88-8; 6, 75961-47-6; 7, 75948-89-9; 8, 3312-37-6; 9, 13304-43-3; 10, 52033-64-4; 11, 42349-44-0; 12, 75948-90-2; 13, 7434-84-6; 14, 3312-38-7; 15, 17932-18-2; 2,3-diphenylindene, 5324-00-5; 1,2-diphenylindene, 18636-54-9; 1,1-dimethylindene, 18636-55-0; 3-(*p*-bromophenyl)-3-phenyl-1-indanol, 75948-91-3; 1-(*p*-bromophenyl)-1,1-diphenylcarbinol, 61623-62-9; PhBr, 108-86-1; *p*-bromobenzophenone, 90-90-4; malonic acid, 141-82-2; phthalic anhydride, 85-44-9; (*p*-bromophenyl)acetic acid, 1878-68-8; benzylidenephthalide, 4767-55-9; *p*-BrC_6H_4Br, 106-37-6; (*p*-methoxyphenyl)acetic acid, 104-01-8; *p*-methoxybromobenzene, 104-92-7; methylcyclopentadiene, 96-38-8; vinylcyclopentadiene, 29647-85-6; formylcyclopentadiene, 56598-51-7; phenylcyclopentadiene, 1961-98-4.

Solvomercuration–Demercuration. 9. Oxymercuration–Demercuration of Chloro-, Epoxy-, and Thiomethyl-Substituted Alkenes

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The oxymercuration–demercuration (OM–DM) of allyl, crotyl, 3-buten-1-yl, 4-penten-1-yl, and 5-hexen-1-yl chlorides and methyl sulfides as well as 3,4-epoxy-1-butene, 4,5-epoxy-1-pentene, and 5,6-epoxy-1-hexene has been studied. Allyl chloride undergoes a slow but normal OM to give the Markovnikov oxymercurial. However, in situ demercuration under the standard conditions (NaOH, $NaBH_4$) gives only allyl alcohol. Fortunately, demercuration with an ethanolic solution of sodium borohydride results in high yields of the chlorohydrin accompanied by small amounts of propylene oxide. In contrast, crotyl chloride fails to give any products resulting from the OM–DM sequence. Thus, 3-buten-2-yl chloride underwent only solvolytic reaction while 2-methylallyl chloride underwent exclusive OM to give, upon DM, the expected Markonikov chlorohydrin. Similarly, 3-buten-1-yl chloride underwent exclusive hydration under the standard OM-DM conditions. In the case of 4-penten-1-yl chloride, the C1–C5 neighboring-group participation was seen during OM. However, 5-hexen-1-yl chloride showed exclusive hydration to give a 94% yield of the Markovnikov chlorohydrin. The approximate rates of solvolysis of a series of representative alkyl halides have been determined under the OM conditions. The OM–DM of 3,4-epoxy-1-butene proceeded to give hydrated products although the yield was low, ca. 60%. On the other hand, 4,5-epoxy-2-pentene gave products arising only from participation of the epoxide ring in the OM stage. Moreover, the yields of these products are very low, only ca. 15%. By contrast, the OM–DM of 4,5-epoxy-1-pentene proceeds cleanly, giving a 96% yield of the Markovnikov epoxy alcohol. In the case of 5,6-epoxy-1-hexene, ~80% of the products arise from epoxide participation in the OM stage. With the exception of the crotyl derivative, the (methylthio)alkenes undergo hydration cleanly, although slowly, to give approximately 70–80% yields of the thio alcohols. The crotyl alkene gave 3-buten-2-ol in only ~20% yield.

In the preceding paper,[2] it was demonstrated that the methoxy, hydroxy, and acetoxy groups in general offered no major difficulties in the oxymercuration–demercuration sequence. Consequently, it appeared appropriate to expand our studies on the OM–DM of representative substituted alkenes. Thus, we examined the chloro, epoxy, and methylthio groups in the allyl, crotyl, 3-buten-1-yl, 4-penten-1-yl, and 5-hexen-1-yl structures.

For various reasons, each of these groups might be expected to pose difficulties, especially during the OM stage. For example, it is well-known that mercury salts catalyze the solvolyses of alkyl halides.[3] Similarly, organosulfur compounds often react readily with mercuric salts to form stable addition compounds.[4] It is shown that certain epoxides are incompatible with the oxymercuration reaction.[5,6]

Results and Discussion

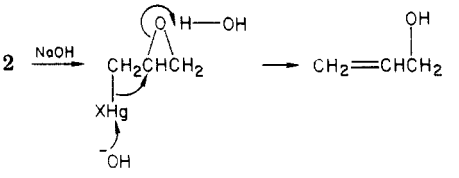
Chloro-Substituted Alkenes. The significant results for the OM–DM of these alkenes are summarized in Table I.

The oxymercuration of allyl chloride is unusually sluggish, requiring 1 h to achieve an approximately 90% conversion of the olefin. However, in situ demercuration under standard conditions (addition of excess sodium hydroxide followed by the addition of an alkaline solution of sodium borohydride) results in an 83% yield of allyl alcohol, rather than the expected Markovnikov chlorohydrin 1. However, ^1H NMR analysis of the OM reaction

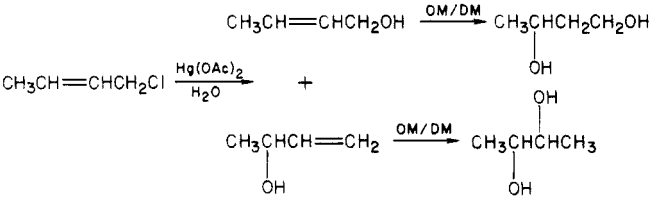
$CH_3C(OH)HCH_2Cl$ (1) $\qquad$ $AcOHgCH_2C(OH)HCH_2Cl$ (2)

mixture indicates that the expected oxymercurial 2 is formed in high yield. Subsequent experiments reveal that the mercurial 2, upon treatment with base, is rapidly converted to allyl alcohol. A reasonable mechanism for this transformation is outlined in Scheme I.[7]

Scheme I



Scheme II



(1) Texaco research fellow at Purdue University, 1972–1973. Graduate research assistant, 1969–1972 on a grant supplied from the Esso Research and Engineering Co.

(2) Brown, H. C.; Lynch, G. J. *J. Org. Chem.* **1981**, *46*, 531.

(3) Roberts, I.; Hammett, L. P. *J. Am. Chem. Soc.* **1937**, *59*, 1063.

(4) Reid, E. E. "Organic Chemistry of Bivalent Sulfur"; Chemical Publishing Co.: New York, 1960; Vol. II, p 53.

(5) Jernow, J. L.; Gray, D.; Closson, W. D. *J. Org. Chem.* **1971**, *36*, 3511.

(6) Barelle, M.; Apparu, M. *Bull. Soc. Chim. Fr.* **1972**, 2016.

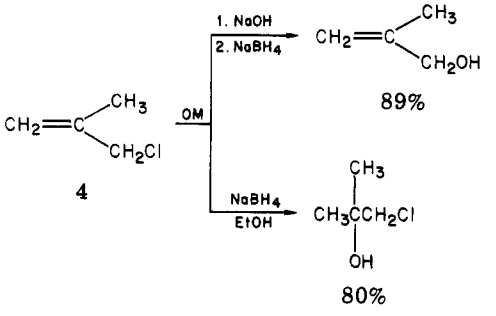
0022-3263/81/1946-0930$01.00/0

Table I. Oxymercuration-Demercuration of Chloroalkenes[a]

R of olefinic chloride	T_1, s[b]	T_2, min[c]	products	% yield (std condit)[d]	% yield ($NaBH_4$/EtOH, 0 °C, DM)[d,e]
allyl	150	60	allyl chloride	9	
			allyl alcohol	83	3
			1-chloro-2-propanol	0	70
			1,2-epoxypropane	0	21
trans-crotyl	135	30[g]	1-chloro-2-butene	31	
			2-buten-1-ol	7	
			1-buten-3-ol	9	
			2,3-butanediol	31	
			1,3-butanediol	21	
			1,2-butanediol	trace	
			1,2-epoxybutane[h]	h	
3-buten-1-yl	15	30	4-chloro-2-butanol	100	
			4-chloro-1-butanol	1[f]	
4-penten-1-yl	15	30[i]	5-chloro-2-pentanol	82[j]	
			5-chloro-1-pentanol	trace	
			4-penten-1-ol	2	
			2-methyltetrahydrofuran	9[l]	
			5-chloro-1-pentene	3	
5-hexen-1-yl	18	30[k]	6-chloro-2-hexanol	94[m]	
			5-hexen-1-ol	trace	
			6-chloro-1-hexene	4	

[a] Standard conditions unless otherwise noted. [b] Time for the yellow color to disappear.[2] [c] Complete time for the oxymercuration stage before initiating reduction. [d] By VPC analysis. [e] A solution of $NaBH_4$ in ethanol was added directly to the reaction solution from the oxymercuration stage without the prior addition of base. [f] Determined from a separate run in which the reduction stage was carried out at 0 °C, and the mixture was then acidified 1 min after reduction with aqueous HCl, saturated with NaCl, and extracted. The total chlorohydrin yield with this procedure was only 57%. This procedure was followed due to the base sensitivity of this compound. [g] No (<2%) 1-chloro-2-butanol nor 4-chloro-2-butanol could be detected in the product. [h] This material could not be seen under the VPC conditions used since it overlapped with THF. [i] Reduction was carried out at 0 °C since the 5-chloro-2-pentanol yield was only 72% with the standard procedure. No 4-chloro-1-pentanol could be detected. [j] Includes 1-2% of 2-acetoxy-5-chloropentane. [k] No (<2%) 2-methyltetrahydropyran could be detected. [l] Determined from a separate run by using water as the only solvent in the oxymercuration stage. [m] Includes 3% of 2-acetoxy-6-chlorohexane.

Scheme III



Because of this deleterious side reaction, a neutral demercuration procedure was employed in which a freshly prepared ethanolic solution of sodium borohydride was added to the OM reaction mixture. Indeed, with this procedure, a 70% yield of 1 is observed along with smaller amounts, 20%, of the cyclization product of 1, propylene oxide.[8]

In contrast to the results exhibited by the allyl system, *trans*-crotyl chloride fails to give any products arising from a simple OM–DM sequence. The mixture of diols and hydroxy alkenes which is obtained is consistent with the mercuric ion catalyzed solvolysis of the crotyl chloride to give a mixture of hydroxy alkenes, which subsequently undergo the OM–DM sequence (Scheme II).

Because of the differences in the chemistry exhibited by these two chlorides, we decided to investigate two additional allylic systems. 3-Buten-2-yl chloride (3) reacts similar to the crotyl system. No products arising from a simple OM–DM of 3 are observed (eq 1). These results

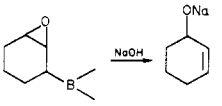
$$\underset{\underset{(18\%)}{3}}{CH_2{=}CHC(Cl)HCH_3} \xrightarrow[T_2 = 30\ min]{T_1 = 96\ s} \underset{14\%}{CH_2{=}CHC(OH)HCH_3} + \underset{5\%}{CH_3CH{=}CHCH_2OH} + \underset{35\%}{CH_3C(OH)HC(OH)HCH_3} + \underset{22\%}{HOCH_2CH_2C(OH)HCH_3} \quad (1)$$

are in accordance with the expected increase in the rate of solvolysis but not the rate of oxymercuration by the placement of an α-methyl group on allyl chloride. On the other hand, methyl substitution at the β position would be expected to increase the rate of oxymercuration and not the rate of solvolysis. Indeed, β-methylallyl chloride (4) undergoes exclusive oxymercuration with no observable evidence for solvolysis (Scheme III).

Unlike the allylic chlorides, 3-buten-1-yl chloride undergoes the standard OM–DM sequence in a normal fashion. The high regioselectivity observed in the formation of the chlorohydrins, 100:1, is typical of a normal olefin such as 1-hexene.[9]

The OM–DM of 4-penten-1-yl chloride under standard conditions results in a ca. 80% yield of chlorohydrins with a very high preference for the Markovnikov isomer. In addition, however, a ca. 11% total yield of two other

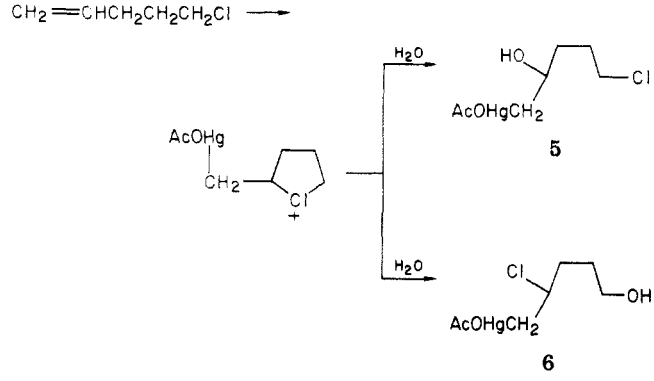
(7) Similar reactions have been previously observed: Zaidlewicz, M., private communication.



(8) No effort was made to minimize the formation of this epoxide.

(9) Brown, H. C.; Geoghegan, P. J., Jr. *J. Org. Chem.* **1970**, *35*, 1844.

Scheme IV



products, 4-penten-1-yl alcohol and 2-methyltetrahydrofuran, is observed as well. Despite the fact that none of the C1–C5 participation product, 4-chloro-1-pentanol, is observed, the possibility for neighboring-group participation still exists (Scheme IV). In contrast to **5**, the exchanged product **6** may be unstable with respect to time, undergoing a rapid demercuration to give 4-penten-1-ol and the elements of ClHgOAc. The hydroxy alkene can then be converted to 2-methyltetrahydrofuran by the OM–DM sequence.[2] However, there are other conceivable pathways to these products which do not involve C1–C5 participation during the oxymercuration stage. Consequently, these observations do not unambiguously indicate such participation.

Finally, the OM–DM of 5-hexen-1-yl chloride proceeds in the expected fashion, giving a 94% yield of the Markovnikov chlorohydrin.

The observation of mercuric ion catalyzed solvolysis in some of the allylic chlorides raised the question as to the structural types of haloalkenes which will tolerate the OM conditions. Examination the OM–DM of a significant number of such substrates would be prohibitive. Consequently, we employed a simpler procedure based on the T_1 value.[9]

The yellow color, generated by the addition of tetrahydrofuran to an aqueous solution of mercuric acetate, disappears upon the addition of ca. 0.75 equiv of acetic acid or ca. 0.50 equiv of hydrochloric acid. Thus, the rate of the solvolytic reaction of a halide which also generates acid can be approximated as the T_1 value. A comparison of the T_1 values for a representative alkyl halide with previously published T_1 values for olefins[9] will give some idea as to the compatibility of a particular type of halide. The results of such a study are summarized in Table II.

The results indicate that considerable difficulty can be expected in the OM–DM of unsaturated tertiary halides, secondary iodides, benzylic bromides, and benzylic iodides. On the other hand, secondary chlorides, benzylic chlorides, primary bromides, and primary iodides should offer no difficulties for most types of olefins.

We subjected these ideas to experimental test, choosing 4-bromo-1-pentene as the substrate. Using 1-pentene as the olefin model, T_1 = 15 s, and the T_1 value for a secondary bromide (5 min), one would expect no difficulties in the OM–DM of this alkene. Indeed, the only products observed, in 87% yield, corresponded to the OM reaction only (eq 2).

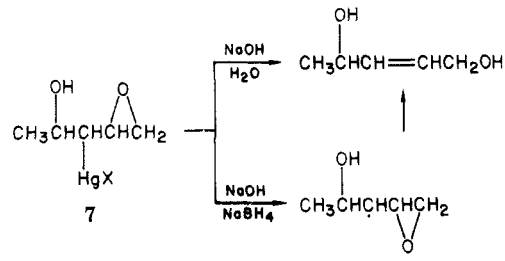
$$\underset{9\%}{CH_2{=}CHCH_2C(Br)HCH_3} \xrightarrow[T_2 = 15\ min]{OM} \xrightarrow[0\ °C]{DM} \underset{82\%}{CH_3C(OH)HCH_2C(Br)HCH_3} + \underset{5\%}{CH_3C(OAc)HCH_2C(Br)HCH_3} \quad (2)$$

Table II. T_1 Values for Halide Solvolyses under Oxymercuration Reaction Conditions[a]

halide	T_1[b]	halide	T_1[b]	halide	T_1[b]
tert-butyl chloride	18 s				
sec-butyl chloride	3.3 days	*sec*-butyl bromide	5 min	isopropyl iodide	7 s
		n-butyl bromide	2.6 days	*n*-butyl iodide	58 min
benzyl chloride	20 h	benzyl bromide	1.33 min		

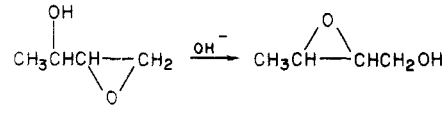
[a] A 5-mmol sample of the halide was added to a stirred mixture of 5 mmol of $Hg(OAc)_2$ in 5 mL of H_2O and 5 mL of THF at room temperature (ca. 25 °C). [b] Time for the yellow color to disappear.

Scheme V



Epoxy-Substituted Olefins. As is the case for the chloro alkenes, the products obtained from the OM–DM of epoxy olefins are very much dependent on the alkene structure. The results are summarized in Table III.

The OM–DM of 3,4-epoxy-1-butene is rapid (T_1 = 40 s). However, the yield of hydration products is low, approximately 60%. In addition to the Markovnikov epoxy alcohol, a small amount of 2,3-epoxy-1-butanol is also observed. However, this product disappears when a less basic demercuration procedure is employed. Evidently the major product, 3,4-epoxy-2-butanol, is being isomerized in the presence of base via a previously documented reaction[10] (eq 3).



(3)

Because of the low material balances observed in both cases, separate experiments were undertaken to determine the ability to recover these epoxy alcohols from aqueous media. Indeed, only 81% of the epoxybutanols can be recovered from reaction mixtures where the standard demercuration procedure is employed. Moreover, with the less basic DM procedure, only 40% recovery is possible. However, correction of the values in Table III for the inefficiency in recovery still results in material balances of approximately 70–75%. While we were unable to account for the remaining material, a good possibility is that during the OM stage, opening of the epoxide linkage occurs to form triols during the DM stage. Such species are extraordinarily difficult to extract from aqueous media. Moreover, triols would be virtually impossible to detect by the VPC methods available to us. The OM–DM of 4,5-epoxy-2-pentene gives products in only ca. 20% yield.

The major product in 12% yield is 2-pentene-1,4-diol. This diol can arise from the expected oxymercurial (**7**) in either of two ways: (1) base-catalyzed elimination of **1** or (2) during the demercuration[11,12] of **1** (Scheme V). The

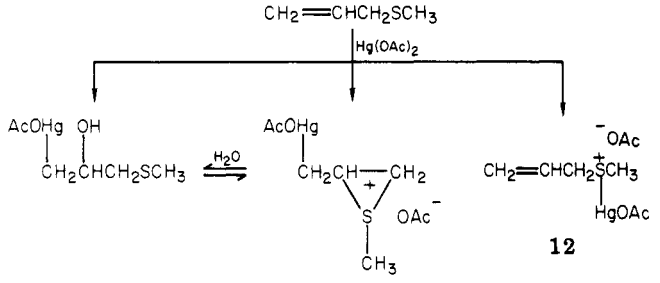
(10) Payne, G. B. *J. Org. Chem.* **1962**, *27*, 3819.

Table III. Oxymercuration–Demercuration of Epoxy-Substituted Olefins[a]

epoxy olefin	T_1,[b] s	T_2,[c] min	products	% yield: normal reducing agents[d,e]	% yield: modified reducing agents[d]
3,4-epoxy-1-butene	40	30	3,4-epoxy-2-butanol	56[f]	31[h,i]
			2,3-epoxy-1-butanol	5[f,g]	
			2-butene-1,4-diol	trace	
4,5-epoxy-2-pentene	140	30	4,5-epoxy-2-pentanol	3[j]	
			2,3-epoxy-1-pentanol[g]		
			1,2-epoxy-3-pentanol	trace	
			2-pentene-1,4-diol	12	
			triols	k	
			others	l	
4,5-epoxy-1-pentene	3	30	4,5-epoxy-2-pentanol	96	
5,6-epoxy-1-hexene	3	30	4,5-epoxy-2-hexanol	5[m]	7[h,m] (6)[h,m,p]
			cis-5-methyltetrahydrofurfuryl alcohol	23	19[h] (20)[h,p]
			trans-5-methyltetrahydrofurfuryl alcohol	10[n]	7[h,n] (8)[h,n,p]
			cis-6-methyl-3-hydroxytetrahydropyran[o]	27[n]	21[h,n] (21)[h,n,p]
			trans-6-methyl-3-hydroxytetrahydropyran[o]	21	20[h] (17)[h,p]

[a] Standard OM stage; DM stage carried out at 0 °C in all cases. [b] Time for yellow color to disappear. [c] Complete time for the OM stage before initiating DM stage. [d] By VPC analysis. [e] For a 5-mmol scale: 5 mL of 3 M NaOH first and then 5 mL of 0.5 M $NaBH_4$ in 3 M NaOH; K_2CO_3 salt out at 0 °C. [f] A control experiment using 100 reaction percent 3,4-epoxy-2-butanol in a blank OM-DM carried out under identical reaction and workup conditions shows that only 81% of epoxybutanols can be recovered. Furthermore, the recovered epoxybutanols are a mixture of 64% 3,4-epoxy-2-butanol and 17% of 2,3-epoxy-1-butanol (as two isomers) resulting from partial basic equilibration. [g] As a mixture of two distinguishable (VPC) isomers, presumably the cis-trans pair. [h] 2 equiv of NaOH and then 0.5 M $NaBH_4$ in H_2O with the ether layer present during DM and with NaCl for saturation. [i] A control experiment using 100 reaction percent 3,4-epoxy-2-butanol in a blank OM-DM carried out under identical reaction and workup conditions shows that only 41% of the epoxybutanol can be recovered and that none of the two 2,3-epoxy-1-butanol isomers are present in the recovered material. [j] This peak has an identical retention time (Carbowax 20M) by mixed injection with both 4,5-epoxy-2-pentanol and with the shorter retention time isomer of the cis-trans pair of 2,3-epoxy-1-pentanol. [k] The ^1H NMR experiment described in the text suggests that the major reaction products are triols. [l] In the VPC of the reaction mixture, an additional unidentified component of ca. 6% is present with a retention time similar to that of the epoxypentanols. [m] By ^1H NMR analysis. [n] Approximate values; combination of VPC and NMR analysis; total yield of *cis*-8 plus *trans*-9 by VPC. The numerical values of each were assigned by assuming the same proportion of *cis*-8 and *trans*-9 found by NMR in an isolated sample of the VPC peak of all three reactions combined. [o] Tentative assignment; see Experimental Section and text. [p] A 0 °C OM stage was employed.

Scheme VI

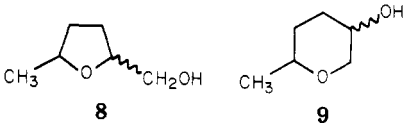


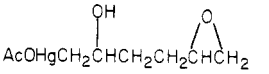
remainder of the products consists of a mixture of epoxy pentanols, which result from the DM of 1 along with ca. 5% of an unidentified compound.

In this case, the material balance is very low, indicating the presence of large amounts of nonvolatile products. Consequently, we examined the OM of 4,5-epoxy-2-pentene in D_2O by ^1H NMR. Indeed, the majority of the products from the oxymercuration reaction appears to be the mercurated triol, obtained by opening of the epoxide linkage. Previously Barelle and Apparu[6] reported that the OM–DM of 3,4-epoxycyclooctene resulted in several products, apparently a consequence of the opening of the epoxide ring.

In marked contrast to the previous cases, the OM–DM of 4,5-epoxy-1-pentene proceeds cleanly with no side reactions to give a 96% yield of the Markovnikov alcohol, 4,5-epoxy-2-pentanol. No evidence for epoxide ring cleavage is observed.

Closson and co-workers[5] have recently examined the OM–DM of 5,6-epoxy-1-hexene. They reported the products to be a complicated mixture of alcohols and that a ^1H NMR analysis revealed no epoxy compounds. On the basis of a series of reactions carried out on the products, these workers concluded that the initial alcohol products were probably a mixture of 8 and 9.





10

We have reexamined the OM–DM of this epoxy alkene in more detail. Indeed, the majority of the products appears to be 8 and 9 in ca. 80% total yield.[13] However, a small amount of the Markovnikov epoxy alcohol is ob-

(11) Demercurations with sodium borohydride have been shown to proceed via a free radical pathway: Pasto, D. J.; Gontarz, J. A. *J. Am. Chem. Soc.* **1969**, *91*, 719; Grey, G. A.; Jackson, W. R. *Ibid.* **1969**, *91*, 6205; Whitesides, G. M.; Fillippo, J. S. *Ibid.* **1970**, *92*, 6611.

(12) Radical transformations of this type are not unprecedented: Suzuki, A.; Miyaura, N.; Itoh, M.; Brown, H. C.; Holland, G. W.; Negishi, E. *J. Am. Chem. Soc.* **1971**, *93*, 2792.

(13) We were able to positively identify 8. However, the structure for 9 is based solely on a ^1H NMR analysis and must be considered tentative: see the Experimental Section.

(14) Another possibility is the hydrolysis of sulfur adduct of the mercuric salt, e.g.

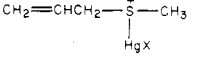


Table IV. Oxymercuration-Demercuration of Allyl Methyl Sulfide[a]

mercury salt	% excess mercury salt	T_2[c]	product yield, %[d,e] 1-(thiomethyl)-2-propanol[f]	product yield, %[d,e] allyl methyl sulfide
$Hg(OAc)_2$	0	30 min[b]	24	65
	0	2 h	54	40
	0	18 h	66	25
	0	48 h	67	20
	0	8 days	58	18
	50	2 h	57	27
	50	18 h	62	14
	100	18 h	65	19
$Hg(O_2CCF_3)_2$	0	30 min	70	20
	0	2 h	78	15
	0	18 h	70	16

[a] Standard conditions unless otherwise noted. [b] T_1 (= 7.5 min) is the time for the yellow color to disappear. [c] Complete time for the OM stage before initiating reduction. [d] By VPC analysis. [e] Small amounts, ca. 1-3%, of allyl alcohol were also observed. [f] A small amount of a peak of slightly shorter retention time (Carbowax 20M) was observed and was assumed to be the corresponding acetate on the basis of retention time and irregularity in magnitude from run to run corresponding to different times of basic contact. This percent value is not included in the table but only amounted to an estimated 1-4%.

served as well, resulting from the formation and subsequent DM or **10**.

Clearly, the results of this study corroborate the previous conclusion that the oxymercuration of 5,6-epoxy-1-hexene proceeds with participation of the epoxide ring. It should be pointed out that when the OM–DM is carried out at 0 °C, essentially identical results are obtained. This would rule out the possibility that the cyclic ethers arise from an acid-catalyzed opening of the epoxide ring in the oxymercurial **10**.

Methylthio-Substituted Alkenes. Sulfides have been traditionally characterized as the solid addition compounds they form with mercuric salts.[4] Consequently, we were interested to see if sulfur-substituted alkenes would undergo the oxymercuration reaction. Indeed, allyl methyl sulfide underwent reaction, albeit slowly, to produce 1-(thiomethyl)-2-propanol. The remainder of the material appears to be the starting alkene plus small amounts of allyl alcohol (Table IV).

The OM with mercuric acetate is unusually sluggish, T_1 = 7.5 min. Moreover, after a reaction time of 30 min ($4T_1$), only a 24% yield of the hydrated product is observed. However, the T_1 value usually corresponds to 40–60% reaction.[9] These exceptional observations would indicate that some other mercury-containing species is also being formed in addition to the Markovnikov oxymercurial. The most likely possibilities are the mercurated episulfonium salt **11** or the sulfur-coordinated adduct of mercuric acetate **12** (Scheme VI). We were unable to determine the exact nature of this species. When mercuric trifluoroacetate is used, a faster rate of oxymercuration is observed with slightly higher yields of the hydration product.

There are several possible pathways to small amounts of allyl alcohol.[14] The most likely one appears to be demercurithiomethylation[15] during the reduction of either the anti-Markovnikov mercurial or the interchanged mercurial resulting from alternate opening of **11** (eq 4).

$$HOCH_2C(HgOAc)HCH_2SCH_3 \xrightarrow{DM} HOCH_2CH{=}CH_2 \xleftarrow{DM} HOCH_2C(SCH_3)HCH_2HgOAc \quad (4)$$

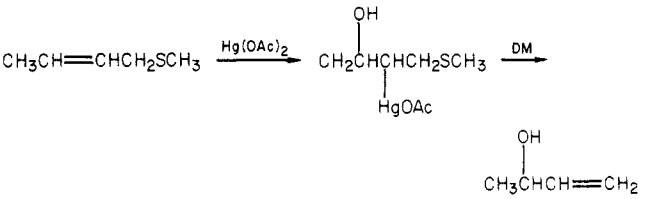
In the case of crotyl methyl sulfide, the only product observed is 3-buten-2-ol in ca. 25% yield. The remainder of the material is the starting alkene. Moreover, this reaction is even more sluggish than that for the allyl sulfide (Table V).

Table V. Oxymercuration-Demercuration of Crotyl Methyl Sulfide[a]

mercury salt	T_2,[c] h	product yield, %[d,e] 3-buten-2-ol	product yield, %[d,e] crotyl methyl sulfide
$Hg(OAc)_2$	4[b]	15	72
	8	20	72
	24	25	62
$Hg(O_2CCF_3)_2$	1	17	76
	4	19	70
	8	23	73

[a,c,d] See corresponding footnotes in Table IV. [b] T_1 = 1.5 h. See footnote *b* of Table IV. [e] No significant amount of 1-(methylthio)-2-butanol nor 4-(methylthio)-2-butanol was present.

Scheme VII



As was the case for the allyl sulfide, these results are readily attributable to the loss of $AcOHgSCH_3$ from the normal oxymercurial during demercuration (Scheme VII). It should also be pointed out that because the crotyl alkene is an internal disubstituted olefin, it should undergo the OM reaction at a significantly slower rate than the allyl alkene,[16] thus allowing the competing formation of the sulfur adduct to predominate, e.g., $CH_3CH{=}CHCH_2S^+CH_3(HgX)$.

The reaction of 3-buten-1-yl methyl sulfide is rapid, T_1 = 55 s. The only products in this case are the hydration products. However, there is a remarkably high amount of the anti-Markovnikov thiol, ca. 8%, present in the product (Table VI).

Such poor regioselectivity from a terminal olefin is presumably due to the formation of a significant amount

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Table VI. Oxymercuration–Demercuration of 3-Buten-1-yl Methyl Sulfide[a]

	% yield of products[d]		
T_2[c]	Markovnikov alcohol[e]	anti-Markovnikov alcohol[f]	3-buten-1-yl methyl sulfide
30 min[b]	61	8	25
2 h	67	8	22
24 h	76	9	7

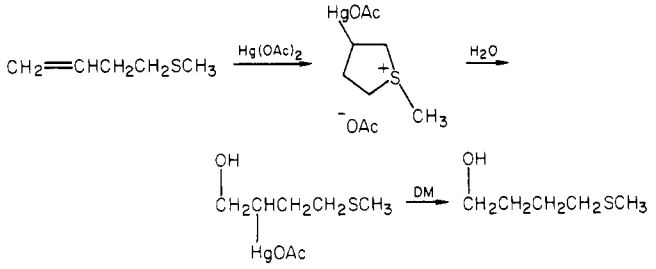
[a,c,d] See corresponding footnotes in Table IV. [b] T_1 = 55 s. See footnote b of Table IV. [e] 2-Hydroxy-4-(thiomethyl)butane. [f] 1-Hydroxy-4-(thiomethyl)butane.

Table VII. Oxymercuration–Demercuration of 4-Penten-1-yl Methyl Sulfide[a]

		product yield, %[d]	
% excess mercuric acetate	T_2[c]	5-(thiomethyl)-2-pentanol[e]	4-penten-1-yl methyl sulfide
0	30 min[b]	45	44
0	2 h	62	33
0	24 h	76	21
50	2 h	76	17
50	24 h	78	10

[a,c,d] See corresponding footnotes in Table IV. [b] T_1 = 44 s. See footnote b of Table IV. [e] Plus its acetate; see text.

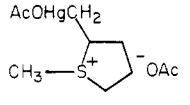
Scheme VIII



of the five-membered cyclic sulfonium ion, which, upon nucleophilic attack by water, is converted to the anti-Markovnikov oxymercurial (Scheme VIII).

The OM–DM of 4-penten-1-yl methyl sulfide results in two products, the Markovnikov alcohol and the corresponding acetate in a 60:40 ratio (Table VII). With other substrates also we observed some acetates, although in much smaller amounts. As the time for demercuration (contact time with base) was approximately the same for all cases, we must conclude that for some unknown reason 4-penten-1-yl methyl sulfide undergoes oxymercuration to produce an unusually large amount of the acetate.

The T_1 value, 44 s, indicates an extraordinarily rapid reaction with mercuric acetate. However, the rate of formation of OM products is unusually slow. This indicates the possibility of the formation of another mercury-containing species, either the sulfur adduct or possibly the five-membered cyclic sulfonium ion **13**.



13

The OM–DM of nonallylic, unsaturated primary chlorides proceeds to give high yields of the Markovnikov chlorohydrin. Allyl chloride undergoes the OM reaction cleanly; however, the resulting oxymercurial must be demercurated under neutral conditions to obtain the chlorohydrin.

On the other hand, crotyl chloride fails to give any chlorohydrins. The only products observed result from a mercuric ion catalyzed solvolysis. Moreover, this deleterious side reaction is expected to be significant in the reaction of mercuric salts with unsaturated tertiary halides, secondary iodides, or benzylic bromides and iodides.

In contrast, the OM–DM of unsaturated epoxides usually results in the opening of the epoxide ring, either in the OM or DM stage, which results in low yields of the Markovnikov epoxy alcohols. Only 4,5-epoxy-1-pentene undergoes the OM–DM sequence to give a high yield of the desired alcohol.

On the other hand, the OM–DM of (methylthio)alkenes usually proceeds to give 70–80% yields of thioalcohols. However, the OM stage is quite sluggish, probably due to the formation of either episulfonium salts or sulfur adducts of mercury. Only the crotyl alkene fails to give any of the hydration product.

Experimental Section

Materials. All of the substrates were either commercially available or prepared as described below. The purity and structure of each of the substrates were confirmed by VPC analysis and by other physical properties (n^{20}_D, IR and NMR spectra).

4-Bromo-1-pentene. 4-Penten-2-ol was prepared according to the literature procedure.[17] The isolated product contained 6% of paraldehyde impurity. By using a combination of Schleyer's[18] and Tipson's[19] procedures, 10.2 g of the 94% pure 4-penten-2-ol was converted into 25.2 g (95%) of a crude oily tosylate and was converted directly to the bromide.[20] The middle fraction during distillation weighed 5.1 g (95% pure by VPC); bp 110–112 °C (lit.[21] bp 111–112 °C).

4,5-Epoxy-2-pentene. 1-Bromo-1-propene was converted to 1-chloro-3-penten-2-ol by literature procedures[22-25] in 69% yield, bp 68–72 °C (16 mm) [lit.[25] bp 66–67 °C (15 mm)], which gave a 77% yield of 98% pure (cis–trans mixture) 4,5-epoxy-2-pentene, bp 102–104 °C [lit.[26] bp 101–102 °C (trans isomer), 103–104 °C (cis isomer)], according to the literature procedure.[26]

4,5-Epoxy-1-pentene. Allylmagnesium bromide was reacted with chloroacetaldehyde, and the resulting chlorohydrin, bp 65–70 °C (16–17 mm) (lit.[27] bp 163 °C), was obtained in 80% yield. Cyclization with NaOH gave 4,5-epoxy-1-pentene, bp 92–94 °C (lit.[27] bp 93.5 °C), in 71% yield (99% purity).

5,6-Epoxy-1-hexene. The title compound was prepared according to a literature[28] procedure in 70% yield; bp 119–120 °C [lit.[28] bp 119–121 °C (760 mm)]. VPC analysis indicated about 95% purity.

Crotyl Methyl Sulfide. Crotyl methyl sulfide was prepared according to the literature procedure.[29]

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3-Buten-1-yl Methyl Sulfide. A literature procedure[30] was followed for the preparation of this compound.

4-Penten-1-yl Methyl Sulfide. 5-Chloro-1-pentene was converted to 4-penten-1-yl methyl sulfide according to a known procedure.[31]

Standard Analytical OM–DM Procedure. The procedure was identical with that described previously.[2] As mentioned in the text, the DM of epoxides was carried out at 0 °C. For the OM–DM of the sulfides, the THF layer was removed without further extraction. Other modifications have been indicated in the text in the appropriate places.

VPC Analysis. See the preceding paper.[2]

OM–DM of Allyl Chloride. A sample of 1-chloro-2-propanol was prepared according to a literature procedure.[32] A sample of 3-chloro-1-propanol (Matheson Coleman and Bell) was commercially available.

The allyl alcohol arising from OM–DM of allyl chloride was identified by VPC and NMR.

The modified reduction procedure for obtaining the chlorohydrin from allyl chloride was as follows. After a normal 10-mmol-scale OM stage (T_2 = 1 h), the reaction mixture was cooled to 0 °C, and a solution of 0.38 g (10 mmol) of $NaBH_4$ in 20 mL of ethanol was added dropwise to maintain the reaction temperature between −4 and +4 °C, with cooling with a dry ice–acetone bath as needed. The solution was stirred for an additional 20 min after all of the $NaBH_4$ solution had been added, and the aqueous phase was saturated with K_2CO_3. An appropriate hydrocarbon standard was added, the layers were separated, and the aqueous phase was extracted with an additional 10 mL of THF. The combined extracts were dried over K_2CO_3. The resulting 1-chloro-2-propanol was identified by mixture VPC and comparison of the IR and NMR spectra of the material purified by preparative VPC with those of an authentic sample of 1-chloro-2-propanol.

It was stated in the text that the difficulty with hydrating allyl chloride by using the standard OM–DM procedure was traced to the stage at which the NaOH solution was added to initiate reduction. Experiments which led to this conclusion are as follows.

It was first established that no significant amount of allyl alcohol is present after completion of the oxymercuration stage and that the normal oxymercurial is formed. Thus, allyl chloride was oxymercurated under standard conditions for 1 h. The reaction mixture was evaporated by gradually decreasing the pressure to ca. 1 mm, and the volatile components were collected in a dry ice–acetone trap. Saturation of the trap contents with K_2CO_3 followed by the addition of a hydrocarbon standard and subsequent VPC analysis revealed that no allyl alcohol was present in the volatile components; only a small amount of allyl chloride was present in the trap. The residual viscous liquid remaining in the reaction flask was weighed (0.87 ± 0.02 g for a 2.5-mmol-scale reaction; theoretical weight for $C_3H_5Cl(OH)HgOAc$ is 0.88 g) and then dissolved in D_2O. The NMR spectrum was consistent with the structure of 1-(acetoxymercuri)-3-chloro-2-propanol.

Analysis of the yellow precipitate formed on addition of NaOH accounted for 88% of the mercury.

Another experiment established that allyl alcohol was formed when base was added to initiate reduction. Thus, after allyl chloride was oxymercurated in normal fashion for 1 h, the standard amount of 3 M NaOH was added, and the volatile components were condensed in a dry ice–acetone trap. Saturation of the aqueous phase with K_2CO_3 and addition of a hydrocarbon standard followed by VPC analysis indicated the presence of 82% of allyl alcohol in the trap.

OM–DM of 2-Methyl-3-chloro-1-propene. A sample of 1-chloro-2-methyl-2-propanol was prepared by the preparative OM–DM of 2-methyl-3-chloro-1-propene by using the $NaBH_4$ in ethanol reduction procedure described for allyl chloride: bp 55–56 °C (30 mm) (lit.[33] bp 126.7 °C); NMR (CCl_4) δ 1.30 (s, 6), 1.8 (s, 1, OH by D_2O exchange), 3.45 (s, 2); mass spectrum, *m/e* (relative intensity) 29 (40), 59 (100), 93 (52), 95 (17).

OM–DM of 4-Chloro-1-butene. A sample of 4-chloro-2-butanol was prepared by the preparative OM–DM of 4-chloro-1-butene described below. A sample of 4-chloro-1-butanol was commercially available (Matheson Coleman and Bell) and was purified by distillation prior to use. Isomer analysis was done on a 5 ft × 0.25 in., 10% Carbowax 1540 on Fluoropak 80 since 4-chloro-1-butanol does not undergo extensive decomposition on this column whereas it does on columns packed with normal Chromosorb supports.[34]

4-Chloro-2-butanol. Mercuric acetate (15.94 g, 50 mmol) was dissolved in 50 mL of water, and then 50 mL of THF was added followed by 4.93 mL (50 mmol) of 4-chloro-1-butene. The solution was stirred for 30 min and then cooled with an ice–water bath, and 50 mL of 3 M NaOH was added dropwise. Then was added dropwise 50 mL of 0.5 M $NaBH_4$ in 3 M NaOH. The solution was stirred for 30 min, the cooling bath was then removed, and 130 g of K_2CO_3 was added. The layers were separated, and the aqueous layer was extracted with two 50-mL portions of THF. The combined extracts were dried over K_2CO_3, filtered, concentrated on the rotary evaporator, and then distilled to give 3.41 g (63% yield) of 4-chloro-2-butanol: bp 77–78 °C (30 mm); $n^{20.5}_D$ 1.4415 [lit.[35] bp 64–65 °C (15 mm); n^{20}_D 1.4412].

OM–DM of *trans*-1-Chloro-2-butene. 4-Chloro-2-butanol, prepared as described above, and a 84:16 mixture of 1-chloro-2-butanol with 2-chloro-1-butanol, respectively, was prepared by the chlorohydration of 1-butene by using a procedure[36] described for the chlorohydration of styrene (except that no emulsifying agent was used, and THF was added as cosolvent and antifreeze). The major component elutes before the minor one on Carbowax 20M. Both components were isolated by preparative VPC and identified by their spectra. Yields and the isomer distribution of diols were estimated by VPC using Carbowax 20M and DC-710 columns. Both of the possible chlorohydrins were easily resolved from the diols under the VPC conditions employed and had shorter retention times than the diols.

OM–DM of 3-Chloro-1-butene. A sample of 3-chloro-2-butanol was not available. However, since both 1-chloro-2-butanol and 4-chloro-2-butanol elute well before the diols on Carbowax 20M and DC-710 columns, the 3-chloro-2-butanol should have easily been seen since it is predicted to have a shorter retention time than either of the isomers mentioned above by analogy to the behavior of the butanediols (relative retention time on Carbowax 20M from shortest to longest is 2,3-butanediol, 1,2-butanediol, and 1,3-butanediol). Preparative OM–DM of 3-chloro-1-butene using the $NaBH_4$ in ethanol reduction procedure at 0 °C afforded no isolable amount of product boiling in the range reported for 3-chloro-2-butanol.

OM–DM of 5-Chloro-1-pentene. Product yields were determined by using a combination of normal Carbowax 20M and DC-710 columns. Unlike 4-chloro-1-butanol, 5-chloro-2-pentanol does not undergo extensive decomposition on columns packed with Chromosorb (W, AW, DMCS) supports. The distribution of isomeric chloropentanols was determined by acetylating a portion of the dried THF extract with acetic anhydride and a catalytic amount of methanesulfonic acid (room temperature, 24 and 48 h) and analyzing the resulting acetates. The order of elution is 2-acetoxy-5-chloropentane first, then 1-acetoxy-4-chloropentane, and finally 1-acetoxy-5-chloropentane. A sample of 5-chloro-2-pentanol was prepared by the preparative OM–DM of 5-chloro-1-pentene. A portion of it was acetylated to obtain a sample of 2-acetoxy-5-chloropentane. A sample of 1-acetoxy-4-chloropentane was prepared by the reaction of 2-methyltetrahydrofuran with acetyl chloride in benzene under titanium tetrachloride catalysis.[37] A mixture containing the anti-Markovnikov isomer, 5-acetoxy-1-chloropentane, was prepared by the hydroboration–oxidation of 5-chloro-1-pentene followed by acetylation. Samples of 2-methyltetrahydrofuran, 4-penten-1-ol, and 4-penten-1-yl acetate were available from previous work.[2] The small

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amount of 4-penten-1-ol from the OM–DM was identified by VPC both in the direct analysis of the reaction mixture and as 4-penten-1-yl acetate in the acetylated reaction mixture.

5-Chloro-2-pentanol. To 23.90 g (75 mmol) of mercuric acetate dissolved in water were added 75 mL of THF and 8.65 mL (75 mmol) of 5-chloro-1-pentene with stirring at room temperature. After 30 min, the contents were cooled to 3 °C, and 75 mL of 3 M NaOH was added dropwise over a 10–15-min period, maintaining the reaction temperature between 0 and 4 °C. Then a cold solution of 1.42 g (37.5 mmol) of $NaBH_4$ in 75 mL of water was added dropwise over a 10–15-min period, and the temperature was maintained below 4 °C. After all of the hydride solution had been added, the mixture was stirred at 0 °C for an additional 10 min, the aqueous phase saturated with NaCl, and the organic layer separated. The aqueous phase was then extracted with two 75-mL portions of THF. The combined extracts were dried over Na_2SO_4, filtered, concentrated on the rotary evaporator, and distilled through a Vigreux column to give 6.96 g (76%) of 5-chloro-2-pentanol: bp 52–53 °C (2.1 mm) [lit.[38] bp 66–68 °C (3 mm)].

2-Acetoxy-5-chloropentane. A 3.06-g (25 mmol) portion of 5-chloro-2-pentanol was stirred at room temperature for 18 h with 25 mL of acetic anhydride and a couple of crystals of *p*-toluenesulfonic acid monohydrate. Then was added 50 mL of water, and after 0.5 h of stirring, pentane was added. After an additional hour of stirring, the layers were separated, and the aqueous phase was extracted twice with 20-mL portions of pentane. The combined extracts were washed first with one-third their volume of saturated $NaHCO_3$ solution and second with saturated NaCl, dried over $MgSO_4$, filtered, concentrated, and distilled to give 3.40 g (81%) of 2-acetoxy-5-chloropentane, bp 84–85 °C (13 mm) [lit.[38] bp 102–106 °C (30 mm); n^{25}_D 1.4309].

Hydroboration–Oxidation of 5-Chloro-1-pentene Followed by Acetylation. The procedure used was modeled after that described by Brown and Keblys[34] for the hydroboration of 4-chloro-1-butene with disiamylborane followed by oxidation using the simultaneous mode of addition of base and hydrogen peroxide. However, an equivalent amount of BH_3 was used instead of disiamylborane. The crude chlorohydrin was acetylated directly by being stirred with acetic anhydride for 18 h at room temperature and worked up in the normal fashion. VPC analysis showed the presence of a product peak of slightly longer retention time than 2-acetoxy-5-chloropentane.

OM–DM of 6-Chloro-1-hexene. A sample of 6-chloro-2-hexanol was prepared by preparative OM–DM as described below, whereas, 2-methyltetrahydropyran was available from previous work.[2]

6-Chloro-2-hexanol. A procedure identical with that described above for the preparative OM–DM of 5-chloropentene was used. From 50 mmol of 6-chloro-1-hexene there was obtained 5.80 g of 6-chloro-2-hexanol, bp 59–60 °C (1.2 mm) [lit.[39] bp 58 °C (1.1 mm)]. VPC analysis on DC-710 indicated a purity of ca. 97–98% with 2–3% of a longer retention time peak which was shown to be the corresponding acetate by mixed injection with a crude sample of the acetate prepared by acetylating 6-chloro-2-hexanol with isopropenyl acetate and a catalytic amount of methanesulfonic acid.

OM–DM of 4-Bromo-1-pentene. The 4-bromo-2-pentanol was prepared by preparative OM–DM. The corresponding acetate was obtained by acetylating the OM–DM products.

4-Bromo-2-pentanol. To a solution of 2.63 g (17.6 mmol) of 4-bromo-1-pentene in 17.5 mL of water and 17.5 mL of THF was added 5.43 g (17.6 mmol) of mercuric acetate. After the mixture was stirred for 15 min at room temperature, the flask was cooled with an ice bath and the mixture stirred for an additional 15 min. Then was added dropwise 17.5 mL of cold 3 M NaOH over a 6-min period, followed by 17.5 mL of cold 0.5 M $NaBH_4$ in 3 M NaOH over a ca. 10-min period. The mixture was stirred for an additional 5 min, the aqueous phase was saturated with NaCl, and the layers were separated. The aqueous phase was extracted twice with 20-mL portions of ether. The combined extracts were dried first over Na_2SO_4 and then over $MgSO_4$ and $CaSO_4$, filtered, concentrated on a rotary evaporator, and distilled through a small distillation apparatus containing a small Vigreux section to give 2.92 g (66%) of 4-bromo-2-pentanol product, bp 78–79 °C (12 mm). Both the IR and NMR spectra showed the presence of an acetate impurity. VPC analysis on Carbowax 20M and DC-710 columns indicated a purity of ca. 90% with 7% of 2-acetoxy-4-bromopentane impurity and ca. 3% of much shorter retention time peaks. The 4-bromo-2-pentanol appears as two closely spaced peaks on both VPC columns and presumably is a mixture of the two possible diastereoisomers. The diastereoisomer of shorter retention time is present in roughly twice the amount of the longer retention time diastereoisomer. Evidence for a mixture of isomers was also obtained in the NMR spectra above since the sextet region was not clean. Since a relatively large amount of acetate impurity was present, another experiment was performed for the purpose of analysis in which the crude bromohydrin products were acetylated for analysis. This experiment is described below.

2-Acetoxy-4-bromopentane. The OM–DM of 4-bromo-1-pentene was carried out in a manner identical with that described above except on a slightly smaller scale (15 mmol), and the crude bromohydrin was used in the conversion to the acetate. After evaporation of the solvent from the OM–DM reaction, the residue was stirred with 20 mL of acetic anhydride and 100 μL of dry pyridine for 3 days at room temperature. Then was added 40 mL of water, and after the mixture was stirred for 2 h, the product was extracted with two 25-mL portions of pentane. The combined pentane extracts were washed twice with 1:1 H_2O–saturated $NaHCO_3$ solution, dried first over Na_2SO_4 and then over $MgSO_4$, filtered, concentrated, and distilled to give 1.85 g (59%) of 2-acetoxy-4-bromopentane, bp 68–70 °C (4.5 mm).

VPC analysis on DC-710 indicated a purity of ca. 98–99%. This material is presumably a mixture of diastereoisomers but appeared as only one peak under the VPC conditions above. The observation of splitting of the sextets in the NMR spectrum also suggests a mixture of isomers.

OM–DM of 3,4-Epoxy-1-butene. Samples of 3,4-epoxy-2-butanol, 2,3-epoxy-1-butanol, and 3,4-epoxy-1-butanol were prepared as described below by the epoxidation of the corresponding unsaturated alcohols. A sample of 2-butene-1,4-diol (General Aniline and Film Corp.) was available.

3,4-Epoxy-2-butanol. To 3.60 g (50 mmol) of 3-buten-2-ol (Columbia) in 75 mL of methylene chloride was added dropwise a solution of 11.0 g of 85% *m*-chloroperbenzoic acid (Aldrich) in 120 mL of methylene chloride with the temperature maintained at 25 °C. The solution was stirred overnight (ca. 15 h), and then 50 mL of water was added followed by a few crystals of sodium thiosulfate. Both layers then gave a negative starch–iodide paper test. Saturated aqueous K_2CO_3 solution was added portionwise with shaking until both layers were neutral or slightly basic (ca. pH 8) to Hydrion A paper. The layers were separated, and the aqueous phase was extracted with an additionl 50 mL of methylene chloride. The combined extracts were dried over Na_2SO_4, filtered, concentrated on the rotary evaporator, and distilled to give 1.18 g (27%) of 3,4-epoxy-2-butanol as a mixture of isomers, presumably the erythro–threo pair, bp 77–79 °C (47 mm) [lit.[40] bp 76–80 °C (45 mm), also as a mixture of diastereoisomers].

2,3-Epoxy-1-butanol. To 3.60 g (50 mmol) of crotyl alcohol (Aldrich) in 50 mL of methylene chloride was added a solution of 10.4 g of 85% *m*-chloroperbenzoic acid in 125 mL of methylene chloride at such a rate that the temperature did not exceed 25 °C. After being stirred overnight, the solution was cooled to 0 °C and the solid quickly filtered. The solid was washed with two portions of methylene chloride. The combined filtrates were then washed first with 50 mL of saturated aqueous $NaHCO_3$ solution and then with 50 mL of saturated NaCl solution. After being dried over Na_2SO_4 and filtered, the solution was concentrated and distilled to give 1.06 g (24%) of a cis/trans mixture of 2,3-epoxy-1-butanol, bp 76–79 °C (20 mm) [lit.[10] bp (cis isomer) 69–70 °C (10 mm), bp (trans isomer) 58–59 °C (10 mm)]]. VPC analysis on a Carbowax 20M column showed two peaks in an area ratio of ca. 85:15, with the larger component eluting first; this was presumably a mixture of trans and cis isomers, respectively. The starting crotyl alcohol used also shows the same ratio of two components, 85:15, again with the larger one eluting first and again

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presumably being a mixture of trans and cis isomers, respectively.

3,4-Epoxy-1-butanol. The procedure is the same as that described for 2,3-epoxy-1-butanol, bp 89–90 °C (19 mm) [lit.[41] bp 80–82 °C (16 mm)].

OM–DM of 4,5-Epoxy-2-pentene. Samples of 4,5-epoxy-2-pentanol and 1,2-epoxy-3-pentanol were prepared as described below. A sample containing 2,3-epoxy-1-pentanol was prepared by basic equilibration of 1,2-epoxy-3-pentanol. A sample of 2-pentene-1,4-diol was available from the acetic acid catalyzed opening of 4,5-epoxy-2-pentene in aqueous THF as described below. VPC analysis of the OM–DM reaction mixture on a Carbowax 20M column showed the following elution order: 1,2-epoxy-3-pentanol, 4,5-epoxy-2-pentanol, which overlaps with the shorter retention time cis–trans isomer of 2,3-epoxy-1-pentanol, the unidentified 6% peak from the OM–DM which partially overlapped the previous peak, the longer retention time isomer of the cis–trans pair of 2,3-epoxy-1-pentanol, 3-pentene-1,2-diol, and finally 2-pentene-1,4-diol.

The OM reaction was repeated in D_2O and analyzed by ^1H NMR.

4,5-Epoxy-2-pentanol. In a manner identical with that described above for 2,3-epoxy-1-butanol, there was obtained from 4.3 g (50 mmol) of 4-penten-2-ol (Chemical Samples, 99%) by using a 12-h reaction time 2.35 g (42%) of 4,5-epoxy-2-pentanol, bp 84–86 °C (17 mm).[42] Both the IR (5.82 μm) and NMR (singlets at δ 2.12 and 2.17) indicated the presence of carbonyl impurities (10% estimated from the NMR). The starting 4-penten-2-ol showed no carbonyl impurity.

1,2-Epoxy-3-pentanol. The procedure is identical with that given for 2,3-epoxy-1-butanol. 1,2-Epoxy-3-pentanol, bp 69–74 °C (18 mm) [lit.[40] bp 80–86 °C (37 mm)], was prepared in 62% yield from 1-penten-3-ol.

Basic Equilibration of 1,2-Epoxy-3-pentanol. A 100-μL sample of 1,2-epoxy-3-pentanol was stirred with 1 mL of 3 M NaOH for 45 min at room temperature. The aqueous phase was saturated with K_2CO_3, and the product was extracted with ether and dried over K_2CO_3. VPC analysis on a Carbowax 20M column indicated (normalized percentages) 34% of 1,2-epoxy-3-pentanol remaining and the appearance of two longer retention time peaks, 43% and 28%, respectively, in order of increasing retention time, which were assumed to be the trans and cis isomers of 2,3-epoxy-1-pentanol. The equilibration of 2,3-epoxy 1-alcohols is a well-known process.[10]

2-Pentene-1,4-diol and 3-Pentene-1,2-diol from 4,5-Epoxy-2-pentene. 4,5-Epoxy-2-pentene (5 mmol) was stirred with 5 mmol of acetic acid in 5 mL of water and 5 mL of THF for 30 min at room temperature. The aqueous phase was saturated with K_2CO_3, and the layers were separated. The aqueous phase was extracted with 5 mL of ether, and the combined extracts were dried over K_2CO_3. VPC on Carbowax 20M showed the presence of two long retention time peaks of approximately the same intensity. Each peak was isolated by preparative VPC and identified spectroscopically. The shorter retention time peak was 3-pentene-1,2-diol.

Attempted Basic Cyclization of 4,5-Epoxy-2-pentanol. In an attempt to obtain a sample of 5-methyl-3-hydroxytetrahydrofuran, 100 μL of 4,5-epoxy-2-pentanol was stirred with 1 mL of 3 M NaOH for 3 days at room temperature. Workup, as described above, followed by VPC analysis, showed no volatile products.

OM–DM of 4,5-Epoxy-1-pentene. A sample of 4,5-epoxy-2-pentanol was available from the preparation described above. In addition to identifying the 4,5-epoxy-2-pentanol product from OM–DM by mixture VPC injection in the analytical run, another OM–DM run was made in which no hydrocarbon standard was added. After the extract was dried, the solvent was removed on a rotary evaporator, and the NMR of the residue was identical with that of the authentic sample of 4,5-epoxy-2-pentanol except for the position of the OH proton.

OM–DM of 5,6-Epoxy-1-hexene. Samples of *cis*- and *trans*-5-methyltetrahydrofurfuryl alcohol were available from the reaction of *m*-chloroperbenzoic acid with 5-hexen-2-ol described below. The *cis*- and *trans*-3-hydroxy-6-methyltetrahydropyrans were isolated by preparative VPC from the OM–DM reaction mixture described below. VPC analysis on a Carbowax 20M column had *cis*-5-methyltetrahydrofurfuryl alcohol eluting first, followed by completely overlapping *trans*-5-methyltetrahydrofurfuryl alcohol and *cis*-3-hydroxy-6-methyltetrahydropyran and, finally, *trans*-3-hydroxy-6-methyltetrahydropyran.

***cis*- and *trans*-5-Methyltetrahydrofurfuryl Alcohols from Epoxidation of 5-Hexen-2-ol.** To 5.0 g (50 mmol) of 5-hexen-2-ol (Chemical Samples, 99%) in 75 mL of methylene chloride was added a solution of 10.4 g (50 mmol) of nominal 85% *m*-chloroperbenzoic acid (found to be 83.5% pure) in 125 mL of methylene chloride. The temperature was maintained at 22–24 °C throughout the addition, and the reaction was stirred for 24 h at room temperature. Hydrolysis of an aliquot, followed by VPC, indicated only 2% of 5-hexen-2-ol remaining. Examination by NMR of an aliquot showed no epoxy protons. Next were added 50 mL of water and a few crystals of sodium thiosulfate. After the mixture was shaken, the aqueous phase was brought to pH 8 with K_2CO_3. The layers were separated, the aqueous phase was extracted with a 25-mL portion of methylene chloride, and the combined extracts were dried over K_2CO_3. Filtration, concentration, and distillation gave 4.20 g (70%) of a mixture of *cis*- and *trans*-5-methyltetrahydrofurfuryl alcohols, bp 78–81 °C (16 mm) [lit.[43] (for the cis isomer) bp 74 °C (15 mm)]. VPC analysis on Carbowax 20M indicated approximately equal amounts of both components, and the NMR spectrum of the distilled material also indicated a mixture since two methyl doublets were observed. Each component was isolated by preparative VPC and identified spectroscopically and chemically by conversion of a VPC-isolated sample to the tosylate and subsequent reduction, as described below.

The first-eluting (Carbowax 20M) component was *cis*-5-methyltetrahydrofurfuryl alcohol, as characterized spectroscopically.[44] For further characterization, the alcohol was converted to its tosylate, followed by reduction with $LiAlH_4$. VPC analysis on a Carbowax 20M column showed the major product peak to be identical by mixed injection with the shorter dimethyltetrahydrofuran isomer present in the smallest amount from dioxymercuration–demercuration of 1,5-hexadiene. The smaller dimethyltetrahydrofuran isomer from this reaction has already been shown[45] to be the cis isomer, which is the isomer of shorter retention time on Carbowax 20M. Consequently, tosylation and reduction of the first component gave *cis*-2,5-dimethyltetrahydrofuran. Addition of a hydrocarbon standard to the isolated ether solution, followed by VPC analysis, indicated an overall yield of *cis*-2,5-dimethyltetrahydrofuran of 42% from the *cis*-5-methyltetrahydrofurfuryl alcohol.

The second component eluting on a Carbowax 20M column was *trans*-5-methyltetrahydrofurfuryl alcohol which showed satisfactory spectral characteristics. High-resolution mass spectroscopy on the parent ion gave *m/e* 116.085 (calcd for $C_6H_{12}O_2$ *m/e* 116.084).

Assignment of stereochemistry for this second component was accomplished by converting a 117-mg (1.01 mmol) preparative VPC sample to the crude tosylate (265 mg, 98%) and reducing it with $LiAlH_4$. The major product peak was identified as *trans*-2,5-dimethyltetrahydrofuran since it had an identical retention time by mixed injection with the major dimethyltetrahydrofuran isomer from dioxymercuration–demercuration of 1,5-hexadiene under the VPC conditions which separated both isomers. This major component has previously been shown to be the trans isomer.[45] Determination of the yield of *trans*-dimethyltetrahydrofuran thus obtained in a manner identical with that described above gave a value of 45%.

Isolation of Products from OM–DM of 5,6-Epoxy-1-hexene. After the three experiments listed in Table III were carried out, the reaction mixtures were combined and the components isolated by preparative VPC on Carbowax 20M. Three principal

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peaks appeared as indicated previously in addition to a minor peak of retention time intermediate between those of the *trans*-8/*cis*-9 overlapping peak and the *trans*-9 peak.

The first-eluting component from these combined OM–DM reaction mixtures had an NMR spectrum identical with that of *cis*-8.

The NMR spectrum of the second-eluting component revealed that it was a mixture since two sets of methyl doublets at δ 1.15 and 1.18 (J = 6 Hz each) were observed, with the δ 1.15 doublet isomer being the major component. By measurement of the peak heights of the lowest field component of each doublet, the percentage of the δ 1.15 doublet isomer was estimated to be 70%. By comparison of the spectrum to that for *trans*-8, it could be concluded that the minor isomer present in this isolated VPC peak was *trans*-8. By integration of the lowest half of the lowest field multiplet for *trans*-8 in this mixture, a percentage of 24% was calculated, compared to the 30% value from the doublet heights above. Consequently, the average value of 27% was used to partition this peak into the percentage actually due to *trans*-8, and it was assumed that this relative 27% was the same for all three experiments. Integration of the downfield absorptions in the NMR of this mixture from ca. δ 3.2 to 4.4 gave five hydrogens (four HC–O plus one OH) relative to 7 hydrogens from δ 1.0–2.3. Thus, the unidentified component like *trans*-8 is a cyclic ether. Since *trans*-3-hydroxy-6-methyltetrahydropyran was identified below, this major component in the second-eluting peak was assumed to be the corresponding cis isomer.

The NMR of the minor (ca. 8% by VPC) component revealed that it was a mixture of at least two acetoxy ethers.

The fourth component could be tentatively identified as *trans*-3-hydroxy-6-methyltetrahydropyran on the basis of its IR and NMR spectral characteristics.[46,47]

OM–DM of Allyl Methyl Sulfide. A sample of 1-(methylthio)-2-propanol was prepared by the preparative OM–DM of allyl methyl sulfide described below. A sample of 3-(methylthio)-1-propanol was prepared by the reaction of trimethylenechlorohydrin with $NaSCH_3$.

1-(Methylthio)-2-propanol. Preparative OM–DM of allyl methyl sulfide on a 50-mmol scale by using the standard procedure with a 20-h T_2 gave 2.52 g (48%) of 1-(methylthio)-2-propanol: bp 60 °C (12 mm); n^{20}_D 1.4808 [lit.[48] bp 69–70 °C (20 mm); n^{20}_D 1.4817]. VPC analysis on Carbowax 20M indicated a purity of greater than 99%.

3-(Methylthio)-1-propanol. To 3.5 g (50 mmol) of $NaSCH_3$ in 25 mL of 1,2-dimethoxyethane (distilled from $LiAlH_4$ under N_2 prior to use) was added 4.72 g of trimethylenechlorohydrin (Matheson Coleman and Bell) with stirring (exothermic!). After being stirred vigorously for 3 h, the contents were heated on a steam bath for 30 min, cooled, and filtered. Distillation gave 4.25 g (80%) of 3-(methylthio)-1-propanol, bp 89–92 °C (13 mm) [lit.[15] bp 105–105.5 °C (30 mm)].

OM–DM of Crotyl Methyl Sulfide. A sample of 1-(methylthio)-2-butanol was prepared by the reaction of 1,2-epoxybutane with $NaSCH_3$ in DME. A sample of 4-(methylthio)-2-butanol was available from the preparative OM–DM of 3-buten-1-yl methyl sulfide. Analysis for products from OM–DM on a Carbowax 20M column showed approximately 2–3% of an unidentified component, presumably 3-(methylthio)-2-butanol, resulting from OM–DM of the small amount of 3-buten-2-yl methyl sulfide impurity in the starting crotyl methyl sulfide.

1-(Methylthio)-2-butanol. To 3.5 g (50 mmol) of $NaSCH_3$ in 25 mL of 1,2-dimethoxyethane (distilled from $LiAlH_4$ under N_2) was added 3.64 g (50 mmol) of 1,2-epoxybutane (K&K). The mixture was heated under reflux with vigorous stirring for 2 h, cooled, and diluted with an equal volume of water. The aqueous phase was saturated with K_2CO_3 and extracted with ether, and the ether layer was dried (K_2CO_3) and distilled to give 4.23 g (72%) of 1-(methylthio)-2-butanol, bp 72 °C (12 mm).

Anal. Calcd for $C_5H_{12}OS$: C, 49.96; H, 10.06; S, 26.67. Found: C, 49.99; H, 10.29; S, 27.76.

5-(Methylthio)-2-pentanol. Preparative OM–DM of 14.8 mmol of 4-penten-1-yl methyl sulfide with a 100% excess of mercuric acetate for T_2 = 18 h gave 1.50 g (76%) of 5-(methylthio)-2-pentanol, bp 106–107 °C (13 mm).

Anal. Calcd for $C_6H_{14}OS$: C, 53.68; H, 10.51; S, 23.89. Found: C, 53.81; H, 10.72; S, 23.64.

4-(Methylthio)-2-butanol and 4-(Methylthio)-1-butanol. Preparative OM–DM of 7.5 mmol of 3-buten-1-yl methyl sulfide by using a stoichiometric amount of mercuric acetate for T_2 = 12 h and following the standard procedure gave 0.65 g (72%) of a mixture of the two products in three fractions: first fraction, bp 88–91 °C (13 mm); the boiling point of the second and third fractions could not be determined due to the small scale [lit.[15] (for 4-(methylthio)-2-butanol) bp 66–72 °C (2 mm)]. The first fraction was 94% pure and was identified as 4-(methylthio)-2-butanol from its NMR spectrum. The remaining two fractions contained much more of the anti-Markovnikov product, and this product was isolated by preparative VPC and identified spectroscopically as 4-(methylthio)-1-butanol.

Registry No. 4-Bromo-1-pentene, 31950-56-8; 4-penten-2-ol, 625-31-0; 1-bromo-1-propene, 590-14-7; 1-chloro-3-penten-2-ol, 76137-47-8; *cis*-4,5-epoxy-2-pentene, 57530-65-1; *trans*-4,5-epoxy-2-pentene, 57530-64-0; 4,5-epoxy-1-pentene, 6790-38-1; 1-chloro-2-hydroxy-4-pentene, 13390-80-2; chloroacetaldehyde, 107-20-0; 5,6-epoxy-1-hexene, 10353-53-4; crotyl methyl sulfide, 32931-14-9; 3-buten-1-yl methyl sulfide, 20582-83-6; 4-penten-1-yl methyl sulfide, 69632-05-9; 5-chloro-1-pentene, 928-50-7; 1-chloro-2-propanol, 127-00-4; 2-methyl-3-chloro-1-propene, 563-47-3; 1-chloro-2-methyl-2-propanol, 558-42-9; 4-chloro-2-butanol, 2203-34-1; 4-chloro-1-butene, 927-73-1; *trans*-1-chloro-2-butene, 4894-61-5; 3-chloro-1-butene, 563-52-0; 3-chloro-2-butanol, 563-84-8; 5-chloro-2-pentanol, 15146-94-8; 5-acetoxy-1-chloropentane, 20395-28-2; 5-chloro-2-pentanol, 15146-94-8; 2-acetoxy-5-chloropentane, 60903-99-3; 6-chloro-1-hexene, 928-89-2; 6-chloro-2-hexanol, 18804-33-6; 4-bromo-2-pentanol, 76137-48-9; 4-bromo-2-pentanol acetate, 76137-49-0; 4-bromo-1-pentene, 31950-56-8; 2-acetoxy-4-bromopentane, 76137-49-0; 3,4-epoxy-1-butene, 930-22-3; 2,3-epoxy-1-butanol, 872-38-8; 3,4-epoxy-2-butanol, 765-44-6; 3,4-epoxy-1-butanol, 19098-31-8; 4,5-epoxy-2-pentene, 6790-41-6; 1,2-epoxy-3-pentanol, 4798-48-5; 4,5-epoxy-2-pentanol, 32815-71-7; 2,3-epoxy-1-pentanol, 76137-50-3; 2-pentene-1,4-diol, 7397-59-3; 3-pentene-1,2-diol, 6736-21-6; *cis*-5-methyltetrahydrofurfuryl alcohol, 16015-08-0; *trans*-5-methyltetrahydrofurfuryl alcohol, 54774-28-6; *cis*-3-hydroxy-6-methyltetrahydropyran, 76137-51-4; *trans*-3-hydroxy-6-methyltetrahydropyran, 76137-52-5; 5-hexen-2-ol, 626-94-8; allyl methyl sulfide, 10152-76-8; 1-(methylthio)-2-propanol, 6943-87-9; 3-(methylthio)-1-propanol, 505-10-2; 1,2-epoxybutane, 106-88-7; 1-(methylthio)-2-butanol, 76137-53-6; 4-(methylthio)-2-butanol, 13296-23-6; 5-(methylthio)-2-pentanol, 10428-55-4; 4-(methylthio)-1-butanol, 20582-85-8.

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