First Total Synthesis of (±)-Peridinin, (±)-Pyrrhoxanthin and the Optically Active Peridinin

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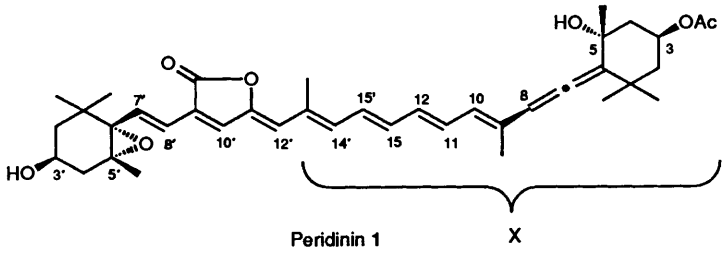
The first total synthesis of peridinin **1** and pyrrhoxanthin **2** has been accomplished *via* the reaction of the C_{15}-epoxy formyl ester **21** with the C_{22}-allenic sulfone **28** or the C_{22}-acetylenic sulfone **39**. A synthesis of optically active peridinin has also been achieved starting from the (4*R*,6*R*)-hydroxy ketone **5**.

The unique C_{37}-skeletal nor-carotenoids, peridinin **1**[1] and pyrrhoxanthin **2**[2] were isolated from the planktonic algae, dinoflagellates causing 'red tide' and their absolute stereostructures were determined by the Jensen group.[3,4] These carotenoids contain a 4-alkylidenebutenolide system carrying an allene or an acetylene function in the main polyene chain. The main pigment peridinin is known as an auxiliary light harvesting pigment for photosynthesis[5] in the sea. It is worthwhile for a synthetic chemist to take up the challenge of the synthesis of such an attractive carotenoid, peridinin. In previous communications, we have reported two Wittig methods[6,7] directed towards the synthesis of carotenoidal alkylidenebutenolides such as **4** (Scheme 1), but they were found to be inappropriate for the preparation of compounds containing a longer conjugated polyene chain because of the drastic reaction conditions employed. As an alternative method, we recently developed a novel synthetic method (a sulfone method)[8,9] which is the reaction of the conjugated formyl ester **3** with various allylic sulfones in the presence of lithium diisopropylamide (LDA) at −78 °C (Scheme 1). By the application of this methodology, the first total synthesis of the 4-alkylidenebutenolide carotenoids, (±)-peridinin **1**, (±)-pyrrhoxanthin **2**, and optically active peridinin was accomplished previously.[8,10] The present paper is concerned with a full account of the experiments.

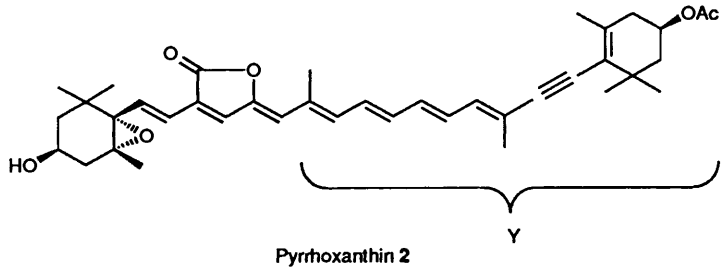
Synthesis of the C_{15}*-Epoxy Formyl Ester* **21**.—Treatment of the *tert*-butyldimethylsilyl (TBS) ether **6** (Scheme 2) of the 4-hydroxy-2,2,6-trimethylcyclohexanone **5**[11] with *N*-phenyltrifluoromethanesulfonimide (Tf_2NPh)[12] in the presence of LDA gave the enol triflate **7** (89%), which underwent a coupling reaction[13] with methyl acrylate in the presence of palladium catalyst to afford the diene ester **8** (93%). Reduction of the ester group in **8** with lithium aluminium hydride (LAH) followed by acetylation gave the allylic acetate **9** (80%), which was treated with sodium sulfinate catalysed by $Pd(PPh_3)_4$[14] to provide the allylic sulfone **10** (89%). Introduction of a methoxycarbonyl group into **10** followed by alkylation with allyl bromide and subsequent deprotection gave the compound **13** (61%). Regioselective oxidation of **13** at the terminal vinyl group with sodium periodate and a catalytic amount of osmium tetroxide

Table 1 ^{1}H NMR spectroscopic data of epoxides

		2ax-H (2'ax-H)	2eq-H (2'eq-H)
syn-group	**51**	1.54	1.38
	19	1.57	1.34
	20	1.65	1.36
	48	1.58	1.41
anti-group	**52**	1.40	1.63
	21	1.26	1.63
	22	1.37	1.67
	49	1.39	1.63
	1	1.26	1.63
	2	1.22	1.60
	35	*ca.* 1.40	1.66

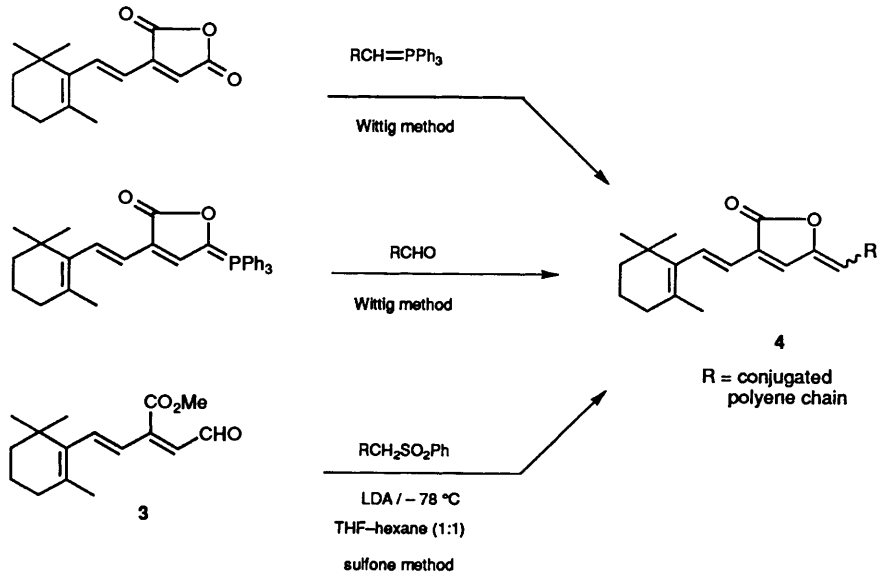


Peridinin **1** X

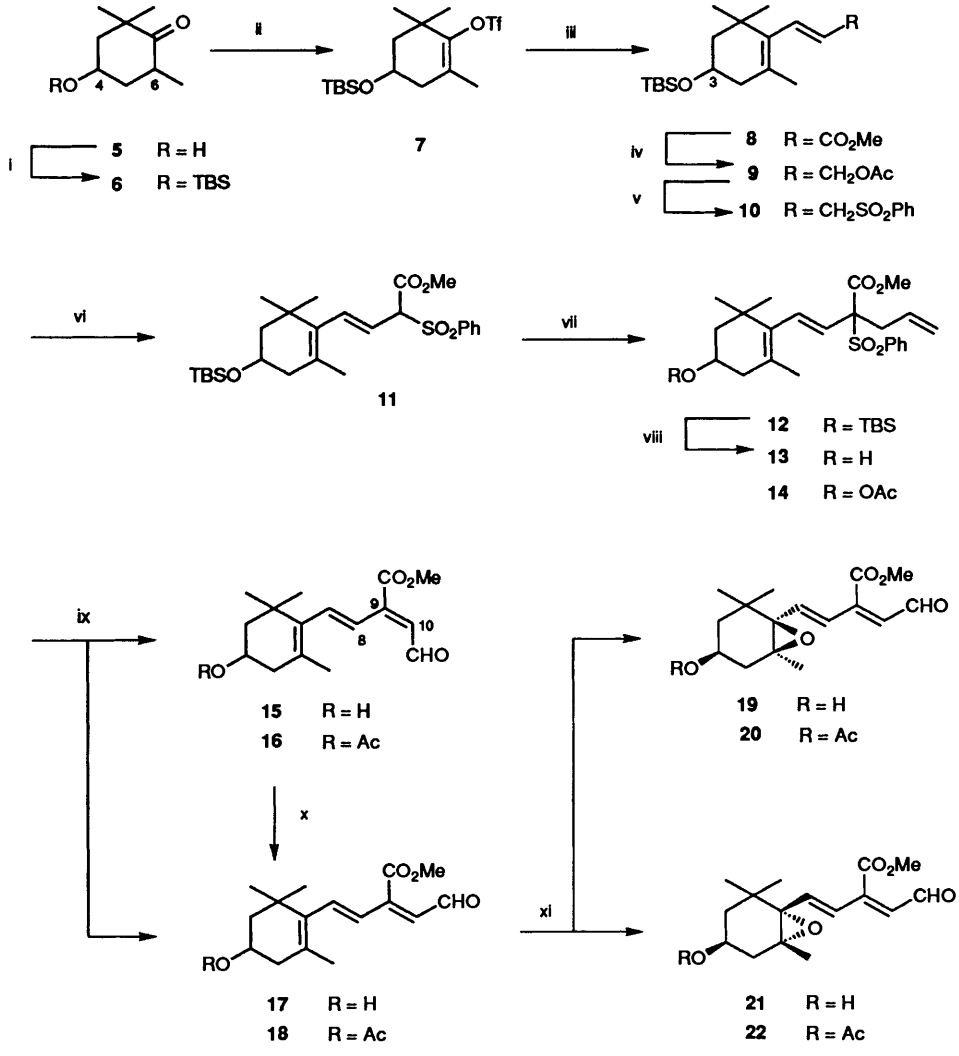


Y

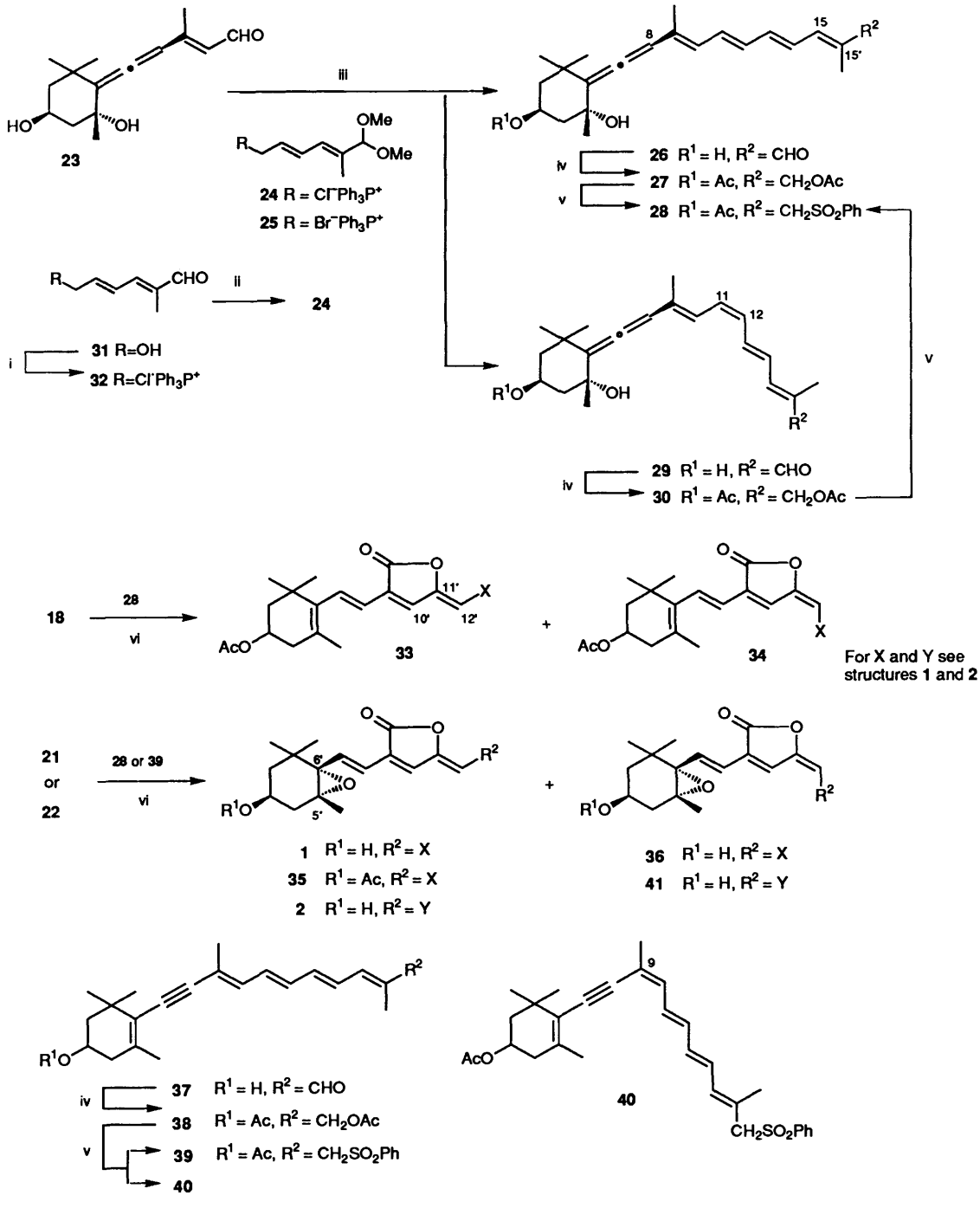
Pyrrhoxanthin **2**



Scheme 1



Scheme 2 *Reagents:* i, TBSCl, Et_3N, DMAP, CH_2Cl_2; ii, LDA, Tf_2NPh, THF; iii, $CH_2{=}CHCO_2Me$, $PdCl_2(PPh_3)_2$, Et_3N, DMF; iv, LAH, Et_2O, then Ac_2O, Py; v, $PhSO_2Na$, $Pd(PPh_3)_4$, THF–MeOH; vi, BuLi, $ClCO_2Me$, THF; vii, NaH, $BrCH_2CH{=}CH_2$, DMF; viii, TBAF, THF; ix, OsO_4, $NaIO_4$, dioxane–H_2O, then Al_2O_3; x, I_2, Et_2O–hexane; xi, MCPBA, CH_2Cl_2



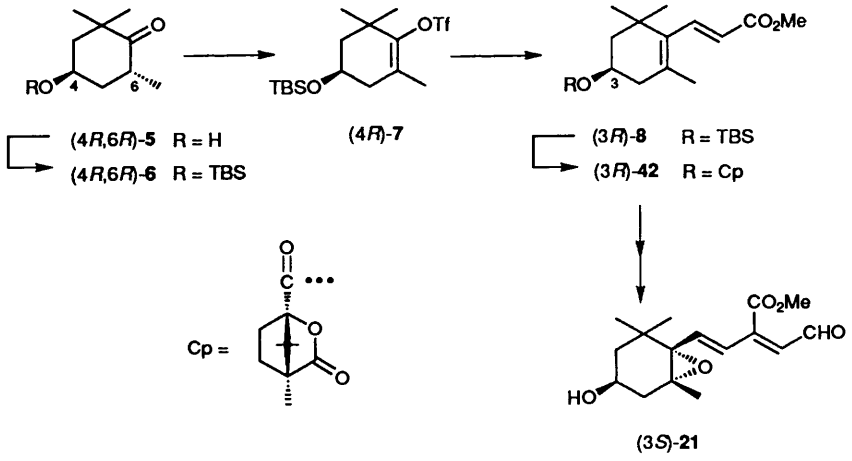
Scheme 3 *Reagents and conditions:* i, LiCl, MsCl, γ-collidine, DMF, then PPh_3; ii, $HC(OMe)_3$, H^+, MeOH; iii, NaOMe, CH_2Cl_2, then H^+; iv, $NaBH_4$, MeOH, then Ac_2O, Py; v, $PhSO_2Na$, propan-2-ol-H_2O, reflux; vi, LDA, THF, −78 °C

and the subsequent elimination of the sulfone group with Al_2O_3 afforded a mixture of the 9*E*-formyl ester* **15** (21%) and the 9*Z*-isomer **17** (17%) which were cleanly separated by preparative HPLC (pHPLC). The stereochemistry around the newly formed 9,10-double bond was determined from the comparison of the chemical shifts for 8-Hs and 10-Hs in both isomers. In the 9*Z*-isomer **17**, 8-H and 10-H signals appear at δ 6.22 and 6.09, respectively, whereas the corresponding signals (8-H; δ 6.67 and 10-H; δ 6.66) in the 9*E*-isomer **15** are at lower field owing to the anisotropic effect of the formyl and ester groups, respectively.

Treatment of the 9*E*-isomer **15** with a catalytic amount of iodine provided a mixture (*ca.* 3:4) of **15** and **17**. Epoxidation of **17** with *m*-chloroperbenzoic acid (MCPBA) gave a mixture of the *syn*-(β)-epoxide **19** (56%) and the *anti*-(α)-epoxide **21** (19%). Relative configurations between hydroxy and epoxy groups in the two isomers were confirmed by ^1H NMR spectroscopic data (see Table 1).

*Synthesis of the All-*E*-C_{22}-Allenic Sulfone* **28**.—The all-*E*-C_{22}-allenic sulfone **28** was synthesized from the C_{22}-allenic apocarotenals **26** and **29** which were previously prepared [15] *via* a Wittig condensation of the C_{15}-allenic aldehyde **23** with the C_7-phosphonium bromide **25** (Scheme 3). At this time, this Wittig condensation was modified by use of the C_7-

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



Scheme 4

phosphonium chloride **24** instead of **25**. Reduction of the formyl group in **26** with $NaBH_4$ followed by acetylation gave the acetate **27**, which was refluxed with sodium sulfinate in propan-2-ol and water to afford the sulfone **28** (63% from **26**). The 11*Z*-apocarotenal **29** was also converted into the all-*E*-sulfone **28** (51%) through **30** in the same manner as in the case of the all-*E*-isomer **26**. Isomerization might occur during sulfonization of the acetate **30** with heating. Thus, **28** was synthesized in 5 steps from C_{15}-aldehyde **23** in 51% yield without separation of the isomers **26** and **29**. The structure of **28** was determined from its ^1H NMR spectrum.

Synthesis of (±)-*Peridinin* **1**.—In order to accomplish the total synthesis of **1**, synthesis of peridinin acetate **35** (Scheme 3) was achieved as the preliminary experiment using the 3-acetoxy compound **14** (Scheme 2) prepared previously.[7] First, regioselective epoxidation at the 5',6'-double bond was examined in the C_{37}-skeletal compound **33**, which was synthesized *via* reaction of the allenic sulfone **28** with the 3-acetoxy-C_{15}-formyl ester **18** derived from **14**. The carbanion prepared from the sulfone **28** and LDA in a mixture (1:1) of tetrahydrofuran (THF) and hexane was treated with the formyl ester **18** at −78 °C to afford a mixture (20%; *ca.* 6:1) of the skeletal compound **33** and its 11'*E*-isomer **34**. The structures of two isomers were confirmed on the basis of their spectral data (see Experimental section). In the IR spectrum, both isomers showed an absorption (ν/cm^{-1} 1745) due to an α,β-unsaturated γ-lactone. The stereochemistry around the newly formed 11',12'-double bond was determined from the chemical shifts for 10'-Hs (**33**; δ 7.03 and **34**; δ 7.41) in both isomers on the basis of the empirical rule.[10] Unfortunately, the epoxidation of **33** with MCPBA gave complicated products, in which only a small amount of the desired peridinin acetate **35** was contained (detection only by HPLC). In contrast, treatment of the formyl ester **18** with MCPBA resulted in the regioselective epoxidation at the 5,6-double bond to give a mixture of the *syn*-(β)-epoxide **20** (47%) and *anti*-(α)-epoxide **22** (20%) (Scheme 2). Then, the condensation of the sulfone **28** with the *anti*-epoxide **22** gave the peridinin acetate **35** (13%) without the opening of the epoxide ring. Spectral properties of synthetic **35*** were identical with those of a semi-synthetic sample prepared from authentic peridinin† (Scheme 3).

Based on the synthesis of peridinin acetate, the sulfone **28** was condensed with the 3-hydroxy-*anti*-epoxide **21** in the presence of LDA to provide the condensed product (18%), repeated purification of which by pHPLC in the dark led to peridinin **1** and its 11'*E*-isomer **36** in pure form, respectively. Spectral properties of the synthetic peridinin* were in good agreement with those of natural specimen.†

Synthesis of (±)-*Pyrrhoxanthin* **2**.—The total synthesis of (±)-pyrrhoxanthin **2** was also accomplished by the application of the sulfone method. Similar treatment of the known C_{22}-acetylenic apocarotenal **37** as in the case of the preparation of the allenic sulfone **28** gave a mixture of all-*E*-acetylenic sulfone **39** (31%) and its 9*Z*-isomer **40** (31%). The exceptional stability of 9*Z*-isomers in the case of carotenoids with a 7,8-triple bond has been noted.[16] Thus, the isomerization occurred during sulfonization of the acetate **38** with heating.

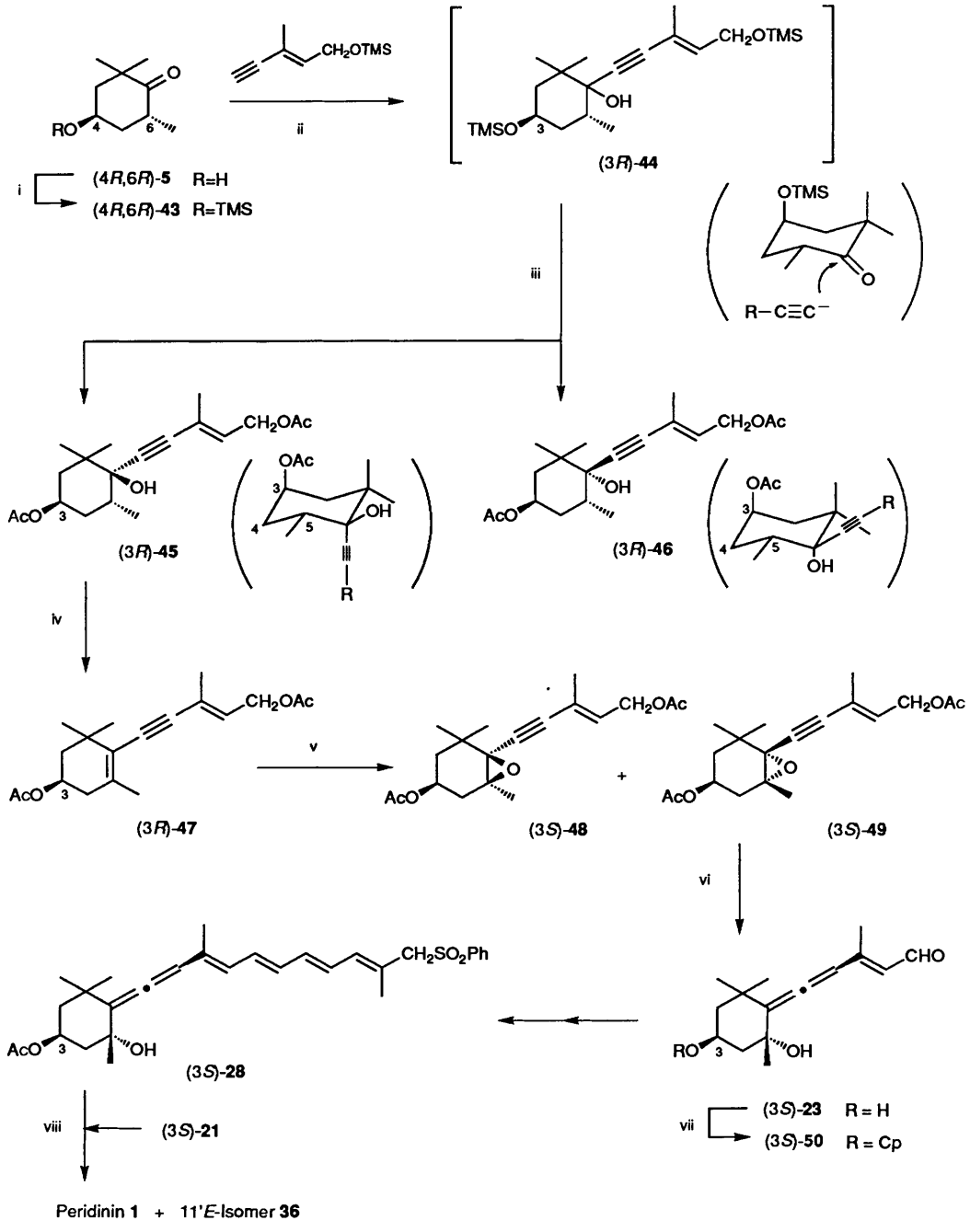
Condensation between the acetylenic sulfone **39** and the *anti*-epoxide **21** in the presence of LDA produced a mixture (13%; *ca.* 1:1) of pyrrhoxanthin **2** and its 11'*Z*-isomer, which was cleanly separated by pHPLC in the dark. Spectral properties of the synthetic **2** were in accordance with those reported.[4]

Synthesis of Optically Active Peridinin.—Optically active C_{15}-epoxy formyl ester **21** was prepared (Scheme 4) from the readily available chiral hydroxy ketone **5**[17] in the same pathway as described in the synthesis of racemic **21** (Scheme 2). The optical purity was determined (88% e.e.) by HPLC analysis of the camphanate **42**.

The optically active C_{22}-allenic sulfone **28** was also prepared from the same chiral synthon **5** according to the route as shown in Scheme 5. Treatment of the trimethylsilyl (TMS) ether **43** of the (4*R*,6*R*)-hydroxy ketone **5** with the lithium salt of the TMS ether of (*E*)-3-methylpent-2-en-4-yn-1-ol gave the hydroxy compound **44** which, without purification, was deprotected and then acetylated to afford a mixture (7:1) of the hydroxy diacetates **45** and **46** (82% from the ketone **43**). Its recrystallization gave a major diastereoisomer **45** in pure form, whose optical purity (97% e.e.) was determined by use of the camphanate **50** of the allenic aldehyde **23**. The stereochemistry of these isomers were established by ^1H NMR spectroscopy including 2D NOESY experiment: 3-Hs (**45**; δ 4.95, quint, *J* 3 and **46**; δ 5.00, quint, *J* 3) of both isomers were assigned as equatorial (see Scheme 5) from their small *J* values. 5-Hs (**45**; δ 2.25, dqd, *J* 13, 6.5, 4 and **46**; δ 2.24, dqd, *J* 13, 6.5, 4) of both isomers were axial, owing to their large $J_{4ax,5}$ values (13 Hz). In 2D NOESY experiments, the cross-peaks between 6-OH and 1ax methyl protons were not observed in **46** but were observed in **45**. Thus the conformations of these isomers must be as shown in Scheme 5. It is considered that the attack of the C_6-acetylenic

* This seems to be a mixture of diastereoisomers.

† This was kindly supplied by Dr. Y. Tanaka, Kagoshima University, Japan. A mixed HPLC of the synthetic and the natural pigment showed no separation.



Scheme 5 *Reagents and conditions:* i, TMSCl, Et_3N, Et_2O; ii, BuLi, Et_2O; iii, *p*-TsOH, MeOH, then Ac_2O, Py; iv, $POCl_3$, Py, 75 °C; v, MCPBA, CH_2Cl_2; vi, DIBAL, CH_2Cl_2, then MnO_2; vii, TBAF, THF, then (−)-CpCl, Et_3N, DMAP, CH_2Cl_2; viii, LDA, THF, −78 °C

component on the less hindered side of the ketone **43** resulted in the formation of **45**. Dehydration of **45** with phosphorus oxychloride in pyridine gave the optically active enyne diacetate **47** (67%).

Conversion of (3*R*)-**47** into the optically active C_{15}-allenic aldehyde **23**[11,18] was carried out according to the synthesis of the racemic **23**.[15] Treatment of **47** with MCPBA led to a mixture of the *syn*-(β)-epoxide **48** (24%) and *anti*-(α)-epoxide **49** (20%). Reduction of the *anti*-epoxide **49** with diisobutyl aluminium hydride (DIBAL) followed by treatment with MnO_2 gave the allenic aldehyde **23** (84%). The C_{22}-allenic sulfone (3*S*)-**28** was prepared from (3*S*)-**23** in the same way as described in the synthesis of the racemic **28** (Scheme 3).

Condensation between the allenic sulfone (3*S*)-**28** and the formyl ester (3*S*)-**21** in the presence of LDA produced a mixture (11%; *ca.* 1 : 1) of optically active peridinin **1** and its 11'*E*-isomer which was cleanly separated by pHPLC in the dark (Scheme 5). Spectral data [UV–VIS, IR, NMR and MS] were identical with those of the natural specimen. In addition, its CD spectrum (Fig. 1) was nearly superimposable on that reported by the Jensen group.[3] This is the first total synthesis of optically active peridinin.

^1H NMR Spectral Properties of Epoxides.—Conformation of a number of epoxides prepared in the present work was determined by the comparison of their ^1H NMR spectroscopic data (Table 1) with those of the known[15,19] *syn*- and *anti*-epoxides **51** and **52**. Consequently, characteristic properties were found in the chemical shifts of 2-Hs in these epoxides. In *anti*-epoxides, chemical shift correlation between 2ax-Hs and 2eq-Hs is normal. However, in *syn*-epoxides, 2ax-Hs situated close to the oxygen of the epoxy ring are found at lower field

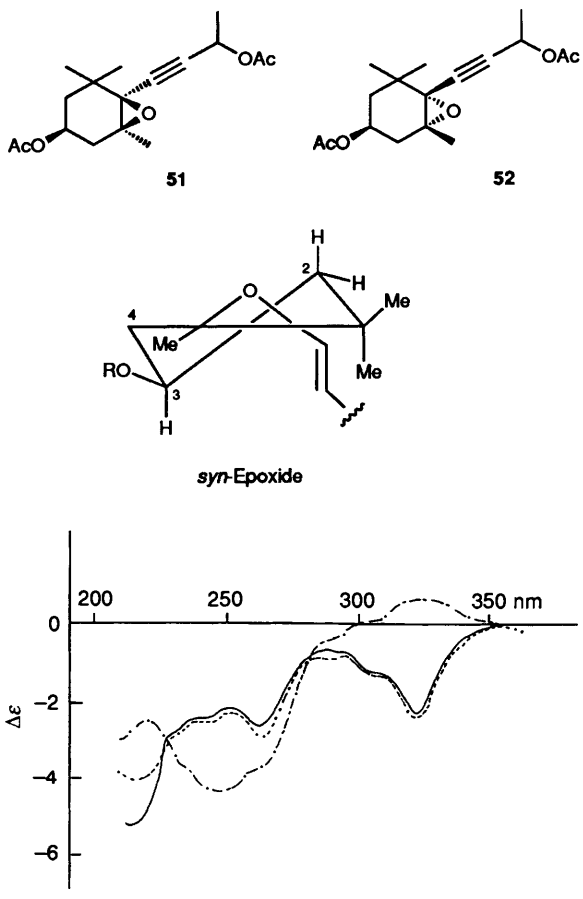


Fig. 1 CD spectra in EPA (Et_2O–isopentane–EtOH, 5:5:2) of peridinin **1** and its 11′*E*-isomer **36**. Natural peridinin · · · ·; synthetic peridinin ——; 11′*E*-isomer **36** — - — - —

than 2eq-Hs. This deshielding may be ascribed to van der Waals interactions between the 2ax-H and the oxygen atom or to the effect of lone-pair electrons of the oxygen. The same correlations were observed in the literature.[20,21] These results can be effectively used to determine the stereochemistry of 5,6-epoxy compounds having an oxygen functional group at the 3-position.

Experimental

M.p.s are uncorrectred. UV–VIS spectra were recorded on a Shimadzu UV-200 or UV-200S or UV-160 instrument and IR spectra on a Shimadzu IR-27G spectrometer in a chloroform solution. ^1H NMR spectra at 60, 200 or 500 MHz were measured on a JEOL JNM-PMX 60, or a Varian XL-200 or a Varian VXR-500 superconducting FT-NMR spectrometer, respectively, in deuteriochloroform solutions using tetramethylsilane as an internal reference. ^{13}C NMR spectra at 50 MHz were determined on a Varian XL-200 superconducting FT-NMR spectrometer in deuteriochloroform solutions using tetramethylsilane as an internal standard. Mass spectra were taken on a Hitachi M-80 or a JEOL JMS-SX 102. Optical rotations were measured on a JASCO DIP-181 or a JASCO DIP-370 and CD spectra in EPA (Et_2O–isopentane–EtOH, 5:5:2) solution on a JASCO J-500C. Column Chromatography (CC) was performed on silica gel: Merck Art. 7734 for open columns and Merck Art. 7739 for short columns under reduced pressure. Low-pressure column chromatography was conducted on a Yamazen Low Pressure Liquid Chromatography System using a Lobar Column (Merck LiChroprep Si60). Preparative TLC (pTLC) was performed on silica gel plates (Merck silica gel $60F_{254}$ pre-coated plates, 0.25 or 0.5 mm thickness). Analytical and preparative HPLC was carried out on Shimadzu LC-3A, 5A, and 6A instruments with a UV–VIS detector.

Unless otherwise stated, solvent extracts were dried over anhydrous sodium sulfate and all operations were carried out under nitrogen or argon. Evaporation of the extract or the filtrate was carried out under reduced pressure. Ether refers to diethyl ether. The NMR assignments are given using the carotenoid numbering system except for compounds **6**, **7** and **43**.

Synthesis of Racemic Peridinin **1**

4-tert-*Butyldimethylsilyloxy*-2,2,6-*trimethylcyclohexanone* **6**.—TBSCl (15.0 g, 100 mmol) was added to a stirred solution of the hydroxy ketone **5**[11] (14.50 g, 93 mmol), triethylamine (14.3 cm^3, 102 mmol) and 4-dimethylaminopyridine (DMAP) (12.0 g, 98 mmol) in dry CH_2Cl_2 (30 cm^3) at 0 °C. The mixture was stirred at room temp. for 2 h, poured into chilled water and extracted with ether. The extracts were washed successively with aqueous 5% HCl, saturated aqueous $NaHCO_3$ and brine. Evaporation of the dried solution followed by distillation (98–102 °C/0.08 mmHg) gave **6** (23.42 g, 93%) as a colourless oil; ν_{max}/cm^{-1} 1700 (C=O); δ_H(60 MHz) 0.08 (6 H, s, SiMe × 2), 0.87 (9 H, s, Bu^t), 1.00 (3 H, d, *J* 6, 6-Me), 1.03 and 1.33 (each 3 H, s, gem-Me) and 4.23 (1 H, m, 4-H).

4-tert-*Butyldimethylsilyloxy*-2,6,6-*trimethylcyclohex*-1-*enyl Trifluoromethanesulfonate* **7**.—A solution of butyllithium (BuLi) (1.59 mol dm^{-3} in hexane; 23.1 cm^3, 37 mmol) was added to a stirred solution of diisopropylamine (5.13 cm^3, 37 mmol) in dry THF (75 cm^3) at −78 °C and the mixture was stirred for a further 30 min. To this LDA solution was added dropwise a solution of the ketone **6** (9.00 g, 33 mmol) in dry THF (75 cm^3). Upon completion of the addition, the mixture was stirred for 1 h at −78 °C, after which a solution of Tf_2NPh (12.50 g, 35 mmol) in dry THF (75 cm^3) was added dropwise at the same temperature. The ice-cooled mixture was stirred for 5 h. The reaction was quenched with saturated aqueous NH_4Cl. After evaporation of THF, the residue was extracted with ether. The extracts were washed with brine, dried and evaporated. The residue was purified by CC (ether–hexane, 4:96) to afford the vinyl triflate **7** (11.88 g, 89%) as a colourless oil; ν_{max}/cm^{-1} 1398 and 1130 (OSO_2); δ_H(200 MHz) 0.08 (6 H, s, SiMe × 2), 0.89 (9 H, s, Bu^t), 1.15 and 1.21 (each 3 H, s, gem-Me), 1.75 (3 H, s, 2-Me), 2.16 (1 H, ddd, *J* 17, 9, 1, 5-H), 2.36 (1 H, br dd, *J* 17, 6, 5-H) and 4.02 (1 H, m, 4-H); δ_C(50 MHz) 17.59 (4-CH_3), 36.75 (C-2), 64.26 (C-4), 118.76 (q, *J* 318, CF_3), 123.91 (C-6) and 149.05 (C-1) (Found: *m/z* 402.151. $C_{16}H_{29}F_3O_4SSi$ requires *M*, 402.151).

Methyl (E)-3-(4-tert-*Butyldimethylsilyloxy*-2,6,6-*trimethylcyclohex*-1-*enyl*)*prop*-2-*enoate* **8**.—$PdCl_2(PPh_3)_2$ (330 mg, 0.47 mmol) was added to a solution of the vinyl triflate **7** (6.49 g, 16 mmol), methyl acrylate (5.73 cm^3, 65 mmol) and triethylamine (7.94 cm^3, 57 mmol) in dry dimethylformamide (DMF) (45 cm^3). The mixture was heated and stirred at 75 °C for 22 h. After cooling, the reaction mixture was diluted with ether and washed with aqueous 5% HCl, saturated aqueous $NaHCO_3$ and brine. Evaporation of the dried solution gave a residue which was purified by CC (ether–hexane, 7:93) to afford the dienyl ester **8** (5.10 g, 93%) as a colourless oil; λ_{max}(EtOH)/nm 278; ν_{max}/cm^{-1} 1707 (conj. CO_2Me); δ_H(200 MHz) 0.08 (6 H, s, SiMe × 2), 0.90 (9 H, s, Bu^t), 1.08 and 1.10 (each 3 H, s, gem-Me), 1.48 (1 H, t, *J* 12.5, 2ax-H), 1.66 (1 H, ddd, *J* 12.5, 4, 1.5, 2eq-H), 1.76 (3 H, s, 5-Me), 2.08 (1 H, br dd, *J* 17.5, 9, 4ax-H), 2.27 (1 H, br dd, *J* 17.5, 6, 4eq-H), 3.76 (3 H, s, CO_2Me), 3.94 (1 H, m, 3-H), 5.82 (1 H, d, *J* 16, 8-H) and 7.37 (1

H, br d, *J* 16, 7-H) (Found: *m/z* 338.228. $C_{19}H_{34}O_3Si$ requires *M*, 338.228).

(E)-3-(4-tert-*Butyldimethylsilyloxy*-2,6,6-*trimethylcyclohex*-1-*enyl*)*allyl Acetate* **9**.—A solution of the dienyl ester **8** (11.97 g, 35 mmol) in dry ether (200 cm^3) was added dropwise to a stirred suspension of LAH (1.01 g, 27 mmol) in dry ether (200 cm^3) at 0 °C and the mixture was stirred at 0 °C for 30 min. The excess of LAH was decomposed by dropwise addition of water. The mixture was extracted with ether and the extracts were washed with brine and dried. Evaporation of the solvent gave the hydroxy compound, which without purification was dissolved in pyridine (Py) (50 cm^3) and acetic anhydride (10 cm^3). The mixture was stirred at room temperature for 16 h, poured into ice–water and extracted with ether. The extracts were washed successively with aqueous 5% HCl, saturated aqueous $NaHCO_3$ and brine. Evaporation of the dried extracts gave a residue which was purified by CC (ether–hexane, 1:9) to afford the acetate **9** (9.97 g, 80%) as a colourless oil; ν_{max}/cm^{-1} 1730 (OAc); δ_H(200 MHz) 0.08 (6 H, s, SiMe × 2), 0.90 (9 H, s, Bu^t), 1.01 and 1.03 (each 3 H, s, gem-Me), 1.67 (3 H, s, 5-Me), 2.07 (3 H, s, OAc), 3.93 (1 H, m, 3-H), 4.62 (2 H, d, *J* 6.5, 9-H_2), 5.52 (1 H, dt, *J* 16, 6.5, 8-H) and 6.13 (1 H, br d, *J* 16, 7-H) (Found: *m/z* 352.245. $C_{20}H_{36}O_3Si$ requires *M*, 352.243).

(E)-[3-(4-tert-*Butyldimethylsilyloxy*-2,6,6-*trimethylcyclohex*-1-*enyl*)*allyl*]*sulfonylbenzene* **10**.—A solution of $Pd(PPh_3)_4$ (735 mg, 0.64 mmol) in THF (18 cm^3) was added to a mixture of the acetate **9** (4.49 g, 13 mmol) and $PhSO_2Na{\cdot}2H_2O$ (2.81 g, 14 mmol) in MeOH (9 cm^3) and THF (18 cm^3) and the reaction mixture was stirred at room temperature for 1 h. After the reaction had been quenched by the addition of aqueous potassium cyanide (150 mg, 2.3 mmol), the mixture was extracted with ether. The extracts were washed with brine, dried and evaporated to give an oil which was purified by short CC (ether–hexane, 1:3) to provide the sulfone **10** (4.91 g, 89%) as colourless crystals, m.p. 82–83 °C; ν_{max}/cm^{-1} 1310 and 1300 (split) (SO_2) and 1132 (SO_2); δ_H(200 MHz) 0.06 (6 H, s, SiMe × 2), 0.89 (9 H, s, Bu^t), 0.85 and 0.91 (each 3 H, s, gem-Me), 1.39 (1 H, t, *J* 12, 2ax-H), 1.59 (3 H, s, 5-Me), 1.98 (1 H, br dd, *J* 18, 9.5, 4ax-H), 2.17 (1 H, br dd, *J* 18, 6, 4eq-H), 3.87 (1 H, m, 3-H), 3.90 (2 H, d, *J* 7.5, 9-H_2), 5.32 (1 H, dt, *J* 16, 7.5, 8-H), 5.96 (1 H, br d, *J* 16, 7-H), 7.49–7.66 (3 H, m, ArH) and 7.86–7.92 (2 H, m, ArH) (Found: *m/z* 434.231 $C_{24}H_{38}O_3SSi$ requires *M*, 434.231) (Found: C, 66.1; H, 8.85; S, 7.6. $C_{24}H_{38}O_3SSi$ requires C, 66.31; H, 8.81; S, 7.38%).

Methyl (E)-4-(4-tert-*Butyldimethylsilyloxy*-2,6,6-*trimethylcyclohex*-1-*enyl*)-2-*phenylsulfonylbut*-3-*enoate* **11**.—A solution of BuLi (1.59 mol dm^{-3} in hexane; 13.8 cm^3, 22 mmol) was added to a stirred solution of the sulfone **10** (4.78 g, 11 mmol) in dry THF (80 cm^3) at −78 °C. The mixture was stirred for a further 30 min after which methyl chloroformate (1.72 cm^3, 13 mmol) was added to it and stirring continued at −78 °C for 20 min. The reaction was quenched with saturated aqueous NH_4Cl. After evaporation of THF, the residue was extracted with ether. The extracts were washed with brine, dried and evaporated to afford a residue which was purified by low pressure column chromatography (ether–hexane, 1:3) to provide the ester **11** (3.99 g, 74%) as a colourless solid and recovered starting material (1.03 g, 22%); ν_{max}/cm^{-1} 1738 (CO_2Me), 1315 and 1300 (split) (SO_2) and 1139 (SO_2); δ_H(200 MHz) 0.07 (6 H, s, SiMe × 2), 0.90 (9 H, s, Bu^t), 0.92 and 0.93 (each 3/2 H, s, 1-Me), 0.98 (3 H, s, 1-Me), 1.64 and 1.66 (each 3/2 H, s, 5-Me), 3.74 (3 H, s, CO_2Me), 3.90 (1 H, m, 3-H), 4.61 (1 H, d, *J* 9.5, 9-H), 5.50 and 5.52 (each 1/2 H, dd, *J* 16, 9.5, 8-H), 6.15 and 6.17 (each 1/2 H, br d, *J* 16, 7-H), 7.51–7.72 (3 H, m, ArH) and 7.85–7.93 (2 H, m, ArH) (Found: *m/z* 351.235. $C_{20}H_{35}O_3Si$ requires *M* − SO_2Ph, 351.232).

Methyl (E)-2-[2-(4-tert-*Butyldimethylsilyloxy*-2,6,6-*trimethylcyclohex*-1-*enyl*)*vinyl*]-2-*phenylsulfonylpent*-4-*enoate* **12**.—A suspension of sodium hydride (60% oil dispersion; 0.46 g, 11.5 mmol) in dry DMF (12 cm^3) was added to a stirred solution of the ester **11** (4.08 g, 8.3 mmol) in dry DMF (22 cm^3) at 0 °C. The mixture was stirred at room temperature for 40 min after which allyl bromide (0.79 cm^3, 9.1 mmol) was added to it at 0 °C. The mixture was then stirred at 0 °C for 10 min and at room temperature for 15 min. After the reaction had been quenched with saturated aqueous NH_4Cl, the mixture was extracted with ether. The extracts were washed with brine, dried and evaporated to give a residue which was purified by short CC (ether–hexane, 3:7) to provide the allyl ester **12** (4.32 g, 98%) as a colourless oil; ν_{max}/cm^{-1} 1735 (CO_2Me), 1638 (C=C), 1312 and 1300 (split) (SO_2) and 1138 (SO_2); δ_H(200 MHz) 0.08 (6 H, s, SiMe × 2), 0.91 (9 H, s, Bu^t), 1.02 and 1.06 (9/2 H and 3/2 H, each s, gem-Me), 1.68 and 1.72 (each 3/2 H, s, 5-Me), 3.06 (2 H, m, 10-H_2), 3.70 (3 H, s, CO_2Me), 3.95 (1 H, m, 3-H), 5.11 (1 H, s-like, 12-H), 5.17 (1 H, d-like, *J* 7, 12-H), 5.60 (1 H, m, 11-H), 5.76 and 5.77 (each 1/2 H, d, *J* 16, 8-H), 6.36 (1 H, br d, *J* 16, 7-H), 7.51–7.72 (3 H, m, ArH) and 7.81–7.87 (2 H, m, ArH) (Found: *m/z* 391.267. $C_{23}H_{39}O_3Si$ requires *M* − SO_2Ph, 391.267).

Methyl (E)-2-[2-(4-*Hydroxy*-2,6,6-*trimethylcyclohex*-1-*enyl*)*vinyl*]-2-*phenylsulfonylpent*-4-*enoate* **13**.—A solution of tetrabutylammonium fluoride (TBAF) (1 mol dm^{-3} in THF; 80 cm^3, 80 mmol) was added to a solution of **12** (5.50 g, 10 mmol) in THF (100 cm^3) and the mixture was stirred at room temperature for 4 h. This was diluted with ether and the organic layer was washed with brine. Evaporation of the dried solvent gave a residue which was purified by short CC (MeOH–CH_2Cl_2, 2:98) to provide **13** (3.62 g, 84%) as a colourless oil; ν_{max}/cm^{-1} 3605 and 3450 (OH), 1735 (CO_2Me), 1315 and 1302 (split) (SO_2) and 1140 (SO_2); δ_H(200 MHz) 1.04 and 1.07 (9/2 H and 3/2 H, each s, gem-Me), 1.70 and 1.74 (each 3/2 H, s, 5-Me), 3.06 (2 H, m, 10-H_2), 3.70 (3 H, s, CO_2Me), 3.98 (1 H, m, 3-H), 5.10 (1 H, s-like, 12-H), 5.16 (1 H, d-like, *J* 8, 12-H), 5.58 (1 H, m, 11-H), 5.77 (1 H, d, *J* 16, 8-H), 6.36 (1 H, br d, *J* 16, 7-H), 7.48–7.71 (3 H, m, ArH) and 7.80–7.86 (2 H, m, ArH) (Found: *m/z* 277.180. $C_{17}H_{25}O_3$ requires *M* − SO_2Ph, 277.180).

(2E/Z,4E)-5-(4-*Hydroxy*-2,6,6-*trimethylcyclohex*-1-*enyl*)-3-*methoxycarbonylpenta*-2,4-*dienal* **15** *and* **17**.—Osmium tetroxide (40 mg, 0.16 mmol) was added to a solution of **13** (4.80 g, 11 mmol) in dioxane (45 cm^3) and water (15 cm^3) at room temperature and the mixture was stirred for 5 min. Sodium metaperiodate (5.70 g, 27 mmol) was then added in small portions to the mixture over 30 min. After being stirred at room temperature for 3 h, the reaction mixture was diluted with ether and washed with brine. Evaporation of the dried solvent gave an oil which was dissolved in ether (300 cm^3). To this solution was added aluminium oxide for CC (Merck Art. 1064, 50 g) and the mixture was stirred at room temperature. Upon disappearance of the TLC spot of the starting material, aluminium oxide was filtered off. Evaporation of the filtrate gave a residue which was purified by short CC (acetone–hexane, 1:1) followed by pHPLC [LiChrosorb Si 60 (7 μm) 2.5 × 25 cm; acetone–hexane, 1:3] to provide the 9*E*-formyl ester **15** (658 mg, 21%) and the 9*Z*-isomer **17** (542 mg, 17%), as yellow oils, respectively. Compound **15**: λ_{max}(EtOH)/nm 210, 270sh and 325sh; ν_{max}/cm^{-1} 3600 and 3440 (OH), 1730 (CO_2Me) and 1670 (conj. CHO); δ_H(200 MHz) 1.11 and 1.12 (each 3 H, s, gem-Me), 1.49 (1 H, t, *J* 12, 2ax-H), 1.81 (3 H, s, 5-Me), 2.10 (1 H, dd, *J* 17, 9, 4ax-H), 2.44 (1 H, br dd, *J* 17, 5, 4eq-H), 3.87 (3 H, s, CO_2Me), 4.02 (1 H, m, 3-H), 6.59 (1 H, br d, *J* 16, 7-H), 6.66 (1 H, d, *J* 7.5, 10-H), 6.67 (1 H, d, *J* 16, 8-H) and 10.07 (1 H,

d, *J* 7.5, CHO) (Found: *m/z* 278.152. $C_{16}H_{22}O_4$ requires *M*, 278.152).

Compound **17**: λ_{max}(EtOH)/nm 265 and 331; ν_{max}/cm^{-1} 3610 and 3450 (OH), 1730 (CO_2Me) and 1670 (conj. CHO); δ_H(200 MHz) 1.09 and 1.10 (each 3 H, s, gem-Me), 1.47 (1 H, t, *J* 12, 2ax-H), 1.78 (3 H, s, 5-Me), 2.07 (1 H, br dd, *J* 17, 10, 4ax-H), 2.43 (1 H, br dd, *J* 17, 5, 4eq-H), 3.95 (3 H, s, CO_2Me), 4.00 (1 H, m, 3-H), 6.09 (1 H, d, *J* 7.5, 10-H), 6.22 (1 H, d, *J* 16, 8-H), 6.65 (1 H, br d, *J* 16, 7-H) and 9.79 (1 H, d, *J* 7.5, CHO) (Found: *m/z* 278.152. $C_{16}H_{22}O_4$ requires *M*, 278.152).

Isomerization of the 9E-*Formyl Ester* **15**.—A solution of iodine in hexane (0.01%, w/v; 250 cm^3) was added to a stirred solution of the formyl ester **15** (1.12 g, 4 mmol) in ether–hexane (5:3; 400 cm^3) and the mixture was stirred at room temperature for 30 min. It was then washed with aqueous 1% sodium thiosulfate and brine, dried and evaporated to give an oil. This was purified in the same way as described above to provide **15** (370 mg, 33%) and **17** (522 mg, 46%).

Epoxidation of the 9Z-*Formyl Ester* **17**.—A solution of MCPBA (396 mg, 2.30 mmol) in CH_2Cl_2 (22 cm^3) was added to a cooled solution of **17** (426 mg, 1.53 mmol) in CH_2Cl_2 (8 cm^3). After being stirred at 0 °C for 5 h, the reaction mixture was diluted with CH_2Cl_2 and washed with saturated aqueous $NaHCO_3$ and brine. Evaporation of the dried solution gave a residue which was purified by pHPLC [LiChrosorb Si 60 (5 μm) 1.0 × 30 cm; MeOH–ether–hexane, 3:50:47] to provide the *syn*-epoxide **19** (254 mg, 56%) and the *anti*-epoxide **21** (87 mg, 19%), as pale yellow oils, respectively. Compound **19**: λ_{max}(EtOH)/nm 283; ν_{max}/cm^{-1} 3610 and 3450 (OH), 1730 (CO_2Me), 1675 (conj. CHO) and 1622 (C=C); δ_H(200 MHz) 1.01, 1.17 and 1.21 (each 3 H, s, gem-Me and 5-Me), 1.34 (1 H, ddd, *J* 13, 4, 1, 2eq-H), 1.57 (1 H, dd, *J* 13, 11, 2ax-H), 1.87 (1 H, dd, *J* 15, 9, 4ax-H), 2.21 (1 H, ddd, *J* 15, 7, 1, 4eq-H), 3.87 (1 H, m, 3-H), 3.94 (3 H, s, CO_2Me), 6.15 (1 H, d, *J* 7.5, 10-H), 6.37 (1 H, d, *J* 16, 8-H), 6.46 (1 H, d, *J* 16, 7-H) and 9.84 (1 H, d, *J* 7.5, CHO) (Found: *m/z* 294.146. $C_{16}H_{22}O_5$ requires *M*, 294.146).

Compound **21**: λ_{max}(EtOH)/nm 283; ν_{max}/cm^{-1} 3600 and 3420 (OH), 1730 (CO_2Me), 1675 (conj. CHO) and 1622 (C=C); δ_H(200 MHz) 0.99, 1.16 and 1.21 (each 3 H, s, gem-Me and 5-Me), 1.26 (1 H, dd, *J* 12.5, 11, 2ax-H), 1.63 (1 H, ddd, *J* 12.5, 3.5, 1.5, 2eq-H), 1.65 (1 H, dd, *J* 14, 9, 4ax-H), 2.42 (1 H, ddd, *J* 14, 5, 1.5, 4eq-H), 3.91 (1 H, m, 3-H), 3.94 (3 H, s, CO_2Me), 6.14 (1 H, d, *J* 7.5, 10-H), 6.38 (1 H, d, *J* 16, 8-H), 6.52 (1 H, d, *J* 16, 7-H) and 9.83 (1 H, d, *J* 7.5, CHO) (Found: *m/z* 294.148. $C_{16}H_{22}O_5$ requires *M*, 294.146).

Preparation of the C_7-*Phosphonium Chloride* **32**.—A solution of lithium chloride (0.41 g, 9.6 mmol) in dry DMF (3 cm^3) was added to a stirred mixture of the formyl alcohol **31**[15] (1.20 g, 9.5 mmol) and 2,4,6-trimethylpyridine (γ-collidine) (1.4 cm^3, 10 mmol) at 0 °C and the mixture was stirred for 10 min. To this reaction mixture, was added methanesulfonyl chloride (MsCl) (0.81 cm^3, 10 mmol) and stirring continued at 0 °C for a further 1 h. The mixture was poured into ice–water and extracted with ether. The organic layer was washed with aqueous 3% HCl, saturated aqueous $NaHCO_3$ and brine. Evaporation of the dried extract provided a residue which was purified by short CC (ether–hexane, 2:3) to afford the corresponding chloride (1.19 g). Subsequently, triphenylphosphine (2.05 g, 7.8 mmol) was added to a solution of the chloride (1.19 g, 7.4 mmol) in CH_2Cl_2 (60 cm^3) and the mixture was refluxed for 22 h. Evaporation of the solvent gave a residue which was washed with ether to provide the phosphonium chloride **32** (2.23 g, 55%) as a pale yellow solid; λ_{max}(EtOH)/nm 225 and 275; ν_{max}/cm^{-1} 1680 (conj. CHO).

[1R*(2E,4E,6E/Z,8E)2α,4β]-(±)-11-(2,4-*Dihydroxy*-2,6,6-*trimethylcyclohexylidene*)-2,9-*dimethylundeca*-2,4,6,8,10-*pentaenal* **26** *and* **29**.—To a solution of the C_7-phosphonium chloride **32** (1.10 g, 2.6 mmol) in MeOH (5 cm^3), were added an acidic solution (1 cm^3) prepared from toluene-*p*-sulfonic acid (*p*-TsOH) (150 mg) and H_3PO_4 (0.2 cm^3) in MeOH (50 cm^3), and methyl orthoformate (1 cm^3). The reaction mixture was stirred at room temperature for 18 h and neutralized with NaOMe until just before the red colour of a ylide appeared to give a Wittig salt **24** solution. To this solution, were added a solution of the C_{15}-allenic aldehyde **23**[15] (316 mg, 1.26 mmol) in CH_2Cl_2 (15 cm^3) and a NaOMe solution prepared from Na (70 mg) and MeOH (2 cm^3). After being stirred at room temperature for 30 min, the reaction mixture was poured into ice–water and extracted with ether. The extracts were shaken with aqueous 3% HCl until the fine structure in the UV spectrum disappeared and then washed with saturated aqueous $NaHCO_3$ and brine. Evaporation of the dried extract provided a residue which was purified by short CC (acetone–hexane, 3:7) to afford an isomeric mixture of the allenic apocarotenals. pHPLC separation [LiChrosorb Si 60(7 μm) 2.5 × 25 cm; propan-2-ol–THF–hexane, 1:35:64] of the mixture provided the all-*E*-isomer **26** (168 mg, 41%) and the 11*Z*-one **29** (164 mg, 38%), as orange solids, respectively. These isomers were identical with the samples prepared previously.[15]

[1β,3α,4R*(3E,5E,7E,9E)]-(±)-3-*Hydroxy*-4-(3,10-*dimethyl*-11-*phenylsulfonylundeca*-1,3,5,7,9-*pentaenylidene*)-3,5,5-*trimethylcyclohexyl Acetate* **28**.—(a) *From the all*-E-*apocarotenal* **26**. $NaBH_4$ (16 mg, 0.42 mmol) was added to an ice-cooled solution of **26** (290 mg, 0.85 mmol) in MeOH (12 cm^3). The mixture was stirred for 15 min and then poured into ice–water and extracted with ether. The extracts were washed with brine and dried. Evaporation of the solvent gave the triol, which without purification was dissolved in Py (11 cm^3) and acetic anhydride (3.5 cm^3). The mixture was stirred at room temperature for 15 h, poured into ice–water and extracted with ether. The extracts were washed with aqueous 5% HCl, saturated aqueous $NaHCO_3$ and brine. Evaporation of the dried extracts provided the diacetate **27** (320 mg); λ_{max}(EtOH)/nm 315sh, 329, 345 and 364; ν_{max}/cm^{-1} 3600 and 3420 (OH), 1930 (C=C=C) and 1725 (OAc). To a solution of the diacetate **27** (320 mg, 0.78 mmol) in propan-2-ol (6 cm^3) were added water (2 cm^3) and $PhSO_2Na{\cdot}2H_2O$ (204 mg, 1.02 mmol) and the mixture was refluxed for 20 h. After cooling, the reaction mixture was diluted with ether, washed with brine and evaporated. The residue was purified by short CC (acetone–hexane, 1:3) and then pHPLC [LiChrosorb Si 60(5 μm) 1.0 × 30 cm; THF–hexane, 3:7] to provide the sulfone **28** (272 mg, 63% from **26**) as a yellow foam.

(b) *From the* 11*Z*-*apocarotenal* **29**. In the same manner as described above, **29** (135 mg) provided the all-*E*-sulfone **28** (103 mg, 51%) through the diacetate **30** [λ_{max}(EtOH)/nm 313sh, 327, 342 and 361; ν_{max}/cm^{-1} 3600 and 3420 (OH), 1930 (C=C=C) and 1725 (OAc)].

(c) *From the* C_{15}-*allenic aldehyde* **23**. A mixture of the C_{22}-apocarotenals **26** and **29** prepared from **23** (320 mg) was treated in a manner similar to that used for the preparation of **28** from **26** to provide the all-*E*-sulfone **28** (244 mg, 51% from **23**); λ_{max}(EtOH)/nm 321sh, 336, 353 and 372; ν_{max}/cm^{-1} 3590 and 3470 (OH), 1930 (C=C=C), 1728 (OAc), 1305 and 1295 (split) (SO_2) and 1140 (SO_2); δ_H(500 MHz) 1.10 (3 H, s, 1-Me), 1.37 and 1.41 (each 3 H, s, 1-Me and 5-Me), 1.81 (3 H, s, 9-Me), 1.92 (3 H, s, 15′-Me), 2.08 (3 H, s, OAc), 3.84 (2 H, s, 14′-H_2), 5.42 (1 H, m, 3-H), 5.76 (1 H, d, *J* 11, 15-H), 6.06 (1 H, s, 8-H), 6.08 (1 H, d, *J* 12, 10-H), 6.16 (1 H, dd, *J* 14.5, 12, 13-H), 6.30 (1 H, dd, *J* 14.5, 12, 12-H), 6.36 (1 H, dd, *J* 14.5, 11, 14-H), 6.53 (1 H, dd, *J* 14.5, 12, 11-H), 7.58 (2 H, t, *J* 8, ArH), 7.68 (1 H, t, *J* 8, ArH)

and 7.89 (2 H, t, *J* 8, ArH) (Found: *m/z* 510.241. $C_{30}H_{38}O_5S$ requires *M*, 510.244).

(2E/Z,4E)-5-(4-*Acetoxy*-2,6,6-*trimethylcyclohex*-1-*enyl*)-3-*methoxycarbonylpenta*-2,4-*dienal* **16** *and* **18**.—In the same manner as described for the preparation of **15** and **17** from **13**, the allyl ester **14**[7] (500 mg) provided an isomeric mixture of the formyl esters which was purified by low pressure column chromatography (ether–hexane, 1:4) to yield the 9*E*-isomer **16** (80 mg, 23%) and the 9*Z*-isomer **18** (74 mg, 21%), as yellow oils, respectively. Compound **16**: λ_{max}(EtOH)/nm 233 (ε 8600), 273sh (ε 6000) and 325sh (ε 3600); ν_{max}/cm^{-1} 1725 (OAc and CO_2Me), 1670 (conj. CHO) and 1605 (C=C); δ_H(200 MHz) 1.11 and 1.15 (each 3 H, s, gem-Me), 1.60 (1 H, t, *J* 12, 2ax-H), 1.80 (3 H, s, 5-Me), 1.81 (1 H, ddd, *J* 12, 4, 2, 2eq-H), 2.06 (3 H, s, OAc), 2.14 (1 H, br dd, *J* 17.5, 9, 4ax-H), 2.51 (1 H, br dd, *J* 17.5, 6, 4eq-H), 3.87 (3 H, s, CO_2Me), 4.06 (1 H, m, 3-H), 6.57 (1 H, br d, *J* 16, 7-H), 6.66 (1 H, d, *J* 7, 10-H), 6.66 (1 H, d, *J* 16, 8-H) and 10.06 (1 H,d,*J*7,CHO)(Found:*m/z*321.170.$C_{18}H_{25}O_5$requires*M* + H, 321.170).

Compound **18**: λ_{max}(EtOH)/nm 267 (ε 10400) and 325 (ε 11400); ν_{max}/cm^{-1} 1725 (OAc and CO_2Me), 1670 (conj. CHO) and 1605 (C=C); δ_H(200 MHz) 1.09 and 1.13 (each 3 H, s, gem-Me), 1.59 (1 H, t, *J* 12, 2ax-H), 1.76 (3 H, s, 5-Me), 1.79 (1 H, ddd, *J* 12, 4, 2, 2eq-H), 2.05 (3 H, s, OAc), 2.12 (1 H, br dd, *J* 17.5, 9, 4ax-H), 2.49 (1 H, br dd, *J* 17.5, 6, 4eq-H), 3.94 (3 H, s, CO_2Me), 4.03 (1 H, m, 3-H), 6.09 (1 H, d, *J* 7.5, 10-H), 6.21 (1 H, d, *J* 16, 8-H), 6.62 (1 H, br d, *J* 16, 7-H) and 9.78 (1 H, d, *J* 7.5, CHO) (Found: *m/z* 321.169. $C_{18}H_{25}O_5$ requires *M* + H, 321.170).

Isomerization of the 9E-*Formyl Ester* **16**.—In the same manner as described for isomerization of **15**, the 9*E*-formyl ester **16** (282 mg) was treated with iodine to provide **16** (107 mg, 38%) and **18** (106 mg, 38%).

Condensation of the Formyl Ester **18** *and the Allenic Sulfone* **28**.—A solution of BuLi (1.59 mol dm^{-3} in hexane; 0.53 cm^3, 0.84 mmol) was added to a stirred solution of diisopropylamine (0.12 cm^3, 0.84 mmol) in dry THF (1.5 cm^3) and hexane (1.5 cm^3) at −78 °C and the mixture was stirred for a further 20 min. To this LDA solution, was added a solution of the sulfone **28** (216 mg, 0.42 mmol) in dry THF (2.5 cm^3) and hexane (2.5 cm^3). After the mixture had been stirred for 20 min at −78 °C, a solution of the formyl ester **18** (90 mg, 0.28 mmol) in dry THF (2.5 cm^3) and hexane (2.5 cm^3) was added at the same temperature. The reaction mixture was stirred at −78 °C for 10 min before being allowed to warm to room temperature over *ca.* 20 min with stirring. After being quenched with saturated aqueous NH_4Cl, the mixture was extracted with ether. The extracts were washed with brine, dried and evaporated to give a residue which was purified by CC (acetone–hexane, 1:4) and then pTLC (acetone–hexane, 7:13) to afford an isomeric mixture (**33**:**34** = *ca.* 6:1) (36 mg, 20% from **18**). pHPLC separation [LiChrosorb Si 60(5 μm) 0.75 × 30 cm; AcOEt–cyclohexane–benzene, 2:4:4] of the mixture provided the 11′*Z*-isomer **33** and the 11′*E*-isomer **34**, as red glasses, respectively. Compound **33**: λ_{max}(EtOH)/nm 475; λ_{max}(hexane)/nm 435sh, 461 and 491; ν_{max}/cm^{-1} 3590 and 3440 (OH), 1927 (C=C=C), 1745sh and 1725 (OAc and C=O); δ_H(500 MHz) 1.06 and 1.35 (each 3 H, s, 1-gem-Me), 1.11 and 1.13 (each 3 H, s, 1′-gem-Me), 1.38 (3 H, s, 5-Me), 1.76 (3 H, s, 5′-Me), 1.80 (3 H, s, 9-Me), 2.03 and 2.05 (each 3 H, s, OAc × 2), 2.23 (3 H, s, 13′-Me), 5.05 (1 H, m, 3′-H), 5.38 (1 H, tt, *J* 11.5, 4.4, 3-H), 5.71 (1 H, s, 12′-H), 6.05 (1 H, s, 8-H), 6.11 (1 H, d, *J* 11.5, 10-H), 6.20 (1 H, d, *J* 16.4, 8′-H), 6.38 (1 H, dd, *J* 14.4, 11.2, 12-H), 6.44 (1 H, d, *J* 11.5, 14′-H), 6.50 (1 H, dd, *J* 14.2, 11.2, 15-H), 6.60 (1 H, dd, *J* 14.4, 11.5, 11-H), 6.61 (1 H, dd, *J* 14.2, 11.5, 15′-H), 7.03 (1 H, s, 10′-H) and 7.22 (1 H, d, *J* 16.4, 7′-H) (Found: *m/z* 656.370. $C_{41}H_{52}O_7$ requires *M*, 656.371).

Compound **34**: λ_{max}(EtOH)/nm 480; λ_{max}(hexane)/nm 435sh, 465 and 491; ν_{max}/cm^{-1} 3590 and 3440 (OH), 1925 (C=C=C) and 1745sh and 1725 (OAc and C=O); δ_H(500 MHz) 1.05 and 1.33 (each 3 H, s, 1-gem-Me), 1.11 and 1.13 (each 3 H, s, 1′-gem-Me), 1.37 (3 H, s, 5-Me), 1.76 (3 H, s, 5′-Me), 1.80 (3 H, s, 9-Me), 2.02 and 2.04 (each 3 H, s, OAc × 2), 2.10 (3 H, s, 13′-Me), 5.04 (1 H, m, 3′-H), 5.36 (1 H, tt, *J* 12.1, 4.2, 3-H), 6.03 (1 H, s, 8-H), 6.09 (1 H, d, *J* 11.7, 10-H), 6.22 (1 H, d, *J* 16.2, 8′-H), 6.37 (1 H, dd, *J* 14.2, 11.0, 12-H), 6.37 (1 H, s, 12′-H), 6.42 (1 H, d, *J* 11.7, 14′-H), 6.51 (1 H, dd, *J* 14.2, 11.0, 15-H), 6.59 (1 H, dd, *J* 14.2, 11.7, 11-H), 6.61 (1 H, dd, *J* 14.2, 11.7, 15′-H), 7.31 (1 H, d, *J* 16.2, 7′-H) and 7.41 (1 H, s, 10′-H) (Found: *m/z* 656.371. $C_{41}H_{52}O_7$ requires *M*, 656.371).

Epoxidation of the 9*Z*-*Formyl Ester* **18**.—In the same manner as described for MCPBA-oxidation of **17**, the formyl ester **18** (335 mg) was treated with MCPBA to give oxidation products, which were purified by pHPLC [LiChrosorb Si 60(5 μm) 1.0 × 30 cm; ether–hexane, 35:65] to provide the *syn*-epoxide **20** (164 mg, 47%) and the *anti*-epoxide **22** (70 mg, 20%), as pale yellow oils, respectively. Compound **20**: λ_{max}(EtOH)/nm 282; ν_{max}/cm^{-1} 1730 (OAc and CO_2Me), 1677 (conj. CHO) and 1625 (C=C); δ_H(200 MHz) 1.00, 1.19 and 1.23 (each 3 H, s, gem-Me and 5-Me), 1.36 (1 H, ddd, *J* 12.5, 4.5, 1.5, 2eq-H), 1.65 (1 H, t, *J* 12.5, 2ax-H), 1.87 (1 H, dd, *J* 15, 9.5, 4ax-H), 2.02 (3 H, s, OAc), 2.33 (1 H, ddd, *J* 15, 7.5, 1.5, 4eq-H), 3.94 (3 H, s, CO_2Me), 4.90 (1 H, m, 3-H), 6.15 (1 H, d, *J* 7.5, 10-H), 6.36 (1 H, d, *J* 16, 8-H), 6.46 (1 H, d, *J* 16, 7-H) and 9.85 (1 H, d, *J* 7.5, CHO) (Found: *m/z* 336.158. $C_{18}H_{24}O_6$ requires *M*, 336.157).

Compound **22**: λ_{max}(EtOH)/nm 282; ν_{max}/cm^{-1} 1730 (OAc and CO_2Me), 1677, (conj. CHO) and 1623 (C=C); δ_H(200 MHz) 1.00, 1.18 and 1.21 (each 3 H, s, gem-Me and 5-Me), 1.37 (1 H, dd, *J* 13.5, 9, 2ax-H), 1.67 (1 H, ddd, *J* 13.5, 3.5, 1, 2eq-H), 1.78 (1 H, dd, *J* 15, 8, 4ax-H), 2.02 (3 H, s, OAc), 2.42 (1 H, ddd, *J* 15, 5.5, 1, 4eq-H), 3.94 (3 H, s, CO_2Me), 4.93 (1 H, m, 3-H), 6.15 (1 H, d, *J* 7.5, 10-H), 6.40 (1 H, d, *J* 16, 8-H), 6.52 (1 H, d, *J* 16, 7-H) and 9.84 (1 H, d, *J* 7.5, CHO) (Found: *m/z* 336.156. $C_{18}H_{24}O_6$ requires *M*, 336.157).

Preparation of (±)-*Peridinin Acetate* **35**.—According to the procedure described for the condensation between **18** and **28**, the *anti*-epoxide **22** (100 mg, 0.30 mmol) was treated with the allenic sulfone **28** (242 mg, 0.47 mmol) to give crude products, which were purified by short CC (acetone–hexane, 7:13) and then pHPLC [LiChrosorb CN(7 μm) 0.7 × 25 cm; AcOEt–hexane, 3:17] to afford peridinin acetate **35** (26 mg, 13% from **22**) as a red glass. Spectral properties of synthetic **35*** were identical with those of a semi-synthetic sample prepared from the authentic peridinin† λ_{max}(EtOH)/nm 473; λ_{max}(hexane)/nm 430sh, 456 and 486; ν_{max}/cm^{-1} 3690 and 3595 (OH), 1925 (C=C=C) and 1740 (OAc and C=O); δ_H(500 MHz) (0.99 and 1.23 (each 3 H, s, 1′-gem-Me), 1.07 and 1.35 (each 3 H, s, 1-gem-Me), 1.20 (3 H, s, 5′-Me), 1.39 (3 H, s, 5-Me), *ca.* 1.40 (2′ax-H + 2ax-H), 1.66 (1 H, dd, *J* 13.5, 3, 2′eq-H), 1.79 (1 H, dd, *J* 15, 7, 4′ax-H), 1.80 (3 H, s, 9-Me), 2.00 (1 H, ddd, *J* 12.5, 4, 2, 2eq-H), 2.03 and 2.04 (each 3 H, s, OAc × 2), 2.23 (3 H, s, 13′-Me), 2.29 (1 H, ddd, *J* 13, 4, 2, 4eq-H), 2.41 (1 H, dd, *J* 15, 5.5, 4′eq-H), 4.94 (1 H, m, 3′-H), 5.38 (1 H, tt, *J* 11.5, 4, 3-H), 5.74 (1 H, s, 12′-H), 6.05 (1 H, s, 8-H), 6.11 (1 H, d, *J* 12, 10-H), 6.38 (1 H, dd, *J* 14.5, 11, 12-H), 6.40 (1 H, d, *J* 15.5, 8′-H), 6.45 (1 H, d, *J*

* This seems to be a mixture of diastereoisomers.

† This was kindly supplied by Dr. Y. Tanaka, Kagoshima University, Japan. A mixed HPLC of the synthetic and the natural pigment showed no spearation.

11.5, 14'-H), 6.51 (1 H, dd, *J* 14.5, 11, 15-H), 6.61 (2 H, br t-like, *J* 14, 11-H + 15'-H), 7.03 (1 H, s, 10'-H) and 7.19 (1 H, d, *J* 15.5, 7'-H) (Found: *m/z* 672.366. $C_{41}H_{52}O_8$ requires *M*, 672.366).

Preparation of (±)-*Peridinin* **1**.—According to the procedure described for the condensation of **18** and **28**, the *anti*-epoxide **21** (142 mg, 0.48 mmol) was treated with the allenic sulfone **28** (365 mg, 0.72 mmol) to give crude products, which were purified by short CC (acetone–hexane, 7:13) and then pTLC (acetone–hexane, 9:11) to afford a condensed isomeric mixture (54 mg, 18% from **21**) as a red glass. pHPLC separation [LiChrosorb CN(7 μm) 0.7 × 25 cm; MeOH–acetone–hexane, 1:30:170] of the mixture provided the 11'*Z*-isomer (peridinin) **1** (8.7 mg) and the 11'*E*-isomer **36** (8.5 mg). Spectral properties of synthetic peridinin* were in good agreement with those of natural specimen;†,[22] Compound **1**: λ_{max}(EtOH)/nm 472; λ_{max}(hexane)/nm 431sh, 456 and 485; ν_{max}/cm^{-1} 3600 and 3450 (OH), 1928 (C=C=C) and 1742 (C=O); δ_H(500 MHz) 0.97, 1.20 and 1.21 (each 3 H, s, 1'-gem-Me and 5'-Me), 1.07 and 1.35 (each 3 H, s, 1-gem-Me), 1.26 (1 H, dd, *J* 12.5, 10.5, 2'ax-H), 1.38 (3 H, s, 5-Me), 1.38 (1 H, dd, *J* 12, 6, 2ax-H), 1.50 (1 H, t-like, *J* 13, 4ax-H), 1.63 (1 H, br d-like, *J* 12.5, 2'eq-H), 1.64 (1 H, dd, *J* 14.5, 9, 4'ax-H), 1.80 (3 H, s, 9-Me), 1.99 (1 H, ddd, *J* 12, 4, 2, 2eq-H), 2.04 (3 H, s, OAc), 2.23 (3 H, s, 13'-Me), 2.28 (1 H, ddd, *J* 13, 4, 2, 4eq-H), 2.40 (1 H, ddd, *J* 14.5, 4, 1.5, 4'eq-H), 3.90 (1 H, m, 3'-H), 5.38 (1 H, tt, *J* 12, 4, 3-H), 5.73 (1 H, s, 12'-H), 6.05 (1 H, s, 8-H), 6.11 (1 H, d, *J* 12, 10-H), 6.37 (1 H, d, *J* 15.5, 8'-H), 6.38 (1 H, dd, *J* 14, 11, 12-H), 6.45 (1 H, d, *J* 12, 14'-H), 6.51 (1 H, dd, *J* 14, 11, 15-H), 6.61 (2 H, dd, *J* 14, 12, 11-H + 15'-H), 7.02 (1 H, s, 10'-H) and 7.17 (1 H, d, *J* 15.5, 7'-H) (Found: *m/z* 630.354. $C_{39}H_{50}O_7$ requires *M*, 630.355).

Compound **36**: λ_{max}(EtOH)/nm 475; λ_{max}(hexane)/nm 431sh, 456 and 484; ν_{max}/cm^{-1} 3600 and 3450 (OH), 1928 (C=C=C) and 1742 (C=O); δ_H(500 MHz) 0.96 (3 H, s, 1'-Me), 1.06 and 1.34 (each 3 H, s, 1-gem-Me), 1.19 (6 H, s, 1'-Me + 5'-Me), 1.25 (1 H, dd, *J* 12, 10, 2'ax-H), 1.37 (3 H, s, 5-Me), 1.37 (1 H, dd, *J* 11, 7, 2ax-H), 1.49 (1 H, t-like, *J* 12.5, 4ax-H), 1.62 (1 H, br d-like, *J* 12, 2'eq-H), 1.63 (1 H, dd, *J* 14.5, 9, 4'ax-H), 1.79 (3 H, s, 9-Me), 1.98 (1 H, ddd, *J* 11, 4, 2, 2eq-H), 2.03 (3 H, s, OAc), 2.09 (3 H, s, 13'-Me), 2.27 (1 H, ddd, *J* 12.5, 4, 2, 4eq-H), 2.38 (1 H, ddd, *J* 14.5, 4, 1.5, 4'eq-H), 3.89 (1 H, m, 3'-H), 5.37 (1 H, tt, *J* 11, 4, 3-H), 6.04 (1 H, s, 8-H), 6.10 (1 H, d, *J* 11.5, 10-H), 6.36 (1 H, dd, *J* 14.5, 11, 12-H), 6.39 (1 H, s, 12'-H), 6.40 (1 H, d, *J* 15.5, 8'-H), 6.43 (1 H, d, *J* 11.5, 14'-H), 6.52 (1 H, dd, *J* 14.5, 11, 15-H), 6.59 (1 H, dd, *J* 14.5, 11.5, 11-H), 6.62 (1 H, dd, *J* 14.5, 11.5, 15'-H), 7.24 (1 H, d, *J* 15.5, 7'-H) and 7.43 (1 H, s, 10'-H) (Found: *m/z* 630.355. $C_{39}H_{50}O_7$ requires *M*, 630.355).

Synthesis of Racemic Pyrrhoxanthin **2**

(3E/Z,5E,7E,9E)-(±)-4-(3,10-*Dimethyl*-11-*phenylsulfonyl*-*undeca*-3,5,7,9-*tetraen*-1-*ynyl*)-3,5,5-*trimethylcyclohex*-3-*enyl Acetate* **39** *and* **40**.—Following the procedure as described for the preparation of the allenic sulfone **28** from the apocarotenal **26**, the all-*E*-acetylenic apocarotenal **37**[15] (845 mg, 2.6 mmol) gave an isomeric mixture of sulfones which was purified by short CC (ether–hexane, 1:1) and then pHPLC [LiChrosorb Si 60(7 μm) 2.5 × 25 cm; ether–hexane, 2:3] to provide the all-*E*-isomer **39** (398 mg, 31%) and 9*Z*-one **40** (396 mg, 31%), as yellow foams, respectively. Compound **39**: λ_{max}(EtOH)/nm 350sh, 366 and 386; ν_{max}/cm^{-1} 2270 (C≡C), 1728 (OAc), 1310 and 1300 (split) (SO_2) and 1142 (SO_2); δ_H(500 MHz) 1.17 and 1.19 (each 3 H, s, gem-Me), 1.56 (1 H, t, *J* 12, 2ax-H), 1.83 (1 H, ddd, *J* 12, 4, 2, 2eq-H), 1.88 and 1.90 (each 3 H, s, 5-Me and 15'-Me), 1.97 (3 H, s, 9-Me), 2.04 (3 H, s, OAc), 2.13 (1 H, br dd, *J* 17.5, 9.5, 4ax-H), 2.49 (1 H, br dd, *J* 17.5, 5.5, 4eq-H), 3.80 (2 H, s, 14'-H_2), 5.03 (1 H, m, 3-H), 5.71 (1 H, br d, *J* 11.5, 15-H), 6.14 (1 H, dd, *J* 14.5, 11.5, 13-H), 6.28 (1 H, dd, *J* 14, 11.5, 12-H), 6.35 (1 H, dd, *J* 14.5, 11.5, 14-H), 6.38 (1 H, dd-like, *J* 11.5, 1.5, 10-H), 6.46 (1 H, dd, *J* 14, 11.5, 11-H), 7.54 (2 H, t-like, *J* 8, ArH), 7.64 (1 H, tt, *J* 8, 1.5, ArH), and 7.84 (2 H, d-like, *J* 8, ArH) (Found: *m/z* 492.231. $C_{30}H_{36}O_4S$ requires *M*, 492.233).

Compound **40**: λ_{max}(EtOH)/nm 266sh, 275, 348sh, 363 and 382; ν_{max}/cm^{-1} 2170 (C≡C), 1730 (OAc), 1310 and 1300 (split) (SO_2) and 1142 (SO_2); δ_H(200 MHz) 1.21 and 1.23 (each 3 H, s, gem-Me), 1.59 (1 H, t, *J* 12, 2ax-H), 1.86 (1 H, ddd, *J* 12, 4, 2, 2eq-H), 1.87, 1.94 and 1.99 (each 3 H, s, 5-Me, 9-Me and 15'-Me), 2.06 (3 H, s, OAc), 2.16 (1 H, br dd, *J* 18, 10, 4ax-H), 2.53 (1 H, br dd, *J* 18, 6, 4eq-H), 3.80 (2 H, s, 14'-H_2), 5.05 (1 H, m, 3-H), 5.74 (1 H, d, *J* 11, 15-H), 6.11 (1 H, dd, *J* 14, 11, 13-H), 6.23 (1 H, d, *J* 11, 10-H), 6.27 (1 H, dd, *J* 14, 11, 12-H), 6.35 (1 H, dd, *J* 14, 11, 14-H), 6.71 (1 H, dd, *J* 14, 11, 11-H), 7.54 (2 H, t-like, *J* 7, ArH), 7.65 (1 H, tt, *J* 7, 2.5, ArH) and 7.86 (2 H, d-like, *J* 7, ArH) (Found: *m/z* 492.232. $C_{30}H_{36}O_4S$ requires *M*, 492.233).

Preparation of (±)-*Pyrrhoxanthin* **2**.—According to the procedure as described for the condensation between **18** and **28**, the *anti*-epoxide **21** (146 mg, 0.50 mmol) was treated with the acetylenic sulfone **39** (393 mg, 0.80 mmol) using diisopropylamine (0.13 cm^3, 0.93 mmol) and BuLi (1.49 mol dm^{-3} in hexane; 0.63 cm^3, 0.93 mmol) to give crude products, which were purified by short CC (acetone–hexane, 1:3) and then pTLC (MeOH–CH_2Cl_2, 3:97) to afford a condensed isomeric mixture (41 mg, 13% from **21**) as a red glass. pHPLC separation [LiChrosorb CN(7 μm) 0.7 × 25 cm; acetone–hexane, 12:88] of the mixture provided the 11'*Z*-one (pyrrhoxanthin) **2** (18 mg) and the 11'*E*-isomer **41** (15 mg). Spectral properties of the synthetic pyrrhoxanthin* were in accordance with those reported.[4] Compound **2**: λ_{max}(EtOH)/nm 466; λ_{max}(hexane)/nm 437sh, 459 and 487; ν_{max}/cm^{-1} 3600 and 3570 (OH), 2160 (C≡C) and 1745 (C=O); δ_H(500 MHz) 0.94 (3 H, s, 1'-Me), 1.14 (3 H, s, 1-Me), 1.16 (6 H, s, 1-Me + 5'-Me), 1.17 (3 H, s, 1'-Me), 1.22 (1 H, dd, *J* 12.5, 10, 2'ax-H), 1.53 (2ax-H), 1.60 (1 H, br d-like, *J* 12.5, 2'eq-H), 1.60 (1 H, dd, *J* 14.5, 9, 4'ax-H), 1.80 (1 H, ddd, *J* 12.5, 3, 1.5, 2eq-H), 1.87 (3 H, s, 5-Me), 1.96 (3 H, s, 9-Me), 2.06 (3 H, s, OAc), 2.10 (1 H, dd, *J* 17, 9, 4ax-H), 2.19 (3 H, s, 13'-Me), 2.36 (1 H, ddd, *J* 14.5, 5, 1.5, 4'eq-H), 2.46 (1 H, br dd, *J* 17, 5, 4eq-H), 3.87 (1 H, m, 3'-H), 5.00 (1 H, m, 3-H), 5.70 (1 H, s, 12'-H), 6.34 (1 H, d, *J* 15.5, 8'-H), 6.36 (1 H, dd, *J* 14.5, 11.5, 12-H), 6.40 and 6.41 (each 1 H, d, *J* 11.5, 10-H and 14'-H), 6.46 (1 H, dd, 14, 11.5, 15-H), 6.54 (1 H, dd, *J* 14.5, 11.5, 11-H), 6.60 (1 H, dd, *J* 14, 11.5, 15'-H), 6.98 (1 H, s, 10'-H) and 7.14 (1 H, d, *J* 15.5, 7'-H) (Found: *m/z* 612.344. $C_{39}H_{48}O_6$ requires *M*, 612.345).

Compound **41**: λ_{max}(EtOH)/nm 473; λ_{max}(hexane)/nm 437sh, 458 and 488; ν_{max}/cm^{-1} 3600 and 3480 (OH), 2160 (C≡C) and 1745 (C=O); δ_H(500 MHz) 0.98 (3 H, s, 1'-Me), 1.18 (3 H, s, 1-Me), 1.20 (6 H, s, 1-Me + 5'-Me), 1.21 (3 H, s, 1'-Me), 1.26 (1 H, dd, *J* 12.5, 10.5, 2'ax-H), 1.57 (2ax-H), 1.64 (2'eq-H), 1.64 (1 H, dd, *J* 14.5, 9, 4'ax-H), 1.84 (1 H, ddd, *J* 12.5, 4, 2, 2eq-H), 1.91 (3 H, s, 5-Me), 2.01 (3 H, s, 9-Me), 2.05 (3 H, s, OAc), 2.10 (3 H, s, 13'-Me), 2.14 (1 H, dd, *J* 17, 9, 4ax-H), 2.40 (1 H, ddd, *J* 14.5, 5, 1.5, 4'eq-H), 2.50 (1 H, br dd, *J* 17, 5, 4eq-H), 3.91 (1 H, m, 3'-H), 5.04 (1 H, m, 3-H), 6.41 (1 H, s, 12'-H), 6.42 (1 H, d, *J* 15.5, 8'-H), 6.45 (2 H, d-like, *J* 11.5, 10-H + 14'-H), 6.52 (1 H, dd, 14, 11, 15-H), 6.60 (1 H, dd, *J* 14.5, 11.5, 11-H), 6.63 (1 H, dd, *J* 14.5, 11.5, 15'-H), 7.26 (1 H, d, *J* 15.5, 7'-H) and 7.45 (1 H, s, 10'-H) (Found: *m/z* 612.341. $C_{39}H_{48}O_6$ requires *M*, 612.345).

*,† See preceding page.

Synthesis of Optically Active Peridinin **1**

Preparation of the Optically Active Compounds **6**, **7** *and* **8**.—According to the preparation of the racemic compounds, optically active compounds **6**, **7** and **8** were prepared. **6**: $[\alpha]_D^{20}$ −69.9 (*c* 2.94, MeOH). **7**: $[\alpha]_D^{25}$ −50.9 (*c* 1.93, MeOH). **8**: $[\alpha]_D^{23}$ −46.0 (*c* 1.28, MeOH).

Conversion of the (3R)-*Dienyl Ester* **8** *into the Camphanate* **42** *and Determination of its Optical Purity*.—Following the procedure given for **13**, treatment of (3*R*)-**8** (111 mg) with TBAF followed by purification by short CC (acetone–hexane, 1:3) afforded the 3-hydroxy compound (65 mg, 88%). To a mixture of this compound (65 mg, 0.29 mmol), triethylamine (0.12 cm^3, 0.86 mmol) and DMAP (72 mg, 0.59 mmol), was added (−)-camphanic acid chloride (CpCl) (192 mg, 0.89 mmol) at 0 °C. The reaction mixture was stirred at 0 °C for 30 min, poured into ice–water and extracted with CH_2Cl_2. The extracts were washed with brine, dried and evaporated. The residue was purified by short CC (ether–hexane, 2:3) to afford the camphanate **42** (114 mg, 97%). The optical purity of **42** was 88% e.e. based on HPLC analysis [LiChrosorb Si 60(5 μm) 0.4 × 30 cm; AcOEt–cyclohexane, 7:93; 1.2 cm^3 min^{-1}; 280 nm detect.]. λ_{max}(EtOH)/nm 275; ν_{max}/cm^{-1} 1780 (C=O), 1715 (conj. CO_2Me) and 1630 (C=C); δ_H(200 MHz) 0.98 and 1.07 (each 3 H, s, Cp-gem-Me), 1.12 (6 H, s, Cp-Me + 1-Me), 1.17 (3 H, s, 1-Me), 1.77 (3 H, s, 5-Me), 3.78 (3 H, s, CO_2Me), 5.83 (1 H, d, *J* 16, 8-H) and 7.36 (1 H, br d, *J* 16, 7-H) (Found: *m/z* 404.218. $C_{23}H_{32}O_6$ requires *M*, 404.220).

Preparation of the Optically Active Compounds **9**–**13**, **15**, **17**, **19** *and* **21**.—According to the preparation of the racemic compounds, optically active compounds **9**–**13**, **15**, **17**, **19** and **21** were prepared. **9**: $[\alpha]_D^{23}$ −63.0 (*c* 1.28, MeOH). **10**: $[\alpha]_D^{23}$ −55.2 (*c* 1.14, MeOH). **11**: $[\alpha]_D^{23}$ −41.1 (*c* 1.07, MeOH). **12**: $[\alpha]_D^{23}$ −41.4 (*c* 0.99, MeOH). **13**: $[\alpha]_D^{23}$ −54.6 (*c* 1.41, MeOH). **15**: $[\alpha]_D^{22}$ −57.8 (*c* 0.21, MeOH). **17**: $[\alpha]_D^{22}$ −58.4 (*c* 0.43, MeOH). **19**: $[\alpha]_D^{24}$ +26.7 (*c* 0.86, MeOH). **21**: $[\alpha]_D^{25}$ −77.0 (*c* 0.79, MeOH).

[1R,4S/R,5R-(E)]-4-(5-*Acetoxy*-3-*methylpent*-3-*en*-1-*ynyl*)-4-*hydroxy*-3,3,5-*trimethylcyclohexyl Acetate* **45** *and* **46**.—TMSCl (22.5 cm^3, 177 mmol) was added dropwise to a stirred solution of the (4*R*,6*R*)-hydroxy ketone **5**[17] (25.00 g, 160 mmol) and triethylamine (20.0 g, 198 mmol) in dry ether (250 cm^3) at 0 °C and the mixture was stirred at room temperature for 7 h. The mixture was filtered to remove the salt and the filtrate was washed with brine. Evaporation of the dried solution followed by distillation (80–83 °C/0.03 mmHg) gave the TMS ether **43** (33.83 g, 93%) as a colourless oil; ν_{max}/cm^{-1} 1700 (C=O); δ_H(60 MHz) 0.13 (9 H, s, SiMe × 3), 1.00 (3 H, d, *J* 7, 6-Me), 1.01 and 1.32 (each 3 H, s, gem-Me), 3.17 (1 H, m, 6-H) and 4.08 (1 H, quint, *J* 3, 4-H). BuLi (1.62 mol dm^{-3} in hexane; 106 cm^3, 171 mmol) was added dropwise to a solution of TMS ether of (*E*)-3-methylpent-2-en-4-yn-1-ol (30.79 g, 171 mmol) in ether (150 cm^3) at 0 °C. To this mixture, was added dropwise a solution of (4*R*,6*R*)-**43** (30.00 g, 132 mmol) in ether (150 cm^3) at 0 °C and the reaction mixture was stirred for 1.5 h at room temperature. After the reaction had been quenched with saturated aqueous NH_4Cl, the mixture was extracted with ether. The extracts were washed with brine, dried and evaporated to give the crude hydroxy compound **44** which, without purification, was dissolved in MeOH (450 cm^3) and *p*-TsOH (450 mg) was added to it. After being stirred for 1 h at room temperature, the mixture was diluted with AcOEt and the organic layer was washed with saturated aqueous $NaHCO_3$ and brine. Evaporation of the dried solution gave the triol which, without purification, was dissolved in Py (300 cm^3) and acetic anhydride (120 cm^3) was added to it. The mixture was stirred at room temperature for 16 h, poured into ice–water and extracted with ether. The extracts were washed successively with aqueous 5% HCl, saturated aqueous $NaHCO_3$ and brine. Evaporation of the dried extracts gave a residue which was purified by CC (ether–hexane, 1:1) to afford a mixture of (3*R*)-**45** and (3*R*)-**46** [7:1 based on HPLC analysis: 36.39 g, 82% from (4*R*,6*R*)-**5**]. It was recrystallized from ether–hexane to give the pure (3*R*)-**45** [32.17 g, 73% from (4*R*,6*R*)-**5**] as colourless crystals (m.p. 76–79 °C). pHPLC separation [LiChrosorb Si 60(7 μm) 1.0 × 25 cm; ether–hexane, 1:2] of a part of the evaporated filtrate gave the pure (3*R*)-**46** as an oil.

Compound **45**: $[\alpha]_D^{26}$ −24.1 (*c* 0.99, MeOH); ν_{max}/cm^{-1} 3600 and 3450 (OH) and 1730 (OAc); δ_H(500 MHz) 1.07 (3 H, d, *J* 6.5, 5-Me), 1.10 (3 H, s, leq-Me), 1.14 (3 H, s, lax-Me), 1.64 (1 H, ddd, *J* 15, 13, 3, 4ax-H), 1.73 (2 H, m, 2-H_2), 1.76 (1 H, br d, *J* 15, 4eq-H), 1.88 (3 H, dt, *J* 1.5, 0.5, 9-Me), 1.92 (1 H, s, OH), 2.04 and 2.07 (each 3 H, s, OAc × 2), 2.25 (1 H, dqd, *J* 13, 6.5, 4, 5-H), 4.64 (2 H, dd-like, *J* 7, 0.5, 11-H_2), 4.95 (1 H, quint, *J* 3, 3-H), 5.90 (1 H, tq, *J* 7, 1.5, 10-H) (Found: *m/z* 336.194. $C_{19}H_{28}O_5$ requires *M*, 336.194) (Found: C, 67.8; H, 8.5. $C_{19}H_{28}O_5$ requires C, 67.83; H, 8.39%).

Compound **46**: $[\alpha]_D^{21}$ −13.5 (*c* 0.97, MeOH); ν_{max}/cm^{-1} 3600 and 3450 (OH) and 1730 (OAc); δ_H(500 MHz) 1.06 (3 H, s, leq-Me), 1.10 (3 H, d, *J* 6.5, 5-Me), 1.20 (3 H, s, lax-Me), 1.57–1.62 (2 H, m, 4eq-H + 2eq-H), 1.68 (1 H, ddd, *J* 15, 13, 3, 4ax-H), 1.74 (1 H, s, OH), 1.77 (1 H, dd, *J* 15, 3, 2ax-H), 1.87 (3 H, m, 9-Me), 2.03 and 2.07 (each 3 H, s, OAc × 2), 2.24 (1 H, dqd, *J* 13, 6.5, 4, 5-H), 4.64 (2 H, dd-like, *J* 7, 0.5, 11-H_2), 5.00 (1 H, quint, *J* 3, 3-H), 5.90 (1 H, tq, *J* 7, 1.5, 10-H) (Found: *m/z* 336.194. $C_{19}H_{28}O_5$ requires *M*, 336.194).

[1R-(E)]-4-(5-*Acetoxy*-3-*methylpent*-3-*en*-1-*ynyl*)-3,5,5-*trimethylcyclochex*-3-*enyl Acetate* **47**.—Phosphorus oxychloride (15 cm^3) was added slowly to a stirred solution of (3*R*)-**45** (17.50 g, 52 mmol) in Py (100 cm^3) and the mixture was stirred at 75 °C for 15 h. After cooling, the reaction mixture was cautiously poured into ice–water. The resultant mixture was neutralized with $NaHCO_3$ and extracted with ether. The extracts were washed successively with aqueous 5% HCl, saturated aqueous $NaHCO_3$ and brine. Evaporation of the dried solution gave a residue which was purified by CC (ether–hexane, 1:1) to afford the enyne diacetate **47** (11.13 g, 67%) as a pale yellow oil. Spectral properties of this optically active **47** were identical with those of racemic one;[23] $[\alpha]_D^{23}$ −48.5 (*c* 1.03, MeOH).

Preparation of Optically Active Epoxides **48** *and* **49**.—In the same manner as described for MCPBA-oxidation of **17**, the enyne diacetate **47** (16.0 g) was treated with MCPBA to give oxidation products, which were purified by low pressure column chromatography (ether–hexane, 3:7) to provide the *syn*-epoxide **48** (4.56 g, 27%) and the *anti*-epoxide **49** (3.82 g, 23%), as pale yellow oils, respectively. Spectral properties of these optically active epoxides were identical with those of racemic analogues;[15] **48**: $[\alpha]_D^{26}$ −45.7 (*c* 1.09, MeOH); **49**: $[\alpha]_D^{25}$ +4.8 (*c* 1.04, MeOH).

{2R-[1R*(E),2α,4β]}-5-(2,4-*Dihydroxy*-2,6,6-*trimethylcyclohexylidene*)-3-*methylpenta*-2,4-*dienal* **23**.—A solution of DIBAL (4.96 g, 36 mmol) in dry CH_2Cl_2 (100 cm^3) was added dropwise to a stirred solution of the *anti*-epoxide **49** (2.00 g, 6 mmol) in dry CH_2Cl_2 (100 cm^3) at 0 °C. After the mixture had been stirred for a further 1 h, the excess of reagent was decomposed by dropwise addition of water. The mixture was saturated with NaCl and then thoroughly extracted with CH_2Cl_2. The extracts were washed with brine, dried and evaporated to give the crude allenic triol which, without purification, was dissolved in THF. The solution was shaken with active MnO_2 (12 g) at room temperature for 4 h. The

mixture was filtered through Celite. Evaporation of the filtrate gave a residue, which was purified by short CC (acetone–hexane, 35:65) to provide the allenic aldehyde **23** (1.26 g, 84%) as a pale yellow solid. Spectral properties of this optically active **23** were identical with those of racemic one;[15] $[\alpha]_D^{27}$ −60.0 (*c* 1.00, MeOH).

Conversion of the (3S)-*Allenic Aldehyde* **23** *into the Camphanate* **50** *and Determination of its Optical Purity.*—Py (1 cm^3) and (−)-CpCl (37 mg, 0.17 mmol) was added to a stirred solution of the allenic aldehyde **23** (36 mg, 0.14 mmol) in dry CH_2Cl_2 (2 cm^3) at 0 °C. After being stirred at 0 °C for 30 min, the reaction mixture was diluted with ether. The organic layer was washed with aqueous 3% HCl, saturated aqueous $NaHCO_3$ and brine. Evaporation of the dried solution gave a residue which was purified by pTLC (acetone–hexane, 1:2) to afford the camphanate **50** (47 mg, 76%). The optical purity of **50** was 96% e.e. based on HPLC analysis [LiChrosorb Si 60(5 μm) 0.4 × 30 cm; THF–hexane, 1:4, 1.5 cm^3 min^{-1}; 300 nm detect.]; λ_{max}(EtOH)/nm 277; ν_{max}/cm^{-1} 3600 and 3430 (OH), 1935 (C=C=C), 1783 (C=O), 1725 (C=O), 1655 (conj. CHO) and 1605 (C=C); δ_H(200 MHz) 0.98 and 1.07 (each 3 H, s, Cp-gem-Me), 1.13 (6 H, s, Cp-Me + 1-Me), 1.40 and 1.43 (each 3 H, s, 1-Me and 5-Me), 2.16 (3 H, d, *J* 1, 9-Me), 5.96 (1 H, d, *J* 8, 10-H), 6.11 (1 H, s, 8-H) and 10.05 (1 H, d, *J* 8, CHO) (Found: *m/z* 430.236. $C_{25}H_{34}O_6$ requires *M*, 430.235).

{3R-[1β,3α,4R*(3E,5E,7E,9E)]}-3-*Hydroxy*-4-(3,10-*dimethyl*-11-*phenylsulfonylundeca*-1,3,5,7,9-*pentaenylidene*)-3,5,5-*trimethylcyclohexyl Acetate* **28**.—According to the preparation of the racemic **28** from the racemic aldehyde **23**, the optically active **28** was prepared; $[\alpha]_D^{22}$ −13.7 (*c* 1.46, MeOH).

Preparation of the Optically Active Peridinin **1**.—According to the preparation of the racemic peridinin, the (3*S*)-formyl ester **21** was treated with the (3*S*)-allenic sulfone **28** to give the 11′*Z*-isomer (peridinin) **1** and the 11′*E*-one **36**. Spectral properties of these compounds were identical with those of racemic one. In addition, the CD spectrum of synthetic **1** was nearly superimposable on that reported by the Jensen group[3] (see Fig. 1). **1** (Found: *m/z* 630.355. $C_{39}H_{50}O_7$ requires *M*, 630,356); **36** (Found: *m/z* 630.356. $C_{39}H_{50}O_7$ requires *M*, 630.356).

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