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FAVORSKII REARRANGEMENTS—I

ONE ELECTRON TRANSFER FROM α′-ENOLATE INTERMEDIATES TO $^3O_2$ IN APROTIC, POLAR- PROTIC AND MIXED MEDIA

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Abstract—Evidence for the trapping of α′-enolate intermediates in Favorskii rearrangements by one-electron transfer (ET) to $^3O_2$ is presented. The mechanism of the ET reaction has been elucidated from studies of the extent of ET trapping, compared to H/D exchange. The trapping efficiency (alkene/esters) was found to be dependent on the reaction medium, the pK_a of the α′ C-acid, (a larger pK_a favouring greater ET) and the substrate concentration. Conclusions from this work of relevance to the mechanism of the Favorskii rearrangement are outlined.

INTRODUCTION

The Favorskii rearrangement;[1] (Fr) the reaction of α-halogeno ketones with nucleophilic bases to give rearranged carboxylic acid derivatives, has been studied extensively in the last 25 yr. The mechanism of this rearrangement, and in particular steps towards the postulated symmetrical cyclopropanone intermediate(s), have stimulated much research. Current ideas indicate the products of the rearrangement and the mechanism are solvent dependent. In NaOMe–MeOH an α′-enolate π-participation-ionization leaving group release mechanism has been found to account for the kinetics of the rearrangement of the isomeric ketones; $ArCHClCOCH_3$[2a,b] and $ArCH_2COCH_2Cl$,[2b] and also the $ArCH_2COCHClCH_3$[2c] and $PhCH_2COCHClPh$[2c] systems. The conversion of the α′-enolate to a cyclopropanone intermediate via a delocalised planar oxyallyl intermediate (Aston-Dewar mechanism[2d,e]) was proposed.†[2a,b] With a precursor α-halocyclohexanone, the semi-U[3] requirements of the α′-enolate for the operation of this mechanism, required the presence of a *quasi*-axial leaving group in the TS for substituent release.[4a,b] The formation of an oxyallyl intermediate[2e,f] formed prior to,[1,5] and in equilibrium[5] with cyclopropanone intermediates was proposed to account for the non-stereospecific nature of the rearrangements in polar-protic media.

Product analysis from previous studies of rearrangements occurring in non-polar aprotic media have shown that rearrangements occur with predominant inversion[1,6a,b] at the nucleofugal centre in the precursor α-halogeno ketone. This result was consistent with the mechanism of Loftfield[6c] who proposed that the cyclopropanone intermediate was formed from the α′-enolate by an internal nucleophilic displacement. With a precursor α-halocyclohexanone, the semi-W[3] requirements of the α′-enolate for the operation of this ElcB inversion mechanism required the presence of a *quasi*-equatorial leaving group in the TS for substituent release.[4a,b]

The present research arose, because of the initial findings of another worker[7] which indicated the medium had no effect on the stereospecificity of the rearrangement of ketones **1a** and **2a**. The reactions with NaOMe in both ether and MeOH were found to give the ring contracted 1α- and 2α-esters, **7a** and **8a** respectively, but in different ratios in the two media. A symmetrical mechanism was implicated. The esters arose by both retention (**1a**) and inversion (**2a**) of configuration at C-3 in the media. It was important to investigate this finding, as in aprotic media, if the usual[8a,b] inversion mechanism was accepted, the results could only be rationalised, if reaction of **1a** occurred via **2a**. (i.e. equilibration occurred at the α-enolate). Also the Δ[1]α′-enolate from **2a** would necessarily have to react via an A-ring boat conformation (for the semi-W requirement).

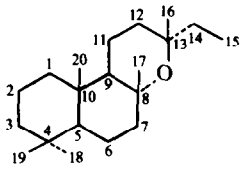
The second reason for the present work was to clarify the results of House,[4b] relating to the rearrangement of 9-chloro-*trans*-1-decalone (axial Cl) induced by NaOMe in aprotic media. This rearrangement was considered to proceed via the intermediacy of the α′-enolate to give a cyclopropanone intermediate by a concerted inversion mechanism. If the ground state semi-U[3] arrangement of the α′-enolate is maintained throughout the release mechanism, the rearrangement of this compound requires a retention mechanism[3,5] at the nucleofugal centre, if the mechanism is an internal displacement as visualised.

No systematic study of the stereochemical requirements of the leaving group for rearrangements induced by alkoxides in different media, and proceeding by an established symmetrical mechanism has appeared. By establishing the mechanism, it was hoped that previous differing interpretations of the stereochemical requirements in different media could be rationalised.[4b,5]

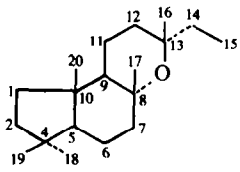
The ketones **1a**, **1b**, **2a**, **2b**, **4a**, **4b**, **4c** and **5a** were prepared.‡ These ketones had the necessary structural features for an examination of the symmetrical mechanism, i.e. (a) potential reaction *via* isomeric α′-enolate intermediates and (b) leaving groups of defined stereochemistry, but had features (4β- and 10β-Me's) which would suppress epoxy-ether formation (the principle side reaction of α-bromocyclohexanones).[9] As well, in order to clarify the previous results[7] for **1a** and **2a**, the rearrangements of ketones **3a** and **6a** were also studied.

†A planar dipolar-like transition state (TS) for release, with disrotation accompanying completion of release and leading directly to the cyclopropanone was initially,[2a,b] also proposed.

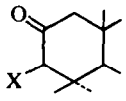
‡The synthesis of starting ketones will be reported in full elsewhere. The leaving group configuration and orientation and A-ring conformation of each ketone was established by spectroscopic and chemical techniques and will be discussed more fully elsewhere (see Tables 4A and 4B for spectroscopic data).



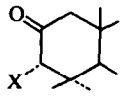
8,13-epoxylabdane



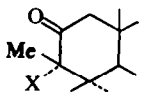
8,13-epoxy-3-norlabdane



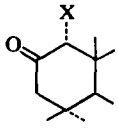
1a: X = Br
b: X = Cl
c: X = H
d: X = Me



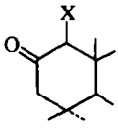
2a: X = Br
b: X = Cl
c: X = Me



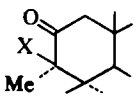
3a: X = Br
b: X = Me



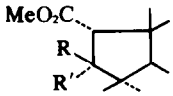
4a: X = OMs
b: X = OTs
c: X = Br
d: X = OMe
e: X = OAc
f: X = OH



5a: X = OMs
b: X = OAc
c: X = OH



6a: X = Br
b: X = OH



7a: R = R' = H
b: R = H, R' = D
c: R = Me, R' = H

These ketones contain leaving groups of axial and equatorial orientation, respectively, at non-epimerisable centres.

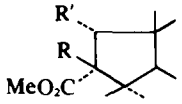
To aid the mechanistic analysis of the Fr, it was hoped side reactions may occur via key intermediates, e.g. *a'*-enolate→*α'*-enol→*α*-methoxyketone[10,11] (in NaOMe–MeOH). Mechanistic analysis of the rearrangements is reported in this paper and following papers in the series.[11]

RESULTS AND DISCUSSION

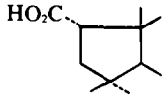
The Fr of **5a** in 0·05 M NaOMe–MeOH gave a low yield of alkene **13a**† amongst other products. As no attempt was made to exclude O_2, it was suspected this may be the source of the alkene. Thus, when the reactions of **1a** and **3a** with NaOMe in DME–MeOH, were performed in an O_2 atmosphere, alkenes **13a** and **13b**,[12] respectively, were found in the products. Subsequently it was found that **1b**, **2a**, **2b**, **4a**, **4b** and **4c** also gave alkene **13a** in different media with O_2 (necessarily present in the $^3\Sigma_g$ state[13]).

Ring contracted alkenes have not previously been detected during studies of the Fr. However both thermal[14] and photochemical[14f,g,15] decarbonylation of cyclopropanones (or proposed cyclopropanone intermediates) yield alkenes. In the present work, participation of an intermediate cyclopropanone in the above manner was eliminated, by observing alkene formation in the dark at room temperature and below.

†This alkene was characterised by comparison with authentic samples prepared by several unambiguous routes using A-nor derivatives as precursors.[17]



8a: R = R' = H
b: R = H, R' = D
c: R = Me, R' = H



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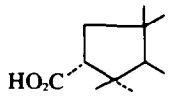

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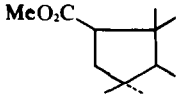

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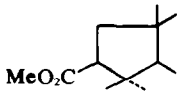

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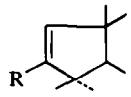
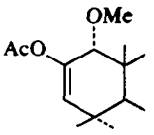


13a: R = H
b: R = Me
c: R = D



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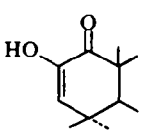

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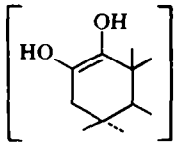


16

Product analysis of the reactions of **4a** and **5a** with NaOMe in mixed media, with and without O_2, established that O_2 was trapping a Favorskii intermediate, as only esters were formed in the absence of O_2. With the knowledge that O_2 can react in both radical and ET reactions,[16] data was collected and experiments devised, to indicate the trapping point, the function of O_2, and the mechanism of the reaction. Since O_2 is known to react with enolate anions,[18] both α and α'-enolates were considered as trapping points. As well, the postulated[2d,e] oxyallyl intermediate was also considered. It was assumed O_2 had a primary function as an oxidant in the basic conditions of the Fr.

In order to investigate whether O_2 was a specific one-electron oxidant, the more efficient,[19] base stable one-electron acceptors; nitrobenzene[20] m-dinitrobenzene[18a,20a] and 2 - chloro - 2 - nitropropane[18c] were substituted. With **1a** or **1b** as substrate, and with a parallel blank experiment, Fr products but no alkene was formed in Favorskii conditions with degassed solvents in an O_2-free dry N_2 atmosphere. These results showed that the alkene was not formed from an α or α'-alkanoyl radical or derived radical species. Thus O_2 was a specific oxidant.

A. *Elimination of the α-enolate as the trapping point*

The occurrence of a prior α-enolate equilibrium on the pathway could be detected from spectral analysis of the esters formed in deuterated media. The results for **4a** and **5a** are given in Table 1. A structural assignment for one ester was made by application of the Karplus equation, ($J_{1,2}$ v $\phi_{1,2}$) used in an approximate manner[21] on the non-deuterated analogue, **7a**. For **7a**, the 1β-H formed a quartet, with a bandwidth of 9·1 Hz (Table 2). The d_1 species had an AX pattern. (J 8 Hz, Table 1). Therefore one coupling of small magnitude was implicated for **7a**. Only the 1α- and 2β-substituents have couplings close to zero when the more favoured β-envelope or half-chair conformations[21] (or between these basic forms) are considered, i.e. the *trans* 1β, 2α-coupling. As the 2β-configuration (Table 2) for the ester was ruled out by synthesis,[11] the d_1 species (J 8 Hz) was equated with a 1α-ester configuration with a 1β, 2β H,H-coupling. This coupling was consistent with the 1β,2β-couplings of various 2α-deuterated 1α-A-nor derivatives.[17]

A structural assignment for the second ester was also made from Table 2. In the non-deuterated analogue, **8a**, the couplings for the 2β-H indicated either a 1β or 2α-ester configuration. As the 1β-configuration (Table 2) was ruled out by synthesis,[11] a 2α-configuration was established. The assignment of the d_1 species of **8a** (J 7 Hz, Table 1) to **8b**, i.e. 1β,2β-coupling, was consistent with the 1β,2β-couplings of other 1α-deuterated 2α-A-nor derivatives.[17] Assignment from Table 2 was not unambiguous. Both 1α/1β- and 2α/2β-ester pairs were related by equilibration experiments.[11]

These results showed little 1β-D substitution† had occurred in both esters, and therefore ruled out a prior α-enolate equilibrium for **4a** or **5a** (assuming no prerate internal return). Thus the α-enolate could be eliminated as the trapping point for alkene synthesis.

Alkene formation from **3a**. The formation of alkene **13b**, from a ketone where equilibration via an α-enolate is blocked by methyl substitution, confirmed the results obtained above.

B. *Investigation of the α'-enolate as the trapping point*

The trapping modes considered at this point were, (a) ET before leaving group release and (b) ET synchronously with leaving group release.

ET before leaving group release. This mode of trapping would be expected to form an α-ketohydroperoxide.[22] However this mode could be ruled out from the kinetics of the ET process (*vide infra*). As well, a reasonable mechanism[22] could not be established for alkene formation from an α-ketohydroperoxide.

Before investigating trapping by mode (b) from the α'-enolate, it was necessary to eliminate the oxyallyl intermediate as the trapping point. This species could possibly act as a weak donor in an ET reaction with O_2, and then collapse to alkene (via **3**, scheme 3).

Elimination of the oxyallyl intermediate as the trapping point. A symmetrical‡ Fr mechanism for **4a** and **5a** was deuterated media (Table 1). This was indicated from the similar deuterium abundances for the two esters, and by the common coupling assignments (vide supra) for the d_1 esters **7b** (2α-D) and **8b** (1α-D).§ In these conditions ketone **4a** had a low trapping efficiency (alkene/esters) in the presence of O_2. Symmetrical intermediates for the rear-

†Lack of significant 1β-D and 2β-D in the 1α- and 2α-esters, respectively, also indicated that these esters were formed under kinetic control in normal Favorskii conditions (a necessary requirement for mechanistic studies).

‡Proceeds via a cyclopropanone intermediate and/or equivalent.[11]

§This stereochemistry indicated that ring opening had occurred with retention of configuration (SE_i). A steric preference is the favoured explanation.[23]

Table 1. Mass spectral and PMR data of esters formed in deuterated media with NaOMe.

Ketone	Ester analysed	MS data	PMR data (carbinol proton)
[a]	1α	24%d_0, 76%d_1	2.63 δ (sh.d,1H); J 8.0 Hz
	2α	26%d_0, 74%d_1	2.82 (br.d,~1H); 7.0
 [b]	1α	15%d_0,69%d_1,16%d_2	2.63 (sh.d,~1H); 8.0
	2α	15%d_0,67%d_1,18%d_2	2.82 (br.d,1H); 7.0

[a] in DME-MeOD (10:1, v/v) in an O_2 atmosphere. A 7.5% yield of deuterated alkene was also obtained. This was entirely d_0 species.

[b] in DME-MeOD (10:1) in a N_2 atmosphere.

Table 2. Coupling and configurational assignments for Favorskii esters

Substituent	Configuration	J Hz (carbinol proton)	H-Configuration	Conformation C_s^{α}	Conformation C_2	Conformation C_s^{β}
				$\phi^*_{1,2}(J_{1,2})$	$\phi_{1,2}(J_{1,2})$	$\phi_{1,2}(J_{1,2})$
1α	q. $\lvert J_{AX} + J_{BX}\rvert$ 9.1 [a] (ABX)	1β,2α	120° (2.1 Hz)	108±2 (0.3–0.8)	96±4 (~0.3–0.8)	
		1β,2β	0 (8.2)	14±3 (7.5–7.9)	29±4 (5.7–6.7)	
2α	q. J_{AX} 7.0, J_{MX} 11.6 [b] (AMX)	1α,2β	120 (2.1)	134±4 (3.7–5.0)	148±4 (5.9–7.1)	
		1β,2β	0 (8.2)	14±3 (7.5–7.9)	29±4 (5.7–6.7)	
1β	q. J_{AX} 8.0, J_{MX} 11.3 [b] (AMX)					
2β	q. J_{AX} 11.2, J_{MX} 2.6 [a] (AMX)					

[a] in $CDCl_3$

[b] in $CDCl_3$ with $Eu(DPM)_3$ addition

* The validity of these angles as obtained from Dreiding models has been questioned by Altona, but as only configurational data are being obtained, this table, although approximate has been retained. See C. Altona, Conformational Analysis, G. Chiurdoglu, Ed., Academic Press, N.Y. (1971) p.9

rangement of **1a** (reaction *via* an isomeric α′-enolate intermediate) were also established by formation of both 1α- and 2α-esters in different media.[7,11]

A parallel experiment in the presence of O_2 was conducted with ketones **1a** and **4b**. A higher trapping efficiency resulted for **1a** (expt a, Table 3). Both ketones undergo Fr via symmetrical intermediates in these conditions (**4b**, by analogy with **4a**) to give the 1α- and 2α-esters in the same ratio. This result is consistent with a common Fr mechanism[11] for **1a** and **4b**. If this mechanism occurred via oxyallyl, the same trapping efficiency would be expected, if trapping occurred at this point. Also, a comparison of both donor abilities and the thermodynamics of the ET process would favour trapping at the α′-enolate (formed prior to oxyallyl) (*vide infra*).

α′-Enolate as trapping point

ET synchronous with leaving group release. Previous results indicated the trapping efficiency was a function of the α′-enolate. Trapping by mode (b) above for the α′-enolate was therefore considered. With such an ET mode, the influence of the α′-enolate on the trapping efficiency is maintained (*vide infra*).

Introduction

The rates of ET to O_2 in DMSO–t-BuOH 80% (v/v) of the carbanions and enolates studied by Russell, depended on the pK_a values of their conjugate carbon acids.[18a] The acids could be placed into three classes: (I) the weakly acidic hydrocarbons (e.g. triphenylmethane, pK_a 28–33). (II) monoketones (e.g. acetophenone, pK_a 19) and (III) β-keto esters (e.g. ethyl acetoacetate, pK_a 11),[24] the carbanions from class 1 acids being the most reactive. The ease of ET thus depended on the relative stability of the anion and the corresponding radical.[25]

Alkylphenone autoxidations in the above medium, were catalysed[18a] (or inferred[25a]) by nitroaromatics, which showed (if Scheme 1 is operative for the uncatalyzed reaction[18a]) that $k_e[O_2] < k_d$.[18b] For α - d - triphenylmethane however, there was no nitroaromatic catalysis, and the rate of ionization controlled the rate of ET to O_2. In this medium in fact, $k_e[O_2] > k_h$.[26] (i.e. ET was near diffusion controlled. However the reaction medium was found to have a pronounced influence on the rate of ET to O_2, e.g. triphenylmethide anion had a low trapping efficiency ($k_e[O_2]/k_d$) in t-BuOD,[20b] a solvent which favours tight ion-pairs.

Table 3. Favorskii rearrangements in the presence of O_2

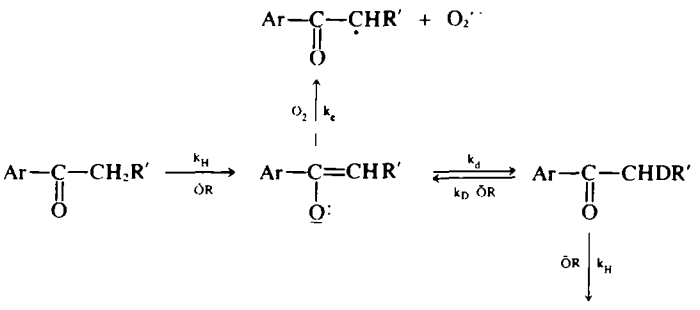
Experiment	Ketone	Substrate conc M	Reaction conditions[a]	Product yields %[b] Acid[c] 9	Ester 7a	Acid[c] 10	Ester 8a	Alkene 13a	Relative yields %[b] Alkene	Fr products
(a)	1a	0.057	DME – 2MMeŌ/MeOH (9:1, v/v)	–	19	–	9	18[d]	35	65
	4b	0.057		–	45	–	22	6	6	94
(b)	1a	0.057	DME–2MMeŌ/MeOH (9:1, v/v)	–	13.5	–	6	13[d]	35	65
	1b	0.057		–	9	–	5	8[d]	32.5	67.5
(c)	4a	0.055	DME–dry NaOMe[e]	9	7	7	7	13.5	27	73[g]
	4b	0.055	HMPT – dry NaOMe[e]	3	–	6[f]	–	31	73.5	26.5[g]
(d)	1c	0.013	E – dry NaOMe[e]	–	22.5	–	8.5	27	42[h]	58
	4c	0.013	DME – dry NaOMe[e]	–	50	–	35.5	(trace < 10%)		>91%

[a] Parallel experiments at room temperature. [b] Yields from weights of chromatographic (Plc) fractions.

[c] Favorskii acids were derived from the esters by O-alkyl-fission. [d] There are considerable losses at the α-enolate in the presence of O_2 only. These acidic products were not investigated but are not Favorskii acids (tlc).

[e] Heterogeneous suspensions. [f] May contain some 1β-CO_2H.

[g] Reaction time only affects relative yields of esters/acids. [h] Acid fraction not analysed (ET figure may be high).



Scheme 1.

Studies of the relative trapping efficiencies ($k_r[O_2]/k_d$) of α'-enolate intermediates

1. *Δ^2-Enolates with substituents of different leaving ability.* In order to determine if the leaving ability of substituents was effecting the ET rate, experiments were conducted with **4a** and **4d** (only the former having a good leaving group) to compare the trapping efficiencies of their α'-enolates. **4a** and **4d** were chosen because (a) enolisation occurred only towards the α'-enolate for both ketones (**4d** forming enol acetate **14**) and (b) the pK_a's of their α' C-acids would be similar, because of similar inductive, steric and medium effects. The structure of the primary intermediate resulting from ET could be deduced from the change in the ET rate, as gauged from the relative trapping efficiencies of the α'-enolates of **4a** and **4d**. For a meaningful comparison of the results, experiments were conducted under parallel conditions, (medium, substrate concentration, base), so that the indicated trapping efficiencies would not be due to the different enolate nature.[20b]

The 1α-axial assignment for the substituents in **4a** and **4d** followed from the spectral results (Table 4A). The axial

Table 4A. Physical properties of ketones

Ketone	mp°C	IR (CCl_4) cm^{-1} [a]			CD(C=O n→π*)							
		ν(C=O) (ε_a)	Δν(C=O)	Orientation	λnm[b]	Δλnm	Orientation[27]	Δε	ΔΔε	Octant or Antioctant[27,30]	Solvent[c]	Fine Structure[d]
1c	92-94	1712 (352)			300			+1.30			H	S
					297			+1.51			D	M
					293			+1.56			M	O
1a[7]	171-172	1729	+17	eq[27]	298	+5	eq	+1.19	-0.37		M	O
2a[7]	90	1709	-3	ax[27]	309	+15	ax	+10.30	+8.74	O_{ax}	M	O
4a	100	1730(297)	+18		310	+10	ax	+2.53	+1.23		H	W
					307	+14	ax	+2.43	+0.87		M	O
5a	160	1736(400)	+24		295	-5	eq	+2.44	+1.14		H	S
					294	+1	eq	+2.33	+0.77		M	W
4b	115	1729(300)	+17		310	+10		+2.58	+1.28		H	O
					305	+12		+2.40	+0.84		M	O
4c	105	1718(253),1723(247)	+6,+11		320	+20	ax	-4.33	-5.63	O_{ax}	H	M
					309	+16	ax	-3.84	-5.40	O_{ax}	M	O
4d	60	1723(352)	+11		315	+22		+2.34	+0.78		M	O
4e	143	1732(215)	+20		307	+7	ax	+3.17	+1.87	AO_{ax}	H	MS
					305	+12	ax	+3.16	+1.60	AO_{ax}	M	O
5b	88.5-89	1731	+19		290	-7	eq	+2.02	+0.51		D	M
4f	128	1720(3617 free OH)		ax[29]	307	+7	ax	+1.68	+0.38		H	O
					306	+13	ax	+1.60	+0.04		M	O
5c	122-122.5	1709(3462 bonded OH)	158(ΔνOH)[28]	eq[29]		-9[g]	eq					
1d	114-115	1711(547)			296			+1.38			M	O
2c	liq(bp100°/0.2mm)	f			299			+2.19			CH[e]	MS
3a	94-98	1713(475)	+2	ax[27]	314	+18	ax	+7.25	+5.87	O_{ax}	M	O
6a	148-150	1726(279)	+15	eq[27]	296			+3.21			M	O

[a] Recorded in a 0.5 mm cell, hydrogen bonding studies: in a variable path length cell (~ 2.2 mm), c. ε 0.005 M.

[b] Principal CD maxima only are shown. [c] M. MeOH; H. hexane; CH. cyclohexane; D. dioxane.

[d] Fine structure; O, none; W, weak; M, medium; S, strong. [e] Performed at the University of Canterbury.

[f] The value was taken as 1711 cm^{-1}. This ketone was unstable, epimerising readily to 1d

[g] a^{300}_{260} + 92M (ORD), cf 1d, a^{309}_{267} +64M (ORD).

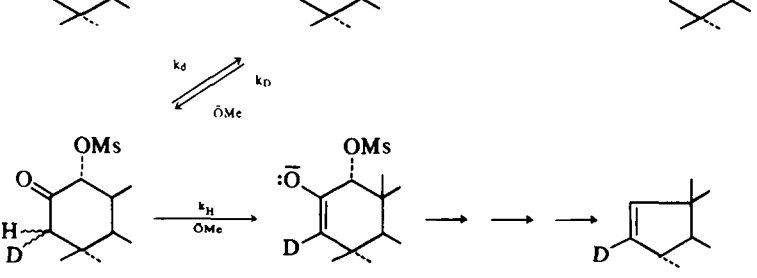
Table 4B. Physical properties of ketones

Ketone	PMR data: Carbinol proton (δ, J Hz)	PMR data: $-CH_2-C=O$	PMR data: $CH_3-\dot{C}-Br$	Analyses: Found % C H	Mol. Formulae	Analyses: Requires % C H
1a[7]	d. 4.63, J 1	H_A 2.67, H_B 2.17, J_{AB} 12		62.3; 8.8; 20.6(Br)	$C_{20}H_{33}O_2Br$	62.3; 8.6; 20.9(Br)
2a[7]	d. 3.97, J 2	H_A 3.03, H_B 2.24, J_{AB} 12		62.5; 8.5; 21.1(Br)		
3a	-	H_A 3.26, H_B 2.33, J_{AB} 12.8	s. 1.77	63.3; 9.0; 19.8(Br)	$C_{21}H_{35}O_2Br$	63.2; 8.8; 20.0(Br)
6a	-	s. 2.47	s. 2.00	63.45; 9.0; 19.8(Br)		
4a	s. 4.32	H_A 2.78, H_B 2.07, J_{AB} 13		63.2; 8.8	$C_{21}H_{36}O_5S$	63.0; 9.1
4b	s. 4.04	H_A 2.75, H_B 1.91, J_{AB} 12.6		68.3; 8.6	$C_{27}H_{40}O_5S$	68.0; 8.5
4c	d. 3.99, J 2	H_A 3.28, H_B 2.03, J_{AB} 14		62.3; 8.5	$C_{20}H_{33}O_2Br$	62.3; 8.6
5a	s. 4.95	H_A 2.42, H_B 2.20, J_{AB} 12.5		63.1; 9.2	$C_{21}H_{36}O_5S$	63.0; 9.1
1b	d. 4.38 J 1	H_A 2.59, H_B 2.16, J_{AB} 12		$(M-15)^+$ 325 (MS)		
2b	d. 3.72, J 1.5	H_A 2.79, H_B 2.19, J_{AB} 12.5		$(M-15)^+$ 325 (MS)	$C_{20}H_{33}O_2Cl$	(MS) Cl^{35}; $M^{+\cdot}$ 340

orientation for the OMs group in **4a** was shown by the bathochromic shift[27] in the CD_{max} *cf* **5a**. Confirmatory evidence for this assignment was obtained from the results for the α-ketol **4f** (precursor of **4a**) and the α-ketol acetate **4e**. For **4f** no evidence for intramolecular H-bonding was indicated from dilute solution IR studies. (*cf* **5c**). This indicated a torsional angle ($\phi_{C=O,1\text{-}OH}$) of *ca.* −120°.[29] A 1α-axial assignment for **4e** was shown by the bathochromic shift in the CD_{max} *cf* **5b**, and anti-octant behaviour for the α-OAc group.[17,30] The assignment for **4d** was consistent with the bathochromic CD_{max} shift and anti-octant behaviour for the α-OMe group.[31] As the OH, OMe, OAc and OTs groups have similar $-\Delta G^\circ_x$ values,[32] similar orientations would be expected.

at C-3, to the exclusion of ET; MS 20% d_0, 39% d_1, 41% d_2 species, PMR > CHOMe at δ 3·07 (s, 1H). This indicated a low trapping efficiency for the α′-enolate, i.e. $k_e[O_2] \ll k_d$. However reaction of **4a** with NaOMe in E–MeOH (9:1) or DME–MeOD (10:1) in the presence of O_2, gave a low yield of alkene. In the latter medium, the 7·5% yield of alkene **13a** was entirely d_0 species by MS. This indicated a high trapping efficiency, i.e. $k_e[O_2] \gg k_d$‡ (if Scheme 2 is operative), and ionization to be rate limiting.

2. *Δ¹-enolates.* In DME–MeOD (9:1), ET trapping by O_2 of the α′-enolate derived from ketone **1a**, gave alkene which consisted of 35% d_0 and 65% d_1, species (MS). The d_1 species was assigned structure **13c** by PMR spectral comparison with C-1 deuterated alkene prepared in



Scheme 2.

No reaction was observed† with **4d**, O_2 and NaOMe in either MeOH, diethyl ether (E)–MeOH (9:1) or DME–MeOD (10:1) at room temperature. In the latter medium, recovered **4d** indicated deuterium exchange had occurred

another study.[17] The position of the deuterium atom showed that there was an α-enolate preequilibrium prior to alkene formation, and also that no H/D exchange occurred at C-1 prior to ET, i.e. $k_e[O_2] \gg k_d$. [An interruption experiment to detect H/D exchange at C-1 may have been more conclusive however, as 1β-H abstraction is severely hindered and β-face deuteration of the enolate may also be hindered§].

An increase in the ET rate was also observed for the ketone **3a**. Alkene **13b** was formed in conditions (aprotic and mixed media) were ketone **3b** was recovered unchanged.

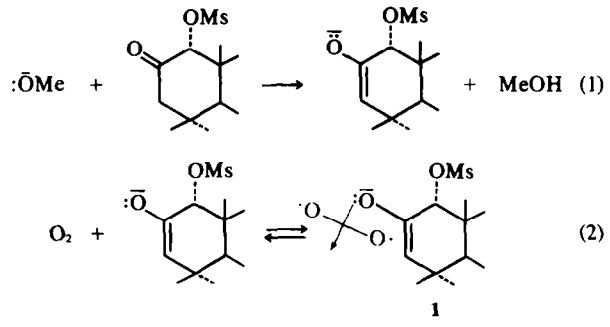
Mechanistic analysis of the ET reaction

(a) *Nature of the intermediate.* The ET rate enhance-

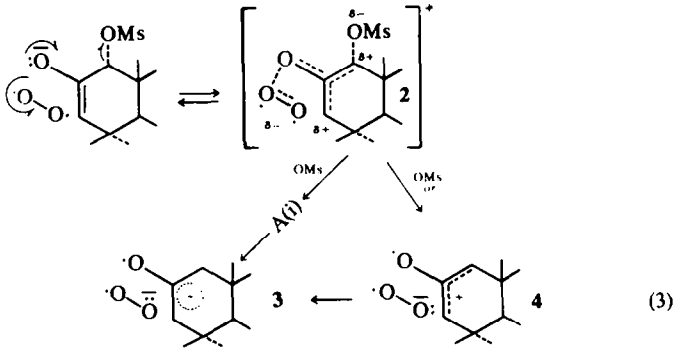
†The unsubstituted 2-oxo compound **1c**, is readily autoxidised. This may reflect a steric problem for ET, due to the crowding of the α-face in the transition state.

‡Even if β-face deuteration of the α′-enolate from **4a** is hindered, the primary isotope effect (k_H vs k_D) would ensure the competitive abstraction of the enolisable 3β-H. Therefore deuterium label in the alkene would result if $k_e[O_2] \leq k_d$.

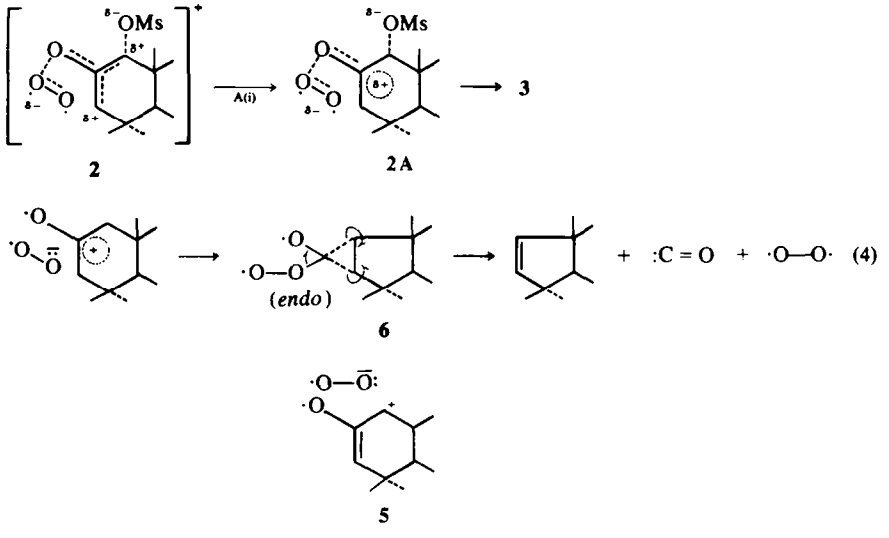
§However hydrogenation (5% Pd/C–MeOH, RT) of the diosphenol **15**, produced a 1:3 ratio of the α-ketols **4f** and **5c** respectively.[17] This result required β-face protonation at C-1 of an enediol (**16**) intermediate.



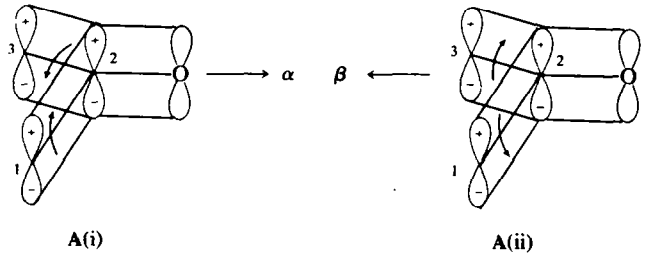
(a) *Release before disrotation*



(b) *Disrotation with release*



(c) *Disrotatory modes*



Scheme 3.

ment observed for **4a** is consistent with a TS involving further electron delocalisation[33a] through the p–π network, relative to the TS for **4d**. The delocalisation is accomplished, if ET is synchronous with the ionization of the leaving group (ETI) (Scheme 3). This ET process forms a radical cation. (*cf* the less stable α'-alkanoyl radical[33b] for enolates).

The cage biradical non-classical ion pair **3** (or less likely **4**) is envisaged to be an intermediate. The requirement of a caged superoxide ion to irreversibly trap the product of ET, was consistent with the absence of nitrobenzene catalysis of the autoxidation. Superoxide cages as intermediates (rather than a radical chain mechanism)[18a] have been proposed previously for the autoxidation of enolate anions.[18a,d] The intermediate 3 is formed by thermal ET[34] from the contact charge-transfer[35] (CT) intermediate **1**, and has [1,3]π-bonding, similar to that of homoaromatic cations,[36] which are stabilised by electron delocalisation. Although **3** and **4** could both explain the subsequent addition at C-2, **3** should be more stable because of increased coulombic attraction, and anionic attack at C-2 before cage separation would be more likely for **3** than **4**. Non-vanishing overlap between donor and acceptor orbital determines the geometry of 1.[37] This geometry must rule out formation of intermediate **5**.

(b) *Stereochemical requirements of the allyl→cyclopropyl transformation.* The nucleophilic[38] superoxide ion initiates the completion of the disrotatory closure for **3** [The allyl-cyclopropyl conversion is a 2π Hückel type[39]]. Initial attack on the less-hindered α-face of the α'-enolate gives the CT complex 1 which then leads via **3** to the *endo*-biradical intermediate **6**. This addition can therefore be considered as a reversal for this [3.1.0] bicyclic system, of the usual cyclopropyl-allyl opening, concerted with the loss of an *endo*-leaving group.[40] The disrotatory mode A(i) leading to **3**, and then to the α-cyclopropyl derivative **6**, is favoured over mode A(ii) (Scheme 3) as β-face steric interactions increase the energy of this geometry (kinetically controlled asymmetric transformation).

Reactions proceeding by thermal ET within a CT complex, followed by collapse of the biradical ion-pair intermediate have ample precedent.[41] These are (2 + 2) cycloadditions. Ring strain would be expected to rule out cycloaddition in this case. The biradical **6** is suggested as an intermediate which is expected to undergo facile homolytic fragmentation[42] as indicated, to give alkene. This reaction is fast because ring strain is relieved.

(c) *Mechanism of the oxidative decarbonylation of cyclopropanones.* Oxidative decarbonylation of *trans* - di - t - butylcyclopropanone[14d] or proposed cyclopropanone intermediates[43] to give alkene, was explained by the intermediacy of an adduct formed by nucleophilic attack at the carbonyl group by either hydroperoxide anion or peracid. Ionic[43a] (HOO^-) or free radical[43b] (RCO_3H) fragmentation of this adduct was postulated to form alkene.

α-Haloketones[43a] could be used as substrates for this reaction. Indeed, when **1a** was treated with alkaline H_2O_2 (30% aq.) in DME or DME–MeOH, alkene **13a** was obtained in preparative yields.[7] The structural similarity of these adducts with intermediate **6** (Scheme 3) supports the mechanism of the ET reaction outlined. However the sole intermediacy of a cyclopropanone[43a] in alkene formation from α-haloketones is disputed.[11]

(d) *Conformational analysis of the ET reaction.* The orientation of the leaving group in the precursor ketone was found to be unimportant for the operation of the ionization mechanism. A semi-U TS (**2**, Scheme 3) (*quasi*-ax leaving group) is required for the effective participation of the α'-alkanoyl radical in the ionization. The favoured conformation of the Δ^2 α'-enolate is 1,2-diplanar[44] with the 1α-x *quasi*-ax and the 1β-x *quasi*-eq while for the $\Delta^1\alpha'$-enolate, the favoured conformation would be either monoplanar, 3β-x *quasi*-eq, 3α-x *quasi*-ax or 1,2-diplanar, 3β-x, 3α-x bisectional. In these conformations torsional strain and non-bonding interactions are minimised.

Reaction of **5a** *via* **4a** could be ruled out, (no prior α-enolate equilibrium, *vide supra*) as could reaction of **1a** via **2a**.[11] Thus the semi-U TS requirement for ETI can only be obtained for **1a** and **5a** if a flexible α'-enolate conformation is adopted.[45] Disrotation accompanying completion of release[2a] cannot explain the ionization for **1a** and **5a** as the unfavourable disrotatory mode A (ii) is required. However this latter mode of release (**2**→**2A**→**3**; Scheme 3) could explain the ionization for **3a** and **4a** as the required A(i) disrotatory mode assists the backside departure of the leaving group.

Factors influencing the trapping efficiency (alkene/esters) (Table 3)

(a) *Dependence on solvent polarity.* The rates of the ET reactions of carbanions are influenced by the type of ion-pair present.[20b,46] (i) In the present work, and increased trapping efficiency was observed in E cf DME (expt d). The α'-enolate must change in nature from contact ion-pairs and aggregates in E, to weaker cation–anion associations in the more polar DME. In this medium solvated contact ion-pairs (and aggregates) may be in equilibrium with a higher percentage (*cf* E) of solvent separated species.[47] Thus ETI was more competitive in E where more negative charge is located on oxygen.[47] (ii) There was an increased trapping efficiency in the more polar solvent HMPT[48] cf DME (expt c). This indicated that the TS for ETI (Scheme 3) was more polar than for enolate substituent release (ESr).

(b) *Dependence on substrate concentration.* An increased trapping efficiency was observed at higher substrate concentration; (i) in DME (*cf* expt c and d) (assuming a minor change in the basicity of the enolate, see below) and (ii) for **1b** in MeOH (0·004 M *cf* 0·025 M). In the latter case, for reaction in 0·7 M NaOMe in MeOH, no trapping was evident at the lower substrate concentration. An increase in the percentage of looser associations of the enolate at lower substrate concentration, must favour reactions of the enolate cf. ETI.

(c) *Dependence on the* pK_a *of the* α' C-*acid.* The position of the α'-enolate influenced the trapping efficiency (expt a). The results were consistent with an increased donor ability[49] (lower ionization potential) of the more basic $\Delta^1\alpha'$-enolate (larger pK_a). The relative pK_a's of the α'C-acids depend on the relative stabilities of the corresponding enolate anions. For steroids (A/B *trans*) Δ^1-enes are less stable than Δ^2-enes.[50] This order of stability should be magnified in the enolates by the presence of the 3-substituents and the 4,4-*gem*-dimethyl group.

(d) Br/Cl *leaving group effect.* Trial experiments with **1a** and **1b** and 0·5 M NaOMe in MeOH at 0° in the presence of O_2, indicated that the reaction rate for **1b** to give esters and alkene, was substantially decreased *cf* **1a**. This indicated that the ETI stage in alkene formation, and the release step in ester formation were at least partially rate-determining for **1b**.[9] An increase in the rate of alkene

formation for **1a** *cf* **1b** was due to the better leaving ability of Br *cf* Cl in the ETI process. In mixed media (expt b), **1b** had only a slightly decreased trapping efficiency *cf* **1a**, consistent with a slightly decreased basicity of the enolate. If the kinetics in MeOH can be translated to mixed media, a similar trapping efficiency is consistent with ionization release mechanisms also operating for ester formation.

CONCLUSIONS

Results from this work relating to the mechanisms of the co-occurring Fr may be summarised.

(a) α'-Enolates are intermediates in *all* media (EIcB).

(b) The variations in the trapping efficiency of the α'-enolate with structure and medium are consistent with a competition between ET and pathways leading to esters.

(c) The mechanism of the ET reaction indicates (with high probability) that the rearrangements induced by NaOMe will occur by α'-enolate π-participation ionization mechanisms[2b,11] in *all* media. α'-Enolate internal nucleophilic displacement mechanisms are thus ruled out.

(d) The ionization mechanism can operate from a ketone with *either* an α-axial or an α-equatorial leaving group. The conformational flexibility of the α'-enolate in this system allows the required semi-U TS to be attained.

EXPERIMENTAL

M.ps are uncorrected. IR spectra were determined with a Perkin-Elmer model 137 or 357 spectrophotometer. CD results were recorded at Westfield College (University of London) by courtesy of Prof. W. Klyne. The PMR spectra (5–10% $CDCl_3$ solns) were determined at 60 mHz with a Varian model T-60, and at 100 mHz with a Varian HA-100 spectrometer. The chemical shift values are expressed in δ values (ppm) relative to a $SiMe_4$ internal standard. Mass Spectra were recorded on a CH-7 mass spectrometer. Isotopic distributions were calculated according to Biemann[51] from M^+, $(M-15)^+$ or $(M-29)^+$ clusters depending upon intensity, with corrections for natural abundance isotopes as taken from the same clusters of the parent undeuterated esters, ketone or alkene. Microchemical analyses were performed by Prof. A. D. Campbell and associates of this department. TLC was used routinely for monitoring reactions and chromatographic separations.

Nomenclature use is according to J. W. Rowe's third revised rules for diterpene nomenclature (1968). The term "labdane" implies the configurations of carbons 5, 8, 9, 10 and 13, specification only being necessary when a deviation from the normal labdane stereochemistry occurs.

A. *Experiments conducted in the absence of* O_2

Solvents. Ethers were dried with Na wire and LAH and distilled under N_2. t-BuOH was distilled from Na. MeOH was spectroscopic grade, dried over 3A molecular sieves. Solvents were degassed by freeze-thaw degassing or passing O_2-free dry N_2 (alkaline pyrogallol) through the solvent by sintered bubbler for 15 min at 0°. Experiments were conducted under N_2. The use of a microhydrogenation apparatus allowed for evacuation and gas entry.

(a) *Experiments with organic one-electron nitroacceptors*

General. Nitrobenzene and *m*-dinitrobenzene were analar materials. 2 - Chloro - 2 - nitropropane was prepared from the potassium salt of 2-nitropropane, according to the method for the preparation of 2 - bromo - 2 - nitropropane.[52] Cl_2 gas was bubbled into the aqueous soln of the K salt at 30° (ice-cooling) with stirring. A heavier layer separated near the completion of the addition. Workup gave 2 - chloro - 2 - nitropropane and unchanged 2-nitropropane. The latter was removed by washing with 4M NaOH, and treatment with NaOMe/MeOH. Evaporation to 20 ml, filtration, E addition, followed by work-up and distillation, gave pure 2 - chloro - 2 - nitropropane. The middle fraction (b.p. 40–45°/20 nm) being used; IR (liq. film) 1550 (NO_2 ass str.), 1395, 1375, 1340 (NO_2 sym str. and CH_3 def.), 1168, 1125, 925, 847 cm^{-1} (skeletal); PMR methyls at δ 2·1 (6H, s). *m*-Dinitrobenzene and 2 - chloro - 2 - nitropropane reacted with NaOMe in mixed media but were stable in MeOH–t-BuOH (4:6) and MeOH respectively. Nitrobenzene was relatively stable in the conditions for Fr in all media, although yellow solns, darkening to orange for experiments in t-BuOH–t-BuOK were noticed.[53] The more powerful oxidants, 1,5 or 1,8-dinitronaphthalene and 1,4,5,8 - tetranitronaphthalene reacted with the base and were insoluble in the media, while nitrosobenzene[20a] was stable only in E (for short periods). With nitrobenzene as acceptor a parallel blank experiment (without acceptor) was always performed.

The following is a typical procedure: A flask containing a solution of **1a** (152 mg, 0·39 mmol), 18 ml of DME and 0·43 ml (0·21 M, 10 molar excess) of nitrobenzene was equilibrated at 20·0 ± 0·5° in a constant temp bath. A flask with a soln of NaOMe (Fisher) in MeOH [NaOMe 825 mg (15·3 mmol) in 4 ml MeOH] was also equilibrated at 20°. 1·5 Ml of this soln was added separately to the flask with the acceptor and to a blank, with a syringe through a rubber septum, and the soln stirred for 20 hr at 20°. Workup gave no indication of alkene in either experiment (TLC), only esters being formed. Similar experiments in 0·7 M NaOMe–MeOH with **1a**, 0·13M t-BuOK–t-BuOH with **1a** or **1b** with concentrations of nitrobenzene from 0·5 M to 2M, and with the acceptors *m*-dinitrobenzene (**1a**, **1b**) and 2-chloro-2-nitropropane (**1a**) indicated only products from Fr (esters or acids).

(b) *Experiment in deuterated media.* Results relevant to this study are listed in Table 1. Methanol-O-d (Koch-Light) was ≥99 atom%D.

A soln of **5a** (98 mg, 0·25 mmol) and NaOMe (260 mg, 4·8 mmol) in 22 ml DME–MeOD (10:1) was stirred for 21 hr at RT. Workup gave 83·6 mg of neutral material which on PLC gave 53·6 mg of deuterated 1α-ester and 20·5 mg of deuterated 2α-ester.

B. *Experiments with* O_2 *in aprotic, protic and mixed media*

General. Solvents were presaturated with dry O_2 by passing the gas through a sintered bubbler into the solvent (with ice-cooling) for at least 15 min. The reactions were performed under O_2 with the use of the microhydrogenation apparatus described previously. For parallel experiments (Table 3) the reaction conditions were kept as similar as possible as regards stirring rate and solvent volumes. This was done to minimise the different behaviour of the α'-enolates towards O_2 as being due to different gas-solvent contact. Agitation was accomplished in isolated experiments with flask shakers, but in parallel experiments (Table 3), magnetic stirring bar stirrers were used. For the latter, room temperature conditions were used as insufficient agitation was obtained using the constant temperature bath with water driven magnetic stirrers. HMPT was dried over molecular sieves (13×) and redistilled under vacuum (b.p. 80°/32 mm) to remove Me_2NH, and stored over molecular sieves.

(a) *The following are typical procedures*

(i) *Fr of* 3α *- bromo -* 3β *- methyl -* 8,13 *- epoxylabdan -* 2 *- one* **3a**. To a soln of 337 mg (0·84 mmol) of **3a** in 25 ml of DME in a standard 100 ml hydrogenation flask wrapped with Al foil (dark conditions), was added a soln of 755 mg (14·0 mmol) of NaOMe in 3 ml MeOH. The flask was shaken for 20 hr at RT. Workup gave 300 mg of neutral material. PLC (H/E, 4:1) gave 4 bands. In order of decreasing R_f they were:

(1) **13b** As an oil, 11·2 mg (4·6%) identical to an authentic sample[12] produced by $SOCl_2$/pyridine on 2α - methyl - 8,13 - epoxy - 3 - norlabdan - 2β - ol; IR (film) 1135, 1120, 1105, 1098, 1080, 1038, 998 (C–O and skeletal), 822 cm^{-1} (R′CH=CR″R‴); PMR methyls at δ 0·84 (t, J 7 Hz), 0·87, 0·88, 0·98, 1·20, 1·31; CH_3–C=CH 1·60 (d, J 1·5 Hz); –CH=C–CH_3 5·63 (d, J 1·5 Hz). (2) **7c**[17] as an oil, 22·3 mg (7·5%). (3) An inseparable mixture of a small amount of **8c**[17] and starting ketone **3a**, 82 mg, and (4) the α-ketol, **6b**, 146 mg (51%) identical to an authentic sample.[12] (PMR, TLC, IR).

Parallel experiments with ketones reacting via isomeric α'-enolate intermediates (ketones **1a** *and* **4b**) *in mixed media* (Table 3). A 2M soln of NaOMe in MeOH was made by dissolving 0·46 g of freshly cut Na in MeOH, and making up to the mark in a 10 ml standard flask. Flask 1 contained 110 mg (0·29 mmol) of **1a**, 3β-bromo-8,13-epoxylabdan-2-one dissolved in 4·5 ml of DME, while flask 2 contained 136 mg (0·29 mmol) of **4b** dissolved in 4·5 ml of DME. The 2 flasks were allowed to equilibrate under a slightly positive O_2 pressure, with stirring. In order to prevent solvent losses evacuation was not performed. 0·5 ml of the 2M base soln was added (1 ml (in 0·01 ml) measuring pipette) to each flask through a B14 joint, and the stoppers quickly replaced (substrate conc. 0·057 M in each flask). The flasks were stirred overnight (slightly positive O_2 pressure applied). Workup into acids and neutrals gave from ketone **1a**, 64·1 mg of neutrals and 44·3 mg of acids. The acid fraction contained no Favorskii acids (**9** and **10**). PLC (H/E, 9:1) of the neutrals gave in order of decreasing R_f (a) **13a**,[54] 14·5 mg (18%); IR (film) 1132, 1098, 1066, 1040 (C–O), 756 cm^{-1} (*cis*-CH=CH–); PMR methyls at δ 0·84 (t, J 7 Hz), 0·92, 0·92, 1·04, 1·20, 1·31; –CH=CH– as an AB system, H_B (H_2) 5·50, H_A(H_1) 5·97 J_{AB} 6 Hz. M^+ 276(MS) (b) ester **7a** 18 mg (19%) and (c) ester **8a**[11] 9 mg (9%). Similarly, the ketone **4b** gave neutrals (84 mg) and acids (14·2 mg). PLC of the neutrals gave the products listed in Table 3. The acids indicated only traces of Favorskii acids. Other parallel experiments are listed in Table 3. In aprotic media, with heterogeneous suspensions of NaOMe, the dry base was added to the solutions of starting ketones. Where Favorskii acids were isolated these were compared with authentic samples prepared by ester hydrolysis.[11]

(b) *Experiment with added nitrobenzene*

In parallel experiments (in the presence and absence of nitrobenzene) **2a** 367 mg (0·95 mmol) and 25 ml of 0·75 M NaOMe in MeOH containing 2 ml of nitrobenzene (0·5 M) gave neutral material containing **13a**, and esters **7a** and **8a**. TLC indicated no difference in relative intensities between alkene and esters in the two experiments.

(c) *α'-Enolate ET trapping vs H/D exchange experiments*

(i) To a soln of **1a** 179 mg (0·46 mmol) in 18 ml of DME and 2 ml of MeOD, was added 415·8 mg (7·7 mmol) of dry NaOMe via a boat adaptor. 60·5 mg of neutrals gave on PLC (H/E, 9:1) 18 mg of alkene **13a** + **13c**, MS *m/e* 276 (35% d_0) *m/e* 277 (65% d_1). PMR $-C_1\underline{H}=C_2D-$ at δ 5·98 s, $-C_1H_A=C_2H_B$ H_B 5·50 (d, J_{AB} 6·0 Hz), and mixed esters **7a** and **8a**.

(ii) To a soln of **4a** 117 mg (0·29 mmol) in 23·1 ml of DME and 2·31 ml of MeOD, was added 312 mg (5·8 mmol) of NaOMe and the mixture was stirred for 22 hr at RT. Workup gave 83 mg of neutrals which on PLC gave 6·1 mg of d_0 alkene **13a** (MS), 50·9 mg of deuterated 1α-ester and 18·9 mg of deuterated 2α ester MS, PMR (Table 1).

(iii) To a soln of 110 mg (0·33 mmol) of **4d**[7] in 25 ml of DME and 2·5 ml of MeOD was added 225 mg (4·2 mmol) of NaOMe, and the soln was stirred for 18 hr at RT. Workup in a two-phase system of 2M HCl and E gave a quantitative recovery of starting material, m.p. 60°. A sample distilled under vacuum for MS indicated 20% d_0, 39% d_1 and 41% d_2 species, (some back exchange had occurred on workup). PMR methyls at δ 0·69, 0·81, 0·87 (t, J 7 Hz), 1·04, 1·18, 1·27; >C$\underline{H}$OMe 3·07 (1H, s); –OC$\underline{H}_3$ 3·24 (3H, s).

Enol acetylation[55] *of* 1α - *methoxy* - 8,13 - *epoxylabdan* - 2 - *one* **4d**

To a soln of 175·5 mg (0·52 mmol) of **4d** in 40 ml of DME under N_2, was added 425 mg of dry t-BuOK (3·8 mmol), and the soln was stirred for 5 hr at RT. The mixture was cooled to −50° and 3 ml of freshly distilled Ac_2O was added. The mixture was brought to RT over 1 hr. Workup by partitioning between E and 100 ml of sat $NaHCO_3$ aq, washing with sat NaCl aq, and drying (Na_2SO_4) gave 177 mg of material which was essentially 1 spot on TLC. PLC gave the enol acetate **16**; IR (film) 1758 (C=O), 1695, 1650 (H$\underline{C}$=C<), 1216 cm^{-1} (acetate C–O); PMR methyls at δ 0·83 (t, J 7 Hz), 0·90, 0·90 1·00, 1·18, 1·28; –O–C(=O)–C$\underline{H}_3$ at 2·10 (3H, s); >C$\underline{H}$OMe 3·20 (1H, s); –OC$\underline{H}_3$, 3·38 (3H, s); $\underline{H}$C=C< 5·15 (1H, s).

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REFERENCES

[1] A. A. Akhrem, T. K. Ustynuk and Yu. A. Titov, *Russ. Chem. Rev.* **39**, 732 (1970).

[2a] F. G. Bordwell and R. G. Scamehorn, *J. Am. Chem. Soc.* **90**, 6751 (1968); [b] F. G. Bordwell, R. G. Scamehorn and W. R. Springer, *Ibid.* **91**, 2087 (1969); [c] F. G. Bordwell and M. W. Carlson, *Ibid.* **92**, 3370 (1970); [d] J. G. Aston and J. D. Newkirk, *Ibid.* **73**, 2900 (1951); A. A. Sacks and J. G. Aston, *Ibid.* **73**, 3902 (1951); [e] J. G. Burr and M. J. S. Dewar, *J. Chem. Soc.* 1201 (1954); [f] B. K. Carpenter, *Ibid.* Perkin (II), 1 (1974).

[3] A. Nickon and N. H. Werstiuk, *J. Am. Chem. Soc.* **89**, 3914 (1967).

[4a] H. O. House and H. W. Thompson, *J. Org. Chem.* **28**, 164 (1963); [b] H. O. House and G. A. Frank, *Ibid.* **30**, 2948 (1965); H. O. House and F. A. Richey, Jr., *Ibid.* **32**, 2151 (1967).

[5] F. G. Bordwell and J. G. Strong, *Ibid.* **38**, 579 (1973).

[6a] G. Stork and I. J. Borowitz, *J. Am. Chem. Soc.* **82**, 4307 (1960); [b] H. O. House and W. F. Gilmore, *Ibid.* **83**, 3980 (1961); [c] R. B. Loftfield, *Ibid.* **73**, 4707 (1951).

[7] K. S. Low, Ph.D Thesis, University of Otago (1971).

[8a] F. G. Bordwell and B. B. Jarvis, *Ibid.* **95**, 3585 (1973); [b] O. S. Tee, J. A. Altmann and K. Yates, *Ibid.* **96**, 3141 (1974).

[9] F. G. Bordwell, R. R. Frame, R. G. Scamehorn, J. G. Strong and S. Meyerson, *Ibid.* **89**, 6704 (1967).

[10] F. G. Bordwell and M. W. Carlson, *Ibid.* **92**, 3377 (1970).

[11] Favorskii Rearrangements II, *Tetrahedron* in press.

[12] L. N. Nixon, Ph.D Thesis, University of Otago (1970).

[13] D. R. Kearns, *Chem. Rev.* **71**, 411 (1971).

[14a] R. G. Carlson and J. H. Bateman, *J. Org. Chem.* **32**, 1608 (1967); [b] R. G. Doerr and P. S. Skell, *J. Am. Chem. Soc.* **89**, 4684 (1967); [c] T. A. Spencer, A. L. Hall and C. F. Von Reyn, *J. Org. Chem.* **33**, 3369 (1968); [d] N. S. Turro, *Accounts of Chem. Res.* **2**, 25 (1969); [e] G. Buchi and B. Egger, *J. Org. Chem.* **36**, 2021 (1971); [f] J. K. Crandall, W. W. Conover, J. B. Komin and W. H. Machleder, *Ibid.* **39**, 1723 (1974); [g] J. F. Pazos, J. G. Pacifici, G. O. Pierson, D. B. Sclove and F. D. Greene, *Ibid.* **39**, 1990 (1974).

[15a] N. J. Turro, P. A. Leermakers, H. R. Wilson, D. C. Neckers, G. W. Byers and G. F. Vesley, *J. Am. Chem. Soc.* **87**, 2613 (1965); [b] L. L. Barber, O. L. Chapman and J. D. Lassila, *Ibid.* **91**, 3664 (1969).

[16a] J. A. Howard, Radical reactions of oxygen, *Free Radicals* (Edited by J. K. Kochi) Vol. 2, p. 3. Wiley, New York (1973); [b] S. Fallab, *Angew. Chem.* Internat. Ed. **6**, 496 (1967).

[17] Unpublished results.

[18a] G. A. Russell, E. G. Janzen, A. G. Bemis, E. J. Geels, A. J. Moye, S. Mak and E. T. Strom, Selective Oxidation Processes in *Adv. Chem. Series* No. 51, p. 112. A.C.S., Washington, DC (1965); [b] G. A. Russell, *Pure Appl. Chem.* **15**, 190 (1967); [c] G. A. Russell and G. Kaupp, *J. Am. Chem. Soc.* **91**, 3851 (1969); [d] H. R. Gersmann, H. J. W. Nieuwenhuis and A. F. Bickel, *Tetrahedron Letters* 1383 (1963).

[19a] M. E. Peover, *Trans. Faraday Soc.* **60**, 479 (1964); [b] M. E. Peover and B. S. White, *Chem. Comm.* 183 (1965); [c] Ref. 18*a*, p. 146.

[20a] G. A. Russell, E. G. Janzen and E. T. Strom, *J. Am. Chem. Soc.* **86**, 1807 (1964); [b] R. D. Guthrie, G. R. Weisman and L. G. Burdon, *Ibid.* **96**, 6955 (1974).

[21] P. K. Grant and M. J. A. McGrath, *Tetrahedron* **26**, 1619 (1970).

[22] F. G. Bordwell and A. C. Knipe, *J. Am. Chem. Soc.* **93**, 3416 (1971).

[23a] P. S. Wharton and A. R. Fritzberg, *J. Org. Chem.* **37**, 1899 (1972); [b] A. Nickon, J. J. Frank, D. F. Covey and Y-i Lin, *J. Am. Chem. Soc.* **96**, 7574 (1974).

[24]H. O. House, *Modern Synthetic Reactions* (2nd Edit), p. 494 W. A. Benjamin (1972).
[25a]G. A. Russell, A. J. Moye and K. Nagpal, *J. Am. Chem. Soc.* **84**, 4154 (1962); [b]G. A. Russell and J. Lokensgard, *Ibid.* **89**, 5059 (1967).
[26]G. A. Russell and A. G. Bemis, *Ibid.* **88**, 5491 (1966).
[27]C. Djerassi, *Optical Rotatory Dispersion*, p. 111. McGraw-Hill, New York (1960).
[28]M. J. A. McGrath, Ph.D Thesis, University of Otago (1968).
[29]L. Joris and P. V. R. Schleyer, *J. Am. Chem. Soc.* **90**, 4599 (1968).
[30a]J. R. Bull and P. R. Enslin, *Tetrahedron* **26**, 1525 (1970); [b]L. Bartlett, D. N. Kirk, W. Klyne, S. R. Wallis, H. Erdtman and S. Thorén, *J. Chem. Soc.* (C), 2678 (1970).
[31]S. S. Stradling and D. S. Tarbell, *J. Org. Chem.* **29**, 1170 (1964).
[32]L. N. Ferguson, *Highlights of Alicyclic Chemistry*, part 1, p. 74. Franklin (1973).
[33a]S. N. Zelenin and M. L. Khidekel, *Russ. Chem. Rev.* **39**, 103 (1970); [b]D. M. Camaioni, H. F. Walter, J. E. Jordan and D. W. Pratt, *J. Am. Chem. Soc.* **95**, 7978 (1973).
[34a]E. M. Kosower, *An Introduction to Physical Organic Chemistry*, p. 179. Wiley, New York (1968); [b]R. Foster, *Organic Charge-Transfer Complexes*, p. 311. Academic Press, London (1969).
[35]R. S. Mulliken and H. Tsubomura, *J. Am. Chem. Soc.* **82**, 5966 (1960).
[36a]S. Winstein, *Carbonium Ions*, Vol. 3, p. 965. Wiley-Interscience, New York (1972); [b]P. R. Story and B. C. Clark, Jr., Ref. 36*a*, p. 1007.
[37]H. Levanon and G. Navon, *J. Phys. Chem.* **73**, 864 (1969).
[38]Specialist Periodical Reports, *Electrochemistry*, Vol. 2, p. 57. Chemistry Society, London (1972).
[39]T. L. Gilchrist and R. C. Storr, *Organic Reactions and Orbital Symmetry*, p. 38. Cambridge University Press (1972).
[40]Ref. 39, p. 52.
[41]Ref. 34*a*, p. 189.
[42]D. H. Gibson and C. H. DePuy, *Chem. Rev.* **74**, 605 (1974).
[43a]J. E. Baldwin and J. H. I. Cardellina, *Chem. Comm.* 558 (1968); [b]J. K. Crandall, W. H. Machleder and S. A. Sojka, *J. Org. Chem.* **38**, 1149 (1973).
[44]E. Toromanoff, *Topics in Stereochemistry*, Vol. 2, p. 1962. Interscience, New York (1967).
[45]V. J. Shiner and J. G. Jewett, *J. Am. Chem. Soc.* **87**, 1383 (1965).
[46]M. Szwarc, *Accounts of Chem. Res.* **5**, 169 (1972).
[47]H. O. House, R. A. Auerbach, M. Gall and N. P. Peet, *J. Org. Chem.* **38**, 514 (1973).
[48]H. Normant, *Russ. Chem. Rev.* **39**, 460 (1970).
[49]Ref. 34*a*, p. 183.
[50]H. B. Henbest, G. D. Meakins and G. W. Wood, *J. Chem. Soc.* 800 (1954).
[51]K. Biemann, *Mass Spectrometry*, p. 204. McGraw-Hill, New York (1962).
[52]E. E. Van Tamelen and G. Van Zyl, *J. Am. Chem. Soc.* **71**, 825 (1949).
[53]R. D. Guthrie and D. P. Wesley, *Ibid.* **92**, 4057 (1970).
[50]H. B. Henbest, G. D. Meakins and G. W. Wood, *J. Chem. Soc.* 800 (1954).
[51]K. Biemann, *Mass spectroscopy*, p. 204. McGraw-Hill, New York (1962).
[52]E. E. Van Tamelen and G. Van Zyl, *J. Am. Chem. Soc.* **71**, 825 (1949).
[53]R. D. Guthrie and D. P. Wesley, *Ibid.* **92**, 4057 (1970).
[54]J. M. Robertson, Ph.D Thesis, University of Otago (1969).
[55]H. O. House, W. L. Roelofs and B. M. Trost, *J. Org. Chem.* **31**, 646 (1966).