Origin of stereofacial selectivity in electrophilic additions to methylenecyclohexanes and methylenedioxanes. A theoretical and experimental study

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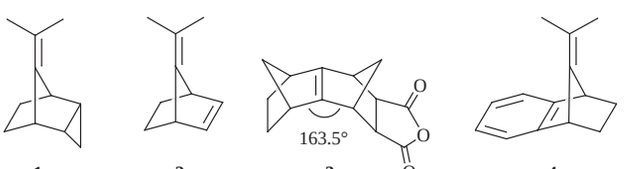
Addition reaction studies and *ab initio* calculations on methylenecyclohexane and 5-methylene-1,3-dioxane systems suggest that two electronic factors contribute to the stereoselectivity of epoxidation and diimide reduction. These are respectively the spatial anisotropy of the HOMO with respect to the two faces of the double bond, common to both molecules, which is likely to be responsible for the overall axial stereofacial selectivity exhibited, and a similar anisotropy in the electrostatic potential field of the methylenedioxane caused by the oxygens; which also favours attack from an axial direction by polarisable electrophilic species. The anisotropy of the HOMO arises from the important topological difference between the contributions made to the HOMO by the periplanar β C–H σ bonds and opposing β C–O or C–C σ bonds. Catalytic reduction proceeds with equatorial face selectivity for both the cyclohexane and the dioxane systems and appears to be governed largely by steric effects.

Prediction of the stereochemistry of reaction of a simple functional group, such as a double bond or carbonyl group, with a given reagent is still an inexact science. Where such a reaction is kinetically controlled, apart from steric effects, a number of factors which may be loosely described as stereoelectronic in nature have previously been invoked to account for the observed stereochemistry. For example, an anisotropy in the electron distribution about the double bond in 7-methylenenorbornane compounds **1** and **2** has been used to rationalise



1 **2** **3** **4**

their stereoreactivity.[1,2] For the case of norbornene itself, Fukui and co-workers[3] have predicted this anisotropy by theoretical calculation. The *exo* selectivity of these systems has been rationalised on the basis of the predicted increased *exo* extension of the highest occupied molecular orbital (HOMO). Both the early and more recent calculations show that here this anisotropy is due to the interaction of the C–C–C methylene bridge σ orbitals with the π system, which differs from that of the ethano bridge as a result of the different torsion angle.[3,4]

Alternatively, structural perturbations, arising out of the electronic structure of the molecule (rather than steric effects), have been invoked. Thus, in *syn* sesquinorbornene **3** the double bond is bent in the *endo* direction by 14.4°, although there are no obvious steric interactions that could cause this perturbation.[5] Additions to sesquinorbornenes show a high degree of *exo* selectivity which it has been suggested arises from this bending. Calculations by Houk and his colleagues[6–8] have predicted a similar displacement of the hydrogens bound to the double bond in norbornene by 3.4° in an *endo* direction. This has been used to explain the pronounced *exo* reactivity of these systems.

A third factor that has been considered is the electrostatic potential field on either face of the functional group. Thus *anti* stereoselectivity is generally observed in additions of neutral electrophiles to the exocyclic double bond of 9-isopropylidenebenzonorbornenes **4**.[9,10] However, in 1,2,3,4-tetrafluoro-9-isopropylidenebenzonorbornene, *syn* addition is observed for a number of neutral electrophiles and this is thought to be due to a strong electropositive region *syn* to the double bond, which promotes charge separation in the electrophile and the more common *anti* addition is promoted by homo-aromatic participation by the benzene ring.[11,12] More recently, Houk and his colleagues[13] have also calculated electrostatic potentials for the system **4** and have concluded that weak electrophiles, such as *m*-chloroperbenzoic acid (*m*-CPBA) and *tert*-butyl hypochlorite, which have lone pair electrons, are effectively 'negative' in their ground states and as such add to the less electron rich face of the alkene, *i.e.* they give *anti* addition with **4**, because they are repelled by the high electron density of the *syn* face due to the electron rich aromatic ring. Positive electrophiles favour *syn* addition because they are attracted by this highly negative region.†

A further issue is the importance of destabilising interactions between a developing bond and adjacent eclipsing bonds which have long been suggested as a major factor in determining stereofacial selectivity in additions to ketones and is the basis of the torsional strain model proposed by Felkin and co-workers.[14]

In the stereofacial selectivity of additions to carbonyl compounds, the role of substituents in a fixed conformation has been examined previously by a number of workers. Klein[15] studied the sodium borohydride reduction of cyclohexanones and concluded that the interaction of the σ and σ* orbitals of the β C–C bonds with the π and π* orbitals of the carbonyl group was responsible for the preferred axial addition of H to the C=O group. His view and that of Felkin have been challenged by the conclusions of Cieplak *et al.*[16] as a result of his group's comprehensive study on stereofacial selectivity in the reactions of 3-substituted cyclohexanones and 3-substituted

† There is some confusion here between the calculations of the Paquette group and those of Houk. Paquette speaks of a *positively* charged region, but talks of a charged electrophile being 'guided in' by the electron density, whereas Houk indicates that the predominant factor is a high electron density region, *i.e.* a *negatively* charged space on this side of the molecule.[11–13]

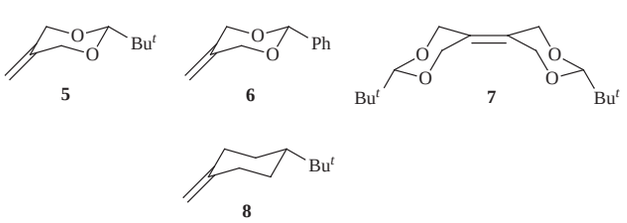
methylenecyclohexanes. The influence of the distant substituent was large and could be directly related to its relative electronegativity. The authors concluded that their results strongly supported Cieplak's previously proposed hypothesis that back-donation from the eclipsing β C–C and C–H σ bonds into the σ* orbital of the new bond being formed is the major factor that controls stereofacial selectivity.[17]

To summarise, many hypotheses have been put forward to rationalise the stereochemistry of reaction of different systems. In a number of cases different hypotheses can be used to explain the same data and there is often debate about which rationalisation is most useful. Molecular orbital calculations, whether *ab initio* or semi-empirical, often provide valuable information in this regard. The challenge comes in interpreting the calculations in a manner that is not only applicable to the system in hand, but which may also provide simple yet powerful insights into the reactivity of many other systems as well. The best known example where this has been achieved resulted in the Woodward–Hoffmann rules for pericyclic reactions.

Although a great deal of work has been carried out on the addition of nucleophilic reagents to carbonyl groups and carbonyl conjugated alkenes, there has been relatively little attention paid to electrophilic additions to C–C double bonds and in particular to unsymmetrically di-substituted alkenes. The most significant amongst the studies are the work of Srivasta and le Noble on additions to 5-substituted-2-methyleneadamantanes[18] and that of Berti and co-workers[19] on the stereoselective epoxidation of cyclohexenes β-substituted with alkyl, methoxy and acetoxy groups. These in particular confirm the fact that stereoelectronic control of π face diastereoselection by substituents, often quite distant, is a powerful but not fully understood factor.

Our interest has been in examining how the stereoselectivity of addition to a double bond is influenced by a β-substituent in a conformation fixed with respect to the double bond. In particular we have been interested in isolating the electronic factors that determine this stereoselectivity. Hence we wished to carry out reactivity studies on suitable model compounds and accompany them with appropriate theoretical calculations. The aim was to work towards developing a consistent theory that could be applied to a wide range of systems and a wide range of neutral and electrophilic addition reagents.

We have chosen to examine the 5-methylene-1,3-dioxane system, as represented by the model compounds **5**, **6** and **7**, together with the methylenecyclohexane system as **8**. The two



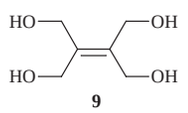
5 **6** **7** **8**

systems have been studied both theoretically, using *ab initio* molecular orbital calculations, and experimentally by physicochemical means using photoelectron spectroscopy and by establishing their stereoreactivity in some common addition reactions. The phenyl and *tert*-butyl groups in the models are present for their ability to conformationally stabilise the six-membered rings and make ring inversion highly unlikely during reaction. One would expect that these substituents would be too remote to have any primary influence on the double bond.

Results

The model compounds **5** and **6** were prepared using the elegant synthesis previously described by Weiss *et al.*[20] In this route the double bond is protected by cyclopentadiene, the rest of the molecule is constructed and the cyclopentadiene cleaved off in a retro Diels–Alder reaction by flash pyrolysis as the final step. A similar strategy, using anthracene as the protecting group, has been employed by Ripoll to prepare 2,3-bis(hydroxymethyl)but-2-ene-1,4-diol (ethylenetetramethanol) **9**.[21] We have adapted his method to synthesise the previously unknown compound **7**.

Anthracene protected tetrol **10**, prepared by Ripoll's method, was condensed with pivalaldehyde under acid catalysis. Two isomeric products were obtained, easily separated by crystallisation. The sparingly soluble isomer, with mp 322 °C, was shown to contain two planes of symmetry by NMR spectroscopy and was assigned structure **11**. (The alternative sym-



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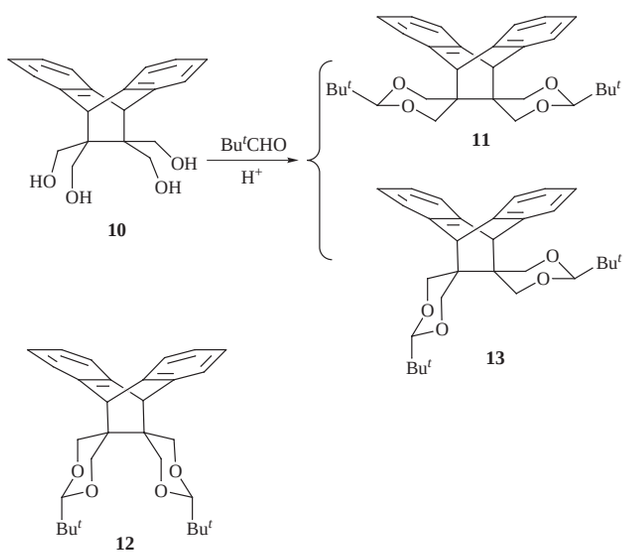
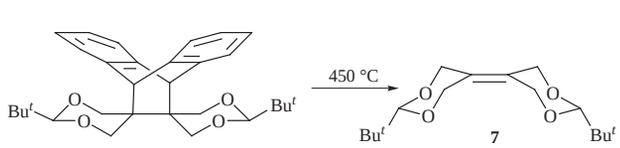


10 **11** **13**

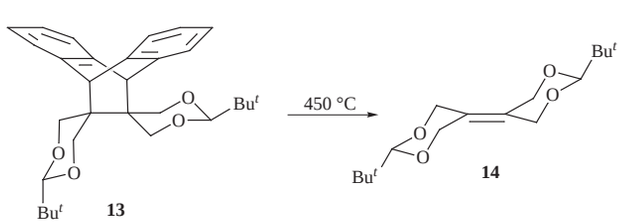
12

metrical product **12** is unlikely to form due to the large steric effects.) The other isomer, readily soluble in chloroform, with mp 207 °C, had an NMR spectrum which showed it to contain only a single plane of symmetry and was assigned structure **13**. Sublimation of **11** under vacuum through a scrupulously clean



11 **7**

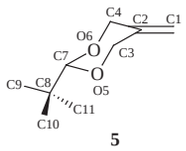
quartz column heated to 450 °C resulted in clean pyrolysis. No epimerisation occurred at the acetal carbons and stereoisomerically pure **7** could be separated from anthracene by flash chromatography. Similar pyrolysis of **13** cleanly afforded the *trans* isomer **14**.



13 **14**

Fully geometry optimised *ab initio* restricted Hartree–Fock calculations using the 6-31G basis set were carried out on both models 2-*tert*-butyl-5-methylene-1,3-dioxane **5** and 1-*tert*-butyl-4-methylenecyclohexane **8**. They were performed using the

Table 1 Atomic coordinates for 2-*tert*-butyl-5-methylene-1,3-dioxane **5** (Å)



5

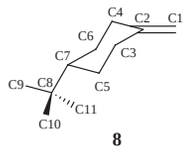
	x	*y*	*z*
C1	3.561	0.000	−0.554
C2	2.381	0.001	0.042
C3	1.640	−1.253	0.426
C4	1.639	1.257	0.418
C5	0.263	−1.161	−0.019
C6	0.262	1.162	−0.011
C7	−0.427	0.002	0.450
H11	4.067	−0.913	−0.808
H12	4.066	0.911	−0.813
H31	1.676	−1.400	1.503
H32	2.040	−2.127	−0.059
H41	1.674	1.411	1.495
H42	2.038	2.129	−0.071
H71	−0.446	0.005	1.540
C8	−1.848	0.000	−0.112
C9	−2.575	1.259	0.392
H91	−3.600	1.260	0.038
H92	−2.600	1.292	1.478
H93	−2.087	2.157	0.038
C10	−2.574	−1.256	0.399
H101	−2.086	−2.155	0.049
H102	−2.600	−1.282	1.484
H103	−3.600	−1.259	0.045
C11	−1.808	−0.004	−1.648
H111	−1.297	−0.883	−2.017
H112	−2.820	−0.005	−2.041
H113	−1.296	0.872	−2.022

Table 2 Bond lengths and primary three-centre bond angles and dihedral angles calculated for 2-*tert*-butyl-5-methylene-1,3-dioxane **5**. Symmetry unique values only are quoted.

Bond lengths/Å		Bond angles/°		Dihedral angles/°	
C1–H11	1.074	H11–C1–C2	121.9	H11–C1–C2–C3	−0.3
C1–C2	1.321	H11–C1–H12	116.2	C1–C2–C3–O5	−133.3
C2–C3	1.506	C1–C2–C3	123.4	C2–C3–O5–C7	−51.8
C3–O5	1.439	C3–C2–C4	113.1	C3–O5–C7–O6	−56.2
O5–C7	1.420	C2–C3–O5	110.3	C1–C2–C3–H31	15.0
C3–H31	1.088	C3–O5–C7	114.8	C1–C2–C3–H32	−106.8
C3–H32	1.077	O5–C7–O6	111.5	O5–C7–C8–C9	59.9
C7–H71	1.090	O5–C7–C8	107.5	O5–C7–C8–C10	−60.1
C7–C8	1.528	C7–C8–C9	109.5		
C8–C9	1.539	C7–C8–C10	109.4		
C9–H91	1.084	C2–C3–H31	110.5		
C9–H92	1.086	C2–C3–H32	123.0		
C9–H93	1.081				
C8–C10	1.536				
C10–H101	1.081				
C10–H111	1.084				
C10–H112	1.086				

GAMESS program package[22] implemented on an SGI Origin 2000 workstation (R10 000, 2 × 80 MHz IP27 processors, 256 Mbytes main memory). Convergence of the SCF iterations was monitored using changes in the density matrix and the calculations were considered converged when the density change between two consecutive SCF iterations was less than 10^{-5}. Geometry optimisations were performed with GAMESS using analytic gradient techniques. Convergence was monitored using the energy gradients and was considered to have occurred when the maximum gradient was less than 1×10^{-4} hartree bohr^{-1} and the rms gradient was less than 3.3×10^{-5} hartree bohr^{-1}. No symmetry constraints were imposed and a chair conformation with *tert*-butyl equatorially substituted was assumed as a starting conformation. No other constraints were imposed. The first job was completed in 374 min, the second in 644 min.

Table 3 Atomic coordinates for 1-*tert*-butyl-4-methylenecyclohexane **8** (Å)



8

	x	*y*	*z*
C1	3.708	−0.004	−0.470
C2	2.526	0.000	0.130
C3	1.780	−1.259	0.498
C4	1.782	1.264	0.483
C5	0.351	−1.253	−0.078
C6	0.352	1.256	−0.091
C7	−0.436	0.004	0.346
H11	4.214	−0.918	−0.720
H12	4.215	0.907	−0.730
H31	1.719	−1.333	1.583
H32	2.317	−2.134	0.150
H41	1.721	1.351	1.567
H42	2.320	2.135	0.127
H51	0.414	1.299	−1.161
H52	−0.155	−2.153	0.249
H61	0.413	1.293	−1.175
H62	−0.151	2.159	0.230
H71	−0.461	0.010	−1.438
C8	−1.937	0.001	−0.104
C9	−2.658	−1.226	0.495
H91	−3.722	−1.167	0.296
H92	−2.302	−2.157	0.072
H93	−2.524	−1.270	1.572
C10	−2.647	1.261	0.436
H101	−3.714	1.194	0.256
H102	−2.498	1.366	1.507
H103	−2.295	2.166	−0.043
C11	−2.095	−0.034	−1.636
H111	−3.148	−0.022	−1.900
H112	−1.632	0.824	−2.109
H113	−1.662	−0.929	−2.066

The values of the electrostatic potentials and all contour maps were calculated using the MOLDEN package.[23] Each contour plot is based on a grid of 61 × 61 values and plot width 12.5 Å.

Atomic coordinates of **5**, after optimisation, are given in Table 1. Key bond lengths and dihedral angles are given in Table 2. The corresponding values for **8** are given in Tables 3 and 4. The energies of the lowest unoccupied molecular orbital and the five highest occupied molecular orbitals are given in atomic units in Table 5. Iso-contour surfaces for the HOMOs of **5** and **8**, contoured at the 0.005 au level, are shown in Figs. 1(a) and (b), and 2(a) and (b) respectively. Views of each surface are displayed from both the axial and the equatorial perspectives with respect to the double bond. Calculated cross sections of the molecular electrostatic potential field, perpendicular to the plane of the double bond, are given in Fig. 3 for **5** and in Fig. 4 for **8**.

He(I) photoelectron spectra of **5** and **8** have been recorded and the low energy regions of these spectra are presented in Fig. 5. The spectrum of **8** is essentially identical to that reported previously.[24] Neither spectrum shows interpretable structure for ionisation energies (E_i) of greater than *ca.* 11 eV. In that of **8**, the first ionisation is clearly defined, with a vertical potential of 9.09 eV. It shows a vibrational progression with an interval of about 1370 cm^{-1}: a feature typical of ionisations from carbon–carbon double bonds. The spectrum of **5** contains a broad band stretching from 9.55 to 10.4 eV, showing evidence of fine structure, and which presumably comprises the ionisations from a

Table 4 Bond lengths and primary three-centre bond angles and dihedral angles calculated for 1-*tert*-butyl-4-methylenecyclohexane **8**. Symmetry unique values only are quoted.

Bond lengths/Å		Bond angles/°		Dihedral angles/°	
C1–H11	1.074	H11–C1–C2	121.8	H11–C1–C2–C3	−0.78
C1–C2	1.326	H11–C1–H12	116.4	C1–C2–C3–C5	−125.4
C2–C3	1.509	C1–C2–C3	123.0	C2–C3–C5–C7	−53.4
C3–C5	1.541	C3–C2–C4	114.1	C3–C5–C7–C6	−55.2
C5–C7	1.543	C2–C3–C5	111.1	C1–C2–C3–H31	−0.8
C3–H31	1.089	C3–C5–C7	111.3	C1–C2–C3–H32	−114.8
C3–H32	1.084	C5–C7–C6	111.4	C2–C3–C5–H51	67.4
C5–H51	1.086	C5–C7–C8	110.0	C2–C3–C5–H52	−175.8
C5–H52	1.083	C7–C8–C9	109.5	C3–C5–C7–C8	177.5
C7–H71	1.091	C7–C8–C10	109.5	C5–C7–C8–C9	60.0
C7–C8	1.566	C2–C3–H31	109.1	C5–C7–C8–C10	−60.0
C8–C9	1.544	C2–C3–H32	110.5		
C9–H91	1.084				
C9–H92	1.082				
C9–H93	1.086				
C8–C10	1.544				
C10–H101	1.085				
C10–H111	1.086				
C10–H112	1.083				

Table 5 Energies of the lowest unoccupied and the five highest occupied molecular orbitals for **5** and **8** (au)

	E/au	
Occupancy	**5**	**8**
0	0.159	0.182
2	−0.372	−0.338
2	−0.420	−0.413
2	−0.425	−0.421
2	−0.450	−0.436
2	−0.454	−0.452

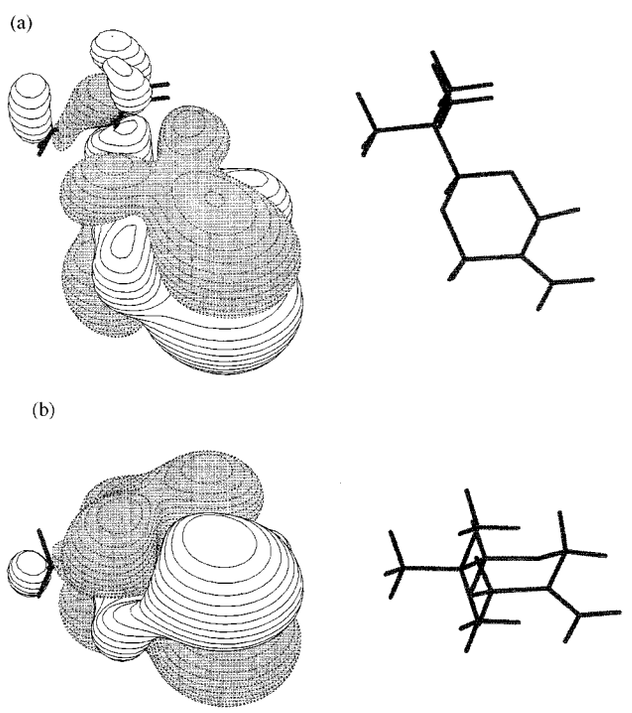


Fig. 1 2-*tert*-Butyl-5-methylenedioxane (**5**): HOMO electron density. Isocontour surface (a) from axial face (contoured at 0.005 au), and (b) from equatorial face (contoured at 0.005 au).

number of the highest lying occupied molecular orbital although these cannot be individually distinguished.

Addition studies were carried out on compounds **5**, **6** and **7** under kinetic conditions. Epoxidation using *m*-CPBA was selected as an example of an electrophilic addition reagent;

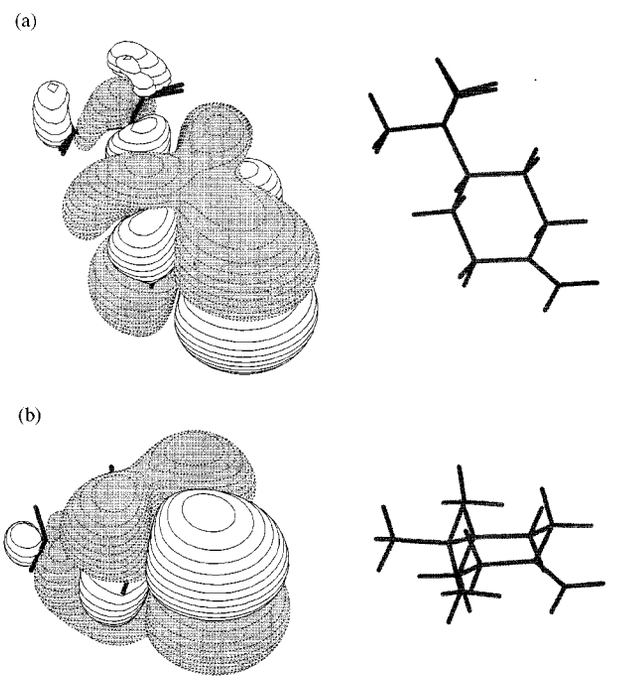


Fig. 2 1-*tert*-Butyl-4-methylenecyclohexane (**8**: HOMO electron density. Isocontour surface (a) from axial face (contoured at 0.005 au), and (b) from equatorial face (contoured at 0.005 au).

reduction with diimide as a potentially frontier molecular orbital (FMO) controlled reaction as it is known to transfer H_2 by an electrocyclic mechanism.[25] However, calculations by Skancke[26] have shown that the primary interaction in the transition state involves donation from the pi orbitals of the double bond that is being reduced into the antibonding sigma orbitals of the N–H bonds of diimide, supporting the idea that this reagent has significant electrophilic character and may also be classified as electrophilic. The compounds were also reduced under catalytic conditions (Pt and H_2) as an example of an electroneutral addition process.

The stereochemistry of the products of the addition of hydrogen were, in all cases, readily identifiable by interpretation of the coupling pattern of the H5 in the ^{1}H NMR spectra of the isolated products **15a**,**b**, **16a**,**b**, **19** and **20**. The stereochemistry of the products of epoxidation were not so readily determined. Each was isolated and separately reduced with $LiAlH_4$. The products of reduction of **17b** and **18b** were shown to be 5-hydroxy-5-methyl-1,3-dioxanes, **27** and **28**, readily identifiable

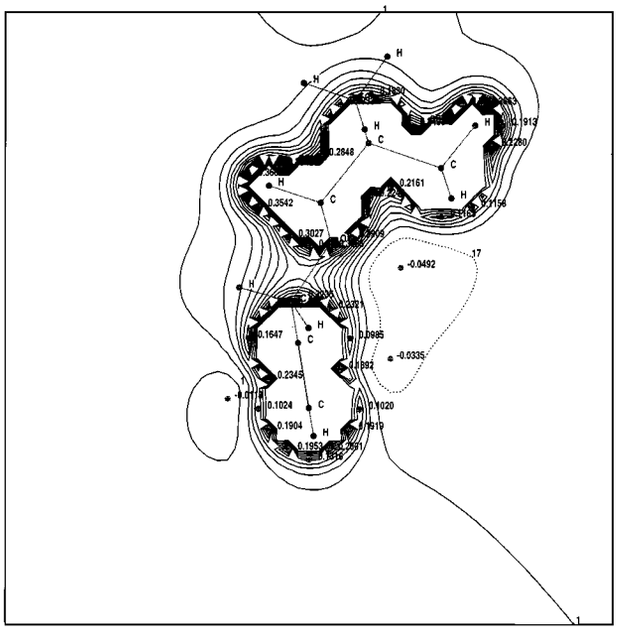


Fig. 3 Mid-plane cross section of molecular electrostatic potential field for 2-*tert*-butyl-5-methylenedioxane (**5**)

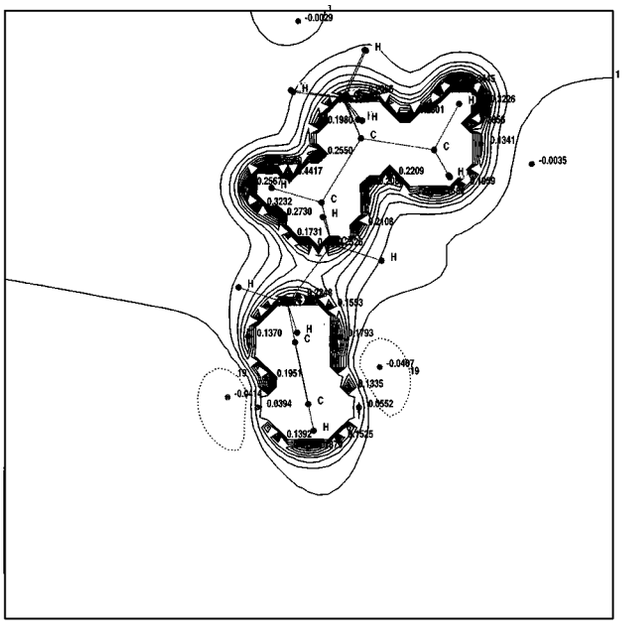


Fig. 4 Mid-plane cross section of molecular electrostatic potential field for 1-*tert*-butyl-4-methylenecyclohexane (**8**)

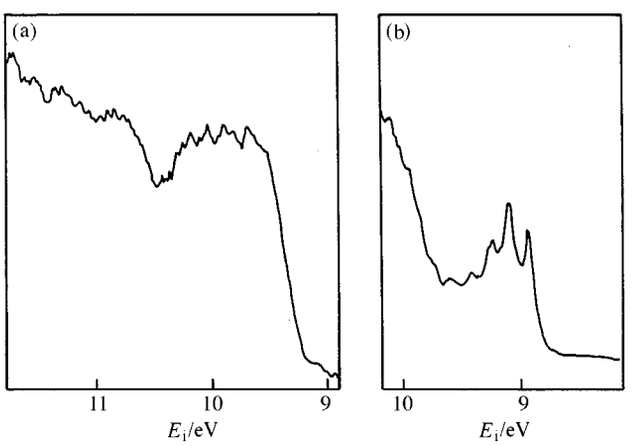
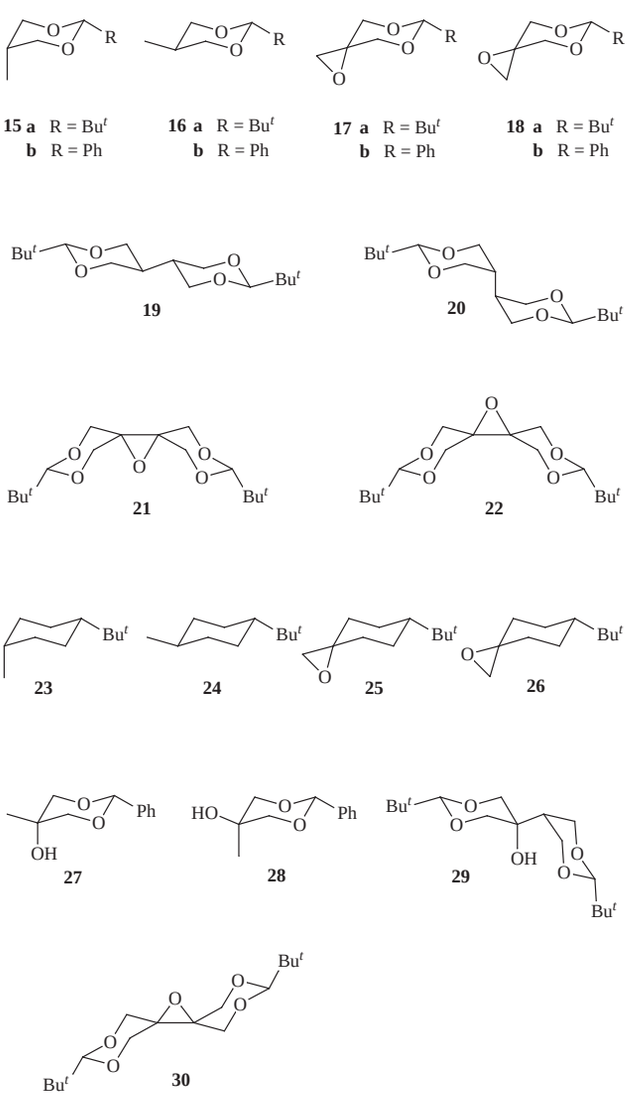


Fig. 5 He(I) photoelectron spectra for (a) 2-*tert*-butyl-5-methylene-1,3-dioxane (**5**) and (b) 4-*tert*-butylmethylenecyclohexane (**8**)



by comparison of their spectral properties with those reported by Eliel and Enanoza for analogous molecules.[27] The use of dilute solution IR spectra as well as the ^{1}H NMR shifts of the methyl groups allowed the stereochemical assignment. The stereochemistry of the product of reduction of **21**, compound **29**, was identified from the coupling pattern of the 4′-, 5′- and 6′-hydrogens and this was corroborated using the IR spectrum as for **27** and **28**.

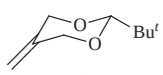
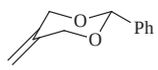
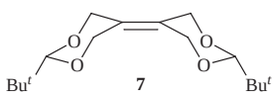
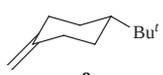
The following control experiments largely rule out the possibility that, during the epoxidation reaction, acid catalysed epimerisation of the dioxane ring had occurred with consequent formation of a thermodynamically controlled mixture of products. Each of the epoxides **17a** and **17b** was separately subjected to the identical reaction conditions as for epoxidation. For **17a**, no isomerisation was detectable even after the addition of toluene-*p*-sulfonic acid. The phenyl compound **17b** was found to isomerise to a small extent (30%), but only after 7 days reaction. Epoxidation of the unsymmetric bi(dioxanylidene) **14** under the same conditions as for **7** gave exclusively a single unsymmetric epoxide **30** strongly suggesting that no epimerisation occurred during the epoxidation of either **7** or **14**.

Table 6 contains details of the product ratios obtained in all the reactions, together with results of similar experiments previously carried out on the methylenecyclohexane **8**.[28,29]

Discussion

Both **5** and **8** retain a chair conformation when optimised. This is flatter in **5** (C1–C2–C3–O5 = −133.5°) than it is in **8** (C1–C2–C3–C5 = −125.4°). As a consequence the equatorial

Table 6 Products formed in the reactions with peracid, diimide and Pt–hydrogen. Ratio of products from axial and equatorial attack. (Structures in parentheses.)

Alkene	Orientation	Peracid	Diimide	Pt–hydrogen
 **5**	Axial	56 (**17a**)	95 (**16a**)	9 (**16a**)[a]
	Equatorial	44 (**18a**)	5 (**15a**)	91 (**15a**)
 **6**	Axial	54 (**17b**)	100 (**16b**)	2 (**16b**)
	Equatorial	46 (**28b**)	0 (**15b**)	98 (**15b**)
 **7**	Axial	62 (**21**)	100 (**19**)	0 (**19**)
	Equatorial	38 (**22**)	0 (**20**)	100 (**20**)
 **8**	Axial	70 (**25**)[b]	51 (**24**)[c]	16 (**24**)[d]
	Equatorial	30 (**26**)	49 (**23**)	84 (**23**)

[a] Data from ref. 36. [b] Data from ref. 37. [c] Data from ref. 26. [d] Data from ref. 27.

hydrogens on the α-carbons (H31 and H41) in **5** lie at an angle of 15° above the plane of the double bond whereas in **8** they are in the plane of the double bond. Only negligible deviations from planarity are predicted for the double bonds in both **5** and **8**, less than one degree in each case. These are too small to be of any significance experimentally. For both molecules the *tert*-butyl group maintains a conformation in which one methyl group points upwards away from the double bond and lies in the C1–C2–C7 plane.

The HOMO and LUMO for both **5** and **8** are largely constituted from the p_z orbitals on C1 and C2 in phase and antiphase respectively. The oxygen lone pairs appear to contribute little to either the HOMO and LUMO of **5**. They do contribute significantly to each of the next three occupied orbitals although in each case the contribution is not overwhelming and each of these orbitals otherwise show similar features to respectively the second, fourth and fifth highest occupied molecular orbitals of **8**. The energies of the highest occupied orbitals of both **5** and **8** and the ionisation energies determined from the photoelectron spectra are in good agreement assuming equivalence according to Koopman's theorem.

The eigenvectors of the HOMOs of both molecules were examined for evidence of what has previously been described as 'orbital twisting'.[30,31] This would arise out of mixing of some small s and p_x contributions in with the much larger p_z orbital contribution on atoms C1 and C2, and would lead to an anisotropy in the HOMO in the close vicinity of the double bond. Very little s and p_x contribution on C1 and C2 was found. Therefore, although other workers have claimed it as an important effect, we do not think that orbital twisting is significant here.

Because there is no twisting of the π orbital there is no anisotropy immediately above and below the double bond. However, examination of Figs. 1 and 2 reveal there is a significant anisotropy in the HOMOs of both of these molecules further away from the π system. On the equatorial face there is clearly a node between C1 and both C3 and C4. Such a node also exists on the axial face. However, it is obscured by two lobes extending beyond [C or O]5 and [C or O]6, which are in phase with the lobe from the π system on that side. Because they are in phase and because they are adjacent to the π system they may be considered, in effect, to extend the π lobe of the HOMO over a large region of the axial face. If this is so then it might be expected that the attack of an electrophile sensitive to frontier orbital effects might be biased towards axial rather than equatorial attack, for both 5-methylenedioxanes and methylenecyclohexanes.

As well as exhibiting anisotropy in its HOMO, **5** also exhibits an anisotropy in its molecular electrostatic potential. This has a significant negative potential well on the axial face of the double bond and therefore might be expected to again favour axial attack of electrophiles on the dioxanes **5** and **6**. No similar anisotropy is present in the cyclohexane **8**.

One further factor that needs to be considered is the relative steric accessibility of the two faces of the double bond. On this basis it would be anticipated that for all the molecules **5**, **6**, **7** and **8** and for all the reagents, there should be a bias towards equatorial attack and that equatorial attack should be more favoured for **8** than for **5** and **6** on account of both the additional steric effect of the axial hydrogens at C3 and C5 and the fact that the methylenedioxane 'chair' is noticeably flatter than that of methylenecyclohexane.

The anisotropy of the HOMO described for both **5** and **8** deserves further consideration. Its existence has been demonstrated using calculations employing a full MO representation. However it is common to consider the HOMOs of systems such as **5** and **8** as localised π-orbitals which are perturbed by interaction with a σ-framework. Such a description is useful as it can be easily transferred to other similar systems. A close examination of the eigenvectors from the calculations on **5** and **8** reveal that there is a large contribution to the HOMO from the orbitals that make up respectively the two β C–H_{ax} and the two β C–O (in **5**) or C–C (in **8**) σ bonds. In terms of perturbational interaction between localised orbitals, these contributions can be described as arising out of two different types of four-electron interactions. One is the interaction between the β C–H_{ax} σ bond and the $\pi_{C=C}$ [Fig. 6(a)] and one is the interaction between the β C–C or C–O σ bond and the $\pi_{C=C}$ [Fig. 6(b)]. In both cases, the filled–filled interaction raises the HOMO energy. The interaction between β C–H_{ax} and the $\pi_{C=C}$ is completely out of phase and results in a node in the HOMO between C2, and C3 and C4. This is not entirely the case for the interaction between β C/O–C σ and $\pi_{C=C}$, however. Unlike the β C–H_{ax} σ orbital, the β C/O–C σ orbital has p character at both ends. Most of the orbital makes an out of phase contribution. However the orbital lobes pointing away from the β C/O atom

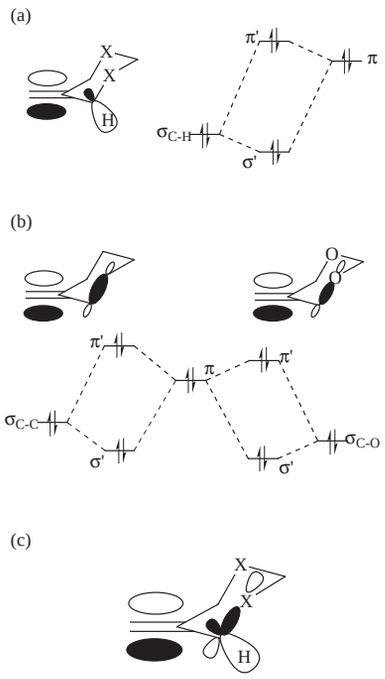


Fig. 6

into the axial face are *in phase* with the π contribution and, as a result appear to extend the π lobe of the axial face HOMO. The large scale anisotropy in the HOMO therefore can be thought to arise out of the *difference* between these two types of σ–π interaction. The effect is illustrated schematically in Fig. 6(c).

It is worth noting that there is a significant distinction between the perturbational interactions in **5** and those in **8**. The C–O σ orbital is lower in energy than the C–C σ orbital and should interact less strongly with the π system, resulting in a smaller increase in the HOMO energy of **5** than in **8**. The photoelectron spectra of **5** and **8** support this. The latter shows a band at 9.09 eV corresponding to the ionisation from the occupied π orbital. This is higher in energy by at least 0.4 eV than the corresponding band in the spectrum of **5**, the precise position of which is unclear as it is convoluted with the two bands likely to be due to the p type lone pairs of the endocyclic oxygens. These two bands, due to ionisation from the anti-symmetric and symmetric combination orbitals of the lone pairs, have been observed at 10.1 and 10.4 eV in the parent 1,3-dioxane.[32] Their position in the spectrum of **5** appears little changed and indicates that in the methylenedioxane system these lone pairs are not involved in interaction with the double bond. The lack of any involvement by the lone pairs in the HOMO of **5** and the higher energy for the HOMO of **8** with respect to **5**, determined by calculation, are consistent with these observations.

Our theoretical study has adduced three factors that might influence the kinetic stereoselectivity of electrophile addition (i) the axial HOMO anisotropy, (ii) the electrostatic effect and (iii) the preferred equatorial access. The experimental results might therefore be expected to reflect an interplay between these factors.

The addition reactions of *m*-CPBA (and diimide) with the methylenecyclohexane **8** show a slight preference for axial attack, despite the steric bias against this direction. This suggests that the influence of the anisotropy of the HOMO overrides the steric effect in these reactions. This conclusion is bolstered by the observation that catalytic reduction, where the steric accessibility to the catalyst surface should be most significant and the influence of the HOMO liable to have less importance, proceeds preferentially from the equatorial face. The addition reaction of *m*-CPBA with the dioxanes **5**, **6** and **7** also proceeds with a slight preponderance of axial attack. This preference is marginally less than that for addition to **8** and leads to the conclusion that the influence of the electrostatic potential field on *m*-CPBA epoxidations of molecules such as **5**, **6** and **7** is small. This is contrary to the case of peracid epoxidation of allylic alcohols, where hydrogen bonding of the reagent to the hydroxy group is the factor which controls the stereochemistry.[33] The reason for a smaller extent of axial epoxidation on **5** and **6**, as opposed to **8** is not entirely clear. However, it could be a consequence of the conclusion by Houk and co-workers that *m*-CPBA is a 'nucleophilic' electrophile with the tendency to attack the less negative side of an alkene.[13]

The addition reaction of diimide with **5**, **6** and **7** proceeds with striking axial face selectivity, in contrast with the equivalent reaction for **8** and is also in total contrast to the catalytic reduction of these compounds, which occurs almost exclusively from the equatorial face. This difference in selectivity between the two types of reduction is much more pronounced than that observed for **8**. Given the results from the epoxidation and the calculations, this cannot be described to a frontier orbital effect. It is more probable that it is caused by the electrostatic potential field anisotropy in **5**, **6** and **7** demonstrated by the calculations. Unlike the epoxidation, the diimide reduction is carried out in a polar solvent, which would tend to promote electrostatic effects. Recent kinetic evidence from the diimide reduction of maleate and fumarate anions supports the view that there is a large electrostatic effect in its reduction reactions.[34]

The greater equatorial selectivity observed in the catalytic reduction of **5**, **6** and **7** over that for **8** may most reasonably be ascribed to an effect of product development control as previously proposed by Siegel and co-workers.[28,35] In the course of reduction of **8** from the equatorial face, the incipient methyl group approaches an axial position and experiences unfavourable interactions with the axial hydrogens at C3 and C5. Such interactions will not occur in the reduction of methylenedioxanes owing to the absence of these hydrogens. It is well known that, unlike methylcyclohexane, 5-methyl-1,3-dioxanes prefer a conformation with the methyl group axial.

The Cieplak hypothesis[16] suggests that axial selectivity in additions to both cyclohexanones and methylenecyclohexanes is caused by the more favourable back-donation from the β C–H σ bond periplanar with the π bond into the σ* orbital of a bond forming on the axial side compared with that from the equivalently placed β C–C σ bonds to the σ* orbital of a bond forming on the equatorial side. Consideration of the molecules we have studied in the light of this postulate leads to the conclusion that for the methylenedioxanes, **5**, **6** and **7**, the extent of axial attack should be greater than is observed for the cyclohexane case, due to the poorer hyperconjugating ability of the C–O σ bond as compared with that of the C–C σ bond. Our experimental results for epoxidation are completely at variance with this expectation. While we do not rule out involvement of the back-donation proposed by Cieplak, we suggest that the HOMO anisotropy shown by the calculations can be used to rationalise the results in a more straightforward manner.

Conclusions

The addition reaction studies on methylenecyclohexane and 5-methylene-1,3-dioxane have demonstrated a bias for axial attack by electrophilic species, despite the axial face being the more sterically hindered. The calculations suggest that two electronic factors contribute to the stereoselectivity observed.

The first is the spatial anisotropy of the HOMO with respect to the two faces of the double bond. This arises out of the significant hyperconjugative interactions of the C–C, C–O and C–H bonds positioned β to the π system. These interactions are particularly strong in **8** and **5** because the β C–C, C–O and axial C–H bonds are ideally oriented for interaction with the π system. We believe that this anisotropy is responsible for the overall axial stereofacial selectivity exhibited both by **8** and **5**

towards electrophiles. Particularly noteworthy is the observation that because a C–H σ orbital (1 node) is topologically distinct from a C–C or C–O σ orbital (2 nodes), a β C–H bond aligned with a π system contributes to the stereofacial distribution of the HOMO in a fashion which is different from that of the interaction of a periplanar β C–C or C–O bond with the same π system.

The second effect is the electrostatic field potential which results from the endocyclic oxygens in the dioxane ring. This also favours attack from an axial direction by polarisable electrophilic species and accounts for the greatly enhanced axial selectivity exhibited by diimide for reaction with **5**, **6** and **7** as compared to **8**.

Catalytic reduction, a non-electrophilic process, proceeds with equatorial face selectivity for both the carbocyclic and the dioxane systems and appears to be governed largely by steric considerations.

Experimental

All solvents were dried and distilled before use. Flash column chromatography was carried out on MN Kieselgel 60 (230–400 mesh). Melting points were determined on a Gallenkamp solid block apparatus and are uncorrected. Elemental analyses were performed at the Microanalytical laboratory, University College, London. Infrared spectra were recorded on a Perkin-Elmer 298 Infrared Spectrophotometer. All spectra were recorded in chloroform solution. Unless otherwise stated the cell thickness was 0.1 mm. All NMR spectra were recorded on a Varian Associates XL-100-12 with internal lock in $CDCl_3$ as solvent. *J* values are given in Hz.

General procedures

Catalytic hydrogenation. A solution of the substrate, in absolute ethanol, containing Adam's catalyst (50 mg) was hydrogenated at rt and atmospheric pressure in a standard apparatus until one equiv. of hydrogen had been taken up. The catalyst was filtered off and the solvent evaporated at reduced pressure to yield the crude product.

Diimide reduction. The substrate was dissolved in distilled *tert*-butyl alcohol and hydrazine hydrate (5 equiv.) added with stirring. Diimide was generated by the addition of a mixture of *tert*-butyl hydroperoxide and *tert*-butyl peroxide (70 : 30) (5 equivs. based on oxygen). When all the starting material had been consumed (TLC), the solvent and excess reagents were removed under reduced pressure to afford crude product.

Epoxidations. The substrate was dissolved in chloroform and *m*-chloroperbenzoic acid (from 1.5 to 3 equivs.) added. The solution was stirred at rt until the reaction was complete (TLC). The mixture was washed (NaOH, 2 × H_2O), dried, filtered and solvent removed under reduced pressure to afford crude product.

Syntheses ‡

Preparation of (*E*,*E*) and (*Z*,*E*)2,2″-di-*tert*-butyldispiro[(1,3-dioxane)-5,11′-(9,10-dihydro-9,10-ethanoanthrarene)-12′,5″-(1,3-dioxane)], 11 and 13. 9,10-Dihydro-9,10-ethanoanthracene-11,11,12,12-tetramethanol (prepared by Ripoll's method)[21] (4.39 g, 0.013 mol) and pivalaldehyde (2.49 g, 0.029 mol) were refluxed in benzene (200 ml) under nitrogen in the presence of toluene-*p*-sulfonic acid (30 mg) for 90 min. The cold reaction mixture was diluted with chloroform (150 ml) and cooled to 4 °C. The colourless powder that precipitated was collected (3.14 g). Purification of this material was carried out by continuous Soxhlet extraction with chloroform to give **11**. The crude original filtrate was washed ($NaHCO_3$, 25 ml, 2 × H_2O), dried, filtered and the solvent evaporated under reduced pressure. The combined solid residues were recrystallised from ethanol–water to yield fine colourless needles of a second product (2.07 g), **13**. Reducing the quantity of solvent and increasing reaction times increased the yield of the first product at the expense of the second.

11, Mp 322–323 °C, ν(1.0 mm, $CHCl_3$)/cm^{-1} 2860, 1599, 1455, 1338, 1106, 969; δ_H(100 MHz, $CDCl_3$) 1.03 (s, 18H) 3.12 (d, *J* 10, 4H), 3.54 (d, *J* 10, 4H), 4.05 (s, 2H), 4.97 (s, 2H), 7.25 (m, 8H).

13, Mp 207–208 °C (Found: C, 77.8; H, 8.10. $C_{28}H_{38}O_4$ requires C, 77.8; H, 8.30%); ν/cm^{-1} 2980, 2970, 1489, 1160, 1126, 1118, 1111, 1050; δ_H(100 MHz, $CDCl_3$), 0.97 (s, 9H), 1.02 (s, 9H), 3.35 (d, *J* 11.5, 2H), 3.475 (s, 1H), 3.965 (s, 2H), 4.12 (d, *J* 11.5, 2H), 5.02 (s, 1H), 7.08 (m, 6H), 7.4 (m, 2H); δ_C(25.18 MHz, $CDCl_3$) 24.6, 34.8, 35.0, 40.8, 42.3, 48.3, 53.2, 71.1, 73.8, 107.4, 107.8, 124.4, 125.6, 126.2, 126.4, 139.8, 141.8.

Preparation of (*Z*)-2,2′-di-*tert*-butyl-5,5′-bi(1,3-dioxan-5-ylidene) 7. Compound **11** (520 mg) was pyrolysed by sublimation into and through a quartz pyrolysis tube [50 × 1.5 cm, packed with quartz glass fragments and wound with nichrome resistance wire (5 Ω m^{-1}), with a pitch of 4 mm, on top of alumina cement (3 mm thick)] heated to 450 °C, at a pressure of 1 mmHg. The condensate at the top of the column was collected and chromatographed (silica, toluene) to remove anthracene. Compound **7** was collected as colourless crystals (173 mg) (ethanol–water), mp 121.5–122.5 °C (Found: C, 67.1; H, 10.25. $C_{16}H_{28}O_4$ requires C, 67.6, H, 9.90%); ν/cm^{-1} 2985, 2965, 2835, 1484 1404, 1366, 1145, 1080; δ_H(100 MHz, $CDCl_3$) 0.92 (s, 18H), 4.02 (br d, *J* 13, 4H), 4.19 (s, 2H), 4.733 (br d, *J* 13, 4H); δ_C(25.18 MHz, $CDCl_3$) 24.7, 35.0, 64.0, 107.6, 124.3.

(*E*)-2,2′-Di-*tert*-butyl-5,5′-bi(1,3-dioxan-5-ylidene) 14. Compound **13** (360 mg) was pyrolysed under the same conditions as for **11**. After chromatography (silica, toluene), this gave colourless crystalline material (166 mg) mp 133–134 °C, recrystallised from ethanol–water (Found: C, 67.1; H, 10.20. $C_{16}H_{28}O_4$ requires C, 67.6; H, 9.90%); ν/cm^{-1} 3021, 2841, 1485, 1406, 1366, 1145, 1081, 1050; δ_H(100 MHz, $CDCl_3$) 0.90 (s, 18H), 4.20 (s, 2H), 4.23 (d, *J* 13.7, 4H), 4.64 (d, *J* 13.7, 4H); δ_C(25.18 MHz, $CDCl_3$) 24.7, 34.9, 66.1, 107.8, 124.3.

Catalytic hydrogenation of 5-methylene-2-phenyl-1,3-dioxane. Reduction of **6** (0.850 g) in EtOH (6 ml) with $PtO_2 \cdot H_2O$ (50 mg) at 18 °C took 70 min. Some excess consumption of hydrogen occurred due to hydrogenolysis of the benzylidene acetal. Crude product (0.675 g) was obtained. Pure 5-methyl-2-phenyl-1,3-dioxane as a mixture of *cis* and *trans* isomers (9 : 1 by NMR spectroscopy) could be obtained by chromatography (silica, toluene). The isomer ratio was identical to that in the crude material.

Diimide reduction of 5-methylene-2-phenyl-1,3-dioxane. Reduction of **6** (0.51 g) in *tert*-butyl alcohol (20 ml) was complete in 2 h. Chromatography (silica, toluene) afforded a colourless volatile oil (130 mg) that was a mixture of *cis* and *trans* isomers, 5 : 95 by NMR spectroscopy, identical to that in the crude material.

(*Z*)-5-Methyl-2-phenyl-1,3-dioxane 15b. ν/cm^{-1} 2945, 1600, 1450, 1385, 1270, 1110, 1065, 1020, 950; δ_H(100 MHz, $CDCl_3$) 1.35 (d, *J* 6, 3H), 1.65 (m, 1H), 3.93 (br d, *J* 11, 2H), 4.11 (br d, *J* 11, 2H), 5.48 (s, 1H), 7.4 (m, 5H) [Found (HRMS): 178.091. Required for $C_{11}H_{14}O_2$: 178.099].

(*E*)-5-Methyl-2-phenyl-1,3-dioxane 16b. ν/cm^{-1} 2970, 1600, 1455, 1385, 1270, 1160, 1070, 1025, 970; δ_H(100 MHz, $CDCl_3$) 0.73 (d, *J* 7, 3H), 2.3 (m, 1H), 3.2 (dd, *J* 11.5, 11.5, 2H), 4.17 (dd, *J* 11.5, 5, 2H), 5.4 (s, 1H), 7.4 (m, 5H).

Diimide reduction of 5-methylene-2-*tert*-butyl-1,3-dioxane. Reduction of **5** (0.530 g) in *tert*-butyl alcohol (20 ml) was complete in <24 h. Removal of solvent afforded a volatile oil (135

‡ The products have been named using *E* and *Z* terminology to describe the positions of the two substituents relative to the plane of the dioxane ring. *Z* indicates that the two substituents are located on the same side of the ring, and *E* indicates that they are on opposite faces of the ring. Where there are two substituents on a single ring carbon normal priority rules are obeyed. In the case of **7** and **14**, the stereochemistry is assigned in relation to the entire bidioxanylidene unit.

mg). From the ^{1}H NMR spectrum, this appeared to contain only the *E* isomer of 5-methyl-2-(*tert*-butyl)-1,3-dioxane **16a**. *v*/cm^{-1} 2960, 1482, 1460, 1163, 1111, 984; δ_H(100 MHz, $CDCl_3$) 0.69 (d, *J* 7, 3H), 2.0 (m, 1H), 3.27 (dd, *J* 12, 11.5, 2H), 4.02 (s, 1H), 4.03 (dd, *J* 11.5, 4.5, 2H).

Catalytic reduction of (*Z*)-2,2′-di-*tert*-butyl-5,5′-bi(1,3-dioxan-5-ylidene). Hydrogenation of **7** (200 mg) in EtOH (5 ml) with $PtO_2 \cdot H_2O$ (20 mg) took 20 min. A white solid (180 mg) was obtained that appeared from the NMR spectrum to consist solely of the *Z*,*Z* isomer (**20**) of 2,2′-di-*tert*-butyl-5,5′-bi(1,3-dioxanyl). Recrystallisation (EtOH–H_2O) afforded colourless plates of (Z,Z)-2,2′-*di*-tert-*butyl*-5,5′-*bi*(1,3-*dioxanyl*) **20**, mp 132–133 °C (Found: C, 66.8; H, 10.80. $C_{16}H_{30}O_4$ requires C, 67.1; H, 10.55%); *v*/cm^{-1} 2990, 2965, 2905, 1484, 1465, 1405, 1364, 1143, 1073; δ_H(100 MHz, $CDCl_3$) 0.88 (s, 18H), 1.86 (br s, 2H), 3.86 (br d, *J* 11, 4H), 4.165 (s, 2H), 4.18 (br d, *J* 11, 4H); δ_C(25.18 MHz, $CDCl_3$) 24.6, 32.3, 35.1, 68.7, 108.2.

Diimide reduction of (*Z*)-2,2′-di-*tert*-butyl-5,5′-bi(1,3-dioxan-5-ylidene). Reduction of **7** (0.200 g) in *tert*-butyl alcohol (35 ml) at 53 °C took 4 days. A white solid (174 mg) was obtained that appeared from the NMR spectrum to consist solely of the *E*,*E* isomer (**19**) of 2,2′-di-*tert*-butyl-5,5′-bi(1,3-dioxanyl). Recrystallisation (EtOH–H_2O) afforded colorless plates of (E,E)-2,2′-*di*-tert-*butyl*-5,5′-*bi*(1,3-*dioxanyl*) **19**, mp 208–209 °C (Found: C, 67.2; H, 10.50. $C_{16}H_{30}O_4$ requires C, 67.1; H, 10.55%); *v*/cm^{-1} 2980, 2970, 1484, 1403, 1145, 1076; δ_H(100 MHz, $CDCl_3$) 1.77 (m, 2H), 3.44 (dd, *J* 11, 9, 4H), 4.02 (s, 2H), 4.03 (dd, *J* 11, 4, 4H); δ_C(25.18 MHz, $CDCl_3$) 24.7, 34.1, 34.8, 69.6, 107.9.

Epoxidation of 2-*tert*-butyl-5-methylene-1,3-dioxane. Epoxidation of **5** (400 mg) with *m*-CPBA (1.0 g) in $CHCl_3$ (15 ml) took two days and afforded crude product (0.475 g). Chromatography [silica, light petroleum (bp 40–60 °C)–CH_2Cl_2] gave the two diastereoisomeric epoxides as oils.

(Z)-6-tert-*Butyl*-1,5,7-*trioxaspiro*[2.5]*octane* **17a**, *v*/cm^{-1} 2980, 2955, 2857, 1481, 1353, 1110, 950; δ_H(100 MHz, $CDCl_3$) 0.95 (s, 9H), 2.875 (s, 2H), 3.61 (d, *J* 11.5, 2H), 3.98 (d, *J* 11.5, 2H), 4.15 (s, 1H).

(E)-6-tert-*Butyl*-1,5,7-*trioxaspiro*[2.5]*octane* **18a**, *v*/cm^{-1} 2980, 2960, 1480, 1325, 1106, 947; δ_H(100 MHz, $CDCl_3$) 0.97 (s, 9H), 2.69 (s, 2H), 3.57 (d, *J* 13, 2H), 4.24 (s, 1H), 4.26 (d, *J* 13, 2H).

Epoxidation of 5-methylene-2-phenyl-1,3-dioxane. Epoxidation of **6** (0.948 g) with *m*-CPBA (1.43 g) in $CHCl_3$ (20 ml) took 7 days and gave a colourless solid (0.78 g). Chromatography (silica, $CHCl_3$) separated this into the two diastereomeric epoxides. Reduction of each epoxide separately [$LiAlH_4$ (1 equiv.) in diethyl ether, rt] afforded, in each case, a single 5-hydroxy-1,3-dioxane as reduction product.

(Z)-6-*Phenyl*-1,5,7-*trioxaspiro*[2.5]*octane* **17b**, mp 85–86.5 °C (pentane); *v*/cm^{-1} 2980, 2850, 1495, 1460, 1390; δ_H(100 MHz, $CDCl_3$) 2.915 (s, 2H), 3.77 (d, *J* 12, 2H), 4.24 (d, *J* 12, 2H), 5.63 (s, 1H), 7.5 (m, 5H).

(Z)-5-*Methyl*-2-*phenyl*-1,3-*dioxan*-5-*ol* **27**. *v*(pathlength 1.0 mm)/cm^{-1} 3690, 3575, 2975, 2860, 1604, 1454; δ_H(100 MHz, $CDCl_3$) 1.04 (s, 3H), 3.52 (br s, disappears slowly on D_2O shake, 1H), 3.785 (d, *J* 12, 2H), 3.875 (d, *J* 12, 2H), 5.41 (s, 1H), 7.44 (m, 5H).

(E)-6-*Phenyl*-1,5,7-*trioxaspiro*[2.5]*octane* **18b**, mp 86–86.5 °C (cyclohexane); *v*/cm^{-1} 2980, 2850, 1505, 1456, 1447, 1395, 1113; δ_H(100 MHz, $CDCl_3$) 2.71 (s, 2H), 3.72 (d, *J* 13, 2H), 4.48 (d *J* 13, 2H), 5.57 (s, 1H), 7.45 (m, 5H).

(E)-5-*Methyl*-2-*phenyl*-1,3-*dioxan*-5-*ol* **28**. *v*(pathlength 1.0 mm)/cm^{-1} 3690, 3605, 3575, 2860, 1604, 1454; δ_H(100 MHz, $CDCl_3$) 1.43 (s, 3H), 1.93 (s, 1H), 3.68 (d, *J* 10.2, 2H), 3.87 (d, *J* 10.2, 2H), 5.51 (s, 1H), 7.39 (m, 5H).

Epoxidation of (*Z*)-2,2′-di-*tert*-butyl-5,5′-bi(1,3-dioxan-5-ylidene). Epoxidation of **7** (202 mg) with *m*-CPBA (370 mg) in $CHCl_3$ (15 ml) took 5 days and afforded a colourless crystalline material. Fractional recrystallisation (EtOH–H_2O) separated the two solid diastereoisomers. The major product (60 mg) was reduced [$LiAlH_4$ (30 mg) in THF (10 ml), reflux for 24 h] to afford a single compound.

(Z,Z)-2,2′-*Di*-tert-*butyl*-5,5′-*epoxy*-5,5′-*bi*(1,3-*dioxanyl*) **21**, mp 215–215.5 °C (sublimes above 209 °C) (Found: C, 63.7; H, 9.25. $C_{16}H_{28}O_5$ requires C, 63.9; H, 9.40%); *v*(pathlength 1.0 mm)/cm^{-1} 2845, 1361, 1139, 1081, 967; δ_H(100 MHz, $CDCl_3$) 0.935 (s, 18H), 3.82 (d, *J* 13, 4H), 4.07 (d, *J* 13, 4H), 4.175 (s, 2H); δ_C(25.18 MHz, $CDCl_3$) 24.5, 35.0, 59.1, 67.8, 107.2.

(Z,Z)-2,2′-*tert*-*Butyl*-5-*hydroxy*-5,5′-*bi*(1,3-*dioxanyl*) **29**, mp 228.5–229.5 °C (sublimes above 209 °C) (Found: C, 63.4; H, 9.95. $C_{16}H_{30}O_5$ requires C, 63.55; H, 10.00%); *v*(pathlength 0.1 mm)/cm^{-1} 3570, 2960, 1483, 1402, 1362, 1154, 1118, 968; (pathlength 1.0 mm) 3560, 2965, 1360, 1150, 1118, 970; δ_H(100 MHz, $CDCl_3$) 0.88 (s, 9H), 0.95 (s, 9H), 1.3 (m, 1H), 3.46 (s, disappears on D_2O shake, 1H), 3.80 (dd, *J* 11.5, 4, 2H), 3.85 (d, *J* 11, 2H), 4.01 (d, *J* 11, 2H), 4.15 (s, 1H), 4.06 (s, 1H), 4.36 (br d, *J* 11.5, 2H); δ_C(25.18 MHz, $CDCl_3$) 24.5, 24.8, 34.9, 37.5, 66.4, 73.5, 79.3, 107.8, 108.1.

(E,E)-2,2′-*Di*-tert-*butyl*-5,5′-*epoxy*-5,5′-*bi*(1,3-*dioxanyl*) **22**, mp 119–120 °C; *v*/cm^{-1} 2985, 2965, 1484, 1364, 1142, 1119, 1100; δ_H(100 MHz, $CDCl_3$) 0.94 (s, 18H), 3.84 (d, *J* 12, 4H), 4.00 (d, *J* 12, 4H), 4.25 (s, 2H); δ_C(25.18 MHz, $CDCl_3$) 24.6, 34.9, 60.3, 66.8, 107.2.

Epoxidation of (*Z*)-2,2′-di-*tert*-butyl-5,5′-bi(1,3-dioxan-5-ylidene). Epoxidation of **14** (130 mg) with *m*-CPBA (240 mg) in $CDCl_3$ (15 ml) took 4 days and afforded a single crystalline compound **30** (157 mg), mp 176.5–177 °C (ethanol–water) (Found: C, 63.9; H, 9.70. $C_{16}H_{28}O_5$ requires C, 64.0; H, 9.40%); *v*/cm^{-1} 2965, 1484, 1364, 1154, 1097, 980; δ_H(100 MHz, $CDCl_3$) 0.92 (s, 9H), 0.96 (s, 9H), 3.75 (d, *J* 11.5. 2H), 3.85 (d, *J* 11.5, 2H), 4.145 (s, 1H), 4.21 (s, 1H), 4.31 (d, *J* 12, 2H); δ_C(25.18 MHz, $CDCl_3$) 24.6, 34.7, 34.9, 57.1, 61.4, 66.6, 69.2, 107.0, 107.7.

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