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Bacterial Carotenoids. XLVIII.* Total Syntheses of Carotenes of the 1,2-Dihydro Series

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The total syntheses of 1,2,7,8,1′,2′,7′,8′-octahydro-ψ,ψ-carotene (*1*), 1,2,7,8-tetrahydro-ψ,ψ-carotene (*2*), 1,2,1′,2′-tetradehydro-ψ,ψ-carotene (*3*), 1,2-dihydro-ψ,ψ-carotene (*4*), 1,2-dihydro-3,4-didehydro-ψ,ψ-carotene (*5*), and 1,2,1′,2′-tetrahydro-3,4,3′,4′-tetrahydro-ψ,ψ-carotene (*6*) are described. The properties of products and intermediates, including the three new apocarotenals 1,2,7,8-tetrahydro-12′-apo-ψ-caroten-12′-al (*20*), 1,2-dihydro-8′-apo-ψ-caroten-8′-al (*25*), and 1,2-dihydro-3,4-didehydro-8′-apo-ψ-caroten-8′-al (*32*), are reported.

A fragment ion at M−68 on electron impact appears to be characteristic for carotenoids with a 1,2,7,8-tetrahydro end-group.

A photosynthetic bacterium isolated by Eimhjellen [1] and subsequently named *Rhodopseudomonas viridis* [2] was initially [3] considered to contain common aliphatic carotenes, mainly neurosporene. However, Malothra *et al.*[4,5] demonstrated that common aliphatic carotenes were only minor constituents, the major carotenes were of a novel 1,2-dihydro (1,2,1′,2′-tetrahydro) aliphatic series, both in normal cells and cells grown in the presence of diphenylamine.

Due to the restricted quantities available some of these carotenes were identified on the basis of their visible light absorptions and fragmentation patterns on electron impact alone. Total synthesis have now been performed in order to allow full physical characterization.

The synthesis of the lycopene derivatives *3* and *4* has previously been reported in a priority note.[6] We now describe in full the preparations of the series *1*—*6*.

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RESULTS AND DISCUSSION

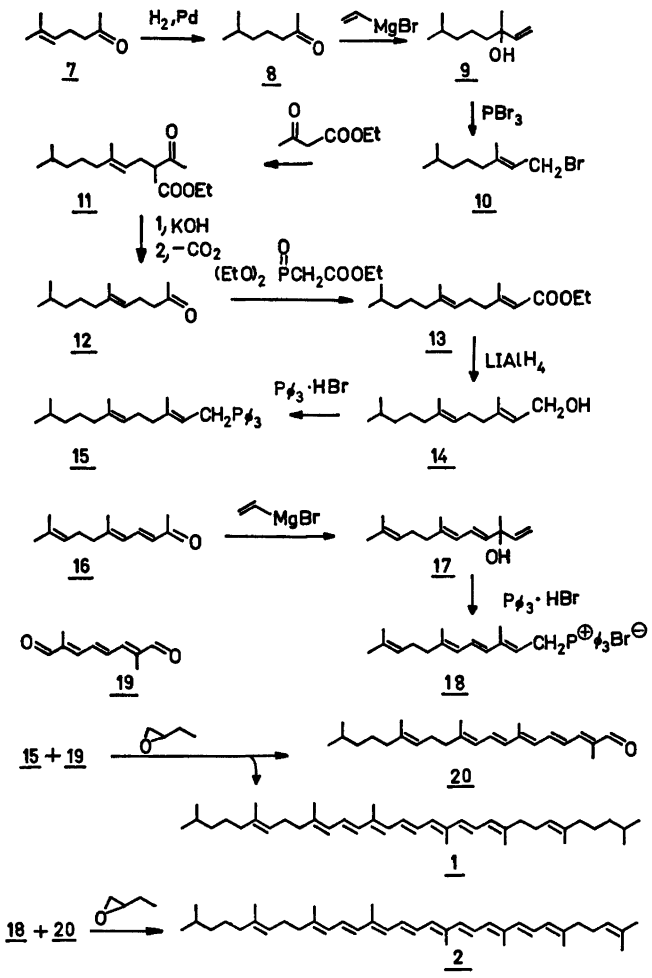
The synthesis of 1,2,7,8,1′,2′,7′,8′-octahydro-ψ,ψ-carotene (*1*) and 1,2,7,8-tetrahydro-ψ-ψ-carotene (*2*) is summarized in Scheme 1.

Methylheptenone (*7*) was hydrogenated in the presence of palladium catalyst to give the saturated ketone *8*. Reaction of *8* with vinyl magnesium bromide gave the tertiary allylic alcohol *9* which was converted to the primary allylic bromide *10* with phosphorus tribromide. Condensation of *10* with acetoacetic ester gave *11* which was hydrolyzed and decarboxylated directly to give dihydrogeranylacetone (*12*). Horner condensation of *12* with ethyl diethylphosphonoacetate gave the conjugated ester *13* which was reduced to the allylic alcohol *14* with $LiAlH_4$ and subsequently converted to the phosphonium salt *15* with triphenylphosphonium bromide.

Similarly pseudoionone (*16*) was converted to the phosphonium salt *18 via* the tertiary alcohol *17*.

Wittig condensation of the ylid of *15* with the C_{10}-dialdehyde *19* gave a mixture of 1,2,7,8,1′,2′,7′,8′-octahydro-ψ,ψ-carotene (*1*, with heptaene chromophore) and the C_{25}-aldehyde *20* which were separated by chromatography. The C_{25}-aldehyde *20* was subsequently condensed with the ylid of the phosphonium salt *18* in a second Wittig reaction to 1,2,7,8-tetrahydro-ψ,ψ-carotene (*2*, with nonaene chromophore).

1,2,1′,2′-Tetrahydro-ψ,ψ-carotene (*3*) and 1,2-dihydro-ψ,ψ-carotene (*4*) were synthesized as depicted in Scheme 2:

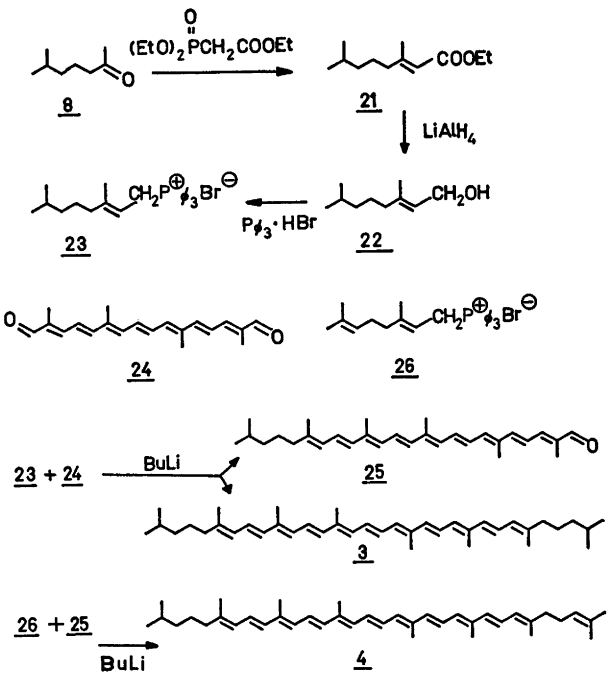


Scheme 1.

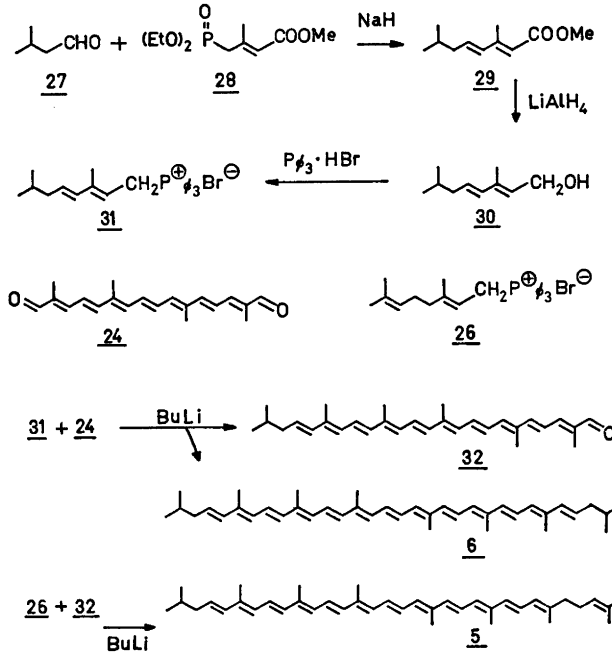
The saturated ketone *8* was condensed with ethyl diethylphosphonoacetate in a Horner reaction to give the unsaturated ester *21* which was reduced with $LiAlH_4$ to dihydrogeraniol (*22*), in turn converted to the phosphonium salt *23* with triphenylphosphonium bromide. Wittig condensation of the ylid of *23* with crocetindial (*24*) gave a mixture of 1,2,1′,2′-tetrahydro-ψ,ψ-carotene (*3*, with undecaene chromophore) and the C_{30}-carotenal *25* which were separated by chromatography. A second Wittig condensation of *25* with geranyltriphenylphosphonium bromide (*26*) provided the lycopene derivative 1,2-dihydro-ψ,ψ-carotene (*4*). The physical properties of *3*, *4*, and *25* are compiled in Tables 1—3.

The preparation of 1,2-dihydro-3,4-didehydro-ψ,ψ-carotene (*5*, with dodecaene chromophore) and 1,2,1′,2′-tetrahydro-3,4,3′,4′-tetradehydro-ψ,ψ-carotene (*6*, with tridecaene chromophore) was accomplished as depicted in Scheme 3:

Horner condensation of isovaleraldehyde (*27*) and the phosphonate *28* gave the conjugated ester *29* which gave the allylic alcohol *30* on reduction with $LiAlH_4$. Treatment of *30* with triphenylphosphonium bromide resulted in the phosphonium salt *31*, the ylid of which was condensed with crocetindial (*24*) in a Wittig reaction to give a mixture of *6* and the apocarotenal *32*. Separation of these products by chromatography and subsequent Wittig condensation of *32* with the ylid of geranyltri-



Scheme 2.



Scheme 3.

phenylphosphonium bromide (*26*) gave *5*.

The IR spectra of the hydrocarbons *1*—*6*, as well as of the apo-carotenals *20*, *25* and *32* were not informative and only normal carotenoid CH absorptions as well as carbonyl frequencies for the apo-carotenals were observed.

The visible light properties were all consistent with those observed for the analogues of the common aliphatic series.[7] Certain deviations in extinction coefficients and spectral fine-structure may be due to the purity of the samples.

In the ^{1}H NMR spectra the only characteristic feature is a six proton doublet at *ca.* δ 0.88 caused by the isopropyl end group coupled to the C-1 methine proton. All other signals were in close agreement with those observed for the common analogues.[7]

The mass spectra (Table 1) all showed fragments derived by in-chain eliminations (Table

Table 1. Fragmentations induced by electron impact of carotenoids of the 1,2-dihydro series.

A. In-chain eliminations.

Compound	Molecular ion *m/e* (rel.int.)	Relative intensity of fragments M−68	M−79	M−92	M−106	M−158	Base peak
1	544 (100)	15.3	–	0.7	–	–	544
2	540 (100)	12.2	0.4	1.8	1.4	–	540
3	540 (57)	–	0.4	6.7	5.6	1.4	43
4	538 (100)	–	0.9	7.4	15.4	1.5	538
5	536 (25)	–	0.5	1.5	26.6	9.8	91
6	536 (55.5)	–	–	2.1	55.5	–	69
20	354 (100)	21	–	–	–	–	354
25	418 (100)	–	0.8	1.8	0.8	–	418
32	416 (34.5)	–	–	0.8	17.1	–	91

B. In-chain cleavages.

Compound	Losses from the molecular ion [x, (rel. int.)] derived by cleavage of bond 3,4	7,8	11,12	15,15′	11′,12′	7′,8′	3′,4′
1	–	139(5.1)	207(0.9)	–	–	–	–
2	–	139(1.8)	207(0.5)	–	203(0.4)	137 (0.6)	69(1.4)
3	71(0.6)	139(1.0)	205(1.5)	–	–	–	–
4	71(0.5)	139(0.7)	205(1.3)	–	203(1.6)	137(0.9)	69(2.9)
5	–	137(9.8)	–	–	–	137(9.8)	–
6	–	–	–	–	–	–	–
20	71(0.9)	139(82)	207(24.6)	–	–	–	–
25	71(1.1)	139(1.3)	205(2.6)	149(2.3)	–	–	–
32	–	–	–	149(1.7)	–	–	–

C. Other losses.

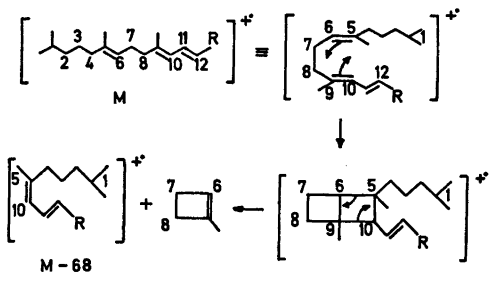
Compound	Expelled fragments [M−x, (rel.int.)]
5	M−80(0.5)
6	M−24(1.2), M−26(0.4), M−40(1.8), M−66(1.9), M−68(0.9), M−132(0.8), M−175(2.9)
20	M−15(0.6), M−29(0.5), M−83(1.0), M−85(0.7), M−113(2.0), M−126(12.3)
25	M−16(0.7), M−28(0.4), M−29(0.4), M−83(0.7), M−85(0.7), M−113(0.7), M−121(0.7, M−135(1.0), M−137(0.8)
32	M−40(0.7), M−54(0.9), M−66(1.4), M−120(1.2)

1A). For *1* only the loss of 92 (toluene) mass units (m.u.) was observed in agreement with its structure and the accepted mechanism for these fragmentations.[7] The other C_{40}-compounds all exhibited losses of 79 (methylcyclopentadienyl),[8] 92 (toluene), 106 (xylene), and 158 (dimethylcyclodecapentaene)[8] m.u. except for *6* which only exhibited losses of 92 and 106 m.u. The C_{30}-carotenals *25* and *32* exhibited losses of 92 and 106 m.u. but no loss of 158 m.u. was observed.

Diagnostic important fragments derived by in-chain cleavages of the 3,4; 7,8; 11,12; 15,15'; 11',12'; 7',8' and 3',4' bonds were also observed (Table 1 B). For compounds *1*—*4*, *20*, and *25* these fragments are observed at 2 m.u. higher than the corresponding fragments of the common aliphatic (1,2-ene) analogues.

For the carotenes *1* and *2* and the apocarotenal *20* a relatively strong fragment ion M−68 (Table 1), previously not encountered in carotenoid mass spectra, was observed. This fragmentation, supported by a metastable peak, seems restricted to the 1,2,7,8-tetrahydro end group, since it has not been observed for carotenoids with the 1,2- or 7,8-dihydro end groups alone.[6,8,9] The fragmentation may be explained by an in-chain elimination of methylcyclobutene (Scheme 4). This thermally forbidden rearrangement[10] could take place under electron impact. When a 1,2-double bond is present, this type of reaction appears to be suppressed by the favoured simple cleavage of the 3,4-bond (M−69). Malhotra *et al.*[5] reported no M−68 fragment for their natural 1,2,7,8-tetrahydrocarotenes, possibly due to different recording conditions (200−240 °C, 70 eV? *vs.* 150−200 °C, 70 eV in our work).

A number of other fragments were also observed, but have no obvious diagnostic value (Table 1C).



Scheme 4.

In view of the very similar adsorptive and visible light properties of the carotenoids of this 1,2-dihydro series with those of the common (1,2-ene) series[7] it is imperative that full spectral characterization, including MS and advisably ^{1}H NMR, be employed even for the identification of carotenes.

So far the occurrence of these 1,2-dihydrocarotenes is restricted to *Rhsp. viridis*. However, this restricted occurrence is not considered definite, since misidentification with common carotenes is possible.

EXPERIMENTAL

Materials and methods were as normally employed in our laboratory and are summarized elsewhere.[12] If of satisfactory purity, as judged by ^{1}H NMR spectrometry or other criteria, crude intermediates were used directly without further purifications. Otherwise purifications by distillation or chromatography on columns or thin layer plates were resorted to.

6-Methylheptan-2-one (8). Methylheptenone (*7*, 12.6 g) in methanol (100 ml) was hydrogenated in the presence of palladium (10 % on $BaSO_4$) catalyst (0.5 g) until hydrogen uptake had ceased, *ca.* 30 h. Filtration and removal of the solvent afforded 12.1 g (95 %) crude *8*; $n_D^{19}=1.4283$; ν_{max} (liq) 3000−2820 (CH), 1720 (C=O), 1670 (CH_2), 1390, 1370 (CH_3), 1172, 793, 767 and 683 cm^{-1}; δ ($CDCl_3$) 0.86 (d, 6 H, *J* 5 Hz, isopropyl CH_3), 1.0−1.9 (m, 5 H, $2\times CH_2+H$), 2.00 (s, 3 H, methyl ketone), 2.36 (t, 2 H, *J* 7 Hz, α-CH_2).

3,7-Dimethyloct-1-ene-3-ol (dihydrolinalool, 9). Vinylmagnesium bromide, prepared from magnesium (5.6 g) and vinyl bromide (25 g) in dry ether (20 ml), was reacted with *8* (15 g) in dry ether (20 ml) at room temperature for 3 h. The reaction mixture was decomposed with saturated aqueous NH_4Cl and the reaction products extracted into ether. The extract was washed with water, dried over $MgSO_4$ and evaporated to give 13 g (70 %) crude *9*; δ ($CDCl_3$) 0.88 (d, 6 H, *J* 6 Hz, isopropyl CH_3), 1.25 (s, 3 H, CH_3 at C-3), 1.15−1.6 (m, ~7 H, $3\times CH_2+H$) 2.19 (1 H, OH), 5.0 (dd, 1 H, $J_{1,2}$ 10.5 Hz, $J_{1,1'}$ 2 Hz, H-1, *cis*), 5.14 (dd, 1 H, $J_{1',2}$ 17.5 Hz, $J_{1,1'}$ 2 Hz, H-1, *trans*), 5.94 (dd, 1 H, $J_{1,2}$ 10.5 Hz, $J_{1',2}$ 17.5 Hz, H-2).

3,7-Dimethyloct-2-enyl bromide (dihydrogeranyl bromide, 10). Dihydrolinalool (*9*, 13 g) in petroleum ether (25 ml) and pyridine (2.5 ml) were cooled to −10 °C and phosphorus tribromide (10.5 g) in petroleum ether (15 ml) was added dropwise. The reaction mixture was stirred at −10 °C for a further 20 min and then decomposed with ice and water. The reaction

products were extracted into petroleum ether, the extract washed with water, $NaHCO_3$ solution and dried over $MgSO_4$. Evaporation of the solvent afforded 14 g (71 %) crude *10*; δ ($CDCl_3$) 0.89 (d, 6 H, *J* 6 Hz, isopropyl CH_3), 1.1–1.7 (5 H, $2\times CH_2$+H), 1.71 (s, 3 H, CH_3 at C-3), 2.02 (t, 2 H, *J* 6 Hz, H-4), 3.99 (d, 2 H, *J* 8 Hz, H-1).

6,10-Dimethylundeca-5-ene-2-one (dihydrogeranyl acetone, 12). Acetoacetic ester (11.5 g) and *10* (14 g) were cooled to −15 °C and sodium ethoxide solution (prepared from sodium (4.5 g) and ethanol (100 ml), 35 ml) was added dropwise while the temperature was kept at *ca.* −10 °C. The reaction was continued at room temperature overnight. The solution was heated to 80 °C and 10 % aqueous sodium hydroxide (110 ml) was added with vigorous stirring and the reaction mixture kept at 80 °C for 4 h. The mixture was cooled, the products extracted into petroleum ether, the extract washed with water and dried over $MgSO_4$. Evaporation of the solvent and distillation of the residue gave 10 g (85 %) *12* of b.p. 152 °C/15 Torr; δ ($CDCl_3$) 0.88 (d, 6 H, *J* 6 Hz, isopropyl CH_3), 1.1–1.7 (5 H, $2\times CH_2$+H), 1.61 (s, 3 H, CH_3 at C-6), 1.75–2.5 (2×2 H, allylic, CH_2), 2.10 (s, 3 H, CH_3-1), 2.39 (t, 2 H, *J* 5 Hz, CH_2-3), 5.08 (t, 1 H, *J* 6.5 Hz, H-5).

Ethyl 3,7,11-trimethyldodeca-2,6-dienoate (ethyl dihydrogeranylacetonylidene acetate, 13). Ethyl diethylphosphonoacetate (60 g) was added to a suspension of sodium hydride (50 % in mineral oil, 1.35 g, washed repeatedly with petroleum ether before use) and the mixture stirred until hydrogen evolution had ceased (*ca.* 1 h). *12* (4.1 g) was added and the mixture was reacted overnight and then decomposed with water. The products were extracted into ether, the extract washed with water and dried over Na_2SO_4. Evaporation of the solvent gave 4.54 g (81 %) crude *13*; ν_{max} (liq) 2960–2870 (CH), 1720 (C=O), 1650 (C=C), 1455 (CH), 1385, 1369 (CH_3, isopropyl), 1220, 1157, 1142, 1055, and 862 cm^{-1}; δ ($CDCl_3$) 0.87 (d, 6 H, *J* 6 Hz, isopropyl CH_3), 1.26 (t, 3 H, *J* 7 Hz, ethyl CH_2), 1.60 (s, 3 H, CH_3 at C-7), 1.89 and 2.16 (d + d, 3 H, *J* 1 Hz, CH_3 at C-3, *cis*+*trans*), 4.14 (q, 2 H, *J* 7 Hz, ethyl CH_2), 5.10 (m, 1 H, H-6), 5.65 (broad s, 1 H, H-2).

3,7,11-Trimethyldodeca-2,6-dien-1-ol (dihydrogeranylacetonylidene ethanol, 14). 13 (4.07 g) in dry ether (25 ml) was reduced with $LiAlH_4$ (1 g) at 0 °C for 4 h. Saturated aqueous NH_4Cl solution was added, the mixture filtered and the filtrate extracted with ether and dried over Na_2SO_4. Evaporation of the solvent gave 3.33 g (97.5 %) crude *14*; ν_{max} (liq) 3320 (OH), 2950–2865 (CH), 1470 (CH), 1385, 1367 (CH_3, isopropyl) and 1005 cm^{-1}; δ ($CDCl_3$) 0.86 (d, 6 H, *J* 6 Hz, isopropyl CH_3), 1.51 (s, 3 H, CH_3 at C-7), 1.68 (s, 3 H, CH_3 at C-3), 4.10 and 4.14 (d+d, 2 H, *J* 7 Hz, CH_2-1, *cis*+*trans*), 5.10 (m, 1 H at C-6), 5.32 and 5.42 (t+t, 1 H, *J* 7 Hz, H at C-7, *cis*+*trans*).

(3,7,11-Trimethyldodeca-2,6-dienyl)triphenylphosphonium bromide (15). 14 (2.78 g) in dry $CHCl_3$ (70 ml) was reacted with triphenylphosphonium bromide (4.43 g) at room temperature for 60 h. Crystallization from ethyl acetate/ether gave 2.71 g (40 %) colourless crystals of *15*, m.p. 121 °C; ν_{max} (KBr) 3045–2780 (CH), 1587 (C=C), 1435 (CH), 1383, 1366 (CH_3, isopropyl). 1112, 996, 887, 856, 745, 725, and 692 cm^{-1}; δ ($CDCl_3$) 0.87 (d, 6 H, *J* 6 Hz, isopropyl CH_3), 1.33 and 1.41 (s+s, 3 H, CH_3 at C-3), 1.52 (s, 3 H, CH_3 at C-7), 4.2–5.3 (m, 4 H, CH_2 at C-1 and olefinic H), 7.73 (s, *ca.* 15 H, phenyl-H).

3,7,11-Trimethyldodeca-1,4,6,10-tetraene-3-ol (17). The Grignard reagent, prepared by treating vinyl bromide (8.25 g) in tetrahydrofuran (100 ml) with magnesium (1.9 g), was cooled to 0 °C and ψ-ionone (*16*, 2.5 g) in tetrahydrofuran (50 ml) was added dropwise. The mixture was stirred for a further 30 min at 20 °C followed by addition of saturated aqueous ammonium chloride (*ca.* 50 ml). The organic phase was extracted with ether, the extracts washed several times with water and dried over Na_2SO_4 and K_2CO_3. Evaporation of the solvent and distillation (76 °C, 0.1 Torr) gave 2.46 g (85 %) of the alcohol *17* as a colourless oil; λ_{max} (methanol) 243 nm (ε 21 600); ν_{max} (liq) 3370 (OH), 3082–2930 (CH), 1450 (CH), 1377, 1105, 1090, 970, 920, 830, and 690 cm^{-1}; δ ($CDCl_3$) 1.28 (s, 3 H, CH_3 at C-3), 1.52 and 1.58 (s+s, 6 H, 2 CH_3 at C-11), 1.67 (s, 3 H, CH_3 at C-7), 2.0–2.2 (m, 4 H, 2 CH_2 allylic), 4.8–6.7 (7 H, olefinic H).

(3,7,11-Trimethyldodeca-2,4,6,10-tetraene-1-yl)triphenylphosphonium bromide (18). 17 (1.98 g) in abs. methanol (45 ml) was reacted with triphenylphosphonium bromide (3.16 g) at room temperature for 24 h. The solvent was evaporated, the residue dissolved in hot ethyl acetate and the resulting solid precipitate recrystallized in ethyl acetate giving 380 mg colourless crystals of *18*, m.p. 148 °C (decomp.); λ_{max} (methanol) 295.5 nm (ε 28 800); ν_{max} (KBr) 3050–2780 (CH), 1587 (C=C), 1437 (CH), 1112, 995, 955, 745, 725, and 694 cm^{-1}; δ ($CDCl_3$) 1.60 and 1.66 (s+s, 2 CH_3 at C-11), 1.77 (s, CH_3 at C-3 and C-7), 2.0–2.3 (m, CH_2-8 and -9), 4.5–6.3 (m, CH_2-1 and olefinic H), 7.72 (s, phenyl-H). The combined mother liquors after evaporation of the solvent provided further 4.36 g *18* as a viscous oil.

1,2,7,8-Tetrahydro-12'-apo-ψ-carotene-12'-al (20). Butylene oxide (4 ml), $CHCl_3$ (4 ml), C_{10}-dial (*19*, 482 mg) and *18* (801 mg) were reacted in a sealed tube under N_2-atmosphere at 90 °C for 1 h. The reaction mixture was cooled and suspended in benzene/ether, washed several times with water and dried over Na_2SO_4. Chromatography on alumina grade 2 [13] using benzene and collection of the main fraction gave 304 mg *20* (58.5 %) as an oil; λ_{max} (acetone) 392.5 nm (ε 53 700); ν_{max} (liq) 3035 (olefinic CH), 2950–2800 (CH), 2705 (−CHO), 1673

(C=O), 1610, 1560 (C=C), 1470–1430 (CH), 1405, 1380, 1355 (CH_3), 1265, 1203, 1185, 1008, 990, 960 (*trans* –CH=CH–), 883, 835 (>C=CH–) and 690 cm^{-1}; δ ($CDCl_3$) 0.87 (d, 6 H, *J* 6 Hz, isopropyl CH_3), 1.1–1.4 (m, 4 H, CH_2-2 and -3), 1.60 (s, 3 H, CH_3 at C-5), 1.64 (d, 1 H, *J* 6 Hz, *tert.* H), 1.84 (s, 6 H, CH_3 at C-9 and C-13′), 2.00 (s, 3 H, CH_3 at C-13), 1.8–2.3 (m, 6 H, CH_2-4,7,8), 4.95–5.3 (H at C-6), 5.7–7.2 (m, 7 H, olefinic), 9.42 (1 H, aldehydic); *m/e* (Table 1).

1,2,7,8,1′,2′,7′,8′-Octahydro-ψ,ψ-carotene (1,2,-1′,2′-tetrahydro-ξ-carotene, 1). Butylene oxide (1 ml), C_{10}-dial (*19*, 20 mg) and *15* (200 mg) were reacted in a sealed tube under N_2 at 90 °C for 30 min. The reaction mixture was cooled and suspended in benzene. Triphenylphosphinoxide was removed by filtration and the product purified by TLC on silica using petroleum ether as developer; yield 20 mg (30 %) *1* as an oil; λ_{max} (light petroleum) 378.5, 399 and 424 nm % III/II [11] = 70; ν_{max} (liq 3040–2820 (CH), 1740, 1635 (C=C), 1480–1440 (CH_2), 1390, 1370 (CH_3), 970 (*trans* –CH=CH–), 890 and 790 cm^{-1}; δ $CDCl_3$) 0.87 (d, 12 H, *J* 6 Hz, 4×CH_3 at C-1,1′), 1.60 (s, 6 H, CH_3 at C-5,5′), 1.81 (s, 6 H, CH_3 at C-9,9′), 1.94 (s, 6 H, CH_3 at C-13,13′), 5.12 (m, 2 H, H-6,6′) and 5.7–6.8 (10 H, olefinic); *m/e* (Table 1).

1,2,7,8-Tetrahydro-ψ,ψ-carotene (1,2-dihydro-neurosporene, 2). *18* (2 g) and *20* (334 mg) in 12 ml butylene oxide/$CHCl_3$ (1:1) were reacted in a sealed tube under N_2-atmosphere at 90 °C for 1 h. The reaction mixture was cooled, suspended in benzene/ether, washed with water and dried over Na_2SO_4. The residue was chromatographed twice on alumina (Woelm, grade 3 [13]) gradually eluted with increasing amounts of benzene in hexane (1:1–2:1) for the first column and increasing amounts of ether (5–10 %) in hexane for the second column, separating the main fraction into two zones. From the more polar zone *2* (108 mg) was isolated as a *cis-trans* mixture. The less polar zone gave 79 mg mainly *all-trans 2* (total yield 37 %). Further purification of the *all-trans* product by TLC on silica using 3 % acetone in hexane and crystallization from acetone/methanol gave 14.4 mg crystalline *all-trans 2*, m.p. 96 °C; λ_{max} (hexane) 468.5, 439 (ε 138 200) and 415 nm; % III/II = 102; ν_{max} (KBr) 3040 (olefinic CH), 2950–2860 (CH), 1627 (C=C), 1480–1420 (CH_2), 1383, 1367 (CH_3), 960 (*trans* –CH=CH–), 885, and 825 cm^{-1}. δ ($CDCl_3$) 0.89 (d, 6 H, *J* 6 Hz, CH_3 isopropyl), 1.1–1.4 (m, CH_2-2,3), 1.61 (s, 6 H, CH_3 at C-5 and C-1′), 1.70 (s, 3 H, CH_3 at C-1′), 1.83 (s, 6 H, CH_3 at C-5′ and 9), 1.97 (s, 9 H, CH_3 at C-13, 13′ and 9′), 1.8–2.3 (m, CH_2-4,7,8), 5.0–5.35 (m, 2 H at C-6 and C-2′), 5.7–6.9 (13 H olefinic); *m/e* (Table 1).

Ethyl 3,7-dimethyloct-2-enoate (21). To sodium hydride (50 %) in mineral oil, 3.12 g) in dry dimethoxyethane (40 ml) was added ethyl diethylphosphonoacetate (11.5 g). The mixture was stirred until hydrogen evolution had ceased (*ca.* 1 h). *8* (6.4 g) in dry dimethoxyethane (50 ml) was added and the mixture stirred at room temperature for 24 h. Water (1.5 l) was added and the product extracted with ether. The combined ether extracts were washed with water until neutral and dried over calcium chloride. Evaporation of the solvent afforded 9.9 g (100 %) crude *21*; $n_D^{19} = 1.4550$; ν_{max} (liq) 3000–2820 (CH), 1720 (C=O), 1650 (conj. C=C), 1465 (CH), 1388, 1360 (CH_3, isopropyl), 1227, 1151 (C–O–) and 1050 cm^{-1}; δ ($CDCl_3$) 6.14 and 5.60 (q+q, 1 H, *J ca.* 1 Hz, *cis*+*trans* α-H), 4.10 (q, 2 H, *J* 7 Hz, CH_2CH_3), 2.13 d and 1.88 (d+d, 3 H, *J ca.* 1 Hz, *trans*+*cis* β-CH_3), 1.25 (t, 3 H, *J* 7 Hz, CH_2CH_3), 2.1–1.0 (m, 7 H, 3×CH_2+*tert.* H), and 0.90 (d, 6 H, *J* 5 Hz, isopropyl CH_3).

3,7-Dimethyloct-2-en-1-ol (22). *21* (5.0 g) in dry ether (30 ml) was added to a cooled (0 °C) suspension of lithium aluminium hydride (0.7 g) in dry ether (20 ml) and the mixture was stirred at room temperature for 5 h. Ammonium chloride (0.9 g) in water (3 ml) was added and stirring continued for ½ h. The mixture was filtered, the filter washed with ether and the combined filtrates evaporated to dryness; yield 3.9 g (99 %) crude *22*; ν_{max} (liq) 3600–3100 (bonded OH), 3000–2820 (CH), 1470 (CH), 1388, 1370 (CH_3, isopropyl), 1010 (OH), and 762 cm^{-1}; δ ($CDCl_3$) 5.83 and 5.42 (t, 1 H, *J* 7 Hz, *cis*+*trans* α-H), 4.13 (d, 2 H, *J* 7 Hz, CH_2O-), 3.05 (s, 1 H, OH), *ca.* 2.0 (m, allylic CH_2), 1.69 (s, 3 H, β-CH_3), 2.0–1.0 (m, 5 H, 2×CH_2+*tert.* H), 0.90 (d, 6 H, *J* 6 Hz, isopropyl CH_3).

(3,7-Dimethyloct-2-enyl)triphenylphosphonium bromide (23). *22* (3.12 g) and triphenylphosphonium bromide (7.2 g) in methanol (50 ml) were stirred under nitrogen at room temperature for 24 h and finally refluxed for 4 h. The reaction mixture was poured into water and extracted with chloroform. The combined extracts were dried over anhydrous sodium sulfate, the solvent evaporated and the resultant oil triturated with ethyl acetate. Filtration and recrystallization from chloroform-ethyl acetate afforded 4.94 g (50.5 %) *23* of m.p. 168–170 °C; δ ($CDCl_3$) *ca.* 7.8 (m, 15 H, aromatic), 5.13 (t, 1 H, *J* 7 Hz, α-H), 4.57 (dd, 2 H, J_{H-P} 15 Hz, J_{H-H} 7 Hz, CH_2P-), *ca.* 1.9 (m, 2 H, allylic CH_2), 1.40 and 1.34 (s+s, 3 H, CH_3), 1.5–1.0 (m, 5 H, 2×CH_2+*tert.* H), and 0.80 (d, *J* 6 Hz, isopropyl CH_3).

1,2,1′,2′-Tetrahydro-ψ,ψ-carotene (3) and 1,2-dihydro-8′-apo-ψ-caroten-8′-al (25). To a suspension of *23* (1000 mg) in dry ether (30 ml) was added 0.6 N butyl lithium (8 ml) and the resultant deep red solution stirred for *ca.* 5 min. Crocetindial (*24*, 600 mg) in methylene chloride (30 ml) was added and the mixture refluxed under nitrogen for 70 min. The reaction mixture was poured into water and the products extracted with ether. The combined extracts were washed with water and evaporated with benzene to dryness.

The individual pigments were separated by chromatography on alumina grade 2.[13] Rechromatography afforded the homogeneous pigments. Crocentindial (*24*, 323 mg) was recovered.

1,2-Dihydro-8'-apo-ψ-caroten-8'-al (25, 232 mg) was eluted with 10 % ether in petroleum ether from alumina grade 2. Crystallization from acetone-methanol afforded crystalline *25* (69.4 mg) of m.p. 128–130 °C; λ_{max} (acetone) 467 (ε = 107 000) and (490) nm; ν_{max} (KBr) 3040 (olefinic CH), 3000–2800 (CH), 2720 (–CH=O), 1682 (C=O), 1630, 1625 (conj. C=C), 1590, 1560, 1520 (C=C), 1470–1440 (CH), 1405, 1388, 1370, 1360 (CH_3), 1320, 1280, 1185, 1160, 1030, 1005, 990, 960 (*trans* –CH=CH–), 888, 835 (>C=CH–), 740, 696, and 660 cm^{-1}; δ ($CDCl_3$) 9.50 (s, 1 H, aldehydic), 7.0–5.75 (m, 13 H, olefinic), 2.3–2.0 (m, 2 H, allylic CH_2), 2.00 (s, 3 × 3 H, in-chain CH_3), 1.91 (s, 3H, α-CH_3), 1.83 (s, 3 H, end-of-chain CH_3) 1.8–1.0 (5 H, 2 × CH_2 + *tert.* H), 0.90 (d, 6 H, *J* 6 Hz, isopropyl CH_3); *m/e* (Table 1).

1,2,1',2'-Tetrahydro-ψ,ψ-carotene (3, 104 mg) was eluted with 15–25 % ether in petroleum ether from alumina grade 1.[13] Crystallization from methylene chloride-methanol afforded crystalline *3* (59.4 mg) of m.p. 150–155 °C; λ_{max} (petroleum ether) 442, 468.5 (ε = 171 000), and 499 nm; % III/II = 67; ν_{max} (KBr) 3040 (olefinic CH), 3000–2820 (CH), 1630, 1550 (C=C), 1470–1430 (CH), 1386, 1369 (CH_3), 961 (*trans* –CH=CH–) and 828 (>C=CH–) cm^{-1}; δ ($CDCl_3$) 6.90–5.80 (16 H, olefinic), 3.03 (2 × 2 H, allylic CH_2), 1.87 (s, 4 × 3 H, in-chain CH_3), 1.82 (s, 2 × 3 H, end-of-chain CH_3), 1.7–1.1 (6 H, 2 × CH_2 + 2 × *tert.* H), and 0.87 (d, 4 × 3 H, *J* 6 Hz, isopropyl CH_3); *m/e* (Table 1).

1,2-Dihydro-ψ,ψ-carotene (4). To a suspension of geranyltriphenyl phosphonium bromide (*26*, 240 mg) in dry ether (10 ml) was added 0.6 N butyl lithium (2 ml) and the resultant dark red solution stirred for *ca.* 1 min. 1,2-Dihydro-apo-8'-lycopenal (*25*, 104 mg) in dry ether (40 ml) was added and the mixture refluxed under nitrogen for 90 min. Geranyltriphenylphosphonium bromide (*28*, 240 mg) was treated with 0.6 N butyl lithium (2 ml) and this was added to the solution. The reaction was stopped after a further 15 min by the addition of water. The products were extracted with ether and the combined extracts washed with water, evaporated with benzene to dryness and the pigments were purified by chromatography twice on alumina grade 2. *4* (83.5 mg) was eluted with 5 % ether in petroleum ether. Crystallization from acetone-methanol afforded crystalline *4* (18 mg) of m.p. 162–165 °C; λ_{max} (light petroleum) 443, 469 (ε = 164 000) and 499.5 nm % III/II = 63; ν_{max} (KBr) 3040 (olefinic CH), 3000–2820 (CH), 1720, 1675, 1630, 1550 (C=C), 1470–1430 (CH), 1385, 1370, (CH_3), 961 (*trans* –CH=CH–), 888 and 828 (>C=CH–) cm^{-1}; δ ($CDCl_3$) 7.0–5.8 (16 H, olefinic), 5.15 (m, 1 H, H-2'), 2.22 (3 × 2 H, allylic CH_2), 1.98 (s, 4 × 3 H, in-chain CH_3), 1.83 (s, 2 × 3 H, end-of-chain CH_3), 1.72 s and 1.63 (s+s, 3+3 H, isopropenyl CH_3), 1.6–1.0 (m, 3 H, non-allylic CH_2 + *tert.* H), and 0.88 (d, 2 × 3 H, *J* 6 Hz, isopropyl CH_3); *m/e* (Table 1).

Methyl 3,7-dimethylocta-2,4-dienoate (29). To a suspension of sodium hydride (50 % in mineral oil, 3.1 g, washed repeatedly with petroleum ether) was added methyl 3-methyl-4-diethylphosphonocrotonate (*30*, 16 g) in dry ether (20 ml) and the mixture stirred until H_2-evolution had ceased. Isovaleraldehyde (*27*, 7.9 g) was added and the reaction run overnight with stirring. The reaction mixture was poured into water, the products extracted into ether, the extract washed with water, dried over $MgSO_4$ and evaporated to give 8.4 g (92 %) crude *29*; ν_{max} (liq) 3040 (olefinic CH), 3000–2820 (CH), 1720 (>C=O), 1640, 1610, 1430–1470 (CH), 1385, 1370 (CH_3), 1240, 1150, 1040, 960–980, 850 cm^{-1}; δ ($CDCl_3$) 0.92 (d, 6 H, *J* 6 Hz, CH_3 isopropyl), 1.5–2.0 (m, H-6), 2.0 and 2.3 (d+d, 3 H, *J* 1 Hz, CH_3 vinylic *trans* and *cis*), 3.70 (s, 3 H, $-OCH_3$), 5.67 and 5.77 (m+m, 1 H at C-2, *trans* and *cis*), 6.19 (dt, 1 H, $J_{4,5}$ 16 Hz, $J_{5,6}$ 7 Hz, H at C-5), 7.67 (d, 1 H, *J* 16 Hz, H at C-4).

3,7-Dimethylocta-2,4-diene-1-ol (30). *29* (4.6 g) in dry ether (30 ml) was added to a cooled (0 °C) suspension of $LiAlH_4$ (1 g) in dry ether (30 ml) and the reaction continued at room temperature for 1 h. Excess $LiAlH_4$ was destroyed by addition of ethyl acetate, the reaction mixture was poured into ice–1 N H_2SO_4, and the products extracted into ether. The ether extract was washed with water and dried over $MgSO_4$. Evaporation of the solvent gave 2 g (52 %) crude *30*; n_D^{19} = 1.4350; ν_{max} (liq) 3600–3100 (OH), 3000–2820 (CH), 1640, 1610, 1470–1430 (CH), 1370 (CH_3), 1240, 1150, 1040, and 980 cm^{-1}; δ ($CDCl_3$) 0.91 (d, 6 H, *J* 6 Hz, CH_3 isopropyl), 1.5–2.0 (m, H-6), 1.76 and 1.83 (d+d, 3 H, *J* 1 Hz, CH_3 vinylic *trans* and *cis*), 1.7–2.2 (m, CH_2), 3.92 (s, 1 H, OH), 4.22 (d, 2 H, *J* 7 Hz, $-CH_2O-$), 5.3–6.6 (m, 3 H, olefinic *cis* and *trans*).

(3,7-Dimethylocta-2,4-dienyl)triphenylphosphonium bromide (31). Triphenylphosphonium bromide (4.5 g) and *30* (2 g) in dry methanol (25 ml) were stirred at room temperature for 56 h. Removal of the solvent gave an oil which was triturated with ether. The resultant viscous oily product was dried in high vacuum and gave a colourless semi-solid (2 g, 44 %) which was used without further purification.

1,2-Dihydro-3,4-didehydro-8'-apo-ψ-caroten-8'-al (32). To *31* (250 mg) and crocetindial (*24*, 100 mg) in dimethylformamide (30 ml) was added 1.1 N $NaOCH_3$ (0.5 ml) dropwise with stirring, the reaction mixture stirred at room temperature for 1.5 h and then poured into water. The pigments were extracted into benzene, the extract washed with water, dried over Na_2SO_4 and evaporated to dryness. The products were chromatographed on alumina

grade 2.[13] *32* was eluted with benzene. Evaporation of the solvent and crystallization twice from petroleum ether gave 50 mg (36 %) *32* of m.p. 110–112 °C. λ_{max} (acetone) 473 (ε = 99 800) nm; ν_{max} (KBr) 3000–2820 (CH) 1750, 1675 (C=O), 1610 (C=C), 1470–1440 (CH_2), 1385, 1369 (CH_3), 961 (*trans* –CH=CH–) cm^{-1}. δ ($CDCl_3$), 0.87 (d, 6 H, *J* 7 Hz, isopropyl CH_3), 1.82 (s, 6 H, CH_3 at C-5 and C-9′), 1.97 (s, 9 H, CH_3 at C-9,13 and 13′), 5.8–7.0 (15 H, olefinic), 9.50 (s, 1 H, aldehydic); *m/e* (Table 1).

1,2,1′,2′-Tetrahydro-3,4,3′,4′-tetradehydro-ψ,ψ-carotene (6). To a suspension of *31* (250 mg) in dry ether (25 ml) was added 1 N butyl lithium (0.55 ml) and the mixture stirred until the phosphonium salt had dissolved. Methylene chloride (3 ml) followed by crocetindial (*24*, 140 mg) in methylene chloride (25 ml) were added. The reaction mixture was refluxed under N_2 for 2 h, cooled and poured into water. The pigments were extracted with ether, the extract washed with water, dried over $MgSO_4$, evaporated and the residue chromatographed on alumina grade 2. *6* was eluted with 10 % ether in petroleum ether. The solvent was evaporated and the residue redissolved in petroleum ether, isomerized with iodine in light and rechromatographed. Evaporation of the solvent and crystallization from acetone-methanol afforded 60 mg (25 %) *6* of m.p. 197–199 °C; λ_{max} (pet. ether) 460, 488 (ε = 168 100) and 520 nm; % III/II = 43; ν_{max} (KBr) 3040–2800 (CH), 1470–1440 (CH_2), 1373, 1368 (CH_3), 970 (*trans* –CH=CH–) and 830 (>C=CH–) cm^{-1}; δ ($CDCl_3$) 0.87 (d, 12 H, *J* 6 Hz, isopropyl CH_3), 1.91 (s, 6 H, CH_3 at C-5,5′), 1.96 (s, 12 H, CH_3 at C-9,13,13′ and 9′), 5.8–7.0 (20 H, olefinic); *m/e* (Table 1).

1,2-Dihydro-3,4-didehydro-ψ,ψ-carotene (5). To a suspension of geranyltriphenylphosphonium bromide (*26*, 100 mg) in ether (20 ml) was added 1 N butyl lithium in ether (0.25 ml) and the resultant deep red ylid solution stirred until all phosphonium salt had gone into solution. Methylene chloride (3 ml) followed by *32* (40 mg) in methylene chloride (10 ml) were added and the reaction mixture refluxed for 1 h. Another portion of ylid, prepared from *26* (50 mg) and butyl lithium (0.12 ml), was added and the reaction continued for another 30 min. The reaction mixture was poured into water and the pigments extracted into ether. The extract was washed with water, dried over $MgSO_4$ and evaporated. The crude product was chromatographed on alumina, grade 2, and eluted with 10 % ether in light petroleum. The pigment was isomerized with iodine in light and rechromatographed. Evaporation of the solvent and crystallization from acetone-methanol afforded 13 mg (25 %) *5* of m.p. 180–185 °C; λ_{max} (light petroleum) 453, 480 (ε = 163 400) and 513 nm; % III/II = *64*; ν_{max} (KBr) 3040 (=CH–), 3000–2820 (CH), 1570, 1540 (C=C), 1470–1440 (CH_2), 1378, 1369 (CH_3), 960 (*trans* –CH=CH–), and 830 (>C=CH–) cm^{-1}; δ ($CDCl_3$) 0.87 (d, 6 H, *J* 6 Hz, isopropyl CH_3), 1.62 and 1.69 (s+s, 3+3 H, 2×CH_3 at C-1), 1.77 (s, 3 H, CH_3 at C-5), 1.87 (s, 3 H, CH_3 at C-5′), 1.97 (s, 12 H, CH_3 at C-9,13,13′,9′), 2.12 (6 H, allylic CH_2), 5.15 (m, 1 H, H-2), 5.8–7.0 (18 H, olefinic), *m/e* (Table 1).

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