Hydroboration. XXVI. The Hydroboration of 2-Butenyl (Crotyl) and Related Derivatives Containing Representative Substituents. Control of the Elimination Reaction of β-Substituted Organoboranes[1]

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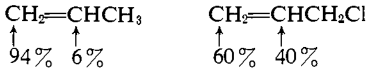
Abstract: The hydroboration of representative 2-butenyl (crotyl) derivatives in tetrahydrofuran was examined in order to establish the magnitude of the directive effects of substituents on the addition of the boron–hydrogen bond to a symmetrically substituted carbon–carbon double bond. As compared to the allyl system previously examined, there is observed a marked enhancement in the addition of the boron to the β position, with an accompanying marked reduction in the formation of the γ derivative. Thus crotyl chloride yields essentially 100% addition of the boron to the β position, as compared to a 40% β, 60% γ distribution realized with allyl chloride under the same conditions. With decreasing electronegativity of the substituent, there is observed a modest decrease in the directive effect: crotyl chloride, 100% β; crotyl acetate, 95% β; crotyl tetrahydropyranyl ether, 91% β; crotyl benzyl ether, 91% β; crotyl alcohol, 90% β; crotyl thexylboronate ester, 88% β; crotyl borate, 86% β; crotyl disiamylborinate ester, 86% β; crotyl phenyl ether, 86% β; and crotyl ethyl ether, 84% β. Whereas the β-boron derivatives of crotyl chloride and crotyl acetate both eliminate spontaneously at 0° in 1 hr, making it impractical to utilize them for synthetic purposes under these conditions, the elimination of the other derivatives is sufficiently slow that the boron derivatives can be so utilized. In particular, there are advantages in protecting the hydroxyl groups of crotyl alcohol and related derivatives in the form of the tetrahydropyranyl ether, the benzyl ether, or the disiamylborinate ester in order to minimize the elimination and provide on oxidation and removal of the protecting group a good yield of the corresponding 1,2-diols. Although the phenyl ether derivative is relatively stable under hydroboration conditions, it does undergo a rapid base-catalyzed elimination to form the corresponding olefin. The β-boron-substituted disiamylborinate esters are stable at 0°, but undergo elimination in refluxing tetrahydrofuran to the corresponding olefin. Consequently, this provides a general means of moving the double bond from its more stable β,γ position to the α,β position, with simultaneous loss of the hydroxyl group. Consequently, it appears that hydroboration of α,β-unsaturated aldehydes and ketones or the related alcohols can be utilized to prepare the β-substituted boron compounds which through oxidation yield the corresponding 1,2-diols or through thermal elimination the corresponding olefins with a shifted double bond. These synthetic possibilities were tested on a number of representative derivatives.

In the hydroboration of allylic derivatives, we observed a marked increase in the amount of boron adding to the 2 position as compared to the parent hydrocarbon.[3,4] Thus 40% of the boron adds to the secondary position in allyl chloride, as compared to only 6% in the parent olefin (I). In simple allyl derivatives, the percentage of boron adding to the 2-position varies from 19% for the ethyl ether to 45% for the tosylate (II). Evidently, the directive effect is markedly influenced by the electronegativity of the substituent.



$$\underset{\underset{94\%}{\uparrow}}{CH_2}{=}\underset{\underset{6\%}{\uparrow}}{C}HCH_3 \qquad \underset{\underset{60\%}{\uparrow}}{CH_2}{=}\underset{\underset{40\%}{\uparrow}}{C}HCH_2Cl$$

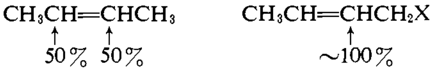
I

$$CH_2{=}\underset{\underset{19\%}{\uparrow}}{C}HCH_2OC_2H_5 \qquad CH_2{=}\underset{\underset{45\%}{\uparrow}}{C}HCH_2OTs$$

II

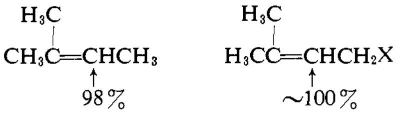
In the case of the allylic derivatives, this minor formation of the β-boron derivatives was considered to be a nuisance. It could be circumvented by the use of disiamylborane as the hydroborating reagent.[3,4]

In allyl derivatives, the directive effect of the substituent must compete against the normal tendency of the boron to add to the primary carbon atom. It was evident that in the corresponding 2-butenyl and related derivatives the major product would contain the boron in the position adjacent to the substituent (III, IV). Such derivatives exhibit a greatly enhanced tendency to undergo elimination (V).[3–7]



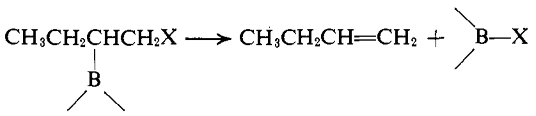
$$CH_3\underset{\underset{50\%}{\uparrow}}{C}H{=}\underset{\underset{50\%}{\uparrow}}{C}HCH_3 \qquad CH_3CH{=}\underset{\underset{\sim100\%}{\uparrow}}{C}HCH_2X$$

III



$$CH_3\overset{\overset{H_3C}{|}}{C}{=}\underset{\underset{98\%}{\uparrow}}{C}HCH_3 \qquad H_3C\overset{\overset{H_3C}{|}}{C}{=}\underset{\underset{\sim100\%}{\uparrow}}{C}HCH_2X$$

IV



$$CH_3CH_2\underset{\underset{/\ \backslash}{\underset{|}{B}}}{C}HCH_2X \longrightarrow CH_3CH_2CH{=}CH_2 + {>}B{-}X$$

V

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[1] Based upon a thesis submitted by Robert M. Gallivan, Jr., in 1966 to the Faculty of Purdue University in partial fulfillment of the requirements for the Degree of Doctor of Philosophy.

[2] Graduate research assistant, 1963–1965, on Grant No. GM-10937 of the National Institutes of Health.

[3] H. C. Brown and K. A. Keblys, *J. Am. Chem. Soc.*, **86**, 1791 (1964).

[4] H. C. Brown and O. J. Cope, *ibid.*, **86**, 1801 (1964).

[5] P. Binger and R. Köster, *Tetrahedron Letters*, 156 (1961).

[6] L. Cagliotti and G. Cainelli, *Atti Acad. Nazl. Lincei, Rend. Classe Sci. Fis., Mat. Nat.*, [8] 30, 225 (1961).

[7] D. J. Pasto and R. Snyder, *J. Org. Chem.*, 31, 2777 (1966).

Table I. The Stoichiometry of the Reaction between Crotyl Derivatives and Excess Diborane at 0° [a]

Time, min	1-Hexene	Crotyl chloride	Crotyl acetate[b]	Crotyl alcohol[c]	Crotyl borate	Crotyl disiamylborinate	Crotyl phenyl ether	Crotyl ethyl ether
5	0.96	1.33	2.78	1.28	0.95	1.07	0.95	0.98
15	0.98	1.63	2.96	2.36	1.38	0.98	1.10	0.96
30	1.00	1.74	3.18	2.35	1.41	1.00	1.15	0.99
45	0.99	1.81	3.41	2.36	1.44	0.99	1.27	1.02
60	1.00	1.85	3.52	2.38	1.45	1.02	1.18	1.05
90	0.99	1.90	3.67	2.40	1.45	1.05	1.33	1.07
120	0.99	1.96	3.84	2.41	1.48	1.06	1.33	1.10
180	1.00	1.96	3.95	2.44	1.48	1.08	1.40	1.11
240	1.01	1.99	4.08	2.47	1.50	1.08	1.44	1.15

[a] Mmoles of hydride consumed per double bond. Except where otherwise indicated 16.7 mmol of borane was used for 12.5 mmol of compound. [b] 19.6 mmol of borane. [c] 18.6 mmol of borane.

Accordingly, as part of our systematic exploration of the hydroboration reaction,[8] we undertook a study of the hydroboration of a number of 2-butenyl (crotyl) and related derivatives in order to establish whether the predicted predominant formation of the β-boron derivatives would actually occur, and whether the elimination reaction in these relatively unstable derivatives could be controlled sufficiently to make them useful in synthesis.[9]

This is the second of a closely related group of three studies, involving the hydroboration of 3-butenyl,[10] 2-butenyl (crotyl), and 1-butenyl[11] (vinyl) derivatives, as well as some closely related compounds possessing the same structural features.

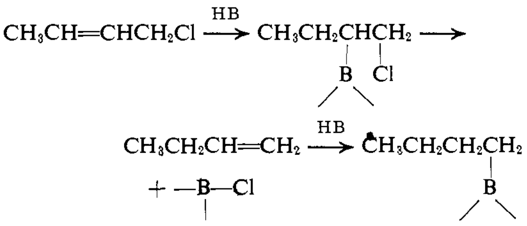
Results and Discussion

Stoichiometry Studies with Diborane. The following crotyl compounds were selected for study: chloride, acetate, alcohol, borate, ethyl ether, and phenyl ether.

For the stoichiometry studies 12.5 mmol of each crotyl compound in 5 ml of tetrahydrofuran solution was added over 2 min to 16.7 mmol of borane (50 mequiv of "hydride") in 45 ml of tetrahydrofuran solution at 0°. The solution was therefore 1 N in "hydride." (In the case of crotyl alcohol and crotyl acetate the borane used was increased somewhat to compensate for the "hydride" utilized for hydrogen evolution in the case of the alcohol and reduction of the ester grouping in the case of the acetate.) At appropriate intervals of time, 5-ml aliquots were removed and analyzed for residual hydride by hydrolysis. The results of these experiments are summarized in Table I.

The uptake of hydride per mole of compound under these conditions is indicated in Figures 1 and 2.

A simple olefin, such as 1-hexene, utilizes rapidly 1 equiv of hydride/mol of compound, and no further uptake of hydride occurs with time. Crotyl ethyl ether approximates this behavior, with only a slow further uptake of hydride. On the other hand, crotyl chloride exhibits an uptake of 1.63 H^- in 15 min, and this rapidly approaches 2.0 where it levels off. Clearly this corresponds to a quantitative addition of boron to the β position, followed by elimination and rehydroboration (VI).



$$\mathrm{CH_3CH{=}CHCH_2Cl \xrightarrow{HB} CH_3CH_2\underset{\displaystyle \overset{|}{B}\!\diagup\!\diagdown}{C}H\underset{\displaystyle \overset{|}{Cl}}{C}H_2 \longrightarrow}$$

$$\mathrm{CH_3CH_2CH{=}CH_2 + {-}\underset{|}{B}{-}Cl \xrightarrow{HB} CH_3CH_2CH_2\underset{\displaystyle \overset{|}{B}\!\diagup\!\diagdown}{C}H_2}$$

VI

Crotyl acetate shows a utilization of four hydrides per mole. This corresponds to the utilization of two hydrides for hydroboration, placing the boron essentially quantitatively in the β position, elimination, and rehydroboration, plus two hydrides for reduction of the eliminated acetoxy group to the alcohol stage.

Crotyl alcohol rapidly liberates 1 mol of hydrogen/mol of alcohol, probably forming the dicrotyloxyborane, $(RO)_2BH$.[12] Accordingly, the utilization of 2.47 hydrides/mol of alcohol in 4 hr corresponds to 47% elimination–rehydroboration. Similarly, crotyl borate and crotyl phenyl ether exhibit additional uptake of hydride corresponding to 50 and 44% elimination–rehydroboration, respectively.

The disiamylboronate was not part of our original study. However, after we began to consider means of avoiding this elimination reaction in crotyl alcohol and related derivatives, we discovered that prior treatment of the alcohol with disiamylborane[13] yielded the corresponding borinic ester. This was much stabler than the alcohol (actually, the dicrotyloxyborane) or the borate ester toward the elimination reaction, as indicated by Figure 2.

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[8] H. C. Brown, "Hydroboration," W. A. Benjamin Co., Inc., New York, N. Y., 1962.

[9] A number of individual examples of hydroborations involving double bonds β,γ to a substituent have appeared in the literature: (a) myrtenal and verbenone, Y. Chretien-Bessiere, *Bull. Soc. Chim. France*, **9**, 2182 (1964); (b) α,β-unsaturated steroid ketones, L. Caglioti and G. Cainelli, *Atti. Accad. Nazl. Lincei, Rend. Classe Sci. Fis., Mat. Nat.*, [8] **29**, 555 (1960); L. Caglioti, G. Cainelli, G. Maina, and A. Selva, *Gazz. Chim. Ital.*, **92**, 309 (1962); L. Caglioti, G. Cainelli, G. Maina, and A. Selva, *Tetrahedron*, **20**, 957 (1964); (c) cinnamic acid derivatives, K. Kratzl and P. Claus, *Monatsh. Chem.*, **94**, 1140 (1963); (d) substituted 2-cyclohexen-1-ols, A. Uzarewicz, I. Uzarewicz, and W. Zacharewicz, *Roczniki Chem.*, **34**, 19 (1965); (e) isophorone, J. Klein and E. Dunkelblum, *Tetrahedron Letters*, 6047 (1966); (f) crotonaldehyde and related derivatives, L.-S. Tai and C.-T. Chien, *Hua Hsueh Hsueh Pao*, **31** (5), 370 (1965); C.-T. Chien, C.-C. Hiseh, and L.-S. Tai, *ibid.*, **31**, (5), 376 (1965); (g) 1,4-dihalo-2-alkenes, J. G. Scharefkin and S. H. Pohl, *J. Org. Chem.*, **29**, 2050 (1964); (h) 3-methyl-2,5-dihydrothiophene 1,1-dioxide, R. C. Krug and D. E. Boswell, *ibid.*, **27**, 45 (1962); (i) methyl esters of N-carbobenzyloxy-3,4-dehydro-DL-proline and -4,5-dehydro-DL-pipecolic acid, Y. Fukita, F. Irreverre, and B. Witcop, *J. Am. Chem. Soc.*, **86**, 1795 (1964).

[10] H. C. Brown and M. K. Unni, *ibid.*, **90**, 2902 (1968).

[11] H. C. Brown and R. L. Sharp, *ibid.*, **90**, 2915 (1968).

[12] In unpublished research with D. B. Bigley we have observed that many alcohols react with borane in tetrahydrofuran at 0° to form the corresponding dialkoxyborane, with further reaction to form the borate being very slow.

[13] H. C. Brown and G. Zweifel, *J. Am. Chem. Soc.*, **83**, 1241 (1961).

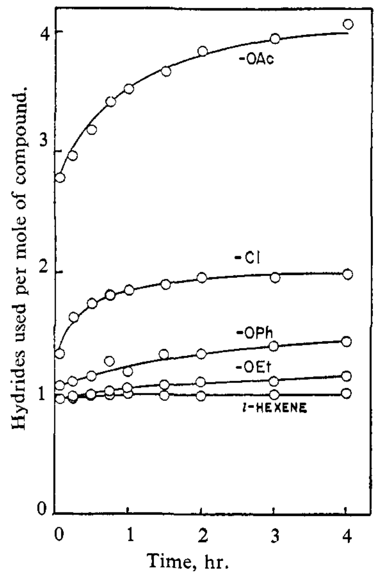

Figure 1. Relative rates of reaction of various crotyl compounds with diborane at 0°.

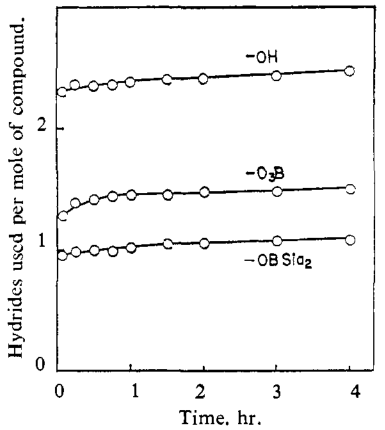

Figure 2. Relative rates of reaction of crotyl compounds with diborane at 0°.

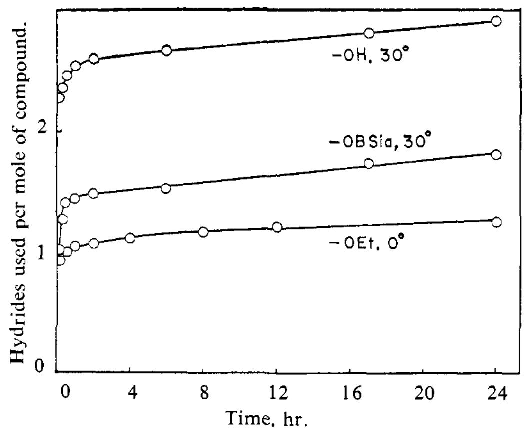

Figure 3. Relative rates of reaction of various crotyl compounds with diborane over extended periods of time.

The observation that crotyl alcohol exhibits an uptake of only 2.47 hydrides/mol, instead of 3.0 estimated for complete hydroboration–elimination–rehydroboration, could be the result either of an incomplete elimination reaction or of a reaction in which a considerable fraction of the boron had added to the more remote γ position. That the former is the correct interpretation is indicated by Figure 3. Here, in 24 hr at 30° the hydride utilization rises to 2.9. Even the disiamylborinate ester exhibits a considerably enhanced tendency toward elimination at the more elevated temperatures. Consequently, to minimize the elimination reaction one should work at as low a temperature as is convenient.

Product Studies. Although these stoichiometry experiments appeared to support the expectation that hydroboration of these crotyl derivatives proceeds to place the boron atom predominantly in the 2 position, it appeared desirable to confirm this conclusion by a study of the products formed in the oxidation of the organoborane intermediates by alkaline hydrogen peroxide. In these experiments 20 mmol of the crotyl compound was added generally to 20 mmol of borane (contained as a 1.00 M solution) in tetrahydrofuran at 0°. Hydrolysis and oxidation with alkaline hydrogen peroxide produced a mixture of alcoholic and glycolic products. These were transferred from the aqueous to dry tetrahydrofuran phase with the aid of potassium carbonate. Analysis by glpc followed. The results are summarized in Table II.

Since the 3-boron derivative does not undergo the facile elimination of the 2- and is readily oxidized under these conditions to the corresponding 3-hydroxy compound,[11] the amount of boron adding to the 3 (or γ) position is readily estimated from the yield of the 3-hydroxy isomer. The amount of boron adding to the 2 (or β) position is estimated from the sum of the 2-hydroxy isomer plus the combined yield of 1- and 2-butanol (assumed to arise from elimination–rehydroboration), as well as from the amount of boron established from the product to have added to the 3 position.

Interpretation of Data. We are now in position to consider in detail what occurs in the hydroboration of each of the standard crotyl derivatives.

In the hydroboration of crotyl chloride there was an uptake of 1.33 equiv of hydride in 5 min, with a total of 1.99 equiv in 4 hr. Since the hydroboration of the double bond only requires 1 equiv of hydride, it is evident that even in the initial stages the side reaction that utilizes additional hydride must be proceeding. This side reaction utilizes a total of one hydride/mol of compound. The product study revealed no chlorobutanols. There was obtained only 77% 1-butanol and 7% 2-butanol.

These results are in agreement with a mechanism in which the addition of boron has proceeded essentially 100% to the 2 position, followed by a rapid elimination and rehydroboration (VI).[4] There is one minor discrepancy. The hydroboration–oxidation of 1-butene produces 6–7% of 2-butanol in the product. However, here the 2-butanol is 9% of the product. Either the chloroboranes produced in the elimination stage result in a slightly different ratio of isomers in the rehydroboration stage[14] or a small amount of the 2-butanol arises from an internal reduction in an intermediate—Pasto's transfer reaction (VII).[15]

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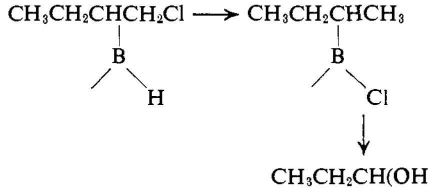
[14] However, D. J. Pasto and P. Balasubramaniyan, *J. Am. Chem. Soc.*, **89**, 295 (1967), and G. Zweifel, *J. Organometal. Chem.* (Amsterdam), **9**, 215 (1967), have recently reported that hydroboration with chloroboranes results in a slightly lower percentage of the minor isomer.

[15] D. J. Pasto and R. Snyder, *J. Org. Chem.*, 31, 2773 (1966).

Table II. Products of the Reaction of Crotyl Derivatives with Diborane

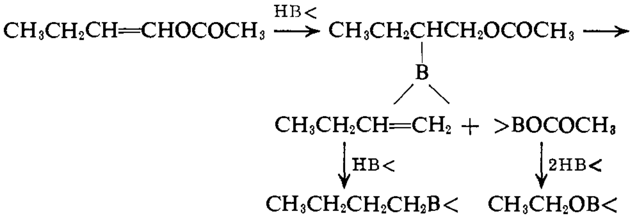
Compound[a]	Borane, mmol	Hydride[b] utilized	Oxidation product	Yield, %	Addn to 2 posn, %
Crotyl chloride	20.0	1.97	1-Butanol	76.9	100
			2-Butanol	7.5	
Crotyl acetate	45.0	3.89	1-Butanol	82.5	95
			2-Butanol	8.9	
			Ethanol	85.1	
Crotyl alcohol	30.0	2.32[c]	1-Butanol	26.1	90
			2-Butanol	2.2	
			1,2-Butanediol	38.5	
			1,3-Butanediol	9.5	
Crotyl borate	20.0	1.43	1-Butanol	38.7	86
			2-Butanol	3.3	
			1,2-Butanediol	40.7	
			1,3-Butanediol	13.1	
Crotyl phenyl ether	20.0	1.07	1-Phenoxy-2-butanol	68.3 (82.5)[d]	86
			4-Phenoxy-2-butanol	14.8 (12.8)	
			Phenol	13.8 (3.6)	
Crotyl ethyl ether	20.0	1.00	1-Ethoxy-2-butanol	83.7	84
			4-Ethoxy-2-butanol	15.2	

[a] Compound, 20.0 mmol in all cases. [b] Equivalents of hydride per equivalent of crotyl compound. [c] 1.0 equiv of hydrogen was evolved. [d] Oxidation with simultaneous addition of hydrogen peroxide and sodium hydroxide.



VII

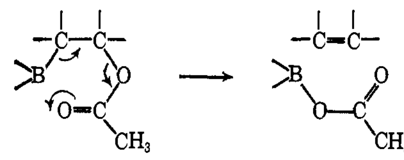
Crotyl acetate was observed to consume 2.8 equiv of hydride in 5 min and 3.95 equiv in 3 hr. Under these conditions the utilizations of hydride in 5 min by a simple ester, such as *n*-butyl acetate, is negligible. It follows that hydroboration, elimination, rehydroboration, and reduction of the eliminated acetoxy group must all be quite fast to show a utilization of 2.8 hydrides within 5 min. The product study revealed no formation of a 3-hydroxy derivative, with a nearly quantitative yield of 1- and 2-butanol,[16] as well as ethanol. It follows that the hydroboration must proceed to place the boron essentially quantitatively in the 2 position, followed by a fast elimination reaction (VIII).



VIII

Both the rehydroboration reaction and the reduction of the acetoxyboron intermediate[17] must be very fast to account for the observed hydride consumption in 5 min.

Chloride is an excellent leaving group, so that the rapid elimination of the β-chloroalkylboron derivative is not surprising. However, acetoxy is a far poorer leaving group. As was pointed out earlier[4] the very fast elimination observed in the acetate may be the result of an unusually favorable situation in this derivative for *cis* elimination (IX).



IX

The reaction of crotyl alcohol with diborane liberates hydrogen very rapidly. Consequently it is probable that the first step is the formation of a crotyloxyborane, $ROBH_2$, or dicrotyloxyborane, $(RO)_2BH$.[12] This intermediate or intermediates then undergo rapid hydroboration at the double bond. In contrast to the previous cases, approximately 10% of the boron adds to the 3 position, with 90% going to the 2. The stoichiometry study revealed that 2.3 equiv of hydride is consumed in 5 min and 2.47 equiv is used in 4 hr at 0°. At 30° there is a rapid increase in hydride utilization to 2.5, and a slow subsequent rise to 2.9 in 24 hr. This suggests that there must be at least two different intermediates present, one of which undergoes elimination much more rapidly than the other or others.

The results with crotyl borate are very similar to those realized with crotyl alcohol, except for the initial evolution of hydrogen. This is in agreement with the postulated initial formation of derivatives of borate esters in the initial phase of the reaction.

The disiamylborinate group is evidently a considerably poorer leaving group than the borate group or its hydride derivatives. Thus crotyl disiamylborinate exhibits only 8% excess hydride utilization after 4 hr. The products in this case will be discussed in the following section.

The stoichiometry study on crotyl phenyl ether indicated that 1.07 equiv of hydride was consumed in 5 min and 1.44 in 4 hr. This indicates that hydroboration to form the boron intermediate is very rapid, with the subsequent elimination proceeding quite slowly.

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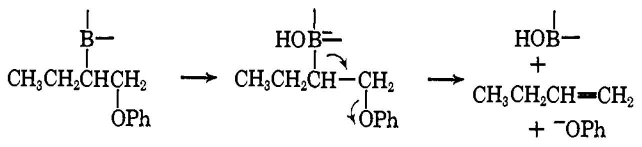
(16) Again the ratio of 2-butanol:1-butanol is appreciably higher than in the hydroboration–oxidation of 1-butene.

(17) It has been previously observed that the reduction of carboxylic acids by diborane is extraordinarily fast. This has been attributed to the formation of a triacyloxyboron intermediate, $(RCO_2)_3$, with an unusually reactive carbonyl group: H. C. Brown and B. C. Subba Rao, *J. Am. Chem. Soc.*, **82**, 681 (1960).

In the product study it was noted that normal oxidation with alkaline hydrogen peroxide yielded considerable amounts of phenol, whereas oxidation under conditions which minimized the exposure of the intermediate to base resulted in a marked reduction in the formation of phenol. It was previously observed that 1-phenoxy-2-propylboron species undergo a rapid elimination under the influence of alkali.[4] The base presumably coordinates with the boron atom, facilitating heterolysis of the boron–carbon bond, yielding the olefin (X).



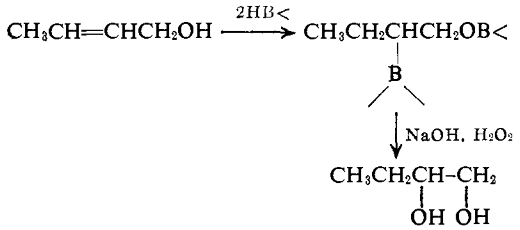
$$\mathrm{CH_3CH_2\overset{\overset{|}{B}-}{C}H\underset{OPh}{CH_2}} \longrightarrow \mathrm{CH_3CH_2\overset{HO\overset{|}{B}^{-}}{C}H{-}\underset{OPh}{CH_2}} \longrightarrow \mathrm{HO\overset{|}{B}-} + \mathrm{CH_3CH_2CH{=}CH_2} + {}^{-}\mathrm{OPh}$$

X

Although the boron still adds preferentially to the 2 position, attachment to the 3 carbon is becoming significant, as shown by the formation of 14% of the 3-hydroxy derivative (4-phenoxy-2-butanol).

Finally, at 0° the ethyl ether undergoes simple hydroboration, with relatively little tendency to undergo subsequent elimination under the hydroboration conditions. This is indicated by the stoichiometry studies where 0.95 equiv of hydride was utilized in 5 min, increasing only moderately to 1.15 equiv in 4 and to 1.24 equiv in 24 hr at 0°.[18] In the product study quantitative yields of the hydroxy ethers were obtained, with 16% of the γ isomer present. Therefore the ethoxy group likewise places boron predominantly at the 2 position with a growing quantity appearing at the 3. It is evident that the distribution of boron between the 2 and 3 positions corresponds roughly to the predicted inductive influence of the substituent.

Protective Groups. The marked directive effect observed in the hydroboration of crotyl alcohol (90% 2) could be very useful in converting alcohols of this kind into the corresponding 1,2-diols, provided one could avoid the elimination reaction (XI). Unfortunately, even with the utmost precaution, elimination–rehydroboration accounted for approximately 50% of the 2-boron derivative (Table II), resulting in a yield of only 38.5% of the 1,2-butanediol.[19] Accordingly, we decided to explore the applicability of various protective groups for the hydroxy group of crotyl alcohol.



$$\mathrm{CH_3CH{=}CHCH_2OH} \xrightarrow{2\mathrm{HB}<} \mathrm{CH_3CH_2\underset{\underset{/\ \backslash}{B}}{C}HCH_2OB<} + \mathrm{H_2} \xrightarrow{\mathrm{NaOH,\ H_2O_2}} \mathrm{CH_3CH_2\underset{OH}{CH}{-}\underset{OH}{CH_2}}$$

XI

It is evident that for such a group to be useful it should be both easily introduced and easily removed, and it should not undergo elimination under hydroboration conditions.

While acid groups are readily introduced and removed, the evidence is that they would undergo elimination in the hydroboration stage. Consequently they were ruled out from consideration, except for disiamylborinate and thexylboronate. This appeared to leave only certain ethers and acetals. Simple alkyl ether groups offer the disadvantage that they are not easily removed. However, the benzyl group can be removed by hydrogenolysis and the trityl group should be removable by methanolysis. Finally, the tetrahydropyranyl ethers are readily formed by acid-catalyzed addition of the alcohols to the double bond of dihydropyran. Such ethers should be stable to hydroboration, and removal of the protecting group can be achieved by acid-catalyzed alcohol exchange with excess methanol.

The addition of 1 mol of disiamylborane to 1 mol of crotyl alcohol in tetrahydrofuran at 0° liberates 1 mol of hydrogen, forming the disiamylborinate ester *in situ*. Addition of diborane in tetrahydrofuran rapidly hydroborates the double bond. Oxidation with alkaline hydrogen peroxide converts the carbon–boron bond to a hydroxyl group, simultaneously removing the protective group. A satisfactory yield of the 1,2-butanediol (81%) is realized.

An attempt to simplify the reaction by the use of 3 mol of disiamylborane to achieve both the formation of the protective group and the hydroboration failed. The hydroboration stage was very slow at 0°. At room temperature the hydroboration proceeded in 3 hr, but was evidently accompanied by significant elimination, as indicated by the utilization of 2.3 equiv of hydride. Evidently there is also a steric influence which increases the yield of 1,3-butanediol.

Thexylborane, either in a ratio of 1 mol of reagent/mol of crotyl alcohol or 2 mol of reagent/mol of crotyl alcohol, achieves the introduction of a suitable protective group and the subsequent hydroboration of the double bond. Again, oxidation by alkaline hydrogen peroxide removes the protective group and converts the intermediate into the diol in satisfactory yield (83%).

After 1 hr at 0° crotyl tetrahydropyranyl ether utilized 1.05 equiv of hydride from borane in tetrahydrofuran. Oxidation yielded the hydroxy ethers. The product was dissolved in a large excess of methanol and a trace of *p*-toluenesulfonic acid was added to transfer the protective group. Analysis revealed an 85% yield of 1,2-butanediol.

Crotyl benzyl ether utilized 1.06 equiv of hydride in 1 hr at 0°, indicating hydroboration without significant elimination. Oxidation yielded the 1-benzyl ethers of 1,2- and 1,3-butanediol. The crude product was hydrogenated over the palladium-on-carbon catalyst in ethanol.[20] Hydrogenolysis required 3 hr at room temperature. Again, a satisfactory yield of 1,2-butanediol was realized.

Again, hydroboration–oxidation of the trityl ether of crotyl alcohol appeared to proceed satisfactorily. However, the methanolysis of the product in the presence of *p*-toluenesulfonic acid appeared to proceed to an equilibrium product containing 23% of the 1,2-diol and none of the 1,3-diol. Although the absence of the 1,3-diol is of major interest, we did not pursue this lead. The possibility exists that resolution of the dif-

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[18] At room temperature β-alkoxyboranes undergo a relatively rapid *cis* elimination.[7] Consequently, it is important to carry out the hydroboration of such derivatives at 0° (or lower) to realize such high yields of the hydroboration product.

[19] Even lower yields of 1,2-diols have been recently reported for the hydroboration–oxidation of crotonaldehyde, cinnamaldehyde, and elated derivatives.[9f]
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[20] C. A. Brown and H. C. Brown, *J. Org. Chem.*, 31, 3989 (1966).

Table III. The Hydroboration of Crotyl Alcohol Protected with Various Blocking Groups

Crotyl alcohol	Hydroborating agent	Hydride utilized	Products,[a] % 1,2-Butanediol	1,3-Butanediol	1-Butanol
Disiamylborinate ester	BH_3	2.04[b]	80.9	12.8	5
Disiamylborinate ester	Sia_2BH	2.30[b]	37.5	19.6	*c*
Thexylboronate ester (1:1)[d]	*t*-$HexBH_2$	1.96[b]	73.3	11.8	7
Thexylboronate ester (2:1)[d]	*t*-$HexBH_2$	2.08[b]	83.0	11.0	10
Tetrahydropyranyl ether	BH_3	1.05	85.3	8.0	None
Benzyl ether	BH_3	1.06	83.7	8.1	None
Triphenylmethyl ether	BH_3	0.96	23.0[e]	None	None

[a] By glpc analysis. [b] 1 equiv of hydrogen evolved. [c] Present, but not analyzed for. [d] Ratio of thexylborane to crotyl alcohol. [e] Low yield due to difficulties in removal of protecting group.

ficulty we encountered in removing the trityl group might provide the 1,2-diol in a higher isomeric purity than the other procedures. However, it is quite clear that the use of the disiamylborinate ester, the tetrahydropyranyl ether, and the benzyl ether permit hydroboration of crotyl alcohols, and presumably related compounds, without significant elimination, making possible the conversion of such compounds into the 1,2-diols in quite satisfactory yields. Finally, the use of thexylborane provides a one-stage procedure for this conversion. These results are summarized in Table III.

Application of the Glycol Synthesis. In order to test the applicability of this new glycol synthesis to other representative systems, a number of compounds were selected: three allylic alcohols, cinnamyl alcohol, 2-cyclohexen-1-ol, and 2-cyclopenten-1-ol, and three α,β-unsaturated ketones, mesityl oxide, phorone, and isophorone. Cinnamyl alcohol was converted into its tetrahydropyranyl ether, which was then hydroborated-oxidized in the usual manner. All the alcohols were treated with disiamylborane to form the esters, and these were then hydroborated-oxidized by the standard procedure. Finally, the ketones were reduced with disiamylborane to the ester derivative and these were handled in the same way, *in situ*. In all cases satisfactory yields of diols were realized (Table IV).

Table IV. The Hydroboration of Representative Compounds and Conversion to Glycols

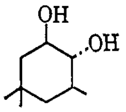
Compound	Amount, g (mol)	Disiamylborane, mmol	Borane–THF, ml (mmol)	Product yield, %[b]
Cinnamyl alcohol[a]	26.31 (0.196)		60 (0.212)	91[c]
Cinnamyl alcohol	67.32 (0.501)	0.55	150 (0.56)	92[c]
2-Cyclohex-en-1-ol	14.2 (0.145)	0.198	140 (0.161)	90.4[d]
2-Cyclopenten-1-ol	67.2 (0.80)	0.895	750 (0.840)	72.4[e]
Mesityl oxide	44.32 (0.452)	0.50	200 (0.510)	85[f]
Phorone	49.10 (0.354)	0.350	200 (0.386)	50.2[g]
Isophorone	69.9 (0.505)	0.523	195 (0.277)	69.1[h]

[a] Tetrahydropyran ether prepared in situ and utilized without purification. [b] Based on total distilled glycols. [c] 90% 3-phenyl-1,2-propanediol, 10% 1-phenyl-1,3-propanediol. [d] 92% *trans*-1,2-, 5% *cis*-1,2-, 4% *trans*-1,3-, 0% *cis*-1,3-cyclohexanediol. [e] 90–94% *trans*-1,2-, 0% *cis*-1,2-, 5–8% *trans*-1,3-, 1–2% *cis*-1,3-cyclopentanediol. [f] Glpc showed more than one glycol. The individual isomers were not separated or characterized. [g] The partially solid product appeared to be a relatively complex mixture of isomers—not separated or characterized. [h] Major product was a diol, mp 101.7–102.5°, characterized as the *trans*-diequatorial diol (*trans*-2-hydroxy-*cis*-3-methyl-5,5-dimethylcyclohexanol). See ref 8e and Discussion.

From the literature the yield of diol from cinnamyl alcohol[9c] and cinnamaldehyde[9f] is quite low. Consequently the >90% yields of diol realized either with the tetrahydropyranyl or the disiamylboron protective groups confirm the utility of such protective groups in minimizing elimination in such derivatives.

Similarly, in the present study an attempt to hydroborate mesityl oxide without prior introduction of a protective group resulted in 60% elimination in 1 hr at 0°. On the other hand, use of disiamylborane to introduce the protective group greatly reduced the elimination, and an 85% yield of diols was realized.

Originally we assumed that the protective group was equally essential for the cyclic derivatives, such as 2-cyclopenten-1-ol, 2-cyclohexen-1-ol, and isophorone. However, a recent development has shaken this belief. Isophorone, after protection with disiamylborane, gave a 69.1% yield of essentially one diol, mp 101.7–102.5°. Recently, Klein and Dunkelblum[9e] reported that simple hydroboration of unprotected isophorone provided a 65% yield of a single diol, mp 93°, to which they assigned the *trans*-diequatorial-1,2-diol structure XII. We were puzzled by the discrepancy in the melting point, but especially by the comparable yield. Consequently, we undertook to carry out the hydroboration–oxidation of unprotected isophorone.[21] We realized a 68.5% yield of product, predominantly one isomeric diol, mp 103.9–104.5°. This compares with a 69.1% yield realized through the route involving initial protection with disiamylborane. Moreover, the product diol realized in the three reactions (Knights, Gallivan, Klein) is evidently the same material, as indicated by the pmr and infrared spectral data.[9e] It should be noted that 2-cyclohexen-1-ol and 2-cyclopenten-1-ol likewise give the *trans*-1,2-diols predominantly.



XII

This opens up the possibility that in these cyclic derivatives hydroboration goes preferentially *trans*, possibly for steric and polar reasons, and these *trans* derivatives are much more stable to elimination than the corresponding aliphatic derivatives where mere rotation can place the eliminating groups in a *cis* arrangement. The failure to find any appreciable amount of the *cis*-1,2-diols in these cyclic intermediates would then be attributed to the relative instability of the *cis*

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(21) We are indebted to Evord F. Knights for this experiment.

Table V. The Hydroboration of Representative Compounds and Elimination

Compound	Amount, g (mmol)	Disiamylborane, mmol	Borane–THF, mmol	Catalyst, ml (mmol)	Time, hr	Yield,[c] %
Cinnamyl alcohol	68.7 (512)	542	485	45[a]	12	75[d]
Crotyl alcohol	2.56 (36.5)	41	41	5[a]	4	37.5[e]
2-Cyclohexen-1-ol	3.63 (37.1)	43	35.4	7.0 (108)[b]	7	82.3[f]
2-Cyclopenten-1-ol	3.01 (35.8)	43	35.4	6.8 (104)[b]	6	77.5[g]
Mesityl oxide	3.46 (35.3)	43	35.4	7.0 (108)[b]	5	63.7[h]

[a] Methanol. [b] Methanesulfonic acid. [c] Glpc analysis 10% SE 30 on Chromosorb W 60–80. [d] Allylbenzene. [e] 1-Butene. [f] Cyclohexene. [g] Cyclopentene. [h] 4-Methyl-2-pentene.

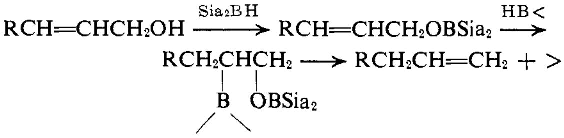
isomer which undergoes elimination and rehydroboration to form the corresponding alcohols. This interesting possibility is now being explored with Evord F. Knights.

On this basis the success of disiamylborane to serve as a satisfactory protective group would be due not so much to its very low leaving characteristics, but to its large steric requirements which make it difficult for both it and the neighboring boron moiety to assume the *cis* conformation that appears to be most favorable for elimination.

Olefin Synthesis. Caglioti and Cainelli and their coworkers have recently utilized hydroboration to convert steroidal enol ethers, enol esters, and α,β-unsaturated ketones into the corresponding steroidal olefins.[9b] In these relatively rigid structures the *trans*-β-boron derivative is relatively stable. Consequently, it survives the hydroboration and is eliminated subsequently in a reaction catalyzed by carboxylic acids or anhydrides.[9b] Ketones have also been converted into olefins recently *via* hydroboration of the enamines and acid-catalyzed elimination of the β-aminoorganoborane.[22]

Although a major emphasis of this study was the development of feasible means of circumventing the elimination reaction in the hydroboration of crotyl-like derivatives in order to make available a convenient synthesis of 1,2-glycols and related derivatives, it soon became apparent that our success in this endeavor offered promise of extending the possibilities for the Caglioti–Cainelli olefin synthesis.

In attempting to apply the Caglioti–Cainelli synthesis to a conversion of cinnamyl alcohol to allylbenzene, the rapid elimination which occurs during the hydroboration stage results in rehydroboration and a greatly decreased yield. Consequently, it is necessary that elimination be minimized during the hydroboration stage and then induced to occur once the hydroborating agent has been destroyed. Clearly disiamylborane offers promise as a protective group, providing the elimination stage can be made to proceed satisfactorily (XIII).



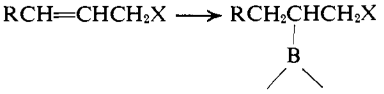
$$\mathrm{RCH{=}CHCH_2OH \xrightarrow{Sia_2BH} RCH{=}CHCH_2OBSia_2 \xrightarrow{HB<} RCH_2\underset{\underset{/\ \backslash}{B}}{\underset{|}{C}}H\underset{OBSia_2}{\underset{|}{C}}H_2 \longrightarrow RCH_2CH{=}CH_2 + {>}BOBSia_2}$$

XIII

Fortunately, we found that in refluxing tetrahydrofuran, catalyzed by acids,[9b] the elimination proceeds at a satisfactory rate. In this way cinnamyl alcohol was converted into allylbenzene, mesityl oxide into 4-methyl-2-pentene, etc. The results are summarized in Table V. Consequently, with the modification here introduced, the Caligoti–Cainelli olefin synthesis would appear to be generally applicable.

Conclusions

The present study has established that the hydroboration of crotyl-like derivatives proceeds to place the boron atom predominantly β to the substituent (XIV).

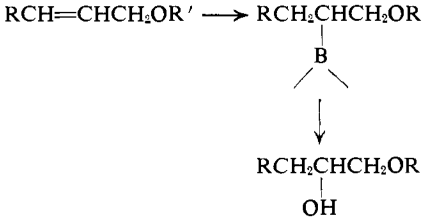


$$\mathrm{RCH{=}CHCH_2X \longrightarrow RCH_2\underset{\underset{/\ \backslash}{B}}{\underset{|}{C}}HCH_2X}$$

XIV

If X is a good leaving group (OTs, Cl, OAc), elimination occurs rapidly, followed by rehydroboration, and no means are presently available for controlling this reaction course in tetrahydrofuran. However, it has been demonstrated that the elimination of β-chloroorganoboranes can be circumvented by carrying out the hydroboration in diethyl ether, followed by a nonaqueous oxidation, such as with *m*-chloroperbenzoic acid.[23]

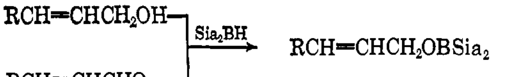
If X is a poor leaving group, alkoxy or aryloxy, the hydroboration reaction can proceed to the boron intermediate and this can be converted to product without significant elimination by working at 0° and minimizing the reaction time (XV).



$$\mathrm{RCH{=}CHCH_2OR' \longrightarrow RCH_2\underset{\underset{/\ \backslash}{B}}{\underset{|}{C}}HCH_2OR' \longrightarrow RCH_2\underset{OH}{\underset{|}{C}}HCH_2OR'}$$

XV

The important alcohol group, or the closely related carbonyl derivatives, are converted to borates in the hydroboration stage with intermediate characteristics, exhibiting approximately 50% elimination during hydroboration. These groups can be protected in a number of ways, particularly conveniently by the use of disiamylborane (XVI). These derivatives can be



$\mathrm{RCH{=}CHCH_2OH}$, $\mathrm{RCH{=}CHCHO} \xrightarrow{Sia_2BH} \mathrm{RCH{=}CHCH_2OBSia_2}$

XVI

hydroborated without concurrent elimination. The

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(22) J. L. Lewis and A. A. Pearce, *Tetrahedron Letters*, 2039 (1964).

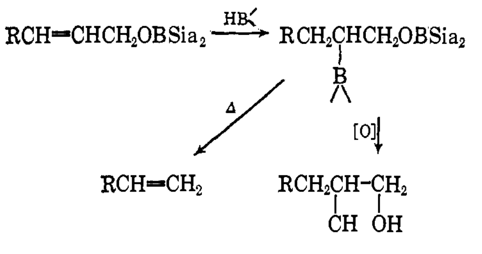
(23) This procedure has been successfully applied to 1-chlorocyclohexene (D. J. Pasto and R. Snyder, *J. Org. Chem.*, **31**, 2777 (1966)), to 7-chlorodibenzobicyclo[2.2.2]octatriene [S. J. Cristol, F. P. Parungo, and D. E. Plorde, *J. Am. Chem. Soc.*, **87**, 2870 (1965)], and to the conversion of 2-chloro-1-butene to 2-chloro-1-butanol (G. Zweifel, private communication).

Table VI. Physical Constants of Crotyl Derivatives and Products

Compound	Bp, °C (mm)	$n^{20}\mathrm{D}$	Purity,[o] %	Reported constants Bp, °C (mm)	Reported constants $n\mathrm{D}$ (t, °C)	Ref
Crotyl acetate[a]	131	1.4189	99	132.5–133	1.4182 (20)	*p*
Crotyl alcohol[b]	121.5–121.7	1.4286	99	*trans* 120–122.5	1.4263 (25)	*q*
				cis 122.4–123.7	1.4325 (25)	
Crotyl borate[c]	109 (17)	1.4438		122 (9)	1.4428 (25)	*r*
Crotyl chloride[b]	84.0–84.1	1.4353	99	*trans* 84.0–84.2	1.4326 (25)	*q*
				cis 85.0–85.8	1.4360 (25)	
Crotyl ethyl ether[d]	100.2–100.5	1.4045	100	100.8–100.9 (762)	1.4038 (21)	*s*
Crotyl phenyl ether[e]	73.0 (4)	1.5210	99	87.1–87.5 (8)	1.5183 (25)	*t*
1-Butanol[f]		1.3994			1.39931 (20)	*u*
2-Butanol[g]		1.3947			1.3949 (20)	*u*
1,2-Butanediol[h]	196			192–194		*v*
1,3-Butanediol[i]	205–206			204	1.4418 (19.5)	*w*
4-Chloro-2-butanol[j]	47–52 (2)			48–50 (2)		*x*
4-Phenoxy-2-butanol[k]	123–124.3 (7)	1.5166		130–140 (7)		*y*
1-Phenoxy-2-butanol[l]	90–91 (2)	1.5165		124 (10)	1.5170 (20)	*z*
4-Ethoxy-2-butanol[m]	71.1 (2.4)	1.4126		64 (2)	1.4125 (25)	*aa*
1-Ethoxy-2-butanol[n]	149	1.1440		147 (740)	1.4135 (20)	*bb*

[a] Columbia Chemical. [b] Aldrich Chemical. [c] By method of footnote *r*. [d] By method of footnote *s*. [e] By method of footnote *t*. [f] J. T. Baker. [g] Eastman Kodak. [h] From butylene oxide and acid hydrolysis. [i] The Matheson Co. [j] By method of footnote *x*. [k] From 4-chloro-2-butanol and potassium phenoxide. [l] From butylene oxide and potassium phenoxide. [m] By method of footnote *aa*. [n] From butylene oxide and sodium ethoxide. [o] By gas chromatography. [p] J. Bandrenghien, *Bull. Soc. Chim. Belges*, **31**, 160 (1922). [q] L. D. Huestis and L. J. Andrews, *J. Am. Chem. Soc.*, **83**, 1963 (1961). [r] W. Gerrard, M. F. Lappert, and H. B. Silver, *J. Chem. Soc.*, 1647 (1957). [s] J. D. Roberts, W. Young, and S. Winstein, *J. Am. Chem. Soc.*, **64**, 2157 (1942). [t] H. L. Goering and R. R. Jacobson, *ibid.*, **80**, 3277 (1958). [u] I. Heilbron, "Dictionary of Organic Compounds," Vol. I, Oxford University Press, New York, N. Y., 1953, p 388. [v] N. Grabowsky and A. Saizew, *Ann.*, **179**, 325 (1875). [w] M. Bergmann, A. Miekeley, and E. von Lippman, *Ber.*, **62**, 1467 (1929). [x] N. C. Gaylord, J. H. Crowdle, W. A. Himmler, and H. J. Pepe, *J. Am. Chem. Soc.*, **76**, 59 (1954). [y] E. Eimers, German Patent 1,048,924; *Chem. Abstr.*, **55**, 4460*f* (1961). [z] V. Prelog, *Ann.*, **545**, 229 (1940). [aa] E. E. Growe and G. Jones, *J. Chem. Soc.*, 3021 (1958). [bb] R. C. Waters and C. A. Van der Werf, *J. Am. Chem. Soc.*, **76**, 709 (1954).

products may then be oxidized to glycols or eliminated to olefins.



XVI

Consequently, hydroboration of crotyl-like derivatives provides convenient synthetic routes to (a) monoalkoxy and monoaryloxy 1,2-glycols, (b) 1,2-glycols, and (c) to the corresponding olefins with a shifted double bond.

Experimental Section

Materials. Tetrahydrofuran and diglyme were freshly distilled from lithium aluminum hydride. Boron trifluoride etherate was purified by distillation from calcium hydride under vacuum. Sodium borohydride from Ventron, Inc., Metal Hydrides Division, was used without purification. Diborane, disiamylborane, and thexylborane stock solutions in tetrahydrofuran were prepared by procedures previously described[24–26]

The physical constants and sources of the crotyl compounds are listed in Table VI. Also included are the products of reaction. The compounds used were examined by glpc and judged to be at least 98% pure.

General Procedure. All glassware used in these experiments was flamed out in a stream of dry nitrogen before use. A positive pressure of nitrogen was kept above the solutions at all times. Except for preparative-scale reactions, all hydroborations were carried out in a one-necked, 100-ml, round-bottomed flask, with thermometer well, inlet tube fitted with a silicon rubber septum, and a Teflon-coated magnetic stirring bar. In those experiments where heating was necessary, a water-cooled reflux condenser was used.

In a typical stoichiometry study of hydroboration, a 5-ml aliquot containing 12.7 mmol of crotyl phenyl ether was added to 15.6 mmol of borane in 45 ml of tetrahydrofuran at 0° over 2 min. The solution was stirred at 0°, and 5-ml samples were removed at the intervals indicated in Table I. The 5-ml aliquots were injected into 20 ml of 1:1:1 glycerine–water–tetrahydrofuran, and the volume of gas evolved was measured in a gas buret. The amount of hydride consumed was the difference between the amount started with and the amount left over in the solution.

In a typical product study, 1.95 g (19.5 mmol) of crotyl ethyl ether was added to 20 ml (20.0 mmol) of borane in tetrahydrofuran at 0° over 5 min. After 1 hr, water was added cautiously to decompose excess hydride. Oxidation was carried out by adding 7 ml of 3 *N* sodium hydroxide, followed by dropwise addition of 2.5 ml of 30% hydrogen peroxide. At this point 1.68 g of phenatole was added as internal standard. The solution was then saturated with potassium carbonate and separated. The ether layer was dried over magnesium sulfate and analyzed by glpc.

The Perkin-Elmer Model 154 vapor fractometer with Leeds and Northrup recorder and printing integrator was used for product analysis. A 2-m column packed with 20% Carbowax 20M on Chromosorb W was used for alcohols. The glycols were determined on a 2-m 10% Carbowax 20M–terephthalic acid on HMDS Chromosorb W 70–80 at 150°.

Protective Groups for Crotyl Alcohol. To 20 ml (20.1 mmol) of disiamylborane stock solution was added 1.42 g (19.6 mmol) of crotyl alcohol at 0°. After hydrogen evolution was complete, 7 ml (20.5 mmol) of borane–tetrahydrofuran was added. After 1 hr, water was added, then 15 ml of 3 *N* sodium hydroxide and 8 ml of 30% hydrogen peroxide, to oxidize the organoboranes. The products were analyzed as above.

Crotyl thexylboronate ester was prepared from 35 ml (42.7 mmol) of thexylborane stock solution and 1.46 g (20.2 mmol) of crotyl alcohol. Excess thexylborane hydroborated the double bond and water removed any excess hydride. The oxidation was conducted using 16 ml of 3 *N* sodium hydroxide and 10 ml of 30% hydrogen peroxide. Isolation and analysis were as above.

Crotyl tetrahydropyranyl ether was prepared by mixing crotyl alcohol with excess dihydropyran in the presence of a trace of

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(24) G. Zweifel, K. Nagase, and H. C. Brown, *J. Am. Chem. Soc.*, **84**, 183 (1962).

(25) G. Zweifel, K. Nagase, and H. C. Brown, *ibid.*, **84**, 190 (1962).

(26) G. Zweifel, N. R. Ayyangar, and H. C. Brown, *ibid.*, **85**, 2072 1963).

Table VII. Physical Constants of Starting Materials and Products

Compound	Bp, °C (mm)	n^{20}D	Reported constants: Bp, °C (mm)	Reported constants: nD (t, °C)	Ref
Cinnamyl alcohol[a]	(mp 32.4–32.8)		(mp 32.5)		*g*
Crotonaldehyde[a]		1.4390		1.4436 (15)	*h*
2-Cyclohexen-1-ol[b]		1.4869		1.4879 (20)	*i*
2-Cyclopenten-1-ol[c]	51.2–52.5 (12)	1.4706	52 (12)	1.4717 (20)	*c*
Isophorone[a]		1.4758		1.4766 (20)	*j*
Mesityl oxide[d]	126.8	1.4427	129.5–130	1.4460 (16)	*k*
				1.4484 (13)	
Phorone[e]	(mp 28)	1.4991	(mp 28)	1.49982 (20)	*l*
Allylbenzene[e]		1.5114		1.5118 (20)	*m*
Cyclohexene[f]		1.4466		1.44507 (22)	*n*
Cyclopentene[f]		1.4298		1.4278 (18)	*o*
cis-4-Methyl-2-pentene[f]		1.3898		1.3849 (25)	*p*
trans-4-Methyl-2-pentene[f]		1.3910		1.3859 (25)	*p*

[a] Eastman Kodak. [b] Aldrich Chemical. [c] By the method of K. Alder and F. H. Flock, *Ber.*, **89**, 1732 (1956). [d] Matheson Coleman and Bell. [e] Columbia Chemical. [f] Phillips Petroleum. [g] S. W. Chaikin and W. G. Brown, *J. Am. Chem. Soc.*, **71**, 123 (1949). [h] H. Hibbert, *ibid.*, **37**, 1759 (1915). [i] A. W. Burgstahler and I. C. Norin, *ibid.*, **83**, 198 (1961). [j] G. R. Cleno, W. Cocker, and S. Hornsby, *J. Chem. Soc.*, 616 (1946). [k] H. Hibbert, *J. Am. Chem. Soc.*, **37**, 1748 (1915). [l] L. von Claisen, *Ann.*, **180**, 1 (1875). [m] J. Stuuman, *Proc. Acad. Sci. Amsterdam*, **38**, 50 (1935). [n] G. H. Coleman and H. F. Johnson, "Organic Synthesis," Coll. Vol. I, John Wiley and Sons, Inc., New York, N. Y., 1932, p 183. [o] W. Meiser, *Ber.*, **32**, 2050 (1899). [p] F. R. Rossini, *et al.*, *J. Res. Natl. Bur. Std.*, **45**, 173 (1950).

p-toluenesulfonic acid. Excess dihydropyran was removed and the product distilled under vacuum from sodium hydroxide pellets; bp 54.0–54.1° (2.1 mm), n^{20}D 1.4511.

Anal. Calcd for $C_9H_{16}O_2$: C, 69.18; H, 10.32. Found: C, 69.51; H, 10.62.

The infrared and pmr spectra were in agreement with the assigned structure.

This compound was hydroborated as in the product study. Following oxidation the protective group was removed by refluxing in methanol with a trace of *p*-toluenesulfonic acid.

Crotyl benzyl ether was prepared from sodium salt of crotyl alcohol and benzyl chloride in toluene. The inorganic material was removed by water and the ether purified by distillation, bp 58.2° (0.5 mm), 91° (2.4 mm), n^{20}D 1.5111. The infrared and pmr spectra were in agreement with the assigned structure.

Anal. Calcd for $C_{11}H_{14}O$: C, 81.44; H, 8.69. Found: C, 81.30; H, 8.90.

This compound was hydroborated and oxidized as in the product study and the benzyl group removed by hydrogenolysis[27] with 5% palladium on charcoal in a Brown and Brown hydrogenator.[20] Products were analyzed as in product study.

Crotyl trityl ether was prepared from crotyl alcohol and trityl chloride in pyridine. A small amount of triphenylcarbinol was removed by column chromatography. Distillation gave bp 204° (2.4 mm), n^{20}D 1.6006, mp 67°. Infrared and pmr spectra were consistent with the assigned formula.

Anal. Calcd for $C_{23}H_{22}O$: C, 87.81; H, 7.01. Found: C, 87.73; H, 7.13.

This compound was hydroborated as before. After oxidation, the trityl group was removed by methanolysis with acid. Incomplete removal of the trityl group was observed. Increasing the amount of methanol or acid did not increase the amount of glycol obtained.

Conversion of Representative Derivatives to Glycols. Various allylic alcohol and α,β-unsaturated ketones (Table VII) were converted to the disiamylborinate ester, hydroborated, and oxidized. The glycols were obtained by distillation. Cinnamyl alcohol serves as a typical example. To 255 ml (0.55 mol) of disiamylborane in tetrahydrofuran was added 67.32 g (0.501 mol) of cinnamyl alcohol. After hydrogen evolution had stopped, 150 ml (0.56 mol) of borane in tetrahydrofuran was added. Excess hydride was decomposed with water and oxidation was conducted by adding 44 g of sodium hydroxide in 100 ml of water and 160 ml of 30% hydrogen peroxide. After salting out the organic layer with potassium carbonate and drying over magnesium sulfate, the products were obtained by distillation, as reported in Table IV.

Glpc analysis showed the presence of two diols in a ratio of 90:10. Oxidation of the organoborane remaining after an elimination experiment revealed the disappearance of the major peak and the continuance of the minor. Consequently, the minor peak must be 1-phenyl-1,3-propanediol from the stable 1,3-boron derivative, and the major peak must arise from the thermally unstable 3-phenyl-1-disiamyloxy-2-boron derivative. It should be stressed that in some cases this procedure provides a highly convenient and useful route to such 1,3-diols.

Authentic samples of the isomeric diols from cyclopentane and cyclohexane were available from earlier work.[28] Consequently, there was no difficulty in analyzing the products from cyclohexen-1-ol and cyclopenten-1-ol.

In one experiment mesityl oxide, 0.25 mol, was added to 0.25 mol of borane in tetrahydrofuran at 0°. Hydrolysis after 1 hr showed that 2.60 equiv of hydride had been consumed, so that 60% elimination had occurred. Glpc examination of the oxidized mixture showed the presence of major amounts of two alcohols with a slightly longer retention time than 3-methyl-2-butanol, probably 4-methyl-2-butanol and 2-methyl-3-butanol, although definite identification was not attempted. The elimination was largely circumvented by the disiamylborane–borane procedure. Distillation yielded a glycol fraction in a yield of 85%. However, no attempt was made to identify the isomeric glycols.

The isophorone results are of special interest, as discussed earlier.

Isophorone (0.5 mol) was converted into the disiamylborinate ester by reduction of the ketone group with disiamylborane. The double bond was hydroborated with borane–tetrahydrofuran. Excess hydride was destroyed with water, and the boron intermediate was oxidized with alkaline hydrogen peroxide. Glpc examination of the crude product revealed the presence of 3-methyl-2-butanol (siamyl alcohol), three minor peaks whose retention time corresponded to alcohols, plus a large peak with the longest retention time. Removal of the ether solvents gave a white, crystalline product in 69% yield. Recrystallization from petroleum ether (bp 60–70°) gave a white solid which melted sharply at 101.7–102.5°. This material was identical with the major peak in the glpc examination of the crude product.

Recently Klein and Dunkelblum reported that hydroboration–oxidation of isophorone yielded a single 1,2-diol, mp 93°, in 65% yield.[9e] They assigned the *trans*-diequatorial diol structure XII to the product. We were puzzled by the fact they indicated that only one isomer is formed, with a melting point significantly lower than that observed for our product, and that their yield was comparable to ours even though they did not use a protective group. Accordingly, we decided to undertake a hydroboration of isophorone with borane–tetrahydrofuran.[21]

Isophorone, 34.6 g (250 mmol), was dissolved in 50 ml of tetrahydrofuran and added dropwise to a solution of 0.333 mol of borane in 500 ml of tetrahydrofuran cooled in an ice bath. After 4 hr, excess hydride was destroyed by the addition of 20 ml of water, and the intermediate was oxidized by adding 60 ml of 3 *M* sodium hydroxide, followed by the addition at 25–35° of 60 ml of

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(27) R. H. Baker, K. H. Cornell and M. Cron, *J. Am. Chem. Soc.*, **70**, 1440 (1948).

(28) H. C. Brown and G. Zweifel, *J. Org. Chem.*, **27**, 4708 (1962); G. Zweifel and H. C. Brown, *J. Am. Chem. Soc.*, **85**, 2066 (1963).

30% hydrogen peroxide. Evaporation of the solvent yielded 26.8 g of material. This was dissolved in refluxing petroleum ether (bp 60–70°), and 20.5 g of white needle crystals was precipitated in three crops. Crop one exhibited mp 95.5–101.2°, crop three, mp 94.7–101.2°. Recrystallization from petroleum ether afforded fine white needles, mp 103.9–104.5°. All washes and crystallization solutions were combined, and the solvent was removed under vacuum. There was obtained 6.3 g of syrup (out of the original 26.8 g of product). Glpc examination revealed 25% of the above diol, a smaller amount of a material whose retention time indicated that it might be an isomeric diol, and three peaks whose retention time corresponded to alcohols. The pmr data of Klein and Dunkelblum correspond exactly with that exhibited by our material, mp 101.7–102.5° (Gallivan) or 103.9–104.5° (Knights). The ir data also agree.

Consequently, in the case of this cyclic derivative it is probable that the use of a protective group may be superfluous. This is under investigation.[29]

Eliminations. In order to determine the best conditions for the elimination reaction, two simultaneous experiments were conducted, using identical amounts of cinnamyl alcohol and disiamylborane. The cinnamyl ester thus produced was hydroborated with borane–tetrahydrofuran for 1 hr at 0°. In one case excess hydride was destroyed with water; in the other, with methanol. Both solutions were then heated at reflux and samples periodically removed for analysis for allylbenzene by glpc. In both cases, the yield became constant in 6 hr.

To see if acids would increase the rate, three simultaneous experiments were run as above, but the excess borane was destroyed with methanol, acetic acid, and methanesulfonic acid and the reaction mixtures were maintained at room temperature ($\sim$30°). After 1 hr the yield of allylbenzene was greatest with methanesulfonic acid, less with acetic, and still less with methanol. However, after 6 hr all of the yields were comparable.

The procedure was tested on a preparative scale with cinnamyl alcohol. Under the usual hydroboration conditions 0.5 mol of cinnamyl alcohol was treated with 0.5 ml of disiamylborane at 0° to form the disiamylborinate ester. The product was hydroborated with 0.5 mol of borane in tetrahydrofuran at 0° for 1 hr. Methanol was added to decompose excess hydride, and the reaction mixture was heated under reflux for 12 hr to achieve the elimination. The volatile products were removed by a crude distillation, bp 65–160°. Glpc analysis indicated the presence of 0.4 mol of allylbenzene. Distillation provided allylbenzene, n^{20}D 1.4950, in 50% yield.

Results with other compounds are given in Table IV.

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[29] A detailed study of such cyclic derivatives is underway by E. F. Knights and will shortly be reported.

Hydroboration. XXVII. The Hydroboration of 1-Butenyl and Related Vinyl Derivatives Containing Representative Substituents. An Unusually Powerful Directive Influence of the Ethoxy Substituent[1]

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Abstract: The hydroboration of vinyl derivatives, $>C_\beta{=}C_\alpha HX$, can proceed to place the boron on both the α and β positions. The rates of hydroboration, the stoichiometry of the reaction, and the products produced under standard conditions were examined for several representative systems: isobutenyl, 1-butenyl, 2-butenyl, and 1-cycloalkenyl. Chloro, acetoxy, and ethoxy were selected as representative substituents in the vinyl position. Hydroboration of isobutenyl chloride and isobutenyl acetate proceeds comparatively slowly, placing practically all of the boron in the α position. These β-substituted derivatives appear to be relatively stable and are readily oxidized to the corresponding aldehyde. On the other hand, the ethoxy derivative reacts exceedingly rapidly and causes a complete reversal, with boron adding to the β (tertiary) position. Oxidation produces 1-ethoxy-2-methyl-2-propanol. With decreasing tendency of the parent hydrocarbon to direct boron to the α position, hydroboration produces less simple results in the case of the chloro and acetoxy derivatives, the addition proceeding to give boron on both the α and β positions. The situation is further complicated by the ability of the β-boron derivatives to undergo elimination and rehydroboration and by the tendency of the α-boron derivative to undergo replacement of the substituent by hydrogen. Consequently, the synthetic aspects of hydroboration of vinyl chlorides are promising but require further exploration. On the other hand, in all derivatives examined, the hydroboration of vinyl ethyl ethers proceeds essentially quantitatively to give the β-boron derivative, and the latter is readily oxidized to the 1-ethoxy-2-hydroxy compound.

The first reaction of a typical vinyl derivative with diborane under representative hydroboration conditions[3] appears to be the study of vinyl chloride described by Hawthorne and Dupont.[4] These authors reported that at −80° diborane dissolved in a dimethyl ether solution of vinyl chloride. On warming to room temperature this solution underwent a violent exothermic reaction. The authors accounted for the formation of the isolated product, β-chloroethylboron dichloride, in terms of a series of elimination reactions following the initial hydroboration[5] (I).

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[1] Based upon a thesis submitted by R. L. Sharp in 1966 to the Faculty of Purdue University in partial fulfillment of the requirements for the Degree of Doctor of Philosophy.

[2] Graduate research assistant, 1963–1966, on Grant No. GM-10937 of the National Institutes of Health.

[3] H. C. Brown, "Hydroboration," W. A. Benjamin, Inc., New York, N. Y., 1962.

[4] M. F. Hawthorne and J. A. Dupont, *J. Am. Chem. Soc.*, **80**, 5830 (1958).

[5] It has been our observation that hydroborations at −80° are very slow, even with ordinary reactive olefins. As will be pointed out in this paper, the vinyl chlorides are much less reactive toward diborane than the simple alkenes. On the other hand, once reaction occurs it is quite exothermic. Consequently, this procedure followed by Hawthorne and Dupont is not advisable.