are not affected by added alkali metal cations (Table II) also supports this presumption.

Concluding Remarks. The present system demonstrated that ion transport of alkali and alkaline earth metal cations can be controlled by light. The novel phenomenon is attained because the crown ether can put on and off a phenoxide anionic cap in response to photoirradiation. Also established is the fact that the countercurrent of proton flux is important (in particular, in the transport of the Ca^{2+} ion). We consider that the concept of "switched-on anionic cap" might lead to a more efficient and selective control of ion transport.

Acknowledgment. We thank Professors T. Kunitake and M. Takagi for helpful discussions. This research was supported by a grant from the Ministry of Education of Japan (No. 56850214).

Registry No. 1, 80764-58-5; *cis*-Cr-*m*, 80764-59-6; *trans*-Cr-*m*, 80764-60-9; *cis*-Cr-*p*, 80764-61-0; *trans*-Cr-*p*, 80764-62-1; *cis*-Cr-*o*, 80764-63-2; *trans*-Cr-*o*, 80780-59-2; Na^+, 17341-25-2; K^+, 24203-36-9; Rb^+, 22537-38-8; Cs^+, 18459-37-5; Ca^{2+}, 14127-61-8; Sr^{2+}, 22537-39-9; Ba^{2+}, 22541-12-4.

Conformational Effects in the Hydrolyses of Rigid Benzylic Epoxides: Implications for Diol Epoxides of Polycyclic Hydrocarbons[1]

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Contribution from the Laboratory of Bioorganic Chemistry, National Institute of Arthritis, Diabetes, Digestive and Kidney Diseases and Laboratory of Chemistry, National Heart, Lung and Blood Institute, National Institutes of Health, Bethesda, Maryland 20205, and Laboratory for Chemical Dynamics, Department of Chemistry, University of Maryland Baltimore County, Baltimore, Maryland 21228. *Received July 20, 1981*

Abstract: The two conformationally rigid, diastereomeric 9,10-oxides derived from *trans*-1,2,3,4,4a,10a-hexahydrophenanthrene have been synthesized, and their relative stereochemistries have been verified by X-ray structure determination of the acetate of the bromohydrin precursor of one of these epoxides. Inspection of molecular models indicates that one of these epoxides has the benzylic C–O bond of the epoxide ring aligned nearly parallel to the π orbitals of the aromatic ring and has the epoxide oxygen cis to the adjacent ring juncture hydrogen, whereas the other epoxide has this C–O bond not aligned with the π orbitals and has the epoxide oxygen trans to the adjacent ring juncture hydrogen. Rates of solvolysis of these two epoxides in 1:9 dioxane–water, ionic strength 0.1 M ($NaClO_4$), at 25 °C, follow the rate law $k_{obsd} = k_{H^+}a_{H^+} + k_0$, with similar values of k_{H^+} for both diastereomers and a value of k_0 for the aligned isomer that is ~40 times larger than that for the nonaligned isomer. Upon solvolysis, the nonaligned isomer yields exclusively trans diol, whereas the aligned isomer yields predominantly cis diol (75%) under acidic conditions and ketone rearrangement product (~85%) under neutral conditions. The predominant diol from acid hydrolysis of both isomers is postulated to arise from attack of solvent on the carbonium ion derived from benzylic C–O cleavage of the epoxide, to yield a pseudoaxial substituent. The observed chemistry of these rigid epoxides is used to explain conformational effects on the rates and products of solvolysis of the conformationally flexible benzo-ring diol epoxides derived from metabolism of polycyclic aromatic hydrocarbons: (1) For the hydronium ion catalyzed process (k_{H^+}), rates are relatively insensitive to conformation, whereas product distribution is influenced (a) by the conformation of the carbonium ion that is *initially formed*, if this ion is relatively unstable, or (b) by the conformation of the carbonium ion that is *preferred at equilibrium*, if the ion is stable enough to undergo conformational equilibration prior to capture by solvent. (2) For the spontaneous process (k_0), the aligned conformation reacts considerably faster than the nonaligned conformation and also gives a carbonium ion with the required geometry for rearrangement to ketone. The observation that diol epoxides with the benzylic hydroxyl group cis to the epoxide ring ("isomer 1 series") ordinarily react via the k_0 process somewhat faster than their diastereomers with this hydroxyl group trans to the epoxide ring ("isomer 2 series") and also yield ketone products suggests that the isomer 1 diastereomers probably react predominantly via the conformer of the carbonium ion that is related to the aligned conformation of the reactant; reaction via this slightly less favored ground-state conformation may provide the lowest energy pathway for generation of the ion. For the isomer 2 series the absence of ketone formation at neutral pH is consistent with reaction only via the conformer of the carbonium ion that is related to the nonaligned ground-state conformation.

In accordance with predictions of the bay-region theory,[2] benzo-ring diol epoxides in which the epoxide group forms part of a bay region of the hydrocarbon are now widely accepted as ultimately carcinogenic metabolites of those polycyclic aromatic hydrocarbons that are biologically active.[3] Despite several investigations into the solvolytic reactivity of benzo-ring diol epoxides,[4] numerous aspects of the mechanisms by which these biologically important molecules react remain to be elucidated.

In particular, the influence of steric, stereoelectronic, and conformational factors on the rates and products of these reactions is difficult to assess for the conformationally mobile diol epoxides and tetrahydroepoxides of the polycyclic aromatic hydrocarbons.

[†] National Institutes of Health.
[‡] University of Maryland.

(1) Supported in part by Public Health Service Grants Nos. CA-17278 and CA-26086 from the National Cancer Institute (D.L.W.).

(2) (a) Jerina, D. M.; Daly, J. W. In "Drug Metabolism from Microbe to Man", Parke, D. V.; Smith, R. L., Eds., Taylor and Francis: London, 1976; pp 13–32. (b) Jerina, D. M.; Lehr, R. E. In "Microsomes and Drug Oxidations", Proceedings of the 3rd International Symposium, Ullrich, V.; Roots, I.; Hildebrandt, A. G.; Estabrook, R. W.; Conney, A. H., Eds.; Pergamon Press: Oxford, England, 1977; pp 709–720.

(3) For a recent review and leading references, see: Nordqvist, M.; Thakker, D. R.; Yagi, H.; Lehr, R. E.; Wood, A. W.; Levin, W.; Conney, A. H.; Jerina, D. M. In "Molecular Basis of Environmental Toxicity"; Bhatnagar, R. S., Ed.; Ann Arbor Science Publishers, Inc.: Ann Arbor, 1980; pp 329–357.

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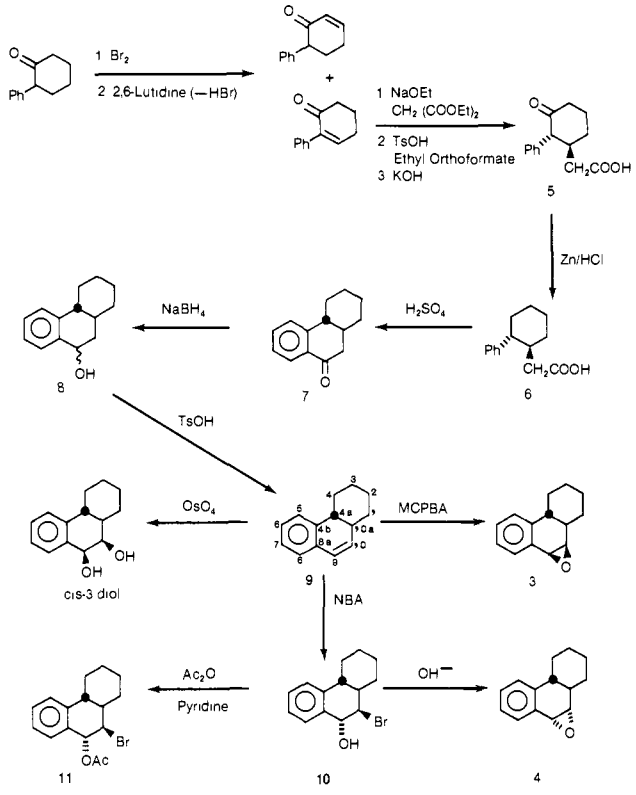
Scheme I



Two diastereomers are possible for the bay-region diol epoxides in which the hydroxyl groups are trans to each other: the benzylic hydroxyl group may be either cis (isomer **1**) or trans (isomer **2**)

1 **2**

to the epoxide oxygen. In the absence of specific steric constraints,[5] the isomer 1 series somewhat prefers the conformation in which the hydroxyl groups are quasidiaxial, whereas the isomer 2 series greatly prefers the conformation in which the hydroxyl groups are quasidiequatorial, such that the epoxide group bears the same spatial relationship to the π system in the major conformation of both isomers.[4a,6] This spatial relationship in the preferred conformers is such that the benzylic C–O bond of the epoxide ring is not parallel (nonaligned) to the π orbitals of the aromatic system. It is not known whether this or the alternative conformation which has the benzylic C–O bond aligned with the aromatic π orbitals is responsible for the observed reaction rates and products.

In order to clarify the role of conformation in benzylic epoxide solvolysis we wished to synthesize model substrates containing a conformationally locked cyclohexane ring that is fused to a benzene ring. Although several approaches to the construction of such model compounds are possible, such as the introduction of a dimethylene bridge between the hydroxyl groups of a diol epoxide, availability of suitable derivatives of the conformationally rigid *trans*-octahydrophenanthrene system[7] suggested *trans*-1,2,3,4,4a,10a-hexahydrophenanthrene as a convenient precursor provided epoxidation of its 9,10 double bond could be achieved from both faces of the hydrocarbon. Such proved to be the case. The present study reports the syntheses, structural analysis, and solvolytic chemistry of these diastereomeric epoxides in which the epoxide oxygen is either trans (**3**) or cis (**4**) to the adjacent ring juncture hydrogen H_{10a}.

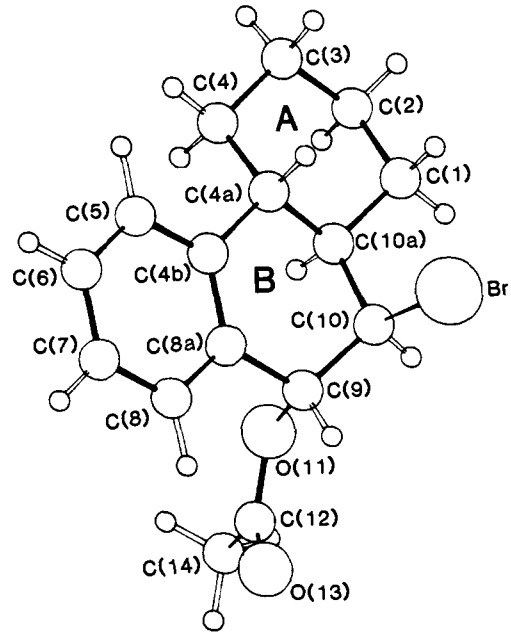


Figure 1. PLUTO[8] drawing of the molecular geometry of **11**, showing the trans fusion of rings A and B and the relative stereochemistry of the oxygen, which establishes the stereochemistry of **4** and its isomer **3**.

Results

The syntheses of epoxides **3** and **4** are summarized in Scheme I. Treatment of olefin **9** with *N*-bromoacetamide, followed by alkaline ring closure, yields a single pure epoxide, and treatment of **9** directly with *m*-chloroperoxybenzoic acid yields the diastereomeric epoxide. Thus, attack by each reagent occurs selectively on one face of the olefin, presumably as a result of steric hindrance by H_{10a} to the approach of the reagent. Similarly, only the cis diol (*cis*-**3**-diol, see below) that is derived from attack on the side of the molecule opposite H_{10a} is isolated from osmium tetraoxide oxidation of **9**.

Comparison of the NMR spectra of **3** and **4** suggests that the stereochemistry of these compounds is that shown in Scheme I. A downfield shift of H_9 in **3** (δ 3.88) relative to **4** (δ 3.73) is consistent with the orientation of these protons (a) in the plane of the aromatic ring in **3** and (b) slightly above it in **4**. Similar differences are observed in the chemical shifts of the benzylic oxirane protons for the diastereomeric pairs of diol epoxides derived from triphenylene and benzo[*e*]pyrene,[5] whose series **1** diastereomers exist in the nonaligned conformation analogous to **3** whereas the series 2 diastereomers prefer the aligned conformational analogous to **4**. The NMR spectra of the diacetates derived from the diol hydrolysis products of **3** and **4** (see below) are also consistent with these structural assignments.

Since the mechanistic interpretation of the observed solvolytic chemistry of **3** and **4** depends entirely upon correct structural assignments for these compounds, unequivocal proof of structure was necessary and was obtained by X-ray analysis of a crystal of bromohydrin acetate **11**. Crystals of **11** are very thin (<0.04 mm) triclinic plates, space group $P\bar{1}$, with dimensions a = 8.3331

(4) See: (a) Whalen, D. L.; Ross, A. M.; Yagi, H.; Karle, J. M.; Jerina, D. M. *J. Am. Chem. Soc.* **1978**, 100, 5218–5221. (b) Rogers, D. Z.; Bruice, T. C. *Ibid.* **1979**, *101*, 4713–4719. (c) Becker, A. R.; Janusz, J. M.; Bruice, T. C. *Ibid.* **1979**, *101*, 5679–5687. (d) Yang, S. K.; McCourt, D. W.; Gelboin, H. V. *Ibid.* **1977**, *99*, 5130–5134 and references within 4a–d.

(5) Yagi, H.; Thakker, D. R.; Lehr, R. E.; Jerina, D. M. *J. Org. Chem.* **1979**, *44*, 3439–3442.

(6) (a) Yagi, H.; Hernandez, O.; Jerina, D. M. *J. Am. Chem. Soc.* **1975**, *97*, 6881–6883. (b) Lehr, R. E.; Schaefer-Ridder, M.; Jerina, D. M. *Tetrahedron Lett.* **1977**, 539–542.

(7) Cook, J. W.; Hewett, C. L.; Robinson, A. M. *J. Chem. Soc.* **1939**, 168–177. Linstead, R. P.; Whetstone, R. R.; Levine, P. *J. Am. Chem. Soc.* **1942**, *64*, 2014–2022.

(8) Program of Dr. W. D. S. Motherwell, as incorporated into the NIH-EPA Chemical Information System. Heller, S. R.; Milne, G. W. A.; Feldmann, R. J. *Science* **1977**, *195*, 253–259.

Table I. Bond Lengths (Å) and Angles (deg) for the Heavier Atoms of 11 with Esd's Given Parenthetically

Br–C(10)	1.986 (5)	C(1)–C(10a)	1.522 (10)
C(2)–C(1)	1.509 (8)	C(3)–C(2)	1.514 (12)
C(4)–C(3)	1.519 (12)	C(4a)–C(10a)	1.538 (9)
C(4a)–C(4)	1.526 (7)	C(4b)–C(4a)	1.526 (10)
C(4b)–C(8a)	1.396 (9)	C(5)–C(4b)	1.395 (9)
C(6)–C(5)	1.381 (14)	C(7)–C(6)	1.369 (13)
C(8)–C(8a)	1.390 (11)	C(9)–C(11)	1.466 (6)
C(9)–C(8a)	1.518 (9)	C(10a)–C(10)	1.498 (7)
C(10)–C(9)	1.505 (9)	O(11)–C(12)	1.352 (8)
C(12)–O(13)	1.188 (8)	C(12)–C(14)	1.491 (9)
C(2)–C(1)–C(10a)	111.3 (5)	C(3)–C(2)–C(1)	111.0 (6)
C(4)–C(3)–C(2)	112.7 (6)	C(4a)–C(4)–C(3)	111.9 (5)
C(4)–C(4a)–C(10a)	107.9 (5)	C(4b)–C(4a)–C(10a)	113.2 (5)
C(4b)–C(4a)–C(4)	114.5 (5)	C(4a)–C(4b)–C(8a)	122.2 (5)
C(5)–C(4b)–C(4a)	119.7 (6)	C(5)–C(4b)–C(8a)	118.0 (7)
C(6)–C(5)–C(4b)	121.2 (7)	C(7)–C(6)–C(5)	120.2 (8)
C(8)–C(7)–C(6)	120.0 (9)	C(7)–C(8)–C(8a)	120.3 (7)
C(4b)–C(8a)–C(9)	121.0 (6)	C(8)–C(8a)–C(4b)	120.4 (6)
C(8)–C(8a)–C(9)	118.6 (5)	C(10)–C(9)–O(11)	103.3 (5)
C(10)–C(9)–C(8a)	114.0 (5)	C(8a)–C(9)–O(11)	108.7 (4)
Br–C(10)–C(10a)	111.7 (4)	Br–C(10)–C(9)	107.0 (4)
C(10a)–C(10)–C(9)	112.9 (4)	C(1)–C(10a)–C(10)	116.1 (5)
C(4a)–C(10a)–C(1)	109.9 (5)	C(4a)–C(10a)–C(10)	112.8 (5)
C(9)–O(11)–C(12)	117.5 (4)	O(11)–C(12)–O(13)	124.8 (6)
O(11)–C(12)–C(14)	110.1 (5)	O(13)–C(12)–C(14)	125.1 (7)

Table II. NMR Spectral Data for Diacetates of Diols Related to 3 and 4[a]

compd	δ (H_9)	δ (H_{10})	$J_{9,10}$	$J_{10,10a}$
trans-4[b]	6.18	5.14	8.5	11
cis-4[b]	6.19	5.02	3.6	11.3
trans-3[b]	5.88	5.06	2.8	~2
cis-3[c]	6.08	5.42	3.3	<2

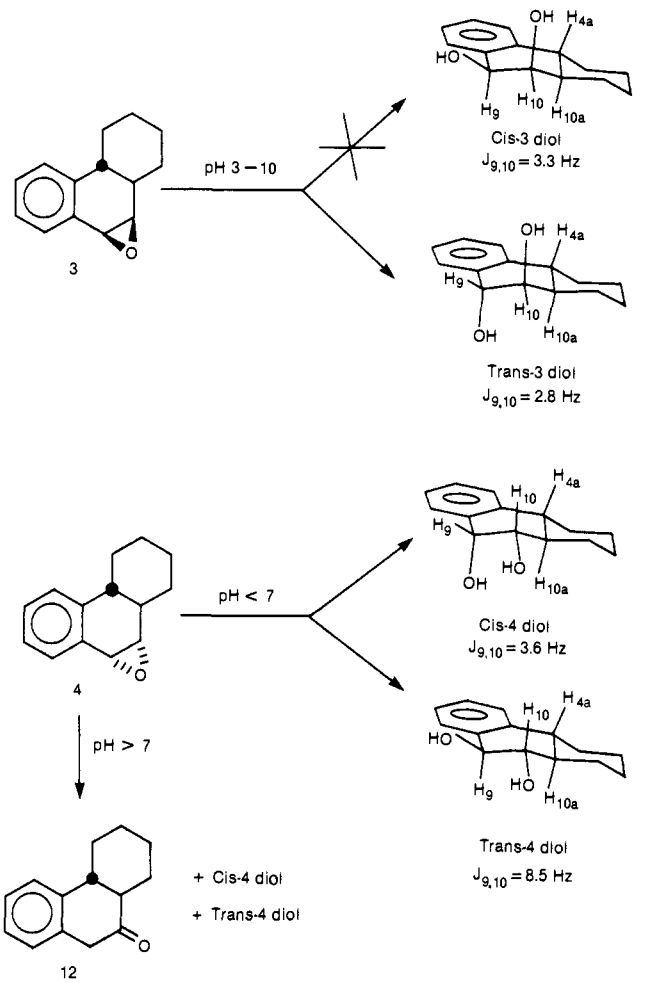
[a] Spectra were measured in $CDCl_3$ at 100 MHz. Chemical shifts are in ppm and coupling constants are in Hz. [b] Diols prepared by hydrolysis in 1:9 dioxane–water containing ~10^{-3} M $HClO_4$. [c] Diol prepared by OsO_4 oxidation of 9.

(6) Å, b = 9.2842 (8) Å, c = 10.3490 (8) Å, α = 107.120 (8)°, β = 98.266 (8)°, γ = 101.525 (8)°, and Z = 2. Three-dimensional X-ray data were refined to an R factor of 5.4%. Full X-ray experimental details are given in the supplementary material (see paragraph at end of paper). The X-ray results confirm the trans fusion of rings A and B and show that O_{11}, the oxygen atom that becomes the epoxide oxygen in **4**, lies on the same side of the ring as H_{10a} (Figure 1). The molecular dimensions, given in Table I, present no unusual features. There are apparently no strong interactions between molecules. The A ring adopts an essentially chair conformation and the B ring can be described as monoplanar, following Bucourt.[9] Two torsion angles are of interest; Br–C_{10}–C_9–O_{11} is −164° and H_9–C_9–C_{10}–H_{10} is 73°. The latter torsion angle cannot be considered to be very accurately determined but the error is unlikely to exceed 10°. The observed NMR coupling constant, $J_{9,10}$ = 2.2 Hz, for **11** is consistent with this angle for the trans, quasidiequatorial hydrogens of **11**.

For identification of the stereochemistry of the diol products obtained upon hydrolysis of **3** and **4**, the four diastereomeric diols which can arise by benzylic C–O cleavage of **3** and **4** were isolated or synthesized and the NMR spectra of their diacetates were measured. The stereochemistry of these diols is shown in Scheme II, along with the NMR coupling constants ($J_{9,10}$) for their diacetates. Because of the rigid geometry in these systems, the two diols that might in principle be derived from benzylic hydrolysis of **3** must have an axial hydroxyl substituent at C_{10} and the other two diols derived from benzylic hydrolysis of **4** must have an equatorial hydroxyl substituent at C_{10} regardless of whether the diol is cis or trans. Relevant spectral data are given in Table II. Hydrolysis of **4** under acidic conditions gives two diols. For the

(9) Bucourt, R. In "Topics in Stereochemistry", Eliel, E. L.; Allinger, N. L., Eds.; Wiley-Interscience: New York, 1974; Vol. 8, pp 159–224.

Scheme II



diacetate of the minor isomer (*trans*-**4**-diol), the large value (8.5 Hz) of $J_{9,10}$ requires that H_9 and H_{10} be quasidiaxial and hence that the hydroxyl groups be trans. The diacetate of the major diol product (*cis*-**4**-diol) from **4** has $J_{9,10}$ = 3.5 Hz, and hence the hydroxyl groups of this diol are cis. For the diacetates of both diols from **4**, $J_{10,10a}$ is large (~11 Hz) because of the trans diaxial orientation of H_{10} and H_{10a} that is required by the rigid geometry of these molecules. Epoxide **3** yields a single hydrolysis product (*trans*-**3**-diol) under both neutral and acidic solvolysis conditions. The value of $J_{9,10}$ = 2.8 Hz for the diacetate of this compound does not unequivocally establish its structure, since the angles between H_9 and H_{10} should be similar for the cis (one pseudoaxial and one equatorial hydrogen) and the trans (one pseudoequatorial and one equatorial hydrogen) diacetates derivable from **3**. The fourth possible diol in this set of diastereomers was synthesized by osmium tetraoxide oxidation of **9**. Formation by osmium tetraoxide oxidation requires that the hydroxyl groups of this diol be cis. The small value of $J_{10,10a}$ for its diacetate indicates that H_{10} is equatorial, since H_{10a} is constrained to be axial. Thus, the diol from osmium tetraoxide oxidation must be *cis*-**3**-diol, derived from attack on the face of olefin **9** that is opposite H_{10a}, consistent with our previous observations for epoxidation reactions. *cis*-**3**-diol was shown chromatographically (Figure 2) to be different from the diol derived from benzylic hydrolysis of **3**. Hence the hydrolysis product must be *trans*-**3**-diol.

Under neutral conditions the major product of solvolysis of **4** in 1:9 dioxane–water is ketone **12**, which was identified by GC–mass spectrometry (CI, NH_3) of a sample isolated from liquid chromatography of a neutral solvolysis mixture: m/e 218 (M + NH_4^+, 201 (M + 1). HPLC separation of the four diols and the ketone is illustrated in Figure 2.

Reactions of **3** and **4** in 1:9 (v/v) dioxane–water, μ = 0.1 M ($NaClO_4$) at 25 °C, follow the rate law $k_{obsd} = k_{H^+}a_{H^+} + k_0$, with

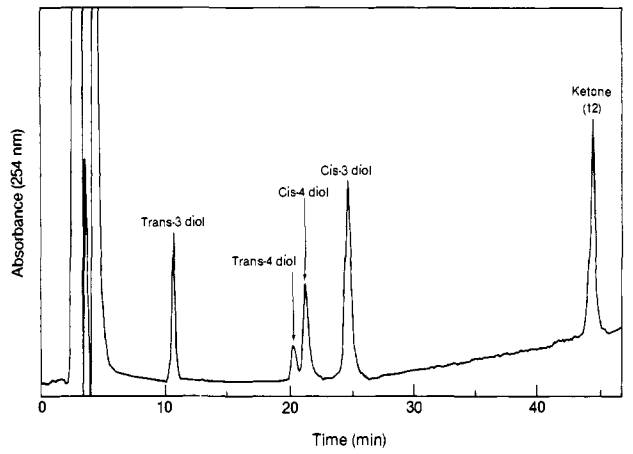


Figure 2. HPLC separation of diols and ketone related to **3** and **4** on a Du Pont Zorbax ODS column, 6.2 × 250 mm, flow rate 1.5 mL/min, eluted isocratically for 20 min with methanol–water, 60:40, followed by an increasing linear gradient of 1% methanol/min. Injection was at time zero.

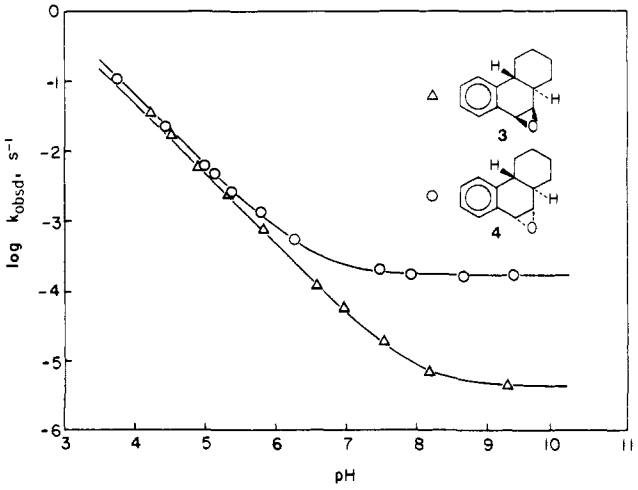


Figure 3. Dependence of log k_{obsd} on pH for hydrolysis of **3** and **4** in 1:9 (v/v) dioxane–water (μ = 0.1 M, $NaClO_4$), 25 °C. The lines correspond to the rate law and rate constants given in the text.

$k_{H^+}(\mathbf{3}) = 480 \pm 20\ M^{-1}\ s^{-1}$, $k_0(\mathbf{3}) = (4.3 \pm 0.5) \times 10^{-6}\ s^{-1}$, $k_{H^+}(\mathbf{4}) = 650 \pm 20\ M^{-1}\ s^{-1}$, and $k_0(\mathbf{4}) = (1.7 \pm 0.7) \times 10^{-4}\ s^{-1}$. pH–rate profiles for the solvolyses are shown in Figure 3. Products of the reactions under kinetic conditions were determined quantitatively by HPLC and are given in Table III. The pH-independent reaction of **4**, which yields predominently ketone **12**, exhibits a kinetic isotope effect, k_0^H/k_0^D, of 1.22 ± 0.04 when deuterium is substituted for hydrogen at C_{10} (**4**-D). Any isotope effect on the product distribution from **4**-D relative to **4** is too small to be measurable within experimental error (cf. Table III).[10]

Discussion

Inspection of molecular models indicates that the *trans*-decalin derivatives **3** and **4** are rigidly held in the conformations shown in Scheme III. Selective benzylic C–O bond cleavage of **3** and **4** should lead to a pair of conformationally rigid, diastereomerically related carbonium ions in which the hydroxyl group is pseudoaxial in one isomer (**3a**) and pseudoequatorial in the other (**4a**). The

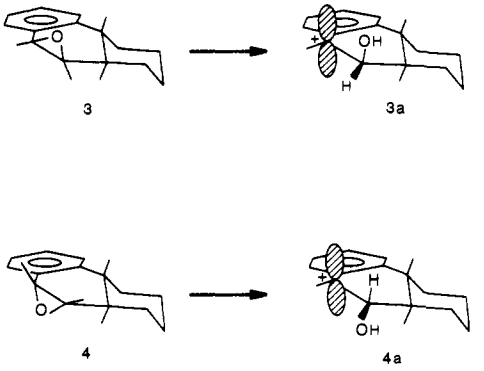
(10) If the rate-determining step does not involve deuterium migration but there is a large deuterium isotope effect on a subsequent, product-determining step, a change in the product distribution from the deuterated product should result. Based on a minimum yield of ~11% diols from undeuterated **4** and the assumption that there is a deuterium isotope effect on ketone but not on diol formation, values of 20% and 27% diol formation from **4**-D are calculated assuming isotope effects of 2 and 3, respectively, for ketone formation. Thus the observed diol yield of ~16% from the deuterated compound suggests that the isotope effect on ketone formation may be ≤2.

Table III. Product Distributions upon Hydrolysis[a] of the *trans*-1,2,3,4,4a,9,10,10a-Hexahydrophenanthrene 9,10-Oxides **3** and **4**

compd	pH	% cis diol	% trans diol	% ketone
3	3.1		100	
	8.96 ± 0.07		100	
4	3.17	75	24	≤1
	7.72 ± 0.07	6[b] (8.4)[b,c]	5[b] (1.1)[b,c]	89[b] (85)[b,c]
4-D[d]	7.80	10	6	83

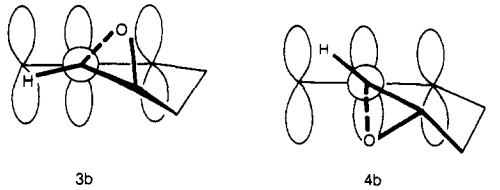
[a] In 1:9 (v/v) dioxane–water, ionic strength 0.1 M ($NaClO_4$); 25 °C. Products were separated by HPLC (see Figure 2). Product ratios were determined by integration of peak areas at 254 nm. [b] Determined after 5 half-lives and corrected for incomplete reaction (3%). [c] The values in parentheses were calculated from the decrease in the peak areas corresponding to total diols at pH 7.72 relative to pH 3.17, using *p*-nitrobenzyl alcohol as an internal standard. [d] Determined by HPLC on a Zorbax ODS column (9.4 × 250 mm) eluted with methanol–water (70:30) for 15 min followed by a linear gradient (1% methanol/min for 20 min), at a flow rate of 3.2 mL/min. Under these conditions retention times of 15, 16, and 30.5 min are observed for *trans*-4-diol, *cis*-4-diol, and ketone, respectively. Impurities eluting at ~19.3 min are not included in the calculation of product composition. Chromatography of 4-D on silica (hexane:tetrahydrofuran, 93:7) reduced, but did not eliminate, these impurities. Product analysis, using the chromatographically purified sample, gave a comparable value (~85%) for ketone formation at pH 7.9 ± 0.1.

Scheme III



kinetics and products of solvolysis of **3** and **4** are consistent with the expected behavior of these ions and related transition states.

Kinetics. The most striking feature of the reaction kinetics of **3** and **4** is the large (~40-fold) acceleration of the spontaneous solvolysis rate (k_0) for **4** relative to **3**. We previously proposed that, for diol epoxides, the transition state for carbonium ion formation from the conformation corresponding to **4** should be favored relative to that from the conformation corresponding to **3**, since the benzylic C–O bond of the epoxide in the conformation of **4** is better aligned to provide overlap between the developing π orbital of the carbonium ion and the aromatic π system.[4a] This idea is illustrated by the partial structures of **3** and **4** shown as Newman projections along the C_9–C_{8a} bond, **3b** and **4b**, respectively, with the bond that breaks indicated by a heavy broken line. Relief of the O–H_{10a} and C_1–H_{10} eclipsing interactions that are present in the ground state of **4** but not of **3** could provide an additional, or alternative, factor that accelerates the solvolytic cleavage of **4**. The proposed effect of alignment should be im-



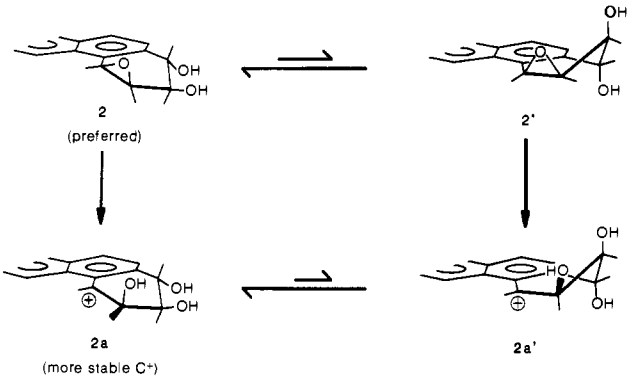
portant only in the transition state for epoxide ring opening. If an intermediate (the zwitterion corresponding to **4a** or **3a**) is

formed during the course of neutral solvolysis, its conversion to products should also be accelerated in **4a** relative to **3a**, but by a different factor, namely that **4a** has the conformation that is required for rearrangement to ketone, presumably by hydride migration[11] to C_9. This rearrangement, which occurs only in the compound whose C_{10}–H bond can achieve a pseudoaxial[12] orientation, provides a mechanistic pathway (in addition to capture of the ion by solvent) for **4** that is not available for **3** and should thus accelerate collapse of the hypothetical intermediate from **4**. Hence, both processes, uncatalyzed ring opening and collapse of an intermediate ion, should be accelerated for **4** relative to **3**.

Since it is not known whether ring opening, collapse of an intermediate, or an unsymmetrical "concerted" process that avoids the highly unstable zwitterionic intermediate best describes the rate-limiting transition state for k_0, the question of which of the conformational factors described above is most responsible for the observed acceleration of k_0 for **4** relative to **3** must be left open. The kinetic isotope effect, $k_0^H/k_0^D = 1.22 \pm 0.04$, that is observed when deuterium is substituted for hydrogen at C_{10} (**4**-D) provides suggestive, but not conclusive, evidence for some involvement of the rearrangement process in rate determination. The small[13] value of this isotope effect suggests a highly unsymmetrical transition state in which C–O cleavage is extensive and hydride migration has barely begun or a mechanism in which both processes contribute to rate determination. It is probably less consistent with purely rate-determining ring opening, since the secondary isotope effect for ring opening is expected to be either negligibly small or inverse ($k^H/k^D \sim 1.0$–0.93).[14,15]

In contrast to the uncatalyzed reaction, both **3** and **4** undergo hydronium-ion-catalyzed hydrolysis with very similar values of k_{H^+}. Furthermore, for polycyclic diol epoxides log k_{H^+} is ~2- to 3-fold less sensitive to the nature of the aromatic system ($\Delta E_{deloc}/\beta$)[16] than is log k_0, consistent with substantially less positive charge development at carbon in the rate-determining transition state for k_{H^+}, compared to k_0. These observations are consistent with a transition state in which C–O cleavage is small for catalysis by the strongly acidic hydronium ion. In such a transition state, little or no advantage would be expected from the relief of eclipsing interactions in **4** or from alignment of the benzylic C–O bond in **4** with the π orbitals of the aromatic system, if rehybridization of carbon is not far enough advanced for bond angles to change and/or for π orbital overlap to provide significant stabilization.

Scheme IV



Scheme V

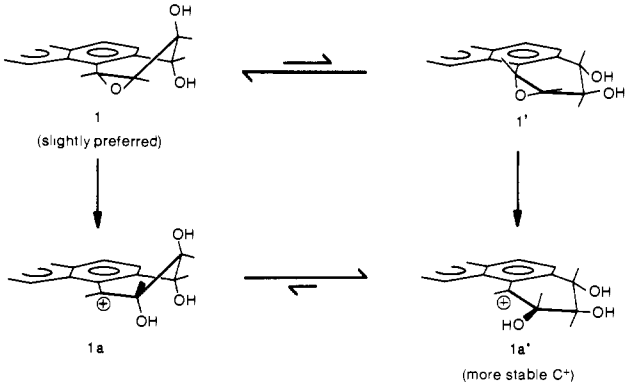


Table IV. Relative Amounts of Cis Hydration in the Acid-Catalyzed Hydrolysis of Bay-Region Diol Epoxides and Tetrahydroepoxides

		% cis hydration		
parent hydrocarbon	$\Delta E_{deloc}/\beta$[a]	diol epoxide 1	diol epoxide 2	H_4 epoxide
benzo[a]pyrene[b,c]	0.794	87	5	80
benz[a]anthracene	0.766	75[d]	<2[d]	50[b,c]
chrysene[b,c]	0.639	57	~1	14
phenanthrene[b,e]	0.658	50	~1	18
naphthalene[f]	0.488			6

[a] References 2b and 16. [b] Reference 4a. [c] Products were determined in 1:3 dioxane-water (μ = 0.1 M, $NaClO_4$). [d] Products were determined in 1:9 dioxane-water (Yagi, H.; Sayer, J. M.; Jerina, D. M., unpublished observations). [e] Products were determined in water (μ = 0.1 M, $NaClO_4$). [f] Reference 4c. Product data from the diol epoxides were not provided.

Products. As shown in Table III, hydronium-ion-catalyzed hydrolysis of **3** proceeds only via trans hydration, whereas **4** undergoes predominantly cis hydration. We believe that these results are most consistent with stereoselective attack of solvent on intermediate carbonium ions **3a** and **4a** to yield a pseudoaxial substituent. These ions are structurally related to cyclohexenyl cations, which have been shown by Goering and co-workers[17] to undergo preferential approach of solvent to yield a pseudoaxial substituent even though this approach may be from the more hindered side of the electron-deficient centers. It is of interest that these types of systems exhibit a considerably higher degree

(11) Whalen, D. L.; Ross, A. M. *J. Am. Chem. Soc.* **1974**, *96*, 3678–3679.

(12) There is a close similarity between the geometry of **4a** (or the corresponding zwitterion) and the proposed structure (based on theoretical calculations) for the transition state for a 1,2-hydride shift in the hydroxyethyl cation: Nobes, R. H.; Rodwell, W. R.; Bouma, W. J.; Radom, L. *J. Am. Chem. Soc.* **1981**, *103*, 1913–1922.

(13) This isotope effect is larger than the values of ~1 for k_0^H/k_0^D found for perdeuteriobenzene oxide and 1-deuterionapthalene 1,2-oxide (Kasperek, G. J.; Bruice, T. C.; Yagi, H.; Jerina, D. M. *J. Chem. Soc., Chem. Commun.* **1972**, 784–785) but much smaller than the values of 2–3 for a pinacol rearrangement in which the hydride shift is rate determining (Collins, C. J.; Rainey, W. T.; Smith, W. B.; Kaye, I. A. *J. Am. Chem. Soc.* **1959**, *81*, 460–466). The observed k_0^H/k_0^D is also smaller than observed values of ~1.5–2.3 for several rearrangements in which hydride migration and leaving group departure are postulated to be concerted and the theoretical value of 1.9 calculated by More O'Ferrall for a symmetrical 1,2-hydride transfer (More O'Ferrall for a symmetrical 1,2-hydride transfer (More O'Ferrall, R. A. *J. Chem. Soc. B* **1970**, 785–790, and references therein).

(14) Hanzlik, R. P.; Westkaemper, R. B. *J. Am. Chem. Soc.* **1980**, *102*, 2464–2467.

(15) One of us has recently observed that there is an even larger isotope effect ($k_0^H/k_0^D \simeq 1.6$) for the migrating hydrogen in the analogous rearrangement of 6-methoxy-3,4-dihydronaphthalene 1,2-oxide, whereas there is essentially no isotope effect for this hydrogen in the k_{H^+} process, which does not lead to rearrangement. This result is consistent with the data reported here and clearly indicates that, in favorable cases, hydrogen migration can contribute significantly to rate determination for the k_0 process. (Whalen, D. L.; Gillilan, R. E.; Pohl, T. M. unpublished observations).

(16) Jerina, D. M.; Sayer, J. M.; Thakker, D. R.; Yagi, H.; Levin, W.; Wood, A. W.; Conney, A. H. In "Carcinogenesis: Fundamental Mechanisms and Environmental Effects"; Pullman, B.; Ts'O, P. O. P.; Gelboin, H., Eds.; D. Reidel Publishing Co.: Dordrecht, Holland, 1980; pp 1–12. Jerina, D. M.; Sayer, J. M.; Yagi, H.; Croisy-Delcey, M.; Ittah, Y.; Thakker, D. R.; Wood, A. W.; Chang, R. L.; Levin, W.; Conney, A. H. In "Biological Reactive Intermediates II. Chemical Mechanisms and Biological Effects, Advances in Experimental Medicine and Biology", Snyder, R.; Parke, D. V.; Kocsis, J. J.; Jollow, D. J.; Gibson, G. G; Witmer, C. M., Eds.; Plenum Publishing Co.: New York; Vol. 136, in press.

(17) For 5-methylcyclohexenyl cations, pseudoaxial approach of solvent is favored by a factor of at least 3 over pseudoequatorial approach and may be much larger: Goering, H. L.; Josephson, R. R. *J. Am. Chem. Soc.* **1962**, *84*, 2779–2785. Goering, H. L. Vlazny, J. C. *Ibid.* **1979**, *101*, 1801–1805.

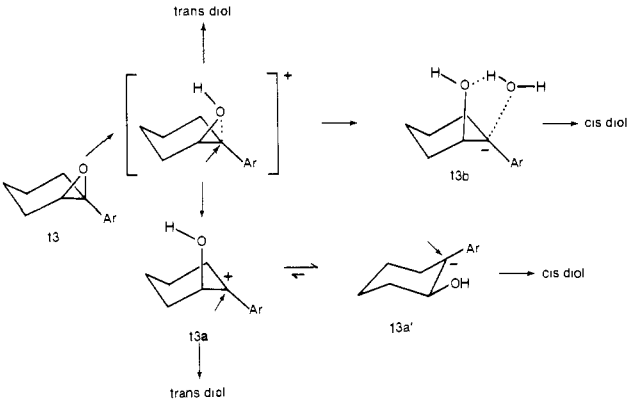
of specificity for the direction of solvent attack (in water) than the diastereomeric 1-phenyl-4-*tert*-butylcyclohexene oxides, both of which undergo approximately equal amounts of cis and trans addition of water under acidic conditions.[18]

At extension of our results to the polycyclic diol epoxides is illustrated in Schemes IV and V. The predominant ground-state conformation of diol epoxides of the isomer 2 series (**2**, Scheme IV) normally has the nonaligned geometry related to **3**.[4a,6] Since there is no apparent conformational preference for hydronium-ion-catalyzed ring opening (vide k_{H^+}(**3**) and k_{H^+} (**4**)), reaction should occur predominantly from this major conformation to give a benzyl cation (**2a**) that is preferentially attacked from the bottom, leading to mainly trans hydration, in accord with experimental observations (Table IV). Isomerization to the less stable[19] conformation **2a′**, which should give predominantly cis hydration, presumably does not occur to any significant extent along the reaction pathway.

Cis-diol epoxides (**1**, Scheme V) also have a small preference for the conformation analogous to **3**.[4a,6] Reaction from this conformation would give **1a**, whose hydration should be predominantly trans, whereas reaction from the less favored ground-state conformation **1′** would give **1a′**, which should undergo predominantly cis hydration. Furthermore, if **1a** and **1a′** are sufficiently long-lived to undergo conformational inversion, equilibration of these two species should favor the more stable **1a′**. The existence of such an equilibrium can account for the differences in product distribution among isomer 1 diol epoxides of different reactivity (Table IV). For the least stable carbonium ions (smallest $\Delta E_{deloc}/\beta$), trapping of **1a** presumably occurs faster than conformational equilibration, leading to more extensive trans hydration. A similar effect is also observed with the tetrahydroepoxides. It is of particular interest that the conformationally unique diol epoxide, benzo[*c*]phenanthrene diol epoxide 1, prefers the aligned conformation, **1′**, and thus should give rise directly to **1a′** upon acid catalyzed cleavage of the major conformer. Thus, even though this compound ($\Delta E_{deloc}/\beta$ = 0.600) should give a carbonium ion whose stability relative to tetraols or starting material is somewhat less than that of the corresponding ions from chrysene or phenanthrene diol epoxides, ~85% cis hydration is observed upon acid hydrolysis, consistent with trapping of **1a′**.[20]

A similar variation in cis/trans product selectivity has been observed by Battistini et al.[21a] for the related 1-arylcyclohexene oxide (**13**) system in which the amount of cis hydration varies from 7.5% for 1-(*p*-nitrophenyl)cyclohexene oxide to 95% for the *p*-methoxy derivative. This difference was attributed to enhanced stabilization of the solvated carbonium ion (**13b**) that gives cis hydration as electron donation from the substituent is increased. An alternative interpretation, which is entirely analogous to our present proposal for the diol epoxides, is that the process that is required for cis-diol formation is the conformational inversion **13a** → **13a′** and that prolonging the life of the carbonium ion permits this inversion to compete favorably with the direct collapse of **13a**. This proposal is speculative since the relative stabilities of **13a** and **13a′** are unknown.[21b]

A striking aspect of product formation from the polycyclic diol epoxides under neutral conditions is the consistent observation of the formation of appreciable amounts of ketone from the isomer 1 series and the complete absence of this rearrangement in the isomer 2 series. This finding can be rationalized on the basis of



schemes such as IV and V, in which the cationic species are replaced by zwitterions. We propose that only zwitterions corresponding to **2a′** and **1a′**, which have the pseudoaxial orientation of the α-H, can give ketone. Thus, ketone formation occurs only in the isomer 1 series, where this is the more stable conformation of the intermediate. The lack of any ketone formation at all from isomer 2 diol epoxides, even though conformation **2′** is expected to react faster than **2** for stereoelectronic reasons (see above), is surprising, especially since conformations **2** and **2′** are probably not very different in energy in some cases.[20] We speculate that the zwitterion corresponding to **2a′** may indeed be formed but undergoes conformational inversion to the more stable analogue of **2a** faster than it rearranges to ketone. According to this interpretation, the zwitterionic intermediate must exist and must rearrange with a rate constant $< \sim 10^9$ s^{-1}.[22]

In summary, we propose the following conformational effects to account for the observed rates and products obtained on solvolysis of aryl epoxides. (1) For the hydronium-ion-catalyzed process, *rates* are relatively insensitive to conformation, so that reaction probably occurs mainly via the predominant ground-state conformer. Product distribution is influenced mainly by the conformation of the carbonium ion that is *initially formed*, when this intermediate is relatively unstable, and by the conformation of the carbonium ion that is *preferred at equilibrium*, when this intermediate is stable enough to undergo conformational equilibration before it is trapped by solvent. For isomer 2 diol epoxides, the initially formed carbonium ion is in the more stable conformation that favors *trans addition* of solvent. For isomer 1 diol epoxides, the reactant opens initially to a carbonium ion that favors trans addition, but isomerization to the more stable conformation that favors cis addition occurs in those cases where the lifetime of the carbonium ion is sufficient to permit its conformational equilibration prior to solvent addition. Thus, an increase in cis products with increasing carbonium-ion stability is normally observed. (2) For the spontaneous reaction, both rate and products are highly sensitive to conformation, the "eclipsed" conformer (**4**, **1′**, and **2′**) being the more reactive. Furthermore, the zwitterionic carbonium ion (or carbonium-ion-like species) related to this conformation (cf. **4a**, and **1a′**) has the geometry that is required for the 1,2-hydride shift that leads to ketone formation. The observations that diol epoxides of the isomer 1 series undergo spontaneous reaction substantially faster than those of the isomer 2 series, and also are the only isomers that give any ketone product, are consistent with their reaction via **1′** and/or the zwitterion corresponding to **1a′**.

Experimental Section

A. Syntheses. Melting points are uncorrected. NMR spectra were measured at 100 MHz and are reported in parts per million (δ) downfield from tetramethylsilane, with coupling constants (*J*) in hertz. A Waters Associates liquid chromatograph equipped with UV and refractive index detectors was used for preparative HPLC; poorly separated peaks were recycled as necessary.

(18) Battistini, C.; Crotti, P.; Damiani, D.; Macchia, F. *J. Org. Chem.* **1979**, *44*, 1643–1647.

(19) Conformation **2a** contains one less gauche butane interaction than **2a′** and has been calculated to be the most stable conformation of this carbonium ion: Shipman, L. L. In "Polynuclear Aromatic Hydrocarbons", Jones, P. W.; Leber, P., Eds.; Ann Arbor Science Publishers, Inc.: Ann Arbor, 1979; pp 569–580.

(20) Sayer, J. M.; Yagi, H.; Croisy-Delcey, M.; Jerina, D. M. *J. Am. Chem. Soc.* **1981**, *103*, 4970–4972.

(21) (a) Battistini, C.; Balsamo, A.; Berti, G.; Crotti, P.; Macchia, B.; Macchia, F. *J. Chem. Soc., Chem. Commun.* **1974**, 712–713. (b) It has been pointed out by Professor Berti (personal communication) that eclipsing of the hydroxyl and aryl groups in **13a′** might cause rotation of the aryl group such that π-orbital overlap between the aryl group and the carbonium ion is unfavorable.

(22) The estimated lifetime of a half-chair conformation of cyclohexene is ~10^{-9} s at 25 °C. Anet, F. A. L.; Haq, M. Z. *J. Am. Chem. Soc.* **1965**, *87*, 3147–3150. Jensen, F. R.; Bushweller, C. H. *Ibid.* **1965**, *87*, 3285–3286.

2-Phenyl-2-cyclohexenone and 6-Phenyl-2-cyclohexenone. 2-Phenylcyclohexanone (3.85 g) was brominated following the procedure of Bachmann and Wick[23] to give a mixture of products (5.0 g, 96%), mp 101–102 °C (lit.[23] mp 103–104 °C). Dehydrobromination[23] of the mixture (400 mg) afforded a mixture of 2-phenyl-2-cyclohexenone and 6-phenyl-2-cyclohexenone, which was separated by HPLC on a Du Pont Zorbax SIL column (6.2 × 250 mm) eluted with 15% ether in cyclohexane (k_1' = 2.5 and k_2' = 3.8, respectively). Preparative chromatography afforded 147 mg (54%) of the desired isomer, 2-phenyl-2-cyclohexenone (k_1'), mp 92–93 °C after recrystallization from ether–petroleum ether.

The product with k_2' = 3.8 (mp 66–67 °C) was characterized as the undesired isomer (80 mg, 29.5%), 6-phenyl-2-cyclohexenone: NMR ($CDCl_3$) δ 1.0–2.6 (m, 4 H, methylenes), 3.59 (t, 1 H, H_6, $J_{5,6} = J_{5',6}$ = 8 Hz), 6.10 (sext, 1 H, H_3, $J_{2,3}$ = 10, $J_{3,4} = J_{3,4'}$ = 2 Hz), 6.9–7.5 (m, 4 aromatic and one olefinic H). Anal. Calcd for $C_{12}H_{12}O$: C, 83.68; H, 7.03. Found: C, 83.62; H, 7.00.

***trans*-1,2,3,4,4a,10a-Hexahydrophenanthrene (9).** 2-Phenyl-2-cyclohexenone was converted to *trans*-2-phenylcyclohexylacetic acid (**6**) following the procedure of Ginsburg and Pappo[24] via ketone **5**. Following published procedures,[7] **6** was cyclized to **7** with sulfuric acid and **7** was reduced with sodium borohydride in methanol to give a mixture of epimeric alcohols, **8**, mp 85–88 °C, which were dehydrated to **9** by refluxing for 0.5 h with *p*-toluenesulfonic acid in benzene. Olefin **9** was obtained from 1.25 g of **8** as an oil (1.14 g, 100%): NMR ($CDCl_3$) δ 1.1–1.8 (m, 10 H, methylenes and methines), 5.70 (q, 1 H, H_{10}, $J_{9,10}$ = 10, $J_{10,10a}$ = 1 Hz), 6.37 (q, 1 H, H_9, $J_{9,10}$ = 10, $J_{9,10a}$ = 2.5 Hz), 6.8–7.3 (m, 4 aromatic H); *m/e* (CI, NO–N_2) 184 (M^+).

Synthesis of 3 by Direct Epoxidation. A mixture of **9** (250 mg), *m*-chloroperoxybenzoic acid (1 g), and anhydrous tetrahydrofuran (3 mL) was allowed to stand at room temperature for 4 h. Workup following the procedure of Yagi et al.[6a,25] gave 250 mg (92%) of colorless oil: NMR ($CDCl_3$) δ 1.0–2.6 (m, 8 H, 4 methylenes and 2 methines), 3.44 (d, 1 H, H_{10}, $J_{9,10}$ = 4.5 Hz), 3.88 (d, 1 H, H_9, $J_{9,10}$ = 4.5 Hz), 7.0–7.6 (m, 3 aromatic H), 8.00 (m, 1 H, H_8); *m/e* (CI, NO–N_2) 200 (M^+). In our experience the direct epoxidation product contained varying amounts of an isomeric contaminant that was not identical with **4** and presumably represents an isomer with the cis A/B ring fusion. Formation of this product could be avoided by careful chromatographic purification of the major component of the olefin **9** on an 8 × 250 mm Hi-eff Micropart silica gel column (Applied Science Lab. Inc., State College, Pa.) eluted with cyclohexane at 4.5 mL/min; k' = 4.3 for the desired olefin; k' = 3.8 for the minor impurity. Alternatively the desired epoxide was purified by HPLC with recycle on a Du Pont Zorbax SIL column (9.4 × 250 mm) eluted with 4% ether in hexane; k' = 2.23 (k' of minor isomer = 2.5).

Synthesis of 4 via Bromohydrin. Olefin **9** (128 mg) was treated with *N*-bromoacetamide (105 mg) in 12 mL of 3:1 tetrahydrofuran–water for 18 h at room temperature. After isolation and crystallization from ether–petroleum ether, 140 mg (71%) of **10** was obtained; mp 101 °C; NMR ($(CD_3)_2CO$–CD_3OD) δ 1.0–2.2 (m, 8 H, methylenes), 2.4–2.75 (m, 2 H, methines), 4.34 (t, 1 H, H_{10}, $J_{9,10} = J_{10,10a}$ = 2 Hz), 4.84 (d, 1 H, H_9, $J_{9,10}$ = 2 Hz), 7.0–7.48 (m, 4 aromatic H).

Bromohydrin **10** (200 mg) was treated with the hydroxide form of Amberlite IRA-400 resin (500 mg) for 7 h at room temperature to afford 140 mg (96.5%) of epoxide **4**. Colorless feathers were obtained after recrystallization from petroleum ether: mp 102–103 °C; NMR ($CDCl_3$) δ 1.0–2.64 (m, 4 methylenes and 2 methines) 3.27 (q, 1 H, H_{10}, $J_{9,10}$ = 4.1, $J_{10,10a}$ = 0.5 Hz), 3.73 (d, 1 H, H_9, $J_{9,10}$ = 4.1 Hz), 7.0–7.3 (m, 3 aromatic H), 7.50 (m, 1 H, H_8); *m/e* (CI, NO–N_2) 200 (M^+).

Preparation of Diols and Diacetates. A mixtures of *trans*-**4**- and *cis*-**4**-diols was prepared by hydrolysis of **4** in 1:9 dioxane–water containing ~10^{-3} M perchloric acid. The solution was neutralized and evaporated and the products were separated by preparative HPLC (3 recycles) on a Du Pont Zorbax ODS column (9.4 × 250 mm) eluted with 60% methanol, k' = 8.1 (trans) and 8.3 (cis). Similar hydrolysis of **3** gave exclusively *trans*-**3**-diol which did not require further purification. *cis*-**3**-Diol was prepared by oxidation of 100 mg of **9** (which had been purified by chromatography on the Du Pont Zorbax ODS column, eluted with acetonitrile at 3.5 mL/min; k' = 1.4) with 150 mg of osmium tetraoxide in 2 mL of redistilled pyridine. After ~2 h the reaction mixture was quenched with a mixture[26] of sodium bisulfite, water, and pyridine and the products were extracted into chloroform. The chloroform was dried (sodium sulfate) and the residue on evaporation of the solvent was crystallized from ether–hexane to give 91 mg of *cis*-**3**-diol (76%). Diacetates of the diols were prepared by treatment with acetic anhydride in pyridine and were purified by reversed phase HPLC on a Zorbax ODS column (eluted with methanol–water), with the exception of *cis*-**3**-diacetate which was extracted into ether after treatment of the pyridine-acetic anhydride reaction mixture with methanol and water. Usual workup provided *cis*-**3**-diacetate which was crystallized from methanol–water.

Bromohydrin Acetate 11. Bromohydrin **10** (20 mg) was acetylated with 50 mg of acetic anhydride and 0.3 mL of pyridine overnight at room temperature. After removal of the pyridine, the residue was taken up in benzene (50 mL). The benzene extract was washed with water, 3% hydrochloric acid, 5% sodium bicarbonate solution, and water. Crude **11** obtained after drying and evaporation of the benzene was recrystallized from petroleum ether to give colorless prisms: mp 95 °C; NMR ($CDCl_3$) δ 1.0–2.2 (m, 8 H, methylenes), 2.08 (s, 3 H, CH_3CO), 2.4–2.8 (m, 2 H, methines), 4.27 (t, 1 H, H_{10}, $J_{9,10} = J_{10,10a}$ = 2.2 Hz), 6.10 (d, 1 H, H_9, $J_{9,10}$ = 2.2 Hz), 7.1–7.44 (m, 4 aromatic H).

B. Kinetics. Rates of reaction were determined spectrophotometrically (235 nm), using a Gilford Model 2400 spectrophotometer, in 1:9 (v/v) dioxane–water, ionic strength 0.10 M ($NaClO_4$), at 25 °C. Where necessary, the pH was controlled with 2 × 10^{-3} M buffers. Dioxane used in the kinetics experiments was distilled from sodium and stored under refrigeration. Typically, reactions were initiated by addition of 10 μL of a dioxane stock solution, containing 4 mg/mL of **3** or **4**, to 3 mL of the reaction solution.

Deuterium Isotope Effect. Ketone **7** (200 mg) was deuterated α to the carbonyl group by treatment at room temperature for a period ≥16 h with 9 mL of deuteriomethanol containing 0.08 mmol of sodium methoxide, followed by solvent evaporation and repetition of the procedure. After 5 cycles, the mixture was acidified with 2 μL of concentrated deuteriosulfuric acid and evaporated to dryness. The residue was extracted into ether and the ether evaporated to yield 135 mg (67% recovery) of ketone. Mass spectral analysis showed the compound to contain ~94% dideuterio, ~4% monodeuterio, and ~2% diprotio ketone. The ketone was converted to **4**-D by the same procedures used for the undeuterated compound, modified by substitution of lithium aluminum hydride (1.2 mol/mol of ketone) in ether for sodium borohydride, to effect the reduction of **7**-D. Mass spectral analysis of bromohydrin **10**-D indicated 92%, and analysis of **4**-D indicated 87% deuterium incorporation, respectively, into these products. Since **4**-D was shown to contain an unknown impurity (see below), which may affect the isotopic analysis, the isotopic purity of **4**-D was taken as 92% from the precursor **10**-D.

Paired kinetic determinations of k_0 for **4** and **4**-D were carried out simultaneously by using a Cary 219 spectrophotometer equipped with a thermostated multiple sample holder. Product analysis of **4**-D indicated the presence of an impurity that could be largely removed by chromotography on a Du Pont Zorbax SIL column eluted with hexane–tetrahydrofuran (93:7). The **4**-D thus purified contained large amounts (~60%) of ketone from degradation on the column. Values of k_0 determined with use of crude and chromatographed **4**-D were identical within experimental error.

Registry No. 3, 28352-32-1; *cis*-**3** diol, 53446-97-2; *cis*-**3** diol diacetate, 80738-29-0; *trans*-**3** diol, 53446-98-3; *trans*-**3** diol diacetate, 80738-30-3; **4**, 28352-34-3; *cis*-**4** diol, 53446-96-1; *cis*-**4** diol diacetate, 80794-86-1; *trans*-**4** diol, 53446-99-4; *trans*-**4** diol diacetae, 80794-87-2; **5**, 80738-31-4; **6**, 52092-27-0; **7**, 21656-46-2; **8**, 25662-65-1; **9**, 16804-85-6; **10**, 28352-33-2; **11**, 80738-32-5; 2-phenyl-2-cyclohexenone, 4556-09-6; 6-phenyl-2-cyclohexenone, 36702-38-2; benz[*a*]anthracene, 56-55-3; benzo[*a*]anthracene diol epoxide 1, 63493-01-6; benzo[*a*]anthracene diol epoxide 2, 63438-26-6.

Supplementary Material Available: X-ray experimental details, tables of atomic parameters and observed and calculated structure factors for **11**, and kinetic data used for the determination of k_0^H/k_0^D for **4** (19 pages). Ordering information is given on any current masthead page.

(23) Bachmann, W. E.; Wick, L. B. *J. Am. Chem. Soc.* **1950**, 72, 3388–3392.

(24) Ginsburg, D.; Pappo, R. *J. Chem. Soc.* **1951**, 938–945.

(25) Yagi, H.; Thakker, D. R.; Hernandez, O.; Koreeda, M.; Jerina, D. M. *J. Am. Chem. Soc.* **1977**, *99*, 1604–1611.

(26) Baran, J. S. *J. Org. Chem.* **1960**, *25*, 257.