Carotenoids and related polyenes. Part 3.[1] First total synthesis of fucoxanthin and halocynthiaxanthin using oxo-metallic catalyst

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The first total synthesis of optically active fucoxanthin **1** and halocynthiaxanthin **2** had been accomplished *via* the 8-oxo compound **5**, efficiently prepared by rearrangement of the α-acetylenic alcohol **10** using oxo-metallic catalyst and subsequent iodine-catalysed double-bond shift.

Introduction

The allenic carotenoid fucoxanthin **1**[2] (Scheme 1) is known to be widely distributed in brown algae and to function as a light-harvesting pigment for photosynthesis[3] in the sea. On the other hand, the acetylenic carotenoid halocynthiaxanthin **2** was first isolated[4] from the sea squirt *Halocynthia roretzi*, together with fucoxanthin and other carotenoids. Recently, it has been found[5] that both carotenoids possessing the β,γ-epoxy keto moiety as a common structure have effective antiproliferative and antitumour-promoting activities. Although over ten years have passed since the absolute stereostructures of these carotenoids were determined, there has been no report on their synthesis, probably because of difficulties in constructing the β,γ-epoxy keto moiety in the polyene chain, which was known[6] to be extremely labile to alkali. Therefore, synthesis of these carotenoids is a fascinating challenge for the organic chemist. In a previous communication,[7] we reported the first total synthesis of fucoxanthin **1** through the skeletal compound (C_{40}) **3** which was constructed by double Wittig condensations of the C_{10}-dialdehyde **7** with the 8†-oxo-Wittig salt (C_{15}) **6** and the allenic Wittig salt (C_{15}) **8** (Scheme 1). In addition, halocynthiaxanthin **2** was first synthesized by the same methodology using the acetylenic Wittig salt (C_{15}) **9**.[8] Three Wittig salts **6**, **8** and **9** were derived from the common intermediate, α-acetylenic alcohol **10**, which was previously synthesized[9] in an optically active form (97% ee) from the readily available (4*R*,6*R*)-4-hydroxy-2,2,6-trimethylcyclohexanone. Rearrangement of acetylenic alcohol **10** by means of oxo-metallic catalyst,[10] followed by a double-bond shift, resulted in the effective formation of the key intermediate **5** leading to the total synthesis of our target compounds **1** and **2**. Here, we describe a full account of these experiments.

Results and discussion

Synthesis of the C_{15}-8-oxo-Wittig salt 6

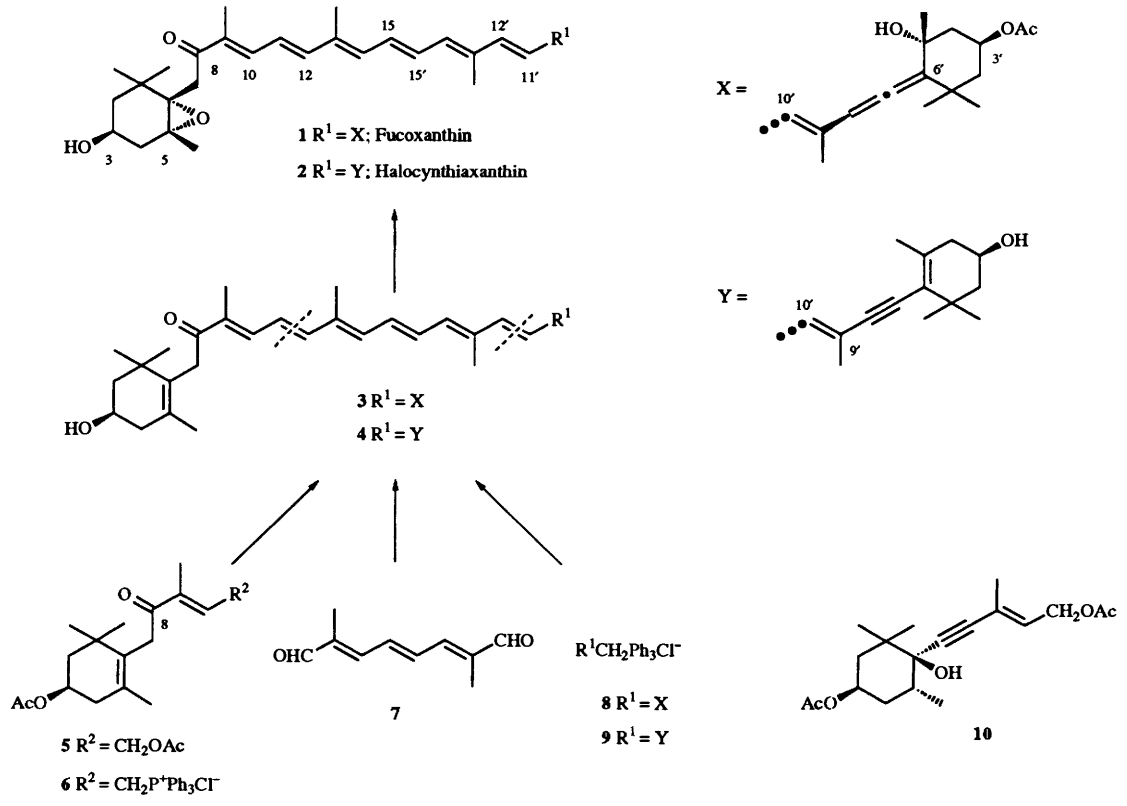
The rearrangement of α-acetylenic alcohols into α,β-unsaturated carbonyl compounds by use of several oxo-metallic catalysts was reported.[10] In the case of the application of this rearrangement to cyclohexanol derivatives, a mixture of α,β- and β,γ-unsaturated carbonyl compounds was produced. Therefore, it is expected that the 8-oxo compound **5**, a precursor of the 8-oxo-Wittig salt **6**, could be obtained by rearrangement of the α-acetylenic alcohol **10**[9] by using oxo-metallic catalyst.

Although most of these rearrangements had been carried out at a high reaction temperature, it was recently reported[10a] that the combined use of tetrabutylammonium perrhenate (Bu_4NReO_4) and toluene-*p*-sulfonic acid (PTSA) effectively catalysed such rearrangement even at room temperature. Thus, we applied this method to the α-acetylenic alcohol **10**. Reaction of compound **10** with Bu_4NReO_4 (5 mol%) and PTSA (5 mol%) at room temperature unfortunately failed to afford the desired β,γ-unsaturated ketone **5**, but instead yielded the rearranged α,β-unsaturated ketones **11a** (6*E*-isomer; 32%) and **11b** (6*Z*-isomer; 50%) accompanied by the dehydrated product **12**[9] (14%) (Scheme 2). The structures of products **11a,b** were confirmed on the basis of their spectral data (see Experimental section). Their IR spectra showed the absorption (~ 1650 cm^{-1}) due to an α,β-unsaturated ketone. The conformations and stereochemistries of these isomers were determined to be as shown in Scheme 2 by ^1H NMR spectroscopy, including 2D nuclear Overhauser enhancement spectroscopy (NOESY) experiments. 3-H (δ 5.27, tt, *J* 11.5 and 4.5 Hz) of the isomer **11a** was assigned as axial and the corresponding hydrogen (δ 5.06, quint-like, *J* 4.5 Hz) of the isomer **11b** as equatorial from their *J*-values. In 2D NOESY experiments, cross-peaks between 7-H and both 1eq- and 9-methyl protons were observed in compound **11a**. On the other hand, cross-peaks between 7-H and both 5-Me and 10-H appeared in compound **11b**. This reaction may be envisaged to proceed *via* the perrhenate ester **I** which undergoes rearrangement to the allenic intermediate **II** to afford the α,β-unsaturated ketones **11a,b**. The dehydrated product **12** may be formed *via* the same intermediate **I** by intramolecular hydrogen shift (C-5 to oxo-metallic oxygen). This was supported by the fact that the same reaction of the alcohol **13**, which was obtained[9] together with its C-6 diastereoisomer **10** as a minor product, gave only rearranged products **11a** (39%) and **11b** (58%).

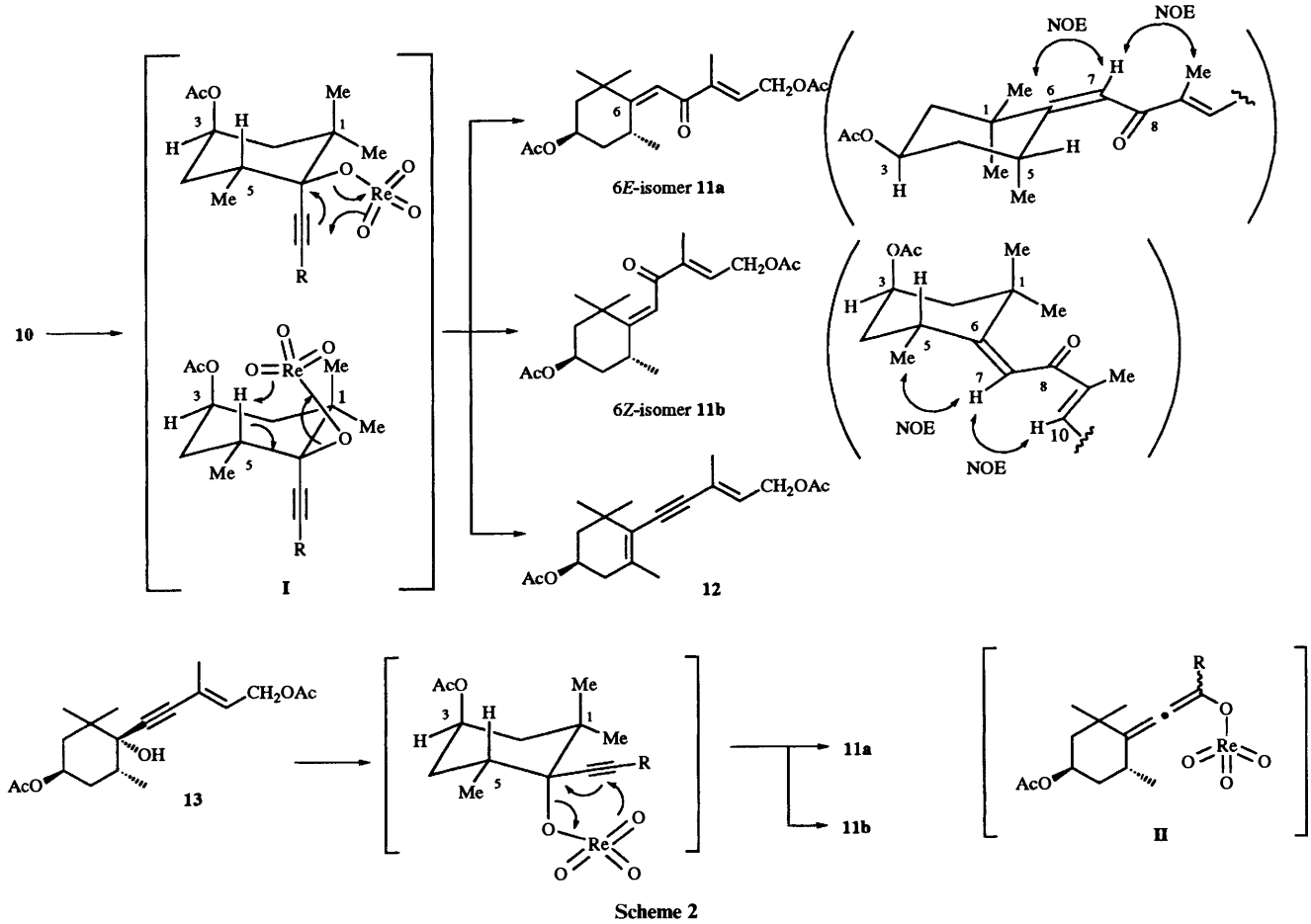
On the other hand, treatment[10b] of compound **10** with tris(triphenylsilyl) vanadate (1 mol%), triphenylsilanol (14 mol%) and benzoic acid (1.6 mol%) in refluxing xylenes gave α,β- and β,γ-unsaturated ketones **11b** (35%) and **5** (58%) (Scheme 3). Under these reaction conditions, compound **11a** was converted into the β,γ-unsaturated ketone **5** (81%); nevertheless compound **11b** remained unchanged (Table 1, entries 1 and 3). Thus, compound **5** was assumed to be derived from the 6*E*-isomer **11a** through the enol intermediate **III** by intramolecular hydrogen shift (C-5 to carbonyl oxygen).

In order to obtain the desired β,γ-unsaturated ketone **5** effectively, conversion of the 6*Z*-isomer **11b** into compound **5** was investigated in detail. Since the 6*E*-isomer **11a** can be converted into the required compound **5**, isomerization of *Z*-**11b** to *E*-isomer **11a** was required. Therefore, the 6*Z*-isomer **11b** was treated with 0.015% iodine in refluxing hexane for 6 h to give the β,γ-unsaturated ketone **5** in 72% yield (Table 1, entry 4). Treatment of 6*Z*-isomer **11b** with a higher concentration of iodine (0.02%) in refluxing heptane instead of hexane afforded compound **5** (80%) effectively in a shorter time (0.8 h) (entry 6). This reaction was found to proceed through the intermediate

† We have employed the numbering system used in the retinoids and carotenoids.



Scheme 1



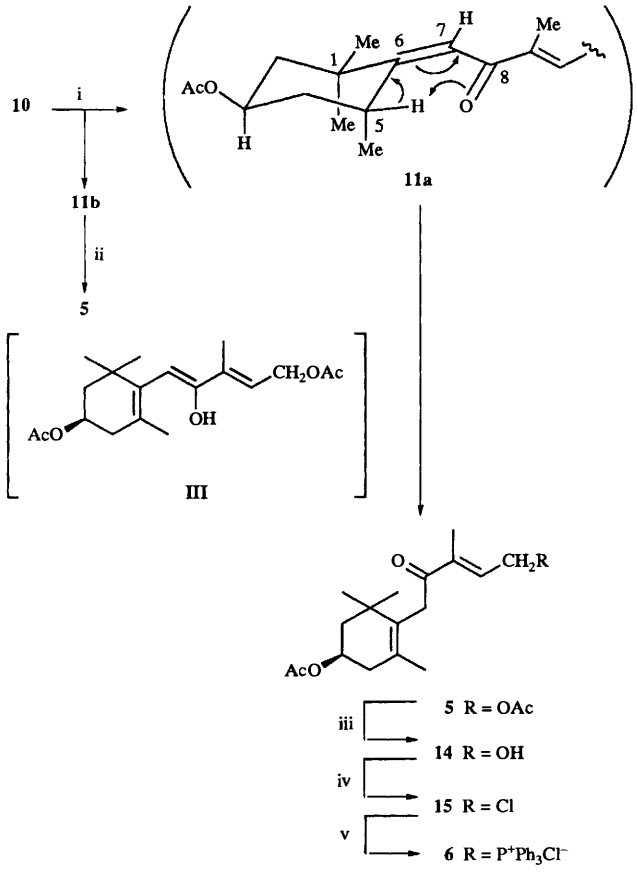
Scheme 2

Table 1 Conversion of the α,β-unsaturated ketones **11a, b** into the β, γ-unsaturated ketone **5**

Entry	Substrate	Reagent	Conditions	Yield (%) of **5**
1	**11a**	$(Ph_3SiO)_3VO$, Ph_3SiOH, $PhCO_2H$	reflux, xylenes, 2.5 h	81
2	**11a**	0.02% I_2 solution	reflux, heptane, 0.8 h	81
3	**11b**	$(Ph_3SiO)_3VO$, Ph_3SiOH, $PhCO_2H$	reflux, xylenes, 6 h	no reaction
4	**11b**	0.015% I_2 solution	reflux, hexane, 6 h	72
5	**11b**	0.02% I_2 solution	reflux, hexane, 2 h	72
6	**11b**	0.02% I_2 solution	reflux, heptane, 0.8 h	80

6*E*-isomer **11a**, which was isolated in the course of the conversion. The 6*E*-isomer **11a** was also transformed into the β,γ-unsaturated ketone **5** (81%) under the same conditions (entry 2).

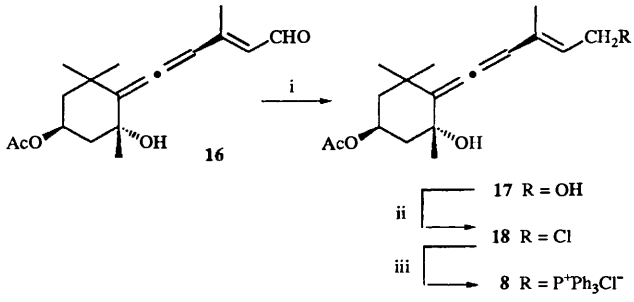
Mild hydrolysis of the ketone **5** with 10% aq. potassium carbonate gave the hydroxy enone **14**, which was allowed to react with lithium chloride and methanesulfonyl chloride (MsCl) followed by treatment of the intermediate chloride **15** with triphenylphoshine to provide the C_{15}-8-oxo-Wittig salt **6** in 60% yield from acetate **5** (Scheme 3).



Scheme 3 *Reagents and conditions*: i, $(Ph_3SiO)_3VO$, Ph_3SiOH, $PhCO_2H$, xylenes, reflux; ii, cat. I_2, heptane, reflux; iii, 10% aq. K_2CO_3; iv, LiCl, MsCl, γ-collidine; v, PPh_3, $CHCl_3$, reflux

Synthesis of the C_{15}-allenic Wittig salt 8

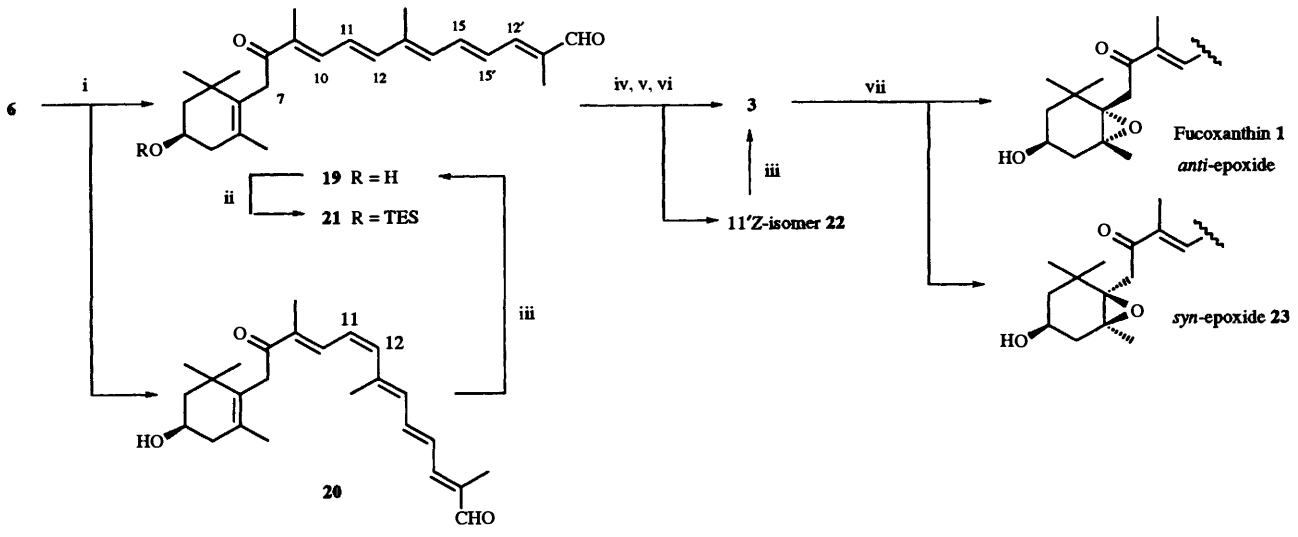
The C_{15}-acetylenic diacetate **10** was transformed in 5 steps into the known allenic aldehyde **16**,[1] which was reduced with sodium boranuide to give the allenic alcohol **17** (96%). Treatment of alcohol **17** with lithium chloride and MsCl and successive reaction of the intermediate chloride **18** with triphenylphosphine gave the C_{15}-allenic Wittig salt **8** in 74% yield (Scheme 4).



Scheme 4 *Reagents and conditions*: i, $NaBH_4$; ii, LiCl, MsCl, γ-collidine; iii, PPh_3, $CHCl_3$, 50 °C

Synthesis of optically active fucoxanthin

The Wittig condensation of phosphonium salt **6** with C_{10}-dialdehyde **7** in the presence of sodium methoxide as a base, followed by hydrolysis, afforded a mixture of 8-oxoapocarotenals. Separation by preparative HPLC (PHPLC) provided the all-*E*-isomer **19** (32%) and the 11*Z*-one **20** (29%) each in pure form (Scheme 5). The latter was isomerized to the former in 94% yield by treatment[11] with a palladium catalyst. Consequently, treatment of a crude mixture of apocarotenals **19** and **20** with a palladium catalyst produced all-*E*-enal **19** in 77% yield from phosphonium salt **6**. Stereochemistries of the newly formed 11,12-double bonds of these isomers were determined from the coupling constants (**19**: 15 Hz; **20**: 11.5 Hz) between 11- and 12-H in the ^1H NMR spectra. NOE experiments (cross-peaks between 7-H_2 and 10-H) showed that the 8,9-single bond in enal **19** is *s-trans*. After protection (79%) of the hydroxy group of compound **19**, the resulting triethylsilyl (TES) ether **21** was treated with the allenic Wittig salt **8** with sodium methoxide as a base to give a mixture of the condensed products, which without purification was acetylated, desilylated by the combined use of tetrabutylammonium fluoride (TBAF) and acetic acid, and subsequently separated by PHPLC to provide the all-*E*-fucoxanthin skeletal compound **3** (22% from **21**) and its 11′*Z*-isomer **22** (27% from **21**). These structures were characterized by spectral data (see Experimental section). Isomerization of the 11′*Z*-isomer **22** by using a palladium catalyst[11] afforded the all-*E*-isomer **3** in 45% yield. Finally, epoxidation of the skeletal compound **3** with *m*-chloroperbenzoic acid (MCPBA) followed by HPLC purification furnished a mixture (36%; ~7:2) of the *syn*-epoxide **23** and the *anti*-epoxide **1** with some recovery (27%) of substrate **3**. Separation of the epoxide mixture by PHPLC using a chiral column



Scheme 5 *Reagents*: i, 7, NaOMe, then 10% NaOH; ii, TESOTf, γ-collidine; iii, $PdCl_2(MeCN)_2$, Et_3N; iv, 8, NaOMe; v, Ac_2O–Py; vi, TBAF, AcOH; vii, MCPBA

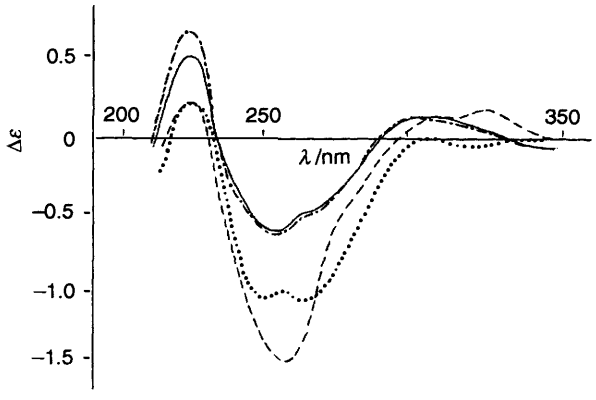


Fig. 1 CD spectra in Et_2O–isopentane–EtOH (5:5:2) of fucoxanthin **1**, *anti*-epoxide **23** and skeletal compound **3**. Natural fucoxanthin – – – –; synthetic fucoxanthin ——; *anti*-epoxide **23** – – – –; skeletal compound **3** • • • •

(CHIRALCEL OD; DAICEL) gave each epoxide in pure form. Spectral data [IR, UV–VIS, ^{1}H NMR,[12] MS and CD (Fig. 1)] of the purified *anti*-epoxide **1** were in good agreement with those of a natural specimen.‡ This is the first total synthesis of optically active fucoxanthin.

Synthesis of optically active halocynthiaxanthin

The total synthesis of optically active halocynthiaxanthin was also accomplished (Scheme 6) in the same pathway as described in the synthesis of fucoxanthin **1**.

According to the literature,[8] the acetylenic Wittig salt **9** was prepared from the diol **25** obtained by hydrolysis (93%) of the diacetate **24**.[9] The Wittig reaction between Wittig salt **9** and the 8-oxoapocarotenal **19** afforded an isomeric mixture (93%; all-*E*:9′*Z*:11′*Z*:9′*Z*,11′*Z* ~ 4:2:2:1) of the condensed products. As these isomers were difficultly separable, the mixture was treated with the previous palladium catalyst[11] to give a simple mixture of all-*E*-isomer **4** (35% from **19**) and 9′*Z*-one **26** (33% from **19**), which was cleanly separated by PHPLC in the dark.

Previous synthetic studies[13] of acetylenic carotenoids and related compounds showed that the condensation between the C_{15}-acetylenic Wittig salt and conjugated aldehydes was accompanied by stereomutation to give a product with a 9*Z*-configuration. To avoid isomerization at position 9, the reverse Wittig reaction was successfully carried out.[13,14] Thus, in order to obtain the all-*E*-skeletal compound **4** exclusively, we attempted the route *via* the apocarotenal **31** from the acetylenic aldehyde **28**. The apocarotenal **31** was prepared (31%) accompanied by the 11*Z*-isomer **32** (17%) and the 13*Z*-one **33** (9%) by a Wittig reaction between the Wittig salt **30** derived from aldehyde **29**[13] and the acetylenic aldehyde **28** prepared by oxidation of the diol **25** with active manganese dioxide. However, the Wittig condensation between aldehyde **31** and Wittig salt **6** did not proceed owing to low reactivity of the ylide formed from phosphonium salt **6** and weak electrophilicity of aldehyde **31**.

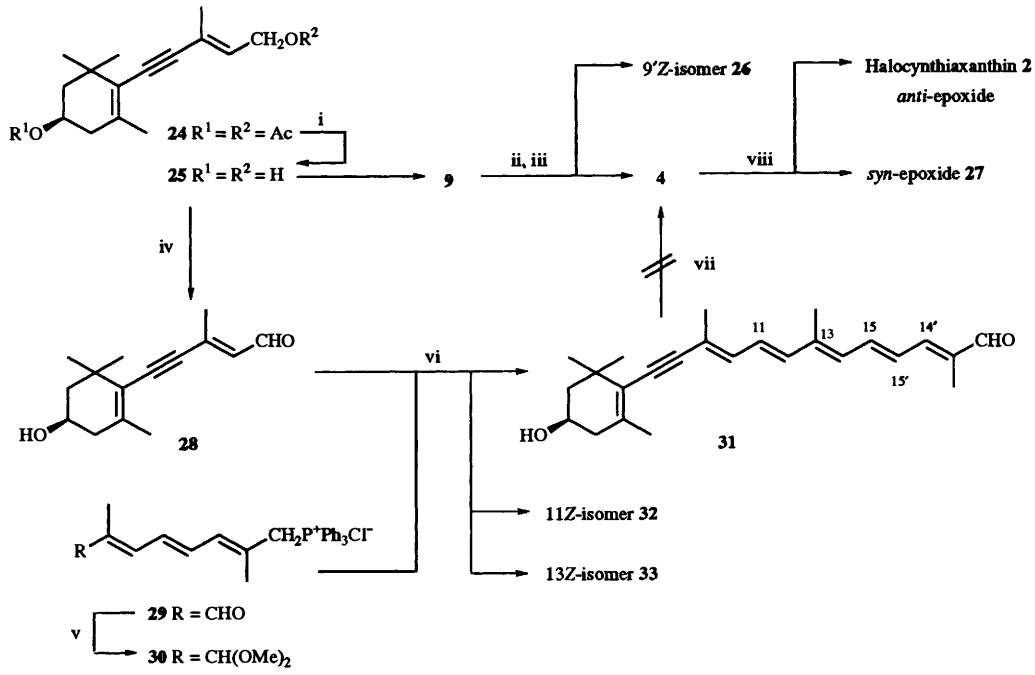
Finally, epoxidation of the skeletal compounds **4** with MCPBA followed by HPLC purification furnished a mixture (49%) of the *syn*-epoxide **27**, the *anti*-one **2** and other unidentified products, along with some recovery (16%) of starting material **4**. Separation of the mixture by PHPLC using a chiral column (CHIRALCEL OD; DAICEL) gave *syn*-epoxide **27** (16%) and halocynthiaxanthin **2** (5%) each in pure form. Spectral data (IR, UV–VIS, ^{1}H NMR and MS) of the purified *anti*-epoxide **2** were in good agreement with those of a natural specimen.§ This is the first total synthesis of optically active halocynthiaxanthin.

Experimental

Mps were measured on a micro melting point apparatus (Yanagimoto) and are uncorrected. UV–VIS spectra were recorded on a JASCO Ubest-55 instrument, IR spectra on a Shimadzu IR-27G spectrometer, and FT-IR spectra on a Shimadzu FT-IR 4000 spectrometer. ^{1}H NMR spectra at 200, 300 or 500 MHz were determined on a Varian XL-200, a Varian Gemini-200, or a Varian Gemini-300 or a Varian VXR-500 superconducting FT-NMR spectrometer, respectively, for deuteriochloroform solutions (tetramethylsilane as internal reference). *J*-Values are given in Hz. Mass spectra were taken on a Hitachi M-80 or a Hitachi M-4100 spectrometer. Optical rotations were measured on a JASCO DIP-181 polarimeter

‡ This was kindly supplied by Professor Y. Koyama, Kwansei Gakuin University, and Professor K. Tsujimoto, Japan Advanced Institute of Science and Technology, Hokuriku.

§ This was kindly supplied by Dr W. Miki, Marine Biotechnology Institute Co., Ltd., Shimizu, Shizuoka, Japan.



Scheme 6 *Reagents*: i, 10% aq. KOH; ii, **19**, NaOMe; iii, $PdCl_2(MeCN)_2$, Et_3N; iv, MnO_2; v, $HC(OMe)_3/H^+$; vi, NaOMe, then H^+; vii, **6**, NaOMe; viii, MCPBA

([α]$_D$-values are in units of 10^{-1} deg cm^2 g^{-1}), and CD spectra on a JASCO J-500C. Short-column chromatography (CC) was performed on silica gel (Merck Art. 7739) under reduced pressure. Preparative TLC (PTLC) was performed on silica gel plates (Merck silica gel $60F_{254}$ precoated plates, 0.5 mm thickness). Analytical and preparative HPLC was carried out on Shimadzu LC-3A, 5A, 6A and Waters Model 510 instruments with a UV–VIS detector.

Standard work-up means that the organic layers were finally washed with brine, dried over anhydrous sodium sulfate (Na_2SO_4), filtered, and concentrated under reduced pressure below 30 °C using a rotary evaporator. All operations were carried out under nitrogen or argon. Ether refers to diethyl ether, and hexane to *n*-hexane. NMR assignments are given using the carotenoid numbering system.

Synthesis of Fucoxanthin 1

Rearrangement of the α-acetylenic alcohol 10 by an ammonium perrhenate catalyst. A solution of the α-acetylenic alcohol **10**[9] (672 mg, 2 mmol), Bu_4NReO_4 (49 mg, 0.1 mmol) and PTSA·$2H_2O$ (19 mg, 0.1 mmol) in CH_2Cl_2 (15 cm^3) was stirred at room temp. for 10 h. The mixture was diluted with ether and washed successively with saturated aq. $NaHCO_3$ and brine. Evaporation of the dried extracts provided a residue, which was purified by short CC (ether–hexane, 3:7) followed by PHPLC [LiChrosorb Si 60 (7 μm) 2.5 × 25 cm; ether–hexane, 1:3] to afford the 6*E*-isomer **11a** (218 mg, 32%), the 6*Z*-one **11b** (334 mg, 50%) and the dehydrated product **12** (86 mg, 14%) as oils. Spectral properties of dienyne **12** were identical with those of the sample prepared previously.[9] *Compound* **11a**: $[\alpha]_D^{21}$ −37.1 (*c* 1.05, MeOH); λ_{max}(EtOH)/nm 238 and 253sh; ν_{max}($CHCl_3$)/cm^{-1} 1730 (OAc) and 1651 (conj. CO); δ_H(500 MHz) 1.23 (3 H, s, 1-Me^{eq}), 1.28 (3 H, s, 1-Me^{ax}), 1.31 (3 H, d, *J* 7.5, 5-Me), 1.46 (1 H, dd, *J* 12.5 and 11.5, 2-H^{ax}), 1.56 (1 H, td, *J* 11.5 and 6, 4-H^{ax}), 1.86 (3 H, d, *J* 1, 9-Me), 1.90 (2 H, m, 2- + 4-H^{eq}), 2.03 and 2.12 (each 3 H, s, OAc × 2), 3.57 (1 H, qdd, *J* 7.5, 6 and 1.5, 5-H), 4.80 (2 H, d, *J* 6, 11-H_2), 5.27 (1 H, tt, *J* 11.5 and 4.5, 3-H), 6.38 (1 H, s, 7-H) and 6.51 (1 H, tq, *J* 6 and 1, 10-H) [Found: (M + H)$^+$, 337.202. $C_{19}H_{29}O_5$ requires M + H, 337.201].

Compound **11b**: $[\alpha]_D^{22}$ −45.4 (*c* 0.97, MeOH); λ_{max}(EtOH)/nm 234; ν_{max}($CHCl_3$)/cm^{-1} 1730 (OAc) and 1652 (conj. CO); δ_H(500 MHz) 1.03 (3 H, s, 1-Me^{eq}), 1.12 (3 H, d, *J* 6.5, 5-Me), 1.24 (3 H, s, 1-Me^{ax}), 1.56 (1 H, ddd, *J* 14, 12.5 and 6.5, 4-H^{ax}), 1.60 (1 H, dd, *J* 14 and 4, 2-H^{ax}), 1.75 (1 H, ddd, *J* 14, 5 and 1.5, 2-H^{eq}), 1.85 (3 H, d, *J* 1, 9-Me), 1.91 (1 H, dtd, *J* 12.5, 4.5 and 1.5, 4-H^{eq}), 2.06 and 2.11 (each 3 H, s, OAc × 2), 2.78 (1 H, m, 5-H^{ax}), 4.80 and 4.84 (each 1 H, br dd, *J* 15 and 6, 11-H_2), 5.06 (1 H, quint-like, *J* 4.5, 3-H), 5.77 (1 H, d-like, *J* 1.5, 7-H) and 6.61 (1 H, tq, *J* 6 and 1, 10-H) [Found: (M + H)$^+$, 337.201].

Rearrangement of the α-acetylenic alcohol 13 by an ammonium perrhenate catalyst. In the same manner as described for the rearrangement of compound **10** by the tetrabutylammonium perrhenate catalyst, the α-acetylenic alcohol **13**[9] (672 mg) provided the 6*E*-isomer **11a** (264 mg, 39%) and the 6*Z*-one **11b** (388 mg, 58%).

Rearrangement of the α-acetylenic alcohol 10 by a silyl vanadate catalyst. A solution of compound **10** (1.68 g, 5.0 mmol), triphenylsilanol (210 mg, 0.72 mmol), tris(triphenylsilyl) vanadate (45 mg, 0.05 mmol) and benzoic acid (10 mg, 0.08 mmol) in xylenes (10 cm^3) was refluxed for 8 h. Evaporation off of the solvent gave a residue, which was purified by short CC (ether–hexane, 3:7) followed by PHPLC [LiChrosorb Si 60 (7 μm) 2.5 × 25 cm; ether–hexane, 1:3] to afford the α,β-unsaturated ketone (6*Z*-isomer) **11b** (594 mg, 35%) and the β,γ-unsaturated ketone **5** (981 mg, 58%) as crystals. *Compound* **5**: mp 76–78 °C (from hexane); $[\alpha]_D^{23}$ −46.9 (*c* 1.13, MeOH); λ_{max}(EtOH)/nm 235; ν_{max}($CHCl_3$)/cm^{-1} 1730 (OAc) and 1680 (conj. CO); δ_H(200 MHz) 0.91 and 1.01 (each 3 H, s, *gem*-Me), 1.45 (3 H, s, 5-Me), 1.62 (1 H, t, *J* 12, 2-H^{ax}), 1.75 (1 H, ddd, *J* 12, 4 and 1.5, 2-H^{eq}), 1.84 (3 H, d, *J* 1, 9-Me), 2.05 and 2.13 (each 3 H, s, OAc × 2), 2.15 (1 H, br dd, *J* 16.5 and 9.5, 4-H^{ax}), 2.38 (1 H, br dd, *J* 16.5 and 6, 4-H^{eq}), 3.43 (2 H, s, 7-H_2), 4.83 (2 H, d, *J* 6, 11-H_2) and 6.66 (1 H, br t, *J* 6, 10-H) [Found: (M + H)$^+$, 337.201. $C_{19}H_{29}O_5$ requires M + H, 337.201] (Found: C, 67.65; H, 8.5. $C_{19}H_{28}O_5$ requires C, 67.83; H, 8.39%).

Conversion of α,β-unsaturated ketones 11a (6*E*-isomer) and 11b (6*Z*-isomer) into the β,γ-unsaturated ketone 5 (Table 1). *General work-up procedure*.—The reaction was continued until the peak of the starting material disappeared on analytical

HPLC [LiChrosorb Si 60 (5 μm) 0.4 × 30 cm; ether–hexane, 1:3]. The yields (see Table 1) of each reaction were calculated by comparison of the chromatogram of diluted solutions of each final reaction mixture with that of a standard solution of compound **5** by analytical HPLC.

(a) *Treatment of compound* **11a** *with a silyl vanadate catalyst* (*entry* 1).—A solution (2.5 cm^3) prepared from tris(triphenylsilyl) vanadate (11.3 mg), triphenylsilanol (52.5 mg) and benzoic acid (2.5 mg) in xylenes (10 cm^3) was added to compound **11a** (105 mg) and the mixture was refluxed for 2.5 h.

(b) *Treatment of compound* **11a** *with* 0.02% *iodine in refluxing heptane* (*entry* 2).—A solution of iodine in heptane (0.02%, w/v; 5 cm^3) was added to compound **11a** (22 mg) and the mixture was refluxed for 50 min.

(c) *Treatment of compound* **11b** *with a silyl vanadate catalyst* (*entry* 3).—A solution (0.25 cm^3) prepared from tris(triphenylsilyl) vanadate (11.3 mg), triphenylsilanol (52.5 mg) and benzoic acid (2.5 mg) in xylenes (10 cm^3) was added to a solution of compound **11b** (10 mg) in xylenes (3 cm^3) and the mixture was refluxed for 6 h.

(d) *Treatment of compound* **11b** *with* 0.015% *iodine in refluxing hexane* (*entry* 4).—A solution of iodine in hexane (0.015%, w/v; 10 cm^3) was added to compound **11b** (20 mg) and the mixture was refluxed for 6 h.

(e) *Treatment of compound* **11b** *with* 0.02% *iodine in refluxing hexane* (*entry* 5).—A solution of iodine in hexane (0.02%, w/v; 5 cm^3) was added to compound **11b** (20 mg) and the mixture was refluxed for 2 h.

(f) *Treatment of compound* **11b** *with* 0.02% *iodine in refluxing heptane* (*entry* 6).—A solution of iodine in heptane (0.02%, w/v; 5 cm^3) was added to compound **11b** (20 mg) and the mixture was refluxed for 50 min.

Preparation of the 8-oxo-Wittig salt 6. Aq. 10% K_2CO_3 (5 cm^3) was added to an ice-cooled solution of the β,γ-unsaturated ketone **5** (850 mg, 2.53 mmol) in MeOH (20 cm^3) and the mixture was stirred at 0 °C for 15 min. After the reaction had been quenched with saturated aq. NH_4Cl, the organics were extracted with ether followed by standard work-up to give the crude monoalcohol **14** (740 mg). A solution of LiCl (113 mg, 2.66 mmol) in dry dimethylformamide (DMF) (4 cm^3) was added to a stirred mixture of the monoalcohol **14** (740 mg, 2.52 mmol) in 2,4,6-trimethylpyridine (γ-collidine) (0.375 cm^3, 2.79 mmol) at 0 °C and the mixture was stirred at 0 °C for 15 min. To this reaction mixture was added MsCl (0.215 cm^3, 2.78 mmol) and stirring of the mixture was continued at 0 °C for a further 1.5 h. The mixture was poured into ice–water and extracted with ether. The organic layer was washed successively with aq. 3% HCl, saturated aq. $NaHCO_3$ and brine. Evaporation of the dried extracts provided a residue, which was purified by short CC (ether–hexane, 3:7) to afford the *chloride* **15** (620 mg, 78% from **5**) as an oil; $\nu_{max}(CHCl_3)/cm^{-1}$ 1720 (OAc) and 1680 (conj. CO); δ_H(60 MHz) 0.92 and 1.00 (each 3 H, s, *gem*-Me), 1.46 (3 H, s, 5-Me), 1.88 (3 H, s, 9-Me), 2.02 (3 H, s, OAc), 3.40 (2 H, s, 7-H_2), 4.25 (2 H, d, *J* 6, 11-H_2), 5.05 (1 H, m, 3-H) and 6.72 (1 H, br t, *J* 6, 10-H).

Subsequently, triphenylphosphine (657 mg, 2.22 mmol) was added to a solution of chloride **15** (620 mg, 1.98 mmol) in $CHCl_3$ (15 cm^3) and the mixture was refluxed for 19 h. Evaporation of the solvent gave a residue, which was washed with ether to provide the *phosphonium chloride* **6** (875 mg, 60% from **5**) as a solid; $\nu_{max}(CHCl_3)/cm^{-1}$ 1720 (OAc) and 1680 (conj. CO); δ_H(200 MHz) 0.79 and 0.90 (each 3 H, s, *gem*-Me), 1.36 (3 H, s, 5-Me), 1.57 (3 H, d, *J* 4.5, 9-Me), 2.03 (3 H, s, OAc), 3.23 (3 H, s, 7-H_2), 5.00 (1 H, m, 3-H), 5.26 (2 H, dd, *J* 16.5 and 8, 11-H_2), 6.59 (1 H, br q, *J* 8, 10-H) and 7.66–8.02 (15 H, m, ArH).

(1*R*,3*S*,6*R*)-6-[(*E*)-5-Hydroxy-3-methylpenta-1,3-dienylidene]-1,5,5-trimethylcyclohexane-1,3-diol 3-acetate 17. $NaBH_4$ (323 mg, 8.5 mmol) was added to an ice-cooled solution of the allenic aldehyde **16**[1] (2.48 g, 8.49 mmol) in MeOH (30 cm^3). The mixture was stirred at 0 °C for 30 min and then poured into ice–water. The organics were extracted with ether followed by standard work-up to give a residue, which was purified by short CC (acetone–hexane, 2:5) to afford the *allenic alcohol* **17** (2.40 g, 96%) as plates, mp 125–128 °C (from CH_2Cl_2–hexane); $[\alpha]_D^{27}$ −15.0 (*c* 1.00, MeOH); $\nu_{max}(CHCl_3)/cm^{-1}$ 3600 and 3450 (OH), 1938 (C=C=C) and 1725 (OAc); δ_H(200 MHz) 1.07, 1.35 and 1.37 (each 3 H, s, *gem*-Me and 5-Me), ~1.38 (4-H^{ax}), 1.48 (1 H, t, *J* 12, 2-H^{ax}), 1.55 (1 H, br s, OH), 1.69 (3 H, s, 9-Me), 1.73 (1 H, s, OH), 1.98 (1 H, ddd, *J* 12, 4 and 2, 2-H^{eq}), 2.03 (3 H, s, OAc), 2.27 (1 H, ddd, *J* 13, 4 and 2, 4-H^{eq}), 4.28 (2 H, dd, *J* 6 and 4, 11-H_2), 5.37 (1 H, m, 3-H), 5.60 (1 H, br t, *J* 6, 10-H) and 5.97 (1 H, s, 8-H) (Found: C, 69.1; H, 9.0. $C_{17}H_{26}O_4$ requires C, 69.36; H, 8.90%).

Preparation of the allenic Wittig salt 8. A solution of LiCl (55 mg, 1.29 mmol) in dry DMF (2 cm^3) was added to a stirred mixture of the allenic alcohol **17** (350 mg, 1.19 mmol) in γ-collidine (0.192 cm^3, 1.43 mmol) at 0 °C and the mixture was stirred at 0 °C for 15 min. To this reaction mixture was added MsCl (0.101 cm^3, 1.30 mmol) and the mixture was stirred at 0 °C for a further 1.5 h. The mixture was poured into ice–water and extracted with ether. The organic layer was washed successively with aq. 3% HCl, saturated aq. $NaHCO_3$ and brine. Evaporation of the dried extracts provided a residue, which was purified by short CC (ether–hexane, 2:1) to afford the *chloride* **18** (300 mg, 81%) as an oil; $\nu_{max}(CHCl_3)/cm^{-1}$ 3600 and 3450 (OH), 1938 (C=C=C) and 1726 (OAc); δ_H(200 MHz) 1.07, 1.35 and 1.38 (each 3 H, s, *gem*-Me and 5-Me), 1.49 (1 H, dd, *J* 13 and 11.5, 4-H^{ax}), 1.74 (3 H, d, *J* 1, 9-Me), 2.00 (1 H, ddd, *J* 12.5, 4 and 2, 2-H^{eq}), 2.04 (3 H, s, OAc), 2.30 (1 H, ddd, *J* 13, 4 and 2, 4-H^{eq}), 4.20 (2 H, d, *J* 8, 11-H_2), 5.37 (1 H, tt, *J* 11.5 and 4, 3-H), 5.62 (1 H, br t, *J* 8, 10-H) and 5.98 (1 H, s, 8-H).

Subsequently, triphenylphosphine (302 mg, 1.15 mmol) and triethylamine (0.01 cm^3) were added to a solution of the chloride **18** (300 mg, 0.96 mmol) in $CHCl_3$ (4 cm^3) and the mixture was heated at 50 °C for 17 h. Evaporation of the solvent gave a residue, which was washed with ether to provide the *phosphonium chloride* **8** (505 mg, 74% from **17**) as a pale yellow solid; $\nu_{max}(CHCl_3)/cm^{-1}$ 3600 and 3450 (OH), 1938 (C=C=C) and 1725 (OAc); δ_H(200 MHz) 0.96 (3 H, s, 1-Me), 1.24 (3 H, d, *J* 4, 9-Me), 1.27 and 1.32 (each 3 H, s, 1- and 5-Me), 2.01 (3 H, s, OAc), 4.74 and 4.91 (each 1 H, td, *J* 16 and 8, 11-H_2), 5.23–5.43 (2 H, m, 3- + 10-H), 5.91 (1 H, s, 8-H) and 7.62–7.93 (15 H, m, ArH).

(2*E*,4*E*,6*E*,8*E*/*Z*,10*E*)-13-(4-Hydroxy-2,6,6-trimethylcyclohex-1-enyl)-2,7,11-trimethyl-12-oxotrideca-2,4,6,8,10-pentaenal 19 and 20. A solution of the Wittig salt **6** (402 mg, 0.70 mmol) in CH_2Cl_2 (5 cm^3) was added dropwise to a stirred solution of C_{10}-dialdehyde **7** (149 mg, 0.91 mmol) and NaOMe (1.0 mol dm^{-3} in MeOH; 0.84 cm^3, 0.84 mmol) in CH_2Cl_2 (5 cm^3) at 0 °C. After being stirred at 0 °C for 2 h, the reaction mixture was diluted with CH_2Cl_2 followed by standard work-up to give an oil, which was dissolved in MeOH (10 cm^3). To this solution was added aq. 5% NaOH and the mixture was stirred at room temp. for 15 min. This was diluted with ether and the organic layer was followed by standard work-up to give a residue, which was purified by short CC (ether–hexane, 3:1) followed by PHPLC [LiChrosorb CN (7 μm) 1.0 × 25 cm; MeOH–ether–hexane, 1.5:10:88.5] to provide the all-*E*-isomer **19** (86 mg, 32% from **6**) and the 11*Z*-one **20** (78 mg, 29% from **6**) as orange solids. *Compound* **19**: λ_{max}(EtOH)/nm 394 and 414; $\nu_{max}(CHCl_3)/cm^{-1}$ 3680 and 3610 (OH), 1662 (conj. CO + conj. CHO) and 1605 (C=C); δ_H(500 MHz) 0.93 (3 H, s, 1-Me^{eq}), 0.99 (3 H, s, 1-Me^{ax}), 1.48 (3 H, s, 5-Me), 1.55 (1 H, t, *J* 12, 2-H^{ax}), 1.75 (1 H, ddd, *J* 12, 3.5 and 2, 2-H^{eq}), 1.91 (3 H, s, 13'-Me), 1.99 (3 H, s, 9-Me), 2.08 (3 H, s, 13-Me), 2.11 (1 H, dd, *J* 16.5 and 9,

4-H^{ax}), 2.35 (1 H, br dd, *J* 16.5 and 6, 4-H^{eq}), 3.44 and 3.49 (each 1 H, d, *J* 17.5, 7-H_2), 4.01 (1 H, m, 3-H), 6.43 (1 H, br d, *J* 11.5, 14-H), 6.69 (1 H, d, *J* 15, 12-H), 6.75 (1 H, dd, *J* 15 and 10.5, 11-H), 6.78 (1 H, dd, *J* 14.5 and 11.5, 15′-H), 6.97 (1 H, br d, *J* 11.5, 14′-H), 7.04 (1 H, dd, *J* 14.5 and 11.5, 15-H), 7.22 (1 H, dd-like, *J* 10.5 and 1, 10-H) and 9.49 (1 H, s, CHO) (Found: M^+, 382.250. $C_{25}H_{34}O_3$ requires M, 382.251).

Compound **20**: λ_{max}(EtOH)/nm 289, 393 and 408sh; ν_{max}($CHCl_3$)/cm^{-1} 3680 and 3600 (OH), 1675 (conj. CO + conj. CHO) and 1608 (C=C); δ_H(500 MHz) 0.92 (3 H, s, 1-Me^{eq}), 0.96 (3 H, s, 1-Me^{ax}), 1.49 (3 H, s, 5-Me), 1.54 (1 H, t, *J* 12, 2-H^{ax}), 1.73 (1 H, ddd, *J* 12, 3.5 and 2, 2-H^{eq}), 1.88 (3 H, s, 13′-Me), 1.97 (3 H, s, 9-Me), 2.10 (1 H, dd, *J* 16.5 and 9, 4-H^{ax}), 2.18 (3 H, s, 13-Me), 2.34 (1 H, br dd, *J* 16.5 and 5.5, 4-H^{eq}), 3.39 and 3.46 (each 1 H, d, *J* 18, 7-H_2), 4.00 (1 H, m, 3-H), 6.34 (1 H, d, *J* 11.5, 12-H), 6.41 (1 H, br d, *J* 11.5, 14-H), 6.46 (1 H, t, *J* 11.5, 11-H), 6.75 (1 H, dd, *J* 14.5 and 11.5, 15′-H), 6.97 (1 H, br d, *J* 11.5, 14′-H), 7.00 (1 H, dd, *J* 14.5 and 11.5, 15-H), 7.69 (1 H, br d, *J* 11.5, 10-H) and 9.48 (1 H, s, CHO) (Found: M^+, 382.251).

Isomerization of the 11*Z*-isomer 20. A solution (3 cm^3) prepared from $PdCl_2(MeCN)_2$ (65 mg), triethylamine (0.035 cm^3) and water (6 cm^3) in MeCN (50 cm^3) was added to a solution of compound **20** (120 mg) in MeCN (25 cm^3) and the mixture was stirred at room temp. until the peak of compound **20** disappeared (~2.5 h) on analytical HPLC [LiChrospher CN (5 μm) 0.4 × 25 cm; MeOH–ether–hexane, 1.5:10:88.5]. HPLC analysis of the final reaction mixture indicated a 94% yield of the all-*E*-isomer **19**. The solvent was evaporated off to give a residue, which was purified by short CC (ether–hexane, 3:1) to afford compound **19** (104 mg, 87%).

Preparation of the all-*E*-apocarotenal 19 from the Wittig salt 6 without separation of the isomers 19 and 20. In the same manner as described for the preparation of apocarotenals **19** and **20**, Wittig reaction between the phosphonium chloride **6** (1.15 g, 2.0 mmol) and the dialdehyde **7** (426 mg, 2.6 mmol) followed by hydrolysis gave a crude mixture of apocarotenals **19** and **20** (630 mg, 82% from **6**), which was treated with the palladium catalyst in the same manner as that in isomerization of 11*Z*-isomer **20** to provide the all-*E*-isomer **19** (586 mg, 77% from **6**).

(2*E*,4*E*,6*E*,8*E*,10*E*)-2,7,11-Trimethyl-12-oxo-13-[2,6,6-trimethyl-4-(triethylsiloxy)cyclohex-1-enyl]trideca-2,4,6,8,10-pentaenal 21. TES triflate (0.218 cm^3, 0.96 mmol) was added slowly to a stirred solution of the apocarotenal **19** (335 mg, 0.88 mmol) and γ-collidine (0.23 cm^3, 1.74 mmol) in CH_2Cl_2 (5 cm^3) at 0 °C and the mixture was stirred for a further 10 min. The mixture was poured into ice–water and extracted with ether followed by standard work-up to give a residue, which was purified by short CC (ether–hexane, 3:5) to afford the *TES ether* **21** (320 mg, 79%); λ_{max}(EtOH)/nm 394 and 413; ν_{max}($CHCl_3$)/cm^{-1} 1665 (conj. CO + conj. CHO) and 1606 (C=C); δ_H(200 MHz) 0.59 (6 H, q, *J* 8, $SiCH_2Me$ × 3), 0.94 and 0.97 (each 3 H, s, *gem*-Me), 0.97 (9 H, t, *J* 8, $SiCH_2Me$ × 3), 1.46 (3 H, s, 5-Me), 1.91 (3 H, s, 13′-Me), 1.99 (3 H, s, 9-Me), 2.08 (3 H, s, 13-Me), 3.40 and 3.52 (each 1 H, d, *J* 18, 7-H_2), 3.98 (1 H, m, 3-H), 6.44 (1 H, br d, *J* 11.5, 14-H), 6.60–6.86 (3 H, m, 11- + 12- + 15′-H), 6.99 (1 H, br d, *J* 11.5, 14′-H), 7.06 (1 H, dd, *J* 14.5 and 11.5, 15-H), 7.24 (1 H, br d, *J* 10, 10-H) and 9.50 (1 H, s, CHO) (Found: M^+, 496.338. $C_{31}H_{48}O_3Si$ requires M, 496.337).

Preparation of the fucoxanthin skeletal compounds 3 and 22. A solution of NaOMe (1.0 mol dm^{-3} in MeOH; 2.8 cm^3, 2.8 mmol) was added to an ice-cooled solution of the Wittig salt **8** (825 mg, 1.44 mmol) and the TES ether **21** (220 mg, 0.44 mmol) in CH_2Cl_2 (20 cm^3). After being stirred at room temp. for 1.5 h, the reaction mixture was diluted with CH_2Cl_2. The organic layer was followed by standard work-up to give an oil, which was dissolved in pyridine (Py) (11 cm^3) and acetic anhydride (3 cm^3). The mixture was stirred at room temp. for 15 h, poured into ice–water, and extracted with ether. The extracts were washed successively with aq. 3% HCl, saturated aq. $NaHCO_3$ and brine. Evaporation of the dried extracts gave a residue, which was purified by short CC (acetone–hexane, 5:95) to afford a mixture of the TES ethers of skeletal compounds **3** and **22** (300 mg, 89% from **21**). A solution of acetic acid [1.0 mol dm^{-3} in tetrahydrofuran (THF); 1.2 cm^3, 1.2 mmol] and a solution of TBAF (1.0 mol dm^{-3} in THF; 1.2 cm^3, 1.2 mmol) was added to a solution of the above mixture (300 mg, 0.40 mmol) in THF (2 cm^3) and the mixture was stirred at room temp. for 1 h. This was diluted with ether and the organic layer was washed successively with saturated aq. $NaHCO_3$ and brine. Evaporation of the dried solvent gave a residue, which was purified by short CC (acetone–hexane, 3:7) followed by PHPLC (CHEMCOSORB 7-ODS-H, 1.0 × 30 cm; MeOH–water, 95:5) to provide the all-*E*-isomer **3** (63 mg, 22% from **21**) and the 11′*Z*-one **22** (78 mg, 27% from **21**) as red solids.

Compound **3**: λ_{max}(EtOH)/nm 266, 447 and 466sh; λ_{max}(hexane)/nm 263, 421, 444 and 472; ν_{max}(KBr)/cm^{-1} 3600 (OH), 1932 (C=C=C), 1735 (OAc), 1650 (conj. CO) and 1610 (C=C); δ_H(500 MHz) 0.93 (3 H, s, 1-Me^{eq}), 0.99 (3 H, s, 1-Me^{ax}), 1.07 (3 H, s, 1′-Me^{eq}), 1.35 (3 H, s, 5′-Me), 1.39 (3 H, s, 1′-Me^{ax}), 1.41 (1 H, t, *J* 12, 2′-H^{ax}), 1.48 (3 H, s, 5-Me), 1.51 (1 H, t-like, *J* 12.5, 4′-H^{ax}), 1.54 (1 H, t, *J* 12, 2-H^{ax}), 1.74 (1 H, ddd, *J* 12, 4 and 2.5, 2-H^{eq}), 1.81 (3 H, s, 9′-Me), 1.97 (3 H, s, 9-Me), 1.99 (3 H, s, 13′-Me), 1.99 (2′-H^{eq}), 2.00 (3 H, s, 13-Me), 2.04 (3 H, s, OAc), 2.11 (1 H, br dd, *J* 17 and 9, 4-H^{ax}), 2.29 (1 H, ddd, *J* 13, 4.5 and 2, 4′-H^{eq}), 2.34 (1 H, br dd, *J* 17 and 5, 4-H^{eq}), 3.43 and 3.49 (each 1 H, d, *J* 17.5, 7-H_2), 4.01 (1 H, m, 3-H), 5.38 (1 H, tt, *J* 12 and 4.5, 3′-H), 6.06 (1 H, s, 8′-H), 6.13 (1 H, dd-like, *J* 11.5 and 1, 10′-H), 6.27 (1 H, br d, *J* 11.5, 14′-H), 6.35 (1 H, d, *J* 15, 12′-H), 6.40 (1 H, br d, *J* 11.5, 14-H), 6.59 (1 H, dd, *J* 15 and 11.5, 11′-H), 6.60 (1 H, dd, *J* 15 and 11, 11-H), 6.64 (1 H, dd, *J* 14.5 and 11.5, 15-H), 6.68 (1 H, d, *J* 15, 12-H), 6.73 (1 H, dd, *J* 14.5 and 11.5, 15′-H) and 7.23 (1 H, dd-like, *J* 11 and 1, 10-H) (Found: M^+, 642.426. $C_{42}H_{58}O_5$ requires M, 642.428).

Compound **22**: λ_{max}(EtOH)/nm 268, 332, 445 and 465sh; λ_{max}(hexane)/nm 227, 315, 328, 421sh, 442 and 471; ν_{max}(KBr)/cm^{-1} 3460 (OH), 1930 (C=C=C), 1739 and 1725 (split) (OAc), 1660 (conj. CO) and 1610 (C=C); δ_H(500 MHz) 0.93 (3 H, s, 1-Me^{eq}), 0.99 (3 H, s, 1-Me^{ax}), 1.08 (3 H, s, 1′-Me^{eq}), 1.36 (3 H, s, 5′-Me), 1.39 (3 H, s, 1′-Me^{ax}), 1.41 (1 H, t, *J* 12, 2′-H^{ax}), 1.48 (3 H, s, 5-Me), 1.51 (1 H, t-like, *J* 12.5, 4′-H^{ax}), 1.55 (1 H, t, *J* 12, 2-H^{ax}), 1.74 (1 H, ddd, *J* 12, 4 and 2.5, 2-H^{eq}), 1.79 (3 H, s, 9′-Me), 1.97 (3 H, s, 9-Me), 1.98 (2′-H^{eq}), 2.00 (3 H, s, 13-Me), 2.04 (3 H, s, OAc), 2.11 (1 H, br dd, *J* 17 and 9, 4-H^{ax}), 2.12 (3 H, s, 13′-Me), 2.29 (1 H, ddd, *J* 13, 4 and 2, 4′-H^{eq}), 2.34 (1 H, br dd, *J* 17 and 5, 4-H^{eq}), 3.43 and 3.49 (each 1 H, d, *J* 17.5, 7-H_2), 4.01 (1 H, m, 3-H), 5.38 (1 H, tt, *J* 12 and 4, 3′-H), 5.98 (1 H, d, *J* 12, 12′-H), 6.07 (1 H, s, 8′-H), 6.27 (1 H, t, *J* 12, 11′-H), 6.32 (1 H, br d, *J* 11, 14′-H), 6.40 (1 H, br d, *J* 11, 14-H), 6.61 (1 H, dd, *J* 15 and 11, 11-H), 6.63 (1 H, br d, *J* 12, 10′-H), 6.65 (1 H, dd, *J* 15 and 11, 15-H), 6.68 (1 H, d, *J* 15, 12-H), 6.71 (1 H, dd, *J* 15 and 11, 15′-H) and 7.23 (1 H, dd-like, *J* 11 and 1, 10-H) (Found: M^+, 642.427).

Isomerization of the 11′*Z*-isomer 22. In the same manner as described for the isomerization of the 11*Z*-apocarotenal **20**, compound **22** (33 mg) was treated with the palladium catalyst (1.5 h) and purified by PHPLC (CHEMCOSORB 7-ODS-H, 1.0 × 30 cm; MeOH–water, 95:5) to provide the skeletal compound **3** (15 mg, 45%).

Preparation of optically active fucoxanthin 1. A solution of MCPBA (13.3 mg, 0.077 mmol) in CH_2Cl_2 (2 cm^3) was added to a cooled solution of the skeletal compound **3** (45 mg, 0.070 mmol) in CH_2Cl_2 (10 cm^3). After being stirred at 0 °C for 1 h, the reaction mixture was diluted with CH_2Cl_2 and washed successively with aq. 1% $Na_2S_2O_3$ and brine. Evaporation of the dried solvent gave a residue, which was purified by

PHPLC (CHEMCOSORB 7-ODS-H, 1.0 × 30 cm; MeOH–water, 93:7) to provide the epoxide mixture (**1**:**23** ~ 2:7) (16 mg, 36%) as a red solid and recovered starting material (12 mg, 27%). PHPLC separation (CHIRALCEL OD; DAICEL IND., Ltd., 1.0 × 25 cm; EtOH–hexane, 15:85; 37 °C) of the mixture provided the *syn*-epoxide **23** and the *anti*-epoxide (fucoxanthin) **1**, each in pure form. Spectral properties of the synthetic fucoxanthin **1** were in accord with those of a natural specimen.[12,¶]

Compound **1**: λ_{max}(EtOH)/nm 266, 449 and 467sh; λ_{max}(hexane)/nm 264, 426, 448 and 477; ν_{max}(KBr)/cm^{-1} 3440 (OH), 1929 (C=C=C), 1734 (OAc), 1658 (conj. CO) and 1608 (C=C); δ_H(500 MHz) 0.96 (3 H, s, 1-Me^{eq}), 1.04 (3 H, s, 1-Me^{ax}), 1.07 (3 H, s, 1′-Me^{eq}), 1.22 (3 H, s, 5-Me), ~1.35 (2-H^{ax}), 1.35 (3 H, s, 5′-Me), 1.39 (3 H, s, 1′-Me^{ax}), 1.41 (1 H, t, *J* 12, 2′-H^{ax}), ~1.49 (2-H^{eq}), 1.51 (1 H, t, *J* 13, 4′-H^{ax}), 1.79 (1 H, dd, *J* 14 and 9, 4-H^{ax}), 1.82 (3 H, s, 9′-Me), 1.95 (3 H, s, 9-Me), 1.99 (6 H, s, 13- + 13′-Me), ~2.00 (2′-H^{eq}), 2.04 (3 H, s, OAc), 2.29 (1 H, ddd, *J* 13, 4 and 2, 4′-H^{eq}), 2.32 (1 H, br dd, *J* 14 and 4.5, 4-H^{eq}), 2.60 and 3.66 (each 1 H, d, *J* 18, 7-H$_2$), 3.82 (1 H, m, 3-H), 5.38 (1 H, m, 3′-H), 6.06 (1 H, s, 8′-H), 6.13 (1 H, dd-like, *J* 11 and 1, 10′-H), 6.27 (1 H, br d, *J* 11.5, 14′-H), 6.35 (1 H, d, *J* 15, 12′-H), 6.41 (1 H, br d, *J* 11.5, 14-H), 6.57 (1 H, dd, *J* 15 and 11, 11-H), 6.60 (1 H, dd, *J* 15 and 11, 11′-H), 6.64 (1 H, dd, *J* 14.5 and 11.5, 15-H), 6.67 (1 H, d, *J* 15, 12-H), 6.75 (1 H, dd, *J* 14.5 and 11.5, 15′-H) and 7.15 (1 H, br d, *J* 11, 10-H) (Found: M$^+$, 658.420. $C_{42}H_{58}O_6$ requires M, 658.423).

Compound **23**: λ_{max}(EtOH)/nm 266, 450 and 467sh; λ_{max}(hexane)/nm 264, 427, 449 and 478; ν_{max}(KBr)/cm^{-1} 3440 (OH), 1929 (C=C=C), 1734 (OAc), 1657 (conj. CO) and 1609 (C=C); δ_H(500 MHz) 0.94 (3 H, s, 1-Me^{ax}), 1.07 (3 H, s, 1′-Me^{eq}), 1.10 (3 H, s, 1-Me^{eq}), 1.22 (3 H, s, 5-Me), 1.32 (1 H, ddd, *J* 13, 3.5 and 1, 2-H^{eq}), 1.35 (3 H, s, 5′-Me), 1.39 (3 H, s, 1′-Me^{ax}), 1.41 (1 H, t, *J* 12, 2′-H^{ax}), 1.51 (1 H, t, *J* 12, 4′-H^{ax}), 1.54 (1 H, dd, *J* 13 and 10, 2-H^{ax}), 1.81 (3 H, s, 9′-Me), 1.88 (1 H, dd, *J* 15 and 8, 4-H^{ax}), 1.94 (3 H, s, 9-Me), 1.99 (1 H, ddd, *J* 12, 4 and 2, 2′-H^{eq}), 1.99 (6 H, s, 13- + 13′-Me), 2.04 (3 H, s, OAc), 2.23 (1 H, ddd, *J* 15, 6 and 1, 4-H^{eq}), 2.29 (1 H, ddd, *J* 12, 4 and 2, 4′-H^{eq}), 2.72 and 3.57 (each 1 H, d, *J* 18.5, 7-H$_2$), 3.92 (1 H, m, 3-H), 5.38 (1 H, tt, *J* 12 and 4, 3′-H), 6.06 (1 H, s, 8′-H), 6.13 (1 H, dd-like, *J* 11 and 1, 10′-H), 6.27 (1 H, br d, *J* 12, 14′-H), 6.35 (1 H, d, *J* 15, 12′-H), 6.41 (1 H, br d, *J* 11.5, 14-H), 6.57 (1 H, dd, *J* 15 and 11, 11-H), 6.60 (1 H, dd, *J* 15 and 11, 11′-H), 6.64 (1 H, dd, *J* 14.5 and 11.5, 15-H), 6.67 (1 H, d, *J* 15, 12-H), 6.75 (1 H, dd, *J* 14.5 and 12, 15′-H) and 7.14 (1 H, dd-like, *J* 11 and 1.5, 10-H) (Found: M$^+$, 658.421).

Synthesis of halocynthiaxanthin 2

(1*R*)-4-(5-Hydroxy-3-methylpent-3-en-1-ynyl)-3,5,5-trimethylcyclohex-3-enol 25. Aq. 10% KOH (25 cm^3) was added to an ice-cooled solution of the acetylenic diacetate **24**[9] (3.10 g, 9.75 mmol) in MeOH (60 cm^3) and the mixture was stirred at 0 °C for 3 h. The mixture was extracted with ether followed by standard work-up to give a residue, which was purified by short CC (acetone–hexane, 3:7) to afford the diol **25** (2.12 g, 93%) as crystals, mp 89–91 °C (from ether) (lit.,[8] 92–93 °C). Spectral properties of compound **25** were identical with those reported;[8,15] $[\alpha]_D^{28}$ −106.0 (*c* 0.50, dioxane) {lit.,[8] $[\alpha]_D^{20}$ −105.4 (*c* 0.50, 1,4-dioxane)}; ν_{max}($CHCl_3$)/cm^{-1} 3610 and 3450 (OH), 2187 (C≡C) and 1616 (C=C); δ_H(300 MHz) 1.13 and 1.18 (each 3 H, s, *gem*-Me), 1.44 (1 H, t, *J* 12, 2-H^{ax}), 1.82 (1 H, ddd, *J* 12, 3.5 and 2, 2-H^{eq}), 1.89 and 1.90 (each 3 H, s, 5- and 9-Me), 2.05 (1 H, br dd, *J* 18 and 9.5, 4-H^{ax}), 2.41 (1 H, br dd, *J* 18 and 5.5, 4-H^{eq}), 3.98 (1 H, m, 3-H), 4.25 (2 H, d, *J* 7, 11-H$_2$) and 5.97 (1 H, td, *J* 7 and 1, 10-H) (Found: M$^+$, 234.162. $C_{15}H_{22}O_2$ requires M, 234.162) (Found: C, 75.15; H, 9.3. $C_{15}H_{22}O_2 \cdot 1/4H_2O$ requires C, 75.43; H, 9.49%).

Preparation of the halocynthiaxanthin skeletal compounds 4 and 26. A solution of NaOMe (1.0 mol dm^{-3} in MeOH; 1.02 cm^3, 1.02 mmol) was added to an ice-cooled solution of the Wittig salt **9**[8] (350 mg, 0.68 mmol) and the apocarotenal **19** (173 mg, 0.45 mmol) in CH_2Cl_2 (17 cm^3). After being stirred at 0 °C for 15 min, the reaction mixture was diluted with ether followed by standard work-up to give an oil, which was purified by short CC (acetone–hexane, 3:7) to afford an isomeric mixture (244 mg, 93%; all-*E*:9′*Z*:11′*Z*:9′*Z*,11′*Z* ~ 4:2:2:1) of skeletal compounds. Purification of a part of the isomeric mixture by PHPLC (CHEMCOSORB 7-ODS-H, 1.0 × 30 cm; MeOH) followed by PHPLC [LiChrosorb Si 60 (7 μm) 1.0 × 30 cm; MeOH–THF–hexane, 1:40:59] provided each pure isomer. In the same manner as described for the isomerization of the 11*Z*-apocarotenal **20**, the isomeric mixture was treated with the palladium catalyst (4 h) and purified by PHPLC (CHEMCOSORB 7-ODS-H, 1.0 × 30 cm; MeOH) to give the all-*E*-isomer **4** (93 mg, 35% from **19**) and the 9′*Z*-one **26** (87 mg, 33% from **19**) as red solids.

All-E-isomer **4**: λ_{max}(EtOH)/nm 278, 450 and 470sh; λ_{max}(hexane)/nm 276, 420sh, 448 and 475; ν_{max}(KBr)/cm^{-1} 3430 (OH), 2190 (C≡C), 1655 (conj. CO), 1610 and 1578 (C=C); δ_H(500 MHz) 0.93 (3 H, s, 1-Me^{eq}), 0.99 (3 H, s, 1-Me^{ax}), 1.15 (3 H, s, 1′-Me^{ax}), 1.20 (3 H, s, 1′-Me^{eq}), 1.46 (1 H, t, *J* 12, 2′-H^{ax}), 1.48 (3 H, s, 5-Me), 1.54 (1 H, t, *J* 12, 2-H^{ax}), 1.74 (1 H, ddd, *J* 12, 3.5 and 2, 2-H^{eq}), 1.84 (1 H, ddd, *J* 12, 3.5 and 2, 2′-H^{eq}), 1.93 (3 H, s, 5′-Me), 1.97 (3 H, s, 9-Me), 1.98 (3 H, s, 13′-Me), 2.01 (3 H, s, 13-Me), 2.02 (3 H, s, 9′-Me), 2.07 (1 H, br dd, *J* 17 and 9, 4′-H^{ax}), 2.11 (1 H, br dd, *J* 16 and 9, 4-H^{ax}), 2.34 (1 H, br dd, *J* 16 and 5, 4-H^{eq}), 2.43 (1 H, br dd, *J* 17 and 6, 4′-H^{eq}), 3.43 and 3.49 (each 1 H, d, *J* 17.5, 7-H$_2$), 4.00 (2 H, m, 3- + 3′-H), 6.29 (1 H, br d, *J* 11, 14′-H), 6.36 (1 H, d, *J* 15, 12′-H), 6.40 (1 H, br d, *J* 11, 14-H), 6.46 (1 H, dd-like, *J* 11 and 1, 10′-H), 6.56 (1 H, dd, *J* 15 and 11, 11′-H), 6.63 (1 H, dd, *J* 15 and 11, 11-H), 6.65 (1 H, dd, *J* 14.5 and 11, 15-H), 6.68 (1 H, d, *J* 15, 12-H), 6.73 (1 H, dd, *J* 14.5 and 11, 15′-H) and 7.23 (1 H, dd-like, *J* 11 and 1, 10-H) (Found: M$^+$, 582.406. $C_{40}H_{54}O_3$ requires M, 582.407).

9′Z-Isomer **26**: λ_{max}(EtOH)/nm 241, 279, 340, 446 and 470sh; λ_{max}(hexane)/nm 239, 276, 339, 420sh, 444 and 472; ν_{max}(KBr)/cm^{-1} 3320 (OH), 2190 (C≡C), 1655 (conj. CO), 1610 and 1578 (C=C); δ_H(500 MHz) 0.93 (3 H, s, 1-Me^{eq}), 0.99 (3 H, s, 1-Me^{ax}), 1.19 (3 H, s, 1′-Me^{ax}), 1.26 (3 H, s, 1′-Me^{eq}), 1.48 (3 H, s, 5-Me), 1.49 (1 H, t, *J* 12, 2′-H^{ax}), 1.54 (1 H, t, *J* 12, 2-H^{ax}), 1.74 (1 H, m, 2-H^{eq}), 1.86 (1 H, m, 2′-H^{eq}), 1.95, 1.97, 1.98, 2.00 and 2.01 (each 3 H, each s, 5′-, 9-, 9′-, 13- and 13′-Me), 2.09 (2 H, m, 4- + 4′-H^{ax}), 2.34 (1 H, br dd, *J* 17 and 5, 4-H^{eq}), 2.46 (1 H, br dd, *J* 17 and 5, 4′-H^{eq}), 3.43 and 3.49 (each 1 H, d, *J* 17.5, 7-H$_2$), 4.00 (2 H, m, 3- + 3′-H), 6.28 (1 H, br d, *J* 11.5, 14′-H), 6.31 (1 H, br d, *J* 11.5, 10′-H), 6.36 (1 H, d, *J* 15, 12′-H), 6.40 (1 H, br d, *J* 11, 14-H), 6.60 (1 H, dd, *J* 15 and 11, 11-H), 6.64 (1 H, dd, *J* 14 and 11, 15-H), 6.68 (1 H, d, *J* 15, 12-H), 6.72 (1 H, dd, *J* 14 and 11.5, 15′-H), 6.87 (1 H, dd, *J* 15 and 11.5, 11′-H) and 7.23 (1 H, dd-like, *J* 11 and 1, 10-H) (Found: M$^+$, 582.407).

11′Z-Isomer of **4**: λ_{max}(EtOH)/nm 279, 340, 448 and 475sh; λ_{max}(hexane)/nm 276, 340, 445 and 475sh; ν_{max}(KBr)/cm^{-1} 3400 (OH), 2190 (C≡C), 1655 (conj. CO), 1610, 1570 and 1560 (split) (C=C); δ_H(500 MHz) 0.93 (3 H, s, 1-Me^{eq}), 0.99 (3 H, s, 1-Me^{ax}), 1.15 (3 H, s, 1′-Me^{ax}), 1.20 (3 H, s, 1′-Me^{eq}), 1.46 (1 H, t, *J* 12, 2′-H^{ax}), 1.48 (3 H, s, 5-Me), 1.54 (3 H, t, *J* 12, 2-H^{ax}), 1.74 (1 H, ddd, *J* 12, 3.5 and 2, 2-H^{eq}), 1.84 (1 H, m, 2′-H^{eq}), 1.92 (3 H, s, 5′-Me), 1.97 (3 H, s, 9-Me), 1.99 (3 H, s, 9′-Me), 2.00 (3 H, s, 13-Me), 2.10 (3 H, s, 13′-Me), 2.04–2.14 (2 H, m, 4- + 4′-H^{ax}), 2.34 (1 H, br dd, *J* 16 and 5.5, 4-H^{eq}), 2.43 (1 H, ddd, *J* 17.5, 5 and 1,

¶ This was kindly supplied by Professor Y. Koyama, Kwansei Gakuin University, and Professor K. Tsujimoto, Japan Advanced Institute of Science and Technology, Hokuriku.

4′-H^{eq}), 3.43 and 3.49 (each 1 H, d, *J* 17.5, 7-H$_2$), 4.00 (2 H, m, 3- + 3′-H), 5.99 (1 H, d, *J* 12.5, 12′-H), 6.24 (1 H, t, *J* 12.5, 11′-H), 6.33 (1 H, br d, *J* 10.5, 14′-H), 6.40 (1 H, br d, *J* 10, 14-H), 6.61 (1 H, dd, *J* 14.5 and 11, 11-H), 6.65 (1 H, dd, *J* 14.5 and 10, 15-H), 6.68 (1 H, d, *J* 14.5, 12-H), 6.70 (1 H, dd, *J* 14.5 and 10.5, 15′-H), 6.97 (1 H, br d, *J* 12.5, 10′-H) and 7.23 (1 H, dd-like, *J* 11 and 1, 10-H) (Found: M$^+$, 582.407).

9′*Z*,11′*Z*-*Isomer* of **4**: λ_{max}(EtOH)/nm 241, 281, 340, 444 and 470sh; λ_{max}(hexane)/nm 239, 278, 339, 419sh, 442 and 470; ν_{max}(KBr)/cm^{-1} 3400 (OH), 2190 (C≡C), 1655 (conj. CO), 1610 and 1580 (C=C); δ_H(500 MHz) 0.93 (3 H, s, 1-Me^{eq}), 0.99 (3 H, s, 1-Me^{ax}), 1.17 (3 H, s, 1′-Me^{ax}), 1.23 (3 H, s, 1′-Me^{eq}), 1.48 (1 H, t, *J* 12, 2′-H^{ax}), 1.48 (3 H, s, 5-Me), 1.54 (1 H, t, *J* 12, 2-H^{ax}), 1.74 (1 H, m, 2-H^{eq}), 1.85 (1 H, m, 2′-H^{eq}), 1.95 (3 H, s, 5′-Me), 1.97 (3 H, s, 9-Me), ~2.00 (4- + 4′-H^{ax}), 2.00 (3 H, s, 13-Me), 2.03 (3 H, s, 9′-Me), 2.10 (3 H, s, 13′-Me), 2.34 (1 H, br dd, *J* 15.5 and 5, 4-H^{eq}), 2.45 (1 H, br dd, *J* 17 and 5.5, 4′-H^{eq}), 3.43 and 3.49 (each 1 H, d, *J* 17.5, 7-H$_2$), 4.00 (2 H, m, 3- + 3′-H), 5.98 (1 H, d, *J* 12, 12′-H), 6.30 (1 H, br d, *J* 10.5, 14′-H), 6.40 (1 H, d, *J* 10.5, 14-H), 6.53 (1 H, t, *J* 12, 11′-H), 6.61 (1 H, dd, *J* 15 and 10.5, 11-H), 6.64 (1 H, dd, *J* 15 and 10.5, 15-H), 6.68 (1 H, d, *J* 15, 12-H), 6.70 (1 H, dd, *J* 15 and 10.5, 15′-H), 6.80 (1 H, br d, *J* 12, 10′-H) and 7.23 (1 H, br d, *J* 10.5, 10-H) (Found: M$^+$, 582.406).

(2*E*)-5-[(4*R*)-4-Hydroxy-2,6,6-trimethylcyclohex-1-enyl]-3-methylpent-2-en-4-ynal 28. A solution of the diol **25** (2.12 g, 9.06 mmol) in CH_2Cl_2 was shaken with active MnO_2 (40 g) at room temp. for 15 h. The mixture was filtered through Celite. Evaporation of the filtrate gave an oil, which was purified by short CC (acetone–hexane, 1:4) to give the *acetylenic aldehyde* **28** (1.83 g, 87%) as a yellow solid; $[\alpha]_D^{26}$ −86.5 (*c* 0.96, MeOH); λ_{max}(EtOH)/nm 221, 287 and 327; ν_{max}($CHCl_3$)/cm^{-1} 3606 and 3463 (OH), 2177 (C≡C), 1661 (conj. CHO) and 1589 (C=C); δ_H(300 MHz) 1.13 and 1.19 (each 3 H, s, *gem*-Me), 1.46 (1 H, t, *J* 12, 2-H^{ax}), 1.85 (1 H, ddd, *J* 12, 3.5 and 1.5, 2-H^{eq}), 1.93 (3 H, s, 5-Me), 2.09 (1 H, br dd, *J* 18 and 10, 4-H^{ax}), 2.34 (3 H, d, *J* 1, 9-Me), 2.47 (1 H, br dd, *J* 18 and 5, 4-H^{eq}), 4.00 (1 H, m, 3-H), 6.20 (1 H, br d, *J* 8, 10-H) and 10.03 (1 H, d, *J* 8, CHO) (Found: M$^+$, 232.146. $C_{15}H_{20}O_2$ requires M, 232.146).

(2*E*,4*E*,6*E*,8*E*,10*E*, 2*E*,4*E*,6*E*,8*Z*,10*E* and 2*E*,4*E*,6*Z*,8*E*,10*E*)-13-[(4*R*)-4-Hydroxy-2,6,6-trimethylcyclohex-1-enyl]-2,7,11-trimethyltrideca-2,4,6,8,10-penten-12-ynal 31, 32 and 33. An acidic solution (0.23 cm^3) prepared from PTSA (500 mg) and H_3PO_4 (725 mg) in MeOH (37.5 cm^3) and trimethyl orthoformate (0.23 cm^3, 2.1 mmol) were added to a solution of the Wittig salt **29**[13] (250 mg, 0.56 mmol) in MeOH (10 cm^3). The mixture was stirred at room temp. for 1 h and neutralized with NaOMe until just before the red colour of an ylide appeared to give a solution of the Wittig salt **30**. To this solution was added a solution of the acetylenic aldehyde **28** (86 mg, 0.37 mmol) in CH_2Cl_2 (5 cm^3) and a solution of NaOMe (1.0 mol dm^{-3} in MeOH; 0.84 cm^3, 0.84 mmol), successively. After being stirred at room temp. for 30 min, the mixture was poured into ice–water and extracted with ether. The extracts were shaken with aq. 3% HCl until the fine structure disappeared on UV and washed successively with saturated aq. $NaHCO_3$ and brine. Evaporation of the dried extracts provided a residue, which was purified by short CC (ether–hexane, 3:1) followed by PHPLC [LiChrosorb Si 60 (7 μm) 1.0 × 30 cm; acetone–hexane, 15:85] to afford the all-*E*-isomer **31** (42 mg, 31%), the 11*Z*-one **32** (26 mg, 17%) and the 13*Z*-one **33** (12 mg, 9%) as orange solids.

Compound **31**: λ_{max}(EtOH)/nm 421; ν_{max}(KBr)/cm^{-1} 3420 (OH), 2200 (C≡C), 1667 (conj. CHO), 1615 and 1600 (split) and 1550 (C=C); δ_H(500 MHz) 1.15 (3 H, s, 1-Me^{ax}), 1.20 (3 H, s, 1-Me^{eq}), 1.46 (1 H, t, *J* 12.5, 2-H^{ax}), 1.84 (1 H, br dd, *J* 12.5 and 3.5, 2-H^{eq}), 1.89 (3 H, s, 13′-Me), 1.93 (3 H, s, 5-Me), 2.03 (6 H, s, 9- + 13-Me), 2.07 (1 H, ddd-like, *J* 17.5, 9.5 and 1, 4-H^{ax}), 2.43 (1 H, br dd, *J* 17.5 and 5.5, 4-H^{eq}), 4.00 (1 H, m, 3-H), 6.32 (1 H, br d, *J* 11.5, 14-H), 6.38 (1 H, d, *J* 15, 12-H), 6.47 (1 H, br d, *J* 11.5, 10-H), 6.66 (1 H, dd, *J* 15 and 11.5, 11-H), 6.70 (1 H, dd, *J* 15 and 11.5, 15′-H), 6.96 (1 H, br d, *J* 11.5, 14′-H), 7.02 (1 H, dd, *J* 15 and 11.5, 15-H) and 9.46 (1 H, s, CHO) (Found: M$^+$, 364.241. $C_{25}H_{32}O_2$ requires M, 364.240).

Compound **32**: λ_{max}(EtOH)/nm 307 and 419; ν_{max}(KBr)/cm^{-1} 3400 (OH), 2190 (C≡C), 1660 (conj. CHO), 1610, 1570 and 1550 (C=C); δ_H(500 MHz) 1.14 (3 H, s, 1-Me^{ax}), 1.20 (3 H, s, 1-Me^{eq}), 1.46 (1 H, t, *J* 12.5, 2-H^{ax}), 1.84 (1 H, ddd, *J* 12.5, 4 and 2, 2-H^{eq}), 1.88 (3 H, s, 13′-Me), 1.92 (3 H, d, *J* 1, 5-Me), 2.00 (3 H, s, 9-Me), 2.07 (1 H, ddd-like, *J* 17.5, 9.5 and 1, 4-H^{ax}), 2.13 (3 H, s, 13-Me), 2.43 (1 H, br dd, *J* 17.5 and 5.5, 4-H^{eq}), 3.99 (1 H, m, 3-H), 6.00 (1 H, d, *J* 12, 12-H), 6.32 (1 H, t, *J* 12, 11-H), 6.36 (1 H, br d, *J* 12, 14-H), 6.70 (1 H, dd, *J* 14.5 and 11.5, 15′-H), 6.93 (1 H, br d-like, *J* 12, 10-H), 6.96 (1 H, br d, *J* 11.5, 14′-H), 6.98 (1 H, dd, *J* 14.5 and 12, 15-H) and 9.46 (1 H, s, CHO) (Found: M$^+$, 364.240).

Compound **33**: λ_{max}(EtOH)/nm 307 and 414; ν_{max}(KBr)/cm^{-1} 3400 (OH), 2200 (C≡C), 1675 (conj. CHO), 1615 and 1595 (split) and 1570 (C=C); δ_H(500 MHz) 1.15 (3 H, s, 1-Me^{ax}), 1.21 (3 H, s, 1-Me^{eq}), 1.47 (1 H, t, *J* 12, 2-H^{ax}), 1.84 (1 H, ddd, *J* 12, 3.5 and 2, 2-H^{eq}), 1.88 (3 H, s, 13′-Me), 1.94 (3 H, s, 5-Me), 2.04 (6 H, s, 9- + 13-Me), 2.08 (1 H, ddd-like, *J* 17, 9.5 and 1, 4-H^{ax}), 2.44 (1 H, br dd, *J* 17 and 5.5, 4-H^{eq}), 4.00 (1 H, m, 3-H), 6.20 (1 H, br d, *J* 12, 14-H), 6.51 (1 H, br d, *J* 11.5, 10-H), 6.63 (1 H, dd, *J* 14 and 11.5, 15′-H), 6.65 (1 H, dd, *J* 15 and 11.5, 11-H), 6.90 (1 H, d, *J* 15, 12-H), 6.94 (1 H, br d, *J* 11.5, 14′-H), 7.17 (1 H, dd, *J* 14 and 12, 15-H) and 9.45 (1 H, s, CHO) (Found: M$^+$, 364.241).

Preparation of optically active halocynthiaxanthin 2. In the same manner as described for the preparation of optically active fucoxanthin **1**, the skeletal compound **4** (169 mg, 0.29 mmol) was treated with MCPBA and purified by PHPLC (CHEMCOSORB 7-ODS-H, 1.0 × 30 cm; MeOH) to provide an epoxide mixture (85 mg, 49%) as a red solid and recovered starting material (28 mg, 16%). PHPLC separation (CHIRALCEL OD; DAICEL IND., Ltd., 1.0 × 25 cm; EtOH–hexane, 9:41; 37 °C) of the mixture provided the *syn*-epoxide **27** (27 mg, 16%) and the *anti*-epoxide (halocynthiaxanthin) **2** (9 mg, 5%), each in pure form. Spectral properties of the synthetic halocynthiaxanthin **2** were in agreement with those of a natural specimen.‖

Compound **2**: λ_{max}(EtOH)/nm 279, 423sh, 453 and 475sh; λ_{max}(hexane)/nm 277, 428sh, 452 and 477sh; ν_{max}(KBr)/cm^{-1} 3420 (OH), 2190 (C≡C), 1660 (conj. CO) and 1610 (C=C); δ_H(500 MHz) 0.97 (3 H, s, 1-Me^{eq}), 1.04 (3 H, s, 1-Me^{ax}), 1.15 (3 H, s, 1′-Me^{ax}), 1.20 and 1.22 (each 3 H, s, 1′-Me^{eq} and 5-Me), 1.35 (1 H, dd, *J* 12.5 and 11, 2-H^{ax}), 1.46 (1 H, t, *J* 12.5, 2′-H^{ax}), 1.52 (1 H, m, 2-H^{eq}), 1.79 (1 H, dd, *J* 14 and 9.5, 4-H^{ax}), 1.84 (1 H, ddd, *J* 12.5, 3.5 and 2, 2′-H^{eq}), 1.93 (3 H, s, 5′-Me), 1.95 (3 H, s, 9-Me), 1.98 (3 H, s, 13′-Me), 2.00 (3 H, s, 13-Me), 2.02 (3 H, s, 9′-Me), 2.07 (1 H, ddd-like, *J* 17.5, 9.5 and 1.5, 4′-H^{ax}), 2.32 (1 H, br dd, *J* 14 and 4.5, 4-H^{eq}), 2.43 (1 H, br dd, *J* 17.5 and 5.5, 4′-H^{eq}), 2.60 and 3.65 (each 1 H, d, *J* 18.5, 7-H$_2$), 3.82 (1 H, m, 3-H), 3.99 (1 H, m, 3′-H), 6.29 (1 H, br d, *J* 12, 14′-H), 6.36 (1 H, d, *J* 15, 12′-H), 6.41 (1 H, d, *J* 11.5, 14-H), 6.46 (1 H, dd-like, *J* 12 and 1, 10′-H), 6.57 (1 H, dd, *J* 15 and 12, 11′-H), 6.58 (1 H, dd, *J* 15 and 11, 11-H), 6.65 (1 H, dd, *J* 14.5 and 11.5, 15-H), 6.67 (1 H, d, *J* 15, 12-H), 6.75 (1 H, dd, *J* 14.5 and 12, 15′-H) and 7.15 (1 H, dd-like, *J* 11 and 1, 10-H) (Found: M$^+$, 598.402. $C_{40}H_{54}O_4$ requires M, 598.402).

Compound **27**: λ_{max}(EtOH)/nm 279, 420sh, 453 and 475sh; λ_{max}(hexane)/nm 277, 340, 425sh, 451 and 478; ν_{max}(KBr)/cm^{-1} 3420 (OH), 2190 (C≡C), 1660 (conj. CO), 1610 and 1578 (C=C); δ_H(500 MHz) 0.94 (3 H, s, 1-Me^{ax}), 1.10 (3 H, s, 1-Me^{eq}), 1.15 (3

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H, s, 1′-Me^{ax}), 1.20 and 1.21 (each 3 H, s, 1′-Me^{eq} and 5-Me), 1.33 (1 H, ddd, *J* 12.5, 3.5 and 1, 2-H^{eq}), 1.46 (1 H, t, *J* 12, 2′-H^{ax}), 1.54 (1 H, dd, *J* 12.5 and 10, 2-H^{ax}), 1.84 (1 H, ddd, *J* 12, 4 and 2, 2′-H^{eq}), 1.88 (1 H, dd, *J* 15 and 8.5, 4-H^{ax}), 1.93 (3 H, s, 5′-Me), 1.94 (3 H, s, 9-Me), 1.98 (3 H, s, 13′-Me), 2.00 (3 H, s, 13-Me), 2.02 (3 H, s, 9′-Me), 2.07 (1 H, ddd-like, *J* 17.5, 9.5 and 1, 4′-H^{ax}), 2.23 (1 H, ddd, *J* 15, 6 and 1, 4-H^{eq}), 2.43 (1 H, ddd, *J* 17.5, 5.5 and 1.5, 4′-H^{eq}), 2.72 and 3.57 (each 1 H, d, *J* 18, 7-H$_2$), 3.92 (1 H, m, 3-H), 3.99 (1 H, m, 3′-H), 6.29 (1 H, br d, *J* 11.5, 14′-H), 6.36 (1 H, d, *J* 15, 12′-H), 6.41 (1 H, br d, *J* 11.5, 14-H), 6.46 (1 H, dd-like, *J* 11.5 and 1.5, 10′-H), 6.57 (1 H, dd, *J* 15 and 11.5, 11′-H), 6.58 (1 H, dd, *J* 15 and 11, 11-H), 6.65 (1 H, dd, *J* 14.5 and 11.5, 15-H), 6.67 (1 H, d, *J* 15, 12-H), 6.75 (1 H, dd, *J* 14.5 and 11.5, 15′-H) and 7.14 (1 H, dd-like, *J* 11 and 1, 10-H) (Found: M$^+$, 598.401).

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