Stereoselective total syntheses of atrochrysone, torosachrysone and related 3,4-dihydroanthracen-1(2*H*)-ones

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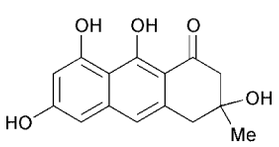
The total synthesis of the pre-anthraquinones atrochrysone **1** and torosachrysone **2** in both enantiomeric forms is described. The synthesis relies on the regioselective Tebbe methylenation of a chiral diester followed by an intramolecular enol ether acylation with *N*-triflyl-4-(dimethylamino)pyridinium triflate. The resulting 3-methoxycyclohex-2-enone **9** is condensed with suitable orsellinic acid derivatives to yield after deprotection the optically active 3,4-dihydroanthracen-1(2*H*)-ones **1** and **2**. This flexible approach can be used for the synthesis of ^{13}C-labelled compounds and should provide access to a series of analogues.

Introduction

Atrochrysone **1** and torosachrysone **2** can be considered as the



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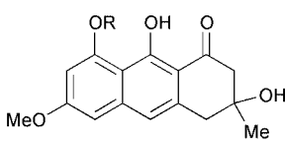

2, R = H
3, R = Me

biosynthetic precursors of octaketide derived anthraquinones from fungi and higher plants. (*R*)-Atrochrysone has been discovered in the toadstools *Cortinarius atrovirens* and *C. odoratus*,[1,2] whereas the (*S*)-enantiomer of **1** occurs in the Australian toadstool WAT 20 881.[3] *Dermocybe splendida* produces (*S*)-torosachrysone,[2,4] whereas other Australian toadstools belonging to *Cortinarius* and *Dermocybe* contain an unequal mixture of the enantiomers of **2**.[5] (*S*)-Torosachrysone has been obtained from *Cassia torosa* and other members of the Fabaceae family,[6–8] and the (*R*)-form from *Araliorhamnus vaginata*.[9] (*S*)-Torosachrysone 8-methyl ether **(*S*)-3** is found in several European *Cortinarius* and *Tricholoma* species.[1,2]

The monomers **1** and **2** serve as precursors in the biosynthesis of a large number of dimeric pre-anthraquinones, which are found in great variety in toadstools of the genus *Cortinarius*[1,2] and in some higher plants.[10] *C*- and *O*-prenylated derivatives of atrochrysone form the vismione group of anthranoids[11] which is characteristic for several plants of the Guttiferae family. Anthranoids of this type have been shown to display antibacterial,[6] antimalarial[12] and insect antifeedant activity.[13]

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The only stereoselective synthesis of a pre-anthraquinone of type **A** (Scheme 1) so far is that of (*R*)-torosachrysone 8-methyl ether **(*R*)-3**. It was derived from (−)-quinic acid in 18 steps, thus providing rigorous proof for the absolute configuration of this pigment.[14] In the present study, we describe a flexible enantioselective synthesis of atrochrysone **1** and torosachrysone **2** which can also be applied to other pre-anthraquinones.

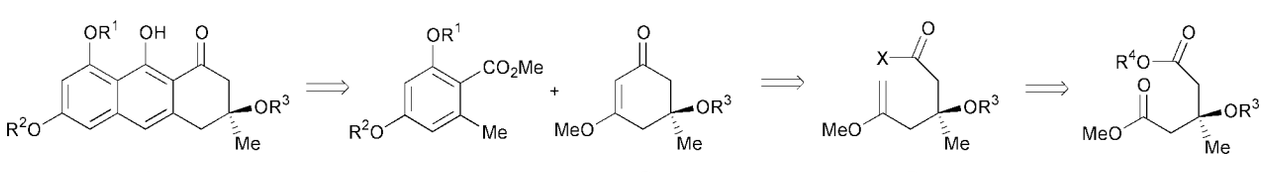
Results and discussion

Synthetic plan

The synthesis of pre-anthraquinones of type **A** presents considerable difficulties due to the high tendency of these compounds towards aromatisation. We considered Weinreb's convergent strategy[15] as the most suitable for the synthesis of the dihydroanthracenone nucleus since it should allow the condensation of an orsellinic acid fragment **B** with an optically active 3-methoxycyclohexenone unit **C** under comparatively mild conditions (Scheme 1). For the synthesis of the chiral building block **C** the intramolecular cyclisation of a carboxylic acid derivative **D** with a terminal methyl enol ether group appeared attractive. We assumed that compounds of this type should be accessible by regioselective Tebbe methylenation of a suitable diester **E** carrying besides the methyl ester a sterically more demanding ester group. Since both enantiomers of **E** can be obtained by known methods[16] this approach should allow the preparation of the pre-anthraquinones **A** in both enantiomeric forms.

Synthesis of fragment C

The stereoselective synthesis of fragment **C** starts from the monomethyl ester **5** obtained in optically pure form by pig liver esterase catalysed hydrolysis of the prochiral diester **4**[17] (Scheme 2). Treatment of **5** with two equivalents of *tert*-



A **B** **C** **D** **E**

Scheme 1 Retrosynthesis of the pre-anthraquinones **A**.

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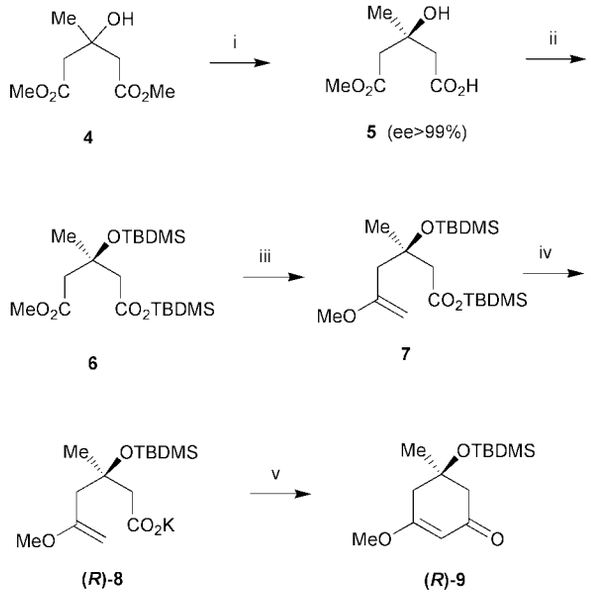
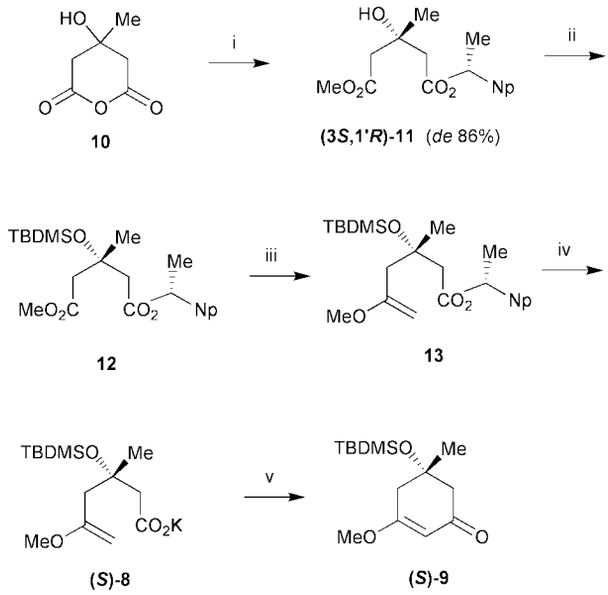


Scheme 2 *Reagents and conditions*: i, pig liver esterase, pH 8, 92%; ii, TBDMS-OTf, lutidine, CH_2Cl_2, 0→rt, 86%; iii, Tebbe reagent, THF, −78 °C, 30 min, then rt, 1 h, 61–85%; iv, aq. K_2CO_3, MeOH; v, Tf_2O, DMAP (each 10 equiv.), CH_2Cl_2, then **(*R*)-8**, −20 °C, 2 h, rt, 2 d, 40–80% over two steps.



Scheme 3 *Reagents and conditions*: i, (*R*)-1-(1′-naphthyl)ethanol, DMAP, CH_2Cl_2, −60 °C, 5 d, then MeOH (4 equiv.), DCC, −40 °C, 2 h, rt, 24 h, 75%; ii, TBDMS-OTf, lutidine (80%); iii, Tebbe reagent, THF, −50→−30 °C, 3 h, 66%; iv, 1 M KOH, EtOH, rt, 28 h; v, Tf_2O, DMAP (each 10 equiv.), CH_2Cl_2, then **(*S*)-8**, −20 °C, 2 h, rt, 2 d, 41% over two steps.

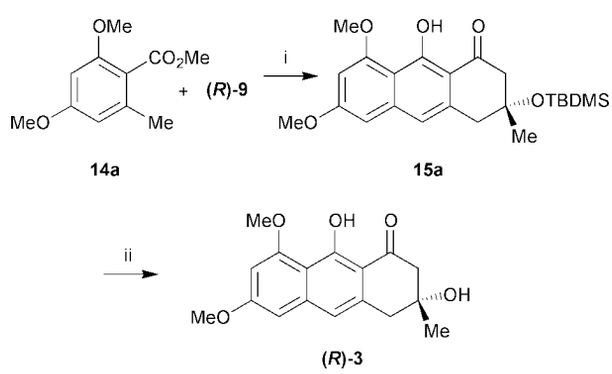
butyldimethylsilyl (TBDMS) triflate[18] yielded the TBDMS ester **6** with simultaneous protection of the tertiary hydroxy group.

The diester **6** was treated with one equivalent of Tebbe reagent.[19] We were pleased to note that at −78 °C and on warming up to room temperature this reaction afforded only the desired enol ether **7** by reaction of the organometallic reagent with the less hindered methyl ester group. To our knowledge this is the first example of a regioselective diester olefination. Selective alkaline hydrolysis of the TBDMS ester with aqueous potassium carbonate[20] yielded the potassium salt **(*R*)-8**. The intramolecular cyclisation of the carboxylate salt **(*R*)-8** proved to be difficult. Thus, conversion of **(*R*)-8** into the corresponding acid chloride by the mild method of Ghosez *et al.*[21] yielded none of the desired cyclohexenone **(*R*)-9**.[22] Finally, the cyclisation was achieved by the reaction of **(*R*)-8** with *N*-triflyl-4-(dimethylamino)pyridinium triflate. This reagent, easily formed from triflic anhydride and DMAP,[23] afforded the enantiomerically pure 3-methoxycyclohexenone **(*R*)-9** in 40–80% yield. The varying yields for the cyclisation step may be explained by the differing quality of the potassium salt **8** from which water has to be completely removed.

Although this five-step reaction sequence provides a short and efficient entry to enantiomerically pure (*R*)-3-methoxycyclohexenone, the method is limited to compounds of the (*R*)-series. Access to both enantiomers, however, is provided by the desymmetrisation of prochiral 3-hydroxy-3-methylpentanedioic anhydride (**10**) with (*R*)- or (*S*)-1-(1-naphthyl)ethanol, respectively, in the presence of DMAP at −60 °C[24] (Scheme 3). To achieve high diastereoselectivity the reaction has to be run for several days at this temperature. Subsequently, methanol and DCC[25] were added and the mixed ester **(3*S*,1′*R*)-11** was thereby obtained starting from (*R*)-1-(1-naphthyl)ethanol in 75% chemical yield with 86% de.[26] In the same manner the enantiomeric diester **(3*R*,1′*S*)-11** (86% de) was prepared from (*S*)-1-(1-naphthyl)ethanol. After protection of the tertiary hydroxy group with the TBDMS residue, treatment of diester **12** with one equivalent of Tebbe reagent at low temperature proceeded with high regioselectivity and afforded the desired methyl enol ether **13**, which was converted to cyclohexenone **(*S*)-9** (86% ee) with *N*-triflyl-DMAP triflate. Starting from diester **(3*R*,1′*S*)-11** the (*R*)-enantiomer of cyclohexenone **9** was obtained by the same methodology.

Synthesis of the dihydroanthracenones A

The TBDMS-protected (*R*)-torosachrysone 8-methyl ether **15a** was prepared in 25% yield by condensation of the lithiated methylbenzoate **14a** with 3-methoxycyclohexenone **(*R*)-9**. (Scheme 4). The removal of the TBDMS group from **15a** was

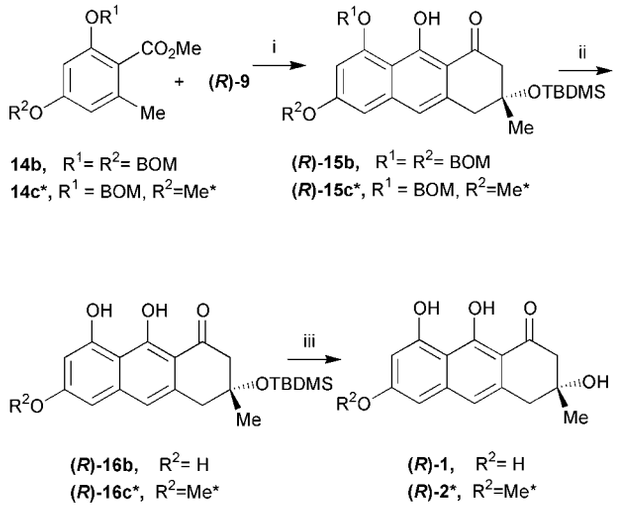


Scheme 4 *Reagents and conditions*: i, LDA, **14a**, THF, −78 °C, then **(*R*)-9**, 25%; ii, HF, CH_3CN, 78%.

best achieved with HF in acetonitrile.[27] The resulting enantiomerically pure (*R*)-torosachrysone 8-methyl ether **3** showed the opposite optical rotation and CD curve to the (*S*)-compound from *Cortinarius splendens*.[2] All other analytical data were in complete agreement.

For the synthesis of atrochrysone **1** and torosachrysone **2** a phenol protecting group that can be removed under very mild conditions had to be attached to the orsellinate fragment. We selected the benzyloxymethyl (BOM) group[28] and prepared methyl 2,4-bis(benzyloxymethoxy)-6-methylbenzoate **14b** and 2-benzyloxymethoxy-4-[^{13}C]methoxy-6-methylbenzoate **14c**** by standard procedures. The ^{13}C-labelled compound **14c*** was needed for the synthesis of both enantiomers of labelled torosachrysone for biosynthetic studies.[29]

Condensation of the BOM-protected orsellinic acid derivatives **14b** and **14c*** with 3-methoxycyclohexenone **(*R*)-9** afforded the pre-anthraquinones **(*R*)-15b** and **(*R*)-15c***, respectively, in moderate to good yields (Scheme 5). The BOM groups were smoothly removed by catalytic hydrogenation to give the



Scheme 5 *Reagents and conditions*: i, LDA, **14**, THF, −78 °C, then **(*R*)-9**; ii, H_2, Pd/C; iii, HF, CH_3CN; * = ^{13}C label.

dihydroanthracenones **(*R*)-16b** and **(*R*)-16c***, which were desilylated with HF in acetonitrile to yield optically pure (*R*)-atrochrysone **(*R*)-1** and (*R*)-torosachrysone **(*R*)-2***, respectively. The use of **(*S*)-9** instead of the (*R*)-enantiomer afforded **(*S*)-1** and **(*S*)-2***. Since the optical purity of the products depends on that of the starting enone **9**, the ee values of the (*S*)-compounds were in the range of 86%. The spectroscopic data of the synthetic pre-anthraquinones were identical with those of the natural products.

Our new method allows the synthesis of both enantiomers of pre-anthraquinones from a single starting material. It demonstrates the use of a regioselective Tebbe reaction and the potential of *N*-triflyl-4-(dimethylaminopyridinium) triflate for effecting the intramolecular acylation of enol ethers. Work on the synthesis of biologically active vismiones along these lines is in progress.

Experimental

General methods

The reactions were performed using oven-dried (130 °C) glassware under an argon atmosphere. CH_2Cl_2 was distilled from Sicapent® (Merck) and THF from potassium immediately prior to use. Light petroleum ether (boiling range 40–60 °C) and ethyl acetate were distilled through a glass column at atmospheric pressure. Melting points and boiling points are uncorrected. ^1H NMR and ^{13}C NMR were recorded on Bruker AMXR 300 and Varian VXR 400 S spectrometers in $CDCl_3$ as solvent with chemical shift values reported in ppm relative to residual chloroform ($\delta_H = 7.26$ or $\delta_C = 77.0$) as internal standard unless otherwise stated. Mass spectra were determined at an ionising voltage of 70 eV and the spectral data are tabulated as *m*/*z*. Optical rotations were measured on a Perkin-Elmer 241 polarimeter. Infrared spectra were recorded using Perkin-Elmer 1420 and Bruker IFS 45 spectrometers. CD- and UV-spectra were recorded on an S. A. Jobin Yvon CD-6-Dichrograph. Elemental analysis were performed at the Microanalytical Laboratory of the Department of Chemistry, LMU München. Unless otherwise noted, flash chromatography was carried out on silica gel (Merck Kieselgel 60 F_{254}, particle size 0.040–0.063 mm). TLC was performed on silica gel 60 F_{254} (Merck).

The known **4**,[30] **10**[31] and methyl 2,4-dihydroxy-6-methylbenzoate[32] were prepared by published procedures. (*R*)- and (*S*)-1-(1-naphthyl)ethanol (>98% ee) were obtained as described by Klibanov[33] or purchased from Fluka. Compound **14a** was purchased from Lancaster, pig liver esterase (EC 3.1.1.1) from Sigma.

(*S*)-3-Hydroxy-3-methylpentanedioic acid monomethyl ester 5

To a solution of dimethyl 3-hydroxy-3-methylpentanedioate (**4**) (2.50 g, 13.1 mmol) in 1 M phosphate buffer (20 cm³, pH 8) was added 1 mg of pig liver esterase (PLE, 1500 U). The pH was kept within the range 7.5–8.0 by addition of aqueous 1 M NaOH. The mixture was incubated for 24 h at 25 °C, after which additional diester **4** (2.50 g) and PLE (1 mg) were added. This was repeated for up to a total of 150 g (78.8 mmol) of diester **4**. The reaction mixture was stirred for an additional 2 d, after which the pH was adjusted to 8.5 and the unreacted starting material extracted with ethyl acetate (50 cm³). The aqueous phase was adjusted to pH 2 and saturated with NaCl prior to extraction with ethyl acetate (3 × 50 cm³). The combined organic phases were dried over $MgSO_4$ and concentrated to afford 12.7 g (92%) of enantiomerically pure **5** as a colourless oil; $[\alpha]_D^{20}$ +1.8 (*c* 1.0, $CHCl_3$); ν_{max} (NaCl)/cm^{-1} 3500, 3010, 2985, 1720, 1435, 1405, 1375, 1345; δ_H (400 MHz) 1.4 (3H, s), 2.65 (1H, d, *J* 15.8 Hz), 2.67 (1H, d, *J* 15.5 Hz), 2.73 (1H, d, *J* 15.8 Hz), 2.74 (1H, d, *J* 15.5 Hz), 3.73 (3H, s); δ_C (100.6 MHz) 27.2, 44.3, 44.9, 51.9, 69.8, 172.5, 175.6; *m*/*z* (EI) 177 [M^+ + H, 0.5%], 143 (5), 117 (5), 43 (100) (Found M^+ + H: 177.0757. Calc. for $C_7H_{13}O_5$: 177.0764).

tert-Butyldimethylsilyl methyl (*R*)-3-(*tert*-butyldimethylsilyloxy)-3-methylpentanedioate 6

2,6-Lutidine (9.10 cm³, 78 mmol) and *tert*-butyldimethylsilyl trifluoromethanesulfonate (15 cm³, 65.0 mmol) were added to a solution of **5** (4.60 g, 26 mmol) in CH_2Cl_2 (25 cm³) at −10 °C. The mixture was stirred for 2 h at rt, then hydrolysed with water and extracted with ethyl acetate (3×). The combined organic phases were washed with aqueous NH_4Cl and brine, dried ($MgSO_4$) and concentrated. Column chromatography (15:1 light petroleum ether–EtOAc) afforded the product (9.05 g, 86%) as a colourless oil; bp 130 °C/4 × 10^{-2} Torr (bulb-to-bulb distillation); $[\alpha]_D^{25}$ −0.9 (*c* 1.0, $CHCl_3$); ν_{max} (NaCl)/cm^{-1} 3490, 2870, 1730, 1710, 1465, 1355, 1340, 1250, 1200, 1150, 1100, 830; δ_H (400 MHz) 0.10 (6H, s), 0.26 (6H, s), 0.83 (9H, s), 0.93 (9H, s), 1.47 (3H, s), 2.68 (1H, d, *J* 15 Hz), 2.77 (2H, s), 2.85 (1H, d, *J* 15 Hz), 3.64 (3H, s); δ_C (100.6 MHz) −4.8, −4.7, −2.2, −2.1, 17.6, 18.0, 25.6, 25.7, 28.5, 45.9, 48.0, 51.2, 73.1, 171.2, 171.3.

Preparation of the Tebbe reagent

A solution of trimethylaluminium (48 mmol) in toluene (2 M, 24 cm³) was added to a stirred solution of dicyclopentadienyltitanium dichloride (5.98 g, 24 mmol) over 1 h. After the mixture had been stirred for 72 h at rt, another portion of the $AlMe_3$ solution (9.6 cm³) was added dropwise. After stirring for an additional 48 h the solution was ready for use in the subsequent steps. The Tebbe reagent is stable for 2 months under argon.

tert-Butyldimethylsilyl (*R*)-3-(*tert*-butyldimethylsilyloxy)-5-methoxy-3-methylhex-5-enoate 7

The Tebbe solution (20 cm³, 7 mmol) was slowly added at −78 °C to a solution of diester **6** (2.02 g, 5.00 mmol) in THF (10 cm³). The solution was warmed to rt and stirred for 3 h. The mixture was quenched with 2 M NaOH (10 cm³), diluted with diethyl ether (40 cm³) and stirred for 12 h at rt. After filtration through Celite, the residue was rinsed with diethyl ether. The filtrate was washed with aqueous $NaHCO_3$ and brine, dried (Na_2SO_4) and evaporated. The residue was chromatographed (15:1 light petroleum ether-EtOAc) to yield **7** (1.23 g, 61%) as a colourless oil; bp 130 °C/7 × 10^{-2} Torr (bulb-to-bulb distillation); $[\alpha]_D^{20}$ −2.4 (*c* 1.0, $CHCl_3$); ν_{max} (NaCl)/cm^{-1} 2940, 2920, 2850, 1710, 1645, 1465, 1455, 1245, 1190, 1155, 1100, 830; δ_H (400 MHz) 0.06 (6H, s), 0.23 (3H, s), 0.24 (3H, s), 0.82 (9H, s), 0.91 (9H, s), 1.37 (3H, s), 2.38 (1H, d, *J* 13 Hz), 2.53 (2H, s), 2.56 (1H, d, *J* 13 Hz), 3.45 (3H, s), 3.93 (2H, s); δ_C (75.5 MHz) −4.8, −2.0, 17.6, 18.2, 25.7, 25.9, 28.2, 47.9, 48.5, 54.5, 74.1,

84.3, 161.3, 171.6; *m/z* (EI) 402 [M^+, 0.1%], 401 [$M^+ - H$, 0.5%], 387 (0.5), 273 (2), 213 (5), 147 (28), 73 (100) (Found M^+: 402.2622. Calc. for $C_{20}H_{42}O_4Si_2$: 402.2650).

(*R*)-5-(*tert*-Butyldimethylsilyloxy)-3-methoxy-5-methylcyclohex-2-en-1-one (*R*)-9

A solution of enol ether **7** (700 mg, 1.72 mmol) in THF (3.5 cm^3) was treated with K_2CO_3 (340 mg, dissolved in 13.5 cm^3 1:3 water–methanol). After stirring for 2 h at rt, the solvent was removed *in vacuo* and the remaining salt **(*R*)-8** dried at 0.1 mbar for 1 h.

The suspension, prepared by slowly adding trifluoromethanesulfonic anhydride (1.7 cm^3, 10 mmol) to a solution of DMAP (2.40 g, 20.0 mmol) in dry CH_2Cl_2 (80 cm^3) at −20 °C under argon, was transferred *via* a double-tipped needle into a second flask containing **(*R*)-8** at −20 °C. After stirring for 2 h, the suspension was allowed to warm to rt, and stirring was continued for 24 h. The mixture was poured into aqueous $NaHCO_3$, the organic phase dried (Na_2SO_4) and concentrated. The residue was purified by column chromatography (2:1 light petroleum ether–EtOAc) yielding **(*R*)-9** (380 mg, 81%) as a colourless oil; bp 75 °C/2 × 10^{-3} Torr (Found: C, 62.55, H 9.78; Calc. for $C_{14}H_{26}O_3Si$: C, 62.18, H, 9.69%); R_f 0.14 (3:1 light petroleum–EtOAc); $[a]_D^{25}$ −38.7 (*c* 1.0, $CHCl_3$); λ_{max}/nm (MeOH) 224 (E_{rel} 0.65), 251 (0.8); CD λ/nm (MeOH): 256 ($\Delta\varepsilon_{max}$ −1.26), 295 (0.18); ν_{max} (NaCl film)/cm^{-1} 2950, 2920, 2850, 1650, 1605, 1370, 1250, 1220, 1135, 1110, 1025, 835; δ_H (400 MHz) 0.01 (3H, s), 0.02 (3H, s), 0.73 (9H, s), 1.32 (3H, s), 2.33 (1H, d, *J* 16 Hz), 2.47 (1H, d, *J* 16 Hz), 2.47 (1H, d, *J* 17 Hz), 2.49 (1H, d, *J* 17 Hz), 3.63 (3H, s), 5.33 (1H, s); δ_C (100.6 MHz) −2.5, −2.4, 17.9, 25.6, 29.2, 44.0, 51.9, 55.8, 73.4, 101.4, 175.8, 198.1; *m/z* (EI) 269 [$M^+ - H$, 0.3%], 255 (5), 215 (3), 214 (12), 213 (100), 195 (7), 181 (42), 171 (10), 139 (10), 89 (12) (Found $M^+ - H$: 269.1573. Calc. for $C_{14}H_{25}O_3Si$: 269.1587).

Methyl (*R*)-1-(1-naphthyl)ethyl (*S*)-3-hydroxy-3-methylpentanedioate (3*S*,1′*R*)-11

To a solution of anhydride **10** (1.54 g, 10.7 mmol) and (*R*)-1-(1-naphthyl)ethanol (2.00 g, 11.6 mmol) in dry acetone–CH_2Cl_2 1:1 (30 cm^3) at −60 °C was added dropwise with stirring a solution of DMAP (1.42 g, 11.6 mmol) in CH_2Cl_2 (10 cm^3). The suspension was kept for 5 d at this temperature.[26] After warming to −40 °C, methanol (1.80 cm^3, 44.5 mmol) and DCC (2.40 g, 11.6 mmol) in CH_2Cl_2 (10 cm^3) were added, and the solution was stirred for 2 h at −40 °C and for 24 h at rt. CH_2Cl_2 (10 cm^3) was added and the mixture filtered. The filtrate was dried (Na_2SO_4) and concentrated and the residue purified by column chromatography (3:1 light petroleum ether–EtOAc) to yield **(3*S*,1′*R*)-11** (2.65 g, 75%) as a colourless oil [14:1 mixture of diastereomers by ^1H NMR spectroscopic analysis of the methyl ester signals, δ 3.67 (major), δ 3.64 (minor)] (Found: C, 69.3; H, 6.6. Calc. for $C_{19}H_{22}O_5$: C, 69.1; H, 6.7%); $[a]_D^{25}$ +15.4 (*c* 4.0, $CHCl_3$); ν_{max} (KBr)/cm^{-1} 2981, 1735, 1598, 1512, 1439, 1349, 1199, 1069, 1044; δ_H (300 MHz) 1.35 (3H, s), 1.73 (3H, d, *J* 6.5 Hz), 2.64–2.84 (4H, m), 3.67 (3H, s), 4.05 (1H, s), 6.69 (1H, q, *J* 6.5 Hz), 7.44–7.58 (3H, m), 7.59 (1H, d, *J* 7.0 Hz), 7.81 (1H, d, *J* 8.3 Hz), 7.88 (1H, d, *J* 8.5 Hz), 8.07 (1H, d, *J* 8.3 Hz); δ_C (75.5 MHz) 21.7, 27.3, 44.8, 45.0, 51.7, 69.7, 69.9, 122.9, 123.2, 125.3, 125.7, 126.4, 128.6, 128.9, 130.1, 133.8, 137.0, 171.3, 172.1; *m/z* (EI) 330 [M^+, 22%], 170 (15), 155 (100) (Found M^+: 330.1501. Calc. for $C_{19}H_{22}O_5$: 330.1467).

Methyl (*S*)-1-(1-naphthyl)ethyl (*R*)-3-hydroxy-3-methylpentanedioate (3*R*,1′*S*)-11

The above procedure was repeated with (*S*)-1-(1-naphthyl)-ethanol yielding **(3*R*,1′*S*)-11** as a colourless oil; $[a]_D^{25}$ −15.0 (*c* 4.0, $CHCl_3$); its spectral characteristics were identical with those of the enantiomer.

Methyl (*R*)-1-(1-naphthyl)ethyl (*S*)-3-(*tert*-butyldimethylsilyloxy)-3-methylpentanedioate 12

To a solution of **(3*S*,1′*R*)-11** (202 mg, 0.61 mmol) in CH_2Cl_2 (20 cm^3) were added 2,6-lutidine (215 μl, 1.84 mmol) and *tert*-butyldimethylsilyl trifluoromethanesulfonate (225 μl, 0.98 mmol) at −20 °C. The mixture was stirred for 2 h at rt, then hydrolysed with water and extracted with ethyl acetate (2×). The combined organic phases were washed with saturated aqueous $NaHCO_3$, aqueous NH_4Cl and brine, dried (Na_2SO_4) and concentrated. Column chromatography (10:1 light petroleum ether–EtOAc) afforded the product (216 mg, 80%) as a colourless oil (Found: C, 67.6; H, 8.1. Calc. for $C_{22}H_{30}O_5Si$: C, 67.5; H, 8.2%); R_f 0.52 (3:1 light petroleum–EtOAc); $[a]_D^{25}$ +15.5 (*c* 1.1, MeOH); ν_{max} (KBr)/cm^{-1} 2954, 2931, 2857, 1739, 1600, 1512, 1473, 1464, 1376, 1345, 1254, 1104; δ_H (300 MHz) 0.08 (6H, s), 0.76 (9H, s), 1.47 (3H, s), 1.70 (3H, d, *J* 6.6 Hz), 2.65–2.93 (4H, m), 3.63 (3H, s), 6.65 (1H, q, *J* 6.6 Hz), 7.43–7.60 (4H, m), 7.79 (1H, d, *J* 8.3 Hz), 7.87 (1H, d, *J* 7.6 Hz), 8.07 (1H, d, *J* 8.1 Hz); δ_C (75.5 MHz) −2.2, 17.9, 21.8, 25.5, 28.4, 46.2, 46.6, 51.2, 69.3, 73.1, 123.1, 123.2, 125.3, 125.6, 126.2, 128.3, 128.9, 130.2, 133.8, 137.4, 170.0, 171.2; *m/z* (CI) 445 [$M^+ + H$, 5%], 391 (2), 291 (21), 233 (5), 197 (6), 155 (100).

(*R*)-1-(1-Naphthyl)ethyl (*S*)-3-(*tert*-butyldimethylsilyloxy)-5-methoxy-3-methylhex-5-enoate 13

The Tebbe reagent solution (7.00 cm^3, 2.45 mmol) was slowly added at −50 °C to a solution of diester **12** (683 mg, 1.54 mmol) in THF (25 cm^3). The mixture was then warmed to −30 °C and stirred for 3 h. After the addition of 2 M NaOH (3 cm^3, gas evolution!) and dilution with diethyl ether (14 cm^3), the mixture was stirred for 12 h at rt. After filtration through Celite, the residue was rinsed with diethyl ether. The combined filtrates were washed with aqueous $NaHCO_3$ and brine, dried (Na_2SO_4) and evaporated *in vacuo*. The residue was chromatographed (10:1 light petroleum ether–EtOAc) to yield **13** (450 mg, 66%) as a colourless oil (Found: C, 70.7, H, 8.5; Calc. for $C_{26}H_{38}O_4Si$: C, 70.6, H, 8.6%); R_f 0.39 (10:1 light petroleum ether–EtOAc); $[a]_D^{25}$ +10.1 (*c* 1.7, MeOH); ν_{max} (KBr)/cm^{-1} 3051, 2953, 2930, 2855, 1737, 1655, 1599, 1253, 1155, 1066, 836, 800, 776; δ_H (300 MHz) 0.06 (3H, s), 0.09 (3H, s), 0.82 (9H, s), 1.42 (3H, s), 1.71 (3H, d, *J* 6.5 Hz), 2.39–2.82 (4H, m), 3.42 (3H, s), 3.92 (2H, s), 6.66 (1H, q, *J* 6.5 Hz), 7.44–7.63 (4H, m), 7.79 (1H, d, *J* 8.1 Hz), 7.86 (1H, d, *J* 7.8 Hz), 8.11 (1H, d, *J* 8.4 Hz); δ_C (75.5 MHz) −2.1, −2.0, 18.1, 21.9, 25.8, 28.0, 47.0, 48.2, 54.5, 69.1, 74.2, 84.3, 123.3, 123.4, 125.3, 125.6, 126.2, 128.3, 128.8, 130.3, 133.8, 137.7, 161.0, 170.3.

(*S*)-5-(*tert*-Butyldimethylsilyloxy)-3-methoxy-5-methylcyclohex-2-en-1-one (*S*)-9

A solution of enol ether **13** (189 mg, 0.43 mmol) in 1 M ethanolic KOH (1.00 cm^3) was stirred for 28 h at rt. The solvent was carefully removed *in vacuo* and the residual **(*S*)-8** dried at 0.1 mbar for 3 h.

Trifluoromethanesulfonic anhydride (600 μl, 3.66 mmol) was slowly added to a solution of DMAP (600 mg, 4.91 mmol) in dry CH_2Cl_2 (100 cm^3) at −20 °C under argon. The suspension was transferred *via* a double-tipped needle into a second flask containing the carboxylate **(*S*)-8** at −50 °C. After stirring for 2 h, the suspension was allowed to warm to rt and poured into aqueous $NaHCO_3$. Work-up as described for the (*R*)-compound afforded **(*S*)-9** (48 mg, 41%) as a colourless oil; $[a]_D^{25}$ +40.2 (*c* 1.0, $CHCl_3$); CD λ/nm (MeOH) 256 ($\Delta\varepsilon_{max}$ 1.26), 295 (−0.17); all other spectral characteristics were identical with those of the enantiomeric material **(*R*)-9**.

Methyl 2,4-bis(benzyloxymethoxy)-6-methylbenzoate 14b

Methanol (1.50 cm^3) and sodium methoxide (81 mg, 1.50 mmol) were added to methyl 2-hydroxy-4-[^{13}C]methoxy-6-

methylbenzoate (118 mg, 0.60 mmol), and the mixture was concentrated *in vacuo*. The residue was suspended in dry THF (5 cm^3), treated with triethylamine (600 µl, 4 mmol) and benzyl chloromethyl ether (400 µl, 2.40 mmol) and stirred for 12 h at rt. The reaction mixture was washed with aqueous $NaHCO_3$ and brine, dried (Na_2SO_4) and the solvent removed. Purification by column chromatography (5:1 light petroleum ether–EtOAc) yielded **14b** (338 mg, 80%) as a colourless oil; δ_H (400 MHz) 2.29 (3H, s), 3.90 (3H, s), 4.69 (2H, s), 4.71 (2H, s), 5.25 (2H, s), 5.26 (2H, s), 6.60 (1H, d, *J* 2.3 Hz), 6.80 (1H, d, *J* 2.3 Hz), 7.28–7.36 (10H, m); δ_C (100.6 MHz) 19.8, 52.1, 70.0, 70.1, 92.1, 92.6, 101.4, 111.0, 127.9, 127.9, 128.0, 128.1, 128.4, 128.5, 137.1, 137.1, 138.1, 155.5, 158.8, 168.5; *m*/*z* (EI) 422 [M^+, 4%], 392 (10), 362 (5), 181 (20), 91 (100) (Found M^+: 422.1731. Calc. for $C_{25}H_{26}O_6$: 422.1728).

Methyl 2-hydroxy-4-[^{13}C]methoxy-6-methylbenzoate [34]

To a suspension of K_2CO_3 (453 mg, 3.28 mmol) in dry acetone (3 cm^3), a solution of methyl 2,4-dihydroxy-6-methylbenzoate (300 mg, 1.65 mmol) and iodo[^{13}C]methane (102 µl, 1.65 mmol) in acetone (1.5 cm^3) was added at rt. After heating the reaction mixture for 3 h at reflux, the precipitate was dissolved in H_2O. The mixture was concentrated *in vacuo* and extracted with ethyl acetate (3×). The combined organic layers were washed with brine (2×), dried (Na_2SO_4) and the solvent removed *in vacuo*. The crude material was purified by column chromatography (8:1 light petroleum ether–EtOAc) to yield methyl 2-hydroxy-4-[^{13}C]methoxy-6-methylbenzoate (295 mg, 91%) as colourless needles, mp 66 °C; R_f 0.42 (5:1 light petroleum ether–EtOAc); ν_{max} (KBr)/cm^{-1} 3046, 2982, 2950, 1649, 1617, 1578, 1456, 1295, 1269, 1218, 1198, 1155, 1041, 816; δ_H (300 MHz) 2.49 (3H, s), 3.79 (3H, d, *J* 144 Hz), 3.92 (3H, s), 6.28 (1H, dd, *J* 2.6, 0.8 Hz), 6.32 (1H, d, *J* 2.6 Hz), 11.78 (1H, s); δ_C (75.5 MHz, $CDCl_3$) 24.0, 51.5, 55.0 [^{13}C], 98.5 (d, *J* 4.7), 105.0, 110.8 (d, *J* 3.5), 142.9, 163.7 (d, *J* 2.0), 165.4, 171.9; *m*/*z* (EI) 197 [M^+, 39%], 165 (100.0), 137 (35), 121 (12) (Found M^+: 197.0777. Calc. for $C_9{}^{13}C_1H_{12}O_4$: 197.0768).

Methyl 2-benzyloxymethoxy-4-[^{13}C]methoxy-6-methylbenzoate 14c*

To methyl 2-hydroxy-4-[^{13}C]methoxy-6-methylbenzoate (118 mg, 0.60 mmol) were added methanol (1.5 cm^3) and sodium methoxide (81 mg, 1.50 mmol), and the mixture was concentrated *in vacuo*. The residue was suspended in dry THF (5 cm^3), treated with triethylamine (120 µl, 0.80 mmol) and benzyl chloromethyl ether (100 µl, 0.66 mmol) and stirred for 12 h at rt. The reaction mixture was washed with aqueous $NaHCO_3$ and brine, dried (Na_2SO_4) and the solvent removed. Purification by column chromatography (5:1 light petroleum ether–EtOAc) yielded **14c*** (162 mg, 85%) as a colourless oil; mp 19 °C; R_f 0.32 (5:1 light petroleum ether–EtOAc); ν_{max} (KBr)/cm^{-1} 3065, 3032, 2951, 1728, 1607, 1270, 1189, 1155, 1059, 740; δ_H (300 MHz) 2.29 (3H, s), 3.36 (3H, d, *J* 144 Hz), 3.88 (3H, s), 4.70 (2H, s), 5.25 (2H, s), 6.39 (1H, d, *J* 2.2 Hz), 6.62 (1H, d, *J* 2.2 Hz), 7.29–7.33 (5H, m); δ_C (75.5 MHz) 19.9, 51.9, 55.4 [^{13}C], 70.0, 92.7, 99.3 (d, *J* 4 Hz), 108.9 (d, *J* 4 Hz), 117.5, 127.9, 128.1, 128.4, 137.1, 138.1, 155.8, 161.2, 168.5; *m*/*z* (EI) 317 [M^+, 5%], 287 (26), 255 (11), 228 (7), 165 (10), 91 (100) (Found M^+: 317.1347. Calc. for $C_{17}{}^{13}C_1H_{20}O_5$: 317.1344).

General procedure for the condensation of the orsellinates 14 with cyclohexenone 9

To a solution of diisopropylamine (220 µl, 1.72 mmol) in dry THF (30 cm^3) was added 2.5 M *n*-butyllithium in hexane (600 µl, 1.50 mmol) at 0 °C. The mixture was stirred for 10 min at 0 °C and then for 10 min at −78 °C. Within 30 s the orsellinate **14** (500 µmol) dissolved in dry THF (3 cm^3) was added, which produced a deep red solution. After 10 min of stirring, cyclohexenone **9** (219 mg, 800 µmol) was added. Stirring was continued at −70 °C for 15 min and the mixture allowed to warm to rt within 30 min. After hydrolysis with saturated aqueous NH_4Cl (200 cm^3), the organic layer was extracted with diethyl ether (3 × 50 cm^3). The combined organic phases were washed with water and brine, and dried over $MgSO_4$. The solvent was removed and the residue purified by chromatography on silica gel (2:1 light petroleum ether–EtOAc).

(*R*)-3-(*tert*-Butyldimethylsilyloxy)-9-hydroxy-6,8-dimethoxy-3-methyl-3,4-dihydroanthracen-1(2*H*)-one 15a. From 2,4-dimethoxy-6-methylbenzoate **14a** and **(*R*)-9** (>99% ee) in 25% yield, light yellow oil; λ_{max}/nm (MeOH) 227 (E_{rel} 0.55), 268 (0.8), 313 (0.15), 388 (0.27); CD λ/nm (MeOH) 213 ($\Delta\varepsilon_{max}$ 0.9), 231 (−1.5), 254 (1.6), 280 (−0.32), 295 (0.45), 309 (0.35), 320 (0.75), 385 (−1.05); δ_H (400 MHz) 0.01 (3H, s), 0.06 (3H, s), 0.62 (9H, s), 1.41 (3H, s), 2.73 (1H, d, *J* 16.8 Hz), 2.83 (1H, dd, *J* 16.8, 1.7 Hz), 2.98 (1H, d, *J* 16.1 Hz), 3.04 (1H, d, *J* 16.1 Hz), 3.90 (3H, s), 3.98 (3H, s), 6.42 (1H, d, *J* 2.2 Hz), 6.55 (1H, d, *J* 2.2 Hz), 6.82 (1H, s), 15.04 (1H, s); *m*/*z* (EI) 416 [M^+, 27%], 359 (100), 341 (15), 317 (34), 285 (15) (Found M^+: 416.2019, Calc. for $C_{23}H_{32}O_5Si$: 416.2017).

(*R*)-6,8-Bis(benzyloxymethoxy)-3-(*tert*-butyldimethylsilyloxy)-9-hydroxy-3-methyl-3,4-dihydroanthracen-1(2*H*)-one (*R*)-15b. From **14b** and **(*R*)-9** (>99% ee) in 50% yield, yellow oil; $[\alpha]_D^{25}$ −2.4 (*c* 1.5, $CHCl_3$); CD λ/nm (MeOH) 215 ($\Delta\varepsilon_{max}$ 2.28), 231 (−2.1), 267 (2.7), 282 (−0.23), 293 (0.43), 305 (0.25), 320 (0.6), 382 (−1.29); ν_{max} (KBr)/cm^{-1} 2955, 2929, 2860, 1624, 1583, 1381, 1171, 1061, 1023, 836; δ_H (400 MHz) 0.02 (3H, s), 0.09 (3H, s), 0.67 (9H, s), 1.43 (3H, s), 2.74 (1H, d, *J* 16.9 Hz), 2.84 (1H, dd, *J* 16.9, 1.7 Hz), 2.98 (1H, d, *J* 16.0 Hz), 3.05 (1H, d, *J* 16.0 Hz), 4.75 (2H, s), 4.88 (2H, s), 5.37 (2H, s), 5.38 (2H, s), 6.86 (1H, s), 6.87 (1H, d, *J* 2.3 Hz), 6.94 (1H, d, *J* 2.3 Hz), 7.28–7.41 (10H, m), 14.97 (1H, s); δ_C (100.6 MHz) −2.4, −2.2, 17.9, 25.5, 28.9, 44.6, 53.2, 70.3, 70.4, 73.5, 92.1, 93.6, 103.5, 104.0, 110.3, 117.1, 127.8, 128.0, 128.1, 128.1, 128.2, 128.4, 128.5, 137.0, 137.2, 137.3, 142.0, 158.3, 159.1, 165.2, 203.0; *m*/*z* (EI) 628 [M^+, 32%], 598 (28), 541 (30), 511 (26), 508 (19), 451 (16), 421 (33), 91 (100) (Found M^+: 628.2856. Calc. for $C_{37}H_{44}O_7Si$: 628.2911).

(*S*)-6,8-Bis(benzyloxymethoxy)-3-(*tert*-butyldimethylsilyloxy)-9-hydroxy-3-methyl-3,4-dihydroanthracen-1(2*H*)-one (*S*)-15b. From **14b** and **(*S*)-9** (86% ee) in 35% yield, yellow oil; $[\alpha]_D^{25}$ +2.2 (*c* 1.4, $CHCl_3$); CD λ/nm (MeOH) 215 ($\Delta\varepsilon_{max}$ −2.28), 231 (2.1), 267 (−2.7), 282 (2.3), 293 (−0.43), 305 (−0.25), 320 (−0.59), 382 (1.29); all other spectral data were identical with those of the enantiomer **(*R*)-15b**.

(*R*)-8-Benzyloxymethoxy-3-(*tert*-butyldimethylsilyloxy)-9-hydroxy-6-[^{13}C]methoxy-3-methyl-3,4-dihydroanthracen-1(2*H*)-one (*R*)-15c*. From **14c*** and **(*R*)-9** (>99% ee) in 36% yield, light yellow oil; $[\alpha]_D^{25}$ −4.0 (*c* 1.7, $CHCl_3$); λ_{max}/nm (MeOH) 225 (E_{rel} 0.46), 268 (0.68), 313 (0.12), 383 (0.25); CD λ/nm (MeOH) 203 ($\Delta\varepsilon_{max}$ −3.19), 216 (0.98), 230 (−1.90), 261 (2.2), 281 (−0.6), 320 (0.82), 385 (−1.05); ν_{max} (KBr)/cm^{-1} 2956, 2930, 2900, 2860, 1616, 1583, 1375, 1165, 1064, 836; δ_H (400 MHz) 0.01 (3H, s), 0.08 (3H, s), 0.64 (9H, s), 1.44 (3H, s), 2.74 (1H, d, *J* 16.9 Hz), 2.84 (1H, dd, *J* 16.9, 1.7 Hz), 2.99 (1H, d, *J* 16.0 Hz), 3.05 (1H, d, *J* 16.0 Hz), 3.87 (3H, d, *J* 144.3 Hz), 4.85 (2H, s), 5.45 (2H, s), 6.63 (1H, d, *J* 2.5 Hz), 6.75 (1H, d, *J* 2.5 Hz), 6.83 (1H, s), 7.28–7.39 (5H, m), 14.94 (1H, s); δ_C (100.6 MHz) −2.4, −2.2, 17.9, 25.5, 28.9, 44.7, 53.2, 55.4 [^{13}C], 70.4, 73.4, 93.4, 100.7 (d, *J* 4.4 Hz), 102.8 (d, *J* 3.8 Hz), 110.1, 116.8, 127.8, 128.1, 128.4, 137.2, 137.4, 141.7, 158.2, 161.6 (d, *J* 2.4 Hz), 165.2, 202.8; *m*/*z* (EI) 523 [M^+, 23%], 493 (38), 436 (100), 418 (12), 394 (25), 346 (35), 330 (32) (Found M^+: 523.2486. Calc. for $C_{29}{}^{13}C_1H_{38}O_6Si$: 523.2471).

(*S*)-8-Benzyloxymethoxy-3-(*tert*-butyldimethylsilyloxy)-9-hydroxy-6-[^{13}C]methoxy-3-methyl-3,4-dihydroanthracen-1(2*H*)-one (*S*)-15c*. From **14c*** and **(*S*)-9** (86% ee) in 46% yield, light yellow oil; $[a]_D^{25}$ +3.9 (*c* 1.7, $CHCl_3$); CD λ/nm (MeOH) 203 ($\Delta\varepsilon_{max}$ 3.20), 216 (−1.0), 230 (1.9), 261 (−2.2), 281 (0.6), 320 (−0.8), 385 (1.0); all other spectral data were identical with those of the enantiomer **(*R*)-15c***.

General procedure for the deprotection of the BOM derivatives

A flask containing a stirred solution of the BOM-protected dihydroanthracenone **15** (50.0 μmol) in MeOH (10 cm^3) was degassed (4×) and refilled with argon. Then, 10% palladium on charcoal (4.5 mg) was added and the atmosphere replaced with hydrogen gas (4×). The solution was stirred for 12 h at 25 °C in the dark. After replacing the hydrogen atmosphere with argon, the suspension was passed through a short plug of Celite, washed with MeOH, and concentrated *in vacuo*. Purification was performed by column chromatography on Sephadex LH 20 (Pharmacia) with methanol as eluent.

(*R*)-3-(*tert*-Butyldimethylsilyloxy)-6,8,9-trihydroxy-3-methyl-3,4-dihydroanthracen-1(2*H*)-one (*R*)-16b. From **(*R*)-15b** in 51% yield, yellow crystals; mp 164–165 °C; $[a]_D^{25}$ −3.5 (*c* 0.5, $CHCl_3$); δ_H (300 MHz) 0.00 (3H, s), 0.07 (3H, s), 0.64 (9H, s), 1.43 (3H, s), 2.73 (1H, d, *J* 17.0 Hz), 2.85 (1H, dd, *J* 17.0, 1.5 Hz), 2.96 (1H, d, *J* 15.8 Hz), 3.02 (1H, d, *J* 15.8 Hz), 5.43 (1H, br s), 6.41 (1H, d, *J* 2.2 Hz), 6.51 (1H, d, *J* 2.2 Hz), 6.77 (1H, s), 9.89 (1H, s), 16.08 (1H, s); *m*/*z* (EI) 388 [M$^+$, 25%], 332 (22), 331 (100), 313 (28), 298 (5), 289 (30), 256 (8) (Found M$^+$: 388.1673. Calc. for $C_{21}H_{28}O_5Si$: 388.1706).

(*S*)-3-(*tert*-Butyldimethylsilyloxy)-6,8,9-trihydroxy-3-methyl-3,4-dihydroanthracen-1(2*H*)-one (*S*)-16b. From **(*S*)-15b** in 51% yield, yellow crystals; mp 164–165 °C; $[a]_D^{25}$ +3.3 (*c* 0.6, $CHCl_3$); all other spectral characteristics were identical with those of the enantiomer **(*R*)-16b**.

(*R*)-3-(*tert*-Butyldimethylsilyloxy)-8,9-dihydroxy-6-[^{13}C]-methoxy-3-methyl-3,4-dihydroanthracen-1(2*H*)-one (*R*)-16c*. From **(*R*)-15c*** in 70% yield, light yellow crystals; mp 127 °C; $[a]_D^{20}$ −4.5 (*c* 2.2, $CHCl_3$); λ_{max}/nm (MeOH) 209 (log ε 0.80), 225 (1.42), 240 (0.74), 270 (2.47), 296 (0.26), 314 (0.42), 339 (0.19), 392 (0.65); ν_{max} (KBr)/cm^{-1} 2956, 2931, 2856, 1639, 1585, 1155, 1023, 839; δ_H (300 MHz) 0.00 (3H, s), 0.07 (3H, s), 0.64 (9H, s), 1.43 (3H, s), 2.72 (1H, d, *J* 17.0 Hz), 2.83 (1H, dd, *J* 17.0, 1.5 Hz), 2.96 (1H, d, *J* 15.7 Hz), 3.02 (1H, d, *J* 15.7 Hz), 3.87 (3H, d, *J* 144.4 Hz), 6.46 (1H, d, *J* 2.3 Hz), 6.52 (1H, d, *J* 2.3 Hz), 6.81 (1H, s), 9.79 (1H, s), 16.01 (1H, s); δ_C (100.6 MHz) −2.3, −2.2, 17.9, 25.5, 29.1, 44.3, 52.4, 55.5 [^{13}C], 73.7, 99.6 (d, *J* 4.9 Hz), 100.9 (d, *J* 3.9 Hz), 108.0, 108.6, 117.3, 136.5, 141.0, 159.7, 163.3 (d, *J* 2.0 Hz), 165.5, 202.8; *m*/*z* (EI) 403 [M$^+$, 32%], 347 (23), 346 (100), 328 (25), 304 (30) (Found M$^+$: 403.1876. Calc. for $C_{21}{}^{13}C_1H_{30}O_5Si$: 403.1896).

(*S*)-3-(*tert*-Butyldimethylsilyloxy)-8,9-dihydroxy-6-[^{13}C]-methoxy-3-methyl-3,4-dihydroanthracen-1(2*H*)-one (*S*)-16c*. From **(*S*)-15c*** in 82% yield, light yellow oil; mp 127 °C; $[a]_D^{20}$ +4.3 (*c* 2.2, $CHCl_3$); CD λ/nm (MeOH) 214 ($\Delta\varepsilon_{max}$ −0.1), 231 (0.15), 261 (−0.39), 283 (−0.03), 300 (−0.12), 310 (−0.1), 321 (−0.15), 393 (0.21); all other spectral data were identical with those of the enantiomer **(*R*)-16c***.

General procedure for the deprotection of the TBDMS derivatives

A 10 cm^3 flask charged with a solution of silyl ether **15a** or **16** (50.0 μmol) in acetonitrile (3 cm^3) was purged with argon. Then, 4 drops of a 40% aqueous HF solution were added, and the mixture was stirred for 2–3 h at 50 °C in the dark. The solution was poured in a separating funnel containing a mixture of aqueous $CaCl_2$ and ethyl acetate. The organic layer was washed with water (2×), dried ($MgSO_4$) and the solvent removed *in vacuo*. Purification of the residue by column chromatography on Sephadex LH 20 (Pharmacia) with methanol as eluent yielded the deprotected pre-anthraquinones.

(*R*)-Torosachrysone 8-methyl ether (*R*)-3. From **15a** in 70% yield, yellow crystals; λ_{max}/nm (MeOH) 225 (E_{rel} 0.35), 269 (0.82), 320 (0.24), 332 (0.27), 365 (0.34); CD λ/nm (MeOH) 213 ($\Delta\varepsilon_{max}$ −1.92), 231 (0.26), 239 (−0.32), 253 (0.56), 267 (−0.11), 278 (−1.08), 293 (0.57), 302 (0.35), 322 (1.36), 385 (−0.20); δ_H (400 MHz) 1.40 (3H, s), 2.79 (1H, d, *J* 17.5 Hz), 2.84 (1H, d, *J* 17.5 Hz), 3.02 (1H, d, *J* 17.0 Hz), 3.06 (1H, d, *J* 17.0 Hz), 3.88 (3H, s), 3.96 (3H, s), 6.41 (1H, d, *J* 2.0 Hz), 6.53 (1H, d, *J* 2.0 Hz), 6.85 (1H, s), 15.1 (1H, s); *m*/*z* (EI) 302 [M$^+$, 100%], 284 (10), 269 (20), 245 (17), 244 (37), 229 (10), 226 (15) (Found M$^+$: 302.1154. Calc. for $C_{17}H_{18}O_5$: 302.1110).

(*R*)-Atrochrysone (*R*)-1. From **(*R*)-16b** in 70% yield, yellow powder; λ_{max}/nm (MeOH) 225 (E_{rel} 0.56), 271 (0.8), 321 (0.14), 333 (0.13), 394 (0.24); CD λ/nm (MeOH) 251 ($\Delta\varepsilon_{max}$ 0.43), 254 (0.39), 258 (0.46), 264 (−0.29), 266 (−0.26), 276 (−1.68), 296 (0.89), 312 (0.53), 324 (0.75), 403 (−0.46); δ_H (400 MHz, $CDCl_3$ + [^{2}H$_6$]acetone) 1.35 (3H, s), 2.71 (1H, d, *J* 17.3 Hz), 2.76 (1H, d, *J* 17.3 Hz), 2.94 (2H, br s), 4.02 (1H, br s), 6.36 (1H, d, *J* 2.3 Hz), 6.46 (1H, d, *J* 2.3 Hz), 6.7 (1H, br s), 8.38 (1H, br s), 9.77 (1H, d, *J* 0.6 Hz), 16.2 (1H, d, *J* 0.6 Hz); *m*/*z* (EI) 274 [M$^+$, 100%], 256 (71), 232 (12), 216 (27), 213 (11), 190 (5) (Found M$^+$: 274.0834. Calc. for $C_{15}H_{14}O_5$: 274.0841).

(*S*)-Atrochrysone (*S*)-1. From **(*S*)-16b** in 70% yield, yellow powder; CD λ/nm (MeOH) 262 ($\Delta\varepsilon_{max}$ −0.57), 277 (0.75), 296 (−0.73), 310 (−0.56), 324 (−0.72), 395 (0.17); all other spectral characteristics were identical with those of the enantiomer **(*R*)-1**.

(*R*)-[*methoxy*-^{13}C]Torosachrysone (*R*)-2*. From **(*R*)-16c*** in 75% yield, yellow crystals; λ_{max}/nm (MeOH) 226 (E_{rel} 0.45), 271.5 (0.85), 316 (0.13), 394 (0.22); CD λ/nm (MeOH) 213 ($\Delta\varepsilon_{max}$ −1.55), 231 (0.19), 238 (−0.15), 259 (0.86), 278 (−0.43), 294 (0.92), 309 (0.72), 322 (1.18), 413 (−0.56); ν_{max} (KBr)/cm^{-1} 2967, 2933, 1638, 1586, 1391, 1346, 1155; δ_H (400 MHz) 1.45 (3H, s), 1.79 (1H, br s), 2.84 (2H, m), 3.04 (2H, m), 3.88 (3H, d, *J* 144.5 Hz), 6.48 (1H, d, *J* 2.2 Hz), 6.53 (1H, d, *J* 2.2 Hz), 6.86 (1H, br s), 9.79 (1H, s), 16.1 (1H, s); δ_C (100.6 MHz, [^{2}H$_6$]-acetone) 29.3, 43.6, 51.4, 55.8 [^{13}C], 70.8, 100.1, 101.3, 108.4, 109.4, 118.0, 138.2, 142.1, 160.4, 164.3, 166.3, 204.4; *m*/*z* (EI) 289 [M$^+$, 100%], 272 (9), 271 (49), 256 (5), 247 (13), 232 (15), 231 (25), 204 (7) (Found M$^+$: 289.1063. Calc. for $C_{15}{}^{13}C_1H_{16}O_5$: 289.1031).

(*S*)-[*methoxy*-^{13}C]Torosachrysone (*S*)-2*. From **(*S*)-16c*** in 75% yield, yellow crystals; mp 186 °C; $[a]_D^{20}$ +7.1 (*c* 1.5, dioxane); CD λ/nm (MeOH) 213 ($\Delta\varepsilon_{max}$ 1.55), 231 (−0.19), 238 (0.15), 259 (−0.86), 278 (0.43), 294 (−0.92), 309 (−0.72), 322 (−1.18), 413 (0.56); all other spectral characteristics were identical with those of the enantiomeric material **(*R*)-2***.

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