and concentrated. Analysis (VPC) of the residue indicated two products formed in 84% yield. The major material (86%) was identical (NMR, VPC collected) with 1-methylcyclohexylnitrile prepared by the procedure of House,[8] while the minor component was identical with 1-carbomethoxycyclohexynitrile prepared from methyl 2-cyano-6-heptenoate.[10]

Aprotic Decomposition of Diazene 2b. In the manner described (vide supra) VPC analysis indicated an overall yield of 90% consisting of *trans*-1,2-dimethylcyclohexylnitrile (**5c**, 46%) [IR (CCl$_4$) 2240 cm^{-1}; NMR (CDCl$_3$) δ 1.08 (3 H, d, J = 8 Hz), 1.34 (3 H, s), and 0.95–2.14 (9 H, m)], *cis*-1,2-dimethylcyclohexylnitrile (**5d**, 17%), identical with a sample prepared from butadiene and tiglic acid,[4b] diastereomeric 2-methyl-1-carbomethoxycyclohexylnitrile (25%) [IR (CCl$_4$) 2245 and 1730 cm^{-1}; NMR (CDCl$_3$) δ 1.04 (3 H, d, J = 6 Hz), 1.15–2.37 (9 H, m), and 3.90 (3 H, s)], and diastereomeric 2-methylcyclohexylnitrile ($\leq$2% **5a** and **5b**), identical with material from the protic decomposition.

Aprotic Decomposition of Diazene 3b. As described (vide supra), a combined yield of 95% was obtained consisting of *trans*-1-methyl-4-*tert*-butylcyclohexylnitrile (53%, **6c**), *cis*-1-methyl-4-*tert*-butylcyclohexylnitrile (17%, **6d**),[7] diastereomeric 1-carbomethoxy-4-*tert*-butylcyclohexylnitrile (23%) [IR (CCl$_4$) 2240 and 1740 cm^{-1}; NMR (CCl$_4$) δ 0.91 (9 H, s), 0.82–2.32 (9 H, m), and 3.91 (3 H, s)], and diastereomeric 4-*tert*-butylcyclohexylnitrile ($\leq$1%, **6a** and **6b**), identical with material from the protic decomposition.

Carbomethoxylation of Diazene 1b. To a mixture of 45 mmol of lithium methoxide (vide supra) and 10.8 g (0.120 mol) of freshly distilled dimethyl carbonate maintained under N$_2$ at 0–5 °C was added dropwise over 25 min 1.95 g (10.0 mmol) of diazene **1b** in 15 mL of DME. After the addition was complete, the solution was allowed to warm to 25 °C, then diluted with 25 mL of H$_2$O and thoroughly extracted with ether, dried, filtered, and concentrated. The residue accounted for an 84% yield (VPC) consisting of cyclohexylnitrile (7%) and 1-carbomethoxycyclohexylnitrile (77%), both spectroscopically (IR and NMR) identical with authentic samples.

Registry No.—**1a**, 61827-29-0; **1b**, 33670-04-1; **2a**, 61827-30-3; **2b**, 33794-84-2; **3a**, 61827-31-4; **3b**, 33670-05-2; **4a**, 61827-32-5; **5a**, 25144-00-7; **5b**, 10479-61-5; **5c**, 61827-33-6; **5d**, 61827-34-7; **6a**, 15619-19-9; **6b**, 15619-18-8; **6c**, 15619-22-4; **6d**, 15619-20-2; methyl carbazate, 6294-89-9; cyclohexanone, 108-94-1; 2-methylcyclohexanone, 583-60-8; 4-*tert*-butylcyclohexanone, 98-53-3; acetone, 67-64-1; *trans*-1-carbomethoxy-4-*tert*-butylcyclohexylnitrite, 61827-35-8; *cis*-1-carbomethoxy-4-*tert*-butylcyclohexylnitrile, 61827-36-9; *trans*-2-methyl-1-carbomethoxycyclohexylnitrile, 61827-37-0; *cis*-2-methyl-1-carbomethoxycyclohexylnitrile, 61827-38-1.

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Rotational Energy Barriers in 1-(3,4,5-Trimethoxyphenyl)benz[*h*]imidazo [1,5-*a*]quinoline and Related Compounds

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During our synthetic investigations on certain benzimidazoquinoline and -isoquinoline systems,[2] it was noted that 1-aryl derivatives of benz[*h*]imidazo[1,5-*a*]quinoline gave rise to temperature-dependent NMR spectra. Hindered rotation of the aryl group about the aryl–C$_1$ bond would account for the observed phenomena.[3a–d] The temperature dependence of the NMR spectra of several of these compounds has now been studied in greater detail.

In the NMR spectrum of 1-(3,4,5-trimethoxyphenyl)-benz[*h*]imidazo[1,5-*a*]quinoline (1) at ambient temperature and above, the three methoxy groups appear as two singlets, a three-proton singlet at 3.79 ppm and a six-proton peak at 3.44 ppm (corresponding to the methoxy groups in the 3 and 5 positions) as shown in Figure 1.[4] The protons on the phenyl ring at the 2 and 6 positions appear as a singlet at 6.50 ppm. As the temperature is lowered the 3- and 5-methoxy groups give rise to two peaks which eventually attain chemical shifts of 2.76 and 4.13 ppm at the lowest temperature obtainable in the deuteriochloroform solvent, −67 °C. At this temperature the peak separation, $\Delta\nu$, is 124 Hz. Likewise, the two phenyl ring protons form two peaks, one at 5.49 ppm, the other buried in the aromatic envelope. Coalescence was observed to occur at −23 ± 2 °C for the peaks of the methoxy groups at the 3 and 5 positions.[5] Of the two sets of signals, those corresponding to the methoxy groups were used for the subsequent line-shape analysis.

Since $\Delta\nu$ in the absence of exchange is important both in the computer and manual calculations, it was desirable to determine whether or not the separation increased significantly at lower temperatures. A plot of $\Delta\nu$ vs. temperature approaches 125 Hz at low temperature, and $\Delta\nu$ was found to be 124.7 Hz at −79 °C in dichloromethane solution. It thus appears that $\Delta\nu$ was within 1 or 2 Hz of its maximum value and an error of a few hertz would have a negligible effect upon the calculations. To avoid residual broadening errors due to rotation of the methoxy groups, the signal at 3.79 ppm was used as a resolution standard. This was found to broaden somewhat as the temperature was lowered when checked against dichloromethane.

A Dreiding model of 1 indicates that complete rotation of the aryl group about the aryl–C$_1$ bond is not allowed. Consequently, in the extreme allowed conformations the 2 and 3 and then the 4 and 5 positions are alternately above and then tilted away from the π-electron cloud of the benz[*h*]quinoline ring system, as in the hexahelicene-like conformations **1a** and **1b**. The model suggests that the benz[*h*]imidazo[1,5-*a*]quinoline ring system is planar, in which case **1a** and **1b** are enantiomeric. Thus the 3- and 5-methoxy groups should give rise to two NMR signals at low temperature. A similar argument can

Table I

Compd	Groups	T_c, °C	$\Delta\nu$, Hz	E_a, kcal/mol	$\Delta H^\ddagger$, kcal/mol	$\Delta S^\ddagger$, eu	$\Delta G^\ddagger$, kcal/mol	Method[a]
1	3,5-CH$_3$O	−23 ± 2	124	10.9 ± 0.3	10.4 ± 0.3	−5.6 ± 1.2	11.8 ± 0.4	1
1	3,5-CH$_3$O	−23 ± 2	124	11.1 ± 0.3	10.6 ± 0.3	−4.3 ± 1.1	11.7 ± 0.4	2
1	3,5-CH$_3$O	−23 ± 2	124				11.8 ± 0.1	3
2	3,5-CH$_3$O	−31 ± 2	89.5	10.6 ± 0.3	10.2 ± 0.3	−5.5 ± 1.1	11.5 ± 0.4	2
2	3,5-CH$_3$O	−31 ± 2	89.5				11.5 ± 0.1	3
3	2,6-H	−29 ± 3	176				11.3 ± 0.1	3

[a] Methods used in data workup: (1) computer line-shape analysis; (2) equations in Experimental Section; (3) Gutowsky–Holm approximation and Eyring equation[3d] at T_c.
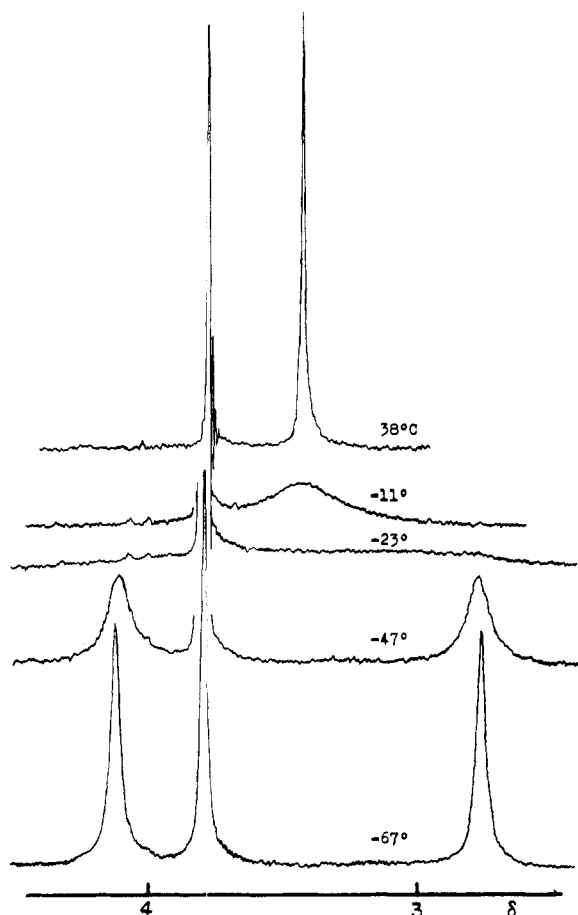

Figure 1. Temperature effects on the NMR spectrum of the methoxy groups of 1.

be made for the 2 and 6 protons. A nonplanar benz[h]imidazo[1,5-a]quinoline system would produce diastereomeric pairs, which could exhibit up to four NMR signals for the 3- and 5-methoxy groups at low temperature. The observed spectra support the planarity indicated by the model.

The rotational energy barrier in 1 was determined by a computer line-shape analysis using a program by D'Agostino[7] and Macomber[8] (similar to DNMR2).[9] Spectra for the methoxy
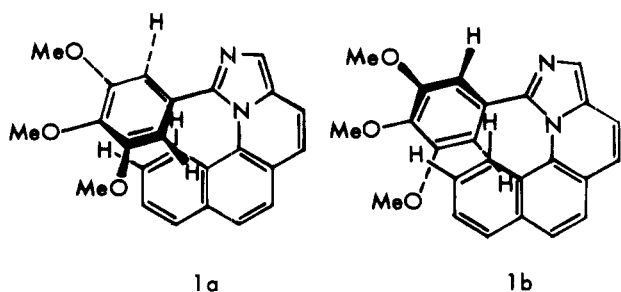

Figure 2. Arrhenius plot for the enantiomerization of 1, computer line-shape analysis.

groups were calculated at various lifetimes and matched to the observed peaks by comparison of the widths at half-height. The natural line width at a given temperature was taken to be that of the 3.79-ppm signal. The matched spectra covered a temperature range of 73 °C. Rate constants were calculated from the appropriate lifetimes and an Arrhenius plot (ln k vs. $1/T$) was constructed as indicated in Figure 2. The activation energy, E_a, was determined to be 10.9 ± 0.3 kcal/mol. The values for the entropy of activation, $\Delta S^\ddagger$, and the free energy of activation, $\Delta G^\ddagger$, from the appropriate equations,[3b] were −5.6 ± 1.2 eu and 11.8 ± 0.4 kcal/mol, respectively.

These results compare favorably with data obtained by less rigorous methods using (a) an Arrhenius plot (see Figure 3) of data derived through manual calculation of lifetimes from approximation equations (Experimental Section) and (b) the Gutowsky–Holm approximation[3c,6] and the Eyring equation[3d] at the coalescence temperature, T_c.[3b] Data derived by the three methods are summarized in Table I.

The good agreement of the data for 1 obtained by the different methods encouraged us to compare 1 with some similar compounds for which computer-derived data were not readily obtainable. An Arrhenius plot for 1-(3,5-dimethoxyphenyl)-benz[h]imidazo[1,5-a]quinoline (2) over a range of 98 °C is shown in Figure 4. The activation energy was determined to be 10.6 ± 0.3 kcal/mol and $\Delta S^\ddagger$ and $\Delta G^\ddagger$ were −5.5 ± 1.1 eu and 11.5 ± 0.4 kcal/mol, respectively. Likewise, for 1-phen-
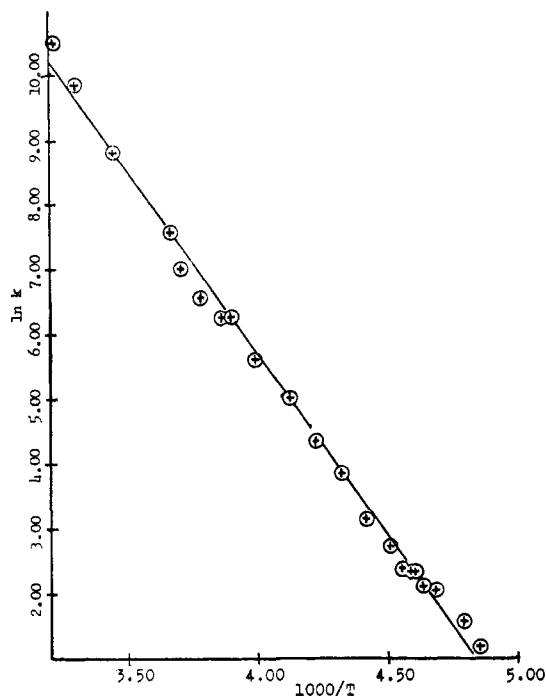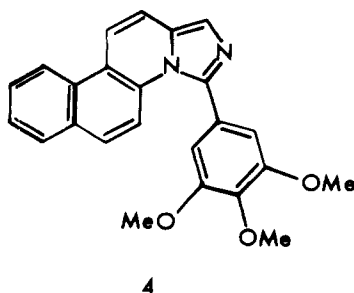
Figure 3. Arrhenius plot for the enantiomerization of **1**, manual calculations.

Figure 4. Arrhenius plot for the enantiomerization of **2**, manual calculations.

ylbenz[h]imidazo[1,5-a]quinoline (**3**), $\Delta G^{\ddagger}$ was determined to be 11.3 ± 0.1 kcal/mol from the Gutowsky–Holm approximation.[6,9] Sample spectral data for **3** are given in Figure 5. In contrast, the spectrum of 1-(3,4,5-trimethoxyphenyl)-benz[f]imidazo[1,5-a]quinoline (**4**) did not show significant

4

broadening of the signal corresponding to the 3- and 5-methoxy groups until −65 °C in deuteriochloroform, indicating a much lower $\Delta G^{\ddagger}$ for this compound.

Comparison of the data for **1, 2**, and **3** summarized in Table I indicates that the π-overlap of the phenyl ring with the benz[h]quinoline ring system must be substantial in the most stable conformation of these compounds, but that complete planarity is sterically precluded. It is likely that, as suggested by the model, the aryl substituent cannot undergo 360° rotation but rather changes conformations only by a rocking motion. This is especially apparent from the data for **3** where removal of the methoxy groups from the phenyl ring caused only a slight decrease in the free energy of activation. The transition state for this process is that conformation in which the phenyl ring is perpendicular to the tetracyclic portion of the molecule.

Experimental Section

Compounds **1, 3** and **4** were prepared as described previously.[2] Compound **2**, 1-(3,5-dimethoxyphenyl)benz[h]imidazo[1,5-a]quinoline, mp 152–154 °C (2-propanol) [Anal. Calcd for $C_{23}H_{18}N_2O_2$ (354.39): C, 77.95; H, 5.12; N, 7.91. Found: C, 77.79; H, 5.17; N, 7.65] was obtained through $POCl_3$-induced ring closure of N-(2-benz[h]-quinolylmethyl)-3,5-dimethoxybenzamide, mp 150–152 °C (aqueous EtOH) [Anal. Calcd for $C_{23}H_{20}N_2O_3$ (372.41): C, 74.17; H, 5.41; N, 7.52. Found: C, 74.17; H, 5.55; N, 7.44].
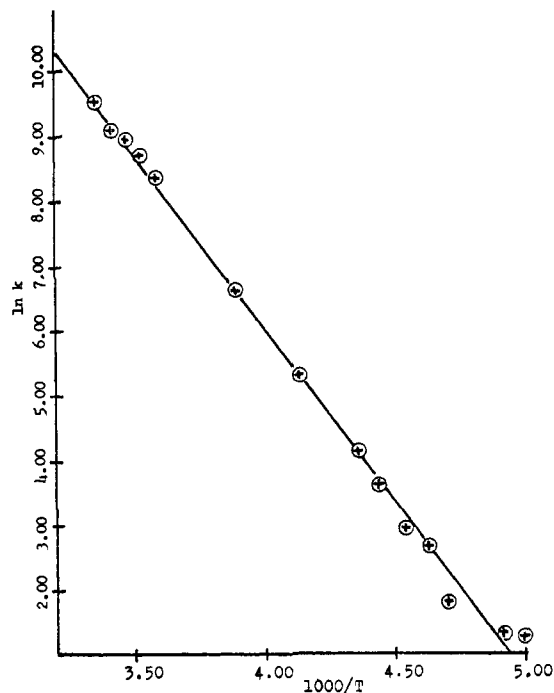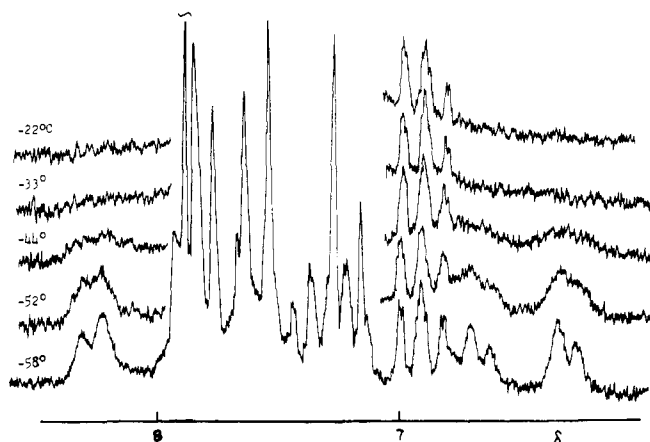

Figure 5. Temperature effects on the NMR spectrum of **3**.

Analytically pure sample was dissolved in $CDCl_3$ or CD_3COCD_3 (**2** only), concentration ca. 5–10%, and filtered into a precision NMR tube. NMR spectra were recorded on a Bruker HFX-10 90-MHz spectrometer equipped with a temperature controller. Frequency sweep was employed using 2–5% Me_4Si as an internal standard and chemical shifts are reported in δ units. A sweep width of 10 Hz/cm was normally employed. For **1**, smaller sweep widths were also used at the low and high temperature extremes. Power levels were carefully adjusted to avoid saturation effects. The probe temperatures was calibrated using methanol as a thermometer liquid and the van Geet equation modified for use at 90 MHz:

$$T\ (K) = 406.0 - 0.367\Delta\nu_T - 28.18\ (\Delta\nu_T/100)^2$$

where $\Delta\nu_T = \nu_{OH} - \nu_{CH_3}$ in Hz

The values obtained using this equation conformed closely to values obtained from a methanol calibration curve supplied with the instrument.

Full widths at half-heights were used for peak widths. The value for the lifetime, τ^*, at a given temperature was determined from the appropriate equation or, for **1**, by matching peak widths with those from computer-derived spectra. The computer program used was that of D'Agostino[7] and Macomber[8] for the interconversion of two A_n spin

systems. Equations used in the manual calculations were as follows: [3c]

$$\text{above } T_c \text{ (where } 1/\tau^* \gg 2\pi\Delta\nu): \quad 1/\tau^* = \pi(\Delta\nu)^2(W^* - W')^{-1} \quad (1)$$

$$\text{at } T_c: 1/\tau^* = \sqrt{2}\pi\Delta\nu \quad (2)$$

$$\text{below } T_c \text{ (where } 1/\tau^* \ll 2\pi\nu): 1/\tau^* = 2\pi(W^* - W') \quad (3)$$

where W^* and W' are the line widths in the presence and absence of exchange, respectively; the line width of the 4-methoxy group peak was used for W'. At each temperature the rate constant, k, was determined and a least-squares plot of $\ln k$ vs. $1/T$ yielded the Arrhenius activation energy, E_a. Values for $\Delta S^{\ddagger}$, $\Delta H^{\ddagger}$, and $\Delta G^{\ddagger}$ were obtained from the appropriate equations.[3b] Alternately, $\Delta G^{\ddagger}$ was obtained from the Gutowsky–Holm approximation[6] (eq 2 above) and Eyring[3b] equation at the coalescence temperature. Errors were determined by a propagation of errors treatment.

Registry No.—1, 37706-47-1; **2**, 61770-02-3; **3**, 37706-46-0; **4**, 37706-35-7; (*N*-(2-benz[*h*]quinolylmethyl)-3,5-dimethoxybenzamide, 61770-03-4.

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### Unusual Effect of Epoxidic Oxygen on the Ease of Base-Catalyzed Decomposition of Epidioxides

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In a parallel study[2] we observed that attempts to separate a mixture of **1** and **2** by column chromatography or preparative TLC over silica gel resulted in rapid destruction of only one of the components, namely **1**. This peculiar selectivity attracted our attention and the reaction was examined in more detail.

Pure **1**, isolated by *rapid* preparative TLC followed by recrystallization, was stirred overnight with silica gel. TLC analysis indicated complete conversion to two new substances which were isolated by preparative TLC in 58 and 30% yield. Both compounds were isomeric hydroxy ketones (IR spectrum) which were differentiated by NMR spectrometry. The NMR spectrum of the major product **3** exhibited a somewhat broadened triplet at 4.28 ppm ($J = 4.5$ Hz, H-3) which was clearly coupled to a doublet at 3.66 ppm (H-2), whereas the minor product **4** had a triplet at 4.06 ppm ($J = 7.5$ Hz, 6) and a singlet at 3.12 ppm (H-2). Under these conditions **2** underwent no significant change, but prolonged stirring with silica gel (5 days) resulted in 51% recovery of **2** and 44% conversion
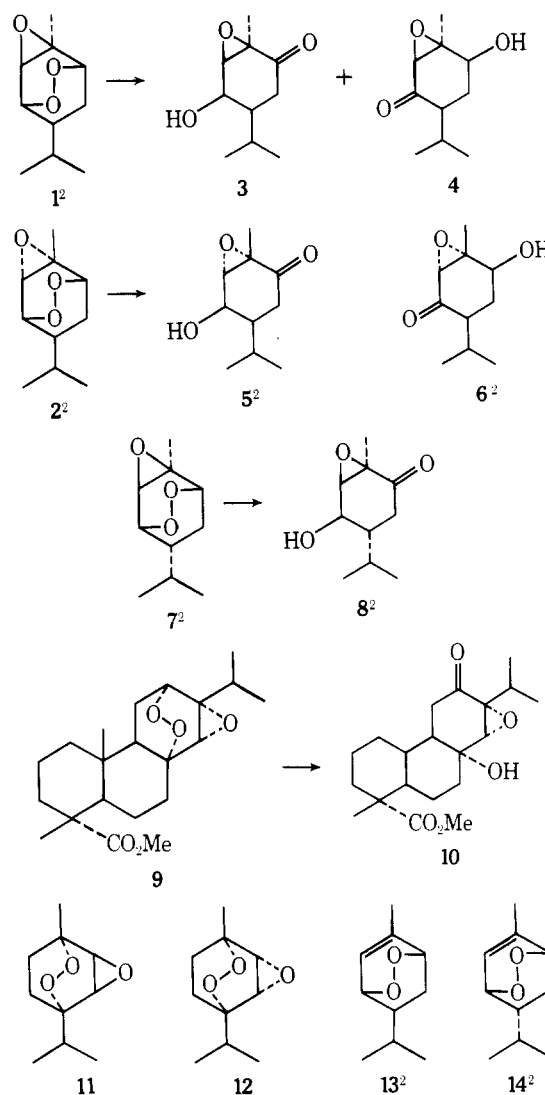
to the known[2] γ-hydroxy-α-epoxy ketone **5**. There was no evidence for formation of the isomeric hydroxy ketone **6**.[2]

The two cis epoxy epidioxides **7**[2] and **9**[5] also underwent essentially quantitative conversion to the γ-hydroxy-α-epoxy ketones **8** and **10** on stirring overnight with silica gel. On the other hand, neither **11** nor **12**, prepared by epoxidation of ascaridole in 48 and 32% yield, respectively, was affected by this procedure. The stereochemistry assigned to **11** and **12** is tentative; the minor, more polar isomer exhibited the signals of H-2 and H-3 as an AB system centered at 3.25 ppm ($J = 5$ Hz), whereas H-2 and H-3 of the major, less polar isomer were a two-proton singlet at 3.31 ppm. The same relationship of chemical shifts and polarities is characteristic of the cis and trans epoxy peroxides **1**[2] and **2**[2] and the cis and trans epoxy peroxides **21** and **22** (vide infra); however, formation of **11** in somewhat larger amount by attack from what appears to be the more hindered side seems surprising.

The 3,6-dihydro-1,2-dioxins **13–18**[2,7–9] were also stable toward silica gel[10] as were the mixtures of α- and β-epoxides **19** and **20** prepared by epoxidation of **16** and **17**.[8] Consequently the facile decomposition of epidioxides under the influence of silica gel depends on two factors: (1) the presence of a proton α to the epidioxide groups, presumably so that decomposition can take place by a process resembling the usual base-catalyzed decomposition of peroxides;[4] (2) the presence of a rigid system in which an epoxidic oxygen is situated cis and in close proximity to the epidioxide function.[12]

The reasons for the unusually facile decomposition of the