry and the mixture worked up as usual. The crude **7** was used without further purification.

5. *(1*S*,3*S*)-3-{[(*tert*-Butyl)dimethylsilyloxy]methyl}-1,2,2-trimethyl-1-vinylcyclopentane* (**8**). A soln. of $MePPh_3Br$ (190 g, 540 mmol) and BuLi (1.6M in hexane, 355 ml, 560 mmol) in THF (600 ml) was stirred for 45 min. Then a soln. of **7** (106.3 g, 338 mmol) in THF (200 ml) was added at such a rate that the temp. did not exceed 25°. After 20 min, the soln. was worked up as usual. FC (hexane/AcOEt 9:1) afforded 90.05 g (94.5%) of **8**. IR ($CDCl_3$): 2920*s*, 2885*s*, 1636*m*, 1470*s*, 1461*s* 1388*m*, 1370*m*, 1251*s*, 1104*s*, 835*vs*. ^1H-NMR (300 MHz, $CDCl_3$): 0.05 (*s*, Me_2Si); 0.79 (*s*, Me–C(2)); 0.91 (*s*, *t*-Bu); 0.93 (*s*, Me–C(1)); 0.98 (*s*, Me–C(2)); 1.31 (*m*, $H_{exo'}$–C(5)); 1.39 (*m*, $H_{exo'}$–C(4)); 1.57 (*dt*, *J* = 12.5, 6.0, H–C(1)); 1.91 (*m*, $H_{endo'}$–C(4), $H_{endo'}$–C(5)); 3.51 (*dd*, *J* = 10.2, 8.1, 1 H, Me–CH_2); 3.67 (*dd*, *J* = 10.2, 5.5, 1 H, Me–CH_2); 5.04 (*d*, *J* = 17.4, 1 H, CH_2=CH, *cis* to C(1)); 5.11 (*d*, *J* = 10.8, 1 H, CH_2=CH, *trans* to C(1)); 5.89 (*dd*, *J* = 17.4, 10.8, CH_2=*CH*). ^{13}C-NMR (75.5 MHz, $CDCl_3$): −5.37 (Me_2Si); 18.25 (Me_3C); 18.40 (*Me*–C(1)); 22.29 (*Me*–C(2)); 22.69 (*Me*–C(2)); 25.15 (C(5)); 25.95 (Me_3*C*); 34.41 (C(4)); 44.65 (C(2)); 49.03 (C(3)); 51.06 (C(1)); 64.72 (CH_2–C(3)); 111.78 (CH_2=CH); 144.97 (CH_2=*C*H). MS: 267 (4, $[M - Me]^+$), 225 (100), 195 (10), 183 (83), 153 (30), 149 (51), 115 (28), 107 (47), 89 (58), 75 (86).

6. *(1*S*,3*S*)-2,2,3-Trimethyl-3-vinylcyclopentane-1-methanol* (**9**). At r.t., **8** (90 g, 319 mmol) was dissolved in THF (650 ml), and Bu_4NF (119.8 g, 382.8 mmol) was added at once. The soln. was stirred for 4 h and diluted with H_2O. The org. phase was extracted with H_2O (7×) and then worked up as usual. FC (hexane/AcOEt 65:35) afforded 53.60 g (100%) of **9**. IR ($CDCl_3$): 3320*s*, 2961*s*, 2885*s*, 1636*m*, 1467*m*, 1370*s*, 1020*s*, 920*s*. ^1H-NMR (400 MHz, $CDCl_3$): 0.67 (*s*, Me–C(2)); 0.91 (*s*, Me–C(3)); 0.96 (*s*, Me–C(2)); 1.31 (*m*, $H_{exo'}$–C(4)); 1.41 (*m*, $H_{exo'}$–C(5)); 1.65 (br. *s*, OH); 1.89 (*m*, $H_{endo'}$–C(4)); 1.97 (*m*, $H_{endo'}$–C(5)); 2.10 (*m*, H–C(1)); 3.51 (*dd*, *J* = 10.2, 8.1, 1H, CH_2–OH); 3.72 (*dd*, *J* = 10.2, 5.5, 1 H, CH_2–OH); 4.92 (*d*, *J* = 17.4, 1 H, CH_2=CH, *cis* to C(3)); 4.98 (*d*, *J* = 10.8, 1 H, CH_2=CH, *trans* to C(3)); 5.86 (*dd*, *J* = 17.4, 10.8, CH_2=*CH*). ^{13}C-NMR (100.61 MHz, $CDCl_3$): 19.56 (*Me*–C(3)); 22.20 (*Me*–C(2)); 22.47 (*Me*–C(2)); 25.43 (C(4)); 34.40 (C(5)); 44.70 (C(2)); 49.40 (C(1)); 50.91 (C(3)); 65.33 (CH_2OH); 112.07 (CH_2=CH); 144.61 (CH_2=*C*H). MS: 168 (1, M^+), 153 (11), 135 (15), 107 (30), 95 (32), 82 (40), 68 (69), 55 (19), 41 (37), 28 (21), 18 (100).

7. *(1*S*,3*S*)-2,2,3-Trimethyl-3-vinylcyclopentane-1-methyl Acetate* (**10**). To a soln. of **9** (53.6 g, 319 mmol) in pyridine/THF 3:5 (400 ml), Ac_2O (60.1 ml, 460 mmol) was added. The soln. was stirred overnight and worked up as usual. Purification by FC (hexane/AcOEt 85:15) gave 66.65 g (99.5%) of **10**. IR ($CDCl_3$): 3082*w*, 2978*s*, 2882*s*, 1739*s*, 1639*w*, 1468*m*, 1394*m*, 1370*m*, 1280*vs*, 1035*s*. ^1H-NMR (300 MHz, $CDCl_3$): 0.69 (*s*, Me–C(2)); 0.91 (*s*, Me–C(3)); 0.97 (*s*, Me–C(2)); 1.34 (*m*, $H_{exo'}$–C(4)); 1.41 (*m*, $H_{exo'}$–C(5)); 1.92 (*m*, $H_{endo'}$–C(4), $H_{endo'}$–C(5)); 2.03 (*s*, Ac); 2.22 (*m*, H–C(1)); 4.00 (*dd*, *J* = 10.2, 8.1, 1H, CH_2–OH); 4.04 (*dd*, *J* = 10.2, 5.5, 1 H, CH_2–OH); 4.92 (*d*, *J* = 17.5, 1H, CH_2=CH, *cis* to C(3)); 4.99 (*d*, *J* = 17.5, 1H, CH_2=CH, *trans* to C(3)); 5.87 (*dd*, *J* = 17.5, 10.8, CH_2=*CH*). ^{13}C-NMR (75.5 MHz, $CDCl_3$): 19.52 (*Me*–C(3)); 21.00 (*Me*CO); 22.24 (*Me*–C(2)); 22.25 (*Me*–C(2)); 25.21 (C(4)); 34.31 (C(5)); 44.81 (C(2)); 45.57 (C(1)); 50.86 (C(3)); 66.71 (CH_2OH); 112.23 (CH_2=CH); 144.41 (CH_2=*C*H); 171.17 (Me*C*O). MS: 210 (6, M^+), 189 (16), 147 (54), 135 (47), 121 (24), 107 (100), 94 (66), 82 (53), 68 (71), 43 (63).

8. *(1*S*,4*R*)-4-(Bromomethyl)-2,2-dimethyl-3-methylidenecyclohexane-1-methyl Acetate* (**11**). At 70°, **10** (66 g, 314 mmol) was dissolved in THF (1000 ml), and TBCO (155 g, 375 mmol, prepared from 2,4,6-tribromophenol and Br_2 in AcOH [17]) was added at once. The brown soln. was stirred for 1 h and then cooled to 30°. Afterwards, AcOH (60 ml, 1.03 mol) and Zn (61 g, 930 mmol) were added, and the slurry was stirred for 45 min at 65°. The slurry was filtered and the org. phase worked up as usual. FC (hexane/AcOEt 99:1) afforded 33 g (34%) of **11/11a** and 34 g (52%) of **10**. The mixture **11/11a** was used for the next step. MS: 288 (0.2, M^+), 250 (25), 228 (23), 213 (22), 185 (9), 149 (100), 135 (69), 121 (45), 107 (84), 93 (66), 79 (42), 67 (24), 55 (23).

9. *(3*R*,5*S*,8*R*)- and (3*S*,5*S*,8*R*)-8-Bromomethyl-4,4-dimethyl-1-oxaspiro[2.5]octan-5-methyl Acetate* (**12**). At r.t., **11/11a** (33 g, 110 mmol) and $3\text{-}ClC_6H_4CO_3H$ (70%, 36.5 g, 145 mmol) were dissolved in CH_2Cl_2 (500 ml). The soln. was stirred for 3 h diluted with hexane and the precipitated acid filtered. The org. phase was worked up as usual, affording 29.92 g (90%) of **12/12a** after FC (hexane/AcOEt 92:8). IR ($CDCl_3$): 3062*w*, 2960*s*, 2864*s*, 1735*vs*, 1470*s*, 1390*s*, 1370*s*, 1245*vs*, 1061*s*, 900*s*. ^1H-NMR (400 MHz, $CDCl_3$)[4]): 0.82 (*s*, Me(16));

[4]) Numbering according to the *IUPAC/IUB* nomenclature rules for carotenoids (see *Scheme 4*).

0.97 (*s*, Me(17)); 1.31 (*qd*, *J* = 12.4, 4, H_{ax}–C(4)); 1.43 (*qd*, *J* = 13.3, 3.7, H_{ax}–C(3)); 1.75 (*ddd*, *J* = 16.1, 8.0, 4, H–C(2)); 1.83 (*qd*, *J* = 13.3, 3.7, H_{eq}–C(3)); 1.93 (*qd*, *J* = 12.4, 3.2, H_{eq}–C(4)); 2.03 (*s*, Ac); 2.39 (*dddd*, *J* = 16.3, 7.0, 5.8, 1.2, H–C(5)); 2.84 (*d*, *J* = 3.2, H–C(7)); 2.89 (*d*, *J* = 3.2, H–C(7)); 2.94 (*dd*, *J* = 10.3, 5.8, 1 H, CH_2–C(5)); 3.13 (*dd*, *J* = 10.3, 7.0, 1 H, CH_2–C(5)); 3.82 (*dd*, *J* = 11.0, 8.1, 1 H, CH_2OAc); 4.16 (*dd*, *J* = 11.0, 3.9, 1 H, CH_2OAc). ^{13}C-NMR (100.61 MHz, $CDCl_3$)[4]): 19.94(C(17)); 20.67(C(16)); 20.95(*Me*CO); 25.78(C(3)); 29.24(C(4)); 32.56(C(18)); 36.86(C(1)); 39.10(C(5)); 42.67(C(2)); 47.16(C(7)); 63.89(C(6)); 65.92(CH_2OAc); 171.04(Me*C*O). MS: 304(1, M^+), 250(4), 226(54), 216(8), 201(10), 165(81), 151(44), 133(97), 121(100), 107(56), 93(69), 79(56), 67(39), 55(46), 43(87).

10. *(3R,5S)- and (3S,5S)-4,4-Dimethyl-8-methylidene-1-oxaspiro[2.5]octan-5-methyl Acetate* (**13**). A slurry of NaH (19 g, 475 mmol) and $MeCH_2C(Me)_2OH$ (61 ml, 570 mmol) in THF (150 ml) was stirred for 1 h. Then, **12/12 a** (29.5 g, 95 mmol) in THF (100 ml) was added at once. The slurry was stirred for 10 min, and then, DMSO (120 ml) was added and the mixture stirred at 70° for 1½ h. The slurry was allowed to cool to r.t., the residue filtered off, and the soln. worked up as usual. The light brown oil was dissolved with THF (100 ml), and then, a soln. of Ac_2O (35 ml) in pyridine (50 ml) was added and stirred overnight. The mixture was worked up as usual, giving 5.6 g (8% rel. to **10**) of **13** after FC (hexane/AcOEt 92:8). IR ($CDCl_3$): 3080*w*, 2978*s*, 2880*s*, 1741*vs*, 1640*m*, 1468*m*, 1390*m*, 1367*s*, 1234*vs*, 1030*s*, 910*s*. ^{1}H-NMR (300 MHz, $CDCl_3$)[4]): 0.86 (*s*, Me(16)); 0.91 (*s*, Me(17)); 1.46 (*qd*, *J* = 13.3, 3.7, H_{ax}–C(3)); 1.84 (*m*, H–C(2), H_{ax}–C(4)); 2.05 (*s*, Ac); 2.15 (*tdt*, *J* = 13.3, 4.8, 1.5, H_{eq}–C(3)); 2.45 (*d*, *J* = 5.5, H–C(7)); 2.50 (*qd*, *J* = 12.4, 3.2, H_{eq}–C(4)); 2.91 (*d*, *J* = 3.2, H–C(7)); 3.89 (*dd*, *J* = 11.0, 8.1, 1 H, CH_2OAc); 4.20 (*dd*, *J* = 11.0, 5.0, 1 H, CH_2OAc); 4.74 ('*s*', H–C(18) *cis* to C(6)); 4.95 ('*s*', H–C(18) *trans* to C(6)). ^{13}C-NMR (75.5 MHz, $CDCl_3$)[4]): 18.12(C(17)); 20.98(*Me*CO); 21.27(C(16)); 25.95(C(3)); 33.18(C(4)); 36.96(C(1)); 45.78(C(2)); 52.71(C(7)); 64.78(C(6)); 65.35(CH_2OAc); 107.08(C(18)); 145.61(C(5)); 171.09(Me*C*O). MS: 181(1, $[M - 43]^+$), 250(4), 226(54), 216(8), 174(3), 164(6), 149(58), 135(15), 121(33), 112(19), 105(18), 91(26), 79(16), 43(30), 18(100).

11. *(1R,3S)- and (1S,3S)-3-[(Acetoxy)methyl]-2,2-dimethyl-6-methylidenecyclohexane-1-carbaldehyde* (**14**). At –5°, **13** (6.54 g, 29 mmol) was dissolved in abs. Et_2O (100 ml) and powdered $MgBr_2 \cdot OEt_2$ (15 g, 58 mmol) added in portions. The mixture was allowed to warm to r.t., and after 4, 7, and 20 h, additional $MgBr_2 \cdot OEt_2$ (3 × 7.5 g) was added as a fine powder. The slurry was carefully diluted with H_2O and worked up as usual. The crude aldehyde **14** was used without further purification.

12. *4-{(1R,3S)- and (1S,3S)-3-[(Acetoxy)methyl]-2,2-dimethyl-6-methylidenecyclohexyl}but-3-en-2-one* (**15**). At –110°, **14** (8 g, 29 mmol) and (acetylmethylidene)triphenylphosphorane (18.4, 58 mmol) were dissolved in toluene (90 ml) and the soln. was refluxed overnight. The soln. was allowed to cool to r.t. and worked up as usual. Purification by FC (hexane/AcOEt 86:14) afforded 3 g of **13** and 2.91 g of **15**. The epoxide **13** was once again subjected to *Exper. 10* and *11*, finally affording 4.7 g (61.4%) of **15**. For spectroscopic data the two diastereoisomeric compounds were separated by FC (hexane/AcOEt 9:1).

*Data of (2S,6R)-***15**[4]): ^{1}H-NMR (400 MHz, $CDCl_3$)[4]): 0.79 (*s*, Me(16)); 0.97 (*s*, Me(17)); 1.37 (*qd*, *J* = 13.3, 4.2, H_{ax}–C(3)); 1.66 (*ddd*, *J* = 16.1, 8.1, 4.0, H–C(2)); 1.85 (*dq*, *J* = 12.4, 4.0, H_{eq}–C(3)); 2.05 (*s*, Ac); 2.10 (*qd*, *J* = 12.4, 4.0, H_{ax}–C(4)); 2.30 (*s*, Me(19)); 2.42 (*qd*, *J* = 12.4, 3.2, H_{eq}–C(4)); 2.60 (*d*, *J* = 10.0, H–C(6)); 3.83 (*dd*, *J* = 11.0, 8.1, 1 H, CH_2OAc); 4.28 (*dd*, *J* = 11.0, 4.0, 1 H, CH_2OAc); 4.48 ('*s*', H–C(18) *cis* to C(6)); 4.85 ('*s*', H–C(18) *trans* to C(6)); 6.12 (*d*, *J* = 16, H–C(8)); 6.90 (*dd*, *J* = 16, 10.3, H–C(7)). ^{13}C-NMR (100.61 MHz, $CDCl_3$)[4]): 15.84(C(17)); 21.00(*Me*CO); 26.91(C(3)); 27.38(C(16)); 27.61(C(19)); 35.49(C(4)); 37.90(C(1)); 46.46(C(2)); 57.52(C(6)); 65.57(CH_2OAc); 109.44(C(18)); 134.03(C(8)); 145.71(C(7)); 147.73(C(5)); 171.09(Me*C*O); 197.86(C(9)). MS: 264(28, M^+), 224(16), 204(8), 189(23), 176(14), 161(71), 149(95), 135(12), 121(56), 105(24), 93(21), 81(26), 69(16), 43(75), 18(100).

*Data of (2S,6S)-***15**[4]): ^{1}H-NMR (400 MHz, $CDCl_3$)[4]): 0.90 (*s*, Me(16)); 0.99 (*s*, Me(17)); 1.38 (*m*, H_{ax}–C(3)); 1.84 (*m*, H–C(2), H_{eq}–C(3)); 2.06 (*s*, Ac); 2.23 (*m*, 2 H–C(4)); 2.25 (*s*, Me(19)); 2.59 (*d*, *J* = 9.0, H–C(6)); 3.86 (*dd*, *J* = 11.0, 8.1, 1 H, CH_2OAc); 4.23 (*dd*, *J* = 11.0, 4.0, 1 H, CH_2OAc); 4.72 ('*s*', H–C(18) *cis* to C(6)); 4.81 ('*s*', H–C(18) *trans* to C(6)); 6.13 (*d*, *J* = 16, H–C(8)); 7.04 (*dd*, *J* = 16, 10.3, H–C(7)). ^{13}C-NMR (100.61 MHz, $CDCl_3$)[4]): 21.00(*Me*CO); 22.65(C(17)); 26.44(C(3)); 27.16(C(16)); 27.52(C(19)); 30.68(C(4)); 36.73(C(1)); 41.12(C(2)); 60.00(C(6)); 65.52(CH_2OAc); 111.14(C(18)); 132.19(C(8)); 146.13(C(7)); 146.85(C(5)); 171.18(Me*C*O); 198.11(C(9)).

13. *(1S,3R)- and (1S,3S)-2,2-Dimethyl-3-[2-(2-methyl-1,3-dioxolan-2-yl)ethenyl]-4-methylidenecyclohexane-1-methyl Acetate* (**17**). To a soln. of **15** (4.7 g, 17.8 mmol) in benzene (120 ml), $(CH_2OH)_2$ (10 ml) and pyridinium toluene-4-sulfonate (15 mg) were added. The soln. was stirred at 80° for 24 h, allowed to cool to r.t. and worked up as usual. FC (hexane/AcOEt 9:1) gave 5.14 g (94%) of **17**.

*Data of (2S,6R)-***17**[4]): ^{1}H-NMR (300 MHz, $CDCl_3$)[4]): 0.79 (*s*, Me(16)); 0.97 (*s*, Me(17)); 1.32 (*qd*, *J* = 13.3, 4.2, H_{ax}–C(3)); 1.63 (*ddd*, *J* = 16.1, 8.1, 4.0, H–C(2)); 1.82 (*dq*, *J* = 12.4, 4.0, H_{eq}–C(3)); 2.05 (*s*, Ac);

2.09 (*qd*, $J = 12.4$, 4.0, H_{ax}–C(4)); 2.30 (*s*, Me(19)); 2.39 (*qd*, $J = 12.4$, 3.2, H_{eq}–C(4)); 2.42 (*d*, $J = 10.0$, H–C(6)); 3.78 (*dd*, $J = 11.0$, 8.1, 1 H, CH_2OAc); 3.85, 3.94 (2*m*, OCH_2CH_2O); 4.27 (*dd*, $J = 11.0$, 4.0, 1 H, CH_2OAc); 4.48 (*'s'*, H–C(18) *cis* to C(6)); 4.78 (*'s'*, H–C(18) *trans* to C(6)); 5.42 (*d*, $J = 16$, H–C(8)); 5.89 (*dd*, $J = 16$, 10.3, H–C(7)). ^{13}C-NMR (75.5 MHz, $CDCl_3$)[4]: 15.69 (C(17)); 21.00 (*Me*CO); 25.17 (C(19)); 27.07 (C(3)); 27.40 (C(16)); 35.58 (C(4)); 37.48 (C(1)); 46.60 (C(2)); 56.97 (C(6)); 64.44 (OCH_2CH_2O); 65.92 (CH_2OAc); 107.27 (C(9)); 108.66 (C(18)); 128.72 (C(8)); 134.08 (C(7)); 149.02 (C(5)); 171.09 (Me*C*O). MS: 308 (41, M^+), 292 (100), 232 (26), 170 (15), 100 (24), 87 (39).

Data of (2S,6S)-**17**[4]: ^{1}H-NMR (300 MHz, $CDCl_3$)[4]: 0.85 (*s*, Me(16)); 0.97 (*s*, Me(17)); 1.38 (*m*, H_{ax}–C(3)); 1.47 (*s*, Me(19)); 1.84 (*m*, H–C(2), H_{eq}–C(3)); 2.06 (*s*, Ac); 2.19 (*m*, 2 H–C(4)); 2.46 (*d*, $J = 9.0$, H–C(6)); 3.84, 3.96 (2*m*, OCH_2CH_2O); 3.86 (*dd*, $J = 11.0$, 8.1, 1H, CH_2OAc); 4.23 (*dd*, $J = 11.0$, 4.0, 1H, CH_2OAc); 4.62 (*'s'*, H–C(18) *cis* to C(6)); 4.71 (*'s'*, H–C(18) *trans* to C(6)); 5.42 (*d*, $J = 16$, H–C(8)); 6.05 (*dd*, $J = 16$, 10.3, H–C(7)). ^{13}C-NMR (75.5 MHz, $CDCl_3$)[4]: 21.02 (*Me*CO); 22.87 (C(17)); 25.02 (C(19)); 26.53 (C(3)); 26.94 (C(16)); 30.65 (C(4)); 36.22 (C(1)); 40.98 (C(2)); 59.11 (C(6)); 64.44 (OCH_2CH_2O); 65.71 (CH_2OAc); 107.37 (C(9)); 109.41 (C(18)); 129.59 (C(8)); 132.21 (C(7)); 148.58 (C(5)); 171.18 (Me*C*O).

14. *(1S,3R)- and (1S,3S)-2,2-Dimethyl-3-[2-(2-methyl-1,3-dioxolan-2-yl)ethenyl]-4-methylidenecyclohexane-1-methanol* (**18**). At r.t., **17** (5.14 g, 16.7 mmol) was dissolved in MeOH (60 ml) and 10% NaOH in MeOH (16.7 ml). The soln. was stirred for 2 h and worked up as usual. Purification by FC (hexane/AcOEt 85:15) gave 4.44 g (100%) of **18**.

Data of (2S,6R)-**18**[4]: IR ($CDCl_3$): 3620*s*, 3060*w*, 2980*s*, 2880*s*, 1640*m*, 1480*s*, 1450*s*, 1380*s*, 1220*s*. ^{1}H-NMR (300 MHz, $CDCl_3$)[4]: 0.65 (*s*, Me(16)); 0.94 (*s*, Me(17)); 1.27 (*qd*, $J = 13.3$, 4.2, H_{ax}–C(3)); 1.46 (*ddd*, $J = 16.1$, 8.0, 4.0, H–C(2)); 1.48 (*s*, Me(19)); 1.96 (*dq*, $J = 12.4$, 4.0, H_{eq}–C(3)); 2.02 (*qd*, $J = 12.4$, 4.0, H_{ax}–C(4)); 2.04 (br. *s*, OH); 2.39 (*qd*, $J = 12.4$, 3.2, H_{eq}–C(4)); 2.40 (*d*, $J = 10.0$, H–C(6)); 3.31 (*dd*, $J = 11.0$, 10.0, 1 H, CH_2OH); 3.85 (*dd*, $J = 11.0$, 4.0, 1 H, CH_2OH); 3.86, 3.96 (2*m*, OCH_2CH_2O); 4.47 (*'s'*, H–C(18) *cis* to C(6)); 4.78 (*'s'*, H–C(18) *trans* to C(6)); 5.41 (*d*, $J = 16$, H–C(8)); 5.88 (*dd*, $J = 16$, 10.3, H–C(7)). ^{13}C-NMR (75.5 MHz, $CDCl_3$)[4]: 15.80 (C(17)); 25.16 (C(19)); 26.93 (C(3)); 27.49 (C(16)); 35.80 (C(4)); 37.49 (C(1)); 50.23 (C(2)); 57.11 (C(6)); 63.83 (CH_2OH); 64.44 (OCH_2CH_2O); 107.33 (C(9)); 108.35 (C(18)); 129.03 (C(8)); 133.78 (C(7)); 149.50 (C(5)). MS: 266 (43, M^+), 251 (100), 232 (6), 177 (6), 165 (15), 147 (11), 133 (13), 105 (16), 100 (29), 87 (44).

Data of (2S,6S)-**18**[4]: ^{1}H-NMR (300 MHz, $CDCl_3$)[4]: 0.79 (*s*, Me(16)); 0.91 (*s*, Me(17)); 1.36 (*m*, H_{ax}–C(3)); 1.46 (*m*, H–C(2)); 1.47 (*s*, Me(19)); 1.81 (br. *s*, OH); 1.90 (*dq*, $J = 13.3$, 4.3, H_{eq}–C(3)); 2.20 (*m*, 2 H–C(4)); 2.39 (*d*, $J = 9.0$ H–C(6)); 3.36 (*dd*, $J = 11.0$, 10.0, 1 H, CH_2OH); 3.80 (*dd*, $J = 11.0$, 4.0, 1 H, CH_2OH); 3.83, 3.92 (2*m*, OCH_2CH_2O); 4.57 (*'s'*, H–C(18) *cis* to C(6)); 4.67 (*'s'*, H–C(18) *trans* to C(6)); 5.39 (*d*, $J = 16$, H–C(8)); 6.06 (*dd*, $J = 16$, 10.3, H–C(7)). ^{13}C-NMR (75.5 MHz, $CDCl_3$)[4]: 22.93 (C(17)); 24.98 (C(19)); 26.27 (C(3)); 27.05 (C(16)); 30.83 (C(4)); 36.22 (C(1)); 44.46 (C(2)); 59.27 (C(6)); 63.56 (CH_2OH); 64.44 (OCH_2CH_2O); 107.39 (C(9)); 109.10 (C(18)); 129.96 (C(8)); 131.87 (C(7)); 149.02 (C(5)).

15. *(1S,3R)- and (1S,3S)-2,2-Dimethyl-3-[2-(2-methyl-1,3-dioxolan-2-yl)ethenyl]-4-methylidenecyclohexane-1-methyl Tosylate* (**19**). To a soln. of **18** (3.51 g, 13.2 mmol) in pyridine (25 ml), TsCl (4.58 g, 23.8 mmol) was added. The mixture was stirred at 4° for 20 h, allowed to warm to r.t., and diluted with (*t*-Bu)OMe. The soln. was extracted with sat. $CuSO_4$ soln. until the aq. phase remained slightly blue. The aq. phase was re-extracted and worked up as usual. FC (hexane/AcOEt 9:1) afforded 5.31 g (95.4%) of **19**.

Data of (2S,6R)-**19**[4]: IR ($CDCl_3$): 3065*w*, 2959*s*, 2880*s*, 1740*m*, 1649*m*, 1601*m*, 1450*m*, 1368*s*, 1179*s*, 1100*s*, 1040*s*, 985*s*. ^{1}H-NMR (300 MHz, $CDCl_3$)[4]: 0.63 (*s*, Me(16)); 0.88 (*s*, Me(17)); 1.25 (*qd*, $J = 13.3$, 4.2, H_{ax}–C(3)); 1.47 (*s*, Me(19)); 1.64 (*ddd*, $J = 16.1$, 8.0, 4.0, H–C(2)); 1.81 (*dq*, $J = 12.4$, 4.0, H_{eq}–C(3)); 2.00 (*qd*, $J = 12.4$, 4.0, H_{ax}–C(4)); 2.34 (*qd*, $J = 12.4$, 3.2, H_{eq}–C(4)); 2.38 (*d*, $J = 10.0$, H–C(6)); 2.47 (*s*, *Me*C_6H_4); 3.77 (*dd*, $J = 11.0$, 10.0, 1 H, CH_2OTs); 3.86, 3.92 (2*m*, OCH_2CH_2O); 4.22 (*dd*, $J = 11.0$, 4.0, 1H, CH_2OTs); 4.49 (*'s'*, H–C(18) *cis* to C(6)); 4.77 (*'s'*, H–C(18) *trans* to C(6)); 5.42 (*d*, $J = 16$, H–C(8)); 5.84 (*dd*, $J = 16$, 10.3, H–C(7)); 7.36 (*d*, $J = 8.1$, arom. H); 7.78 (*d*, $J = 8.1$, arom. H). ^{13}C-NMR (75.5 MHz, $CDCl_3$)[4]: 15.82 (C(17)); 21.64 (*Me*C_6H_4); 25.18 (C(19)); 26.62 (C(3)); 27.31 (C(16)); 35.27 (C(4)); 37.36 (C(1)); 46.80 (C(2)); 56.74 (C(6)); 64.44 (OCH_2CH_2O); 71.91 (CH_2OTs); 107.23 (C(9)); 109.02 (C(18)); 127.86 (arom. C); 128.32 (C(8)); 129.86 (arom. C); 133.14 (arom. C); 134.39 (C(7)); 144.74 (arom. C); 148.49 (C(5)). MS: 420 (21, M^+), 405 (76), 233 (31), 177 (8), 161 (12), 155 (14), 133 (11), 119 (13), 105 (14), 100 (20), 91 (49), 87 (100), 43 (78).

Data of (2S,6S)-**19**[4]: ^{1}H-NMR (300 MHz, $CDCl_3$)[4]: 0.78 (*s*, Me(16)); 0.88 (*s*, Me(17)); 1.28 (*m*, H_{ax}–C(3)); 1.43 (*s*, 3 H–C(19)); 1.81 (*m*, H–C(2), H_{eq}–C(3)); 2.13 (*m*, 2 H–C(4)); 2.39 (*d*, $J = 9.0$, H–C(6)); 2.47 (*s*, *Me*C_6H_4); 3.84, 3.95 (2*m*, OCH_2CH_2O); 3.86 (*dd*, $J = 11.0$, 10.0, 1 H, CH_2OTs); 4.20 (*dd*, $J = 11.0$, 4.0, 1 H, CH_2OTs); 4.62 (*'s'*, H–C(18) *cis* to C(6)); 4.68 (*'s'*, H–C(18) *trans* to C(6)); 5.41 (*d*, $J = 16$, H–C(8)); 5.96 (*dd*, $J = 16$, 10.3, H–C(7)); 7.36 (*d*, $J = 8.1$ arom. H); 7.78 (*d*, $J = 8.1$ arom. H). ^{13}C-NMR (75.5 MHz,

$CDCl_3$)[4]): 21.54(MeC_6H_4); 22.81(C(17)); 24.92(C(19)); 25.93(C(3)); 26.72(C(16)); 30.24(C(4)); 36.02(C(1)); 41.20(C(2)); 58.83(C(6)); 64.44(OCH_2CH_2O); 71.66(CH_2OTs); 107.17(C(9)); 109.69(C(18)); 127.75(arom. C); 129.00(C(8)); 129.76(arom. C); 132.45(C(7)); 133.02(arom. C); 144.67(arom. C); 148.58(C(5)).

16. *(1R,3R)- and (1R,3S)-2,2-Dimethyl-3-[2-(2-methyl-1,3-dioxolan-2-yl)ethenyl]-4-methylidenecyclohexane-1-acetonitrile* (**20**). At 80°, **19** (5.3 g, 12.5 mmol) and NaCN (1.84 g, 37.5 mmol) were dissolved in DMF (30 ml) and stirred overnight. The soln. was allowed to cool to r.t., diluted with (*t*-Bu)OMe and worked up with sat. $NaHCO_3$ soln. The further workup was carried out as usual. FC (hexane/AcOEt 9:1) gave 3.32 g (97%) of **20**.

Data of (2R,6R)-**20**[4]): IR ($CDCl_3$): 3072*w*, 2959*s*, 2924*s*, 2876*s*, 2238*m*, 1670*vs*, 1455*m*, 1385*m*. ^{1}H-NMR (300 MHz, $CDCl_3$)[4]): 0.68 (*s*, Me(16)); 0.94 (*s*, Me(17)); 1.40 (*qd*, *J* = 13.3, 4.2, H_{ax}–C(3)); 1.48 (*s*, Me(19)); 1.74 (*ddd*, *J* = 16.1, 8.0, 4.0, H–C(2)); 2.00 (*dq*, *J* = 12.4, 4.0, H_{eq}–C(3)); 2.08 (*dd*, *J* = 11.0, 8.1, 1 H, CH_2CN); 2.10 (*qd*, *J* = 12.4, 4.0, H_{ax}–C(4)); 2.42 (*qd*, *J* = 12.4, 3.2, H_{eq}–C(4)); 2.43 (*d*, *J* = 10.0, H–C(6)); 3.86, 3.92 (2*m*, OCH_2CH_2O); 2.56 (*dd*, *J* = 11.0, 3.0, 1 H, CH_2CN); 4.53 ('*s*', H–C(18) *cis* to C(6)); 4.82 ('*s*', H–C(18) *trans* to C(6)); 5.46 (*d*, *J* = 16, H–C(8)); 5.89 (*dd*, *J* = 16, 10.3, H–C(7)). ^{13}C-NMR (75.5 MHz, $CDCl_3$)[4]): 14.68(C(17)); 19.12(CH_2CN); 25.20(C(19)); 27.26(C(16)); 28.95(C(3)); 35.49(C(4)); 38.17(C(1)); 44.85(C(2)); 56.54(C(6)); 64.44(OCH_2CH_2O); 107.24(C(9)); 109.42(C(18)); 119.76(CN); 128.42(C(8)); 134.52(C(7)); 148.06(C(5)). MS: 260(100, $[M-15]^+$), 223(3), 188(3), 87(26), 28(32).

Data of (2R,6S)-**20**[4]): ^{1}H-NMR (300 MHz, $CDCl_3$)[4]): 0.76 (*s*, Me(16)); 0.86 (*s*, Me(17)); 1.34 (*m*, H_{ax}–C(3)); 1.38 (*s*, Me(19)); 1.84 (*m*, H–C(2), H_{eq}–C(3)); 2.04 (*dd*, *J* = 11.0, 10.0, 1H, CH_2CN); 2.16 (*m*, 2 H–C(4)); 2.43 (*d*, *J* = 9.0, H–C(6)); 2.50 (*dd*, *J* = 11.0, 4.0, 1 H, CH_2CN); 3.78, 3.88 (2*m*, OCH_2CH_2O); 4.58 ('*s*', H–C(18) *cis* to C(6)); 4.66 ('*s*', H–C(18) *trans* to C(6)); 5.38 (*d*, *J* = 16, H–C(8)); 5.94 (*dd*, *J* = 16, 10.3, H–C(7)). ^{13}C-NMR (75.5 MHz, $CDCl_3$)[4]): 18.41(CH_2CN); 21.64(C(17)); 24.84(C(19)); 26.84(C(16)); 28.20(C(3)); 30.35(C(4)); 36.63(C(1)); 39.14(C(2)); 58.22(C(6)); 64.44(OCH_2CH_2O); 107.02(C(9)); 110.01(C(18)); 119.54(CN); 128.52(C(8)); 132.63(C(7)); 147.34(C(5)).

17. *(1R,3R)- and (1R,3S)-2,2-Dimethyl-3-[2-(2-methyl-1,3-dioxolan-2-yl)ethenyl]-4-methylidenecyclohexane-1-acetaldehyde* (**21**). At −78°, **20** (3.3 g, 11.8 mmol) was dissolved in hexane (50 ml) and DIBAH (16.5 ml, 16.5 mmol) was added by syringe. The soln. was stirred for 4 h and allowed to warm to r.t. Sat. NH_4Cl soln. was added, and the mixture stirred for 30 min, diluted with H_2O and worked up as usual, affording 2.99 g (91%) of **21** after purification by FC (hexane/AcOEt 9:1).

Data of (2R,6R)-**21**[4]): IR ($CDCl_3$): 3081*w*, 2961*s*, 2924*s*, 2887*s*, 1721*s*, 1645*m*, 1260*s*. ^{1}H-NMR (300 MHz, $CDCl_3$)[4]): 0.67 (*s*, Me(16)); 0.88 (*s*, Me(17)); 1.29 (*qd*, *J* = 13.3, 4.2, H_{ax}–C(3)); 1.47 (*s*, Me(19)); 1.61 (*m*, H–C(2)); 1.95 (*dq*, *J* = 12.4, 4.0, H_{eq}–C(3)); 2.10 (*dd*, *J* = 16.5, 3.0, 1 H, CH_2CHO); 2.10 (*m*, H_{ax}–C(4)); 2.33 (*qd*, *J* = 13.6, 2.6, H_{eq}–C(4)); 2.47 (*d*, *J* = 10.3 H–C(6)); 2.58 (*dd*, *J* = 16.5, 3.0, 1H, CH_2CHO); 3.86, 3.92 (2*m*, OCH_2CH_2O); 4.49 ('*t*', *J* = 0.5, H–C(18) *cis* to C(6)); 4.76 ('*t*', *J* = 0.5, H–C(18) *trans* to C(6)); 5.43 (*d*, *J* = 15.6, H–C(8)); 5.89 (*dd*, *J* = 15.6, 10.3, H–C(7)); 9.76 ('*d*', *J* = 0.5, 1H, CH_2CHO). ^{13}C-NMR (75.5 MHz, $CDCl_3$)[4]): 15.31(C(17)); 25.17(C(19)); 27.47(C(16)); 29.96(C(3)); 35.85(C(4)); 35.85(C(1)); 41.60(C(2)); 45.67(CH_2CHO); 56.88(C(6)); 64.44(OCH_2CH_2O); 107.29(C(9)); 108.75(C(18)); 129.11(C(8)); 133.87(C(7)); 148.90(C(5)); 202.59(CH_2CHO). MS: 278(58, M^+), 263(73), 206(67), 165(49), 109(90), 67(100).

Data of (2R,6S)-**21**[4]): ^{1}H-NMR (300 MHz, $CDCl_3$)[4]): 0.78 (*s*, Me(16)); 0.86 (*s*, Me(17)); 1.26 (*m*, H_{ax}–C(3)); 1.42 (*s*, Me(19)); 1.64 (*m*, H_{eq}–C(3)); 2.11 (*m*, H–C(2), H–C(4), 1H of CH_2CHO); 2.21 (*qd*, *J* = 12.4, 4.0, H_{eq}–C(4)); 2.50 (*m*, H–C(6), 1H, CH_2CHO); 3.82, 3.92 (2*m*, OCH_2CH_2O); 4.61 ('*s*', H–C(18) *cis* to C(6)); 4.66 ('*s*', H–C(18) *trans* to C(6)); 5.39 (*d*, *J* = 16, H–C(8)); 6.06 (*dd*, *J* = 16, 10.3, H–C(7)); 9.74 (*s*, 1H, CH_2CHO).

18. *Ethyl 4-{(1R,3R)- and (1R,3S)-2,2-Dimethyl-3-[2-(2-methyl-1,3-dioxolan-2-yl)ethenyl]-4-methylidenecyclohexyl}-2-methylbut-2-enoate* (**22**) At 0°, (diethylphosphinyl)propanoate (3.65 ml, 17 mmol) was dissolved in CH_2Cl_2 (100 ml) and NaOEt (7.5 ml, 20 mmol) was added by syringe. The brown soln. was stirred for 50 min and **21** (2.99, 10.74 mmol) was added. The soln. was stirred for additional 30 min and worked up as usual. Purification by FC (hexane/AcOEt 9:1) afforded 3.72 g (96%) of **22**.

Data of (2R,6R)-**22**[4]): IR ($CDCl_3$): 3082*w*, 2968*s*, 2891*s*, 1700*vs*, 1681*m*, 1480*s*, 1374*s*, 1282*s*, 1217*s*. ^{1}H-NMR (300 MHz, $CDCl_3$)[4]): 0.69 (*s*, Me(16)); 0.93 (*s*, Me(17)); 1.21 (*qd*, *J* = 13.3, 4.2, H_{ax}–C(3)); 1.28 (*t*, $MeCH_2O$); 1.38 (*ddd*, *J* = 16.1, 8.0, 4.0, H–C(2)); 1.48 (*s*, Me(19)); 1.67 (*dq*, *J* = 12.4, 4.0, H_{eq}–C(3)); 1.81 (*s*, Me–C(3″)); 1.89 (*m*, 1 H–C(1″)); 2.01 (*qd*, *J* = 12.4, 4.0, H_{ax}–C(4)); 2.32 (*m*, 1 H–C(1″)); 2.33 (*qd*, *J* = 12.4, 3.2, H_{eq}–C(4)); 2.49 (*d*, *J* = 10.0, H–C(6)); 3.85, 3.96 (2*m*, OCH_2CH_2O); 4.17 (*q*, $MeCH_2O$); 4.47 ('*s*', H–C(18) *cis* to C(6)); 4.73 ('*s*', H–C(18) *trans* to C(6)); 5.41 (*d*, *J* = 16, H–C(8)); 5.91 (*dd*, *J* = 16, 10.3, H–C(7)); 6.74 (*t*, *J* = 6.3, H–C(2″)). ^{13}C-NMR (75.5 MHz, $CDCl_3$)[4]): 12.48($MeCH_2O$); 14.28(*Me*–C(3″)); 15.10(C(17)); 25.18(C(19)); 27.47(C(16)); 29.12(C(3)); 29.73(C(1″)); 36.10(C(4)); 38.63(C(1)); 47.77(C(2));

57.07(C(6)); 60.40(MeCH_2O); 64.44(OCH_2CH_2O); 107.32(C(9)); 108.28(C(18)); 128.34(C(3″)); 129.43(C(8)); 133.62(C(7)); 142.13(C(2″)); 149.52(C(5)); 168.14(C(4″)). MS: 362(35, M^+), 347(94), 317(3), 217(4), 173(15), 147(7), 121(11), 100(18), 87(63), 73(15), 43(25), 28(100).

*Data of (2*R*,6*S*)-**22**[4])*: ^{1}H-NMR (300 MHz, $CDCl_3$)[4]): 0.77 (*s*, Me(16)); 0.87 (*s*, Me(17)); 1.15 (*m*, H_{ax}–C(3)); 1.23 (*t*, *Me*CH_2O); 1.37 (*s*, Me(19)); 1.56 (*m*, H–C(2), H_{eq}–C(3)); 1.74 (*s*, Me–C(3″)); 1.84 (*m*, H_{ax}–C(4)); 2.07 (*m*, 2 H–C(1″)); 2.22 (*m*, H_{eq}–C(4)); 2.41 (*d*, *J* = 9.0, H–C(6)); 3.76, 3.85 (2*m*, OCH_2CH_2O); 4.17 (*q*, MeCH_2O); 4.53 ('*s*', H–C(18) *cis* to C(6)); 4.58 ('*s*', H–C(18) *trans* to C(6)); 5.34 (*d*, *J* = 16, H–C(8)); 5.97 (*dd*, *J* = 16, 10.3, H–C(7)); 6.69 (*t*, *J* = 6.3, H–C(2″)). ^{13}C-NMR (75.5 MHz, $CDCl_3$)[4]): 12.41 (*Me*CH_2O); 14.23(*Me*–C(3″)); 22.35(C(17)); 24.97(C(19)); 26.93(C(16)); 28.43(C(3)); 29.02(C(1″)); 31.04(C(4)); 37.18(C(1)); 41.87(C(2)); 58.90(C(6)); 60.27(MeCH_2O); 64.33(OCH_2CH_2O); 107.21(C(9)); 109.00(C(18)); 128.26(C(3″)); 129.75(C(8)); 131.96(C(7)); 141.98(C(2″)); 148.94(C(5)); 167.92(C(4″)).

19. *4-{(1*R*,3*R*)- and (1*R*,3*S*)-2,2-Dimethyl-3-[2-(2-methyl-1,3-dioxolan-2-yl)ethenyl]-4-methylidenecyclohexyl}-2-methylbut-2-en-1-ol* (**16**). At −70°, **22** (4.13 g, 11 mmol) was dissolved in hexane (110 ml) and DIBAH (1M in hexane, 27.5 ml, 27.5 mmol) was added by syringe at such a rate that the temp. did not exceed −65°. The soln. was allowed to warm up to r.t., diluted with sat. NH_4Cl soln. and worked up with H_2O. FC (hexane/AcOEt 88:12) afforded 1.35 g (38.4%) of (2*R*,6*R*)-**16**[4]) and 2.17 g (61.6%) of (2*R*,6*S*)-**16**[4]).

*Data of (2*R*, 6*R*)-**16**[4])*: IR ($CDCl_3$): 3420*s*, 2980*s*, 2940*s*, 2882*s*, 1741*s*, 1649*m*, 1441*s*, 1374*s*, 1208*s*, 1041*s*. ^{1}H-NMR (400 MHz, $CDCl_3$)[4]): 0.70 (*s*, Me(16)); 0.94 (*s*, Me(17)); 1.22 (*qd*, *J* = 13.3, 4.2, H_{ax}–C(3)); 1.24 (*m*, H–C(2)); 1.26 (br. *s*, OH); 1.50 (*s*, Me(19)); 1.66 (*s*, Me–C(3″)); 1.70 (*dq*, *J* = 12.4, 4.0, H_{eq}–C(3)); 1.73 (*m*, 1 H–C(1″)); 2.01 (*qd*, *J* = 12.4, 4.0, H_{ax}–C(4)); 2.24 (*m*, 1 H–C(1″)); 2.33 (*qd*, *J* = 12.4, 3.2, H_{eq}–C(4)); 2.41 (*d*, *J* = 10.2, H–C(6)); 3.88, 3.98 (2*m*, OCH_2CH_2O); 4.02 (*s*, 2 H–C(4″)); 4.48 ('*s*', H–C(18) *cis* to C(6)); 4.75 ('*s*', H–C(18) *trans* to C(6)); 5.42 (*tm*, *J* = 6.1, H–C(2″)); 5.42 (*d*, *J* = 15.4, H–C(8)); 5.93 (*dd*, *J* = 15.4, 10.2, H–C(7)). ^{13}C-NMR (100.61 MHz, $CDCl_3$)[4]): 13.80(*Me*–C(3″)); 15.11(C(17)); 25.18(C(19)); 27.45(C(16)); 28.38(C(1″)); 28.87(C(3)); 36.25(C(4)); 38.66(C(1)); 48.31(C(2)); 57.19(C(6)); 64.42(OCH_2CH_2O); 68.97(C(4″)); 107.36(C(9)); 108.01(C(18)); 128.34(C(2″)); 129.68(C(8)); 133.41(C(7)); 135.27(C(3″)); 149.94(C(5)). MS: 320(13, M^+), 305(100), 287(3), 235(1), 219(2), 165(3), 135(4), 121(5), 107(8), 100(17), 87(63), 73(15).

*Data of (2*R*,6*S*)-**16**[4])*: ^{1}H-NMR (400 MHz, $CDCl_3$)[4]): 0.83 (*s*, Me(16)); 0.91 (*s*, Me(17)); 1.20 (*m*, H_{ax}–C(3)); 1.45, (*m*, H–C(2)); 1.46 (*s*, Me(19)); 1.50 (br. *s*, OH); 1.65 (*s*, Me–C(3″)); 1.70 (*m*, H_{eq}–C(3)); 1.74 (*m*, 1 H–C(1″)); 2.16 (*m*, 2 H–C(4), 1 H–C(1″)); 2.64 (*d*, *J* = 9.0, H–C(6)); 3.86, 3.95 (2*m*, OCH_2CH_2O); 4.05 (*s*, 2 H–C(4″)); 4.61 ('*s*', H–C(18) *cis* to C(6)); 4.67 ('*s*', H–C(18) *trans* to C(6)); 5.42 (*t*, *J* = 6.3, H–C(2″)); 5.42 (*d*, *J* = 15, H–C(8)); 6.06 (*dd*, *J* = 15, 9, H–C(7)). ^{13}C-NMR (100.61 MHz, $CDCl_3$)[4]): 13.81 (*Me*–C(3″)); 22.48(C(17)); 25.02(C(19)); 27.01(C(16)); 27.70(C(1″)); 28.19(C(3)); 31.24(C(4)); 37.29(C(1)); 42.37(C(2)); 59.03(C(6)); 64.41(OCH_2CH_2O); 68.97(C(4″)); 107.43(C(9)); 108.77(C(18)); 125.96(C(2″)); 130.25(C(8)); 131.66(C(7)); 135.26(C(3″)); 149.49(C(5)).

20. *4-{(1*R*,3*R*)-3-(4-Hydroxy-3-methylbut-2-enyl)-2,2-dimethyl-6-methylidenecyclohexyl}but-3-en-2-one* ((2*R*,6*R*)-**23**)[4]). At 50°, (2*R*,6*R*)-**16** (1.35 g, 4.22 mmol) and pyridinum toluene-4-sulfonate (10 mg) were dissolved in acetone/H_2O 1:1 (20 ml) and stirred for 30 min. The mixture was allowed to cool to r.t. and worked up as usual. FC (hexane/AcOEt 85:15) afforded 1.20 g (100%) of (2*R*,6*R*)-**23**.

*Data of (2*R*,6*R*)-**23**[4])*: IR ($CDCl_3$): 3426*s*, 3080*w*, 2960*s*, 2922*s*, 2861*s*, 1740*s*, 1670*vs*, 1647*m*, 1629*m*, 1440*s*, 1370*s*, 1295*s*, 1000*s*. ^{1}H-NMR (300 MHz, $CDCl_3$)[4]): 0.79 (*s*, Me(16)); 0.95 (*s*, Me(17)); 1.20 (*qd*, *J* = 13.3, 4.2, H_{ax}–C(3)); 1.26 (br.*s*, OH), 1.28 (*m*, H–C(2)); 1.66 (*s*, Me–C(3″)); 1.73 (*m*, 1 H–C(1″)); 1.75 (*dq*, *J* = 12.4, 4.0, H_{eq}–C(3)); 2.03 (*qd*, *J* = 12.4, 4.0, H_{ax}–C(4)); 2.25 (*m*, 1 H–C(1″)); 2.30 (*s*, Me(19)); 2.36 (*qd*, *J* = 12.4, 3.2, H_{eq}–C(4)); 2.57 (*d*, *J* = 10.0, H–C(6)); 4.02 (*s*, 2 H–C(4″)); 4.45 ('*s*', H–C(18) *cis* to C(6)); 4.81 ('*s*', H–C(18) *trans* to C(6)); 5.42 (*tm*, *J* = 6.1, H–C(2″)); 6.10 (*d*, *J* = 16.0, H–C(8)); 6.94 (*dd*, *J* = 16.0, 10.0, H–C(7)). ^{13}C-NMR (75.5 MHz, $CDCl_3$)[4]): 13.80(*Me*–C(3″)); 15.25(C(17)); 27.29(C(19)); 27.62(C(16)); 28.11(C(1″)); 28.64(C(3)); 36.11(C(4)); 39.06(C(1)); 48.10(C(2)); 57.75(C(6)); 68.88(C(4″)); 108.76(C(18)); 125.52(C(2″)); 133.63(C(8)); 135.53(C(3″)); 146.89(C(7)); 148.58(C(5)); 198.11(C(9)). MS: 276(5, M^+), 258(6), 243(3), 233(8), 215(15), 191(8), 175(11), 159(10), 149(73), 135(18), 121(37), 109(38), 93(26), 81(34), 69(35), 55(17), 43(100).

*Data of (2*R*,6*S*)-**23**[4])*: ^{1}H-NMR (300 MHz, $CDCl_3$)[4]): 0.83 (*s*, Me(16)); 0.92 (*s*, Me(17)); 1.20 (*m*, H_{ax}–C(3)); 1.46 (*m*, H–C(2)); 1.61 (*s*, Me–C(3″)); 1.73 (*m*, H_{eq}–C(3)); 1.76 (*m*, 1 H–C(1″)); 1.95 (br. *s*, OH); 2.18 (*m*, 2 H–C(4), 1 H–C(1″)); 2.22 (*s*, Me(19)); 2.60 (*d*, *J* = 9.0 H–C(6)); 3.99 (*s*, 2 H–C(4″)); 4.65 ('*s*', H–C(18) *cis* to C(6)); 4.72 ('*s*', H–C(18) *trans* to C(6)); 5.38 (*t*, *J* = 6.3, H–C(2″)); 6.07 (*d*, *J* = 15.8, H–C(8)); 7.03 (*dd*, *J* = 15.8, 9, H–C(7)). ^{13}C-NMR (75.5 MHz, $CDCl_3$)[4]): 13.71 (*Me*–C(3″)); 22.07(C(17)); 27.12(C(16)); 27.26(C(19)); 27.67(C(1″)); 28.00(C(3)); 31.20(C(4)); 37.75(C(1)); 42.41(C(2)); 59.95(C(6)); 68.62(C(4″)); 110.39(C(18)); 125.12(C(2″)); 131.80(C(8)); 135.47(C(3″)); 147.11(C(7)); 147.61(C(5)); 198.32(C(9)).

21. *1-{(1R,3R)-3-(4-Hydroxy-3-methylbut-2-enyl)-2,2-dimethyl-6-methylidenecyclohexyl}-3-methylpenta-1,4-dien-3-ol* ((2*R*,6*R*)-**24**)[4]). At −50°, (2*R*,6*R*)-**23** (1.2 g, 4.22 mmol) were dissolved in abs. Et_2O (15 ml) and vinylmagnesium bromide (1M in THF, 14.8 ml, 14.8 mmol) was added by syringe. The mixture was stirred for 20 min, allowed to warm up to r.t. and diluted with sat. NH_4Cl soln. Further workup was carried out as usual. Purification by FC (hexane/AcOEt 85:15) afforded 760 mg (60%) of (2*R*,6*R*)-**24**.

*Data of (2R,6R)-**24**[4])*: IR ($CDCl_3$): 3350*s*, 3080*w*, 2960*s*, 2920*s*, 2842*s*, 1640*m*, 1450*m*, 1439*m*, 1386*s*, 1367*s*, 1250*s*, 1000*s*. ^{1}H-NMR (300 MHz, $CDCl_3$)[4]): 0.69 (*s*, Me(16)); 0.95 (*s*, Me(17)); 1.17 (*qd*, *J* = 12.4, 3.3, H_{ax}−C(3)); 1.26 (*tm*, *J* = 11, H−C(2)); 1.41 (*d*, *J* = 2, Me(19)); 1.65 (*s*, Me−C(3″)); 1.70 (*dq*, *J* = 12.4, 4.0, H_{eq}−C(3)); 1.71 (*dm*, *J* = 11.9, 1 H−C(1″)); 1.73 (br. *s*, OH); 2.01 (*td*, *J* = 11.0, 3.5, H_{ax}−C(4)); 2.23 (*ddm*, *J* = 11.9, 4.0, 1 H−C(1″)); 2.33 (*dq*, *J* = 11.0, 3.0, H_{eq}−C(4)); 2.41 (*d*, *J* = 8.4, H−C(6)); 4.01 (*s*, 2 H−C(4″)); 4.49 ('*s*', H−C(18) *cis* to C(6)); 4.75 ('*s*', H−C(18) *trans* to C(6)); 5.07 (*ddd*, *J* = 8.8, 1.5, 1.0, H−C(11) *trans* to C(9)); 5.25 (*ddd*, *J* = 14.4, 1, 1.0, H−C(11) *cis* to C(9)); 5.42 (*dsept.*, *J* = 6.1, H−C(2″)); 5.58 (*d*, *J* = 12.8, H−C(8)); 5.78 (*dd*, *J* = 12.8, 8.4, H−C(7)); 6.00 (*ddd*, *J* = 14.4, 8.8, 1.5, H−C(10)). ^{13}C-NMR (75.5 MHz, $CDCl_3$)[4]): 13.78 (*Me*−C(3″)); 15.13 (C(17)); 27.44 (C(19)); 28.09 (C(16)); 28.38 (C(1″)); 28.85 (C(3)); 36.26 (C(4)); 38.78 (C(1)); 48.36 (C(2)); 57.51 (C(6)); 68.96 (C(4″)); 73.30 (C(9)); 108.00 (C(18)); 112.06 (C(11)); 126.03 (C(2″)); 127.31 (C(7)); 135.24 (C(3″)); 138.51 (C(8)); 144.22 (C(10)); 150.10 (C(5)).

*Data of (2R,6S)-**24**[4])*: ^{1}H-NMR (300 MHz, $CDCl_3$)[4]): 0.82 (*s*, Me(16)); 0.89 (*s*, Me(17)); 1.19 (*dq*, *J* = 9.4, 4.8, H_{ax}−C(3)); 1.35 (*s*, Me(19)); 1.45 (*tm*, *J* = 9.3, H−C(2)); 1.64 (*s*, Me−C(3″)); 1.69 (*ddd*, *J* = 11.0, 6.5, 3.0, H_{eq}−C(3)); 1.72 (br. *s*, OH); 1.76 (*m*, 1 H−C(1″)); 2.15 (*m*, 2 H−C(4), 1 H−C(1″)); 2.47 (*d*, *J* = 7.4, H−C(6)); 4.00 (*s*, 2 H−C(4″)); 4.60 ('*s*', H−C(18) *cis* to C(6)); 4.65 ('*s*', H−C(18) *trans* to C(6)); 5.04 (*ddd*, *J* = 8.8, 1.5, 1.0, H−C(11) *trans* to C(9)); 5.21 (*ddd*, *J* = 14.4, 1, 1.0, H−C(11) *cis* to C(9)); 5.40 (*tm*, *J* = 6.3, H−C(2″)); 5.57 (*d*, *J* = 12.8, H−C(8)); 5.91 (*ddd*, *J* = 12.8, 7.4, 3.5, H−C(7)); 5.93 (*ddd*, *J* = 14.4, 8.8 2, H−C(10)). ^{13}C-NMR (75.5 MHz, $CDCl_3$)[4]): 14.05 (*Me*−C(3″)); 22.42 (C(17)); 27.02 (C(16)); 27.89 (C(1″)); 28.06 (C(19)); 28.15 (C(3)); 31.22 (C(4)); 37.37 (C(1)); 42.04 (C(2)); 59.53 (C(6)); 70.28 (C(4″)); 73.15 (C(9)); 108.66 (C(18)); 112.10 (C(11)); 127.68 (C(7)); 129.49 (C(2″)); 130.47 (C(3″)); 136.96 (C(8)); 144.15 (C(10)); 149.60 (C(5)).

22. *1-{(1R,3R)-3-[4-(Acetoxy)-3-methylbut-2-enyl]-2,2-dimethyl-6-methylidenecyclohexyl}-3-methylpenta-1,4-dien-3-ol* ((2*R*,6*R*)-**25**)[4]). To a soln. of (2*R*,6*R*)-**24** (760 mg, 2.5 mmol) in THF/pyridine 2:1 (30 ml), Ac_2O (5 ml) was added. The soln. was stirred overnight, worked up as usual affording 850 mg (98%) of (2*R*,6*R*)-**25**[4]) after FC (hexane/AcOEt 9:1).

*Data of (2R,6R)-**25**[4])*: ^{1}H-NMR (400 MHz, $CDCl_3$)[4]): 0.67 (*s*, Me(16)); 0.93 (*s*, Me(17)); 1.15 (*qd*, *J* = 12.4, 3.3, H_{ax}−C(3)); 1.26 (*tm*, *J* = 11, H−C(2)); 1.39 (*d*, *J* = 2, Me(19)); 1.64 (*s*, Me−C(3″)); 1.67 (*dq*, *J* = 12.4, 4.0, H_{eq}−C(3)); 1.71 (*dm*, *J* = 11.9, 1 H−C(1″)); 1.73 (br. *s*, OH), 2.01 (*td*, *J* = 11.0, 3.5, H_{ax}−C(4)); 2.06 (*s*, Ac); 2.22 (*ddm*, *J* = 11.9, 4.0, 1 H−C(1″)); 2.32 (*dq*, *J* = 11.0, 3.0, H_{eq}−C(4)); 2.39 (*d*, *J* = 8.4, H−C(6)); 4.45 (*s*, 2 H−C(4″)); 4.48 ('*s*', H−C(18) *cis* to C(6)); 4.73 ('*s*', H−C(18) *trans* to C(6)); 5.06 (*ddd*, *J* = 8.8, 1.5, 1.0, H−C(11) *trans* to C(9)); 5.24 (*ddd*, *J* = 14.4, 1, 1.0, H−C(11) *cis* to C(9)); 5.45 (*dsept.*, *J* = 6.1, H−C(2″)); 5.57 (*d*, *J* = 12.8, H−C(8)); 5.77 (*dd*, *J* = 12.8, 8.4, H−C(7)); 5.98 (*ddd*, *J* = 14.4, 8.8, 1.5, H−C(10)). ^{13}C-NMR (100.61 MHz, $CDCl_3$)[4]): 14.04 (*Me*−C(3″)); 15.10 (C(17)); 20.99 (*Me*CO); 27.42 (C(19)); 28.06 (C(16)); 28.55 (C(1″)); 28.81 (C(3)); 36.21 (C(4)); 38.74 (C(1)); 48.13 (C(2)); 57.46 (C(6)); 70.31 (C(4″)); 73.29 (C(9)); 108.10 (C(18)); 112.03 (C(11)); 127.22 (C(7)); 129.61 (C(2″)); 130.51 (C(3″)); 138.55 (C(8)); 144.22 (C(10)); 150.01 (C(5)); 170.98 (Me*C*O). MS: 346 (0.1, M^+), 328 (5), 310 (46), 292 (14), 283 (4), 271 (6), 248 (23), 243 (34), 203 (15), 187 (12), 175 (12), 159 (14), 147 (25), 135 (23), 119 (27), 107 (28), 99 (30), 93 (25), 81 (20), 75 (26), 69 (21), 55 (20), 43 (63), 28 (65), 18 (100).

*Data of (2R,6S)-**25**[4])*: ^{1}H-NMR (400 MHz, $CDCl_3$)[4]): 0.80 (*s*, Me(16)); 0.88 (*s*, Me(17)); 1.17 (*dq*, *J* = 9.4, 4.8, H_{ax}−C(3)); 1.34 (*s*, Me(19)); 1.45 (*tm*, *J* = 9.3, H−C(2)); 1.61 (*s*, Me−C(3″)); 1.67 (*ddd*, *J* = 11.0, 6.5, 3.0, H_{eq}−C(3)); 1.74 (*m*, 1 H−C(1″)); 1.77 (br. *s*, OH); 2.06 (*s*, Ac); 2.14 (*m*, 2 H−C(4), 1 H−C(1″)); 2.45 (*d*, *J* = 7.4, H−C(6)); 4.44 (*s*, 2 H−C(4″)); 4.59 ('*s*', H−C(18) *cis* to C(6)); 4.63 ('*s*', H−C(18) *trans* to C(6)); 5.02 (*ddd*, *J* = 8.8, 1.5, 1.0, H−C(11) *trans* to C(9)); 5.20 (*ddd*, *J* = 14.4, 1, 1.0, H−C(11) *cis* to C(9)); 5.43 (*tm*, *J* = 6.3, H−C(2″)); 5.56 (*d*, *J* = 12.8, H−C(8)); 5.90 (*ddd*, *J* = 12.8, 7.4, 3.5, H−C(7)); 5.93 (*ddd*, *J* = 14.4, 8.8, 2, H−C(11)). ^{13}C-NMR (100.61 MHz, $CDCl_3$)[4]): 14.05 (*Me*−C(3″)); 20.98 (*Me*CO); 22.42 (C(17)); 27.02 (C(16)); 27.89 (C(1″)); 28.06 (C(19)); 28.15 (C(3)); 31.22 (C(4)); 37.37 (C(1)); 42.04 (C(2)); 59.53 (C(6)); 70.28 (C(4″)); 73.15 (C(9)); 108.66 (C(18)); 112.10 (C(11)); 127.68 (C(7)); 129.49 (C(2″)); 130.47 (C(3″)); 136.96 (C(8)); 144.15 (C(10)); 149.60 (C(5)); 170.98 (Me*C*O).

23. *{5-{(1R,3R)-3-[4-(Acetyloxy)-3-methylbut-2-enyl]-2,2-dimethyl-6-methylidenecyclohexyl}-3-methylpenta-2,4-dienyl}triphenylphosphonium Bromide* ((2*R*,6*R*)-**3**)[4]). At r.t., (2*R*,6*R*)-**25** (790 mg, 2.28 mmol) and $PPh_3 \cdot HBr$ (860 mg, 2.5 mmol) were dissolved in MeOH (7 ml). The soln. was stirred for 20 h and the solvent evaporated at 35°. The light yellow residue was dissolved in a small amount of CH_2Cl_2 and added dropwise to

a cooled and vigorously stirred soln. of (*t*-Bu)OMe/hexane. After complete addition, the solvent was carefully decanted and the precipitate washed several times with cold (*t*-Bu)OMe/hexane. The remaining solvent was carefully evaporated at 35°. The white powder was dried under high vacuum, affording 1.45 g (95%) of (2*R*,6*R*)-**3**, which was directly used for the next step without characterization.

24. *(all-*E*,2*R*,6*R*,2′*R*,6′*R*)-2,2′-Bis(4″-hydroxy-3″-methylbut-2″-enyl)-γ,γ-carotene*[4]) (= *(all-*E*,2*R*,6*R*,2′*R*,6′*R*)-sarcinaxanthin*; (all-*E*,2*R*,6*R*,2′*R*,6′*R*)-**1**). At r.t., (2*R*,6*R*)-**3** (840 mg, 1.05 mmol) and C_{10}-dial **2** (86 mg, 0.525 mmol) were dissolved in CH_2Cl_2 (5 ml) and 5% NaOH/H_2O (3 ml) was added. After $1\frac{1}{2}$ h, 5% NaOH/H_2O (1 ml) was added and the red soln. stirred overnight. The solvent was evaporated and the red residue purified by FC (hexane/AcOEt 95:5 to 85:15) yielding 114.5 mg of **1**, 95 mg of **1**/C_{30}-aldehyde 2:1 and 90 mg of C_{30}-aldehyde. Yield of **1**: 80% rel. to **2**, yield 60% rel. to (2*R*,6*R*)-**3**.

*Data of (all-*E*,2*R*,6*R*,2′6′*R*)-**1***: Recrystallization from hexane/AcOEt. M.p.: 133–136°. UV/VIS (hexane): 468, 437, 414. CD (Et_2O/*i*-PrOH/EtOH 5:5:2, −180°): 200(+0.89), 205(−14.13), 241(−1.43), 267.5(−15.12), 332(+1.28), 405(−2.70), 417(−0.58), 426.5(−2.75), 444(−0.65), 449(−6.22), 466(+2.16), 483(−5.05), 491(+7.04), 509(+1.16). ^{1}H-NMR (400 MHz, $CDCl_3$): *Table*. ^{13}C-NMR (100.61 MHz, $CDCl_3$): *Table*. MS: 704(56, M^+), 686(1), 612(12), 598(2), 241(8), 253(10), 223(16), 209(27), 197(26), 183(27), 171(36), 157(44), 145(53), 133(35), 119(48), 105(45), 91(100), 81(27), 69(28), 43(33), 18(31).

*Data of (2*R*,6*S*,2′*R*,6′*S*)-**1***: UV/VIS (hexane): 468, 437, 414. CD: not measured. ^{1}H-NMR (400 MHz, $CDCl_3$): *Table*. ^{13}C-NMR (100.61 MHz, $CDCl_3$): *Table*.

REFERENCES

[1] M. Gerspacher, H. Pfander, *Helv. Chim. Acta*, **1989**, *72*, 151.
[2] S. Hertzberg, S. Liaaen-Jensen, *Acta Chem. Scand.* **1977**, *31*, 215.
[3] O. B. Weeks, A. R. Montes, A. G. Andrewes, *J. Bacteriol.* **1980**, *141*, 1272.
[4] J. P. Férézou, M. Julia, *Tetrahedron* **1990**, *46*, 475.
[5] H. Wolleb, H. Pfander, *Helv. Chim. Acta* **1986**, *69*, 646.
[6] H. Wolleb, H. Pfander, *Helv. Chim. Acta* **1986**, *69*, 1505.
[7] I. Kitagawa, H. Shibuta, H. Fujioka, A. Kajiwara, Y. Yamamoto, S. Tsuji, A. Takagi, M. Hori, *Chem. Pharm. Bull.* **1981**, *29*, 2540.
[8] K. Weinges, W. Sipos, *Chem. Ber.* **1988**, *121*, 363.
[9] I. Kitagawa, S. Tsuji, H. Fujioka, A. Kajiwara, Y. Yamamoto, H. Shibuta, *Chem. Pharm. Bull.* **1984**, *32*, 1294.
[10] I. Kitagawa, H. Shibuta, H. Fujioka, A. Kajiwara, Y. Yamamoto, S. Tsuji, K. Murakawa, *Chem. Pharm. Bull.* **1981**, *29*, 2548.
[11] H. Mayer, A. Rüttimann, *Helv. Chim. Acta* **1980**, *63*, 1451.
[12] J. R. Schrauder, A. Krief, *Tetrahedron Lett.* **1982**, *23*, 4389.
[13] T. Greene, G. M. Wuts, 'Protective Groups in Organic Chemistry', Wiley Interscience, New York, 1992.
[14] M. Lanz, Diploma Work, University of Bern, 1994.
[15] J. R. Proudfoot, X. Li, C. Djerassi, *J. Org. Chem.* **1985**, *50*, 2026.
[16] Z. Cheng, Ph. D. Thesis, University of Bern, 1994.
[17] V. Caló, F. Ciminale, L. Lopez, P. E. Todesco, *J. Chem. Soc.* **1971**, 3652.