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TETRAHEDRON: *ASYMMETRY*

Asymmetric Diels–Alder addition of cyclopentadiene to chiral naphthoquinones

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Abstract

Diels–Alder reactions of 1,4-naphthoquinones bearing a chiral auxiliary at C-2, with cyclopentadiene under Lewis acid conditions afforded the corresponding Diels–Alder adducts. High levels of diastereomeric excess were obtained using (*R*)-pantolactone, (*S*)-*N*-methyl-2-hydroxysuccinimide and *trans*-2-phenylcyclohexanol as auxiliaries. Moderate asymmetric induction was achieved using Oppolzer's camphorsultam and (*R*)-(+)-4-benzyl-2-oxazolidinone as auxiliaries. X-Ray crystallographic analysis of the pantolactone adduct enabled determination of the stereochemistry of all adducts obtained.

1. Introduction

The Diels–Alder reaction is without doubt one of the cornerstones of organic chemistry. It is undisputedly one of the most attractive tools available to the synthetic chemist and tremendous effort has been focused on the search for regio- and stereoselective variants.[1] Methods for performing asymmetric Diels–Alder reactions involve the use of either a chiral diene,[2] a chiral dienophile[2] or a chiral catalyst,[2,3] although there are only a few cases in which these methods have been applied to 1,4-naphthoquinones.[4–7] In an earlier paper we report only moderate stereoinduction in cycloadditions of naphthoquinones to various dienes using a variety of chiral catalysts.[8] A large number of ligand–Lewis acid catalyst systems were screened without obtaining significant enantiomeric excesses for Diels–Alder adducts, hence we turned our attention to the use of a chiral auxiliary on the naphthoquinone itself.

Our interest in developing an asymmetric Diels–Alder reaction between naphthoquinones bearing an electron withdrawing group at C-2 (**1–5**) and cyclopentadiene, stems from the possibility of stereoselectively forming a cyclopentannulated product **16–25** *via* fragmentation of the C-4,4a bond[9] of

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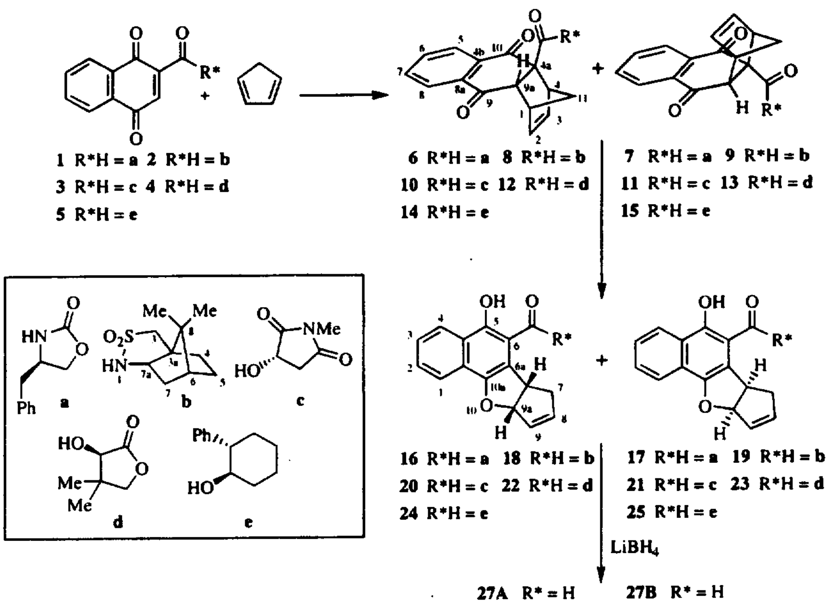
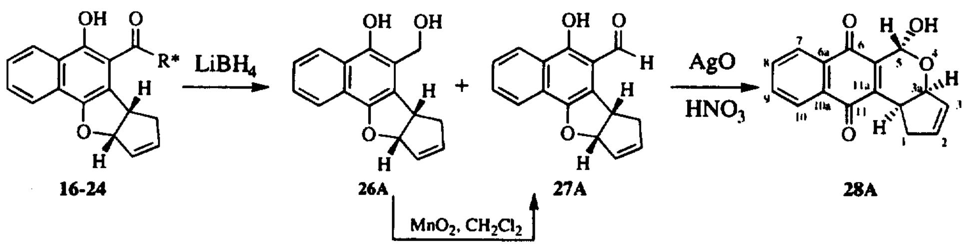
6–15 affording an electrophilic site that is then trapped by a hydroxyl group (Scheme 1). The cyclopentannulated compounds **16–25** can be further transformed into pyranonaphthoquinones **28** after removal of the chiral auxiliary followed by oxidative rearrangement (Scheme 2). Cyclopentannulated pyranonaphthoquinones **28** are closely related to the large family of pyranonaphthoquinone antibiotics which include the antifungal agents kalafungin[10,11] and frenolicin.[12,13]



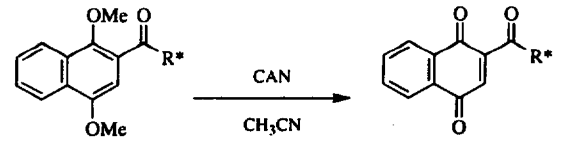
Scheme 1.



Scheme 2.

2. Results and discussion

The work reported herein examined the addition of cyclopentadiene to several 1,4-naphthoquinones bearing a chiral auxiliary at C-2. The various chiral auxiliaries were attached to the naphthoquinone moiety through an ester or amide linkage at C-2. The chiral quinones **1–5** were prepared by oxidation of the corresponding dimethoxynaphthalenes **29–33** (Scheme 3), which in turn were formed from 1,4-dimethoxy-2-naphthoic acid and the chiral auxiliary R*H (**a–e**) in high yield.



29 R*H = a 30 R*H = b
31 R*H = c 32 R*H = d
33 R*H = e

1 R*H = a 2 R*H = b
3 R*H = c 4 R*H = d
5 R*H = e

Scheme 3.

2.1. *Use of a chiral oxazolidinone*

Addition of cyclopentadiene to quinone **1** bearing oxazolidinone **a** as chiral auxiliary at −78°C in the presence of a variety of Lewis acids afforded adducts **6** (major) and **7** in high yield, which were separable by flash chromatography. The optimum diastereoselectivity was achieved using $ZnCl_2$ wherein **6** and **7** were obtained in 96% yield and in a ratio of 2.57:1 (Table 1).

Table 1
Effect of Lewis acid on reaction of **1** with cyclopentadiene†

Lewis Acid	Yield 6 and 7 (%)	Ratio 6:7	D.e. (%)
–	88	1:1.4	18
$Cu(OTf)_2$	74	1.1:1	4
$ZnCl_2$	**96**	**2.6:1**	**44**
$Ti(O^iPr)_4$	85	1.4:1	18
$Sn(OTf)_2$	complex mixture	–	–
$BF_3.OEt_2$	85	2.0:1	34

† Reactions carried out at −78 °C in dichloromethane using 100% Lewis acid.

2.2. *Use of a camphorsultam*

The next chiral auxiliary to be examined was the camphorsultam **b** which has been used effectively in asymmetric Diels–Alder reactions by Oppolzer.[2] Addition of cyclopentadiene to quinone **2**, at −78°C in the presence of a variety of Lewis acids, afforded a mixture of adducts **8** (major) and **9** which were separable by flash chromatography, together with an inseparable mixture of compounds **18** and **19** in some cases (Scheme 1). The optimum Diels–Alder reaction was achieved using $ZnCl_2$ wherein adducts **8** and **9** were obtained in 66% yield and in a ratio of 7.4:1 (Table 2). Adduct **8** could be readily fragmented to **18** using 1 equivalent of tin(IV) chloride in dichloromethane in quantitative yield (Scheme 1).

2.3. *Use of (S)-N-methyl-2-hydroxysuccinimide*

The *Helmchen ligands*[14] (**c** and **d**) were also examined for their ability to achieve asymmetric induction in the Diels–Alder reaction. These auxiliaries, which were attached *via* an ester rather than an amide linkage, could potentially be removed under milder conditions. Addition of cyclopentadiene to quinone **3**, at −78°C in the presence of $Cu(OTf)_2$, $ZnCl_2$ and $Sn(OTf)_2$, afforded inseparable mixtures of adducts **10** (major) and **11** in high yield. The optimum result was achieved using $ZnCl_2$ as the Lewis acid wherein

Table 2
Effect of Lewis acid on reaction of **2** with cyclopentadiene†

Lewis Acid	Yield 8 and 9 (%)	Yield 18 and 19 (%)	Ratio 8:9	D.e. (%)
–	81	0	1.3:1	14
$Cu(OTf)_2$	28	29	1:1.8	28
$ZnCl_2$	**66**	**0**	**7.4:1**	**76**
$Ti(O^iPr)_4$	88	0	1:1.6	22
$Sn(OTf)_2$	58	12	1.7:1	28
$BF_3.OEt_2$	50	8	1:1.1	4

† Reactions carried out at −78 °C in dichloromethane using 100% Lewis acid.

Table 3
Effect of Lewis acid on reaction of **3** with cyclopentadiene†

Lewis Acid	Yield 10 and 11 (%)	Yield 20 and 21 (%)	Ratio 10:11	D.e. (%)
–	45	0	1.2:1	10
$Cu(OTf)_2$	91	0	1.5:1	20
$ZnCl_2$	**87**	**0**	**4.3:1**	**62**
$Sn(OTf)_2$	83	0	1.6:1	22
$BF_3.OEt_2$	0	95	–	46

† Reactions carried out at −78 °C in dichloromethane using 100% Lewis acid.

adducts **10** and **11** were obtained in 87% yield and in a ratio of 4.3:1 (Table 3). Use of $BF_3\cdot Et_2O$ resulted in complete formation of the fragmented products **20** and **21**.

2.4. Use of (R)-pantolactone

In a similar manner, (*R*)-pantolactone[15] **d** was attached to the naphthoquinone moiety *via* an ester linkage. Addition of cyclopentadiene to quinone **4** at −78°C in the presence of a variety of Lewis acids afforded inseparable mixtures of adducts **12** and **13** (major) in high yield. The optimum result was achieved with $ZnCl_2$ wherein adducts **12** and **13** were obtained in 64% yield and in a ratio of 1:45 (96% d.e., Table 4). Adduct **13** was readily fragmented to **23** using 1 equivalent of tin(IV) chloride in dichloromethane in 65% yield (Scheme 1).

In contrast to all the other Diels–Alder adducts and the corresponding fragmented products which were oils, **13** was isolated as a solid. X-Ray crystallography was therefore employed to deduce the stereochemistry of adduct **13**. An ORTEP[16] depiction of **13** is given in Fig. 1. The pantolactone auxiliary shields the lower face of quinone **4** therefore cyclopentadiene adds to the less hindered top face in an *endo* fashion.

2.5. (1R,2S)-2-Phenyl-1-cyclohexanol

The final auxiliary to be examined was (1*R*,2*S*)-(−)-*trans*-2-phenyl-1-cyclohexanol **e**.[17–19] Addition of cyclopentadiene to quinone **5**, at −78°C in the presence of $ZnCl_2$, afforded a 35:1 inseparable mixture (94% d.e.) of adducts **15** (major) and **14** in 60% yield. Compound **15** was readily fragmented to **25**

Table 4
Effect of Lewis acid on reaction of **4** with cyclopentadiene†

Lewis Acid	Yield 12 and 13 (%)	Yield 22 and 23 (%)	Ratio 13:12	D.e. (%)
–	98	–	1.3:1	14
$Cu(OTf)_2$	53	19	5.0:1	67
$ZnCl_2$	**64**	**0**	**45.3:1**	**96**
$Ti(O^iPr)_4$	62	0	1:1.4	16
$TiCl_2(O^iPr)_2$	27	0	1.7:1	24
$Sn(OTf)_2$	60	0	3.2:1	52
$FeCl_3$	complex mixture		–	–
$MgCl_2$	59	0	2.3:1	40

† Reactions carried out at −78 °C in dichloromethane using 100% Lewis acid.

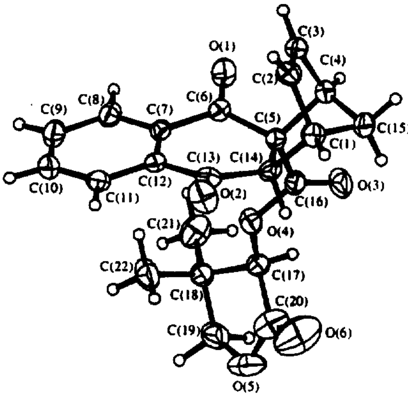


Fig. 1. Major isomer **13**

using 1 equivalent of tin(IV) chloride in dichloromethane in 98% yield (Scheme 1). As a comparison, the uncatalysed reaction afforded a higher yield of adducts **14** and **15** (81%) but lower asymmetric induction (13% d.e.).

2.6. Removal of chiral auxiliaries

In order to form analogues of naphthoquinone natural products it was necessary to examine the ease of removal of the chiral auxiliary. In general it was found that treatment of the fragmented Diels–Alder adducts with a reducing agent such as lithium borohydride effected removal of the auxiliary (Scheme 2).

4-Benzyl-2-oxazolidinone was removed to give enantiomerically pure aldehyde **27** in 63% yield over two steps from Diels-Alder adduct **6**. The camphorsultam was removed from **18** in 61% yield to again give enantiomerically pure **27**. The *Helmchen* ligands were also successfully removed with $LiBH_4$ in 43% and 63% yield for 2-hydroxy-*N*-methylsuccinimide and pantolactone respectively. In a single attempt, *trans*-2-phenyl-1-cyclohexanol was removed using $LiBH_4$ in 17% yield. Attempted saponification of the pantolactone ester using lithium hydroxide[15] afforded only a complex mixture. It was found that any aldehyde (**27**) which was further reduced to alcohol **26** under the reaction conditions could be conveniently oxidized back to aldehyde **27** using MnO_2 in dichloromethane (Scheme 2).

Table 5
Optical rotation of **27** used to determine stereochemistry of **6–15**

Adduct	Aldehyde (%)	$[\alpha]_D$
7 (100% d.e.)	**27B** (63%)	+90.0
8 (100% d.e.)	**27A** (61%)	-90.0
10 (62% d.e.)	**27A** (43%)	-52.0
13 (96% d.e.)	**27B** (63%)	+88.0
15 (94% d.e.)	**27B** (17%)	+87.0

2.7. Determination of stereochemistry

The absolute stereochemistry of adducts **6–15** was determined from the sign of the specific rotation (Table 5) of the derived aldehyde **27** formed *via* fragmentation of **6–15** with tin(IV) chloride and removal of the auxiliary using lithium borohydride. Enantiomeric purity was conserved in the fragmentation and in the removal of the chiral auxiliary. Aldehyde **27** of known absolute configuration was prepared from adduct **13**, the absolute stereochemistry having been determined by X-ray crystallography (*vide supra*).

2.8. Formation of cyclopentannulated pyranonaphthoquinone

Having successfully removed the chiral auxiliary, enantiomerically pure aldehyde **27** could then be used as a starting material for the preparation of optically active pyranonaphthoquinone ring systems such as **28**. Towards this end, silver(II) oxide/nitric acid oxidative rearrangement of aldehyde **27** afforded lactol **28** in 23% yield, whereas the use of ceric ammonium nitrate was ineffective for this transformation.

3. Conclusions

The use of chiral auxiliaries such as pantolactone at C-2 of 1,4-naphthoquinones has enabled levels of up to 96% stereoinduction in Diels–Alder cycloadditions with cyclopentadiene to be achieved. Use of lithium borohydride allowed removal of the chiral auxiliaries from the fragmented products **16–25** in acceptable yields such that oxidative rearrangement to a cyclopentannulated pyranonaphthoquinone ring system, similar to that found in nature, could be effected.

4. Experimental

4.1. General details

Melting points were determined using a Reichert Kofler block and are uncorrected. Infrared absorption spectra were recorded using a Perkin–Elmer 1600 Series FTIR spectrometer as Nujol mulls or thin films between sodium chloride plates. ^{1}H NMR and ^{13}C NMR spectra were obtained using either a Bruker AM 400 or Bruker AC 200 spectrometer. ^{13}C NMR spectra were interpreted with the aid of DEPT 135 and DEPT 90 experiments. Low resolution mass spectra were recorded using a VG 70-SE spectrometer operating at an accelerating voltage of 70 eV. High resolution mass spectra were recorded at a nominal resolution of 5000 or 10000 as appropriate, using EI, CI with ammonia or LSIMS with mnba. High resolution CI mass spectra were recorded at University of Otago, Dunedin, New Zealand and LSIMS mass spectra were recorded at Central Services Laboratory, Hobart, Australia. Flash chromatography was performed using Merck Kieselgel 60 (230–400 mesh) using hexane/ethyl acetate as eluent.

4.2. *1,4-Dimethoxy-2-naphthoic acid*

1,4-Dihydroxy-2-naphthoic acid (5 g, 25 mmol) was dissolved in dry acetone (200 mL) and treated with potassium carbonate (25 g, 184 mmol) followed by iodomethane (8 mL). The mixture was heated under reflux under nitrogen for 12 h. The solvent was then removed and the product partitioned between dichloromethane and water. The organic layer was separated, dried ($MgSO_4$) and the solvent removed *in vacuo*. Purification by flash chromatography (hexane:ethyl acetate, 8:1) gave methyl 1,4-dimethoxy-2-naphthoate as colourless needles (6.15 g, 100%). This solid was dissolved in 1 M sodium hydroxide (200 mL) and acetonitrile (20 mL) and heated under reflux for 1 h. The mixture was washed with dichloromethane (100 mL), acidified with concentrated HCl to pH 1 and extracted with dichloromethane (3×100 mL). The organic extract was dried ($MgSO_4$) and the solvent removed to give the title compound as a pale pink solid (5.45 g, 96%) which was of sufficient purity for subsequent transformations: mp 162–163°C (lit.[20] mp 167–168°C).

4.3. *1,4-Dimethoxy-2-naphthoyl chloride*[21]

1,4-Dimethoxy-2-naphthoic acid (556 mg, 2.39 mmol) was dissolved in thionyl chloride (2 mL) and stirred at room temperature for 15 h. Excess thionyl chloride was then removed *in vacuo* to afford the acid chloride as a brown solid in quantitative yield. The crude product was used immediately in the next step.

4.4. *Representative procedure for formation of amides **29** and **30***

4.4.1. *(−)-(R)-3-(1′,4′-Dimethoxy-2′-naphthoyl)-4-(phenylmethyl)-2-oxazolidinone **29***

To a solution of *n*-butyllithium (1.47 mL of a 2.35 M solution in THF, 3.46 mmol, 1.2 equiv.) in THF (30 mL) at −78°C, was added (*R*)-(+)-4-benzyl-2-oxazolidinone[22] (613 mg, 3.46 mmol) in THF (5 mL) over 5 min. After stirring for 15 min, a solution of 1,4-dimethoxy-2-naphthoyl chloride (720 mg, 2.89 mmol) in THF (5 mL) was added over a further 15 min. The reaction mixture was stirred at −78°C for 15 min, then at room temperature for 20 min. The solvent was removed under reduced pressure and the residue redissolved in dichloromethane (30 mL). The dichloromethane layer was washed with 0.5 M hydrochloric acid (20 mL) and dried over $MgSO_4$. The solvent was removed *in vacuo* and the crude product purified by flash chromatography (hexane:ethyl acetate, 4:1) to give the title compound **29** as an amorphous colourless solid (595 mg, 53% over two steps from 1,4-dimethoxynaphthoic acid): $[\alpha]_D = -18.7$ (c=1.7, $CHCl_3$); ^1H NMR (200 MHz, $CDCl_3$) δ 2.94 (dd, J=13.3, 9.9 Hz, 1H, CH_ACH_BPh), 3.62 (dd, J=13.3, 3.4 Hz, 1H, CH_ACH_BPh), 3.95 (s, 3H, 1′-OMe or 4′-OMe), 4.00 (s, 3H, 4′-OMe or 1′-OMe), 4.24 (dd, J=8.9, 3.8 Hz, 1H, 5-H_B), 4.28 (dd, J=8.9, 8.9 Hz, 1H, 5-H_A), 4.83–4.97 (m, 1H, 4-H), 6.69 (s, 1H, 3′-H), 7.28–7.43 (m, 5H, Ph), 7.52–7.66 (m, 2H, 6′-H and 7′-H), 8.07–8.33 (m, 2H, 5′-H and 8′-H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 38.0 (CH_2, CH_2Ph), 55.7 (CH, C-4), 55.8 (CH_3, 1′-OMe or 4′-OMe), 63.5 (CH_3, 4′-OMe or 1′-OMe), 66.2 (CH_2, C-5), 101.1 (CH, C-3′), 122.6 (quat, C-2′), 127.0 (CH, C-5′ or C-8′), 127.1 (CH, C-8′ or C-5′), 127.4 (CH, Ph), 127.9 (CH, C-6′ or C-7′), 128.0 (CH, C-7′ or C-6′), 128.7 (quat, C-4a′ or C-8a′), 129.0 (CH, Ph), 129.3 (quat, C-8a′ or C-4a′), 129.5 (CH, Ph), 135.3 (quat, Ph), 147.8 (quat, C-1′ or C-4′), 151.9 (quat, C-4′ or C-1′), 152.3 (quat, C-2), 168.0

(quat, amide); IR (film) 1791 (s, amide), 1686 (oxazolidinone), 1595 (C=C), 1460, 1373 (s), 1216 cm^{-1}; *m/z* (EI, %) 391 (M$^+$, 64), 215 ($C_{13}H_{11}O_3$, 34), 144 (36), 129 (37), 91 (C_7H_7, 100); HRMS analysis (EI, M$^+$) ($C_{23}H_{21}O_5N$=391.1420) found *m/z* 391.1409.

4.4.2. *(−)-[3aS-(3aα,6α,7aβ)]-Hexahydro-8,8-dimethyl-1-(1′,4′-dimethoxy-2′-naphthoyl)-3H-3a,6-methano-2,1-benzisothiazole-2,2-dioxide* **30**

Compound **30** was prepared from 1,4-dimethoxy-2-naphthoyl chloride (1.1 g, 4.3 mmol) and [3a*S*-(3aα,6α,7aβ)]-hexahydro-8,8-dimethyl-3*H*-3α,6-methano-2,1-benzisothiazole-2,2-dioxide (925 mg, 4.3 mmol) as a colourless solid (1.6 g, 95%): ^{1}H NMR (200 MHz, $CDCl_3$) δ 0.97 (s, 3H, 8-Me$_A$), 1.30 (s, 3H, 8-Me$_B$), 1.20–2.08 (m, 7H, 6-CH, 7-CH$_2$, 4-CH$_2$ and 5-CH$_2$), 3.45–3.56 (m, 2H, 3-CH$_2$), 3.97 (s, 3H, 1′-OMe or 4′-OMe), 3.97 (s, 3H, 4′-OMe or 1′-OMe), 4.06–4.28 (m, 1H, 7a-H), 6.75 (s, 1H, 3′-H), 7.51–7.63 (m, 2H, 6′-H and 7′-H), 8.08–8.29 (m, 2H, 5′-H and 8′-H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 19.8 (CH_3, 8-Me$_A$), 20.9 (CH_3, 8-Me$_B$), 26.2 (CH_2, C-5), 32.9 (CH_2, C-4), 38.3 (CH_2, C-7), 44.9 (CH, C-6), 47.7 (quat, C-8), 48.6 (quat, C-3a), 52.9 (CH_2, C-3), 55.7 (CH_3, 1′-OMe or 4′-OMe), 63.7 (CH_3, 4′-OMe or 1′-OMe), 64.9 (CH, C-7a), 102.6 (CH, C-3′), 122.4 (CH, C-5′ or C-8′), 122.7 (CH, C-8′ or C-5′), 122.9 (quat, C-2′), 127.0 (CH, C-6′ or C-7′), 127.0 (CH, C-7′ or C-6′), 127.8 (quat, C-4a′ or C-8a′), 128.1 (quat, C-8a′ or C-4a′), 150.0 (quat, C-1′ or C-4′), 151.3 (quat, C-4′ or C-1′), 167.6 (quat, amide); IR (KBr) 1684 (amide), 1653, 1594 (C=C), 1457, 1373, 1340, 1285 cm^{-1}; *m/z* (EI, %) 429 (M$^+$, 40), 157 (7), 129 (12), 108 (16), 28 (100); HRMS analysis (EI, M$^+$) ($C_{23}H_{27}O_5NS$=429.1610) found *m/z* 429.1598.

4.5. *Representative procedure for formation of esters* **31–33**

4.5.1. *(−)-(S)-1-Methyl-2,5-dioxo-3-pyrrolidinyl 1,4-dimethoxynaphthalene-2-carboxylate* **31**

(*S*)-(−)-2-Hydroxy-*N*-methylsuccinimide (650 mg, 5.0 mmol) and 4-dimethylaminopyridine (17 mg, 0.17 mmol) were added to a solution of 1,4-dimethoxy-2-naphthoic acid (445 mg, 1.9 mmol) in dichloromethane (10 mL) under nitrogen at 0°C with stirring. Dicyclohexylcarbodiimide (450 mg, 2.16 mmol) in dichloromethane (5 mL) was then added dropwise over 5 min. The mixture was stirred for a further 5 min at 0°C, then at room temperature for 2 h. The solution was filtered through Celite to remove dicyclohexyl urea and washed with 0.5 M hydrochloric acid solution (15 mL) and 10% sodium hydrogen carbonate solution (15 mL). The organic layer was dried over $MgSO_4$ and the solvent removed *in vacuo*. The crude mixture was purified by flash chromatography (hexane:ethyl acetate, 5:1 then 3:1) to give the title compound (**31**) as a colourless solid (455 mg, 70%): mp 138–140°C; $[\alpha]_D$=−1.00 (*c*=0.4, CH_2Cl_2); ^{1}H NMR (200 MHz, $CDCl_3$) δ 2.89 (dd, *J*=18.4, 4.8 Hz, 1H, 4′-H$_B$), 3.12 (s, 3H, N–Me), 3.34 (dd, *J*=18.4, 8.7 Hz, 1H, 4′-H$_A$), 3.90 (s, 3H, 1-OMe or 4-OMe), 4.08 (s, 3H, 4-OMe or 1-OMe), 5.72 (dd, *J*=8.7, 4.8 Hz, 1H, 3′-H), 7.15 (s, 1H, 3-H), 7.58–7.69 (m, 2H, 6-H and 7-H), 8.15–8.42 (m, 2H, 5-H and 8-H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 25.1 (CH_3, N–Me), 36.0 (CH_2, C-4′), 55.8 (CH_3, 1-OMe or 4-OMe), 63.7 (CH_3, 4-OMe or 1-OMe), 68.2 (CH, C-3′), 103.1 (CH, C-3), 116.8 (quat, C-2), 123.4 (CH, C-5 or C-8), 123.6 (CH, C-8 or C-5), 127.3 (CH, C-6 or C-7), 128.4 (CH, C-7 or C-6), 129.1 (quat, C-4a or C-8a), 129.3 (quat, C-8a or C-4a), 151.5 (quat, C-1 or C-4), 153.2 (quat, C-4 or C-1), 165.1 (quat, ester), 173.4 (quat, C-2′), 173.6 (quat, C-5′); IR (KBr) 1712 (quat, C=O), 1595 (C=C), 1439, 1375, 1217 cm^{-1}; *m/z* (EI, %) 343 (M$^+$, 100), 328 (M−Me, 75), 215 ($C_{13}H_{11}O_3$, 47), 157 (45), 129 (61), 101 (46); anal. found: C, 63.09; H, 5.01; N, 3.90; $C_{18}H_{17}O_6N$ requires C, 62.97; H, 4.99; N, 4.08%.

*4.5.2. (+)-(3′R)-Dihydro-4,4-dimethyl-2-oxo-3-furanyl 1,4-dimethoxynaphthalene-2-carboxylate **32***

Compound **32** was prepared from (*R*)-pantolactone (660 mg, 5.1 mmol) and 1,4-dimethoxy-2-naphthoic acid (400 mg, 1.7 mmol) as a colourless solid (460 mg, 78%): mp 118–120°C; $[\alpha]_D$=+1.44 (*c*=3.2, acetone); ^{1}H NMR (200 MHz, $CDCl_3$) δ 1.28 (s, 3H, 4′-Me), 1.32 (s, 3H, 4′-Me), 4.01 (s, 3H, 1-OMe or 4-OMe), 4.01 (s, 3H, 4-OMe or 1-OMe), 4.10–4.18 (m, 2H, 5′-H_A and 5′-H_B), 5.72 (s, 1H, 3′-H), 7.22 (s, 1H, 3-H), 7.56–7.67 (m, 2H, 6-H and 7-H), 8.17–8.29 (m, 2H, 5-H and 8-H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 20.1 (CH_3, 4′-Me), 23.1 (CH_3, 4′-Me), 40.5 (quat, C-4′), 55.7 (CH_3, 1-OMe or 4-OMe), 63.6 (CH_3, 4-OMe or 1-OMe), 75.6 (CH_2, C-5′), 76.2 (CH, C-3′), 103.3 (CH, C-3), 117.2 (quat, C-2), 122.3 (CH, C-5 or C-8), 123.6 (CH, C-8 or C-5), 127.2 (CH, C-6 or C-7), 128.2 (CH, C-7 or C-6), 129.1 (quat, C-4a or C-8a), 129.2 (quat, C-8a or C-4a), 151.1 (quat, C-1 or C-4), 153.0 (quat, C-4 or C-1), 165.0 (quat, ester), 172.5 (quat, C-2′); IR (KBr) 1797 (C=O), 1710 (C=O), 1596 (C=C), 1461, 1373, 1214 cm^{-1}; *m/z* (EI, %) 344 (M^+, 100), 329 (M−Me, 17), 215 (47), 185 (24), 157 (13), 129 (15), 91 (17); anal. found: C, 66.18; H, 6.07; $C_{19}H_{20}O_6$ requires C, 66.27; H, 5.85%.

*4.5.3. (−)-(1′R,2′S)-2-Phenyl-1-cyclohexyl 1,4-dimethoxynaphthalene-2-carboxylate **33***

Compound **33** was prepared from 1,4-dimethoxy-2-naphthoic acid (660 mg, 2.8 mmol) and (1*R*,2*S*)-(−)-*trans*-2-phenyl-1-cyclohexanol (1.0 g, 5.7 mmol) as a colourless oil (500 mg, 45%): $[\alpha]_D$=−74.6 (*c*=1.9, CH_2Cl_2); ^{1}H NMR (200 MHz, $CDCl_3$) δ 1.13–2.48 (m, 8H, 3′-CH_2, 4′-CH_2, 5′-CH_2 and 6′-CH_2), 2.91 (ddd, *J*=3.4, 11.2, 11.2 Hz, 1H, 2′-H), 3.77 (s, 3H, 1-OMe or 4-OMe), 3.83 (s, 3H, 4-OMe or 1-OMe), 5.25–5.43 (m, 1H, 1′-H), 6.59 (s, 1H, 3-H), 7.12–7.39 (m, 5H, Ph), 7.46–7.63 (m, 2H, 6-H and 7-H), 8.07–8.27 (m, 2H, 5-H and 8-H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 24.8 (CH_2, C-4′), 25.9 (CH_2, C-5′), 32.3 (CH_2, C-3′), 34.4 (CH_2, C-6′), 50.0 (CH, C-2′), 55.5 (CH_3, 1-OMe or 4-OMe), 63.0 (CH_3, 4-OMe or 1-OMe), 76.8 (CH, C-1′), 103.2 (CH, C-3), 119.5 (quat, C-2), 122.1 (CH, C-5 or C-8), 123.2 (CH, C-8 or C-5), 126.4 (CH, C-4″), 126.8 (CH, C-6 or C-7), 127.3 (CH, C-7 or C-6), 127.5 (CH, C-3″), 128.2 (quat, C-4a or C-8a), 128.4 (CH, C-2″), 128.9 (quat, C-8a or C-4a), 143.5 (quat, C-1″), 150.9 (quat, C-1 or C-4), 151.0 (quat, C-4 or C-1), 165.7 (quat, ester); IR (film) 1721 (s, ester), 1596 (C=C), 1461, 1371 (s), 1227 cm^{-1}; *m/z* (EI, %) 390 (M^+, 31), 260 (100), 245 (60), 215 (41), 91 (C_7H_7, 61); HRMS analysis (EI, M^+) ($C_{25}H_{26}O_4$=390.1831) found *m/z* 390.1822.

*4.6. Representative procedure for CAN oxidation to quinones **1–5***

*4.6.1. (±)-(R)-3-(1′,4′-Dioxo-2′-naphthoyl)-4-(phenylmethyl)-2-oxazolidinone **1***

A solution of ceric ammonium nitrate (1.96 g, 3.6 mmol) in water (3 mL) was added dropwise to a solution of **29** (560 mg, 1.4 mmol) in acetonitrile (20 mL). After stirring for 5 min, the mixture was diluted with dichloromethane (70 mL), washed with water (2×30 mL), dried over $MgSO_4$ and filtered through a short florisil column. The solvent was then removed to give the title compound **1** as a bright yellow oil (507 mg, 98%): $[\alpha]_D$=−86.9 (*c*=3.1, $CHCl_3$); ^{1}H NMR (200 MHz, $CDCl_3$) δ 2.97 (dd, *J*=13.6, 9.5 Hz, 1H, CH_AH_BPh), 3.50 (dd, *J*=13.6, 3.3 Hz, 1H, CH_AH_BPh), 4.27 (dd, *J*=9.1, 3.4 Hz, 1H, 5-H_B), 4.36 (dd, *J*=9.1, 9.1 Hz, 1H, 5-H_A), 4.77–4.92 (m, 1H, 4-H), 6.96 (s, 1H, 3′-H), 7.21–7.43 (m, 5H, Ph), 7.74–7.82 (m, 2H, 6′-H and 7′-H), 8.05–8.12 (m, 2H, 5′-H and 8′-H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 37.5 (CH_2, CH_2Ph), 54.8 (CH, C-4), 67.3 (CH_2, C-5), 126.4 (CH, C-5′ or C-8′), 126.7 (CH, C-8′ or C-5′), 127.5 (CH, Ph), 129.0 (CH, Ph), 129.4 (CH, Ph), 131.3 (quat, C-4a′ or C-8a′), 131.8 (quat, C-8a′ or C-4a′), 134.2 (CH, C-6′ or C-7′), 134.3 (CH, C-7′ or C-6′), 134.3 (CH, C-3′), 134.6 (quat, Ph), 144.6 (quat, C-2′), 153.1 (quat, C-2), 163.5 (quat, amide), 181.7 (quat, C-1′ or C-4′), 183.9 (quat, C-4′ or C-1′); IR (film) 1785 (s, amide), 1692 (oxazolidinone), 1668 (quinone), 1595 (C=C), 1358, 1295, 1256

cm^{-1}; *m/z* (EI, %) 361 (M^+, 5), 185 ($C_{11}H_5O_3$, 18), 157 (12), 149 (15), 91 (C_7H_7, 100); HRMS analysis (EI, M^+) ($C_{21}H_{15}O_5N$=361.0950) found *m/z* 361.0969.

*4.6.2. (−)-[3aS-(3aα,6α,7aβ)]-Hexahydro-8,8-dimethyl-1-(1′,4′-dioxo-2′-naphthoyl)-3*H*-3a,6-methano-2,1-benzisothiazole-2,2-dioxide* **2**

Compound **2** was prepared by CAN oxidation of **30** (430 mg, 1.0 mmol) as a yellow oil (390 mg, 98%): $[\alpha]_D$=−59.3 (*c*=0.58, CH_2Cl_2); ^1H NMR (200 MHz, $CDCl_3$) δ 0.95 (s, 3H, 8-Me_A), 1.22 (s, 3H, 8-Me_B), 1.19–2.48 (m, 7H, 6-CH, 7-CH_2, 4-CH_2 and 5-CH_2), 3.36–3.52 (m, 2H, 3-CH_2), 3.99 (dd, *J*=7.8, 4.9 Hz, 1H, 7a-H), 6.97 (s, 1H, 3′-H), 7.69–7.81 (m, 2H, 6′-H and 7′-H), 7.99–8.11 (m, 2H, 5′-H and 8′-H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 19.8 (CH_3, 8-Me_A), 20.3 (CH_3, 8-Me_B), 26.3 (CH_2, C-5), 32.5 (CH_2, C-4), 37.5 (CH_2, C-7), 44.5 (CH, C-6), 47.8 (quat, C-8), 49.0 (quat, C-3a), 52.5 (CH_2, C-3), 64.5 (CH, C-7a), 126.3 (CH, C-5′ or C-8′), 126.6 (CH, C-8′ or C-5′), 131.0 (quat, C-4a′ or C-8a′), 131.6 (quat, C-8a′ or C-4a′), 134.2 (CH, C-6′ or C-7′), 134.2 (CH, C-7′ or C-6′), 135.7 (CH, C-3′), 141.9 (quat, C-2′), 161.6 (quat, amide), 181.2 (quat, C-1′ or C-4′), 183.8 (quat, C-4′ or C-1′); IR (KBr) 1692 (amide), 1670 (quinone), 1595 (C=C), 1460, 1338, 1295, 1253 cm^{-1}; *m/z* (LSIMS, %) 400 (M^++1, 88), 216 (80), 186 ($C_{11}H_5O_3$, 100), 135 (68); HRMS analysis (LSIMS, M^++1) ($C_{21}H_{22}O_5NS$=400.1219) found *m/z* 400.1214.

*4.6.3. (−)-(3′*S*)-1-Methyl-2,5-dioxo-3-pyrrolidinyl 1,4-dioxonaphthalene-2-carboxylate* **3**

Compound **3** was prepared by CAN oxidation of **31** (430 mg, 1.3 mmol) as a yellow oil (380 mg, 98%): $[\alpha]_D$=−53.8 (*c*=1.36, $CHCl_3$); ^1H NMR (200 MHz, $CDCl_3$) δ 2.85 (dd, *J*=18.4, 4.7 Hz, 1H, 4′-H_A), 3.04 (s, 3H, N–Me), 3.29 (dd, *J*=18.4, 8.6 Hz, 1H, 4′-H_B), 5.70 (dd, *J*=4.7, 8.6 Hz, 1H, 3′-H), 7.32 (s, 1H, 3-H), 7.72–7.85 (m, 2H, 6-H and 7-H), 8.01–8.17 (m, 2H, 5-H and 8-H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 25.1 (CH_3, N–Me), 35.5 (CH_2, C-4′), 68.7 (CH, C-1′), 126.4 (CH, C-5 or C-8), 127.0 (CH, C-8 or C-5), 127.1 (quat, C-4a or C-8a), 131.5 (quat, C-8a or C-4a), 134.4 (CH, C-7 or C-6), 134.7 (CH, C-6 or C-7), 137.7 (quat, C-2), 139.3 (CH, C-3), 162.2 (quat, ester), 172.5 (quat, C-2′ or C-5′), 172.8 (quat, C-5′ or C-2′), 180.5 (quat, C-1 or C-4), 184.0 (quat, C-4 or C-1); IR (film) 1713 (b, amide and ester), 1672 (quinone), 1594 (C=C), 1440, 1285, 1222, 1122 cm^{-1}; *m/z* (EI, %) 315 (M+2, 16), 201 (26), 186 ($C_{11}H_6O_3$, 100), 157 ($C_{10}H_5O_2$, 64), 129 (49), 101 (57); HRMS analysis (EI, M^+) ($C_{16}H_{11}O_6N$=313.0586) found *m/z* 313.0573.

*4.6.4. (+)-(3′*R*)-Dihydro-4,4-dimethyl-2-oxo-3-furanyl 1,4-dioxonaphthalene-2-carboxylate* **4**

Compound **4** was prepared by CAN oxidation of **32** (310 mg, 0.9 mmol) as a yellow oil (230 mg, 80%): $[\alpha]_D$=+46.6 (*c*=1.25, $CHCl_3$); ^1H NMR (200 MHz, $CDCl_3$) δ 1.25 (s, 3H, 4′-Me), 1.34 (s, 3H, 4′-Me), 4.10–4.16 (m, 2H, 5′-H_A and 5′-H_B), 5.62 (s, 1H, 3′-H), 7.40 (s, 1H, 3-H), 7.78–7.88 (m, 2H, 6-H and 7-H), 8.04–8.19 (m, 2H, 5-H and 8-H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 19.9 (CH_3, 4′-Me), 22.9 (CH_3, 4′-Me), 40.6 (quat, C-4′), 76.2 (CH_2, C-5′), 76.5 (CH, C-3′), 126.4 (CH, C-5 or C-8), 127.0 (CH, C-8 or C-5), 131.5 (quat, C-4a), 131.5 (quat, C-8a), 134.4 (CH, C-7 or C-6), 134.7 (CH, C-6 or C-7), 138.3 (quat, C-2), 139.1 (CH, C-3), 162.3 (quat, ester), 171.5 (quat, C-2′), 180.6 (quat, C-1 or C-4), 184.1 (quat, C-4 or C-1); IR (film) 1792 (lactone), 1752 (ester), 1672 (quinone), 1595 (C=C), 1299, 1249, 1124 cm^{-1}; *m/z* (EI, %) 316 (M^++2, 9), 226 (13), 185 (100), 157 (82), 129 (45), 101 (69); HRMS analysis (EI, M^++2) ($C_{17}H_{16}O_6$=316.0947) found *m/z* 316.0945.

*4.6.5. (−)-(1′*R*,2′*S*)-2-Phenyl-1-cyclohexyl 1,4-dioxonaphthalene-2-carboxylate* **5**

Compound **5** was prepared by CAN oxidation of **33** (410 mg, 1.1 mmol) as a yellow oil (300 mg, 79%): $[\alpha]_D$=−29.8 (*c*=1.6, CH_2Cl_2); ^1H NMR (200 MHz, $CDCl_3$) δ 1.23–2.41 (m, 8H, 3′-CH_2, 4′-CH_2, 5′-CH_2 and 6′-CH_2), 2.76 (ddd, J=3.3, 11.4, 11.4 Hz, 1H, 2′-H), 5.22 (ddd, J=4.5, 10.5, 10.5 Hz, 1H, 1′-H), 6.52 (s, 1H, 3-H), 7.11–7.34 (m, 5H, Ph), 7.52–7.77 (m, 2H, 6-H and 7-H), 7.94–8.08 (m, 2H, 5-H and 8-H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 24.6 (CH_2, C-4′), 25.5 (CH_2, C-5′), 32.0 (CH_2, C-3′), 35.6 (CH_2, C-6′), 49.8 (CH, C-2′), 78.3 (CH, C-1′), 126.0 (CH, C-5 or C-8), 126.7 (CH, C-4″ and C-8 or C-5), 127.4 (CH, C-3″), 128.3 (CH, C-2″), 131.3 (quat, C-4a or C-8a), 131.5 (quat, C-8a or C-4a), 133.9 (CH, C-6 or C-7), 134.2 (CH, C-7 or C-6), 136.9 (CH, C-3), 139.6 (quat, C-2), 142.3 (quat, C-1″), 162.2 (quat, ester), 180.8 (quat, C-1 or C-4), 184.5 (quat, C-4 or C-1); IR (film) 1738 (s, ester), 1668 (quinone), 1595 (C=C), 1450, 1354, 1249 cm^{-1}; m/z (EI, %) 362 (M^++2, 5), 204 (32), 187 (65), 158 (100), 130 (54); HRMS analysis (EI, M^++2) ($C_{23}H_{22}O_4$=362.1518) found m/z 362.1518.

4.7. *Representative procedure for formation of Diels–Alder adducts 6–15*

4.7.1. *(−)-(4R,1′R,4′S,4a′S,9a′S)- and (+)-(4R,1′S,4′R,4a′R,9a′R)-3-(1′,4′,4a′,9a′-Tetrahydro-1′,4′-methano-9′,10′-dioxo-4a′-anthroyl)-4-(phenylmethyl)-2-oxazolidinone 6 and 7 (using $ZnCl_2$)*

To quinone **1** (23 mg, 0.06 mmol) in dichloromethane (5 mL) at −78°C, was added zinc chloride (64 μL of 1 M solution in CH_2Cl_2, 0.06 mmol). The mixture was then treated with freshly distilled cyclopentadiene (30 μL) and stirred for 2 h. The mixture was poured into 10% sodium hydrogen carbonate solution (6 mL) and extracted with dichloromethane (3×5 mL). The organic layer was dried ($MgSO_4$) and the solvent removed under reduced pressure. The resultant oil was purified by flash chromatography (hexane:ethyl acetate, 4:1) to afford the Diels–Alder adducts **6** and **7** in a 2.57:1 ratio (44% d.e.).

Adduct **6** was isolated as a yellow oil (19 mg, 69%): $[\alpha]_D$=−76.0 (c=1.0, CH_2Cl_2); ^{1}H NMR (200 MHz, $CDCl_3$) δ 1.51–1.74 (m, 2H, 11′-H_A and 11′-H_B), 2.82 (dd, J=13.3, 9.6 Hz, 1H, $CH_AC\textit{H}_BPh$), 3.35 (dd, J=13.3, 3.8 Hz, 1H, $C\textit{H}_ACH_BPh$), 3.42–3.52 (m, 1H, 1′-H), 3.54 (d, J=4.1 Hz, 1H, 9a′-H), 3.78–3.93 (m, 1H, 4′-H), 4.17 (dd, J=9.2, 3.7 Hz, 1H, 5-H_B), 4.53 (dd, J=9.2, 9.2 Hz, 1H, 5-H_A), 4.55–4.82 (m, 1H, 4-H), 5.58 (dd, J=5.5, 3.0 Hz, 1H, 2′-H or 3′-H), 5.83 (dd, J=5.5, 2.7 Hz, 1H, 3′-H or 2′-H), 7.15–7.40 (m, 5H, Ph), 7.57–7.69 (m, 2H, 6′-H and 7′-H), 7.78–7.98 (m, 2H, 5′-H and 8′-H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 38.3 (CH_2, CH_2Ph), 50.4 (CH_2, C-11′), 51.0 (CH, C-1′), 55.2 (CH, C-4), 55.3 (CH, C-4′), 55.7 (CH, C-9a′), 66.3 (quat, C-4a′), 67.2 (CH_2, C-5), 126.1 (CH, C-5′ or C-8′), 126.3 (CH, C-8′ or C-5′), 127.5 (CH, Ph), 129.0 (CH, Ph), 129.3 (CH, Ph), 133.2 (CH, C-6′ or C-7′), 133.7 (CH, C-7′ or C-6′), 134.5 (CH, C-2′ or C-3′), 134.8 (quat, Ph), 135.9 (quat, C-4b′ or C-8a′), 136.2 (quat, C-8a′ or C-4b′), 138.8 (CH, C-3′ or C-2′), 153.1 (quat, C-2), 170.4 (quat, amide), 194.2 (quat, C-9′ or C-10′), 195.8 (quat, C-10′ or C-9′); IR (film) 1777 (s, amide), 1692 (oxazolidinone), 1672 (quinone), 1593 (C=C), 1356, 1295, 1260 cm^{-1}; m/z (CI, CH_4, rel. abundance) 428 (M^++1, 32), 362 (M−C_5H_6, 100), 251 (28), 178 (76), 67 (26); HRMS analysis (LSIMS, M^++1) ($C_{26}H_{22}O_5N$=428.1498) found m/z 428.1505.

Adduct **7** was isolated as a yellow oil (7 mg, 27%): $[\alpha]_D$=+25.3 (c=0.9, CH_2Cl_2); ^{1}H NMR (200 MHz, $CDCl_3$) δ 1.60–1.81 (m, 2H, 11′-H_A and 11′-H_B), 2.75 (dd, J=13.4, 10.1 Hz, 1H, $CH_AC\textit{H}_BPh$), 3.41–3.51 (m, 2H, 1-H and $C\textit{H}_ACH_BPh$), 3.55 (d, J=4.1 Hz, 1H, 9a′-H), 3.93–4.01 (m, 1H, 4′-H), 4.13–4.22 (m, 2H, 5-H_A and 5-H_B), 4.63–4.80 (m, 1H, 4-H), 5.82 (dd, J=5.4, 3.0 Hz, 1H, 2′-H or 3′-H), 5.93 (dd, J=5.4, 2.7 Hz, 1H, 3′-H or 2′-H), 7.12–7.42 (m, 5H, Ph), 7.58–7.72 (m, 2H, 6′-H and 7′-H), 7.84–7.99 (m, 2H, 5′-H and 8′-H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 37.0 (CH_2, CH_2Ph), 50.6 (CH_2, C-11′), 51.0 (CH, C-1′), 55.1 (CH, C-4), 55.3 (CH, C-4′), 56.4 (CH, C-9a′), 65.8 (quat, C-4a′), 66.7 (CH_2, C-5), 126.0 (CH, C-5′ or C-8′), 126.3 (CH, C-8′ or C-5′), 127.3 (CH, Ph), 129.0 (CH, Ph), 129.5 (CH, Ph), 133.3 (CH, C-6′ or C-7′), 133.7 (CH, C-7′ or C-6′), 134.6 (CH, C-2′ or C-3′), 135.3 (quat, Ph), 136.0 (quat, C-4b′ or C-8a′), 136.2 (quat, C-8a′ or C-4b′), 138.8 (CH, C-3′ or C-2′), 153.0 (quat, C-2), 170.4 (quat, amide), 194.4 (quat, C-9′ or C-10′), 195.9 (quat, C-10′ or C-9′); IR (film) 1776 (s, amide), 1691 (oxazolidinone), 1679 (quinone), 1592 (C=C), 1355, 1294, 1262 cm^{-1}; *m/z* (CI, CH_4, rel. abundance) 428 (M^++1, 34), 362 ($M-C_5H_6$, 100), 251 (26), 178 (72), 67 (18); HRMS analysis (LSIMS, M^++1) ($C_{26}H_{22}O_5N$=428.1498) found *m/z* 428.1484. For other Lewis acids see Table 1 in text.

4.7.2. (−)-[3aS-(3aα,6α,7aβ),1′R,4′S,4a′S,9a′S]- and (−)-[3aS-(3aα,6α,7aβ),1′S,4′R,4a′R,9a′R]-Hexahydro-8,8-dimethyl-1-[1′,4′,4a′,9a′-tetrahydro-1′,4′-methano-9′,10′-dioxo-4a′-anthroyl]-3H-3a,6-methano-2,1-benzisothiazole-2,2-dioxide 8 and 9

Compounds **8** and **9** were prepared from quinone **2** (39 mg, 0.1 mmol) and cyclopentadiene using $ZnCl_2$ (1 equiv.), according to the standard procedure outlined above.

Adduct **8** was isolated as a colourless oil (26 mg, 58%): $[\alpha]_D$=−104.6 (*c*=1.2, CH_2Cl_2); ^1H NMR (200 MHz, $CDCl_3$) δ 0.93 (s, 3H, 8′-Me_A), 1.16 (s, 3H, 8-Me_B), 1.21–2.35 (m, 8H, 6-CH, 7-CH_2, 4-CH_2, 5-CH_2 and 11′-H_B), 1.59 (m, 1H, 11′-H_A), 3.23 (d, *J*=13.7 Hz, 1H, 3-H_A), 3.31 (d, *J*=13.7 Hz, 1H, 3-H_B), 3.53–3.62 (m, 1H, 1′-H), 3.84 (d, *J*=4.2 Hz, 1H, 9a′-H), 4.04 (dd, *J*=7.7 Hz, 4.9, 1H, 7a-H), 4.21–4.27 (m, 1H, 4′-H), 5.87 (dd, *J*=5.5, 2.9 Hz, 1H, 2′-H or 3′-H), 5.97 (dd, *J*=5.5, 2.8 Hz, 1H, 3′-H or 2′-H), 7.58–7.70 (m, 2H, 6′-H and 7′-H), 7.96–8.07 (m, 2H, 5′-H and 8′-H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 19.7 (CH_3, 8-Me_A), 21.2 (CH_3, 8-Me_B), 26.3 (CH_2, C-5), 32.8 (CH_2, C-4), 38.7 (CH_2, C-7), 44.5 (CH, C-6), 47.8 (quat, C-8), 48.3 (CH_2, C-11′), 50.1 (quat, C-3a), 51.0 (CH, C-1′), 53.0 (CH, C-4′), 54.5 (CH_2, C-3), 57.9 (CH, C-9a′), 66.9 (CH, C-7a), 67.4 (quat, C-4a′), 126.5 (CH, C-5′ or C-8′), 127.0 (CH, C-8′ or C-5′), 133.6 (CH, C-6′ or C-7′), 134.0 (CH, C-7′ or C-6′), 134.5 (CH, C-2′ or C-3′), 135.3 (quat, C-4b′ or C-8a′), 135.3 (quat, C-8a′ or C-4b′), 138.8 (CH, C-3′ or C-2′), 169.3 (quat, amide), 191.4 (quat, C-9′ or C-10′), 195.3 (quat, C-10′ or C-9′); IR (film, NaCl) 1689 (C=O), 1592 (C=C), 1331, 1262, 1138 cm^{-1}; *m/z* (LSIMS, %) 466 (M^++1, 12), 400 ($M-C_5H_6$, 100), 251 (19), 216 (54), 185 (37), 135 (39); HRMS analysis (LSIMS, M^++1) ($C_{26}H_{29}O_5NS$=466.1688) found *m/z* 466.1674.

Adduct **9** was isolated as a colourless oil (4 mg, 8%): $[\alpha]_D$=+42.5 (*c*=0.16, CH_2Cl_2); ^1H NMR (200 MHz, $CDCl_3$) δ 0.93 (s, 3H, 8-Me_A), 1.13 (s, 3H, 8-Me_B), 1.20–2.37 (m, 7H, 6-CH, 7-CH_2, 4-CH_2 and 5-CH_2), 1.60 (m, 1H, 11′-H_A), 1.76 (d, *J*=9.1 Hz, 1H, 11′-H_B), 3.16 (d, *J*=13.7 Hz, 1H, 3-H_A), 3.31 (d, *J*=13.7 Hz, 1H, 3-H_B), 3.47–3.56 (m, 1H, 1′-H), 3.82–3.89 (m, 1H, 4′-H), 3.92 (dd, *J*=7.7, 5.1 Hz, 1H, 7a-H), 4.08 (d, *J*=4.2 Hz, 1H, 9a′-H), 5.80 (dd, *J*=5.6, 2.9 Hz, 1H, 2′-H or 3′-H), 5.91 (dd, *J*=5.6, 2.8 Hz, 1H, 3′-H or 2′-H), 7.53–7.70 (m, 2H, 6′-H and 7′-H), 7.86–8.00 (m, 2H, 5′-H and 8′-H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 19.4 (CH_3, 8-Me_A), 19.9 (CH_3, 8-Me_B), 26.6 (CH_2, C-5), 32.4 (CH_2, C-4), 37.7 (CH_2, C-7), 43.9 (CH, C-6), 47.8 (quat, C-8), 48.7 (CH_2, C-11′), 50.3 (quat, C-3a), 51.5 (CH, C-1′), 52.5 (CH, C-4′), 52.9 (CH_2, C-3), 57.5 (CH, C-9a′), 65.9 (quat, C-4a′), 66.1 (CH, C-7a), 126.1 (CH, C-5′ or C-8′), 126.3 (CH, C-8′ or C-5′), 133.4 (CH, C-6′ or C-7′), 133.8 (CH, C-7′ or C-6′), 134.8 (CH, C-2′ or C-3′), 135.9 (quat, C-4b′ or C-8a′), 135.9 (quat, C-8a′ or C-4b′), 139.0 (CH, C-3′ or C-2′), 169.2 (quat, amide), 194.0 (quat, C-9′ or C-10′), 195.7 (quat, C-10′ or C-9′); IR (film, NaCl) 1687 (C=O), 1591 (C=C), 1330, 1263, 1137 cm^{-1}; *m/z* (LSIMS, %) 466 (M^++1, 15), 400 ($M-C_5H_6$, 100), 251 (18), 216 (56), 185 (25); HRMS analysis (LSIMS, M^++1) ($C_{26}H_{29}O_5NS$=466.1688) found *m/z* 466.1679. For other Lewis acids see Table 2 in text.

4.7.3. (3S′,1R,4S,4aS,9aS)- and (3S′,1S,4R,4aR,9aR)-1-Methyl-2,5-dioxo-3-pyrrolidinyl 1,4,4a,9a-tetrahydro-1,4-methano-9,10-dioxo-4a-anthracenecarboxylate 10 and 11

Compounds **10** and **11** were prepared from quinone **3** (20 mg, 0.06 mmol) and cyclopentadiene using $ZnCl_2$ (0.06 mmol), according to the standard procedure outlined above, and were isolated as a colourless oil (21 mg, 87%): [4.3:1 ratio (62% d.e.), the asterisk denotes resonances for the minor diastereomer **11**] ^1H NMR (200 MHz, $CDCl_3$) δ 1.63–1.81 (m, 2H, 11-H_A and 11-H_B), 2.48 (dd, *J*=18.3, 4.9 Hz, 1H, 4′-

H_A), 2.73* (dd, J=18.3, 5.0 Hz, 1H, 4′-H_A), 2.95 (s, 3H, N–Me), 2.99* (s, 3H, N–Me), 3.06 (dd, J=18.3, 8.8 Hz, 1H, 4′-H_B), 3.10* (dd, J=18.3, 8.8 Hz, 1H, 4′-H_B), 3.55–3.63 (m, 1H, 1-H), 3.64–3.72 (m, 1H, 9a-H), 3.84–3.94 (m, 1H, 4-H), 5.26* (dd, J=5.0, 8.8 Hz, 1H, 3′-H), 5.58 (dd, J=4.9, 8.8 Hz, 1H, 3′-H), 5.95–6.05 (m, 2H, 2-H and 3-H), 7.65–7.77 (m, 2H, 6-H and 7-H), 7.92–8.13 (m, 2H, 5-H and 8-H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 25.0 (CH_3, N–Me), 35.0 (CH_2, C-4′), 48.6* and 48.7 (CH_2, C-11), 49.1* and 49.3 (CH, C-1), 52.9* and 53.1 (CH, C-4), 54.5 and 54.8* (CH, C-9a), 64.0* and 64.1 (quat, C-4a), 68.0 and 69.1* (CH, C-3′), 127.1 (CH, C-5 or C-8), 127.3* and 127.4 (CH, C-8 or C-5), 134.4 (CH, C-6 or C-7), 134.7 (CH, C-7 or C-6), 135.6 and 135.7* (CH, C-2 or C-3), 136.5 (quat, C-4b or C-8a), 137.7 (CH, C-3 or C-2), 139.6 (quat, C-8a or C-4b), 170.1 and 170.4* (quat, ester), 172.6 (quat, C-2′ or C-4′), 172.8 (quat, C-4′ or C-2′), 192.6* and 192.9 (quat, C-9 or C-10), 195.0 and 195.1* (quat, C-10 or C-9); IR (film) 1753 (ester), 1716 (amide), 1680 (quinone), 1591 (C=C), 1438, 1269, 1211, 1121 cm^{-1}; m/z (EI, %) 379 (M^+, 1), 314 ($M-C_5H_5$, 7), 250 (11), 186 ($C_{11}H_6O_3$, 38), 157 ($C_{10}H_5O_2$, 30), 105 (93), 44 (100); HRMS analysis (EI, M^+) ($C_{21}H_{17}O_6N$=379.1056) found m/z 379.1103. For other Lewis acids see Table 3.

*4.7.4. (3R′,1R,4S,4aS,9aS)- and (3R′,1S,4R,4aR,9aR)-Dihydro-4,4-dimethyl-2-oxo-3-furanyl 1,4,4a,9a-tetrahydro-1,4-methano-9,10-dioxo-4a-anthracenecarboxylate **12** and **13***

Compounds **12** and **13** were prepared from quinone **4** (30 mg, 0.12 mmol) and cyclopentadiene using $ZnCl_2$ (0.12 mmol), according to the standard procedure outlined above, and were isolated as a colourless solid (31 mg, 64%): mp 165–170°C; [45.3:1 ratio of diastereomers **13**:**12** (96% d.e.), the asterisk denotes resonances for the minor diastereomer **12**] ^{1}H NMR (200 MHz, $CDCl_3$) δ 0.66 and 1.09* (s, 3H, 4′-Me), 1.12 and 1.19* (s, 3H, 4′-Me), 1.71 (m, J=9.3 Hz, 1H, 11-H_A), 1.86 (d, J=9.3 Hz, 1H, 11-H_B), 3.64–3.68 (m, 1H, 1-H), 3.77 (d, J=4 Hz, 1H, 9a-H), 3.90–3.99 (m, 3H, 5′-CH_2 and 4-H), 5.34* and 5.35 (s, 1H, 3′-H), 6.01–6.10 (m, 2H, 2-H and 3-H), 7.72–7.76 (m, 2H, 6-H and 7-H), 8.02–8.09 (m, 2H, 5-H and 8-H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 19.3 and 19.7* (CH_3, 4′-Me), 22.7 and 22.9* (CH_3, 4′-Me), 40.1 and 40.2* (quat, C-4′), 48.4 (CH_2, C-11), 48.7 (CH, C-1), 52.0 and 52.5* (CH, C-4), 55.0 and 55.4* (CH, C-9a), 64.0 and 65.0* (quat, C-4a), 75.7 (CH, C-3′), 76.0 (CH_2, C-5′), 126.9 (CH, C-5 or C-8), 127.2 and 127.3* (CH, C-8 or C-5), 134.2 and 134.4* (CH, C-6 or C-7), 134.6 and 134.7* (CH, C-7 or C-6), 134.8 and 135.0* (quat, C-4b), 134.8 and 135.0* (quat, C-8a), 136.4 and 135.9* (CH, C-2 or C-3), 137.7 and 137.6* (CH, C-3 or C-2), 170.1 and 170.2* (quat, ester), 171.4 (quat, C-2′), 193.4 (quat, C-9 or C-10), 194.9 and 195.4* (quat, C-10 or C-9); IR (film) 1789 (lactone), 1756 (ester), 1681 (quinone), 1592 (C=C), 1267, 1210, 1156 cm^{-1}; m/z (EI, %) 380 (M^+, 1), 315 ($M-C_5H_5$, 12), 250, 185 ($C_{11}H_5O_3$, 59), 157 ($C_{10}H_5O_2$, 100), 66 (64); anal. found: C, 69.16; H, 5.47; $C_{22}H_{20}O_6$ requires C, 69.46; H, 5.30%. For an ORTEP diagram of **13** see Fig. 1. For other Lewis acids see Table 4.

*4.7.5. (1R′,2S′,1R,4S,4aS,9aS)- and (1R′,2S′,1S,4R,4aR,9aR)-2-Phenyl-1-cyclohexyl 1,4,4a,9a-tetrahydro-1,4-methano-9,10-dioxo-4a-anthracenecarboxylate **14** and **15***

Compounds **14** and **15** were prepared from quinone **5** (75 mg, 0.21 mmol) and cyclopentadiene using $ZnCl_2$ (0.21 mmol), according to the standard procedure outlined above, and were isolated as a colourless oil (53 mg, 60%); [35:1 mixture of diastereomers (94% d.e.), the asterisk denotes resonances for the minor diastereomer **14**], ^{1}H NMR (200 MHz, $CDCl_3$) δ 1.03–2.09 (m, 10H, 3′-CH_2, 4′-CH_2, 5′-CH_2, 6′-CH_2, 11-H_A and 11-H_B), 2.37 (ddd, J=3.6, 11.5, 11.5 Hz, 1H, 2′-H), 2.54 and 3.37* (d, J=3.9 Hz, 1H, 9a-H), 3.19–3.27 and 3.36–3.44* (m, 1H, 1-H), 3.63–3.71 (m, 1H, 4-H), 4.97 (ddd, J=4.3, 10.8, 10.8 Hz, 1H, 1′-H), 5.84–5.97 (m, 2H, 2-H and 3-H), 6.87–7.29 (m, 5H, Ph), 7.61–7.75 (m, 2H, 6-H and 7-H), 7.87–8.04 (m, 2H, 5-H and 8-H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 24.5 (CH_2, C-4′), 25.5 and 25.6* (CH_2, C-5′), 31.6 and 31.8* (CH_2, C-3′), 33.3 and 34.0* (CH_2, C-6′), 47.8* and 48.0 (CH_2, C-11), 48.0 and

48.2* (CH, C-9a), 49.5* and 49.9 (CH, C-2′), 51.9 (CH, C-1), 54.6 and 55.0* (CH, C-4), 63.9 and 64.9* (quat, C-4a), 77.6 and 78.0* (CH, C-1′), 126.6 and 127.1* (CH, C-4″), 126.4* and 126.7 (CH, C-5 or C-8), 127.0 (CH, C-8 or C-5), 127.3 (CH, C-3″), 128.3* and 128.4 (CH, C-2″), 134.0 (CH, C-6 or C-7), 134.0 (CH, C-7 or C-6), 134.6* and 134.8 (quat, C-4b or C-8a), 134.9* and 135.2 (quat, C-8a or C-4b), 136.2 and 136.4* (CH, C-2 or C-3), 137.0 (CH, C-3 or C-2), 142.4 (quat, C-1″), 169.9* and 170.2 (quat, ester), 192.6* and 193.7 (quat, C-9 or C-10), 195.5 and 196.1* (quat, C-10 or C-9); IR (film) 1739 (s, ester), 1681 (quinone), 1592 (C=C), 1222 cm^{-1}; *m/z* (CI, CH_4, rel. abundance) 427 (M^++1, 20), 361 (100), 269 (15), 203 (42), 159 (58); HRMS analysis (LSIMS, M^++1) ($C_{28}H_{27}O_4$=427.1909) found *m/z* 427.1893.

4.8. Representative procedure for fragmentation of 6–15 to 16–25

4.8.1. (−)-[3aS-(3aα,6α,7aβ),6b′R,9a′R]-Hexahydro-8,8-dimethyl-1-[5′-hydroxy-6b′,7′,9a′-trihydrocyclopenta[b]-naphtho[1,2-d]furan-6′-oyl]-3H-3a,6-methano-2,1-benzisothiazole-2,2-dioxide **18**

A solution of Diels–Alder adduct **8** (11 mg, 0.02 mmol) in dichloromethane (3 mL) cooled to 0°C, was treated with tin(IV) chloride (4 mg) and stirred for 10 min. The mixture was then diluted with dichloromethane (5 mL) and washed with 10% sodium hydrogen carbonate solution (2×5 mL). The organic layer was dried over $MgSO_4$ and the solvent removed *in vacuo*. Purification of the resultant residue by flash chromatography (hexane:ethyl acetate, 3:1) afforded the title compound **18** as a yellow oil (10 mg, 98%): $[\alpha]_D$=−136.0 (*c*=0.4, CH_2Cl_2); ^{1}H NMR (200 MHz, $CDCl_3$) δ 0.93 (s, 3H, 8-Me_A), 1.10 (s, 3H, 8-Me_B), 1.20–2.33 (m, 7H, 6-CH, 7-CH_2, 4-CH_2 and 5-CH_2), 2.39 (dd, *J*=17.4, 2.0 Hz, 1H, 7′-H_B), 2.96 (dd, *J*=17.4, 8.5 Hz, 1H, 7′-H_A), 3.39 (d, *J*=15.3 Hz, 1H, 3-H_A), 3.47–3.64 (m, 1H, 7a-H), 4.08 (d, *J*=15.3 Hz, 1H, 3-H_B), 4.43 (ddd, *J*=8.5, 8.5, 2.0 Hz, 1H, 6b′-H) 6.00–6.17 (m, 3H, 8′-H, 9′-H and 9a′-H), 7.46–7.64 (m, 2H, 2′-H and 3′-H), 7.97 (d, *J*=7.7 Hz, 1H, 1′-H), 8.10 (d, *J*=7.8 Hz, 1H, 4′-H), 11.23 (s, 1H, OH); ^{13}C NMR (50 MHz, $CDCl_3$) δ 20.7 (CH_3, 8-Me_A), 20.8 (CH_3, 8-Me_B), 26.7 (CH_2, C-5), 32.0 (CH_2, C-4), 39.6 (CH_2, C-7), 39.9 (CH, C-6), 43.0 (CH_2, C-7′), 44.5 (CH, C-6b′), 49.6 (quat, C-8), 50.4 (quat, C-3a), 53.7 (CH_2, C-3), 59.8 (CH, C-7a), 94.3 (CH, C-9a′), 103.6 (quat, C-6′), 120.6 (quat, C-6a′), 121.7 (quat, C-4a′ or C-10b′), 121.9 (CH, C-1′ or C-4′), 124.1 (CH, C-4′ or C-1′), 127.1 (CH, C-2′ or C-3′), 127.4 (CH, C-3′ or C-2′), 128.3 (quat, C-10b′ or C-4a′), 129.7 (CH, C-8′), 135.3 (CH, C-9′), 153.6 (quat, C-10a′), 158.8 (quat, C-5′), 168.2 (quat, amide); IR (film, NaCl) 1657 (C=O), 1596 (C=C), 1372, 1261, 1172 cm^{-1}; *m/z* (LSIMS, %) 466 (M^++1, 13), 400 ($C_{21}H_{23}O_5NS$, 39), 250 (69), 216 (26), 186 (100); HRMS analysis (LSIMS, M^++1) ($C_{26}H_{29}O_5NS$=466.1688) found *m/z* 466.1672.

4.8.2. (3′S,6bR,9aR)-1-Methyl-2,5-dioxo-3-pyrrolidinyl 5-hydroxy-6b,7,9a-trihydrocyclopenta[b]-naphtho[1,2-d]furan-6-carboxylate **21**

Compound **21** was prepared by fragmentation of **11** (24 mg) using $SnCl_4$ (1 equiv.) and was isolated as a colourless oil (23 mg, 95%): (2.7:1 ratio, the asterisk denotes resonances for the minor diastereomer **20**), ^{1}H NMR (200 MHz, $CDCl_3$) δ 2.43–2.53 (m, 1H, 7-H_B), 2.73–3.10 (m, 2H, 4′-H_A and 7-H_A), 3.37 (dd, *J*=18.4, 8.6 Hz, 1H, 4′-H_B), 4.53 (ddd, *J*=8.5, 8.5, 3.0 Hz, 1H, 6b-H), 5.79 (dd, *J*=4.7, 8.6 Hz, 1H, 3′-H), 5.87–6.12 (m, 3H, 8-H, 9-H and 9a-H), 7.43–7.53 (m, 1H, 2-H or 3-H), 7.55–7.65 (m, 1H, 3-H or 2-H), 7.86 (d, *J*=7.3 Hz, 1H, 1-H), 8.33 (d, *J*=8.4 Hz, 1H, 4-H), 11.38 and 11.41* (s, 1H, OH); ^{13}C NMR (50 MHz, $CDCl_3$) δ 25.2 (CH_3, N–Me), 35.9* and 36.1 (CH_2, C-4′), 42.2 and 42.4* (CH_2, C-7), 46.7 (CH, C-6b), 68.1 and 68.5* (quat, C-3′), 92.1* and 92.3 (CH, C-9a), 101.5 (quat, C-6), 119.2* and 119.3* (quat, C-6a), 121.7 (CH, C-1 or C-4), 124.5 (CH, C-4 or C-1), 124.7 (quat, C-4a or C-10b), 125.2

(quat, C-10b or C-4a), 126.0 (CH, C-2 or C-3), 129.0 (CH, C-3 or C-2), 129.5* and 129.8 (CH, C-8), 135.9* and 136.5 (CH, C-9), 146.4 (quat, C-10a), 157.4 (quat, C-5), 169.9 (quat, ester), 172.6 (quat, C-2′ or C-4′), 173.0 (quat, C-4′ or C-2′); IR (film) 1714 (s, amide and ester), 1666, 1595 (C=C), 1439, 1386, 1285, 1223 cm^{-1}; *m/z* (EI, %) 379 (M^+, 9), 250 ($C_{16}H_{10}O_3$, 100), 221 (13), 165 (36); HRMS analysis (EI, M^+) ($C_{21}H_{17}O_6N$=379.1056) found *m/z* 379.1009.

4.8.3. (3′R,6bR,9aR)-Dihydro-4,4-dimethyl-2-oxo-3-furanyl 5-hydroxy-6b,7,9a-trihydrocyclopenta[b]-naphtho[1,2-d]furan-6-carboxylate **23**

Compound **23** was prepared by fragmentation of **13** (20 mg, 0.05 mmol) using $SnCl_4$ (1 equiv.) and was isolated as a yellow oil (13 mg, 65%): ^{1}H NMR (200 MHz, $CDCl_3$) δ 1.25 (s, 3H, 4′-Me), 1.30 (s, 3H, 4′-Me), 2.63 (dd, *J*=18.2, 2.7 Hz, 1H, 7-H_B), 3.33 (dd, *J*=18.2, 8.5 Hz, 1H, 7-H_A), 4.07–4.22 (m, 2H, 5′-H_A and 5′-H_B), 4.47 (ddd, *J*=8.5, 8.5, 2.7 Hz, 1H, 6b-H), 5.86 (s, 1H, 3′-H), 5.92–6.13 (m, 3H, 8-H, 9-H and 9a-H), 7.45–7.55 (m, 1H, 2-H or 3-H), 7.56–7.67 (m, 1H, 3-H or 2-H), 7.88 (d, *J*=8.0 Hz, 1H, 1-H), 8.37 (d, *J*=7.9 Hz, 1H, 4-H), 11.63 (s, 1H, OH); ^{13}C NMR (50 MHz, $CDCl_3$) δ 20.5 (CH_3, 4′-Me), 23.2 (CH_3, 4′-Me), 40.5 (quat, C-4′), 42.2 (CH_2, C-7), 46.7 (CH, C-6b), 75.7 (CH, C-3′), 76.3 (CH_2, C-5′), 92.3 (CH, C-9a), 101.6 (quat, C-6), 119.4 (quat, C-6a), 121.7 (CH, C-1 or C-4), 124.5 (CH, C-4 or C-1), 124.8 (quat, C-4a or C-10b), 125.2 (quat, C-10b or C-4a), 126.0 (CH, C-2 or C-3), 128.7 (CH, C-3 or C-2), 129.7 (CH, C-8), 136.8 (CH, C-9), 146.4 (quat, C-10a), 157.5 (quat, C-5), 169.9 (quat, ester), 171.6 (quat, C-2′); IR (film) 1789 (lactone), 1744 (ester), 1665, 1596 (C=C), 1385, 1294, 1153 cm^{-1}; *m/z* (EI, %) 380 (M^+, 16), 250 ($C_{16}H_{10}O_3$, 100), 221 (26), 165 (62), 71 (59); HRMS analysis (EI, M^+) ($C_{22}H_{20}O_6$=380.1260) found *m/z* 380.1260.

4.8.4. (+)-(1′R,2′S,6bR,9aR)-2-Phenyl-1-cyclohexyl 5-hydroxy-6b,7,9a-trihydrocyclopenta[b]-naphtho[1,2-d]furan-6-carboxylate **25**

Compound **25** was prepared by fragmentation of **15** (40 mg, 0.09 mmol) using $SnCl_4$ (1 equiv.) and was isolated as a yellow oil (39 mg, 98%, 94% d.e.): $[\alpha]_D$=+77.2 (*c*=0.58, CH_2Cl_2); ^{1}H NMR (200 MHz, $CDCl_3$) δ 1.01–2.39 (m, 9H, 3′-CH_2, 4′-CH_2, 5′-CH_2, 6′-CH_2′ and 7-H_B), 2.56 (dd, *J*=17.9, 8.5 Hz, 1H, 7-H_A), 2.94 (ddd, *J*=3.2, 11.1, 11.1 Hz, 1H, 2′-H), 4.40 (ddd, *J*=8.6, 8.6, 3.0 Hz, 1H, 6b-H), 5.61–5.78 (m, 1H, 1′-H), 5.79–6.01 (m, 3H, 8-H, 9-H and 9a-H), 7.10–7.35 (m, 5H, Ph), 7.38–7.60 (m, 2H, 2-H and 3-H), 7. 82 (d, *J*=8.3 Hz, 1H, 1-H), 8.31 (d, *J*=8.2 Hz, 1H, 4-H), 12.02 (s, 1H, OH); ^{13}C NMR (50 MHz, $CDCl_3$) δ 24.8 (CH_2, C-4′), 25.8 (CH_2, C-5′), 32.8 (CH_2, C-3′), 36.0 (CH_2, C-6′), 42.4 (CH_2, C-7), 46.7 (CH, C-6b), 49.6 (CH, C-2′), 75.9 (CH, C-1′), 92.0 (CH, C-9a), 103.0 (quat, C-6), 119.8 (quat, C-6a), 121.5 (CH, C-1 or C-4), 124.3 (CH, C-4 or C-1), 124.5 (quat, C-4a or C-10b), 124.8 (quat, C-10b or C-4a), 125.5 (CH, C-9), 126.6 (CH, C-2 or C-3), 127.2 (CH, C-4″), 128.5 (CH, C-3″), 128.9 (CH, C-2″), 128.9 (CH, C-3 or C-2), 136.5 (CH, C-8), 142.9 (quat, C-1″), 145.9 (quat, C-10a), 156.4 (quat, C-5), 170.5 (quat, ester); IR (film) 1643 (ester), 1595 (C=C), 1389, 1232, 1169 cm^{-1}; *m/z* (EI, %) 426 (M^+, 28), 268 (58), 250 (87), 165 (32), 91 (C_7H_7, 100); HRMS analysis (EI, M^+) ($C_{28}H_{26}O_4$=426.1831) found *m/z* 426.1813.

4.9. Representative procedure for removal of chiral auxiliaries

4.9.1. (6bR,9aR*)-6-Formyl-6b,9a-dihydro-5-hydroxy-7H-cyclopenta[b]naphtho[1,2-d]furan* **27**

Camphorsultam **18** (12 mg, 0.026 mmol) was dissolved in THF (2 mL) and lithium borohydride (0.4 mg, 2 equiv.) in THF (0.5 mL) added dropwise. After stirring for 30 min, the solvent was removed under reduced pressure and the residue redissolved in dichloromethane (5 mL). The solution was washed with 10% sodium hydrogen carbonate solution (2×2 mL) and dried over $MgSO_4$. The solvent was then removed *in vacuo* and the crude product purified by flash chromatography (hexane:ethyl acetate, 4:1) to give the title compound (**27A**) as a yellow solid (4 mg, 61%): mp 127–130°C; $[\alpha]_D=-90.0$ (c=0.40, CH_2Cl_2); ^1H NMR (200 MHz, $CDCl_3$) δ 2.64 (dd, J=17.2, 2.5 Hz, 1H, 7-H_B), 3.07 (dd, J=17.2, 8.2 Hz, 1H, 7-H_A), 4.52 (ddd, J=8.5, 8.5, 2.5 Hz, 1H, 6b-H), 5.96–6.12 (m, 3H, 8-H, 9-H and 9a-H), 7.43–7.53 (m, 1H, 2-H or 3-H), 7.58–7.68 (m, 1H, 3-H or 2-H), 7.86 (d, J=7.3 Hz, 1H, 1-H), 8.37 (d, J=8.2 Hz, 1H, 4-H), 10.07 (s, 1H, CHO), 12.59 (s, 1H, OH); ^{13}C NMR (50 MHz, $CDCl_3$) δ 41.3 (CH_2, C-7), 43.1 (CH, C-6b), 93.4 (CH, C-9a), 110.6 (quat, C-6), 119.7 (quat, C-6a), 121.8 (CH, C-1 or C-4), 124.9 (CH, C-4 or C-1), 124.9 (quat, C-4a or C-10b), 126.0 (quat, C-10b or C-4a), 126.0 (CH, C-2 or C-3), 129.5 (CH, C-3 or C-2), 130.4 (CH, C-8), 135.1 (CH, C-9), 149.5 (quat, C-10a), 157.8 (quat, C-5), 193.5 (CH, CHO); IR (film) 1634 (CHO), 1570 (C=C), 1378, 1292 cm^{-1}; m/z (EI, %) 252 (M^+, 100), 237 (21), 221 (27), 165 (25), 147 (25); HRMS analysis (EI, M^+) ($C_{16}H_{12}O_3$=252.0786) found m/z 252.0788.

4.9.2. (3aR,5R,11bS)-3a,5,11b-Trihydro-5-hydroxy-1H-cyclopenta[b]naphtho[2,3-d]pyran-6,11-dione ***28***

Aldehyde **27** (90 mg, 0.36 mmol) and silver(II) oxide (180 mg, 1.45 mmol) were mixed in dioxane (6.0 mL) and nitric acid (1.36 M, 1.60 mL) was added. After stirring the resultant mixture for 5 min, further portions of silver(II) oxide (180 mg, 1.45 mmol) and nitric acid (1.36 M, 1.60 mL) were added. Stirring was then continued for 10 min and water (12 mL) added. The aqueous layer was extracted with dichloromethane (2×10 mL), washed with water (10 mL), dried ($MgSO_4$) and the solvent removed under reduced pressure. The residue was purified by flash chromatography (hexane:ethyl acetate, 4:1), affording the title compound **28** as a pale yellow oil (22 mg, 23%): $[\alpha]_D=+96.0$ (c=0.3, CH_2Cl_2); ^1H NMR (200 MHz, $CDCl_3$) δ 2.25–2.46 (m, 1H, 1-H_A or 1-H_B), 2.97–3.20 (m, 2H, 1-H_B or 1-H_A and 11b-H), 5.11–5.22 (m, 1H, 3a-H), 5.91–6.07 (m, 1H, 2-H or 3-H), 6.16 (s, 1H, 5-H), 6.22–6.29 (m, 1H, 3-H or 2-H), 7.69–7.81 (m, 2H, 8-H and 9-H), 8.05–8.19 (m, 2H, 7-H and 10-H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 34.8 (CH, C-11b), 37.4 (CH_2, C-1), 73.5 (CH, C-3a), 97.5 (CH, C-5), 126.3 (CH, C-7), 126.3 (CH, C-10), 129.2 (CH, C-2 or C-3), 131.6 (quat, C-6a or C-10a), 131.9 (quat, C-10a or C-6a), 133.8 (CH, C-8 or C-9), 134.0 (CH, C-9 or C-8), 139.0 (CH, C-3 or C-2), 139.6 (quat, C-11a), 144.6 (quat, C-5a), 183.0 (quat, C-6 or C-11), 184.8 (quat, C-11 or C-6); IR (film) 3438 (OH), 1726 (C=O), 1663 (C=O), 1594 (C=C), 1326, 1296, 1161 cm^{-1}; m/z (EI, %) 268 (M^+, 14), 252 (100), 209 (65), 152 (52), 105 (75), 76 (85); HRMS analysis (EI, M^+) ($C_{16}H_{12}O_4$=268.0736) found m/z 268.0731.

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