Formal Asymmetric Synthesis of Pentalenolactone E and Pentalenolactone F 1. Retrosynthesis and π-Facial Differentiation in Palladium-Catalyzed and Dipolar [3 + 2]-Cycloaddition Reactions of Bicyclic Alkenes: Evidence for Electrostatic Control of Stereoselectivity

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Received August 25, 1997

Keywords: Pentalenolactones E and F / Palladium / [3 + 2]-Cycloaddition reactions / π-Facial differentiation / Electrostatic interaction

A successful new strategy for the asymmetric synthesis of pentalenolactone E (**2a**) and pentalenolactone F (**2b**) has been developed. This strategy involves the assembly of ring A of **2a** and **2b** through a Binger-type Pd-catalyzed [3 + 2]-cycloaddition reaction of diquinene **7** with the diphenyl-substituted methylenecyclopropane **18**. Diquinene **7** is available in an enantiomerically pure state in 8 steps from diester **8** by using a pig liver esterase catalyzed enantioselective hydrolysis as the key step. Unexpected facial selectivities of 1,3-dipolar and Pd-catalyzed [3 + 2]-cycloaddition reactions as well Michael reactions of **7** have been observed. Thus, **7** reacted with CH_2N_2 with a stereoselectivity of 98% or greater in favour of reaction at the concave side, with formation of the cisoid triquinane **27**. A Trost-type Pd-catalyzed reaction of **7** with **11** gave the transoid triquinane **6** and the cisoid triquinane **12** in ratios of 1:1.7 to 1:5.3 depending on the polarity of the solvent. Binger-type Pd-catalyzed cycloaddition reactions of **7** with methylenecyclopropane (**13**) in toluene afforded a mixture of **6** and **12** in a ratio of 1:7. In the Pd-catalyzed reaction of **7** with the phenyl-substituted methylenecyclopropanes **14a/b** the cisoid triquinane **15** was obtained with a selectivity of 6.7:1 or above. Pd-catalyzed reactions of **7** with the disubstituted methylenecyclopropanes **16** and **18** gave, however, the transoid triquinanes **17** and **19**, respectively, with selectivities of 23:1 and 7:1, respectively. Nakamura-type cycloaddition of **7** to the methylenecyclopropanone ketal **20** led to the quantitative formation of the transoid triquinane **21a** and the cisoid triquinane **22a** in a ratio of 1:2. The structures of cycloadducts **12**, **15**, **19** and **27** were determined by X-ray analyses. The π-facial differentiation may be ascribed mainly to a stabilization of the concave transition states by an electrostatic interaction between the lactone carbonyl group and the nucleophilic reagents. The stereoselectivity model proposed has been substantiated by a study of the analogous cycloaddition reactions of diquinenes **29a**−**c**, which exhibited only a low π-facial stereoselectivity, and by an X-ray structure analysis of **7**, which revealed a slight concave pyramidalization of the double bond. X-ray structure analysis and NMR spectroscopy of diquinane **28a** showed the $_5$E-conformation, in which the hydroxy group occupies the pseudoaxial position, to be the more stable one. According to force-field calculations, the $_5$E-conformation seems to be stabilized by an intramolecular electrostatic interaction between the hydroxylic oxygen atom and the lactone carbonyl group, corresponding to the initial step of an intermolecular nucleophilic attack at the carbonyl group. The O−C1 distance and the O−C1−O angle found in the crystal structure of **28a** support this notion.

Introduction

The isolation of pentalenolactone (**1**) from a *Streptomyces* broth culture by Celmer et al. in 1957[1] marked the beginning of the discovery of a whole family of pentalenolactones. Today, these encompass besides **1** the pentalenolactones A, B, D, E (**2a**), F (**2b**), G, H, O, and P[2][3] (Figure 1). As exemplified by **1** and **2**, the structural diversity of the

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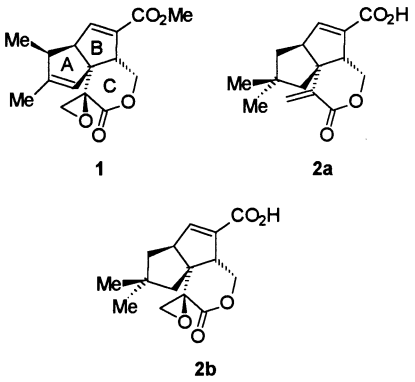
Figure 1. Pentalenolactone and pentalenolactones E and F



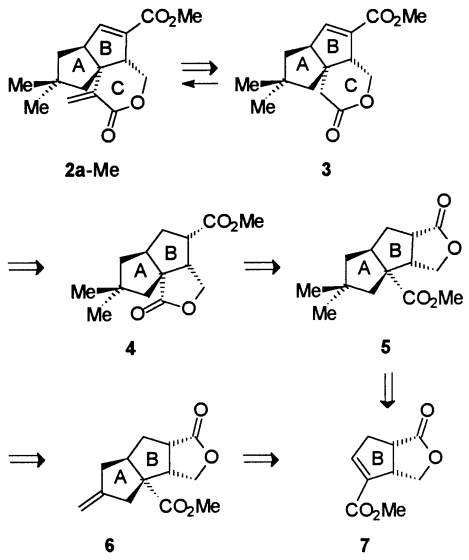
pentalenolactones arises from variations in ring A and of the group in the α-position of the carbonyl group in ring C.

Because of their broad spectrum of biological activities and unique structures, as well as their origin and interesting mode of biosynthesis, pentalenolactones have attracted considerable attention from both organic and bioorganic chemists, as well as from microbiologists. Biological studies have revealed antibiotic, antiviral, antitumor and glycolysis inhibitory activities[4]. Biosynthetic studies disclosed the sesquiterpenoid origin of the pentalenolactones and established the hydrocarbon pentalenene as the parent compound of the pentalenolactone family[2]. Pentalenolactones are rare examples of sesquiterpenoids produced by prokaryotes. Besides the biological and biosynthetic aspects, the synthetic challenge presented by these tricyclic diquinanoids has led to several highly interesting synthetic approaches. A number of elegant syntheses of racemic **1**[5], **2a**[6], **2b**[6c][6d], pentalenolactone G[7], deoxynorpentalenolactone H[8] and pentalenolactone P[9], employing markedly diverse strategies and new methodologies, have been accomplished[10]. However, despite these efforts, there is only one synthesis of a pentalenolactone in an optically active form, **2a**, by Mori et al.[6i] The synthesis of **2a**, featuring a microbiological kinetic resolution for the attainment of a chiral intermediate, starts from a commercially available starting material, requires 32 steps and proceeds in 0.1% overall yield. We report herein and in the following article[11] on a formal asymmetric synthesis of **2a** and **2b** by a new strategy, the key steps of which are an enantioselective enzyme catalysis for the attainment of the first chiral intermediate of the synthetic sequence and a Pd-catalyzed [3 + 2] cycloaddition for the construction of the diquinane skeleton. Pentalenolactones **2a** and **2b** were selected as targets because of the central role they apparently play in the biosynthesis of the other members of the pentalenolactone family and because of their limited accessibility by fermentation. The route described should also allow the asymmetric synthesis of pentalenolactones B, G and H. In the course of our investigations we observed unexpected π-facial stereoselectivities in [3 + 2]-cycloaddition reactions of bicyclic alkenes. In the following we also report the results of these studies and propose a rationalization for the π-facial differentiation observed.

Results and Discussion

Retrosynthetic Analysis and Strategy: In view of the successful conversions of the tricyclic lactone **3** to **2a**-Me[6a][6b][6c][6i], of *rac*-**2a**-Me to *rac*-**2b**-Me[6d] and of *rac*-**2a**-Me to *rac*-**2a**[6c], we selected **3** as the primary target of our synthetic studies (Scheme 1). Scheme 1 shows the retrosynthetic analysis of **3** on which the synthetic strategy was based. Thus, removal of the double bond and ring contraction led, retrosynthetically, to the angular triquinane **4**[12]. A rearrangement of **4** to the linear triquinane **5** and substitution of the geminal methyl groups by a methylene unit gave the linear triquinane **6**. Retrosynthetic disassembly of ring A in **6** and introduction of the double bond pointed to the generation of diquinene **7**[12] as a possible precursor. The latter was considered a good candidate for obtaining, in the synthetic direction, triquinane **6** by a Pd-catalyzed Binger-[13] or Trost-type[14] [3 + 2] cycloaddition[15]. Alternatively, a [3 + 2] annulation of **7** in a stepwise fashion via Michael reaction and intramolecular alkylation under direct formation of **5** could be envisaged[16]. Because of the *cis*-ring fusion in **7**, the steric differentiation between the convex and the concave side[10] should be such as to allow for a highly stereoselective conversion of diquinene **7** to triquinane **6**. The angular triquinane **4** is a key intermediate of our retrosynthetic analysis of **3**. This compound should not only, on grounds of ring strain, allow the regioselective introduction of the double bond of ring B by the selenoxide method[17], but also allow a subsequent homologation of the γ-lactone ring by a selective reduction of the lactone group and a subsequent Horner-Wadsworth-Emmons reaction[18]. A crucial step of this strategy was the rearrangement of the linear triquinane **5** to the angular triquinane **4** in the synthetic direction.

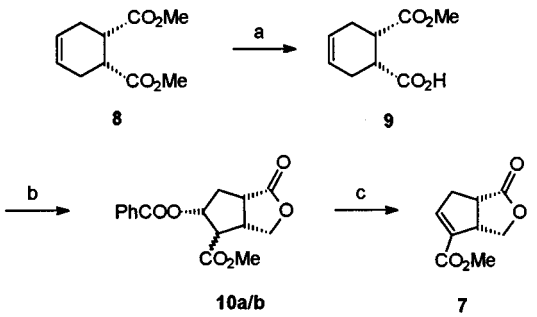
Scheme 1



Synthesis of Diquinene **7***:* The key step in the synthesis of **7** is the pig liver esterase (PLE) catalyzed enantioselective hydrolysis of diester **8**, which affords half-ester **9** with 98% or greater *ee* in 95% yield (Scheme 2)[19]. We have shown

that this reaction can be carried out, if desired, on a multimole scale with practically the same results[19e]. Half-ester **9** had already been converted to a mixture of the epimeric diquinane esters **10a,b** by a seven-step sequence (35% overall yield from **9**), which has been optimized for a mole scale[20]. Treatment of esters **10a,b** with 1,8-diazabicyclo[4.3.0]undec-7-ene (DBU) at room temperature gave diquinene **7** in 93% yield.

Scheme 2

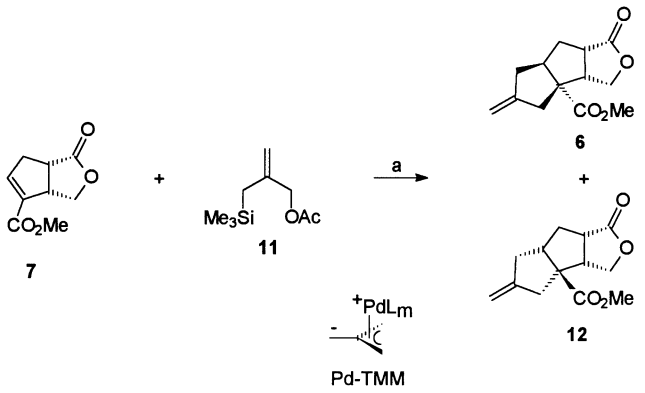


Reagents and conditions: (a) PLE, H_2O, ref[19f]; (b) ref[20]; (c) DBU, THF, 0°C → room temp.

Pd-Catalyzed and Dipolar [3 + 2]-Cycloaddition Reactions of Bicyclic Alkenes (Diquinenes): As part of the planned synthesis of **3**, we needed a method to annulate the five-membered ring of **6** to diquinene **7** in a stereoselective manner. The most elegant way of doing this seemed to us to be the application of one of the aforementioned [3 + 2]-cycloaddition routes. Methylenecyclopropanes are powerful reagents for methylenecyclopentane synthesis in Ni- or Pd-catalyzed [3 + 2] cycloadditions to electron-deficient olefins and some non-activated alkenes[13]. Parallel to this method, a second route to methylenecyclopentanes by a Pd-catalyzed [3 + 2] cycloaddition has been developed, using the allylic acetate **11** as a precursor for the formation of the palladium-trimethylenemethane species Pd−TMM[14]. Both complementary methods have been applied in the synthesis of a wide range of substituted methylenecyclopentanes. We were confident of achieving the stereoselective transformation of **7** to **6** since two examples of highly stereoselective Pd-catalyzed [3 + 2]-cycloaddition reactions of cisoid di- and triquinenes from the convex side have been described previously[21]. Reaction of diquinene **7** with **11** in THF, according to Trost's procedure[14], led to the isolation of a mixture of the transoid triquinane **6** and the cisoid triquinane **12** in a ratio of 1:3 in 81% yield (Scheme 3) (Table 1). Diastereomers **6** and **12** were separated, and the structure of the major isomer **12** was determined by X-ray analysis (Figure 2)[22]. Thus, to our surprise and disappointment, reaction of **7** with Pd−TMM had occurred preferentially from the sterically more hindered concave side, yielding the triquinane with the non-natural configuration as the major product.

The solvent had a significant influence on the stereoselectivity of the cycloaddition reaction (Table 1). In the least polar solvent, the amount of the cisoid triquinene **12** was the highest. When methylenecyclopropane (**13**) was used as

Scheme 3



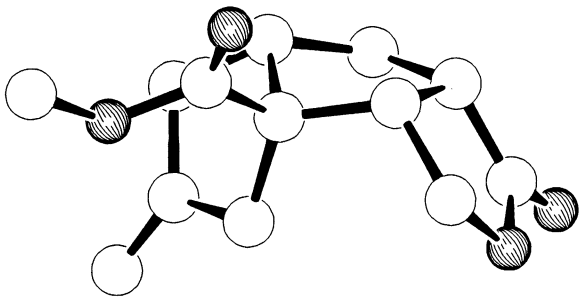
Reagents and conditions: (a) $Pd(OAc)_2$, PPh_3, THF, reflux.

Table 1. Diastereomer ratios in Pd-catalyzed cycloaddition reactions of diquinene **7**

Reagent	Triquinane transoid	Triquinane cisoid	dr
11	**6**	**12**	1:5.3[a]
	6	**12**	1:4.8[b]
	6	**12**	1:3[c]
	6	**12**	1:1.7[d]
13	**6**	**12**	1:7
14		**15**	≤1:≥6.7
16	**17**		≥23:≤1
18	**19**		≥7:≤1
20[e]	**21a**	**22a**	1:2

[a] In toluene. – [b] In diglyme. – [c] In THF. – [d] In DMF. – [e] Without Pd catalysis.

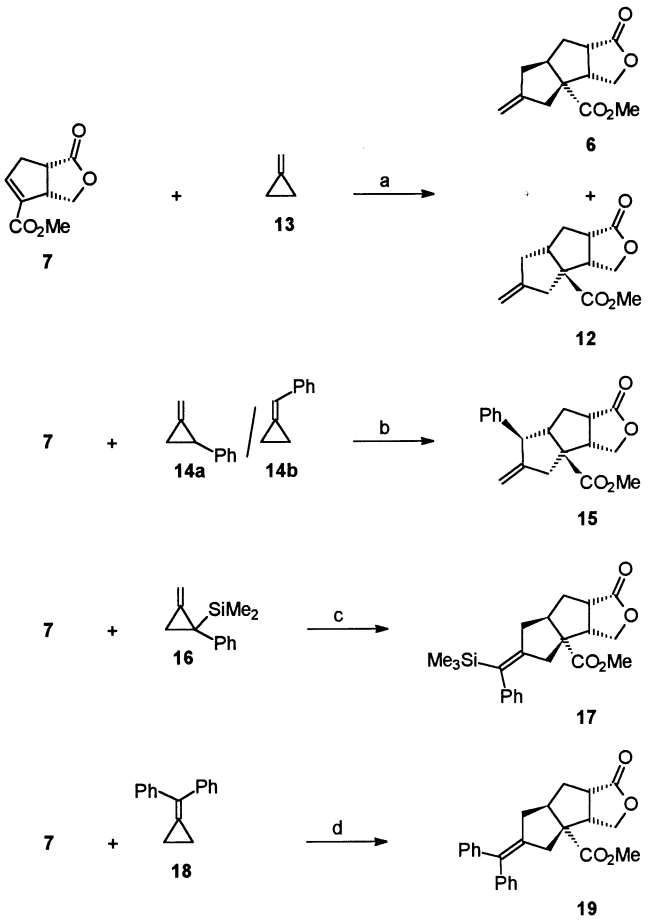
Figure 2. Crystal structure of **12**



the three-carbon component in the Pd-catalyzed cycloaddition[13] of **7**, similar results were obtained (Scheme 4). Heating a mixture of **7** and **13** in the presence of 4 mol% of Pd(Cp)(allyl)/P(*i*Pr)$_3$ (1:1) in toluene to 120°C for 5 h furnished a mixture of **6** and **12** in a ratio of 1:7 in 77% yield.

In order to determine the possible influence of substituents in derivatives of **13** on the stereochemistry of the cycloaddition reaction, we studied the cycloaddition of **7** to the methylenecyclopropane derivatives **14a,b**, **16** and **18**[13b]. Diquinene **7** reacted readily with **14a** in the presence of Pd(Cp)(allyl)/P(*i*Pr)$_3$ (1:1) as catalyst. After heating the reaction mixture to 110°C for 1 h in toluene, a mixture of four [3 + 2] cycloadducts was obtained in 81% yield, in which the cisoid triquinane **15** (87%) dominated. Almost

Scheme 4



Reagents and conditions: (a) Pd(Cp)(allyl), P(iPr)$_3$, toluene, 120°C; (b) Pd(Cp)(allyl), P(iPr)$_3$, toluene, 110°C; (c) Pd(Cp)(allyl), P(iPr)$_3$, o-xylene, 120°C; (d) Pd(Cp)(allyl), P(iPr)$_3$, toluene, 140°C.

the same result was obtained when the isomeric methylenecyclopropane **14b** was used. Cycloadduct **15** could be isolated in 66% (53%) yield. The structure of triquinane **15** was determined by X-ray analysis (Figure 3)[22]. It is worthy to note that in the major isomer **15** the phenyl group is located at a ring position. In all other Pd-catalyzed [3 + 2] cycloadditions with **14a,b** examined to date, the major cycloadduct has had the phenyl group located at the exocyclic double bond[13].

Faced with these results we investigated the reactions of **7** with the disubstituted methylenecyclopropanes **16** and **18**. We hoped that the cycloaddition reactions of **7** with the sterically more demanding Pd−TMMs derived from **16** and **18** would take a different course and lead perhaps to a preferential ring annulation from the convex side. Indeed, reaction of **7** with **16** under the usual conditions afforded in 48% yield a mixture of cycloadducts in a ratio of 94:4:3, in which the transoid triquinane **17** dominated. The configuration of **17** was determined by NOE experiments and by analysis of the vicinal coupling constants. Separation of **17** from the isomers and further by-products by crystallization, however, proved difficult. Eventually, greater success was achieved in the Pd-catalyzed cycloaddition of **7** to the diphenyl-substituted methylenecyclopropane **18**. Reaction of **7** with **18** in toluene solution at 120°C for 8 h under the usual conditions gave a mixture of three isomers in 75% yield, which contained 88% of the desired transoid triquinene **19**. The diastereomerically pure triquinane **19** could be isolated from this mixture through crystallization in 51% yield as colorless crystals. The structure of **19** was determined by X-ray analysis (Figure 4)[22].

Figure 3. Crystal structure of **15**

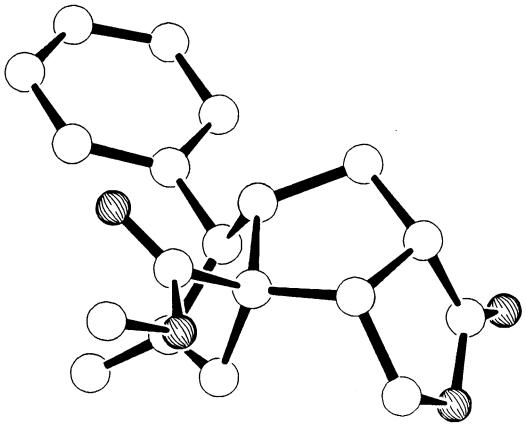
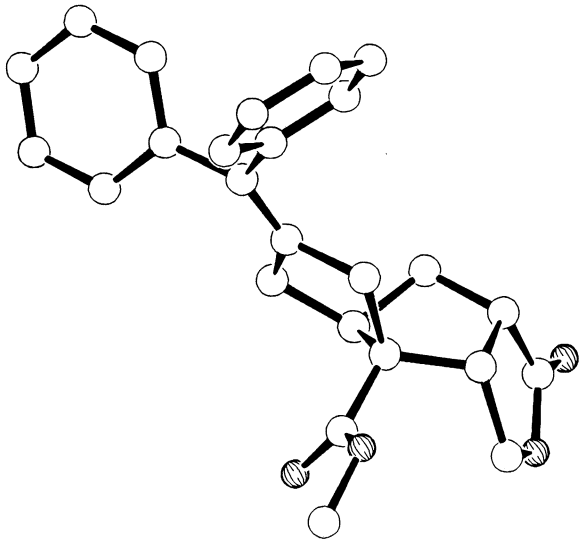
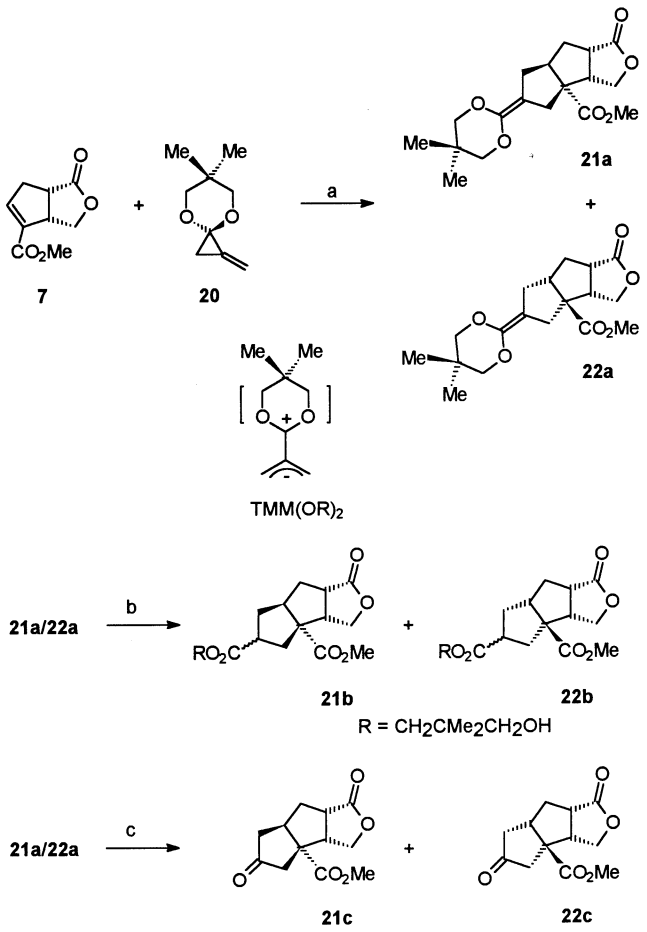


Figure 4. Crystal structure of **19**



The unexpected stereochemical course of the Pd-catalyzed reactions of diquinene **7** with **11**, **13** and **14a,b** prompted us to study the cycloaddition of **7** to the methylenecyclopropanone ketal **20** (Scheme 5)[23]. Ketal **20** serves as a precursor for TMM(OR)$_2$, which reacts with alkenes in a [3 + 2] cycloaddition. Heating a mixture of **7** and **20** in MeCN to 80°C led to the formation of cycloadducts **21a** and **22a** in a ratio of 1:2, in practically quantitative yield. Thus, here too, the dipolar molecule TMM(OR)$_2$ approaches the double bond of **7** preferentially from the concave side. The structures of the ketene acetals **21a** and **22a**, which were rapidly hydrolyzed to esters **21b** and **22b**, respectively, upon attempted chromatographic separation on silica

Scheme 5



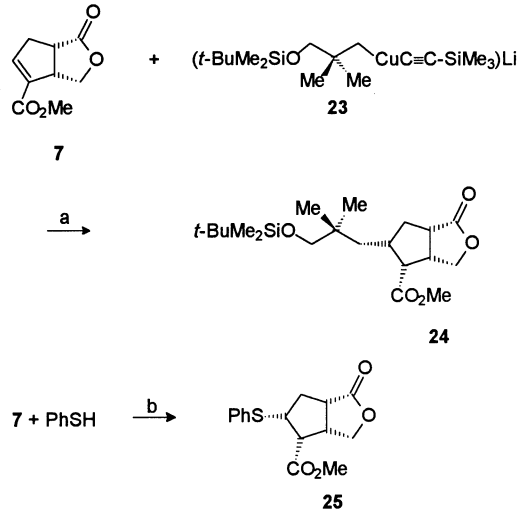
Reagents and conditions: (a) MeCN, 80°C; (b) silica gel, H_2O, EtOAc/*n*-hexane; (c) O_3, CH_2Cl_2, −70°C; 2. Me_2S.

gel[23c], were determined through ozonolysis to ketones **21c** and **22c**, respectively[11].

In view of these stereochemical results, it seems important to note that not only cycloaddition but also Michael reactions of **7** took an unexpected steric course. Thus, reaction of **7** with cuprate **23**[16], which was investigated in order to explore the possibility of a stepwise ring A annulation, gave exclusively adduct **24** in 16% yield (43% conversion) (Scheme 6). Similarly, addition of PhSH to **7** in the presence of NEt_3 afforded sulfide **25** in 39% yield as the major isomer besides three further unidentified isomers in 11, 3 and 2% yield (62% conversion). The configurations of **24** and **25** were determined by NOE experiments in combination with an analysis of the vicinal coupling constants.

In view of the current high level of interest in the factors responsible for the diastereofacial differentiation of additions to alkenes[24], and in an attempt to provide more insight into the present case, we decided to determine the facial selectivity of a typical 1,3-dipolar cycloaddition reaction of **7**. 1,3-Dipolar cycloaddition reactions are perhaps less complex[25] than cycloaddition reactions of Pd−TMM and are thus easier to interpret stereochemically. Thus, CH_2N_2 was selected as a dipolar molecule. Reaction of **7**

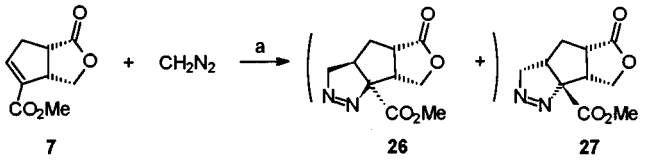
Scheme 6



Reagents and conditions: (a) Me_3SiCl, Et_2O, THF, −70°C → 10°C; (b) NEt_3, THF, room temp.

with an excess of CH_2N_2 in diethyl ether at room temperature proceeded smoothly and gave the cisoid triquinane **27** as the sole isomer in 98% yield (Scheme 7). Formation of the transoid isomer **26** or of regioisomers could not be detected (vide infra). Thus, the regio- and diastereoselectivity of the cycloaddition is judged to be 98% or greater.

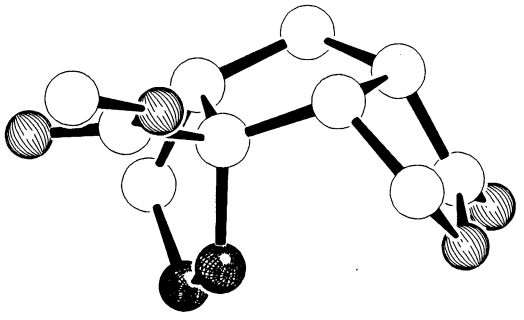
Scheme 7



Reagents and conditions: (a) Et_2O, room temp.

An X-ray analysis of **27** (Figure 5) proved the cisoid configuration of the triquinane skeleton[22]. Thus, with the small dipole CH_2N_2, cycloaddition had occurred exclusively at the concave side of **7**, with high regioselectivity.

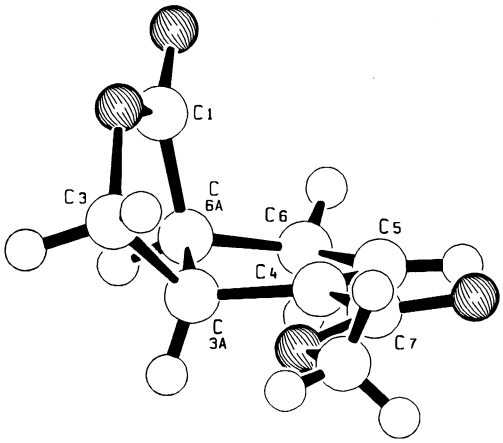
Figure 5. Crystal structure of **27**



To permit a rationalization of the stereochemical preference of the reactions of alkene **7**, we started with the determination of its structure by X-ray analysis (Figure 6)[22]. Not surprisingly, in the crystal diquinene **7** adopts a *gauche* conformation with regard to the C3a−C6a bond (3aH−

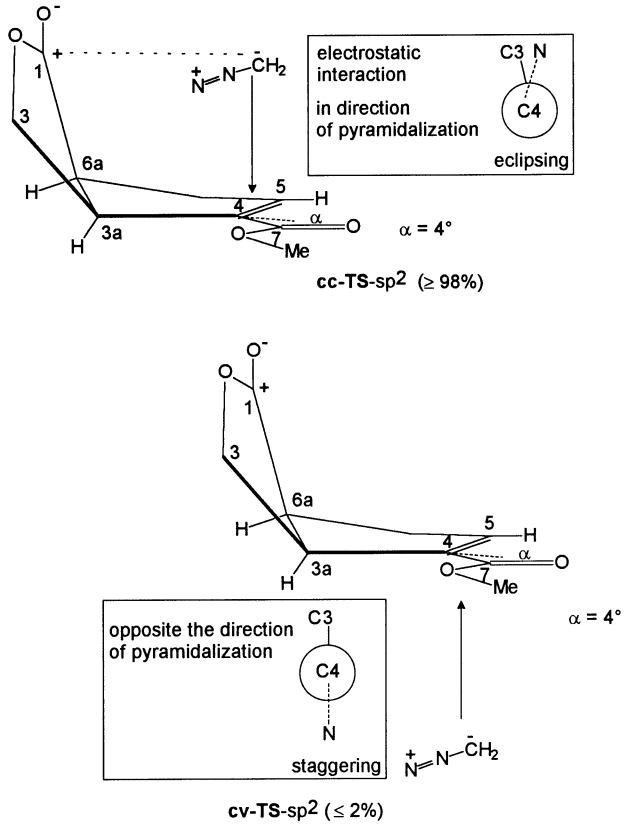
C3a−C6a−6aH 33°), which leads to a ^{6a}E-conformation of the cyclopentene ring. The C atoms of the double bond show a slight pyramidalization towards the concave side. The sp^2 ester and the sp^2-H bonds are distorted by 4° and 6°, respectively, toward the convex side. The distortion of the sp^2-H bond has to be viewed with caution, however, because of the uncertainties connected with the determination of the position of the H atom. The pyramidalization of C4 seems to originate from a torsional interaction between the methylene group in the 3-position and the CO_2Me group, as indicated by a C3−C3a−C4−C7 angle of 55.8°. The further bonding parameters of **7** fall in the expected ranges. In solution, diquinene **7** preferentially adopts, according to an analysis of the vicinal coupling constants, a conformation similar to that in the crystal.

Figure 6. Crystal structure of **7**



What causes CH_2N_2 and the other reagents to react with **7** preferentially at the concave side, which ought to be the sterically more hindered face? Before dealing with this question we have to consider whether the reactions of **7** discussed above are subject to kinetic or thermodynamic control. While we can safely assume that the present cycloaddition reactions of **7** are irreversible, the addition of PhSH and possibly the primary addition of cuprate **23** to the double bond of **7** as well, may be reversible. According to the currently held view, there is a direct link between the ground state geometry distortions of a double bond and activation energy differences in cycloaddition reactions[24][26][27][28][29][30][31][32]. It has been proposed that reactions at a pyramidalized double bond occur preferentially from the direction of the pyramidalization of the C-atom(s)[28]. This model has been successfully applied to rationalize the stereochemistry of cycloaddition reactions of *cis*-3,4-disubstituted cyclobutenes[27][30]. Thus, one contributing factor to the high concave selectivity in cycloaddition of **7** with CH_2N_2 may be the experimentally observed pyramidalization of the C atom(s) of the double bond toward the concave side. Furthermore, while in the concave transition state (**cc-TS**-sp^2) there should be a relief of strain because of an increase of the C3−C3a−C4−C7 angle, in the convex transition state (**cv-TS**-sp^2) strain should increase because of a decrease of this angle (Figure 7).

Figure 7. Transition state models for reaction of **7** with CH_2N_2



We felt, however, that there ought to be an additional and perhaps more important contributing intrinsic factor since, according to Houk′s staggered model, in **cc-TS**-sp^2 the developing eclipsed arrangement of the C3−C3a and the C4−N bond should disfavor the concave attack, while the developing staggered arrangement of these bonds in **cv-TS**-sp^2 should favor the convex attack[26][29]. An inspection of the solid-state structure of **7** gives an important clue as to the possible origin of the concave selectivity (cf. Figure 6). Because of the ^{6a}E-conformation of the cyclopentene ring, the lactone carbonyl group is in close vicinity to the concave face of the double bond. According to a simple molecular modelling of **cc-TS**-sp^2, the C atom of CH_2N_2 can easily be placed in close proximity (≈ 300 pm) to C5 as well as to C1. Thus, in **cc-TS**-sp^2 there could be an electrostatic interaction between the methylene group of CH_2N_2 and C1 of the lactone carbonyl group (Figure 7), which would be expected to stabilize this transition state. Such an electrostatic interaction, which is not available to **cv-TS**-sp^2, would also be possible in the case of the reactions of **7** with Pd−TMMs, $TMM(OR)_2$, thiophenolate and cuprate **23**. The nucleophilic character of CH_2N_2[33], Pd−TMMs[13][14], $TMM(OR)_2$[23d] and cuprates[34] towards carbonyl compounds is well documented. The notion that a transition state stabilizing specific electrostatic interaction of the above type produces an intrinsic facial prefer-

ence in cycloadditions had been proposed previously in order to rationalize the facial selectivities of Diels-Alder reactions of functionalized bicyclic dienes[35]. In addition, electrostatic potential analyses of alkenes, dienes and carbonyl compounds have provided evidence for the importance of electrostatic interactions as factors which influence π-facial selectivity[36][37][38][39][40].

In connection with the proposed electrostatic stabilization of **cc-TS**-sp^2, a digression into a discussion of the conformational behavior of the diquinane **28a**, which served as an intermediate in our synthesis of brefeldin A[41], seems to be appropriate. The interesting point about **28a** is the presence of the nucleophilic hydroxy group at the concave side of the molecule at C-5. In the crystal[22], diquinane **28a** adopts the $_5$E-conformation, in which the hydroxy group occupies the sterically more encumbered pseudoaxial position (Figure 8).

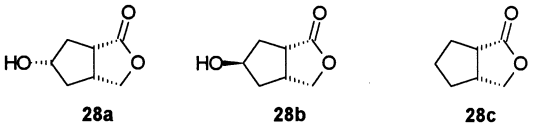
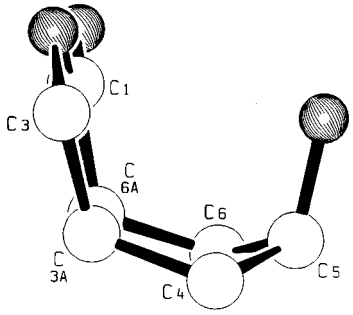


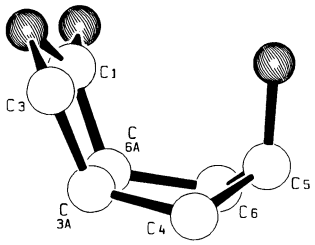
Figure 8. Crystal structure of **28a**



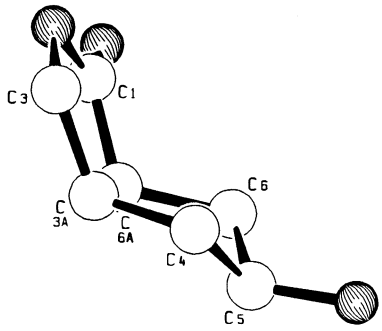
According to an analysis of the vicinal coupling constants, the $_5$E-conformation of **28a** is also the preferred one in solution. In the crystal, which contains two independent molecules, the distances between the hydroxylic oxygen atom and C1 are 302/298 pm and the angles between the oxygen atom and the carbonyl group (O···C1=O) are 109/104°. Dunitz et al. have shown that the incipient attack of an oxygen nucleophile on a carbonyl group involves O···C=O distances of 270−310 pm and that the optimum O···C=O angle is about 105°[42]. Molecular mechanical calculations (PIMM)[43] of **28a**, the epimeric alcohol **28b** and the parent compound **28c** found in each case the $_5$E-conformation to be more stable than the $^5_4$T-conformation (Figure 9). However, whereas the energy difference between the two conformations was determined as 1.8 kJ/mol in the case of **28c** and 1.9 kJ/mol in the case of **28b**, it was found to be 6.7 kJ/mol in the case of **28a**, which bears the hydroxy group at the concave side of the molecule[44]. Thus, the hydroxy substituent in **28a** provides an additional stabilization of the $_5$E-conformation, which may be ascribed to a coulombic interaction between the O-atom and C1 of the carbonyl group, corresponding to the initial step of an intramolecular nucleophilic attack on the carbonyl group[45].

Figure 9. Calculated (PIMM) structures of **28a** (a)(b), **28b** (c)(d) and **28c** (e)(f)

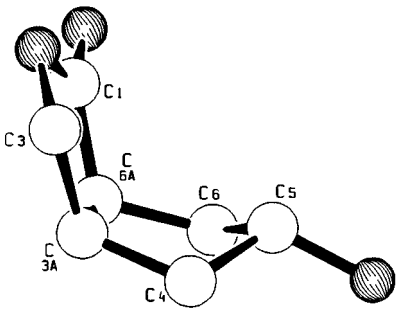
a)



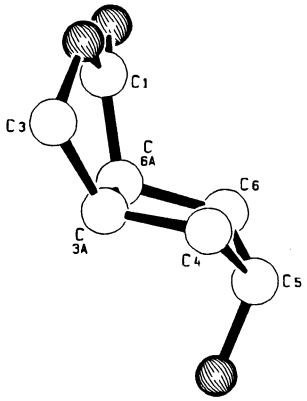
b)



c)

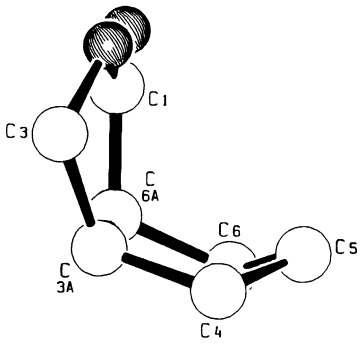


d)

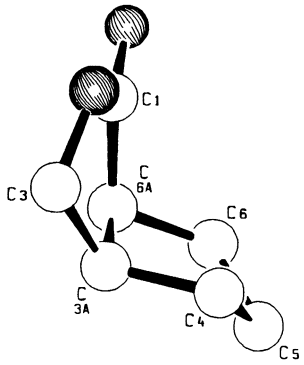


One way of evaluating the hypothesis of an electrostatic stabilization of **cc-TS**-sp^2 and related transition states would be the determination of the reactivity of an analogous diquinene in which C1 is sp^3-hybridized. Following

e)



f)

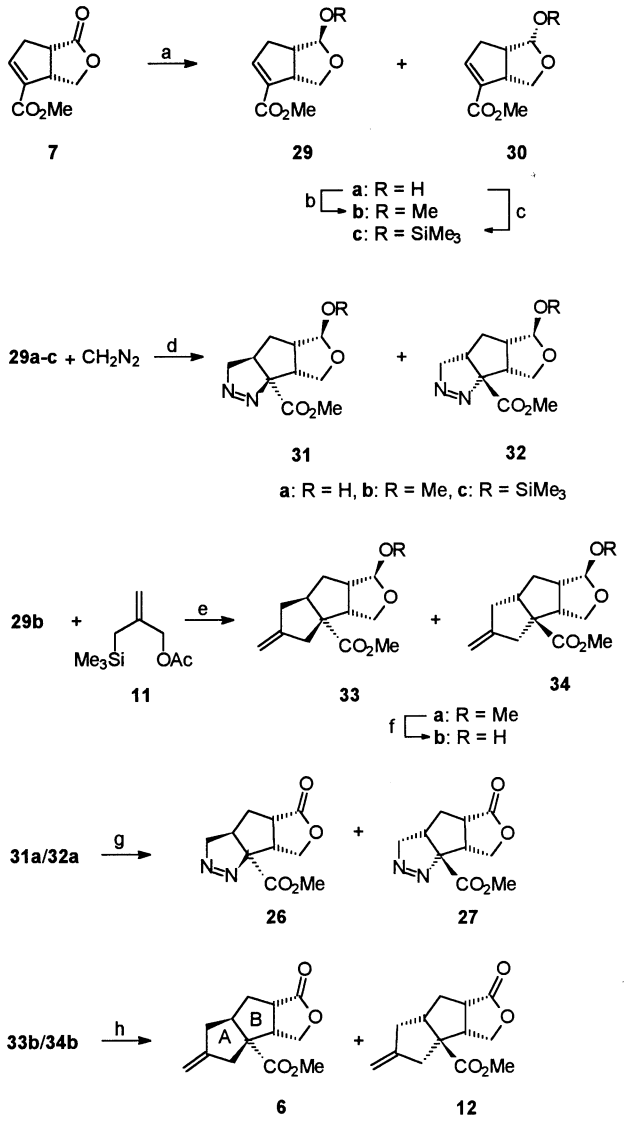


this line of thought, we prepared hemiacetals **29a** and **30a** in 73% yield as a 7:1 mixture by the reduction of **7** with DIBAL-H in THF/toluene at −100°C → −50°C (Scheme 8).

Treatment of the mixture of **29a** and **30a** with MeOH and H_2SO_4 at reflux temperature furnished a 9:1 mixture of acetals **29b** and **30b** in 95% yield. Finally, silylation of **29a** and **30a** with N-(trimethylsilyl)imidazole afforded a mixture of the silyl ethers **29c** and **30c** in a ratio of 7:1 in 45% yield. The configurations of the anomeric centers of **29a**−**c** and **30a**−**c** were determined by analysis of the vicinal coupling constants. Acetals **29a**−**c** seemed to be reasonably good model compounds in order to test the above hypothesis. An electrostatic stabilization of the transition state as in the case of **7** is not possible and the double bond of **29a**−**c** would be expected to exhibit a similar pyramidalization as that in **7**. Possibly because of the anomeric effect, in solution acetals **29a**−**c** adopt, according to NMR spectroscopy, a conformation in which the OR group is in the pseudoaxial and 1-H in the pseudoequatorial position. Thus, 1-H should not interfere with a reagent attacking **29a**−**c** from the concave side. The reaction of **29b** with CH_2N_2 in diethyl ether at room temperature gave a mixture of cycloadducts **31b** and **32b** in a 1:1 ratio in high yield (Table 2).

Similar results were obtained in the case of **29c**. Treatment of **29c** with CH_2N_2 afforded a 1.5:1 mixture of **31c** and **32c** in practically quantitative yield. Diastereomers **31c** and **32c** could be separated by MPLC. Even hemiacetal **29a** reacted with CH_2N_2 in a similar manner and gave a 1:1 mixture of **31a** and **32a** in practically quantitative yield. Not unexpectedly, the Pd-catalyzed cycloaddition reaction of

Scheme 8



Reagents and conditions: (a) DIBAL-H, THF, toluene, −100°C → −50°C. − (b) MeOH, H_2SO_4, reflux. − (c) *N*-(trimethylsilyl)imidazol, DMF, 0°C → room temp. − (d) Et_2O, room temp. − (e) $Pd(OAc)_2$, PPh_3, THF, reflux. − (f) HCl, H_2O, THF, room temp. − (g) pyridinium dichromate, CH_2Cl_2, pyridine, room temp. − (h) pyridinium chloromate, CH_2Cl_2, room temp.

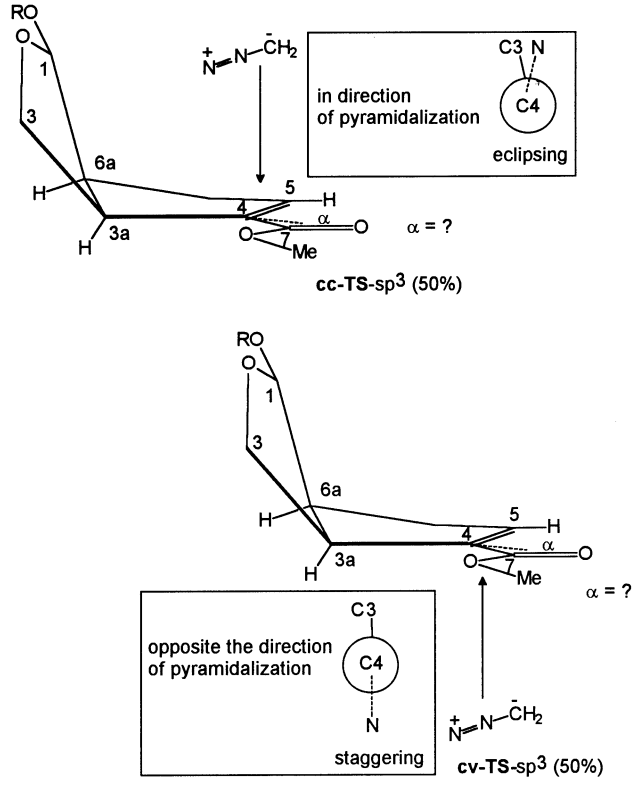
Table 2. Diastereomer ratios in cycloaddition reactions of diquinenes **29a**−**c**

Reagent	Starting compound	Triquinane transoid	Triquinane cisoid	dr
CH_2N_2	**29a**	**31a**	**32a**	1:1
CH_2N_2	**29b**	**31b**	**32b**	1:1
CH_2N_2	**29c**	**31c**	**32c**	1.5:1
11	**29b**	**33**	**34**	2:1

29b followed a similar stereochemical course. Reaction of **29b** with **11** in the presence of $Pd(OAc)_2$ and PPh_3 in THF at 70°C gave a 2:1 mixture of **33** and **34** in high yield. The configurations of the cycloadducts were assigned by analysis of the vicinal coupling constants[46]. This was supported

by the following chemical correlations. Hemiacetals **31a** and **32a** were oxidized to lactones **26** and **27** and acetals **33a** and **34a** were hydrolyzed to hemiacetals **33b** and **34b**. These were then oxidized to lactones **6** and **12**. In the above cycloaddition reactions, diquinenes **29a−c** were found to be contaminated with 10−13% of the epimeric diquinenes **30a−c**, which led to the formation of the corresponding epimeric cycloadducts as minor products. In the reaction of hemiacetal **30a** with CH_2N_2, the two cycloadducts were formed in a 1:1 ratio. In the other cases, the diastereomer ratio could not be determined with certainty. Thus, the lack or absent facial differentiation in the cycloaddition reactions of **29a−c** would nicely support the notion that the preferential reaction of **7** with CH_2N_2, PhSH, Pd−TMM, Pd−TMM(Ph), TMM$(OR)_2$ and **23** at the concave side is mainly caused by an electrostatic stabilization of the corresponding transition states. In the highly stereoselective reactions of Pd−TMM(Ph,Ph) and Pd−TMM(Ph,$SiMe_3$) with **7** at the convex side, this factor is apparently overcome by unfavorable steric interactions. The almost unselective cycloaddition reactions of **29a−c** and **30a** to CH_2N_2 (Table 2) may ultimately be ascribed to a concave pyramidalization of the double bond, although this has yet to be experimentally verified. Because of the staggering of the forming C−N bond and the allylic C−C bond, **cv-TS**-sp^3 should be lower in energy than **cc-TS**-sp^3 (Figure 10). The concave pyramidalization, however, would be expected to lower the energy of **cc-TS**-sp^3 and to raise that of **cv-TS**-sp^3. Alternatively, the unselective reactions of **29a−c** may be explained

Figure 10. Transition state model for reactions of **29a−c** with CH_2N_2



by postulating that neither a pyramidalization of the double bond nor the staggering of the bonds in **cv-TS**-sp^2 are important. The application of these arguments to the reactions of **7**, however, does not rule out the postulate of an electrostatic stabilization of the concave transition state **cv-TS**-sp^2.

Conclusion

Diquinene **7**, the starting material of our retrosynthetic scheme for pentalenolactone E (**2a**) and pentalenolactone F (**2b**), proved to be an unusual alkene because of its preferential reaction with nucleophilic reagents at the concave side. This π-facial differentiation may be ascribed to an electrostatic stabilization of the transition state and, to a certain extent, to the concave pyramidalization of the double bond, as revealed by X-ray analysis. The practically exclusive formation of the cisoid triquinane **27** in the reaction of **7** with CH_2N_2 would thus represent an exceptional example of electrostatic control in a cycloaddition reaction of an alkene by a functional group located in the vicinity of the double bond. Support for this notion comes from the almost unselective cycloaddition reactions of the corresponding diquinenoid acetals **29a−c**, which lack the lactone carbonyl group. In the Pd-catalyzed Binger-type [3 + 2] cycloaddition of the methylenecyclopropane derivatives **16** and **18** to **7**, the inherent stereochemical bias of **7** is overcome, presumably due to steric factors.

The linear triquinane **19** turned out to be a suitable precursor for the synthesis of the key intermediate **3**, which is described in the accompanying paper[11].

Financial support of this work by the *Deutsche Forschungsgemeinschaft*, the *Fonds der Chemischen Industrie* and *E. Merck AG*, Darmstadt, is gratefully acknowledged. The authors would like to thank Dr. *S. Braun*, Dr. *D. Hunkler* and Dr. *J. Runsink* for performing NMR experiments. We are grateful to Dr. *B. Riefling* for the large-scale synthesis of optically active starting materials and to Dr. *H. Hemmerle* for providing a sample of **28a**.

Experimental Section

All reactions were carried out under an argon atmosphere in oven-dried glassware using syringe techniques, except those with methylenecyclopropanes **13** and **18**, which were carried out in a V_4A-steel autoclave (200 ml) equipped with a programmed heating device, a magnetic stirring bar, an internal capillary and a temperature sensor. THF was distilled from potassium benzophenone ketyl. Diethyl ether, *o*-xylene and toluene were distilled from sodium benzophenone ketyl. DMF and CD_3CN were distilled from CaH_2. Other starting materials were either obtained from commercial sources and used without further purification or were prepared according to literature procedures. − TLC was performed with Merck silica gel 60 F_{254}. − Column chromatography was carried out with Merck silica gel 60 (230−400 mesh). − MPLC was performed with Merck LiChroprep Si 60 (15−25 μm). − Capillary GC analysis was carried out using a Carlo-Erba DB5 column (30 m × 32 mm, 0.25 μm). − HPLC analysis was performed using a Merck Lichrospher 100 RP-18 (5 μm) column. − ^{1}H-NMR chemical shifts are reported in ppm relative to TMS: δ = 0.00 or $CHCl_3$: δ = 7.24 as internal standards. Splitting patterns are designated as s, singlet; d, doublet; dd, double doublet; t, triplet; q, quartet; quin, quintet; m,

multiplet. – ^{13}C-NMR chemical shifts are reported in ppm relative to TMS: δ = 0.00 or $CHCl_3$: δ = 77.10 as internal standards. Peaks in ^{13}C-NMR spectra are denoted as "u" for carbons with zero or two attached protons or as "d" for carbons with one or three attached protons, as determined from the APT pulse sequence. Splitting patterns as derived from off-resonance experiments are designated as s, singlet; d, doublet; t, triplet and q, quartet. – Optical rotations were measured at 20°C.

Methyl (3aS-cis)-3,3a,6,6a-Tetrahydro-1-oxo-1H-cyclopenta[c]-furan-4-carboxylate (**7**): To a solution of **10a,b** (26.6 g, 87.5 mmol) in THF (400 ml), DBU (21 ml, 140 mmol) was added with stirring at 0°C. After stirring the suspension for 15 min., it was warmed to room temp. and stirred for a further 3 h. The mixture was then concentrated in vacuo and the residue was taken up in EtOAc. The resulting suspension was washed several times with 2 N aqueous HCl and saturated aqueous $NaHCO_3$. The organic phase was dried (Na_2SO_4) and concentrated in vacuo. Purification of the crude product by filtration through a pad of silica gel with EtOAc, concentration of the filtrate in vacuo and Kugelrohr distillation of the remaining liquid at 85–100°C/10^{-2} Torr gave **7** (14.8 g, 93%) as a viscous oil, which crystallized at room temp. Recrystallization from EtOAc/*n*-hexane furnished **7** as colorless crystals, m.p. 36°C, $[\alpha]_D$ = +163.8 (*c* = 3.33, acetone), $[\alpha]_{365}$ = +570.4 (*c* = 3.33, acetone). – ^{1}H NMR (300 MHz, $CDCl_3$): δ = 2.93 (ddd, $J_{6\alpha,5}$ = 2.3, $J_{6\alpha,6\beta}$ = 17.0, $J_{6\alpha,6a\alpha}$ = 7.8 Hz, 6-Hα, 1 H), 2.95 (ddd, $J_{6\beta,5}$ = 4.6, $J_{6\beta,6\alpha}$ = 17.0, $J_{6\beta,6a\alpha}$ = 3.2 Hz, 6-Hβ, 1 H), 3.29 (ddd, $J_{6a\alpha,3a\alpha}$ = 8.3, $J_{6a\alpha,6\alpha}$ = 7.8, $J_{6a\alpha,6\beta}$ = 3.2 Hz, 6a-Hα, 1 H), 3.78 (s, OMe, 3 H), 3.86 (ddd, $J_{3a\alpha,3\alpha}$ = 5.7, $J_{3a\alpha,3\beta}$ = 3.2, $J_{3a\alpha,6a\alpha}$ = 8.3 Hz, 3a-Hα, 1 H), 4.50 (dd, $J_{3\alpha,3\beta}$ = 10.5, $J_{3\alpha,3a\alpha}$ = 5.7 Hz, 3-Hα, 1 H), 4.52 (dd, $J_{3\beta,3\alpha}$ = 10.5, $J_{3\beta,3a\alpha}$ = 3.2 Hz, 3-Hβ, 1 H), 6.85 (dd, $J_{5,6\alpha}$ = 2.3, $J_{5,6\beta}$ = 4.6 Hz, 5-H, 1 H). – ^{13}C NMR (100 MHz, $CDCl_3$): δ = 36.7 (t, C-6), 41.8 (d), 45.9 (d), 51.8 (q, C-8), 71.2 (t, C-3), 135.5 (s, C-4), 144.2 (d, $J_{C\text{-}5,H\text{-}5}$ = 169.6 Hz, C-5), 164.1 (s, CO), 180.0 (s, CO). – IR ($CHCl_3$): $\tilde{\nu}$ = 3020 (s), 2960 (w), 2920 (w), 2860 (w), 1765 (vs), 1720 (vs), 1710 (vs), 1625 (s), 1480 (m), 1440 (s), 1370 (s), 1360 (s), 1310 (s), 1290 (s), 1270 (s), 1260 (s), 1230 (m), 1200 (s), 1175 (s), 1145 (s), 1110 (s), 1060 (m), 1035 (m), 990 (s), 710 (s). – MS (EI, 70 eV); *m/z* (%): 182 [M^+] (51), 154 (13), 151 (12), 137 (22), 125 (14), 124 (100), 105 (10), 96 (20), 93 (25), 79 (60), 78 (13), 77 (31), 65 (40). – $C_9H_{10}O_4$ (182.1): calcd. C 59.34, H 5.53; found C 59.10, H 5.39.

Methyl [3aS-(3aα,3bβ,6aβ,7aα)]- and Methyl [3aS-(3aα,3bα,6aα,7aα)]-Octahydro-5-methylene-1-oxopentaleno[1,2-c]furan-3b-(1H)-carboxylate (**6** and **12**): Alkene **7** (4.0 g, 22 mmol), $Pd(OAc)_2$ (0.75 g, 3.3 mmol) and PPh_3 (3.6 g, 13.3 mmol) were dissolved in THF (20 ml) and **11** (9.3 g, 50 mmol) was added. The resulting solution was heated to reflux for 9 h. The mixture was then cooled to room temp. and exposed to atmospheric oxygen with stirring in order to destroy the Pd(0) species present. The mixture was subsequently filtered through a pad of silica gel with EtOAc and the filtrate was concentrated in vacuo. Purification of the residue by chromatography (*n*-hexane/EtOAc, 1:1) gave a mixture of **6** and **12** (4.3 g, 81%) in a ratio of 1:3. MPLC (*n*-hexane/EtOAc, 1:1) of this mixture gave **6** (1.06 g, 20%) and **12** (3.17 g, 60%) R_f (**6**) = 0.40, R_f (**12**) = 0.37 (50% *n*-hexane/EtOAc).

6: Colorless crystals, m.p. 103°C (diethyl ether), $[\alpha]_D$ = –33.2 (*c* = 0.22, MeOH), $[\alpha]_{365}$ = –104.1 (*c* = 0.22, MeOH). – ^{1}H NMR (250 MHz, $CDCl_3$): δ = 1.88 (ddd, $J_{7\alpha,6a\beta}$ = 8.0, $J_{7\alpha,7\beta}$ = 13.5, $J_{7\alpha,7a\alpha}$ = 10.0 Hz, 7-Hα, 1 H), 2.23 (dddd, $J_{6\alpha,4\alpha}$ = 2.0, $J_{6\alpha,6\beta}$ = 16.5, $J_{6\alpha,6a\beta}$ = 2.5, $J_{6\alpha,8}$ = 2.0 Hz, 6-Hα, 1 H), 2.36 (ddd, $J_{7\beta,6a\beta}$ = 8.5, $J_{7\beta,7\alpha}$ = 13.5, $J_{7\beta,7a\alpha}$ = 3.7 Hz, 7-Hβ, 1 H), 2.44 (ddd, $J_{4\alpha,\,4\beta}$ = 17.0, $J_{4\alpha,8}$ = 2.0 Hz, 4-Hα, 1 H), 2.72 (dddd, $J_{6\beta,4\beta}$ = 2, $J_{6\beta,6\alpha}$ = 16.5, $J_{6\beta,6a\beta}$ = 8.0, $J_{6\beta,8}$ = 2.0 Hz, 6-Hβ, 1 H), 2.91 (m, 4-Hβ, 6a-Hβ, 2 H), 3.14 (m, 3a-Hα, 7a-Hα, 2 H), 3.71 (s, OMe, 3 H), 3.96 (dd, $J_{3\beta,3\alpha}$ = 10.1, $J_{3\beta,3a\alpha}$ = 4.7 Hz, 3-Hβ, 1 H), 4.41 (dd, $J_{3\alpha,3\beta}$ = 10.1, $J_{3\alpha,3a\alpha}$ = 8.0 Hz, 3-Hα, 1 H), 4.92 (dddd, $J_{8,4\alpha}$ = 2, $J_{8,4\beta}$ = 1.5, $J_{8,6\alpha}$ = 2, $J_{8,6\beta}$ = 2 Hz, 8-H, 2 H). – ^{1}H NMR (300 MHz, C_6D_6): δ = 1.38 (ddd, $J_{7\alpha,6a\beta}$ = 8.0, $J_{7\alpha,7\beta}$ = 13.5, $J_{7\alpha,7a\alpha}$ = 10 Hz, 7-Hα, 1 H), 1.82 (dddd, $J_{6\alpha,4\alpha}$ = 2.0, $J_{6\alpha,6\beta}$ = 16.5, $J_{6\alpha,6a\beta}$ = 2.5, $J_{6\alpha,8}$ = 2.0 Hz, 6-Hα, 1 H), 1.96 (ddd, $J_{4\alpha,4\beta}$ = 17.0, $J_{4\alpha,8}$ = 2.0 Hz, 4-Hα, 1 H), 2.21 (ddd, $J_{7\beta,7\alpha}$ = 13.5, $J_{7\beta,6a\beta}$ = 8.5, $J_{7\beta,7a\alpha}$ = 3.7 Hz, 7-Hβ, 1 H), 2.31 (ddd, $J_{3a\alpha,3\alpha}$ = 8.0, $J_{3a\alpha,3\beta}$ = 4.7, $J_{3a\alpha,7a\alpha}$ = 8.0 Hz, 3a-Hα, 1 H), 2.46 (ddd, $J_{7a\alpha,3a\alpha}$ = 8.0, $J_{7a\alpha,7\alpha}$ = 10.0, $J_{7a\alpha,7\beta}$ = 3.7 Hz, 7a-Hα, 1 H), 2.48 (dddd, $J_{6\beta,6\alpha}$ = 16.5, $J_{6\beta,6a\beta}$ = 8.0, $J_{6\beta,8}$ = 2.0 Hz, 6-Hβ, 1 H), 2.65 (dddd, $J_{6a\beta,6\alpha}$ = 2.5, $J_{6a\beta,6\beta}$ = 8.0, $J_{6a\beta,7\alpha}$ = 8.0, $J_{6a\beta,\,7\beta}$ = 8.5 Hz, 6a-Hβ, 1 H), 2.73 (ddd, $J_{4\beta,4\alpha}$ = 17.0, $J_{4\beta,6\beta}$ = 1.5, $J_{4\beta,\,8}$ = 1.5 Hz, 4-Hβ, 1 H), 3.22 (s, OMe, 3 H), 3.67 (dd, $J_{3\beta,3\alpha}$ = 10.1, $J_{3\beta,3a\alpha}$ = 4.7 Hz, 3-Hβ, 1 H), 3.79 (dd, $J_{3\alpha,3\beta}$ = 10.1, $J_{3\alpha,3a\alpha}$ = 8.0 Hz, 3-Hα, 1 H), 4.83 (dddd, $J_{8,4\alpha}$ = 2, $J_{8,4\beta}$ = 1.5, $J_{8,6\alpha}$ = 2, $J_{8,6\beta}$ = 2 Hz, 8-H, 2 H). – ^{13}C NMR (75 MHz, $CDCl_3$): δ = 35.3 (t), 38.3 (t), 43.4 (t), 44.2 (d), 45.9 (d), 48.7 (d), 52.1 (q, OMe), 64.6 (s, C-3b), 69.9 (t, C-3), 108.3 (t, C-5), 148.1 (s, C-5), 174.8 (s, CO), 179.5 (s, CO). – IR ($CHCl_3$): $\tilde{\nu}$ = 3080 (w), 3025 (m), 1770 (vs), 1725 (vs), 1435 (m), 1225 (m), 1195 (m), 1170 (m), 1030 (m), 890 (m), 790 (m). – MS (EI, 70 eV); *m/z* (%): 236 [M^+] (50), 205 (12), 204 (15), 190 (20), 178 (20), 177 (28), 176 (73), 151 (25), 150 (18), 132 (19), 131 (100), 130 (26), 119 (34), 118 (42), 117 (43), 105 (21), 93 (18), 92 (36), 91 (80), 79 (31), 78 (28), 77 (51). – $C_{13}H_{16}O_4$: calcd. 236.1049; found 236.1059 (MS). $C_{13}H_{16}O_4$ (236.2): calcd. C 66.09, H 6.83; found C 66.09, H 6.86.

12: Colorless crystals, m.p. 81°C (diethyl ether), $[\alpha]_D$ = +48.5 (*c* = 1.63, MeOH), $[\alpha]_{365}$ = +164.7 (*c* = 1.63, MeOH). – ^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.73 (ddd, $J_{7\beta,7\alpha}$ = 14.2, $J_{7\beta,6a\alpha}$ = 8.5, $J_{7\beta,7a\alpha}$ = 5.8 Hz, 7-Hβ, 1 H), 2.22 (dd, $J_{6\beta,6\alpha}$ = 16.5, $J_{6\beta,6a\alpha}$ = 2.0 Hz, 6-Hβ, 1 H), 2.38 (ddd, $J_{4\beta,4\alpha}$ = 17.2, $J_{4\beta,6\beta}$ = 2, $J_{4\beta,8}$ = 2 Hz, 4-Hβ, 1 H), 2.45 (ddd, $J_{7\alpha,6a\alpha}$ = 9, $J_{7\alpha,7\beta}$ = 14.2, $J_{7\alpha,7a\alpha}$ = 10.4 Hz, 7-Hα, 1 H), 2.63 (ddd, $J_{6\alpha,4\alpha}$ = 2.0, $J_{6\alpha,6\beta}$ = 16.5, $J_{6\alpha,6a\alpha}$ = 8.2 Hz, 6-Hα, 1 H), 2.86 (dd, $J_{4\alpha,4\beta}$ = 17.2, $J_{4\alpha,8}$ = 2 Hz, 4-Hα, 1 H), 2.95 (dddd, $J_{6a\alpha,6\alpha}$ = 8.2, $J_{6a\alpha,6\beta}$ = 2.0, $J_{6a\alpha,7\alpha}$ = 9.0, $J_{6a\alpha,7\beta}$ = 8.5 Hz, 6a-Hα, 1 H), 3.18 (ddd, $J_{7a\alpha,3a\alpha}$ = 10.3, $J_{7a\alpha,7\alpha}$ = 10.4, $J_{7a\alpha,7\beta}$ = 5.8 Hz, 7a-Hα, 1 H), 3.44 (ddd, $J_{3a\alpha,3\alpha}$ = 7.7, $J_{3a\alpha,3\beta}$ = 2.7, $J_{3a\alpha,7a\alpha}$ = 10.3 Hz, 3a-Hα, 1 H), 3.71 (s, OMe, 3 H), 4.32 (dd, $J_{3\beta,3\alpha}$ = 10.2, $J_{3\beta,3a\alpha}$ = 2.7 Hz, 3-Hβ, 1 H), 4.41 (dd, $J_{3\alpha,3\beta}$ = 10.2, $J_{3\alpha,3a\alpha}$ = 7.7 Hz, 3-Hα, 1 H), 4.93 (br s, =CH_2, 2 H). – ^{13}C NMR (75 MHz, $CDCl_3$): δ = 34.0 (t), 36.7 (t), 37.8 (t), 44.1 (d), 46.8 (d), 50.4 (d), 52.5 (q, OMe), 63.1 (s, C-3b), 68.8 (t, C-3), 108.6 (t, C-5), 148.2 (s, C-5), 176.1 (s, CO), 180.1 (s, CO). – IR ($CHCl_3$): $\tilde{\nu}$ = 2980–3025 (m), 1760 (vs), 1720 (vs), 1380 (m), 1270 (m), 1170 (s), 1090 (m), 1030 (m), 975 (m), 880 (s). – MS (EI, 70 eV); *m/z* (%): 236 [M^+] (47), 218 (41), 205 (25), 204 (60), 190 (21), 178 (10), 177 (67), 176 (63), 152 (24), 151 (100), 150 (21), 138 (22), 137 (23), 132 (15), 131 (97), 130 (16), 119 (76), 118 (18), 117 (23), 105 (26), 93 (41), 92 (32), 91 (60), 79 (44), 78 (24), 77 (43). – $C_{13}H_{16}O_4$: calcd. 236.1049; found 236.1052 (MS). – $C_{13}H_{16}O_4$ (236.2): calcd. C 66.09, H 6.83; found C 65.88, H 6.76. Analogous experiments were carried out in toluene, diglyme and DMF: In toluene: 79% yield of **6** and **12** in a ratio of 1:5.3; in diglyme: 80% yield of **6** and **12** in a ratio of 1:4.8; in DMF: 30% yield of **6** and **12** in a ratio of 1:1.7. The diastereomer ratios were determined by ^{1}H-NMR spectroscopy using the signals of 3-H.

Synthesis of **6** *and* **12** *from* **7** *and* **13**: An orange solution of Pd(Cp)(allyl) (0.13 g, 0.61 mmol), P(*i*Pr)$_3$ (0.10 g, 0.61 mmol) and **7** (3.05 g, 16.8 mmol) in toluene (30 ml) was placed in an autoclave and cooled to –78°C. Precooled **13** (3.9 g, 72 mmol) was added at this temp. and the mixture was subsequently heated to 120°C for 5

h under stirring. During this time, only a slight exothermic reaction (internal temp. 120−125°C) was observed. The contents of the autoclave (a clear orange solution) were then distilled in vacuo at 10^{-4} Torr. After the collection of 26.9 g of a colorless liquid, containing besides 97.4% toluene, 1.4% of **13** and 0.5% of the cyclodimer of **13** (GC) (b.p. ≤ 25°C), 3.77 g of a second fraction were obtained at 110°C/10^{-4} Torr, containing (GC) 11.7% of unreacted **7**, 9.6% of **6** (9%) and 68.0% of **12** (65%). The remainder consisted of 10 impurities at levels of 1−2%. The second fraction was dissolved in Et_2O (10 ml). After cooling the resulting solution to 0°C, 1.87 g (47%) of 98% pure (GC) **12** was obtained as colorless needles, m.p. 82°C. From the mother liquor, 0.88 g yellow crystals were obtained after cooling to −30°C, m.p. 75−78°C, composed of (GC): 8.3% **7**, 36.4% **6,** 53.5% **12**. Concentration of the mother liquor gave a further 0.74 g of a yellow oil, which contained (GC) 11.6% of an unknown compound, 39.5% of **7**, 5.4% of an unknown compound, 10.1% of **6**, 14.9% of **12**, and 18.5% unknown minor compounds.

Methyl [3aS-(3aα,3bα,6α,6aα,7aα)]-Octahydro-5-methylene-1-oxo-6-phenyl-1H-pentaleno[1,2-c]furan-4a-carboxylate (**15**): To a solution of Pd(Cp)(allyl) (0.11 g, 0.52 mmol) and P(*i*Pr)$_3$ (80 mg, 0.52 mmol) in toluene (10 ml) was added **7** (3.61 g, 19.8 mmol). The red solution was heated to reflux (110°C) and a solution of **14a** (5.94 g, 45.7 mmol) in toluene (10 ml) was added dropwise over a period of 0.5 h. After stirring the mixture for 1 h at 110°C, **7** had been completely consumed (GC). Removal of the toluene in vacuo (20°C, 0.5 Torr) gave 9.80 g of a dark-red oil of the composition (GC-MS): 3.3% (260, M^+), 35.4% (260, M^+), 44.2% **15** (312, M^+) (calcd. 4.33 g, 70.2%), and three isomers of **15** (312, M^+) (calcd. 0.67 g, 10.6%) (1.9%, 3.4% and 1.5%). The oil was redissolved in diethyl ether (10 ml) and the solution was cooled to 0°C. Dropwise addition of *n*-hexane (4 ml) led to the precipitation of 3.10 g (50%) of **15** as colorless crystals, m.p. 77°C. A second crop of 1.01 g (16%) of slightly yellow crystals of **15** was obtained after cooling the mother liquor to −30°C, m.p. 76−77°C, $[\alpha]_D$ = +142.5 (*c* = 1.35, $CHCl_3$). − ^{1}H NMR (200 MHz, $CDCl_3$): δ = 2.01 ($J_{7\alpha,7\beta}$ = 14.1, $J_{7\beta,7a\alpha}$ = 2.7, $J_{7\beta,6a\alpha}$ = 3.1 Hz, 7-Hβ, 1 H), 2.21 (ddd, $J_{7\alpha,7\beta}$ = 14.1, $J_{7\alpha,7a\alpha}$ = 9.7, $J_{7\alpha,6a\alpha}$ = 8.1 Hz, 7-Hα, 1 H), 2.58 (br. d, $J_{4\alpha,4\beta}$ = 17.0 Hz, 4-Hβ, 1 H), 2.97 (ddd, $J_{6a\alpha,6\beta}$ = 8.6, $J_{6a\alpha,7a}$ = 8.1, $J_{6a\alpha,7\beta}$ = 3.1 Hz, 6a-Hα, 1 H), 3.09 (d, $J_{4\alpha,4\beta}$ = 17.0 Hz, 4-Hα, 1 H), 3.15 (td, $J_{7a\alpha,3a\alpha}$ = 9.8, $J_{7a\alpha,7a}$ = 9.7, $J_{7a\alpha,7\beta}$ = 2.7 Hz, 7a-Hα, 1 H), 3.17 (d, $J_{6\beta,6a\alpha}$ = 8.6 Hz, 6-Hβ, 1 H) 3.41 (ddd, $J_{3a\alpha,7a\alpha}$ = 9.8, $J_{3a\alpha,3\alpha}$ = 7.0, $J_{3a\alpha,3\beta}$ = 3.4 Hz, 3a-Hα, 1 H), 3.56 (s, OMe, 3 H) 4.29 (dd, $J_{3\alpha,3\beta}$ = 10.3, $J_{3\beta,3a\alpha}$ = 3.4 Hz, 3-Hβ, 1 H), 4.34 (dd, 3-Hα, 1 H), 4.48 (m, *Z*-H, C=CH_2, 1 H), 4.94 (m, *E*-H, C=CH_2, 1 H), 7.05−7.27 (m, Ph, 5 H). − ^{13}C NMR (50 MHz, $CDCl_3$): δ = 32.68, 38.22 (t, C-4, C-7), 45.48, 46.21 (d, C-3a, C-7a), 52.34 (q, OMe), 56.31, 59.48 (d, C-6, C-6a), 61.46 (s, C-4a), 68.09 (t, C-3), 109.09 (t, C=*C*H_2), 126.46 (d, *p*-Ph), 128.27, 128.30 (d, *o*- and *m*-Ph), 141.66 (s, *i*-Ph), 152.35 (s, C-5), 176.13 (s, CO_2Me), 180.14 (s, C-1). − GC-MS (EI, 70 eV); m/z (%): 312 [M^+] (39), 253 (100), 252 (54). − $C_{19}H_{20}O_4$ (312.6): calcd. C 73.06, H 6.45; found C 73.18, H 6.43. Starting with **14b** instead of **14a**, the alkene **15** was obtained by the above procedure in 53% yield.

Methyl [3aS-(3aα,3bβ,6aβ,7aα)]-Octahydro-5-[(Z)-phenyl(trimethylsilyl)methylene]-1-oxo-1H-pentaleno[1,2-c]furan-4a-carboxylate (**17**): Pd(Cp)(allyl) (0.16 g, 0.75 mmol) and P(*i*Pr)$_3$ (0.12 g, 0.75 mmol) were dissolved in *o*-xylene (20 ml) and **7** (1.80 g, 9.89 mmol) was added. After heating the mixture to 120°C, **16** (2.84 g, 13.2 mmol) was added dropwise at this temp. under stirring. Heating of the mixture to 120°C was continued for 5 h. Removal of the solvent in vacuo (0.5 Torr) afforded 3.86 g of a dark-red oil, which was found to contain (GC-MS) 17.3% **16**, 15.9% (phenyltrimethylsilylmethylene)cyclopropane, 9% **7**, 45.2% **17** [GC-MS: 384, M^+; calcd. 1.74 g (45.5%)] and two isomers of **17** (GC-MS: 384, M^+) (1.2% and 1.7%). The oil was redissolved in diethyl ether (10 ml) and the resulting solution was cooled to 0°C. After 2 h, pure **17** (0.35 g, 9%) was obtained as colorless crystals: m.p. 164°C, $[\alpha]_D$ = +97.9 (*c* = 1.3, $CHCl_3$). − ^{1}H NMR (200 MHz, $CDCl_3$): δ = 0.00 (s, 9 H, $SiMe_3$), 1.81 (ddd, $J_{7\alpha,7\beta}$ = 13.8, $J_{7\alpha,7a\alpha}$ = 9.7, $J_{7\alpha,6a\beta}$ = 8.4 Hz, 7-Hα, 1 H), 2.05 (dd, $J_{4\alpha,4\beta}$ = 18.1, $J_{4\beta,6\beta}$ = 2.1 Hz, 4-Hβ, 1 H), 2.30 (ddd, $J_{7\beta,7\alpha}$ = 13.8, $J_{7\beta,6a\beta}$ = 8.2, $J_{7\beta,7a\alpha}$ = 3.5 Hz, 7-Hβ, 1 H), 2.37 (dd, $J_{6\alpha,6\beta}$ = 16.4, $J_{6\alpha,6a\beta}$ = 1.6 Hz, 6-Hα, 1 H), 2.58 (br. d, $J_{4\alpha,4\beta}$ = 18.1 Hz, 4-Hα, 1 H), 2.76 (m, $J_{6\beta,6\alpha}$ = 16.4, $J_{6\beta,6a\beta}$ = 7.3 Hz, 6-Hβ, 1 H), 2.84−2.99 (m, 2 H, 3a-Hα and 6a-Hβ), 3.05 (m, $J_{7a\alpha,3a\alpha}$ = 9.2, $J_{7a\alpha,7\alpha}$ = 8.4, $J_{7a\alpha,7\beta}$ = 3.5 Hz, 7a Hα, 1 H), 3.62 (s, OMe, 3 H), 3.80 (dd, $J_{3\alpha,3\beta}$ = 10.3, $J_{3\beta,3a\alpha}$ = 5.0 Hz, 3-Hβ, 1 H), 4.28 (dd, $J_{3\alpha,3\beta}$ = 10.3, $J_{3\alpha,3a\alpha}$ = 8.1 Hz, 3-Hα, 1 H), 6.79 (d, *o*-Ph, 2 H), 7.09 (t, *p*-Ph, 1 H), 7.22 (t, *m*-Ph, 2 H). − ^{13}C NMR (50 MHz, $CDCl_3$): δ = −0.29 (q, $SiMe_3$), 35.14, 38.03, 43.18 (t, C-4, C-6, C-7), 43.73, 45.47, 48.42 (d, C-3a, C-6a, C-7a), 63.19 (s, C-4a), 69.85 (t, C-3), 125.10 (d, *p*-C, Ph), 127.09 (d, *m*-Ph), 128.18 (d, *o*-Ph), 138.48 (s, C=*C*Ph,$SiMe_3$), 145.02 (s, *i*-Ph), 150.85 (s, C-5), 174.61 (s, CO_2Me), 179.36 (s, C-1). − MS (GC-MS, 70 eV); m/z (%): 384 [M^+] (56), 89 (57), 73 (100). − $C_{22}H_{28}O_4Si$ (384.5): calcd. C 68.72, H 7.34; found C 68.23, H 7.34.

Methyl [3aS-(3aα,3bβ,6aβ,7aα)]-5-Diphenylmethylene-octahydro-1-oxo-1H-pentaleno[1,2-c]furan-4a-carboxylate (**19**): A dark-red solution of Pd(Cp)(allyl) (0.29 g, 1.37 mmol), P(*i*Pr)$_3$ (0.22 g, 1.37 mmol), **18** (12.6 g, 61.1 mmol) and **7** (10.9 g, 59.9 mmol) in toluene (80 ml) was placed in an autoclave and heated to 140°C for 2 h. The black reaction mixture was then filtered through a pad of polyethylene and Florisil and the filter-cake was washed with CH_2Cl_2. The orange filtrate was concentrated in vacuo (30°C, 0.5 Torr) and the residue (a brown oily solid) was extracted with MeOH for 24 h in a Soxhlet extractor. The white solid residue was recrystallized from 80% CH_2Cl_2/diethyl ether to give pure **19** (10.36 g, 45%) as colorless crystals, m.p. 212°C, $[\alpha]_D$ = +65.8 (*c* = 2.1, $CHCl_3$). From the MeOH extract, a brown oil (11.5 g) was obtained after removal of the solvent, which was found to have the following composition (GC): 29% **7**, 18% **18**, 6.0% and 8.1% isomers of **19** (GC-MS): 388 [M^+], 5.8% **19**, and fifteen 1−2% peaks of unknown compounds. A change of solvent from toluene to THF led to an improved yield of **19**: from **18** (13.45 g, 65.5 mmol), **7** (11.92g, 65.5 mmol), Pd(Cp)(allyl) (0.45 g, 2.12 mmol) and P(*i*Pr)$_3$ (0.34 g, 2.12 mmol) in THF (60 ml), 24.95 g of a yellow solid was obtained after heating the mixture for 2 h at 140°C, filtration through a pad of polyethylene and Florisil and evaporation of the solvent. This was found to contain (GC): 11.7% of **7**, 1.7% of 2-methyl-3,3-diphenylpropene, 1.9% of **18**, 67.7% of **19** [calcd. 16.9 g (66%)], and 3.7% [calcd. 0.9 g (3.5%)] and 5.3% [calcd. 1.3 g (5.1%)] of two isomers of **19**. Soxhlet extraction as described above gave 13 g (51%) of pure **19** as almost colorless crystals. − ^{1}H NMR (200 MHz, $CDCl_3$): δ = 1.93 (ddd, $J_{7\alpha,7\beta}$ = 13.8, $J_{7\alpha,7a\alpha}$ = 10.1, $J_{7\alpha,6a\beta}$ = 7.8 Hz, 7-Hα, 1 H), 2.27−2.42 (m, 2 H, 6-Hα, 7-Hβ), 2.60 (dd, $J_{4\alpha,4\beta}$ = 17.8, $J_{4\alpha,6\beta}$ = 2.0 Hz, 1 H, 4-Hα), 2.81−2.97 (m, 6-Hβ, 6a-Hβ, 2 H), 2.99 (dd, $J_{4\alpha,4\beta}$ = 17.8, $J_{4\beta,6}$ = 1.4, 4-Hβ, 1 H), 3.10−3.19 (m, 3a-Hα, 7a-Hα, 2 H), 3.94 (dd, $J_{3\alpha,3\beta}$ = 10.3, $J_{3\beta,3a\alpha}$ = 4.6 Hz, 3-Hβ, 1 H), 4.37 (dd, $J_{3\alpha,3\beta}$ = 10.3, $J_{3\alpha,3a\alpha}$ = 8.2 Hz, 3-Hα, 1 H), 7.06−7.35 (m, Ph, 10 H). − ^{13}C NMR (50 MHz, $CDCl_3$): δ = 35.29, 37.78, 42.76 (t, C-4, C-6, C-7), 44.02, 45.54, 48.49 (d, C-3a, C-6a, C-7a), 52.09 (q, OMe), 64.43 (s, C-4a), 68.89 (t, C-3), 126.61 (d, *p*-Ph), 128.14, 128.25 (d, *m*-Ph), 128.90, 128.93 (d, *o*-Ph), 136.57, 137.91 (s, C-5, C=*C*Ph_2), 142.19, 142.41 (s, *i*-Ph), 174.66 (s, CO_2Me), 179.51 (s, C-1). − MS (70 eV); *m/z* (%): 388 [M^+] (100), 370 (2.8), 360 (27), 357 (6.5), 356 (16), 342 (27), 330

(23), 329 (27), 328 (55), 167 (55), 165 (62). − IR (KBr): $\tilde{\nu}$ = 1762 (sh), 1755 (s). − Raman: $\tilde{\nu}$ = 1637 (s). − $C_{25}H_{24}O_4$ (388.4): calcd. C 77.32, H 6.23; found C 77.38, H 6.19.

Methyl [3aS-(3aα,3bβ,6aβ,7aα)]- and Methyl [3aS-(3aα,3bα,6aα,7aα)]-Octahydro-5-(5′,5′-dimethyl-1′,3′-dioxan-2′-ylidene)-1-oxo-pentaleno[1,2-c]furan-3b(1H)-carboxylate (**21a** and **22a**): A solution of **20** (87 mg, 0.56 mmol) and **7** (97 mg, 0.53 mmol) in CD_3CN (1 ml) was placed in an oven-dried NMR tube. The tube was then evacuated, flame-sealed and placed in an oil bath at 80°C for 38 h. After that time, a ^{1}H-NMR spectrum indicated complete consumption of **20** and **7** and the formation of a mixture of **21a** and **22a** in a 1:2 ratio.

21a: ^{1}H NMR (300 MHz, CD_3CN): δ = 0.97 (s, Me, 3 H), 0.98 (s, Me, 3 H), 1.83 (ddd, *J* = 8.8, 10.1, 13.8 Hz, 7-H, 1 H), 2.10 (m, 1 H), 2.19 (dd, *J* = 2.7, 13.8 Hz, 1 H), 2.31−2.52 (m, 2 H), 2.72−2.95 (m, 2 H), 3.11−3.16 (m, 2 H), 3.61 (s, 2 × OCH_2, 4 H), 3.64 (s, OMe, 3 H), 3.88 (dd, $J_{3\beta,3\alpha}$ = 10.1, $J_{3\beta,3a\alpha}$ = 4.0 Hz, 3-Hβ, 1 H), 4.34 (dd, $J_{3\alpha,3\beta}$ = 10.1, $J_{3\alpha,3a\alpha}$ = 8.0 Hz, 3-Hα, 1 H). − ^{13}C NMR (75 MHz, CD_3CN): δ = 21.42 (d), 30.50 (u), 32.01 (u), 35.10 (u), 36.51 (u, C-5′), 44.02 (d), 46.07 (d), 48.13 (d), 51.71 (d, OMe), 64.83 (u, C-3b), 70.03 (u, C-3), 76.58 [u, C-4′(6′)], 76.61 [C-6′(4′)], 94.37 (u, C-5), 144.21 (u, C-2), 175.09 (u, CO), 180.11 (u, CO).

22a: ^{1}H NMR (300 MHz, CD_3CN): δ = 0.93 (s, Me, 3 H), 1.02 (s, Me, 3 H), 1.55 (ddd, $J_{7\beta,6a\alpha}$ = 8.4, $J_{7\beta,7\alpha}$ = 13.8, $J_{7\beta,7a\alpha}$ = 5.7 Hz, 7-Hβ, 1 H), 2.10 (dt, $J_{6,4}$ = 2.4, $J_{6\alpha,6\beta}$ = 12.8 Hz, 6-H, 1 H), 2.22 (dd, $J_{4\alpha,4\beta}$= 16.8, $J_{4,6}$ = 2.4 Hz, 4-H, 1 H), 2.37 (ddd, $J_{7\alpha,6a\alpha}$ = 8.8, $J_{7\alpha,7\beta}$ = 13.8, $J_{7\alpha,7a\alpha}$ = 10.4 Hz, 7-Hα, 1 H), 2.31−2.42 (m, 6-H, 2 H), 2.68 (dd, $J_{4\alpha,4\beta}$ = 16.8, $J_{4,6}$ = 0.7 Hz, 4-H, 1 H), 2.72−2.89 (m, 6a-Hα, 1 H), 3.18 (ddd, $J_{7a\alpha,3a\alpha}$ = 10.4, $J_{7a\alpha,7\alpha}$ = 10.4, $J_{7a\alpha,7\beta}$ = 5.7 Hz, 7a-Hα, 1 H), 3.39 (ddd, $J_{3a\alpha,3\alpha}$ = 7.7, $J_{3a\alpha,3\beta}$ = 2.0, $J_{3a\alpha,7a\alpha}$ = 10.4 Hz, 3a-Hα, 1 H), 3.61 (s, OCH_2, 2 H), 3.625 (s, OCH_2, 2 H), 3.634 (s, OMe, 3 H), 4.25 (dd, $J_{3\beta,3\alpha}$ = 10.0, $J_{3\beta,3a\alpha}$ = 2.0 Hz, 3-Hβ, 1 H), 4.36 (dd, $J_{3\alpha,3\beta}$ = 10.0, $J_{3\alpha,3a\alpha}$ = 7.7 Hz, 3-Hα, 1 H). − ^{13}C NMR (75 MHz, CD_3CN): δ = 21.35 (d), 21.50 (d), 31.02 (u), 31.91 (u), 34.15 (u), 37.32 (u, C-5′), 43.93 (d), 46.70 (d), 50.38 (d), 51.98 (d, OMe), 63.18 (u, C-3b), 69.01 (u, C-3), 76.50 [u, C-4′(6′)], 76.54 [u, C-6′(4′)], 94.93 (u, C-5), 148.79 (u, C-2′), 176.12 (u, CO), 180.87 (u, CO). − MS (EI, 70 eV); *m/z* (%): 336 [M^+] (2), 269 (6), 251 (10), 182 (37), 167 (11), 155 (49), 154 (26), 151 (15), 137 (37), 128 (15), 125 (20), 124 (100), 123 (17), 122 (19), 105 (30), 96 (31), 95 (11), 93 (36), 85 (55), 83 (10), 83 (89), 79 (67), 78 (18), 77 (47), 73 (15), 69 (64), 68 (11), 67 (14), 66 (10), 65 (44), 59 (51), 57 (14), 56 (23), 55 (26), 53 (13), 51 (13), 48 (12), 47 (28), 45 (12), 43 (11), 41 (55), 39 (42).

Methyl [3aS-(3aα,3bβ,5α(β),6aβ,7aα)]-Octahydro-5-[(1-hydroxy-2,2-dimethylpropoxy)carboxy]-1-oxo-pentaleno[1,2-c]furan-3b-(1H)-carboxylate (**21b**) *and Methyl [3aS-(3aα,3bα,5α(β),6aα,7aα)]-Octahydro-5-[(1-hydroxy-2,2-dimethylpropoxy)carboxy]-1-oxo-pentaleno[1,2-c]furan-3b-(1H)-carboxylate* (**22b**): A mixture of **20** (150 mg, 1.04 mmol) and **7** (185 mg, 1.02 mmol) in MeCN (4 ml) was heated to reflux for 24 h. After that time, TLC analysis (EtOAc/*n*-hexane, 1:4) indicated complete consumption of the starting materials. The solvent was removed in vacuo and the residue was subjected to column chromatography (EtOAc/*n*-hexane, 1:4), furnishing a mixture of **21b** and **22b** (256 mg, 72%) as a colorless viscous oil. − ^{1}H NMR (300 MHz, $CDCl_3$): δ = 0.904 (s, 3 H, Me), 0.906 (s, 3 H, Me), 1.66 (ddd, *J* = 7.2, *J* = 9.5, *J* = 13.1 Hz, 1 H), 1.76 (m, 2 H), 2.18−2.50 (m, 2 H), 2.55 (dd, *J* = 5.7, *J* = 14.4 Hz, 1 H), 2.63 (dd, *J* = 6.1, *J* = 13.1 Hz, 1 H), 2.90−3.23 (m, 3 H), 3.30 [d, $J_{3',OH}$ = 4.7 Hz, 3′-H, 2 H, (CH_2OH)], 3.23−3.49 (m, 1 H), 3.71 (s, OMe, 3 H), 3.93 [s, 1′-H, 2 H, (OCH_2)], 4.34 (dd, $J_{3\beta,3\alpha}$ = 10.4, $J_{3\beta,3a\alpha}$ = 1.7 Hz, 3-Hβ, 1 H), 4.42 (dd, $J_{3\alpha,3\beta}$ = 10.4, $J_{3\alpha,3a\alpha}$ = 6.7 Hz, 3-Hα, 1 H). − ^{13}C NMR (75 MHz, $CDCl_3$): δ = 21.53 (d), 21.57 (d), 33.11 (u), 33.82 (u), 34.76 (u), 35.30 (u), 35.55 (u), 36.16 (u), 36.29 (u), 36.42 (u), 36.47 (u), 40.77 (d), 42.74 (d), 44.05 (d), 44.58 (d), 45.00 (d), 45.29 (d), 45.51 (d), 46.74 (d), 46.80 (d), 47.69 (d), 48.82 (d), 50.25 (d), 50.77 (d), 51.21 (d, OMe), 52.40 (d, OMe), 52.74 (d, OMe), 63.09 (u, OCH_2), 63.56 (u, OCH_2), 64.94 (u, OCH_2), 65.23 (u, OCH_2), 68.07 (u, OCH_2), 68.18 (u, OCH_2), 68.72 (u, OCH_2), 68.80 (u, OCH_2), 69.60 (u, OCH_2), 69.63 (u, OCH_2), 69.68 (u, OCH_2), 69.87 (u, OCH_2), 174.42 (u, CO), 174.72 (u, CO), 175.23 (u, CO), 176.37 (u, CO), 180.00 (u, CO). − MS (EI, 70 eV); *m/z* (%): 354 [M^+] (1), 336 (1), 323 (2), 269 (52), 252 (15), 251 (100), 237 (16), 223 (27), 205 (11), 191 (38), 163 (30), 119 (16), 117 (19), 105 (16), 91 (12), 79 (11). − IR (neat): $\tilde{\nu}$ = 3500−3450 (s), 2950 (s), 2862 (s), 2720 (w), 1775 (s), 1720 (s), 1460 (s), 1430 (s), 1373 (s), 1270−1150 (s), 1140 (s), 1060−1000 (s), 960 (m), 910 (m), 857 (w), 750 (s), 664 (m). − $C_{13}H_{17}O_6$ [M^+ − C_5H_9O]: calcd. 269.1025; found 269.1025 (MS).

Methyl [3aS-(3aα,3bβ,6aβ,7aα)]-Octahydro-1,5-dioxo-pentaleno[1,2-c]furan-3b(1H)-carboxylate (**21c**) *and Methyl [3aS-(3aα,3bα,6aα,7aα)]-Octahydro-1,5-dioxo-pentaleno[1,2-c]furan-3b(1H)-carboxylate* (**22c**): A mixture of **20** (316 mg, 2.05 mmol) and **7** (364 mg, 2.00 mmol) in MeCN (5 ml) was heated to reflux at 80°C for 40 h. TLC (MeOH/$CHCl_3$, 1:9) indicated complete consumption of the starting materials. The solvent was then removed in vacuo and the residue was redissolved in CH_2Cl_2 (50 ml). A stream of ozone/oxygen was passed through the solution at −70°C until a blue color persisted (5−10 min.). After stirring the solution for a further 1 h at −70°C, argon was passed through the solution to remove excess ozone and then Me_2S (10 ml) was added. The solution was allowed to warm to room temp. and the solvent was removed in vacuo. Purification of the residue by chromatography (MeOH/$CHCl_3$, 1:9) gave, besides 437 mg (53%) of an oily mixture of **21c** (6%), **21b** and **22b**, ketone **22c** (121 mg, 25%) as colorless crystals.

22c: M.p. 185°C, $[\alpha]_D$ = +133.3 (*c* = 1.17, CH_2Cl_2). − ^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.76 (ddd, $J_{7\beta,6a\alpha}$ = 9.4, $J_{7\beta,7\alpha}$ = 15.1, $J_{7\beta,7a\alpha}$ = 6.0 Hz, 7-Hβ, 1 H), 2.20 (d, $J_{4\beta,4\alpha}$ = 18.5 Hz, 4-Hβ, 1 H), 2.26 (d, $J_{6\beta,6\alpha}$ = 19.5 Hz, 6-Hβ, 1 H), 2.60 (ddd, $J_{6\alpha,4\alpha}$ = 1.0, $J_{6\alpha,6\beta}$ = 19.5, $J_{6\alpha,6a\alpha}$ = 8.1 Hz, 6-Hα, 1 H), 2.68 (ddd, $J_{7\alpha,6a\alpha}$ = 1.4, $J_{7\alpha,7\beta}$ = 15.1, $J_{7\alpha,7a\alpha}$ = 10.7 Hz, 7-Hα, 1 H), 2.74 (dd, $J_{4\alpha,4\beta}$ = 18.5, $J_{7\alpha,7\beta}$ = 1.0 Hz, 4-Hα, 1 H), 3.11 (m, 6a-Hα, 1 H), 3.32 (ddd, $J_{7a\alpha,3a\alpha}$ = 10.7, $J_{7a\alpha,7\alpha}$ = 10.7, $J_{7a\alpha,7\beta}$ = 6.0 Hz, 7a-Hα, 1 H), 3.69 (ddd, $J_{3a\alpha,3\alpha}$ = 7.7, $J_{3a\alpha,3\beta}$ = 1.7, $J_{3a\alpha,7a\alpha}$ = 10.7 Hz, 3a-Hα, 1 H), 3.75 (s, OMe, 3 H), 4.22 (dd, $J_{3\beta,3\alpha}$ = 10.4, $J_{3\beta,3a\alpha}$ = 1.7 Hz, 3-Hβ, 1 H), 4.47 (dd, $J_{3\alpha,3\beta}$ = 10.4, $J_{3\alpha,3a\alpha}$ = 7.7 Hz, 3-Hα, 1 H). − ^{13}C NMR (75 MHz, $CDCl_3$): δ = 34.71 (u), 40.88 (u), 42.93 (u), 43.40 (d), 46.18 (d), 47.15 (d), 53.0 (u, OMe), 60.03 (u, C-3b), 68.85 (u, C-3), 174.67 (u, CO), 179.61 (u, CO), 213.64 (u, C-5). − MS (EI, 70 eV); *m/z* (%): 238 [M^+] (41), 211 (16), 210 (17), 207 (13), 206 (52), 196 (12), 179 (47), 178 (59), 177 (11), 168 (14), 165 (11), 164 (22), 153 (11), 152 (16), 151 (23), 150 (52), 148 (11), 139 (12), 138 (20), 137 (18), 136 (22), 134 (11), 133 (18), 127 (11), 126 (11), 125 (12), 122 (19), 121 (44), 120 (10), 119 (15), 113 (14), 112 (15), 111 (10), 109 (17), 108 (22), 107 (41), 106 (30), 105 (73), 104 (14), 103 (10), 98 (10), 95 (15), 94 (12), 93 (68), 92 (40), 91 (100), 82 (24), 81 (49), 80 (11), 79 (91), 78 (25), 77 (88), 74 (23), 67 (13), 65 (41). − IR (KBr): $\tilde{\nu}$ = 2961 (m), 1766 (s, br), 1832 (s), 1633 (m), 1459 (m), 1436 (s), 1384 (s), 1329 (s), 1292 (s), 1261 (s), 1219 (s), 1196 (s), 1173 (s), 1098 (s), 1044 (s), 1025 (s), 1012 (s), 979 (m), 950 (w), 909 (m), 876 (w), 846 (w), 767 (w), 723 (w), 695 (w), 652 (w), 619 (w), 583 (w), 518 (w), 481 (w), 461 (w). − $C_{12}H_{14}O_5$: calcd. 238.0841, found 238.0840 (MS).

Methyl [3aS-(3aα,4β,5β,6aα)]-Hexahydro-5-[3-[[(1,1-dimethylethyl)dimethyl)silyl]oxy]-2,2-dimethylpropyl]-1-oxo-1H-cyclopenta[c]furan-4-carboxylate (**24**): To a solution of $Me_3SiC{\equiv}CH$ (0.5 g, 5.0 mmol) in diethyl ether (10 ml) *t*$BuMe_2Si$-$OCH_2CMe_2CH_2Li$[15] (5.0 mmol, 9.5 ml of a 0.53 M solution in diethyl ether) was added at 0°C. After stirring the solution for 15 min., it was added by syringe at 0°C to a suspension of CuI (0.95 g, 5.0 mmol) in diethyl ether (10 ml). After stirring the resulting solution for 15 min., it was cooled to −80°C and further *t*$BuMe_2$-$SiOCH_2CMe_2CH_2Li$ (5.0 mmol, 9.5 ml of a 0.53 M solution in diethyl ether) was added over a period of 15 min. The stirred mixture was allowed to warm to −40°C within 1 h, and then cooled to −70°C once more, whereupon a mixture of **7** (182 mg, 1.0 mmol) and Me_3SiCl (1.1 g, 10 mmol) in THF (10 ml) was added. The mixture was maintained at −70°C for 3 h and then warmed to 10°C over a period of 16 h. After acidification with 1 N HCl, aqueous NH_4Cl/NH_3 was added and the mixture was extracted with diethyl ether. The organic phase was dried ($MgSO_4$) and concentrated in vacuo. Purification of the residue by MPLC (EtOAc/*n*-hexane, 1:4) gave, besides **7** (104 mg, 57%), **24** (60 mg, 16%) as a colorless viscous oil. − ^{1}H NMR (250 MHz, $CDCl_3$): δ = 0.01 (s, $SiMe_2$, 6 H), 0.80 (s, CMe_2, 6 H), 0.85 (s, CMe_3, 9 H), 1.24 (dd, *J* = 14.0, *J* = 7.5 Hz, 7-H, 1 H), 1.41 (dd, *J* = 14.0, *J* = 3.5 Hz, 7-H, 1 H), 2.04 (ddd, *J* = 4.5, *J* = 13.0, *J* = 15.5 Hz, 6-H, 1 H), 2.31 (m, 2 H), 3.00 (m, 1 H), 3.10 (m, 1 H), 3.17 (s, 9-H, 2 H), 3.65 (s, OMe, 3 H), 4.11 (dd, *J* = 10.0, *J* = 2.0 Hz, 3-Hβ, 1 H), 4.37 (dd, *J* = 10.0, *J* = 7.5 Hz, 3-Hα, 1 H). − ^{1}H NMR (400 MHz, C_6D_6): δ = 0.02 (s, $SiMe_2$, 6 H), 0.76 (s, CMe_2, 3 H), 0.79 (s, CMe_2, 3 H), 0.97 (s, CMe_3, 9 H), 1.29 (dd, *J* = 14.0, *J* = 7.5 Hz, 7-H, 1 H), 1.45 (dd, *J* = 14.0, *J* = 4.0 Hz, 7-H, 1 H), 1.90 (ddddd, $J_{5\alpha,4\alpha}$ = 6.5, $J_{5\alpha,6\alpha}$ = 8.0, $J_{5\alpha,6\beta}$ = 9.5, $J_{5\alpha,7''}$ = 7.5 Hz, 5-Hα, 1 H), 1.97 (ddd, $J_{6\alpha,5\alpha}$ = 8.0, $J_{6\alpha,6\beta}$ = 13.0, $J_{6\alpha,6a\alpha}$ = 10.0 Hz, 6-Hα, 1 H), 2.15 (dddd, $J_{3a\alpha,3\alpha}$ = 7.5, $J_{3a\alpha,3\beta}$ = 2.5, $J_{3a\alpha,4\alpha}$ = 8.0, $J_{3a\alpha,6a\alpha}$ = 10.5 Hz, 3a-Hα, 1 H), 2.19 (ddd, $J_{6\beta,5\alpha}$ = 9.5, $J_{6\beta,5\alpha}$ = 9.5, $J_{6\beta,6\alpha}$ = 13.0, $J_{6\beta,6a\alpha}$ = 5.5 Hz, 6-Hβ, 1 H), 2.47 (ddd, $J_{6a\alpha,3a\alpha}$ = 10.5, $J_{6a\alpha,6\alpha}$ = 10.0, $J_{6a\alpha,6\beta}$ = 5.5 Hz, 6a-Hα, 1 H), 2.59 (dd, $J_{4\alpha,3a\alpha}$ = 8.0, $J_{4\alpha,5\alpha}$ = 6.5 Hz, 4-Hα, 1 H), 3.11 (s, 9-H, 2 H), 3.31 (s, OMe, 3 H), 3.69 (dd, *J* = 10.0, *J* = 2.0 Hz, 3-Hβ, 1 H), 3.81 (dd, *J* = 10.0, *J* = 7.5 Hz, 3-Hα, 1 H). − ^{1}H NMR (400 MHz, $C_6D_6/CDCl_3$, 2:1): δ = − 0.01 (s, $SiMe_2$, 6 H), 0.73 (s, CMe_2, 3 H), 0.76 (s, CMe_2, 3 H), 0.91 (s, CMe_3, 9 H), 1.22 (dd, *J* = 14.0, *J* = 7.5 Hz, 7-H, 1 H), 1.38 (dd, *J* = 14.0, *J* = 4.0 Hz, 7-H, 1 H), 1.90 (ddddd, $J_{5\alpha,4\alpha}$ = 6.5, $J_{5\alpha,6\alpha}$ = 8.0, $J_{5\alpha,\ 6\alpha}$ = 9.5, $J_{5\alpha,7'}$ = 4.0, $J_{5\alpha,7''}$ = 7.5 Hz, 5-Hα, 1 H), 1.97 (ddd, $J_{6\alpha,5\alpha}$ = 8.0, $J_{6\alpha,6\beta}$ = 13.0, $J_{6\alpha,6a\alpha}$ = 10.0 Hz, 6-Hα, 1 H), 2.09 (ddd, $J_{6\beta,5\alpha}$ = 9.5, $J_{6\beta,6\alpha}$ = 13.0, $J_{6\beta,6a\alpha}$ = 5.5 Hz, 6-Hβ, 1 H), 2.20 (dddd, $J_{3a\alpha,3\alpha}$ = 7.5, $J_{3a\alpha,3\beta}$ = 2.5, $J_{3a\alpha,4\alpha}$ = 8.0, $J_{3a\alpha,6a\alpha}$ = 10.5 Hz, 3a-Hα, 1 H), 2.48 (ddd, $J_{6a\alpha,3a\alpha}$ = 10.5, $J_{6a\alpha,6\alpha}$ 10.0, $J_{6a\alpha,6\beta}$ = 5.5 Hz, 6a-Hα, 1 H), 2.59 (dd, $J_{4\alpha,3a\alpha}$ = 8.0, $J_{4\alpha,5\alpha}$ = 6.5 Hz, 4-Hα, 1 H), 3.09 (s, 9-H, 2 H), 3.33 (s, OMe, 3 H), 3.70 (dd, *J* = 10.0, *J* = 2.0 Hz, 3-Hβ, 1 H), 3.77 (dd, *J* = 10.0, *J* = 7.5 Hz, 3-Hα, 1 H). − $C_{20}H_{36}O_5Si$ (384.9): calcd. C 62.46, H 9.43; found C 62.18, H 9.20.

Methyl [3aR-(3aα,4β,5β,6aα)]-Hexahydro-1-oxo-5-phenylthio-1H-cyclopenta[c]furan-4-carboxylate (**25**): To a solution of PhSH (7.0 mmol, 0.7 ml) and **7** (1.4 g, 7.7 mmol) in THF (10 ml) was added NEt_3 (0.2 ml, 0.7 mmol). After stirring the mixture for 6 d at room temp., it was concentrated in vacuo. Chromatography (*n*-hexane/EtOAc, 3:1 and 1:1) of the residue gave a mixture of four adducts (62%) in a ratio of 84:11:3:2 and **7** (38%). MPLC (*n*-hexane/EtOAc, 1:1) of the mixture gave **7** (400 mg, 29%), a mixture of the minor diastereomers (120 mg, 5%) and **25** (880 mg, 39%). Further MPLC gave the pure minor diastereomers. **25**: ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.42 (m, 6-Hα, 6-Hβ, 2 H), 3.15 (ddd, $J_{6a\alpha,3a\alpha}$ = 10.5, $J_{6a\alpha,6\alpha}$ = 9.0, $J_{6a\alpha,6\beta}$ = 4.5 Hz, 6a-Hα, 1 H), 3.28 (dddd, $J_{3a\alpha,3\alpha}$ = 8.0, $J_{3a\alpha,3\beta}$ = 5.0, $J_{3a\alpha,4\alpha}$ = 8.0, $J_{3a\alpha,6a\alpha}$ = 10.0 Hz, 3a-Hα, 1 H), 3.38 (dd, $J_{4\alpha,3a\alpha}$ = 8.0, $J_{4\alpha,5\alpha}$ = 6.1 Hz, 4-H, 1 H), 3.73 (s, OMe, 3 H), 3.87 (q, $J_{5\alpha,6\alpha}$ = $J_{5\alpha,6\beta}$ = 6.1 Hz, 5-H, 1 H), 4.54 (m, 3-Hβ, 3-Hα, 2 H), 7.27−7.35 (m, 3 H), 7.43−7.47 (m, 2 H). − ^{13}C NMR (20 MHz, $CDCl_3$): δ = 35.7 (t, C-6), 40.7 (d), 42.7 (d), 51.3 (d), 51.8 (q, OMe), 53.6 (d), 69.6 (t, C-3), 127.8 (d), 129.2 (d), 132.7 (d), 134.2 (s), 170.6 (s, CO_2Me), 179.3 (s, C-1). − $C_{15}H_{16}O_4S$ (292.4): calcd. C 61.62, H 5.52; found C 61.35, H 5.40. Data for minor diastereomer (11%): ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.47 (dt, *J* = 7 Hz, 6-Hα, 6-Hβ, 2 H), 3.08 (dd, $J_{4,3a\alpha}$ = $J_{4,5}$ = 6.5 Hz, 4-H, 1 H), 3.26 (ddd, $J_{6a\alpha,3a\alpha}$ = 9.5, $J_{6a\alpha,6\alpha}$ = $J_{6a\alpha,6\beta}$ = 7.0 Hz, 6a-Hα, 1 H), 3.51 (dddd, $J_{3a\alpha,3\alpha}$ = 7.5, $J_{3a\alpha,3\beta}$ = 2.5, $J_{3a\alpha,4}$ = 7.0, $J_{3a\alpha,6a\alpha}$ = 9.5 Hz, 3a-Hα, 1 H), 3.64 (s, OMe, 3 H), 3.88 (ddd, $J_{5,4}$ = $J_{5,6a}$ = $J_{5,6\beta}$ = 6.5 Hz, 5-H, 1 H), 4.12 (dd, $J_{3\beta,3\alpha}$ = 10.0, $J_{3\beta,3a\alpha}$ = 2.5 Hz, 3-Hβ, 1 H), 4.50 (dd, $J_{3\alpha,3\beta}$ = 10.0, $J_{3\alpha,3a\alpha}$ = 7.5 Hz, 3-Hα, 1 H), 7.25−7.35 (m, 3 H), 7.40−7.44 (m, 2 H). − MS (EI, 70 eV); *m*/*z* (%): 292 [M^+] (35), 261 (3), 233 (4), 232 (6), 183 (4), 151 (12), 125 (7), 123 (6), 111 (13), 110 (100), 109 (26), 107 (10), 79 (50), 77 (17), 66 (15), 65 (23). − $C_{15}H_{16}O_4S$ (292.3): calcd. C 61.62, H 5.52; found C 61.45, H 5.51. Data for minor diastereomer (3%): ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.02 (ddd, $J_{6\alpha,5}$ = 10.5, $J_{6\alpha,6\beta}$ = 14.0, $J_{6\alpha,6a\alpha}$ = 10.0 Hz, 6-Hα, 1 H), 2.58 (ddd, $J_{6\beta,5}$ = 7.0, $J_{6\beta,6\alpha}$ = 14.0, $J_{6\beta,6a\alpha}$ = 2.5 Hz, 6-Hß, 1 H), 2.99 (dd, $J_{4,3a\alpha}$ = 9.0, $J_{4,5}$ = 10.0 Hz, 4-H, 1 H), 3.13 (ddd, $J_{6a\alpha,3a\alpha}$ = 9.5, $J_{6a\alpha,6\alpha}$ = 9.5, $J_{6a\alpha,6\beta}$ = 2.0 Hz, 6a-Hα, 1 H), 3.37 (dddd, $J_{3a\alpha,3\alpha}$ = 8.5, $J_{3a\alpha,3\beta}$ = 4.0, $J_{3a\alpha,4}$ = 9.0, $J_{3a\alpha,6a\alpha}$ = 9.0 Hz, 3a-Hα, 1 H), 3.67 (s, OMe, 3 H), 3.67 (ddd, $J_{5,4}$ = $J_{5,6\alpha}$ = 10.0, $J_{5,6\beta}$ = 6.5 Hz, 5-H, 1 H), 4.17 (dd, $J_{3\beta,3\alpha}$ = 10.5, $J_{3\beta,3a\alpha}$ = 4.0 Hz, 3-Hβ, 1 H), 4.32 (dd, $J_{3\alpha,3\beta}$ = 10.5, $J_{3\alpha,3a\alpha}$ = 8.5 Hz, 3-Hα, 1 H), 7.30−7.36 (m, 3 H), 7.43−7.45 (m, 2 H). Data for minor diastereomer (2%): ^{1}H NMR (250 MHz, $CDCl_3$): δ = 2.12 (m, 6-Hα, 1 H), 2.57 (ddd, *J* = 7.5, *J* = 10.0, *J* = 14.0 Hz, 6-Hβ, 1 H), 2.74 (dd, $J_{4,3a\alpha}$ = 7.0, $J_{4,5}$ = 7.0 Hz, 4-H, 1 H), 3.14 (m, 6a-Hα, 1 H), 3.24 (m, 3a-Hα, 1 H), 3.65 (s, OMe, 3 H), 3.87 (ddd, $J_{4,5}$ = $J_{5,6\alpha}$ = $J_{5,6\beta}$ = 7.0 Hz, 5-H, 1 H), 4.25 (dd, $J_{3\beta,3\alpha}$ = 10.0, $J_{3\beta,3a\alpha}$ = 2.5 Hz, 3-Hβ, 1 H), 4.45 (dd, $J_{3\alpha,3\beta}$ = 10.0, $J_{3\alpha,3a\alpha}$ = 7.5 Hz, 3-Hα, 1 H), 7.30−7.35 (m, 3 H), 7.40−7.46 (m, 2 H).

Methyl [3aS-(3aα,4aα,7aα,7bα)]-3a,4,4a,5,7,7a-Hexahydro-5-oxofuro[3',4':4,5]cyclopenta[1,2-c]pyrazole-7b(3H)-carboxylate (**27**): To a solution of **7** (180 mg, 1.0 mmol) in diethyl ether (5 ml) was added an excess of CH_2N_2 in the same solvent at room temp. After 10 min., a colorless solid deposited. Further CH_2N_2 in diethyl ether was successively added until the yellow color persisted (1 d). The excess CH_2N_2 was subsequently destroyed by addition of AcOH and the solution was concentrated in vacuo, affording **26** (220 mg, 98%) as light-yellow crystals, which were recrystallized from diethyl ether, m.p. 106°C (dec.), $[\alpha]_D$ = +336.4 (*c* = 0.50, acetone), $[\alpha]_{365}$ = +2218.0 (*c* = 0.5, acetone). − ^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.93 (ddd, $J_{4\beta,3a\alpha}$ = 2.6, $J_{4\beta,4\alpha}$ = 14.3, $J_{4\beta,4a\alpha}$ = 2.6 Hz, 4-Hβ, 1 H), 2.38 (ddd, $J_{4\alpha,3a\alpha}$ = 9.7, $J_{4\alpha,4\beta}$ = 14.3, $J_{4\alpha,4a\alpha}$ = 9.7 Hz, 4-Hα, 1 H), 2.87 (dddd, $J_{3a\alpha,3\alpha}$ = 8.5, $J_{3a\alpha,3\beta}$ = 3.2, $J_{3a\alpha,4\alpha}$ = 9.7, $J_{3a\alpha,4\beta}$ = 2.6 Hz, 3a-Hα, 1 H), 3.08 (ddd, $J_{4a\alpha,4\alpha}$ = 9.0, $J_{4a\alpha,4\beta}$ = 2.1, $J_{4a\alpha,7a\alpha}$ = 9.0 Hz, 4a-Hα, 1 H), 3.77 (s, OMe, 3 H), 3.88 (ddd, $J_{7a\alpha,4a\alpha}$ = 9.0, $J_{7a\alpha,7\alpha}$ = 6.5, $J_{7a\alpha,7\beta}$ = 1.5 Hz, 7a-Hα, 1 H), 4.45 (dd, $J_{7\alpha,7\beta}$ = 9.9, $J_{7\alpha,7a\alpha}$ = 6.4 Hz, 7-Hα, 1 H), 4.68 (dd, $J_{3\beta,3\alpha}$ = 18.7, $J_{3\beta,3a\alpha}$ = 3.2 Hz, 3-Hβ, 1 H), 4.82 (dd, $J_{3\alpha,3\beta}$ = 18.7, $J_{3\alpha,3a\alpha}$ = 8.5 Hz, 3-Hα, 1 H), 5.07 (dd, $J_{7\beta,7\alpha}$ = 9.9, $J_{7\beta,7a\alpha}$ = 1.5 Hz, 7-Hβ, 1 H). − ^{13}C NMR (75 MHz, $CDCl_3$): δ = 33.6 (t, C-4), 40.6 (d), 44.7 (d), 47.7 (d), 53.2 (q, OMe), 66.6 (t, C-7), 87.7 (t, C-3), 106.8 (s, C-7b), 168.8 (s, CO), 178.0 (s, C-5). − IR (KBr): $\tilde{\nu}$ = 3040 (w), 3000 (w), 2950 (m), 1755 (vs), 1735 (vs), 1725 (vs), 1550 (m), 1475 (m), 1450 (s), 1425 (s), 1370 (s), 1335 (m), 1285 (s),

1270 (s), 1235 (s), 1220 (s), 1170 (m), 1155 (s), 1105 (m), 1055 (s), 1025 (m), 1005 (m), 970 (s), 930 (m), 915 (m), 905 (m), 815 (m). – MS (EI, 70 eV); *m/z* (%): 196 [$M^+ - N_2$] (14), 165 (12), 166 (27), 151 (19), 139 (13), 138 (87), 137 (31), 136 (10), 119 (19), 110 (32), 107 (28), 106 (20), 105 (18), 93 (36), 92 (16), 91 (54), 79 (100), 78 (54), 77 (77), 65 (15). – MS (FI); *m/z*: 224 [M^+], 196. – $C_{10}H_{12}N_2O_4$ (224.2): C 53.57, H 5.39, N 12.49; found C 53.60, H 5.44, N 12.49.

Methyl [1S-(1α,3aα,6aα)]- and Methyl [1R-(1α,3aβ,6aβ)]-3,3a,6,6a-Tetrahydro-1-hydroxy-1H-cyclopenta[c]furan-4-carboxylate (**29a** and **30a**): To a solution of **7** (15.4 g, 84 mmol) in a mixture of toluene (500 ml) and THF (150 ml) at −100°C, DIBAL-H (86 mmol, 86 ml of a 1.0 M solution in toluene) was added dropwise under stirring over a period of 45 min. After stirring the mixture for 5.5 h at −90°C, it was warmed to −60°C over 1 h and kept for 16 h at −50°C. At this temp., a mixture of H_2O (10 ml) and THF (20 ml) was added, followed by solid $MgSO_4$ (100 g) and silica gel (50 g) and the resulting mixture was stirred for 1 h at room temp. The suspension was filtered through a pad of silica gel with EtOAc and the filtrate was concentrated in vacuo. Purification of the residue by chromatography (EtOAc) and kugelrohr distillation (80°C/10^{-2} Torr) gave a mixture of **29a** and **30a** (11.2 g, 73%) in a ratio of 7:1 as a colorless viscous oil.

29a: ^{1}H NMR (400 MHz, $CDCl_3$): δ = 2.47 (dddd, $J_{6\beta,3a\alpha}$ = 2.0, $J_{6\beta,5}$ = 3.0, $J_{6\beta,6\alpha}$ = 18.5, $J_{6\beta,6a\alpha}$ = 3.0 Hz, 6-Hβ, 1 H), 2.81 (dddd, $J_{6\alpha,3a\alpha}$ = 2.0, $J_{6\alpha,5}$ = 2.0, $J_{6\alpha,6\beta}$ = 18.0, $J_{6\alpha,6a\alpha}$ = 10.0 Hz, 6-Hα, 1 H), 2.96 (ddd, $J_{6a\alpha,3a\alpha}$ = 9.0, $J_{6a\alpha,6\alpha}$ = 9.0, $J_{6a\alpha,6\beta}$ = 3.5 Hz, 6a-Hα, 1 H), 3.33 (d, $J_{OH,1\beta}$ = 2 Hz, OH, 1 H), 3.68 (m, 3a-Hα, 1 H), 3.75 (s, OMe, 3 H), 3.93 (dd, $J_{3\beta,3\alpha}$ = 9.0, $J_{3\beta,3a\alpha}$ = 2.0 Hz, 3-Hβ, 1 H), 4.18 (dd, $J_{3\alpha,3\beta}$ = 9.0, $J_{3\alpha,3a\alpha}$ = 7.0 Hz, 3-Hα, 1 H), 5.29 (d, $J_{1\beta,OH}$ = 2 Hz, 1-Hβ, 1 H), 6.71 (dd, $J_{5,6\alpha}$ = 2.0, $J_{5,6\beta}$ = 3.0 Hz, 5-H, 1 H). – ^{13}C NMR (20 MHz, $CDCl_3$): δ = 37.4 (t, C-6), 48.8 (d), 49.4 (d), 51.5 (q, OMe), 70.0 (t, C-3), 105.3 (d, C-1), 136.6 (s, C-4), 143.4 (d, C-5), 165.0 (s, CO).

30a: ^{1}H NMR (400 MHz, $CDCl_3$, in part): δ = 5.44 (dd, $J_{1\beta,OH}$ = 3.5, $J_{1\beta,6a\beta}$ = 6 Hz, 1-Hβ, 1 H), 6.80 (dd, $J_{5,6\beta}$ = 2.0, $J_{5,6\alpha}$ = 3.0 Hz, 5-H, 1 H). – ^{13}C NMR (20 MHz, $CDCl_3$, in part): δ = 32.2 (t, C-6), 46.1 (d), 49.7 (d), 51.5 (q, OMe), 70.3 (t, C-3), 98.7 (d, C-1), 145.2 (d, C-5). – IR (neat): $\tilde{\nu}$ = 3420 (b, s), 3070 (w), 2960 (s), 2900 (m), 2850 (w), 1715 (b, vs), 1635 (s), 1440 (s), 1360 (s), 1315 (s), 1270 (s), 1200 (s), 1110 (s), 1090 (s), 1060 (s), 1015 (s), 990 (s), 915 (s), 760 (s). – MS (EI, 70 eV); *m/z* (%): 184 [M^+] (5), 167 (6), 166 (15), 154 (69), 153 (28), 138 (47), 137 (78), 125 (76), 124 (17), 123 (19), 122 (100), 107 (16), 106 (10), 105 (25), 95 (40), 94 (40), 93 (65), 79 (85), 78 (30), 77 (58), 67 (23), 66 (26), 65 (42). – $C_9H_{12}O_4$: calcd. 184.0736, found 184.0740 (MS). – $C_8H_{10}O_3$ [$M^+ - CH_2O$]: calcd. 154.0630, found 154.0632 (MS). – $C_9H_{12}0_4$ (184.2): calcd. C 58.69, H 6.57; found C 58.58, H 6.47.

Methyl [1S-(1α,3aα,6aα)]- and Methyl [1R-(1α,3aβ,6aβ)]-3,3a,6,6a-Tetrahydro-1-methoxy-1H-cyclopenta[c]furan-4-carboxylate (**29b** and **30b**): To a solution of a 7:1 mixture of **29a** and **30a** (3.1 g, 17 mmol) in MeOH (50 ml) was added concentrated H_2SO_4 (1 ml) and the mixture was heated to reflux for 1 d. After cooling to room temp., the acid was neutralized by the addition of solid Na_2CO_3. The organic phase was concentrated in vacuo, the residue was dissolved in EtOAc and saturated aqueous $NaHCO_3$ was added. The organic phase was dried ($MgSO_4$) and concentrated in vacuo. The residue was redissolved in EtOAc, the solution was filtered through a pad of silica gel with EtOAc and the filtrate was concentrated in vacuo. Purification of the residue by kugelrohr distillation (70°C/10^{-2} Torr) gave a mixture of **29b** and **30b** (3.2 g, 95%) in a ratio of 9:1 as a colorless oil. **29b**: ^{1}H NMR (250 MHz, $CDCl_3$): δ = 2.46 (dddd, $J_{6\beta,3a\alpha}$ = 3.0, $J_{6\beta,5}$ = 3.0, $J_{6\beta,6\alpha}$ = 19.0, $J_{6\beta,6a\alpha}$ = 3.0 Hz, 6-Hβ, 1 H), 2.81 (dddd, $J_{6\alpha,3a\alpha}$ = 1.5, $J_{6\alpha,5}$ = 2.5, $J_{6\alpha,6\beta}$ = 19.0, $J_{6\alpha,6a\alpha}$ = 10.0 Hz, 6-Hα, 1 H), 2.95 (dd, $J_{6a\alpha,3a\alpha}$ = 8.5, $J_{6a\alpha,6\alpha}$ = 10.0, $J_{6a\alpha,6\beta}$ = 3.0 Hz, 6a-Hα, 1 H), 3.34 (s, OMe, 3 H), 3.63 (m, 3a-Hα, 1 H), 3.75 (s, OMe, 3 H), 3.89 (dd, $J_{3\beta,3\alpha}$ = 9.0, $J_{3\beta,3a\alpha}$ = 2.0 Hz, 3-Hβ, 1 H), 3.97 (dd, $J_{3\alpha,3\beta}$ = 9.0, $J_{3\alpha,3a\alpha}$ = 6.5 Hz, 3-Hα, 1 H), 4.79 (s, 1-Hβ, 1 H), 6.71 (dd, $J_{5,6\alpha}$ = 3.0, $J_{5,6\beta}$ = 3.0 Hz, 5-H, 1 H). – ^{13}C NMR (20 MHz, $CDCl_3$): δ = 37.6 (t, C-6), 48.1 (d), 49.3 (d), 51.5 (q, OMe), 54.3 (q, OMe), 69.7 (t, C-3), 111.5 (d, C-1), 136.7 (s, C-4), 143.2 (d, C-5), 165.0 (s, CO). **30b**: ^{1}H NMR (250 MHz, $CDCl_3$, in part): δ = 3.73 (s, OMe, 3 H), 4.93 (d, $J_{1\beta,6a\beta}$ = 6 Hz, 1-Hβ, 1 H), 6.76 (dd, $J_{5,6\beta}$ = 2.0, $J_{5,6\alpha}$ = 3.0 Hz, 5-H, 1 H). – ^{13}C NMR (20 MHz, $CDCl_3$, in part): δ = 32.0 (u, C-6), 46.3 (d), 49.8 (d), 70.3 (u, C-3), 105.0 (d, C-1), 145.0 (d, C-5). – IR (neat): $\tilde{\nu}$ = 2980 (w), 2950 (s), 2930 (w), 2900 (s), 2840 (m), 1730 (b, vs), 1640 (s), 1440 (s), 1370 (s), 1315 (m), 1270 (s), 1235 (m), 1195 (s), 1100 (s), 1075 (s), 1040 (m), 1020 (m), 995 (s), 980 (s), 930 (s), 760 (s). – MS (EI, 70 eV); *m/z* (%): 168 [$M^+ - CH_2O$] (85), 167 (55), 153 (14), 138 (15), 137 (41), 121 (10), 110 (11), 109 (87), 108 (15), 107 (22), 105 (25), 93 (22), 92 (11), 91 (15), 80 (11), 79 (100), 78 (39), 77 (73), 66 (11). – MS (CI, NH_3); *m/z* (%): 216 [$M^+ + NH_4$] (13), 184 (100), 167 (16). – $C_{10}H_{14}O_4$: calcd. 198.0892, found 198.0897 (MS). – $C_{10}H_{14}O_4$ (198.2): calcd. 60.50, H 7.12; found C 60,79, H 7.08.

Methyl [1R-(1α,3aα,6aα)]- and Methyl [1S-(1α,3aβ,6aβ)]-3,3a,6,6a-Tetrahydro-1-(trimethylsilyl)oxy-1H-cyclopenta[c]furan-4-carboxylate (**29c** and **30c**): A solution of **29a** and **30a** (0.25 g, 1.3 mmol) in DMF (7 ml) was treated with trimethylsilyl imidazole (0.3 ml, 2.0 mmol) at 0°C and the resulting mixture was stirred at room temp. for 1 h. Cold water was added and the mixture was extracted with EtOAc as rapidly as possible. The organic phase was dried ($MgSO_4$), and the solvents were removed in vacuo at room temp. Purification of the residue by MPLC (EtOAc/*n*-hexane, 1:1) to remove the hemiacetals formed during work-up gave a 7:1 mixture of **29c** and **30c** (150 mg, 45%) as a colorless oil. **29c**: ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.12 (s, $SiMe_3$, 9 H), 2.39 (dddd, $J_{6\beta,3a\alpha}$ = 3.0, $J_{6\beta,5}$ = 3.0, $J_{6\beta,6\alpha}$ = 19.5, $J_{6\beta,6a\alpha}$ = 3.0 Hz, 6-Hβ, 1 H), 2.74 (dddd, $J_{6\alpha,3a\alpha}$ = 2.0, $J_{6\alpha,5}$ = 2.0, $J_{6\alpha,6\beta}$ = 19.5, $J_{6\alpha,6a\alpha}$ = 10.0 Hz, 6-Hα, 1 H), 2.86 (ddd, $J_{6a\alpha,3a\alpha}$ = 8.5, $J_{6a\alpha,6\alpha}$ = 9.5, $J_{6a\alpha,6\beta}$ = 4.0 Hz, 6a-Hα, 1 H), 3.62 (m, 3a-Hα, 1 H), 3.70 (s, OMe, 3 H), 3.82 (dd, $J_{3\beta,3\alpha}$ = 9.0, $J_{3\beta,3a\alpha}$ = 2.0 Hz, 3-Hβ, 1 H), 4.05 (dd, $J_{3\alpha,3\beta}$ = 9.0, $J_{3\alpha,3a\alpha}$ = 7.0 Hz, 3-Hα, 1 H), 5.20 (s, 1-Hβ, 1 H), 6.65 (ddd, $J_{5,3a\alpha}$ = 3.0, $J_{5,6\alpha}$ = 2.0, $J_{5,6\beta}$ = 3.0 Hz, 5-H, 1 H). – ^{13}C NMR (100 MHz, $CDCl_3$): δ = 0.2 (q, $SiMe_3$), 37.5 (t, C-6), 49.4 (d), 50.7 (d), 51.5 (q, OMe), 70.0 (t, C-3), 105.7 (d, C-1), 136.8 (s, C-4), 143.3 (d, C-5) 165.1 (s, CO). **30c**: ^{1}H NMR (400 MHz, $CDCl_3$, in part): δ = 3.69 (s, OMe, 3 H), 5.36 (d, $J_{1\beta,6a\beta}$ = 5.5 Hz, 1-Hβ, 1 H), 6.71 (ddd, $J_{5,3a\beta}$ = 3.0, $J_{5,6\beta}$ = 2.0, $J_{5,6\alpha}$ = 3.0 Hz, 5-H, 1 H). – ^{13}C NMR (100 MHz, $CDCl_3$, in part): δ = 32.6 (t, C-6), 47.2 (d), 49.8 (d), 51.5 (q, OMe), 70.3 (t, C-3), 99.2 (d, C-1), 136.1 (s, C-4), 145.4 (d, C-5). – IR (neat): $\tilde{\nu}$ = 2950 (s), 2920 (m), 2900 (m), 2850 (w), 1720 (b, vs), 1635 (m), 1440 (s), 1370 (s), 1340 (w), 1315 (m), 1265 (s), 1250 (s), 1235 (m), 1195 (m), 1160 (w), 1100 (s), 1070 (m), 1050 (s), 1020 (m), 995 (s), 920 (m), 870 (s), 840 (s), 760 (m). – MS (EI, 70 eV); *m/z* (%): 256 [M^+] (0.5), 255 (1), 241 (4.5), 227 (12), 226 (69), 225 (20), 213 (8), 211 (53), 194 (8), 167 (37), 166 (15), 151 (11), 138 (50), 137 (68), 135 (10), 107 (15), 106 (12), 105 (41), 103 (11), 93 (23), 91 (12), 89 (35), 79 (66), 78 (26), 77 (42), 75 (53), 73 (100), 65 (14), 59 (32), 45 (23). – $C_{11}H_{17}O_4Si$ [M^+ – Me]: calcd. 241.0896, found 241.0897 (MS).

Methyl [3aR-(3aα,4aβ,5β,7aβ,7bα)]- and Methyl [3aS-(3aα,4aα,5α,7aα,7bα)]-3a,4,6a,5,7,7a-Hexahydro-5-hydroxyfuro[3′,4′:4,5]cyclopenta[1,2-c]pyrazole-7b(3H)-carboxylate (**31a** and

32a): A solution of a 7:1 mixture of alkenes **29a** and **30a** (550 mg, 3.0 mmol) in diethyl ether (5 ml) was treated at room temp. with an excess of CH_2N_2 in the same solvent. After stirring the mixture for 3 d, the excess CH_2N_2 and the solvent were removed in vacuo. The residue was dissolved in EtOAc, the solution was filtered through a pad of silica gel with EtOAc, and the filtrate was concentrated in vacuo. Purification of the residue by MPLC (EtOAc) gave a 7.5:7:1:1 mixture of **31a**, **32a** and the isomeric cycloadducts (650 mg, 95%), stemming from the addition of CH_2N_2 to **30a**, as a colorless oil. − ^{1}H NMR (400 MHz, $CDCl_3$, in part): δ = 0.92 (ddd, $J_{4\alpha,3a\alpha}$ = 9.5, $J_{4\alpha,4\beta}$ = 13.5, $J_{4\alpha,4a\alpha}$ = 9.5 Hz, 4-Hα, 1 H, **32a**), 1.59 (ddd, $J_{4\alpha,3a\beta}$ = 3.0, $J_{4\alpha,4\beta}$ = 14.0, $J_{4\alpha,4a\alpha}$ = 8.5 Hz, 4-Hα, 1 H, **31a**), 5.08 (s, 5-Hβ, 1 H, **32a**), 5.20 (s, 5-Hβ, 1 H, **31a**). − ^{13}C NMR (100 MHz, $CDCl_3$, in part): δ = 35.6 (u, C-4), 35.7 (u, C-4), 101.4 (d, C-5), 101.9 (d, C-5), 107.3 (u, C-7b), 111.4 (u, C-7b), 168.3 (u, CO), 169.9 (u, CO). − IR (neat): $\tilde{\nu}$ = 3400 (b, vs), 2960 (s), 2895 (w), 1735 (b, vs), 1435 (b, s), 1225 (b, m), 1060 (b, s), 1015 (b, m), 1000 (b, m), 980 (b, w), 905 (b, s).

Oxidation of **31a** and **32a** to **25** and Methyl [3aR-*(3aα, 4aβ,7aβ,7bα)]-3a,4,4a,5,7,7a-Hexahydro-5-oxofuro[3′,4′:4,5]-cyclopenta[1,2-c]pyrazole-7b(3H)-carboxylate* (**26**): A 7.6:7:1:1 mixture of **31a**, **32a** and the isomeric cycloadducts (17 mg, 75 μmol), stemming from the addition of CH_2N_2 to **30a**, was dissolved in CH_2Cl_2 (9 ml) and pyridine (1 ml) and treated with an excess of pyridinium dichromate at room temp. After stirring the suspension for 4 h at room temp., it was filtered through a pad of silica gel with EtOAc and the filtrate was concentrated in vacuo. Traces of pyridine were removed azeotropically by coevaporation with toluene in vacuo. Purification of the residue by chromatography (EtOAc/*n*-hexane, 1:1) gave a 1:1.6 mixture of **26** and **27** (15 mg, 85%) as a colorless, viscous oil. **26**: ^{1}H NMR (250 MHz, $CDCl_3$): δ = 1.66 (ddd, $J_{4\beta,3a\alpha}$ = 6.0, $J_{4\beta,4\alpha}$ = 14.0, $J_{4\beta,4a\beta}$ = 8.5 Hz, 4-Hβ, 1 H), 2.38 (ddd, $J_{4\alpha,3a\alpha}$ = 9.0, $J_{4\alpha,4\beta}$ = 14.0, $J_{4\alpha,4a\beta}$ = 6.5 Hz, 4-Hα, 1 H), 2.83 (ddd, $J_{4a\beta,4\beta}$ = 8.5, $J_{4a\beta,4\alpha}$ = 6.5, $J_{4a\beta,7a\beta}$ = 9.0 Hz, 4a-Hβ, 1 H), 3.01 (dddd, $J_{3a\alpha,3\beta}$ = 2.0, $J_{3a\alpha,3\alpha}$ = 7.5, $J_{3a\alpha,4\beta}$ = 6.0, $J_{3a\alpha,4\alpha}$ = 9.0 Hz, 3a-Hα, 1 H), 3.78 (s, OMe, 3 H), 3.92 (ddd, $J_{7a\beta,4a\beta}$ = 8.5, $J_{7a\beta,7\beta}$ = 8.0, $J_{7a\beta,7\alpha}$ = 6.5 Hz, 7a-Hβ, 1 H), 4.28 (dd, $J_{7\alpha,7\beta}$ = 10.5, $J_{7\alpha,7a\beta}$ = 6.5 Hz, 7-Hα, 1 H), 4.63 (dd, $J_{3\alpha,3\beta}$ = 18.0, $J_{3\alpha,3a\alpha}$ = 7.5 Hz, 3-Hα, 1 H), 4.68 (dd, $J_{7\beta,7\alpha}$ = 10.5, $J_{7\beta,7a\beta}$ = 8.0 Hz, 7-Hβ, 1 H), 4.82 (dd, $J_{3\beta,3\alpha}$ = 18.0, $J_{3\beta,3a\alpha}$ = 2.0 Hz, 3-Hβ, 1 H). − IR (neat): $\tilde{\nu}$ = 2950 (m), 2920 (w), 1770 (vs), 1735 (vs), 1550 (m), 1460 (m), 1440 (s), 1375 (s), 1280 (s), 1260 (s), 1220 (s), 1155 (s) 1055 (s), 1020 (m), 970 (m), 905 (m).

Methyl [3aR-(3aα,4aβ,5β,7aβ,7bα)]- and Methyl [3aS-(3aα, 4aα,5α,7aα,7bα)]-3a,4,4a,5,7,7a-Hexahydro-5-methoxyfuro-[3′,4′:4,5]cyclopenta[1,2-c]pyrazole-7b(3H)-carboxylate (**31b** and **32b**): To a solution of a 9:1 mixture of **29b** and **30b** (64 mg, 0.32 mmol) in diethyl ether (2 ml) was added an excess of CH_2N_2 in the same solvent. After stirring the mixture for 65 h, excess CH_2N_2 and the solvent were removed in vacuo. Purification of the residue by chromatography (EtOAc/*n*-hexane, 1:1) gave a 10.5:12.2:1:1 mixture of **31b**, **32b** and the isomeric cycloadducts, stemming from the addition of CH_2N_2 to **30b**, as a viscous oil (60 mg, 78%). − ^{1}H NMR (250 MHz, $CDCl_3$, in part): δ = 0.91 (ddd, $J_{4\alpha,3a\alpha}$ = 9.5, $J_{4\alpha,4\beta}$ = 13.5, $J_{4\alpha,4a\alpha}$ = 9.5 Hz, 4-Hα, 1 H, **32b**), 1.55 (ddd, $J_{4\alpha,3a\alpha}$ = 8.5, $J_{4\alpha,4\beta}$ = 14.0, $J_{4\alpha,4a\beta}$ = 3.5 Hz, 4-Hα, 1 H, **31b**), 1.86 (ddd, $J_{4\beta,3a\alpha}$ = 9.5, $J_{4\beta,4\alpha}$ = 14.0, $J_{4\beta,4a\beta}$ = 9.5 Hz, 4-Hβ, 1 H, **31b**), 2.24 (ddd, $J_{4\beta,3a\alpha}$ = 8.5, $J_{4\beta,4\alpha}$ = 13.5, $J_{4\beta,4a\alpha}$ = 8.5 Hz, 4-Hβ, 1 H, **32b**), 3.28 (s, OMe, 3 H, **32b**), 3.30 (s, OMe, 3 H, **31b**), 3.73 (s, OMe, 3 H, **32b**) 3.77 (s, OMe, 3 H, **31b**).

Methyl [3aR-(3aα,4aβ,5β,7aβ,7bα)]- and Methyl [3aS-(3aα, 4aα,5α,7aα,7bα)]-3a,4,4a,5,7,7a-Hexahydro-5-(trimethylsilyl)-oxyfuro[3′,4′:4,5]cyclopenta[1,2-c]pyrazole-7b(3H)-carboxylate (**31c** and **32c**): To a solution of a mixture of **29c** and **30c** (700 mg, 2.75 mmol) in a ratio of 7:1 in diethyl ether (10 ml), an excess of CH_2N_2 in the same solvent was added at room temp. After stirring the mixture for 3 d, excess CH_2N_2 and the solvent were removed in vacuo at room temp. The residue was taken up in EtOAc, the solution was filtered through a pad of silica gel with EtOAc and the filtrate was concentrated in vacuo. Purification of the residue by MPLC (EtOAc/*n*-hexane, 1:1) gave a mixture of **31c**, **32c** and the isomeric cycloadducts (800 mg, 97%), stemming from the addition of CH_2N_2 to **30c.** The ratio of the major isomers **31c** and **32c** was 1.5:1. Further MPLC (EtOAc/*n*-hexane, 1:9) furnished the pure isomers. **31c**: ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.10 (s, $SiMe_3$, 9 H), 1.51 (ddd, $J_{4\beta,3a\alpha}$ = 2.5, $J_{4\beta,4\alpha}$ = 14.0, $J_{4\beta,4a\beta}$ = 8.5 Hz, 4-Hβ, 1 H), 1.78 (ddd, $J_{4\alpha,3a\alpha}$ = 10.0, $J_{4\alpha,4\beta}$ = 13.5, $J_{4\alpha,4a\beta}$ = 10.0 Hz, 4-Hα, 1 H), 2.25 (ddd, $J_{4a\beta,4\beta}$ = 8.5, $J_{4a\beta,4\alpha}$ = 9.5, $J_{4a\beta,7a\beta}$ = 7.0 Hz, 4a-Hβ, 1 H), 2.94 (dddd, $J_{3a\alpha,3\beta}$ = 2.5, $J_{3a\alpha,3\alpha}$ = 8.5, $J_{3a\alpha,4\beta}$ = 2.5, $J_{3a\alpha,4\alpha}$ = 9.5 Hz, 3a-Hα, 1 H), 3.66 (dd, $J_{7\alpha,7\beta}$ = 9.0, $J_{7\alpha,7a\beta}$ = 7.0 Hz, 7-Hα, 1 H), 3.74 (s, OMe, 3 H), 3.75 (ddd, $J_{7a\beta,4a\beta}$ = 7.5, $J_{7a\beta,7\beta}$ = 9.0, $J_{7a\beta,7\alpha}$ = 7.5 Hz, 7a-Hβ, 1 H), 4.31 (dd, $J_{7\beta,7\alpha}$ = 9.0, $J_{7\beta,7a\beta}$ = 9.0 Hz, 7-Hβ, 1 H), 4.59 (dd, $J_{3\beta,3\alpha}$ = 18.5, $J_{3\beta,3a\alpha}$ = 2.5 Hz, 3-Hβ, 1 H), 4.76 (dd, $J_{3\alpha,3\beta}$ = 18.5, $J_{3\alpha,3a\alpha}$ = 8.0 Hz, 3-Hα, 1 H), 5.15 (s, 5-Hα, 1 H). − ^{13}C NMR (75 MHz, $CDCl_3$): δ = 0.1 (q, $SiMe_3$), 35.5 (u, C-4), 37.6 (d), 48.6 (d), 51.5 (d), 52.8 (q, OMe), 69.2 (u, C-7), 87.8 (u, C-3), 102.3 (d, C-1), 111.7 (u, C-7b), 168.5 (s, CO). − MS (EI, 70 eV); *m*/*z* (%): 283 [M^+ − Me] (4), 240 (18), 225 (37), 208 (10), 193 (18), 181 (38), 180 (16), 166 (14), 152 (15), 151 (16), 149 (14), 137 (28), 121 (17), 120 (27), 119 (42), 107 (18), 105 (20), 103 (19), 93 (97), 92 (32), 91 (60), 89 (34), 79 (18), 77 (35), 75 (64), 73 (100), 59 (32), 45 (30). − $C_{13}H_{22}N_2O_4Si$ (298.4): calcd. C 52.32, H 7.43, N 9.39; found C 52.02, H 7.29, N 9.52. **32c**: ^{1}H NMR (400 MHz, $CDCl_3$): δ = 0.10 (s, $SiMe_3$, 9 H), 0.79 (ddd, $J_{4\alpha,3a\alpha}$ = 10.0, $J_{4\alpha,4\beta}$ = 13.5, $J_{4\alpha,4a\alpha}$ = 10.0 Hz, 4-Hα, 1 H), 2.16 (ddd, $J_{4\beta,3a\alpha}$ = 8.5, $J_{4\beta,4\alpha}$ = 13.5, $J_{4\beta,4a\alpha}$ = 8.5 Hz, 4-Hβ, 1 H), 2.72 (m, 3aα, 4aα, 2 H), 3.69 (s, OMe, 3 H), 3.86 (ddd, $J_{7a\alpha,4a\alpha}$ = 9.0, $J_{7a\alpha,7\alpha}$ = 9.0, $J_{7a\alpha,7\beta}$ = 4.5 Hz, 7a-Hα, 1 H), 4.08 (dd, $J_{7\alpha,7\beta}$ = 9.5, $J_{7\alpha,7a\alpha}$ = 9.0 Hz, 7-Hα, 1 H), 4.18 (dd, $J_{7\beta,7\alpha}$ = 9.5, $J_{7\beta,7a\alpha}$ = 4.5 Hz, 7-Hβ, 1 H), 4.36 (dd, $J_{3\alpha,3\beta}$ = 18.0, $J_{3\alpha,3a\alpha}$ = 7.5 Hz, 3-Hα, 1 H), 4.63 (dd, $J_{3\beta,3\alpha}$ = 18.0, $J_{3\beta,3a\alpha}$ = 2.0 Hz, 3-Hβ, 1 H), 5.02 (s, 5-Hβ, 1 H).

Methyl [1R-(1α,3aβ,3bβ,6aβ,7aβ)]- and Methyl [1S-(1α,3aα, 3bα,6aα,7aα)]-Octahydro-5-methylene-1-methoxypentaleno-[1,2-c]furan-3b(1H)-carboxylate (**33a** and **34a**): To a solution of a 9:1 mixture of alkenes **29b** and **30b** (3.0 g, 15 mmol) in THF (15 ml) were added $Pd(OAc)_2$ (0.5 g, 2.3 mmol), PPh_3 (2.4 g, 9.0 mmol) and **11** (6.2 g, 33 mmol). After heating the mixture to reflux for 16 h, it was cooled to room temp., exposed to atmospheric oxygen under stirring in order to destroy Pd(0) species present, and filtered through a pad of silica gel with EtOAc. The filtrate was concentrated in vacuo. Purification of the residue by chromatography (first EtOAc/*n*-hexane, 1:1; then 1:4) gave a mixture of **33a**, **34a** and the isomeric cycloadducts, stemming from the reaction of Pd-TMM with **30b**, as a colorless oil (2.32 g, 61%). The ratio of the major diastereomers **33a** and **34a** was 2:1. **33a**: ^{1}H NMR (250 MHz, $CDCl_3$, in part): δ = 1.62 (ddd, $J_{7\alpha,6a\beta}$ = 8.0, $J_{7\alpha,7\beta}$ = 14.0, $J_{7\alpha,7a\alpha}$ = 9.5 Hz, 7-Hα, 1 H), 1.87 (ddd, $J_{7\beta,6a\beta}$ = 9.0, $J_{7\beta,7\alpha}$ = 14.0, $J_{7\beta,7a\alpha}$ = 5.0 Hz, 7-Hβ, 1 H), 3.28 (s, OMe, 3 H), 3.53 (dd, $J_{3\beta,3\alpha}$ = 9.5, $J_{3\beta,3a\alpha}$ = 4.0 Hz, 3-Hβ, 1 H), 3.68 (s, OMe, 3 H), 3.95 (dd, $J_{3\alpha,3\beta}$ = 9.5, $J_{3\alpha,3a\alpha}$ = 8.0 Hz, 3-Hα, 1 H), 4.72 (s, 1-Hβ, 1 H), 4.86 (bs, =CH_2, 2 H). Data for **34a**: ^{1}H NMR (250 MHz, $CDCl_3$, in part): δ = 1.13 (ddd, $J_{7\alpha,6a\alpha}$ = 10, $J_{7\alpha,7\beta}$ = 13.5, $J_{7\alpha,7a\alpha}$ = 11.5 Hz, 7-Hα, 1 H), 3.11 (ddd, $J_{3a\alpha,3\alpha}$ = 6.0, $J_{3a\alpha,3\beta}$ = 3.0, $J_{3a\alpha,7a\alpha}$ = 9.5 Hz, 3a-Hα, 1 H), 3.67 (s, OMe, 3 H), 3.84 (d, $J_{3\beta,3a\alpha}$ = 3.0 Hz, 3-

Hβ, 1 H), 3.85 (d, $J_{3\alpha,3a\alpha}$ = 6.5 Hz, 3-Hα, 1 H), 4.88 (bd, =CH_2, 2 H). − IR (neat): ṽ = 3070 (w), 2990 (m), 2950 (s), 2910 (m), 2890 (m), 2830 (w), 1730 (b, vs), 1660 (m), 1435 (s).

Hydrolysis of **33a** *and* **34a**: A solution of a mixture of **33a**, **34a** and the isomeric cycloadducts (40 mg, 0.16 mmol), containing the major isomers **33a** and **34a** in a ratio of 2:1 in THF (4.5 ml), was treated with 2 N aqueous HCl (0.5 ml). After stirring the mixture for 65 h at room temp., solid $NaHCO_3$ was added and the solvent and water were removed azeotropically by coevaporation with toluene in vacuo. The residue was extracted with EtOAc/acetone (1:1). Concentration of the organic phase in vacuo and purification of the residue by chromatography (EtOAc/*n*-hexane, 1:1) gave, in addition to 12 mg (30%) of a 3:4 mixture of **33a** and **34a**, a mixture of **33b** and **34b** (16 mg, 42%) in a ratio of 7:3. **33b**: ^{1}H NMR (400 MHz, $CDCl_3$, in part): δ = 1.62 (ddd, $J_{7\alpha,6a\beta}$ = 8.0, $J_{7\alpha,7\beta}$ = 14.0, $J_{7\alpha,7a\alpha}$ = 9.5 Hz, 7-Hα, 1 H), 1.86 (ddd, $J_{7\beta,6a\beta}$ = 9.0, $J_{7\beta,7\alpha}$ = 14.0, $J_{7\beta,7a\alpha}$ = 5.0 Hz, 7-Hβ, 1 H), 3.55 (dd, $J_{3\beta,3\alpha}$ = 9.0, $J_{3\beta,3a\alpha}$ = 5.0 Hz, 3-Hβ, 1 H), 3.68 (s, OMe, 3 H), 4.14 (dd, $J_{3\alpha,3\beta}$ = 9.5, $J_{3\alpha,3a\alpha}$ = 8.5 Hz, 3-Hα, 1 H), 4.87 (bs, =CH_2, 2 H), 5.24 (d, $J_{1\beta,OH}$ = 1.5 Hz, 1-Hβ, 1 H), 5.26 (d, $J_{1\beta,OH}$ = 1.0 Hz, 1-Hβ, 1 H). **34b**: ^{1}H NMR (400 MHz, $CDCl_3$, in part): δ = 1.14 (ddd, $J_{7\alpha,6a\alpha}$ = 10, $J_{7\alpha,7\beta}$ = 13.5, $J_{7\alpha,7a\alpha}$ = 11.5 Hz, 7-Hα, 1 H), 3.87 (dd, $J_{3\beta,3\alpha}$ = 10.0, $J_{3\beta,3a\alpha}$ = 2.0 Hz, 3-Hβ, 1 H), 4.07 (dd, $J_{3\alpha,3\beta}$ = 9.5, $J_{3\alpha,3a\alpha}$ = 7.5 Hz, 3-Hα, 1 H), 4.89 (bd, =CH_2, 2 H). − IR (neat): ṽ = 3450 (b, vs), 3080 (w), 2950 (s), 2920 (s), 2850 (m), 1770 (vs), 1730 (vs), 1660 (m), 1440 (s), 1360 (s).

Oxidation of **33b** *and* **34b**: To a stirred solution of a 7:3 mixture of **33b** and **34b** (15 mg, 60 μmol) in CH_2Cl_2 (4 ml), pyridinium chlorochromate (65 mg, 300 μmol) was added over a period of 4 h at room temp. After stirring the mixture for a further 3 h, it was poured into 2 N aqueous HCl and the resulting mixture was extracted with EtOAc. The organic phase was washed with aqueous $NaHCO_3$, dried ($MgSO_4$), and filtered through a pad of silica gel with EtOAc. Concentration of the filtrate in vacuo and purification of the residue by chromatography (EtOAc/*n*-hexane, 1:1) gave a mixture of **6** and **12** (11 mg, 75%) in a ratio of 2:1 as colorless crystals.

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