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Thiol-catalysed radical-chain redox rearrangement reactions of benzylidene acetals derived from terpenoid diols

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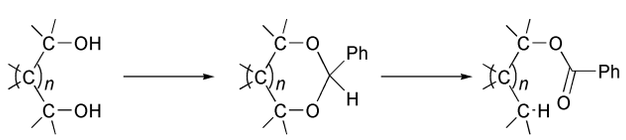
The thiol-catalysed radical-chain redox rearrangement of cyclic benzylidene acetals derived from 1,2- and 1,3-diols of terpene origin has been investigated from both synthetic and mechanistic standpoints. The redox rearrangement was carried out either at *ca*. 70 °C (using Bu^{t}ON=NOBu^t as initiator) or at *ca*. 130 °C (using Bu^{t}OOBu^t as initiator) in the presence of triisopropylsilanethiol or methyl thioglycolate as catalyst; the silanethiol was usually more effective. This general reaction affords the benzoate ester of the monodeoxygenated diol, unless rearrangement of intermediate carbon-centred radicals takes place prior to final trapping by the thiol to give the product, in which case structurally rearranged esters are obtained. For the benzylidene acetals of 1,2-diols prepared by vicinal *cis*-dihydroxylation of 2-carene, α-pinene or β-pinene, intermediate cyclopropylcarbinyl or cyclobutylcarbinyl radicals are involved and ring opening of these leads ultimately to unsaturated monocyclic benzoates. 1,2-Migration of the benzoate group in the intermediate β-benzoyloxyalkyl radical sometimes also competes with thiol trapping during the redox rearrangement of benzylidene acetals derived from 1,2-diols. Redox rearrangement of the benzylidene acetal from carane-3,4-diol, obtained by *cis*-dihydroxylation of 3-carene, does not involve intermediate cyclopropylcarbinyl radicals and leads to benzoate ester in which the bicyclic carane skeleton is retained. The inefficient redox rearrangement of the relatively rigid benzylidene acetal from *exo,exo*-norbornane-2,3-diol is attributed to comparatively slow chain-propagating β-scission of the intermediate 2-phenyl-1,3-dioxolan-2-yl radical, probably caused by the development of adverse angle strain in the transition state for this cleavage. Similar angle strain effects are thought to influence the regioselectivities of redox rearrangement of bicyclic [4.4.0]benzylidene acetals resulting from selected 1,3-diols, themselves prepared by reduction of aldol adducts derived from reactions of aldehydes with the kinetic lithium enolates obtained from menthone and from isomenthone.

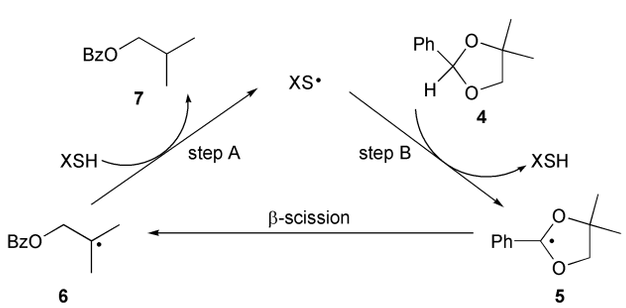
Introduction

We have reported previously that monodeoxygenation of 1,2- and 1,3-diols **1** (n = 0 or 1) can be readily achieved through a thiol-catalysed radical-chain redox rearrangement of the derived benzylidene acetals **2**, to give benzoate esters of the type **3** (Scheme 1).[1,2] The propagation cycle for the rearrangement **2** ⟶ **3** is illustrated in Scheme 2 for the simple case of the benzylidene acetal derived from 2-methylpropane-1,2-diol.[1] The function of the thiol catalyst is to mediate the *overall* abstraction of the benzylic hydrogen atom from the parent 1,3-dioxolane **4** by the nucleophilic alkyl radical **6** to give the dioxolanyl radical **5**, which is also nucleophilic. The *direct* transfer of a hydrogen atom between these two nucleophilic carbon-centred radicals is relatively inefficient because it suffers from adverse polar effects. However, because the thiyl radical is *electrophilic*, both steps A and B in the thiol-catalysed cycle that replaces the direct abstraction benefit from favourable charge transfer in the respective transition states. The thiol fulfils the role of a protic polarity-reversal catalyst.[3]



1 **2** **3**

Scheme 1



6 **5**

Scheme 2

In general, the chemoselectivity of the redox rearrangement is determined by the regioselectivity of the ring-opening β-scission step (*e.g.* **5** ⟶ **6**), in conjunction with any rearrangement reactions that the product alkyl radical may undergo prior to trapping by the thiol. Thus, redox rearrangement of **4** gives exclusively isobutyl benzoate **7** and none of the *tert*-butyl ester, because β-scission of **5** occurs selectively by cleavage of the C(4)–O bond to give the tertiary alkyl radical **6**. We have recently reported an experimental and computational study of the factors that influence regioselectivity in the β-scission of substituted 1,3-dioxolan-2-yl and 1,3-dioxan-2-yl radicals and shown that the relative ease of C–O bond cleavage does not always follow the simplistic 'homolytic' order 3°–C–O > 2°–C–O > 1°–C–O.[4] In particular, for bicyclic 2-phenyl-1,3-dioxan-2-yl radicals such as those derived from carbohydrate benzylidene acetals, examples are found where 1°–C–O bonds cleave in marked preference to 2°–C–O bonds.[2,4,5]

Naturally-occurring terpenes provide ready access to a variety of cyclopropyl- and cyclobutyl-carbinyl radicals that are prone to ring-opening rearrangements[6] and we reasoned that thiol-catalysed monodeoxygenation of 1,2- and 1,3-diols of terpene origin could be of both mechanistic and preparative

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interest. In the present paper we describe the thiol-catalysed radical-chain redox rearrangements of benzylidene acetals derived from selected terpenoid diols.

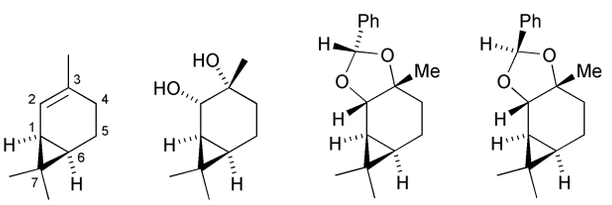
Results and discussion

Apart from pinane-2,3-diol which was obtained commercially, the 1,2-diols studied in this work were prepared by vicinal *cis*-dihydroxylation of terpenoid alkenes by treatment with tetradecylammonium permanganate in a two-phase solvent system consisting of dichloromethane and aqueous sodium hydroxide, as described by Hazra *et al.*,[7] or by the classical reaction with $KMnO_4$ in alkaline aqueous *tert*-butyl alcohol. Selected 1,3-diols derived from menthone and isomenthone, by reduction of aldol adducts obtained from the kinetic lithium enolates of these ketones,[8] were also investigated. All diols were converted into their benzylidene acetals by acid-catalysed condensation with benzaldehyde in refluxing benzene or toluene, with azeotropic removal of the water produced.

Redox rearrangements were carried out using two general methods;[2,4] in hexane solvent (bath temp. 70 °C) using di-*tert*-butyl hyponitrite[9] (TBHN) as initiator (method A) or in octane solvent (bath temp. 140 °C) using di-*tert*-butyl peroxide (DTBP) as initiator (method B). With both procedures the catalyst was usually triisopropylsilanethiol (Pr^i_3SiSH),[2,4,10] although methyl thioglycolate (MeO_2CCH_2SH) was used in some experiments for comparison. It was usual to make multiple additions of TBHN but, because of its relatively slow decomposition at *ca.* 130 °C, a single initial addition of DTBP was sufficient. The results are discussed below under separate headings for each of the parent diols.

Carane-2,3-diol

cis-Dihydroxylation of (1*S*)-(+)-2-carene **8** afforded the diol **9** and thence the benzylidene acetal **10** as a 57 : 43 mixture of the diastereoisomers **10a** and **10b**, the ^{1}H NMR spectra of which were assigned on the basis of selective nuclear Overhauser effect (NOE) experiments. Thus, irradiation of the benzylidene proton at δ 5.81 resulted in strong enhancement of the peaks arising from the C(3)-methyl protons at δ 1.33 and from H(2) at δ 3.97 (carane numbering), confirming that these signals are associated with the more abundant isomer **10a** in which the phenyl group is *trans* to the methyl group on the dioxolane ring. No corresponding enhancements were observed when the benzylidene proton at δ 6.00 was irradiated, confirming that this peak is associated with the minor isomer **10b**.



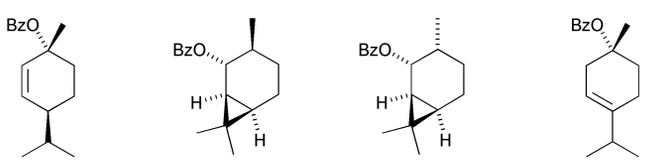
8 **9** **10a** **10b**

When the isomeric mixture of acetals was heated in hexane (method A) for a total of 2.5 h with 5 mol% TBHN present initially, followed by a further three additions of 5 mol% TBHN after 20, 40 and 60 min, about 80% of the starting material remained unchanged. However, in the presence of 5 mol% triisopropylsilanethiol (TIPST) under otherwise identical conditions, essentially none (≤ 2%) of the acetal **10** remained as judged by ^{1}H NMR spectroscopy and the esters **11**–**13** were detected as primary products of the redox rearrangement, together with a trace of a fourth compound subsequently identified as the homoallylic benzoate **14**. The ratio **11** : **12** : **13** : **14** in the crude product was 87 : 5 : 5 : 3 and an isomeric mixture of similar composition was isolated in 90% yield; the individual esters could not be separated by column chromatography. Examination of the reaction mixture after partial conversion of **10** showed[2] that the more abundant isomer **10a** was slightly (*ca.* 1.7 times) more reactive than the minor isomer **10b** towards abstraction of the benzylic hydrogen atom by $Pr^i_3SiS^\bullet$ at *ca.* 70 °C. Of course, the same benzylic radical **15** is formed by abstraction of hydrogen from either isomer.

Table 1 Redox rearrangement of the benzylidene acetal **10** as a function of thiol concentration in hexane at 70 °C[a]

Entry	TIPST/mol%	[TIPST]/M	Conversion (%)	Yield **11** + **14** / Yield **12** + **13** [b]
1	1	0.0056	70	40.0
2	2	0.0111	78	32.3
3	3	0.0167	85	13.3
4	5	0.0276	≥98	9.0
5	10	0.0549	96	4.0
6	15	0.0829	97	3.2
7	20	0.1087	97	2.6
8	40	0.2116	95	1.6

[a] Bath temperature. The concentration of the acetal **10** was *ca.* 0.55 M; TBHN (5 mol%) was added initially and again after 20, 40 and 60 min; the total reaction time was 2.5 h. A single addition of thiol was made at the start of the reaction. [b] Estimated by ^{1}H NMR analysis of the crude reaction product.



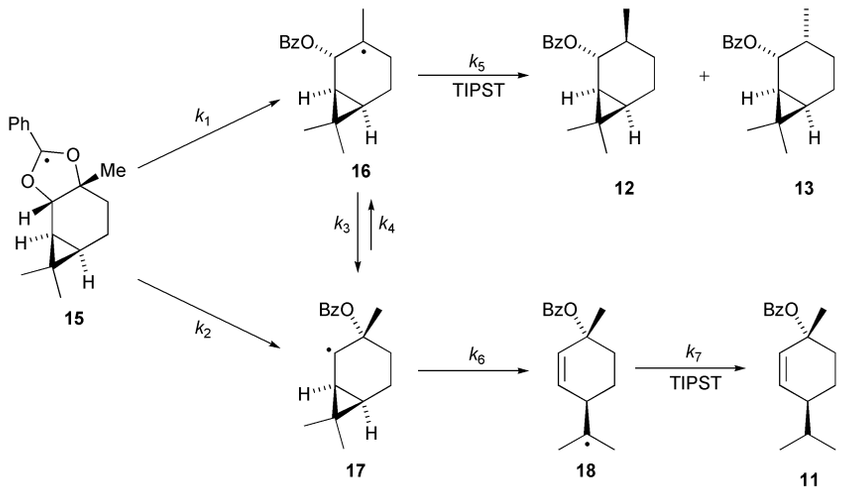
11 **12** **13** **14**

The routes by which compounds **11**–**13** arise from the intermediate benzylic radical are set out in Scheme 3. The product distribution was determined by ^{1}H NMR spectroscopy as a function of the initial thiol concentration and the results are presented in Table 1. As expected, the ratio **12** : **13** (1 : 1) was independent of the thiol concentration, but the relative total yield of alkenes **11** and **14** decreased with increasing concentration of TIPST, indicating that rearrangement of the radical **16** to **17** by the 1,2-shift of the benzoyloxy group[2,11] is competing with trapping of **16** by the thiol to give **12** and **13**. Since the product ratio **12** : **13** is 1 : 1, the rate constants for trapping of radical **16** by TIPST from its *exo* or *endo* face are the same within experimental accuracy. We propose that the benzoate **14** arises from thiol-catalysed radical-chain isomerisation of the initial product **11**, as shown in Scheme 4.

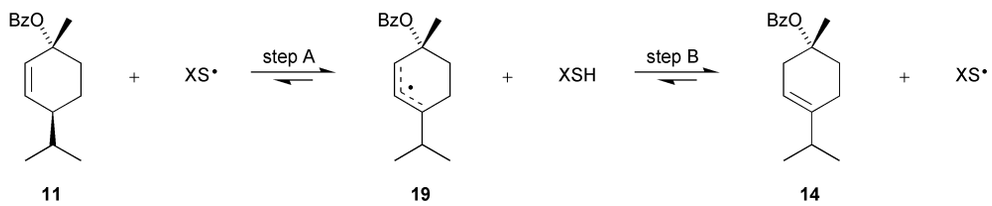
Assuming that the thiol concentration remains effectively constant during the reaction, which would imply that chain termination takes place mainly by coupling of two benzylic radicals **15** (see later), and that k_4 may be neglected in comparison with k_6 (the rate constant for ring opening of the cyclopropylcarbinyl radical **17**) it can be shown that eqn. (1)

$$\frac{\text{Yield } \mathbf{11}+\mathbf{14}}{\text{Yield } \mathbf{12}\ +\ \mathbf{13}} = \frac{k_3}{k_5[\text{TIPST}]}\left(1+\frac{k_2}{k_1}\right)+\frac{k_2}{k_1} \qquad (1)$$

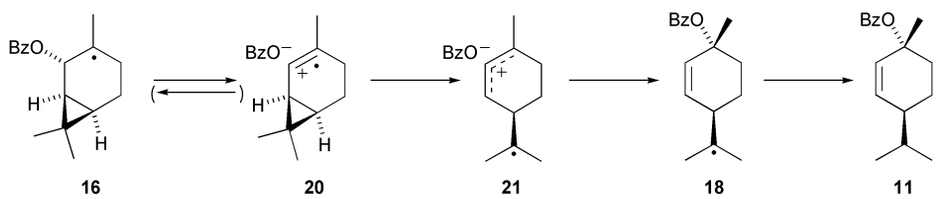
should hold.[2] When the product distribution was monitored as a function of time with 10 mol% TIPST as catalyst, there was no significant change in the ratio **11** + **14** : **12** + **13** (determined by removing small samples of the reaction mixture) as the conversion of **10** increased from 30 to 97%. This supports the adequacy of the assumption that the thiol concentration remains essentially constant during the redox rearrangement in this case. A plot of the combined yield of **11** and **14** relative to that of **12** and **13** against 1/[TIPST], for runs using 10–40 mol% thiol catalyst, gave a best straight line of slope 0.18 M^{-1} and an



Scheme 3



Scheme 4

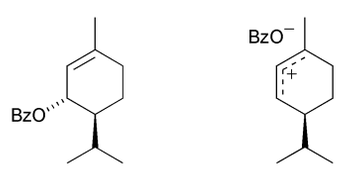


Scheme 5

intercept (= k_2/k_1) of 0.89. Thus, provided the mechanism is as shown in Scheme 3, β-scission of the 2-phenyl-1,3-dioxolanyl radical **15** to give the tertiary alkyl radical **16** is only marginally favoured over the alternative cleavage to give the secondary cyclopropylcarbinyl radical **17**. We have reported similar observations regarding the relative rates of β-scission of radicals of the type ROC$^{\bullet}$(Ph)CH_2X, to give R$^{\bullet}$ and PhC(O)-CH_2X, when R is a tertiary alkyl or a secondary cyclopropylcarbinyl group.[12] This is quite reasonable, because an α-cyclopropyl group provides significantly greater stabilisation to an attached carbon radical centre than does a simple α-alkyl group.[13]

Combining the slope and intercept it can be estimated that k_5 is about 11 times greater than k_3 at 70 °C and, since the former rate constant should be in the region of 10^7 M^{-1} s^{-1},[2,14,15] k_3 must be about 10^6 s^{-1}. Once formed, the cyclopropylcarbinyl radical **17** should undergo very rapid ring opening[6] (k_6 *ca.* 10^8 s^{-1}) to give the homoallylic radical **18** and thence the product **11**.

It should be borne in mind that quantitative kinetic analysis of the results using eqn. (1) could possibly be compromised if the 1,2-benzoyloxy shift takes place *via* initial dissociation of **16** to give a contact ion pair **20**.[11a] In this case, if the 2-carene radical cation[16] were to undergo ring opening before it collapses with the benzoate anion to give **17**, a pathway might exist from **16** to **18** (and thence to **11**) that does not involve the intermediacy of **17**, as shown in Scheme 5. If this were so, k_2 could be smaller relative to k_1 than indicated by the analysis using eqn. (1). However, when the 2-carene radical cation was generated by photo-mediated electron transfer from the parent terpene, it was thought to rearrange to an allylic radical-tertiary carbocation rather than to the isomeric distonic radical cation shown in the ion pair **21**.[16a] Furthermore, some collapse of the ion pair **21** *via* bonding of the benzoyloxy group to the other terminus of the allylic cation moiety to give the ester **22** might be expected to occur, but this compound was not detected as a product from the redox rearrangement under these conditions at 70 °C. We conclude that if the 1,2-shift of benzoate takes place *via* the ion pair **20**, opening of the 3-membered ring in the carene radical cation evidently does not compete with the very rapid collapse of **20** to give **17**.



When the redox rearrangement was carried out at higher temperature in refluxing octane (bath temp. 140 °C, internal temp. *ca.* 130 °C) with 50 mol% DTBP as initiator and 5 mol% TIPST as catalyst (method B), none of the benzylidene acetal **10** remained after 2.5 h. Under these conditions, the ester **22** was indeed detected in addition to **11**–**14** and the product mixture (**11** : **12** : **13** : **14** : **22** = 38 : 3 : 4 : 15 : 40) was isolated in 92% total yield by column chromatography. We propose that **22** is derived from its less stable isomer **11** by an allylic rearrangement proceeding *via* the ion pair **23**, formed by heterolysis of **11** at the relatively high temperature of these experiments.

Quantitatively different results were obtained when the redox rearrangement of **10** was catalysed by methyl thioglycolate (MTG). Conversion was low (*ca.* 40%) with 5 mol% MTG in

Table 2 Rearrangement of the benzylidene acetal **10** in the presence of methyl thioglycolate[a]

Entry	Solvent	Bath temp./°C	MTG/mol%	Collidine/mol%	Initiator/mol%	Final composition (%)					
						10	**11**	**12**	**13**	**14**	**22**
1	Hexane	70	5	None	TBHN (4 × 5)[b]	61	6	12	5	16	—[c]
2	Hexane	70	5	10	TBHN (4 × 5)[b]	5	25	26	9	27	8[d]
3	Octane	140	5	10	DTBP (1 × 50)	2	3	23	10	50	12
4	Octane	140	10	10	DTBP (1 × 50)	2	2	28	13	53	2

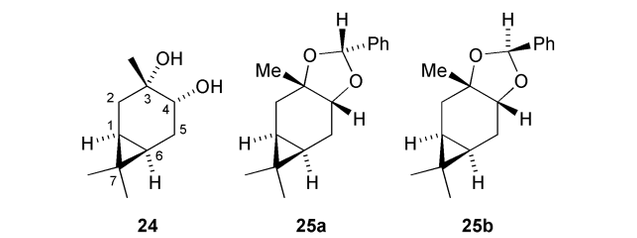
[a] The concentration of **10** was *ca.* 0.6 M and the total reaction time was 2.5 h. [b] TBHN (5 mol%) was added initially and again after 20, 40 and 60 min. [c] Not detected. [d] In a similar experiment with TIPST as catalyst without collidine (see text), none of the ionic rearrangement product **22** was detectable. The presence of collidine appears to facilitate the formation of the ionic rearrangement product **22**.

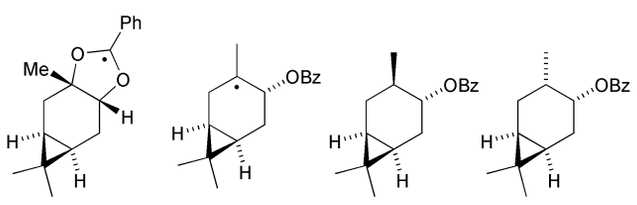
hexane at 70 °C (Table 2, entry 1) under conditions for which complete conversion was obtained using TIPST as catalyst. However, in the additional presence of 10 mol% collidine (2,4,6-trimethylpyridine),[1,2] the conversion rose to 95% (entry 2). In both runs using MTG, much more of the benzoate **14** was formed than when TIPST was used as catalyst: an independent synthesis served to confirm the identity of this ester. At higher temperature even more **14** was formed (entries 3 and 4). The less bulky MTG evidently reacts with the intermediate radical **16** to give relatively more of the *trans*-isomer **12** than does the more sterically demanding TIPST, which gave similar amounts of the isomeric benzoates **12** and **13**. These results can be understood if the radical centre in **16** is more accessible to a thiol from the face *cis* to the benzoate group and *trans* to the cyclopropyl ring, which leads to **13**, than from the opposite face which leads to **12**. An intrinsic preference for formation of the *trans* isomer **12**, which is presumably more stable than the *cis* isomer **13**, could then be offset in the case of reaction with the bulky TIPST because of steric inhibition to the formation of **12**. There was a marked reduction in the yield of **22** relative to that of **14** when the amount of MTG catalyst was increased to 10 mol% (entry 4), probably because the rate of radical rearrangement of **11** to **14** is increased relative that of ionic rearrangement of **11** to **22** when the concentration of thiol is greater.[17]

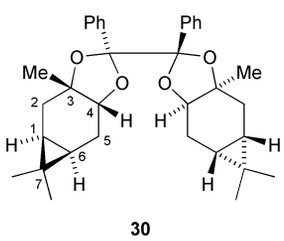
When a partially purified sample of **11** (containing *ca.* 5% each of **12** and **13**, but only traces of **14** and **22**) was subjected to the conditions of entry 3, examination of the crude reaction product by ^{1}H NMR spectroscopy showed it to contain **11**, **14** and **22** in the ratio 8 : 74 : 18 (along with unchanged **12** and **13**). However, when this experiment was repeated in the presence of 3 mol% 4,4′-methylenebis(2,6-di-*tert*-butylphenol) as a radical scavenger, the ratio **11** : **14** : **22** in the crude product was very different at 8 : 5 : 87. This result provides convincing support for our proposal that while the ester **14** arises through a radical-chain allylic rearrangement,[17] as shown in Scheme 4, the benzoate **22** is derived from **11** by a heterolytic rearrangement proceeding *via* the ion pair **23** (and thus its formation is not subject to inhibition by the phenol). The very different rates at which MTG and TIPST induce the radical rearrangement of **11** to **14** is not surprising because, as we have pointed out previously,[17] for this type of process to proceed efficiently *both* of the steps A and B in Scheme 4 must be rapid. It appears that the greater strength of the S–H bond in the silanethiol,[12,18] compared with that in MTG, causes step B to become relatively slow when TIPST is present as the catalyst. With MTG, both steps are evidently sufficiently favourable for significant radical-chain isomerisation to occur even at 70 °C.

Carane-3,4-diol

cis-Dihydroxylation of (1*S*)-(+)-3-carene afforded the diol **24** which was converted to an 87 : 17 mixture of the benzylidene acetals **25a** and **25b**. In NOE experiments, the peaks from H(4) and the C(3)-methyl protons showed strong enhancement when the benzylidene proton at δ 5.74 in the major isomer was irradiated, confirming that this is **25a**. No corresponding enhancements were observed when the benzylidene proton at δ 6.26 in the minor isomer **25b** was irradiated; the isomers were not separable by column chromatography. When the redox rearrangement of **25** was conducted in hexane at 70 °C for a total of 2.5 h, with four additions of 5 mol% TBHN (made initially and again after 20, 40 and 60 min), conversion was only 65–70% with either TIPST or MTG as catalyst. The major isomer **25a** was *ca.* 4.3 times more reactive than **25b** towards benzylic hydrogen abstraction by $Pr^i_3SiS^\bullet$ and *ca.* 3.5 times more reactive towards abstraction by $MeO_2CCH_2S^\bullet$. β-Scission of the benzylic radical **26** takes place essentially exclusively by cleavage of the C(3)–O bond to give the tertiary radical **27**, that is subsequently trapped by thiol from the *exo* or *endo* face to give the *trans*-ester **28** or the *cis*-ester **29** as the only rearrangement products. The ratio **28** : **29** was 52 : 48 with TIPST and 58 : 42 with MTG. A third product, subsequently identified by X-ray crystallography as the benzil bis(acetal) **30**, was formed under these conditions (method A) in a significant yield of *ca.* 14% using either thiol as catalyst. Evidently, this compound is produced by dimerisation of two radicals **26**. Both of the benzylic centres in **30** possess the *R*-configuration and the saturated 6-membered rings adopt only very slightly twisted boat conformations in the crystal. An interesting feature of the ^{1}H NMR spectrum of **30**, which was interpreted with the aid of ^{1}H-^{1}H correlated spectroscopy (COSY) and selective NOE experiments, was an apparent 1 : 3 : 3 : 1 quartet centred at δ −0.60 and assigned to H-6 and H-6′. The splitting pattern arises because of very similar couplings to the three vicinal protons and the origin of the negative chemical shift is evident from the crystal structure, which shows that the two protons in





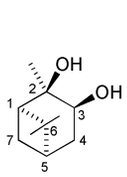


question are positioned directly above the centres of the nearer benzene rings.

Formation of **30** in this relatively high yield (maximum possible yield 50%) indicates that the kinetic chain length for the redox rearrangement is very short and that, at 70 °C, termination by dimerisation of the 2-phenyl-1,3-dioxolan-2-yl radical **26** is competing effectively with its β-scission to give **27**. In contrast, when the redox rearrangement of **25** was carried out at higher temperature under the conditions of method B (octane solvent, bath temp. 140 °C), in the presence of 5 mol% TIPST, the benzylidene acetal was cleanly converted to an inseparable 52 : 48 mixture of **28** and **29**, which was isolated in 89% yield. In similar experiments with MTG as catalyst, conversion to a 57 : 43 mixture of **28** and **29** was also essentially complete. The benzylic radical dimer **30** was not detected amongst the products of these higher temperature reactions. The activation energy for the β-scission of **26** will be appreciably larger[20] than that for its (presumably near-diffusion-controlled) dimerisation and increasing the temperature will lead to a large increase in the rate constant for β-scission relative to that for dimerisation. In contrast to the results obtained with the benzylidene acetal from carane-2,3-diol, no products arising from opening of the 3-membered ring were produced in this case, because no cyclopropylcarbinyl radical is involved.

Pinane-2,3-diol

Commercially available (1*R*,2*R*,3*S*,5*R*)-(−)-pinane-2,3-diol **31**, derived from (1*S*)-(−)-α-pinene, was converted to a 74 : 26 mixture of the benzylidene acetals **32a** and **32b**. The benzylidene proton singlet in **32a** appeared at δ 5.81 and that in **32b** at δ 6.20; the assignments were made on the basis of NOE experiments. β-Scission of the intermediate 2-phenyl-1,3-dioxolan-2-yl radical evidently takes place with essentially complete regioselectivity to give the tertiary radical **33**, although in refluxing octane with 5 mol% TIPST catalyst (method B) the only redox rearrangement product detected was the allylic benzoate **34**, which was isolated in 95% yield and arises from opening of the cyclobutylcarbinyl radical **33**. The isomer **32a** of the benzylidene acetal, in which the benzylic hydrogen atom is in the *exo* position on the bicyclic [4.3.0] fragment of the molecule, is *ca*. 4.3 times more reactive towards $Pr^i_3SiS^{\bullet}$ than the isomer **32b** in which this hydrogen atom is in the corresponding *endo* position.



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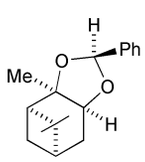
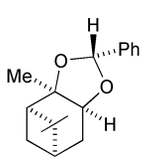
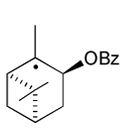


32a



32b

When the reaction was carried out at lower temperature under the conditions of method A with 5 mol% TIPST as catalyst, the redox rearrangement of **32** also proceeded to completion. However, now a small amount (*ca*. 13%) of another product, presumed to be the benzoate **35** that arises from trapping of **33**, was formed alongside the ring-opened compound **34**.



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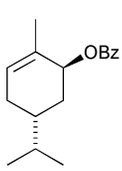

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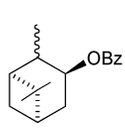
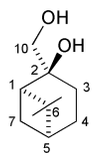


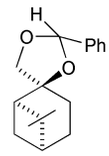
35

Pinane-2,10-diol

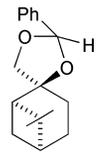
Dihydroxylation of (1*S*)-(−)-β-pinene afforded pinane-2,10-diol **36** and thence a 50 : 50 mixture of the benzylidene acetals **37a** and **37b**. There was an NOE correlation between the benzylidene proton at δ 5.71 and the proton at δ 2.31 attached to C(1), indicating that these signals are associated with the isomer **37a**. The benzylidene proton in **37b** appears at δ 5.85.



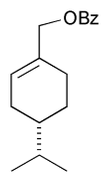
36



37a



37b



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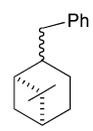

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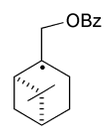
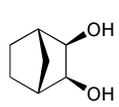


40

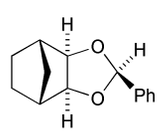
The redox rearrangement of **37** proceeded smoothly to completion in the presence of 5 mol% TIPST, using either method A or B. The allylic benzoate **38** was essentially the only product and none of the bicyclic isomer **39** could be conclusively identified under either set of conditions; **38** was isolated in 90–95% yield. These results show that the first-formed benzylic radical undergoes regioselective β-scission to give the tertiary cyclobutylcarbinyl radical **40** which undergoes rapid opening of the 4-membered ring followed by thiol quenching to give **38**.

Norbornane-2,3-diol

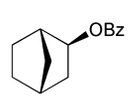
Dihydroxylation of norbornene afforded the *exo*,*exo*-diol **41**, which was converted to the benzylidene acetal **42** containing only a trace (*ca*. 1.7%) of the alternative diastereoisomer.[19a] Even under the more forcing conditions of method B, with 5 mol% TIPST in refluxing octane, the redox rearrangement of **42** was very sluggish and only *ca*. 30% conversion to *exo*-norbornyl benzoate **43** was achieved after 3 h.



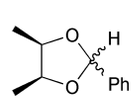
41



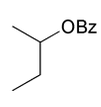
42



43



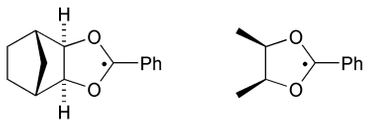
44



45

In contrast, the monocyclic analogue **44**, prepared from *meso*-butane-2,3-diol as a 57 : 43 mixture of the *syn* and *anti* isomers, was completely converted to *s*-butyl benzoate **45** under the conditions of method B. We attribute the markedly different efficiencies with which **42** and **44** undergo redox rearrangement to the relative rigidity of the polycyclic skeleton in the 2-phenyl-1,3-dioxolan-2-yl radical **46**, which leads to additional strain in the transition state for its β-scission compared with the analogous monocyclic radical **47**. When chain termination occurs by dimerisation of pairs of benzylic radicals, the relative rates of redox rearrangement of **42** and **44** should be approximately equal to the ratio of the rate constants for β-scission of

46 and **47** ($k_\beta^{46}/k_\beta^{47}$), provided that the rates of initiation and the rate constants for chain termination are similar for the two systems.

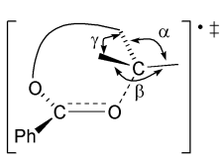


46 **47**

We have reported previously that the relative rates of β-scission of 2-phenyl-1,3-dioxolan-2-yl radicals can be satisfactorily predicted using density functional theory.[4,20] Therefore, similar calculations[20] were carried out to model the β-scission of **46** and **47**, using the Gaussian 98 package of programs.[21] At the UB3LYP/6-31G(d,p)//UB3LYP/6-31G(d,p) level of theory, the computed activation energy for β-scission of **46** was 6.8 kJ mol^{-1} greater than that for **47** and this energy difference is very similar (7.1 kJ mol^{-1}) at the UB3LYP/6-311+G(d,p)//UB3LYP/6-31G(d,p) level. The β-scission of the more flexible **47** was also favoured by entropic factors, such that the computed Arrhenius pre-exponential factor for cleavage **47** was 3.2 times larger than that for **46**. Using these activation parameters, $k_\beta^{46}/k_\beta^{47}$ is predicted to be *ca.* 0.04 at 130 °C, in accord with the observed much slower redox rearrangement of **42** compared with that of **44**. We have proposed[4] that 'umbrella angle strain' (UAS) at the emerging radical centre is a sensitive indicator of the total strain in the transition state for β-scission of this class of radical and, thus, of the relative rates of β-cleavage processes that lead to formally similar types of carbon-centred radical (in the case of both **46** and **47**, to *secondary* alkyl radicals). We defined UAS by eqn. (2),[4] in which Σ is the sum of the

$$\text{UAS} = 352.4° - \Sigma \qquad (2)$$

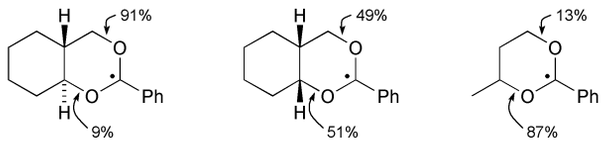
bond angles α, β and γ at the developing radical centre in the generalised transition state structure **48** and reflects the degree of pyramidalisation at this site. Consistent with our earlier conclusions, the computed UAS in the transition state for β-scission of **46** (+2.9°) is appreciably larger than that (−0.6°) in the transition state for cleavage of **47**.



48

1,3-Diols derived from menthone and isomenthone

We have reported that the stereoisomeric bicyclic [4.4.0] 1,3-dioxan-2-yl radicals **49** and **50**, in which the ring junction is respectively *trans* or *cis*, undergo β-scission with markedly different regioselectivity.[4] The selectivities for β-scission at 130 °C are indicated on the structures of these radicals and the *trans*-fused **49** shows a surprisingly strong preference for formation of the *primary* alkyl radical. In contrast, without the constraints of a bicyclic skeleton, the monocyclic analogue **51** undergoes β-scission to give mainly the *secondary* alkyl radical under similar conditions.[1] We have suggested that an intrinsic preference for formation of a secondary rather than a primary radical is offset for **50**, and completely outweighed for **49**, by the development of angle strain in the (chair–chair[4]) transition states for cleavage of these bicyclic dioxanyl radicals and that this strain becomes evident as UAS at the emerging radical centres.[4] The computed UAS is negligible (0.0 ± 0.2°) for cleavage of either the 1°–C–O or the 2°–C–O bond in **51**. However, while the calculated UAS is still small (+0.7°) for cleavage of the 1°–C–O bond in the *trans*-fused **49**, it is much larger (+4.0°) for cleavage of the 2°–C–O bond, leading to a preference for formation of the primary alkyl radical.

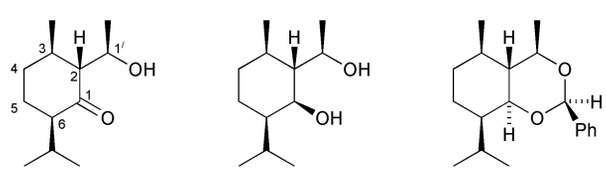


49 **50** **51**

Although consideration of the computed UAS alone provides an internally consistent rationalisation of the regioselectivities observed experimentally for β-scission of a number of 2-phenyl-1,3-dioxolan-2-yl and 2-phenyl-1,3-dioxan-2-yl radicals, it is notoriously risky to quantitatively dissect the total strain of a molecule into its various constituents, because these are not independent of each other. In order to gain further insight into this problem, we investigated the redox rearrangement of some benzylidene acetals of 1,3-diols derived from isomenthone **52** and menthone **53**, on the basis that the presence of the methyl and isopropyl ring substituents would give information regarding the importance of torsional strain interactions that might develop on moving to the transition states for β-scission. Furthermore, such redox rearrangements could provide useful synthetic routes to enantiomerically pure substituted cyclohexyl benzoates.

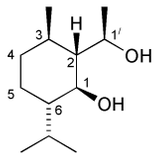
52 **53**

Treatment of the kinetic lithium enolate from (+)-isomenthone **52** with acetaldehyde at −78 °C, as described by Gardiner and co-workers,[8c] afforded the ketoalcohol **54** which was reduced with $LiAlH_4$ to give the 1,3-diol **55** as the major diastereoisomer.[8b] The isomerically pure diol was converted to the crystalline benzylidene acetal **56** and the structure of this was confirmed by X-ray diffraction. The phenyl and two methyl substituents occupy equatorial sites on the *trans*-fused bicyclo-[4.4.0]dioxadecane core, while the isopropyl group is in an axial site. A similar series of reactions starting from (−)-menthone **53** afforded the 1,3-diol **57** as a major product, which was purified by recrystallisation and converted to the crystalline benzylidene acetal **58**. The structure of **58** was also confirmed by X-ray diffraction, which showed that all four substituents occupy equatorial sites on the *trans*-fused bicyclic skeleton.



54 **55** **56**

Redox rearrangement of the menthone-derived acetal **58** in refluxing octane, with 5 mol% TIPST as catalyst and 50 mol% DTBP as initiator (method B), resulted in its complete conversion to the benzoate **59** which was isolated in 96% yield. The same result was achieved at 70 °C using method A and **59** was isolated in 94% yield; none of the isomeric benzoate **60** was detected under either set of conditions. Without a thiol catalyst under otherwise identical conditions, only 4% conversion of **58** to **59** took place using method A and this rose to just 10% using method B. Redox rearrangement of the isomenthone-derived benzylidene acetal **56**, in which the methyl and isopropyl groups



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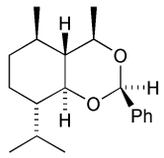

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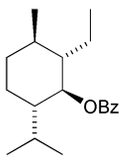

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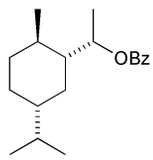

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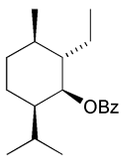
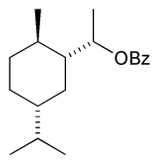
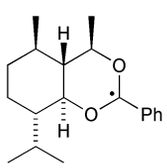


61



62

on the cyclohexane ring are now *cis*, also proceeded efficiently with 5 mol% TIPST catalyst using either method. The only identifiable product was the benzoate **61**, which was formed in high yield (*ca*. 96%), although it was contaminated with a trace of an inseparable unidentified compound with very similar properties; this is believed *not* to be the regioisomeric benzoate **62**. ‡ For each of the intermediate benzylic radicals **63** and **64** the two alternative modes of β-scission both lead to secondary alkyl radicals. However, β-scission is completely regioselective in each case and takes place to give exclusively the exocyclic alkyl radical, in preference to the endocyclic alternative that would result from cleavage of the bridgehead-C–O bond. Evidently, any torsional interactions that develop between the various ring substituents present in **63** and **64** on moving to the product-like[4] transition states do not offset the marked resistance to cleavage of the bridgehead-C–O bond that was observed previously for their unsubstituted *trans*-fused parent **49**.



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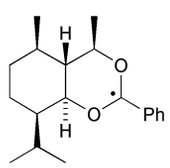
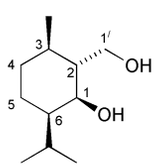


64

Treatment of the kinetic enolate from (+)-isomenthone with gaseous formaldehyde at −78 °C,[22a] followed by reduction of the ketoalcohol, afforded as the major product the diol **65** which has been prepared previously by a different route.[22b] The structure of the derived benzylidene acetal **66** could be deduced unambiguously from its ^{1}H NMR spectrum, thus also confirming the identity of the diol **65**.



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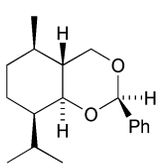
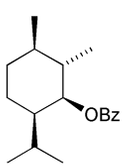


66



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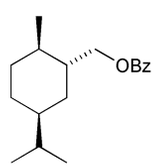
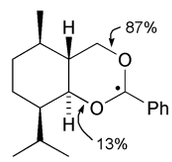


68

Redox rearrangement of **66** in refluxing octane using 5 mol% TIPST as catalyst (method B) proceeded to completion and the benzoate esters **67** and **68** were formed in the ratio 87 : 13. The relative rates of cleavage of the 1°–C–O and 2°–C–O bonds in the intermediate radical **69** are quite similar to those (91 : 9) observed previously[4] for the β-scission of the unsubstituted parent **49**, indicating that the regioselectivity is not significantly influenced by the presence of the equatorial methyl and axial isopropyl groups on the cyclohexane ring in **69**. Taken together with the results from the redox rearrangements of the benzylidene acetals **56** and **58**, we conclude that torsional strain interactions are probably not of major importance in determining the regioselectivity of β-scission for these bicyclic 2-phenyl-1,3-dioxan-2-yl radicals.



69

When the redox rearrangement of **66** was attempted in refluxing hexane, under the conditions of method A, much of the starting material remained unchanged and several unidentified products were formed alongside relatively small amounts of the benzoates **67** and **68**. The difference in behaviour of **66** at the lower temperature is presumably a consequence of the comparatively slow β-scission of **69** leading to the occurrence of side reactions. This result is reminiscent to that obtained for the redox rearrangement of the benzylidene acetal **25** at low temperature and, indeed, the head-to-head dimer of **69** was probably present amongst the products from the reaction of **66** at 70 °C.

Experimental

NMR spectra were recorded using a Bruker AVANCE 500 instrument (500 MHz for ^{1}H, 125.7 MHz for ^{13}C). Unless stated otherwise, the solvent was $CDCl_3$ and chemical shifts are reported relative to residual $CHCl_3$ (δ_H = 7.26) or to $CDCl_3$ (δ_C = 77.0 ppm); *J* values are quoted in Hz and the use of [multiplet] indicates an apparent multiplet associated with an observed line spacing. Column chromatography and TLC were carried out using Merck Kieselgel 60 (230–400 mesh) and Kieselgel 60 F_{254} aluminium-backed pre-coated plates, respectively. Optical rotations were measured using an AA Series Polar 2000 polarimeter (Optical Activity Ltd.) in a 1 dm cell and are given in units of 10^{-1} deg cm^2 g^{-1}. Infrared (IR) spectra were obtained from liquid films or KBr pellets using a Shimadzu FTIR-8700 spectrophotometer; wavenumbers (cm^{-1}) are reported only for strong well-defined bands.

All redox rearrangements and reactions of air-sensitive compounds were carried out under an atmosphere of dry argon or nitrogen and all extracts were dried over anhydrous $MgSO_4$. Petroleum refers to the fraction of bp 40–60 °C.

Materials

Hexane (Aldrich) was dried by heating under reflux over calcium hydride and then distilled from CaH_2 under argon. Anhydrous octane, di-*tert*-butyl peroxide (98%) and methyl thioglycolate were obtained commercially (Aldrich) and were used as received. Triisopropylsilanethiol was prepared according to the method of Soderquist and co-workers[10] or obtained commercially (Aldrich). Di-*tert*-butyl hyponitrite was prepared from sodium hyponitrite, *tert*-butyl bromide and zinc chloride in diethyl ether, as described by Mendenhall.[9b]

(+)-Isomenthone **52** and (−)-menthone **53** were prepared by oxidation with aqueous-acidic potassium dichromate of (+)-isomenthol {$[a]_D^{24}$ +24.0 (*c* 4.2, EtOH)} or (−)-menthol {$[a]_D^{20}$

‡ The benzoate **61** contained *ca* 4% of the unknown contaminant when method B was used for the rearrangement, although this was reduced to *ca*. 2% with method A or with method B when MTG was used as catalyst. The only visible peak in the ^{1}H NMR spectrum of the unknown compound was what appeared to be a broad triplet (*J ca*. 3 Hz) at δ 5.48 and this was assumed to arise from a single proton in the molecule.

−50.4 (*c* 5.6, EtOH, 99% ee}, respectively (both from Aldrich), as described by Brown and co-workers.[23a]

Diols

(1*R*,2*R*,3*S*,5*R*)-(−)-Pinane-2,3-diol **31** (97% ee) and *meso*-butane-2,3-diol were obtained from Aldrich and used as received. Where appropriate, because the compounds are incompletely described in the literature, details of the preparation and/or characterisation of starting materials are given below.

(2*S*,3*R*)-Carane-2,3-diol **9** was prepared by dihydroxylation of (+)-2-carene (Aldrich), using basic $KMnO_4$ in aqueous *tert*-butyl alcohol as described in the literature.[24] The starting 2-carene showed $[\alpha]_D^{20}$ +86.9 (*c*. 3.1, EtOH), which corresponds to an ee of *ca*. 92% according to values in the literature.[25] (3*R*,4*R*)-Carane-3,4-diol[7a] **24** was prepared similarly from (1*S*)-(+)-3-carene (Fluka), which showed $[\alpha]_D^{20}$ +17.2 (neat). This diol showed mp 69 °C (lit.[7a] mp 68 °C); δ_H 0.63 (1 H, [t]d, *J* 9.5 and 4.5, ring-H), 0.85 (1 H, [t], *J* 8.5, ring-H), 0.89 (3 H, s, Me-7), 1.00 (3 H, s, Me-7), 1.20 (3 H, s, Me-1), 1.23 (1 H, dd, *J* 15.6 and 4.5, ring-H), 1.67 (1 H, ddd, *J* 14.6, 8.5 and 4.5, ring-H), 1.70 and 1.82 (2 H, brs, OH), 2.04 (1 H, dd, *J* 14.6 and 7.3, ring-H), 2.10 (1 H, dd, *J* 15.6 and 9.5, ring-H), 3.18 (1 H, dd, *J* 9.5 and 7.5, H-2); δ_C 15.4, 16.2, 17.5, 21.5, 25.4, 26.9, 28.5, 33.2, 70.2, 73.1.

(2*S*)-Pinane-2,10-diol **36** was prepared by dihydroxylation of (1*S*)-(−)-β-pinene (Aldrich), which showed $[\alpha]_D^{20}$ −22.0 (neat), using tetradecyltrimethylammonium permanganate as described by Hazra *et al.*;[7] *exo,exo*-norbornane-2,3-diol[19b] **41** was prepared from norbornene in the same way.

(1′*R*,1*S*,2*R*,3*R*,6*R*)-2-(1-Hydroxyethyl)-6-isopropyl-3-methylcyclohexanol 55.[8a] Butyllithium solution (1.6 M in hexanes, 44.0 mL, 70.4 mmol) was added dropwise under argon to a stirred solution of dry diisopropylamine (7.58 g, 74.9 mmol) in dry tetrahydrofuran (THF, 100 mL) cooled in an ice-water bath. The resulting solution was stirred at this temperature for a further 15 min, then cooled in a solid CO_2-acetone bath. Isomenthone[23b] (10.00 g, 64.8 mmol) in THF (10 mL) was added dropwise during 15 min with stirring and the resulting solution was stirred for a further 1 h. Still with cooling in the solid CO_2–acetone bath, acetaldehyde (3.30 g, 74.8 mmol) was added dropwise during 10 min and the resulting mixture was subsequently stirred at this temperature for a further 1.5 h, before being quenched with saturated aqueous NH_4Cl (200 mL) at −78 °C to room temperature. The organic layer was separated and concentrated by evaporation. The aqueous phase was extracted with diethyl ether (3 × 30 mL) and the combined organic liquid was washed with saturated brine and dried. After evaporation of the solvent, the residue (10.5 g, 53.0 mmol based on the product ketoalcohol **54**) was dissolved in dry diethyl ether (50 mL) and added dropwise with stirring to $LiAlH_4$ (5.00 g, 132 mmol) in diethyl ether (100 mL) cooled in an ice–water bath. After the addition, the mixture was allowed to warm to room temperature and stirred for 30 min, then heated under gentle reflux for 1 h. The reaction mixture was cooled in an ice–water bath and quenched by successive addition of water (5 mL), aqueous NaOH (15% w/v, 5 mL) and water (10 mL). The solid material was removed by filtration and washed on the filter with diethyl ether. Evaporation of the solvent from the filtrate afforded an oily residue that was crystallised from hexane at −4 °C and then recrystallised from the same solvent to afford the *diol* **55** (7.22 g, 68%), mp 98–100 °C, $[\alpha]_D^{25}$ −14.5 (*c* 1.30, $CHCl_3$); δ_H 0.93 (3 H, d, *J* 6.6, CH*Me*$_2$), 1.00 (3 H, d, *J* 6.6, CH*Me*$_2$), 1.12 (3 H, d, *J* 7.1, Me-3), 1.15 (1 H, m, ring-H), 1.28 (3 H, d, *J* 6.3, Me-1′), 1.37 (3 H, m, ring-H and OH), 1.50 (3 H, m, ring-H), 1.56–1.72 (3 H, m, ring-H and OH), 3.87 (1 H, [sextet], *J* 6.3, H-1′), 4.31 (1 H, [q], *J* 3.6, H-1); δ_C 20.5, 21.1, 21.3, 21.4, 23.4, 28.7, 28.9(9), 29.0(2), 44.4, 54.7, 68.2, 69.6; IR (KBr disc) 3456, 3332, 2959, 1456, 1367, 1136, 1006, 981. (Found: C, 72.2; H, 12.2. $C_{12}H_{24}O_2$ requires C, 72.0; H, 12.1%).

(1′*R*,1*S*,2*R*,3*R*,6*S*)-2-(1-Hydroxyethyl)-6-isopropyl-3-methylcyclohexanol 57. This was prepared from (−)-menthone[23a] using the same procedure as for **55** and on the same scale. The final recrystallisation stage afforded the *diol* **57** as colourless needles (3.57 g, 34%), mp 119–120 °C, $[\alpha]_D^{25}$ −33.8 (*c*. 1.36, $CHCl_3$); δ_H 0.79 (3 H, d, *J* 7.0, CH*Me*$_2$), 0.92 (3 H, d, *J* 7.0, CH*Me*$_2$), 0.95 (3 H, d, *J* 6.4, Me-3), 0.98 (2 H, m, ring-H), 1.05 (1 H, [td], *J* 10.0 and 2.8, H-2), 1.24 (1 H, m. ring-H), 1.31 (3 H, d, *J* 6.6, Me-1′), 1.34 (1 H, m, H-3), 1.56 (1 H, m, H^A-5), 1.66 (1 H, m, H^B-5), 2.18 (1 H, septet of doublets, *J* 7.0 and 2.8, C*H*Me$_2$), 2.31 (1 H, brs, OH), 2.39 (1 H, brs, OH), 3.44 (1 H, [t], *J* 10.0, H-1), 4.11 (1 H, m, H-1′); δ_C 15.9, 20.8, 21.1, 22.6, 25.0, 25.7, 34.4, 35.3, 49.8, 57.4, 69.5, 73.0; IR (KBr disc) 3345, 3333, 2950, 1448, 1371, 1124, 1019, 978. (Found: C, 72.3; H, 12.3. $C_{12}H_{24}O_2$ requires C, 72.0; H, 12.1%).

Other isomeric diols were present in the residue from the recrystallisation stage, but no pure compounds could be isolated by column chromatography.

(1*S*,2*R*,3*R*,6*R*)-2-Hydroxymethyl-6-isopropyl-3-methylcyclohexanol 65.[22b] The kinetic lithium enolate derived from (+)-isomenthone (10.00 g, 64.8 mmol) was prepared as described before. Excess gaseous formaldehyde, from the pyrolysis of paraformaldehyde (4.25 g, corresponding to 112 mmol of the monomer), was conducted into the reaction flask during 20 min in a stream of dry argon. The tip of the transfer tube terminated just above the surface of the solution, which was stirred and maintained at *ca*. −78 °C during the addition. The work-up was as described for the ketoalcohol **54** and the crude product (11.5 g, *ca*. 62.5 mmol) was reduced with $LiAlH_4$ (6.00 g, 158.0 mmol) in diethyl ether (100 mL), as described before, to afford the *diol* **65** as a viscous oil (containing *ca*. 8% of a presumed isomer); δ_H (C_6D_6) 0.92 (3 H, d, *J* 6.6, Me-3), 1.00 (3 H, d, *J* 6.5, CH*Me*$_2$), 1.18 (3 H, d, *J* 6.5, CH*Me*$_2$), 1.28 (5 H, m, ring-H), 1.60 (1 H, m, ring-H), 1.66 (1 H, m, ring-H), 1.83 (1 H, m, ring-H), 3.26 (2 H, brs, OH), 3.50 (1 H, dd, *J* 10.5 and 7.9, H^A-1′), 3.81 (1 H, dd, *J* 10.5 and 4.0, H^B-1′), 3.90 (1 H, dd, *J* 7.4 and 3.6, H-1); δ_C 20.7, 22.0, 23.0, 24.6, 27.2, 29.7, 31.0, 45.6, 48.3, 64.8 and 75.7.

This diol was used to prepare the benzylidene acetal **66** without further purification.

Benzylidene acetals

A mixture of the diol (typically *ca*. 20 mmol), benzaldehyde (*ca*. 23 mmol) and, unless stated otherwise, *p*-toluenesulfonic acid (50 mg) in benzene (40 mL) was stirred and heated under reflux for *ca*. 1 h, while water was removed azeotropically using a Dean–Stark trap. The solution was allowed to cool, shaken with calcium carbonate (*ca*. 0.5 g) to neutralise the acid and the suspension was filtered through Celite. The filter cake was washed with diethyl ether, the solvent was removed from the filtrate by evaporation and the acetals were isolated, as oils unless stated otherwise, by flash chromatography (light petroleum–diethyl ether eluent 20 : 1), usually followed by distillation under reduced pressure. The characteristic properties are given below. It should be noted that the optical rotations reported for benzylidene acetals refer to mixtures of stated diastereoisomeric composition.

Acetal 10 from carane-2,3-diol. Yield 88%, bp 115–118 °C/0.05 mmHg as a mixture of **10a** and **10b** in a ratio of 57 : 43; $[\alpha]_D^{18}$ −29.8 (*c* 3.2, EtOH), $[\alpha]_D^{18}$ −24.5 (*c* 1.5, $CHCl_3$). (Found: C, 78.8; H, 8.8. $C_{17}H_{22}O_2$ requires C, 79.0; H, 8.6%).

*Isomer **10a***. δ_H 0.87 (1 H, m, ring-H), 0.97 (3 H, s, Me-7), 1.06 (3 H, s, Me-7), 1.25 (1 H, m, ring-H), 1.33 (3 H, s, Me-3), 1.55

(1 H, m, ring-H), 1.67 (1 H, d, *J* 5.6, H-3), 1.78 (1 H, m, ring-H), 2.07 (1 H, m, ring-H), 3.79 (1 H, s, H-2), 5.81 (1 H, s, PhC*H*), 7.37 (3 H, m, Ph), 7.53 (2 H, m, Ph); δ_C 15.7, 16.5, 17.0, 21.8, 24.4, 25.9, 29.0, 34.3, 77.8, 79.7, 100.3, 127.0, 128.3, 129.2, 137.8.

Isomer ***10b***. δ_H 0.87 (1 H, m, ring-H), 0.99 (3 H, s, Me-7), 1.09 (3 H, s, Me-7), 1.28 (1 H, m, ring-H), 1.34 (3 H, s, Me-3), 1.56 (1 H, m, ring-H), 1.67 (1 H, dd, *J* 5.6 and 1.6, H-3), 1.77 (1 H, m, ring-H), 2.07 (1 H, m, ring-H), 3.97 (1 H, s, H-2), 6.00 (1 H, s, PhC*H*), 7.37 (3 H, m, Ph), 7.53 (2 H, m, Ph); δ_C 15.6, 16.4, 17.0, 21.6, 23.8, 27.1, 28.7, 32.2, 77.6, 79.4, 101.4, 126.7, 128.3, 129.0, 138.3.

Acetal 25 from carane-3,4-diol. Yield 83%, bp 113–115 °C/0.05 mmHg (solidified at room temperature, mp 65–72 °C) as a mixture of the isomers **25a** and **25b** in a ratio of 87 : 13; $[a]_D^{18}$ +3.9 (*c* 2.44, $CHCl_3$). (Found: C, 79.2; H, 8.4. $C_{17}H_{22}O_2$ requires C, 79.0; H, 8.6%).

Isomer ***25a***. δ_H 0.70–0.98 (4 H, complex, ring-H), 1.00 (3 H, s, Me-7), 1.13, (3 H, s, Me-7), 1.31 (3 H, s, Me-3), 2.16 (1 H, dd, *J* 10.2 and 7.2, ring-H), 2.28 (1 H, ddd, *J* 15.4, 7.2 and 2.5, ring-H), 3.99 (1 H, [t], *J* 2.5, H-4), 5.74 (1 H, s, PhC*H*), 7.38 (3 H, m, Ph), 7.55 (2 H, m, Ph); δ_C 14.9, 16.4, 17.6, 18.2, 23.1, 25.4, 28.5, 29.6, 79.5, 80.9, 100.6, 127.2, 128.3, 129.5, 137.3.

Isomer ***25b***. δ_H 0.70–0.98 (4 H, complex, ring-H), 0.98 (3 H, s, Me-7), 1.12, (3 H, s, Me-7), 1.32 (3 H, s, Me-3), 2.17 (1 H, dd, *J* 10.1 and 7.2, ring-H), 2.29 (1 H, ddd, *J* 15.4, 7.2 and 2.6, ring-H), 4.14 (1 H, [t], *J* 2.6, H-2), 6.26 (1 H, s, PhC*H*), 7.38 (3 H, m, Ph), 7.50 (2 H, m, Ph); δ_C 14.3, 17.6, 19.0, 19.2, 24.4, 27.8, 28.4, 30.5, 80.5, 81.0, 104.4, 126.4, 128.3, 128.9, 139.6.

Acetal 32 from pinane-2,3-diol. Prepared using pyridinium *p*-toluenesulfonate (PPTS *ca*. 70 mg) as catalyst in place of *p*-toluenesulfonic acid. Yield 83%, as a mixture of isomers **32a** and **32b** in a ratio of 74 : 26; $[a]_D^{18}$ −19.3 (*c* 1.71, $CHCl_3$). (Found: C, 78.9; H, 8.8. $C_{17}H_{22}O_2$ requires C, 79.0; H, 8.6%).

Isomer ***32a***. δ_H 0.92 (3 H, s, Me-6), 1.35 (3 H, s, Me-6), 1.51 (3 H, s, Me-2), 1.96 (1 H, m, ring-H), 2.10 (1 H, ddd, *J* 14.6, 3.6 and 1.1, ring-H), 2.14–2.25 (3 H, m, ring-H), 2.30 (1 H, m, ring-H), 4.15 (1 H, d, *J* 7.4, H-3), 5.81 (1 H, s, PhC*H*), 7.38 (3 H, m, Ph), 7.57 (2 H, m, Ph); δ_C 24.1, 25.2, 25.6, 27.2, 32.8, 37.9, 40.0, 50.8, 77.5, 83.8, 100.6, 127.0, 128.4, 129.4, 136.7.

Isomer ***32b***. δ_H 0.93 (3 H, s, Me-6), 1.34 (3 H, s, Me-6), 1.37 (3 H, s, Me-2), 2.03 (1 H, m, ring-H), 2.15–2.35 (4 H, m, ring-H), 2.43 (1 H, m, ring-H), 4.43 (1 H, dd, *J* 9.0 and 3.0, H-3), 6.20 (1 H, s, PhC*H*), 7.37 (3 H, m, Ph), 7.50 (2 H, m, Ph); δ_C 24.2, 26.8, 27.2, 28.4, 34.1, 38.8, 39.9, 52.3, 77.4, 83.6, 103.6, 126.4, 128.3, 128.8, 139.7.

Acetal 37 from pinane-2,10-diol. Prepared using PPTS as catalyst. Toluene was used in place of benzene as the solvent for azeotropic removal of water and the reflux period was extended to 4 h. Yield 72%, as a mixture of isomers **37a** and **37b** in a ratio 50 : 50; $[a]_D^{18}$ −2.80 (*c* 1.82, $CHCl_3$). (Found: C, 78.8; H, 8.7. $C_{17}H_{22}O_2$ requires C, 79.0; H, 8.6%).

Isomer ***37a***. δ_H 0.88 (3 H, s, Me-6), 1.26 (3 H, s, Me-6), 1.70–2.35(8 H, complex, ring-H), 3.87 (1 H, d, *J* 8.1, OC*H*^{A}H^B), 3.92 (1 H, d, *J* 8.1, OCH^A*H*^{B}), 5.58 (1 H, s, PhC*H*), 7.36 (3 H, m, Ph), 7.50 (2 H, m, Ph); δ_C 22.7, 24.1, 26.6, 26.9, 29.5, 38.2, 40.2, 51.2, 77.6, 86.1, 101.9, 126.8, 128.3, 129.2, 138.3.

Isomer ***37b***. δ_H 0.88 (3 H, s, Me-6), 1.29 (3 H, s, Me-6), 1.70–2.35 (8 H, complex, ring-H), 3.83 (1 H, d, *J* 8.1, OC*H*^{A}H^B), 4.01 (1 H, d, *J* 8.1, OCH^A*H*^{B}), 5.71 (1 H, s, PhC*H*), 7.36 (3 H, m, Ph), 7.53 (2 H, m, Ph); δ_C 22.8, 23.8, 26.1, 26.8, 29.2, 38.1, 40.1, 49.4, 77.3, 86.4, 101.9, 126.7, 128.3, 129.1, 138.2.

Acetal 42 from norbornane-2,3-diol.[19a] Yield 89%, bp 100–102 °C/0.05 mmHg; δ_H 1.00 (2 H, m, ring-H), 1.12 (1 H, d[quintet], *J* 10.3 and 1.4, ring-H), 1.53 (2 H, m, ring-H), 1.90 (1 H, d[quintet], *J* 10.3 and 1.8, ring-H), 2.44 (2 H, m, ring-H), 4.03 (2 H, d, *J* 1.3, H-3,7), 5.56 (1 H, s, PhC*H*), 7.38 (2 H, m, Ph), 7.54 (2 H, m, Ph); δ_C 23.0, 31.8, 39.8, 83.0, 102.6, 126.8, 128.4, 129.4, 136.3.

Acetal 44 from *meso*-butane-2,3-diol.[26] Yield 95%, bp 63–68 °C/0.05 mmHg, as a mixture of isomers **44a** and **44b** in the ratio 57 : 43. Determination of the stereochemistry at the benzylidene centres in **44a** and **44b** was based on NOE experiments and our assignments of the two ^{1}H NMR spectra are reversed from those reported in the literature.[26] When the benzylidene proton appearing at δ 5.77 in the major isomer was irradiated, the signal at δ 4.34 from H-3,4 on the dioxolane ring in the same isomer showed a strong NOE enhancement, identifying this compound as **44a**. No corresponding enhancement was observed when the benzylidene proton at δ 6.11 in the minor isomer **44b** was irradiated.

(2S,4R,5S)-4,5-Dimethyl-2-phenyl-1,3-dioxolane ***44a***. δ_H 1.27 (6 H, m, Me), 4.34 (2 H, m, MeC*H*), 5.77 (1 H, s, PhC*H*), 7.38 (3 H, m, Ph), 7.50 (2 H, m, Ph); δ_C 15.5, 75.1, 102.8, 126.8, 128.4, 129.3, 137.8.

(2R,4R,5S)-4,5-Dimethyl-2-phenyl-1,3-dioxolane ***44b***. δ_H 1.24 (6 H, m, Me), 4.35 (2 H, m, MeC*H*), 6.11 (1 H, s, PhC*H*), 7.35 (3 H, m, Ph), 7.47 (2 H, m, Ph); δ_C 14.5, 74.6, 101.5, 126.0, 128.3, 120.2, 139.9.

Acetal 56 from the 1,3-diol 55. Prepared using PPTS as catalyst. Colourless crystals from MeOH (yield 94%), mp 103–104 °C, $[a]_D^{25}$ +3.1 (*c* 1.80, $CHCl_3$); δ_H (in C_6D_6, which gives better signal dispersion than $CDCl_3$) 0.80 (3 H, d, *J* 6.5, CH*Me*$_2$), 0.90 (3 H, d, *J* 6.5, CH*Me*$_2$), 0.92 (1 H, m, ring-H) 1.00–1.18 (2 H, complex, ring-H), 1.25 (1 H, tt, *J* 13.5 and 4.1, ring-H), 1.31 (3 H, d, *J* 6.6, Me-3), 1.36 (3 H, d, *J* 6.1, Me-1′), 1.37 (1 H, m, ring-H), 1.63–1.75 (2 H, m, C*H*Me$_2$ and ring-H), 1.94 (1 H, m, ring-H), 3.36 (1 H, dq, *J* 9.0 and 6.1, H-1′), 3.49 (1 H, dd, *J* 10.5 and 4.2, H-1), 5.40, (1 H, s, PhC*H*), 7.12 (1 H, m, Ph), 7.20 (2 H, m, Ph), 7.70 (2 H, m, Ph); δ_C 22.1, 22.4, 23.4, 23.9, 26.2, 27.5, 31.7, 33.7, 44.4, 47.0, 78.2, 84.7, 101.3, 126.8, 128.2, 128.6, 140.3. (Found: C, 79.2; H, 9.9. $C_{19}H_{28}O_2$ requires C, 79.1; H, 9.8%).

Acetal 58 from the 1,3-diol 57. Prepared using PPTS as catalyst. Colourless crystals from MeOH (yield 92%), mp 110 °C, $[a]_D^{25}$ −48.7 (*c* 1.84, $CHCl_3$); δ_H 0.83 (3 H, d, *J* 7.0, CH*Me*$_2$), 0.90(3 H, d, *J* 7.0, CH*Me*$_2$), 1.04 (3 H, d, *J* 6.3, Me-3), 1.18 (3 H, m, ring-H), 1.28 (1 H, m, H-3), 1.46 (3 H, d, *J* 6.0, Me-1′), 1.52–1.72 (4 H, m, ring-H), 2.26 (1 H, m, C*H*Me$_2$), 3.32 (1 H, dd, *J* 10.1 and 9.4, H-1), 3.76 (1 H, dq, *J* 9.2 and 6.0, H-1′), 5.53, (1 H, s, PhC*H*), 7.31 (1 H, m, Ph), 7.36 (2 H, m, Ph), 7.51 (2 H, m, Ph); δ_C 16.0, 20.4, 22.4, 23.1, 23.2, 25.5, 33.2, 36.4, 46.4, 52.8, 77.5, 82.2, 100.0, 125.9, 128.1, 128.3, 139.2. (Found: C, 79.3; H, 9.7. $C_{19}H_{28}O_2$ requires C, 79.1; H, 9.8%).

Acetal 66 from the 1,3-diol 65. Prepared using PPTS as catalyst. Colourless crystals from MeOH (yield 84%), mp 35 °C, $[a]_D^{25}$ −13.4 (*c* 1.04, $CHCl_3$); δ_H 0.90 (3 H, d, *J* 6.0, Me-3), 0.96 (3 H, d, *J* 6.7, CH*Me*$_2$), 1.19 (3 H, d, *J* 6.7, CH*Me*$_2$), 1.20 (2 H, m, ring-H), 1.38–1.48 (2 H, complex, ring-H), 1.70 (1 H, m, ring-H), 1.80 (1 H, m, ring-H), 1.92 (1 H, m, ring-H), 2.20 (1 H, m, C*H*Me$_2$), 3.53 (1 H, [t], *J* 11.0, H^{ax}-1′), 3.76 (1 H, dd, *J* 10.5 and 4.4, H-1), 4.37 (1 H, dd, *J* 11.0 and 4.7, H^{eq}-1′), 5.45 (1 H, s, PhC*H*), 7.35 (3 H, m, Ph), 7.51 (2 H, m, Ph); δ_C 18.5, 22.0, 23.8, 25.7, 27.5, 29.8, 33.4, 39.9, 43.8, 71.5, 85.2, 102.0, 126.2, 128.2, 128.6, 139.0. (Found: C, 78.6; H, 9.8. $C_{18}H_{26}O_2$ requires C, 78.8; H, 9.6%).

The ^{1}H NMR spectrum was assigned with the aid of 2D-COSY experiments and the structure of **66** was confirmed on the basis of selective NOE experiments. The chemical shift of the benzylidene proton (δ 5.45) confirms[2] that, as expected, the phenyl group occupies an equatorial site. When the benzylidene proton was irradiated, H-1 (δ 3.76) and one of the protons

(δ 3.53) attached to C(1′) showed strong NOE enhancement, establishing that all three of these protons occupy axial sites. An NOE enhancement was also observed for Me-3 when the equatorial proton (δ 4.37) attached to C(1′) was irradiated, indicating that this methyl group is also equatorial. The large coupling (10.5 Hz) between H-1 and H-2 confirms the *trans* ring junction stereochemistry and the value of $J_{H(1)-H(6)}$ (4.4 Hz) confirms that the isopropyl group is axial.

General procedures for redox rearrangement

Method A. The acetal (1.0 mmol), dry hexane (1.5 mL), TBHN (0.05 mol) and the thiol catalyst (0.05 mol) were successively introduced into a dry, argon-filled, two necked 10 mL round-bottomed flask, containing a dry magnetic stirrer bar and fitted with a condenser through which a slow downward flow of argon was maintained. The side neck was closed with a stopper and the flask was immersed in an oil bath that had been pre-heated to 70 °C. Further portions of TBHN (0.05 mmol) were added after 20, 40 and 60 min. After the final addition, the mixture was stirred for a further 1.5 h, allowed to cool and the volatile material was removed by evaporation. The crude product was examined by ^{1}H NMR spectroscopy to determine its composition and estimate the extent of conversion to benzoate esters, before the latter were isolated by flash chromatography using petroleum-diethyl ether eluent (20 : 1).

Method B. The procedure was similar to that for Method A, except that the solvent was octane and a single initial addition of DTBP (0.50 mmol) served as initiator in place of TBHN. The reaction mixture was stirred and heated for 2.5 h in an oil bath maintained at 140 °C.

The characteristics of the product benzoates are described below.

Redox rearrangement of 10

The distribution of products **11**–**14** varied depending on the reaction conditions (see text). From the product mixture obtained at 70 °C, the ester **11** containing only small amounts (*ca.* 1–2%) of the isomers **12**–**14** was isolated as an oil by column chromatography; δ_H 0.90 (3 H, d, *J* 6.8, CH*Me*$_2$), 0.92 (3 H, d, *J* 6.8, CH*Me*$_2$), 1.48 (1 H, m, ring-H), 1.62 (1 H, m, ring-H), 1.65 (3 H, s, Me-1), 1.85 (1 H, m, ring-H), 2.05 (1 H, m, C*H*Me$_2$), 2.13 (1 H, m, ring-H), 2.22 (1 H, m, ring-H), 5.75 (1 H, ddd, *J* 10.3, 2.6 and 0.9, H-2), 6.06 (1 H, ddd, *J* 10.3, 2.6 and 1.2, H-3), 7.41 (2 H, m, Ph), 7.52 (1 H, m, Ph), 8.00 (2 H, m, Ph); δ_C 19.5, 19.7, 22.9, 26.0, 31.7, 34.2, 41.1, 81.0, 128.2, 129.4 131.0, 131.8, 132.4, 132.6, 165.6. (Found: C, 79.2; H, 8.5. $C_{17}H_{22}O_2$ requires C, 79.0; H, 8.6%).

The esters **12** and **13** could not be obtained free from **11** and **14**; they were identified from key features of their NMR spectra by comparison with those of the corresponding acetates.[27] In particular, the absorption at δ 4.47 (dd, *J* 10.8 and 2.8) in the ^{1}H NMR spectrum of the mixture was assigned to H-2 in the ester **12** in which H-2 and H-3 are *trans*. The equivalent absorption for the corresponding acetate appears at δ 4.20 (dd, *J* 10.6 and 2.0).[27a] In the isomeric ester **13** H-2 appears at δ 5.12 (dd, *J* 4.2 and 2.4).

The ester **14** was identified by comparison with the authentic compound prepared by benzoylation of 1-methyl-4-isopropylcyclohex-3-en-1-ol,[20a] itself prepared by treatment of 4-isopropylcyclohex-3-enone[28b] with MeMgI. The alcohol showed δ_H 0.99 (6 H, d, *J* 7.2, CH*Me*$_2$), 1.22 (3 H, s, ring-Me), 1.55 (1 H, m, ring-H), 1.67 (2 H, ring-H), 1.90–2.40 (4 H, m, ring-H), 5.29 (1 H, m, H-3); δ_C 21.4, 21.5, 23.6, 28.1, 34.6, 35.6, 39.8, 68.6, 115.9, 142.8.

Benzoyl chloride (1.78 g, 12.7 mmol) was added to a stirred solution of the alcohol (1.62 g, 10.5 mmol) in pyridine (20 mL), with cooling in an ice–water bath, and the mixture was then stirred overnight at room temperature. Ice-cold water (30 mL) was added and the aqueous phase was extracted with diethyl ether (3 × 30 mL). The ethereal solution was washed successively with dilute HCl, saturated aqueous $NaHCO_3$ and saturated brine, then dried. The solvent was removed by evaporation and the residue was purified by flash chromatography, using petroleum ether (20 : 1) as eluent A final distillation gave the *benzoate* **14** (2.23 g; bp 114 °C/0.05 mmHg) as an oil, containing *ca.* 5% of the corresponding saturated benzoate (that arose from saturated ketone present in the original 4-isopropylcyclohex-3-enone); δ_H 0.99 (6 H, d, *J* 6.9, CH*Me*$_2$), 1.66 (3 H, s, ring-Me), 1.84 (1 H, dddd, *J* 14.0, 8.4, 5.8 and 0.8, ring-H), 2.04 (1 H, m, ring-H), 2.13 (1 H, m, ring-H), 2.21 (1 H, [septet], *J* 6.9, Me$_2$C*H*), 2.34 (1 H, m, ring-H), 2.38 (1 H, ddd, *J* 11.5, 5.7 and 1.5, ring-H), 2.67 (1 H, m, ring-H), 5.32 (1 H, m, H-3), 7.40 (2 H, m, Ph), 7.51 (1 H, m, Ph), 7.97 (2 H, m, Ph); δ_C 21.4, 21.5, 23.6, 24.3, 33.0, 34.7, 37.3, 81.1, 115.3, 128.2, 129.3, 132.0, 132.4, 142.6, 165.9. (Found: C, 78.7; H, 8.8. $C_{17}H_{22}O_2$ requires C, 79.0; H, 8.6%).

The ester **22**,[29a] containing only traces of the isomers **11**–**14**, was isolated as the major product from the rearrangement of partially purified **11** in the presence of 3 mol% 4,4′-methylenebis(2,6-di-*tert*-butylphenol) (see text): Oil, δ_H 0.88 (3 H, d, *J* 6.9, Me), 0.98 (3 H, d, *J* 6.9, Me), 1.50 (1 H, m, ring-H), 1.67 (1 H, m, ring-H), 1.70 (3 H, s, Me-1), 1.83 (1 H, m, ring-H), 2.04 (2 H, m, C*H*Me$_2$ and ring-H), 2.05 (1 H, m, ring-H), 5.45 (1 H, m, H-2), 5.52 (1 H, m, H-3), 7.45 (2 H, m, Ph), 7.51 (1 H, m, Ph), 8.06 (2 H, m, Ph); δ_C 18.1, 20.9, 21.3, 23.2, 26.9, 29.6, 44.1, 72.7, 120.9, 128.3, 129.6, 130.6, 132.7, 139.8, 166.6. These NMR data are consistent with those reported for the corresponding acetate.[29b] (Found: C, 78.8; H, 8.8. $C_{17}H_{22}O_2$ requires C, 79.0; H, 8.6%).

Redox rearrangement of 25

The benzoates **28** and **29** were obtained as an inseparable approximately equimolar mixture; their structures were confirmed by NMR spectroscopy in comparison with the data reported for the known acetates.[27a] Because of the equimolar composition of the mixture it was not possible to assign all the peaks to individual isomers. The mixture (an oil) showed δ_H 0.90 (3 H, d, *J* 6.5, Me-7), 0.95 (3 H, d, *J* 6.5, Me-7), 1.02 (6 H, s, Me-3), 1.40–2.40 (14 H, complex, ring-H), 4.61 (1 H, ddd, *J* 15.8, 8.8 and 6.7 for **28**), 4.96 (1 H, m, $W_{½}$ 9.0 Hz for **29**), 7.42 (4 H, m, Ph), 7.54 (2 H, m, Ph), 8.05 (4 H, m, Ph); δ_C 15.1, 16.0, 17.2, 17.4, 17.8, 17.9, 18.2, 18.9, 20.0, 21.3, 24.1, 24.7, 26.8, 28.2, 28.7, 29.1, 31.0, 34.0, 73.3, 78.1, 128.2(6) and 128.2(9), 129.4(7) and 129.4(9), 130.8 and 131.0, 132.6 (2C), 166.3(5) and 166.3(7). (Found: C, 78.8; H, 8.8. $C_{17}H_{22}O_2$ requires C, 79.0; H, 8.6%).

The benzil bis(acetal) 30

Colourless crystals from methanol, mp 197–200 °C; $[a]_D^{18}$ −5.7 (*c* 1.92, $CHCl_3$); δ_H (carane skeleton numbering) −0.60 (2 H, [q], *J* 8.3, H-6,6′), 0.02 (2 H, [q], *J* 8.3, H-1,1′), 0.48 (2 H, dd, *J* 15.8 and 8.4, H^A-2,2′), 0.51 (2 H, ddd, *J* 15.8, 8.4 and 1.6, H^A-5,5′), 0.62 (6 H, s, 2 Me), 0.68 (6 H, s, 2 Me), 0.70 (6 H, brs, 2 Me), 1.86 (2 H, dd, *J* 15.8 and 8.0, H^B-2,2′), 2.13 (2 H, ddd, *J* 15.8, 7.5 and 3.3, H^B-5,5′), 3.46 (2 H, brs, H-4,4′), 7.22 (6 H, m, Ph), 7.60 (4 H, m, Ph); δ_C 14.6, 18.0, 18.4, 18.7, 23.1, 26.2, 28.2, 30.7, 81.7, 82.2, 111.4, 126.1, 127.0, 128.8, 141.5. (Found: C, 79.2; H, 8.1. $C_{34}H_{42}O_4$ requires C, 79.3; H, 8.2%).

Redox rearrangement of 32

(1*S*,5*R*)-2-Methyl-5-isopropylcyclohex-2-enyl benzoate 34. This compound was isolated from the redox rearrangement of **32** in refluxing octane. Oil, $[a]^{18}_D$ −167.8 (*c* 1.5, $CHCl_3$); δ_H 0.88 (3 H, d, *J* 6.7, CH*Me*$_2$), 0.89 (3 H, d, *J* 6.7, CH*Me*$_2$), 1.50 (2 H, m, C*H*Me$_2$ and ring-H), 1.59 (1 H, m, ring-H), 1.73 (1 H, s, Me-2), 1.75 (1 H, m, ring-H), 2.02 (1 H, d[q], *J* 14.0 and

2.0, ring-H), 2.15 (1 H, m, ring-H), 5.49 (1 H, m, H-1), 5.78 (1 H, m, H-3), 7.44 (2 H, m, Ph), 7.55 (1 H, m, Ph), 8.06 (2 H, m, Ph); δ_C 18.2, 19.4, 19.9, 20.7, 28.9, 31.7, 32.7, 34.9, 71.7, 120.9, 128.5, 129.6 130.8, 131.0, 132.7, 166.5. (Found: C, 78.7; H, 8.9. $C_{17}H_{22}O_2$ requires C, 79.0; H, 8.6%).

The benzoate **35**, in which the pinane skeleton is retained, was tentatively identified from its partial ^{1}H NMR spectrum, in particular from the absorption at δ 5.40 (dd, *J* 9.6 and 5.4) which was assigned to the C*H*OBz group in the ester **35**, by analogy with NMR data reported for the corresponding acetate.[30]

Redox rearrangement of 37

(4*S*)-1-Benzoyloxmethyl-4-isopropylcyclohex-1-ene 38. Oil, $[a]^{18}_D$ −46.5 (*c* 1.95, $CHCl_3$); δ_H 0.90 (3 H, d, *J* 6.7, CH*Me*$_2$), 0.91 (3 H, d, *J* 6.7, CH*Me*$_2$), 1.05–1.40 (3 H, m, ring-H), 1.50 (1 H, [octet], *J* 6.7 C*H*Me$_2$), 1.81 (2 H, m, ring-H), 2.13 (2 H, m. ring-H), 4.71(2 H, m, C*H*$_2$OBz), 5.82 (1 H, m, H-2), 7.44 (2 H, m, Ph), 7.55 (1 H, m, Ph), 8.06 (2 H, m, Ph); δ_C 18.2, 19.6, 19.9, 25.9, 26.7, 28.7, 32.2, 39.8, 69.0, 126.2, 128.3, 129.6, 130.4, 132.7(9), 132.8(1), 166.5. (Found: C, 79.2; H, 8.4. $C_{17}H_{22}O_2$ requires C, 79.0; H, 8.6%).

Redox rearrangement of 42

2-*exo*-Benzoyloxynorbornane 43[31]**.** This ester was not isolated in a pure state; it was identified by spectroscopic comparison with the authentic compound prepared in 97% yield from *exo*-norbornan-2-ol and benzoyl chloride in pyridine, as described for **14**. Oil; δ_H 1.20–1.27 (3 H, m, ring-H), 1.50 (1 H, m, ring-H), 1.54–1.70 (3 H, m, ring-H), 1.84 (1 H, ddd *J* 9.6, 7.1 and 2.4, ring-H), 2.34 (1 H, m, ring-H), 2.45 (1 H, d, *J* 4.9, ring-H), 4.86 (1 H, brd, *J* 6.7, H-1), 7.42 (2 H, m, Ph), 7.54 (1 H, m, Ph), 8.02 (2 H, m, Ph); δ_C 24.3, 28.2, 35.4, 40.0, 41.6, 78.1, 128.2, 129.4, 130.8, 132.7, 166.2.

Redox rearrangement of 44

s-Butyl benzoate[32] **45** was isolated as an oil; δ_H 0.98 (3 H, t, *J* 7.6, Me), 1.34 (3 H, d, *J* 6.3, Me), 1.69 (1 H, ddq, *J* 14.5, 7.6 and 6.3, C*H*^{A}H^{B}Me), 1.75 (1 H, ddq, *J* 14.5, 6.3 and 7.6, CH^A*H*^{B}Me), 5.10 (1 H, [sextet], *J* 6.3, H-2), 7.43 (2 H, m, Ph), 7.55 (1 H, m, Ph), 8.05 (2 H, m, Ph); δ_C 9.7, 19.6, 28.9, 72.9, 128.3, 129.5, 130.9, 132.7, 166.3.

Redox rearrangement of 56

(1*S*,2*S*,3*R*,6*R*)-2-Ethyl-3-methyl-6-isopropylcyclohexyl benzoate 56. Viscous oil, $[a]_D^{25}$ +29.5 (*c* 1.65, $CHCl_3$); δ_H 0.88 (3 H, d, *J* 6.7, CH*Me*$_2$), 0.93 (3 H, d, *J* 6.7, CH*Me*$_2$), 0.99 (3 H, t, *J* 7.5, CH$_2$*Me*), 1.06 (3 H, d, *J* 7.1, Me-3), 1.30 (1 H, m, C*H*Me$_2$), 1.35–1.75 (9 H, complex, ring-H), 5.28 (1 H, [t], *J* 2.8, H-1), 7.45 (2 H, m, Ph), 7.55 (1 H, m, Ph), 8.06 (2 H, m, Ph); δ_C 12.3, 20.9(6), 21.0(3), 21.1, 21.2, 24.7, 27.6, 28.9, 30.3, 42.4, 45.6, 75.7, 128.4, 129.6, 131.0, 132.7, 165.9. (Found: C, 78.9; H, 10.1. $C_{19}H_{28}O_2$ requires C, 79.1; H, 9.8%).

Redox rearrangement of 58

(1*S*,2*S*,3*R*,6*S*)-2-Ethyl-3-methyl-6-isopropylcyclohexyl benzoate 59. Viscous oil, $[a]_D^{25}$ −19.7 (*c* 1.59, $CHCl_3$); δ_H 0.82(9) (3 H, d, *J* 6.9, CH*Me*$_2$), 0.83(2) (3 H, t, *J* 7.5, CH$_2$*Me*), 0.88 (3 H, d, *J* 6.9, CH*Me*$_2$), 0.95 (3 H, d, *J* 6.3, Me-3), 1.00–1.20 (3 H, m, ring-H and C*H*$_2$Me), 1.30–1.52 (4 H, m, ring-H), 1.65–1.80 (3 H, ring-H and C*H*Me$_2$), 5.03 (1 H, [t], *J* 10.3, H-1), 7.45 (2 H, m, Ph), 7.55 (1 H, m, Ph), 8.07 (2 H, m, Ph); δ_C 8.4, 16.2, 19.5, 19.8, 21.2, 22.9, 26.5, 33.1, 34.7, 48.5, 49.3, 75.5, 128.3, 129.7, 130.6, 132.7, 166.2. (Found: C, 79.4; H, 10.1. $C_{19}H_{28}O_2$ requires C, 79.1; H, 9.8%).

Redox rearrangement of 66

The benzoates **68** and **69** were obtained as an inseparable 87 : 13 mixture; their structures were verified by NMR spectroscopy. (Found: C, 78.5; H, 9.7. $C_{18}H_{26}O_2$ requires C, 78.8; H, 9.6%).

(1*S*,2*S*,3*R*,6*S*)-2,3-Dimethyl-6-isopropylcyclohexyl benzoate 67. δ_H 0.91 (3 H, d, *J* 6.7, CH*Me*$_2$), 0.92 (3 H, d, *J* 6.7, CH*Me*$_2$), 1.04 (6 H, d, *J* 7.1, Me-2 and 3), 1.40–2.00 (8 H, complex, C*H*Me$_2$ and ring-H), 5.08 (1 H, dd, *J* 5.2 and 3.1, H-1), 7.44 (2 H, m, Ph), 7.55 (1 H, m, Ph), 8.06 (2 H, m, Ph); δ_C 17.4, 20.7, 21.3, 21.5, 22.8, 27.8, 28.1, 34.3, 38.7, 42.2, 78.5, 128.3, 129.5, 130.9, 132.6, 165.9.

(1*R*,2*R*,5*R*)-1-Benzoyloxymethyl-2-methyl-5-isopropylcyclohexane 68. δ_H 0.88 (3 H, d, *J* 6.7, CH*Me*$_2$), 0.89 (3 H, d, *J* 6.7, CH*Me*$_2$), 1.03 (3 H, d, *J* 7.1, Me-2), 1.42–1.98 (10 H, complex, C*H*Me$_2$ and ring-H), 4.25 (1 H, dd, *J* 10.8 and 1.0, H^A-1′), 4.37 (1 H, dd, *J* 10.8 and 5.2, H^B-1′), 7.43 (2 H, m, Ph), 7.56 (1 H, m, Ph), 8.05 (2 H, m, Ph); δ_C 19.7, 20.5, 20.8, 24.9, 26.3, 28.8, 29.1, 31.9, 38.6, 39.5, 74.2, 126.4, 129.4, 130.6, 132.8, 166.7.

X-Ray crystallography §

Single crystals were mounted on glass fibres and all geometric and intensity data were taken from these samples on a Bruker SMART APEX CCD diffractometer, using graphite-monochromated Mo-Kα radiation (λ = 0.71073 Å). Data reduction and integration were carried out with Bruker SAINT+ software[33] and absorption corrections were applied using the program SADABS.[34] Structures were solved by direct methods and developed using alternating cycles of least-squares refinement and difference-Fourier synthesis. All non-hydrogen atoms were refined anisotropically. Hydrogen atoms were placed in calculated positions and their thermal parameters linked to those of the atoms to which they were attached (riding model). Absolute stereochemistry was not determined in the crystallographic experiments. Structure solution and refinement used the SHELXTL PLUS V6.12 program package.[35]

Crystal data for the benzil bis(acetal) 30. Data collected at 293 K. $C_{34}H_{42}O_4$, *M* = 514.68, orthorhombic, space group $P2_12_12_1$, *a* = 10.6743(7), *b* = 16.4346(10), *c* = 16.6813(10) Å, *U* = 2926.4(3) Å^3, *Z* = 4, *F*(000) = 1112, D_c = 1.168 g cm^{-3}, μ(Mo–K$_\alpha$) = 0.075 mm^{-1}, colourless crystal 0.48 × 0.48 × 0.08 mm^3. Full matrix least-squares refinement on 349 parameters gave *R* = 0.0426 (R_w = 0.1077) for 5908 independent reflections [$I > 2\sigma(I)$] and *R* = 0.0507 (R_w = 0.1136) for all 6887 independent reflections for θ in the range 1.74 to 28.33°. The final electron density map was featureless with the largest peak 0.134 e Å^{-3}.

Crystal data for the benzylidene acetal 56. Data collected at 150 K. $C_{19}H_{28}O_2$, *M* = 288.41, orthorhombic, space group $P2_12_12_1$, *a* = 8.804(3), *b* = 10.274(3), *c* = 18.428(5) Å, *U* = 1666.9(8) Å^3, *Z* = 4, *F*(000) = 632, D_c = 1.149 g cm^{-3}, μ(Mo–K$_\alpha$) = 0.072 mm^{-1}, colourless crystal 0.50 × 0.04 × 0.02 mm^3. Full matrix least-squares refinement on 194 parameters gave *R* = 0.0579 (R_w = 0.1220) for 2927 independent reflections [$I > 2\sigma(I)$] and *R* = 0.0817 (R_w = 0.1329) for all 3899 independent reflections for θ in the range 2.21 to 28.26°. The final electron density map was featureless with the largest peak 0.250 e Å^{-3}.

Crystal data for the benzylidene acetal 58. Data collected at 293 K. $C_{19}H_{28}O_2$, *M* = 288.41, orthorhombic, space group $P2_12_12_1$, *a* = 8.5195(11), *b* = 10.0386(13), *c* = 19.370(2) Å, *U* = 1656.6(4) Å^3, *Z* = 4, *F*(000) = 632, D_c = 1.156 g cm^{-3}, μ(Mo–K$_\alpha$)

§ CCDC reference numbers 216435–216437. See http://www.rsc.org/suppdata/ob/b3/b309060b/ for crystallographic data in .cif or other electronic format.

= 0.073 mm^{-1}, colourless crystal 0.50 × 0.10 × 0.08 mm^3. Full matrix least-squares refinement on 195 parameters gave R = 0.0535 (R_w = 0.1178) for 3275 independent reflections [$I > 2\sigma(I)$] and R = 0.0682 (R_w = 0.1251) for all 3974 independent reflections for θ in the range 2.10 to 28.26°. The final electron density map was featureless with the largest peak 0.171 e $Å^{-3}$.

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