Synthesis of Oxochromium(VI) Alkoxides via Epoxide Cleavage. Structure, Reactivity, and Mechanism

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In an NMR spectroscopic study the cleavage of epoxides [ethylene, propylene, and *cis/trans*-butylene oxide] by chromyl chloride giving access to oxochromium(VI) alkoxides was shown to proceed via a bimolecular rate-determining step where two molecules of a complex $CrO_2Cl_2\cdots$epoxide collide. Subsequently one Cl ligand at the first Cr center attacks the backside of an epoxide molecule complexed at the Cr center of a second $CrO_2Cl_2\cdots$epoxide molecule and vice versa. The *trans*-opening of the epoxides was proved by determining the configuration of the chlorohydrins resulting from hydrolysis of the corresponding alkoxide products in the cases of *cis*- and *trans*-butylene oxide. The NMR data provide evidence that each oxochromium(VI) alkoxide adopts one preferred conformation in solution although DFT calculations did not indicate any special stabilizing effects. The product formation was rationalized by DFT calculations concerning the thermodynamics of the reactions.

Introduction

Epoxides are important synthons for the construction of complex organic substances.[1] The development of asymmetric epoxidations of allyl alcohols[2] and olefins[3] made optically pure epoxides easily available, which can serve in turn as valuable starting materials in stereospecific syntheses. For the latter especially ring-opening reactions—catalyzed by Lewis and Brønstedt acids—are of great practical importance.

The mechanism and stereochemistry of the acid-catalyzed ring-opening of 1,2-epoxides in solution strongly depend on several intrinsic factors such as the structures of the epoxides and the nature of the substituents and their positions with respect to the ring, on environmental factors such as the polarity and nucleophilic character of the solvent, as well as on the nature of the acidic catalyst, the temperature, etc.[4] Accordingly the acid-catalyzed alcoholysis of epoxides proceeds via a variety of mechanisms—from the A1 to the A2 extrema[5] (Scheme 1)—with a stereochemistry ranging from complete retention to complete inversion.[6] The acid-catalyzed cleavage
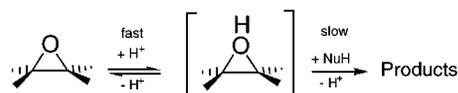
Scheme 1
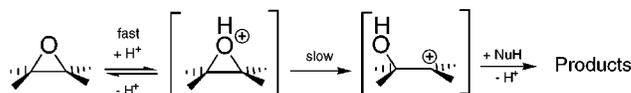
of the simplest asymmetrically substituted epoxide—1,2-propylene oxide—proceeds, for instance, via different mechanisms dependent on the specific reaction site, i.e., A2 reactions at the unsubstituted and A1−A2 at the methyl-substituted carbon atom.[5,7]

An analogous picture emerges if Lewis acids (such as for instance organo-V, -Ti,[8] -Zr[9] and -Y[10] compounds) are employed, which catalyze, as one example, the syntheses of azidohydrins starting from epoxides and Me_3SiN_3. Jacobsen and co-workers recently discovered that chiral Cr(III) salen complexes are unique catalysts for the enantioselective ring-opening of *meso*-epoxides by Me_3SiN_3 and the kinetic resolution of racemic epoxides.[11] Kinetic investigations gave strong evidence for the activation of both the nucleophile (N_3^-) as well as the electrophile (the epoxide) by the catalyst, subsequently reacting with each other in a rate-determining bimetallic

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step. Recently Leung et al. were able to show that *tert*-butylimidochromium(VI) chloride complexes can catalyze the ring-opening of epoxides by Me_3SiN_3, too.[12] The reaction involves intermediate chromium azide species mediating the transfer of the nucleophilic azide to the epoxide substrate in the rate-determining step. In contrast to Jacobsen et al., Leung and co-workers found no evidence for a previous epoxide activation. However, in both cases a $Cr-N_3$ group cleaves one C−O bond of the epoxide under formation of intermediate species with $Cr-OCR_2CR_2N_3$ moieties, which could even be isolated in the case of Jacobsen's system.[11] A similar type of reaction—i.e., a Lewis acid catalyzed ring cleavage by nucleophiles, where the latter derive from the Lewis acid itself—can be found in the reactions of epoxides with BF_3 and $MgBr_2$:[13] The semi-metal- and metal-bound ligands are successively exchanged by alkoxy groups having their origin in the epoxides, and the resulting alkoxide intermediates yield the corresponding fluoro- and bromohydrins on subsequent hydrolysis. However, only a few examples are known where chlorohydrins have been generated from metal chlorides and epoxides, and even fewer attempts have been made to isolate and characterize the alkoxides generated in the primary step.[14] (*t*-$BuN)_2CrCl_2$ for instance shows no pronounced reactivity toward epoxides while the corresponding azide reacts spontaneously.[12]

Ring cleavage by nucleophiles is of course only one reaction path epoxides can move on in the presence of Lewis acidic metal halides or pseudohalides. Alternatives are isomerizations to carbonyl compounds or allyl alcohols.[14]

Results and Discussion

We have recently investigated the low-temperature behavior of epoxides in the presence of chromyl chloride. It has been shown NMR spectroscopically that epoxide complexes of chromyl chloride are formed at −80 °C, which further react at −50 °C under ring cleavage as shown in eq 1 exemplary for ethylene oxide. This novel
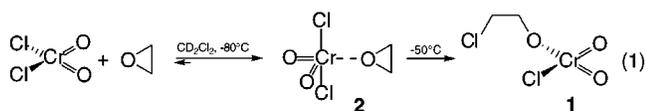
synthetic route to oxochromium(VI) alkoxides enabled the first spectroscopic characterization of representatives bearing α-H-atoms,[15] which occupy a special role within this class of substances, since species with these characteristics have been suggested as intermediates during the oxidation of primary and secondary alcohols. In the course of matrix isolation studies B. Ault found in 1998 that gaseous CrO_2Cl_2 reacts with MeOH in the primary

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Scheme 2
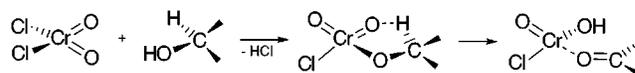
step to give HCl and $ClCrO_2(OCH_3)$ (Scheme 2), i.e., a close derivative of **1**.[16a] The carbonyl compounds obtained in alcohol oxidations could be envisaged to form from such alkoxides via either intramolecular[16b] or intermolecular α-H abstractions through the Cr=O groups−the latter being more likely as, for instance, $ClCrO_2(OCH_3)$ is relatively stable in the dilute gas phase.[16] In line with this idea **1** proved to be very sensitive in solution, decomposing at temperatures above −30 °C to give paramagnetic complexes, whose aqueous workup yielded $HC(O)CH_2Cl$.[15a] Although decomposition is much slower at −50 °C, it is still evident, limiting the time at hand for the NMR spectroscopic investigation of **1** to ca. 2 h.

Propylene oxide reacts in a similar manner, and in this case the two possible regioisomers are formed in a ratio of almost 1:1. This suggests that the C−O bond cleavage has not proceeded far in the transition state of the reaction and proceeds later on the reaction coordinate without discrimination.
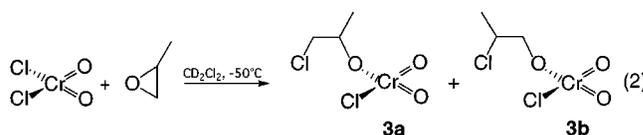
With respect to the significance of the catalytic and stoichiometric ring-opening of epoxides, we were interested in the mechanisms of reactions 1 and 2 as well as in further details concerning the structure of the products in solution.

The Mechanism. In principle there are several mechanistic possibilities for the opening of the epoxide rings by a chloride ligand of chromyl chloride: The ligand could attack in the *trans* position (the backside of the epoxide), but it is also possible that the reaction represents one of the few examples of a *cis*-opening. Furthermore, *intra*- and *inter*molecular reactions of the CrO_2Cl_2···epoxide complexes must be distinguished. While a bimolecular process would probably occur in combination with a *trans*-opening, for an intracomplex reaction both *cis*- and *trans*-openings are possible. The latter seems unrealistic at first sight, but investigations concerning the H⁺-catalyzed gas-phase methanolysis of propylene oxide have shown, for instance, that methanol coordinates at the acidic hydrogen of the protonated epoxide first before it moves around the ring to attack it from its backside.[17] A similar reaction would be possible for chromyl chloride (compare Scheme 3). To clarify this point, attempts were made to follow the kinetics of the ethylene oxide reaction (eq 1) with the aid of ¹H NMR spectroscopy. These were of course hampered by the unstable nature of **1** and the system in general: At −50 °C **1** is produced in a ca. 75% yield within 1 h of reaction time, but at that stage its decomposition rate already becomes faster than the rate of its formation. To decelerate the reaction and to thereby increase the number of data points accessible until the

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Scheme 3

Mechanism of ringopening with $MeOH_2^+$

Mechanism of ringopening with CrO_2Cl_2 ?

Figure 1. ^{1}H NMR spectra displayed by a 1:1 mixture of chromyl chloride and ethylene oxide after annealing from −80 (0 min) to −65 °C as a function of time. The signals marked with an asterisk belong to **1***.

Figure 2. Consumption of **2** plotted according to a second-order rate law. The ratio CrO_2Cl_2:oxirane was always exactly 1, but the concentrations were varied. ○ shows the data obtained for a concentration being higher by a factor of 11.2, △ by a factor of 4.4, and □ by a factor of 2 as compared to the data ◇.

termination of the experiment, the measurements were performed at −65 rather than −50 °C (Figure 1). Only the signals of the new product **1** are suited to be followed quantitatively as a function of time.[18] The signal belonging to the β-H atoms in **1** gets masked at some stage by resonances which were assigned[15a] to $O_2ClCr(OCH_2CH_2)_2$-Cl, **1***, being formed in low yield (ca. 3–8%)[19] simultaneously with **1**. Therefore, the integral of the α-H signal of **1** was used to *calculate* the consumption of complexed ethylene oxide.[20] While the data thus obtained are accurate for the first period of the reaction, with increasing reaction time the decomposition of **1** leads to errors and the resulting paramagnetic compounds impede the determination of the integral.[21] For these reasons it is not possible to start at a high concentration and follow the consumption of ethylene oxide (or better the formation of **1**) until the reaction has reached completion. Instead several samples have to be prepared with exact stoichiometries (CrO_2Cl_2/ethylene oxide = 1) but with varying concentrations. In Figure 2 $\{1/[A] - 1/[A]_0\}$ (A = calculated concentration of complexed oxirane) is plotted vs time for four different starting concentrations. The first observation which can be made is the fact that

(18) With the lack of an NMR spectroscopic probe, the consumption of chromyl chloride cannot be followed by this method, and neither is it possible to obtain reliable *direct* information concerning the consumption rate of **2** via integration of the corresponding NMR signal: As the reaction proceeds, **2** being formed in the first step becomes part of a complicated equilibrium in which oxirane complexes to paramagnetic species produced by the decomposition of **1** (vide supra) are involved, too. Consequently, with increasing reaction time the corresponding ^{1}H NMR signal (which is the averaged resonance of free ethylene oxide and species where it serves as a ligand) becomes more and more shifted and broadened and the integral perturbed as can be seen in Figure 1.

(19) Its yield and therefore its concentration can be slightly raised if the reaction is performed with *1* rather than *2* equiv of oxirane. However, with rising concentration of free oxirane the lifetimes of **1** and **1*** further decrease, so that paramagnetic decomposition products are formed even quicker than usual. In all experiments performed, slow decomposition of the sample at −50 °C, the broadness of the signals at −80 °C, and the limits in concentration because of preparation and solubility at −50 °C thwarted all attempts to record COSY spectra of **1***. Moreover, its most prominent signal in the ^{1}H NMR spectrum (δ_H 5.73 (2 H, br), 3.85 (6 H, m, br)) is masked by the H_β signal of **1**. However, the ^{13}C NMR spectrum shows three resonances (δ_C 71.79, 71.44, 44.3 (all CH_2)) of almost equal intensity which should belong to a $ClCH_2CH_2-O-CH_2$ group [compare the spectrum of 2-(2-chloroethoxy)ethanol (δ_C 72.84, 71.44, 43.55 (all CH_2))], and assuming that a fourth signal is hidden under the low-field signal of **1** (compare for instance δ_C HOCH_2 [2-(2-chloroethoxy)ethanol] − δ_C HOCH_2 [2-chloroethanol] which amounts to only 1.5 ppm), the spectrum may well belong to a $Cr-O-CH_2CH_2-O-CH_2CH_2Cl$ unit.

(20) Since also the formation of **1*** contributes to this consumption, the integral of the corresponding H_α signal[19] was considered as well.

(21) Although the influence of the paramagnetic compounds on the line widths of the signals of **1** is less pronounced in comparison to the effects observed for the ethylene oxide signal, their presence still leads to a broadening of these signals. This in combination with the naturally increasing integrals of the H_α product signals leads to serious overlap with the signal for $CDHCl_2$ at higher sample concentrations, so that the integration errors become larger in the second period of the reaction.
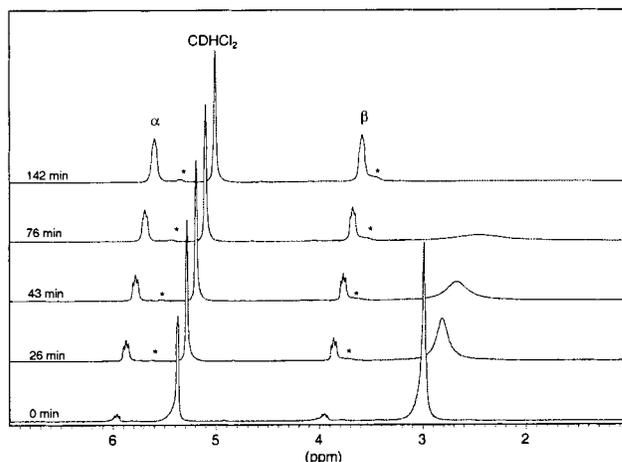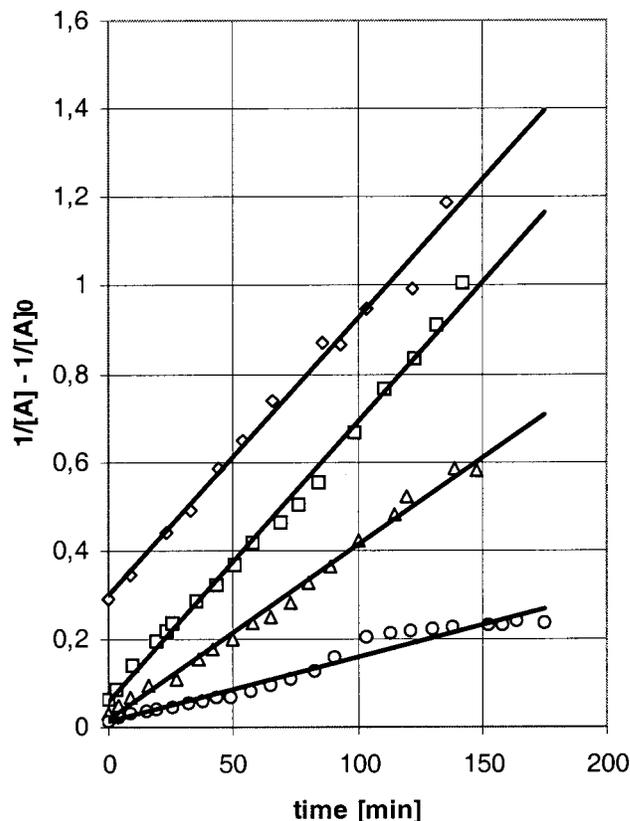
at all concentrations a straight line of data points is obtained for the initial period of the reaction [in the subsequent period the data points spread quite significantly due to decomposition reactions (vide supra)], indicating that it follows a second-order rate law with respect to coordinated oxirane and suggesting a bimolecular rate-determining step. This finding strengthens the assumption that **2** is the reacting species, since other oxirane complexes such as $CrO_2Cl_2[O(CH_2)_2]_2$, **2***, which

Scheme 4
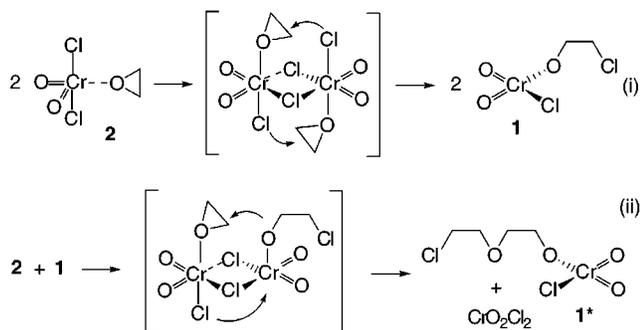
has been proved to form almost quantitatively in a 1:2 reaction of CrO_2Cl_2 and oxirane[15a] and which will therefore be part of the equilibria in solution, too, would not be expected to decompose via a second-order rate law with respect to themselves (any reaction involving free CrO_2Cl_2 should have given rise to a first-order rate law). Considering a possible binuclear intermediate or transition state, it should be noted that with few exceptions the normal coordination number of Cr(VI) is 4. Accordingly, the electron-deficient chromyl chloride is monomeric in solution and in the gas phase,[22a] but the coexistence of dimers in the gas phase has been deduced from mass-spectrometric experiments.[22b] Furthermore, it has been shown that it undergoes rapid ligand exchange with CrO_2F_2 for which a transition state with μ-Cl and μ-F bridges has been suggested.[22c] The proposal of a transition state or an intermediate of high energy similar to the one shown in Scheme 4 (i), being weakly stabilized by either one or two chloride bridges (note the dashed line at one of the Cr centers) and being formed in the rate-determining step, is therefore reasonable. It is also in line with the results found for the reaction of propylene oxide, suggesting that the C−O bonds are still basically intact at that stage. Furthermore, the formation of such a dinuclear species would weaken the remaining terminal Cr−Cl bonds, so that the Cl ligands are readily transferred onto the epoxide moieties, thereby reestablishing lower coordination numbers (if just one chloride bridge is formed, the opening of the two oxirane molecules will of course not proceed in a concerted fashion). Subsequently the resulting dimer of **1** can dissociate. **1*** must be formed in the course of an alkoxide transfer reaction, which correspondingly could proceed as shown in Scheme 4 (ii).

Interestingly, the initial rate constant seems to increase with decreasing concentration of the starting materials. The reason for this will have its origin in the fact that the concentration of **2** reacting to give **1** is determined by several equilibria involving free CrO_2Cl_2 and oxirane as well as **2***. Its contribution to $[A]_0$ will therefore vary slightly with dilution, causing a variation of the gradients in Scheme 4, although the rate constant of course remains the same, *i.e.*, the fact that $[A]_0 \neq [\mathbf{2}]$ is responsible for the effect. The equilibrium is, however, far too complicated to make an attempt to qualitatively explain it. To further support the idea of **2** reacting out of an equilibrium involving CrO_2Cl_2 and **2***, the influence of free chromyl chloride on the rate was studied by

Scheme 5
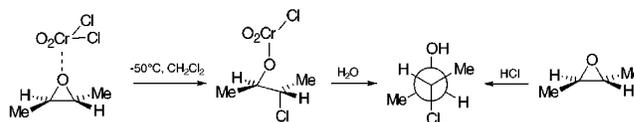
employing it in a 10-fold excess. The reaction then almost reaches completion (95%) already after 20 min, which seems reasonable as an excess of CrO_2Cl_2 lowers the concentration of **2*** in favor of **2**. It is not possible to perform the reaction under pseudo-first-order conditions with an excess of ethylene oxide since the lifetime of **1** proved to decrease drastically with increasing oxirane concentration. The exact reason for this finding is not clear. However, the initial rate observed in such experiments was much lower than the one for the same CrO_2-Cl_2 concentration in the presence of just 1 equiv of oxirane. This is understandable as then **2*** becomes the major compound in solution being unable to react via a mechanism as shown in Scheme 4 without prior dissociation of one ligand.
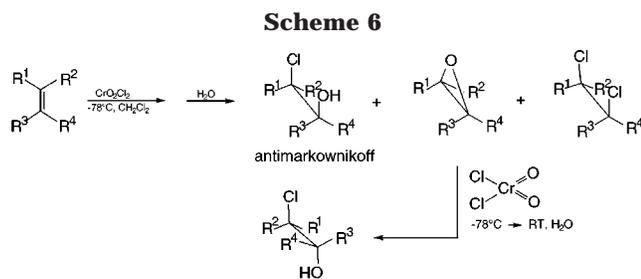
It is obvious that this system is very complex (so that it would not be appropriate to deduce any quantitative information from the kinetic data) and also that a simple plot of $1/[A] - 1/[A]_0$ vs time represents only a very rough approximation becoming more and more erroneous with increasing reaction time.[23] However, these data reliably show that the consumption of complexed oxirane initially obeys a second-order rate law, and thus they are suggesting the formation of **1** according to eq i being supported by other findings, too.

Stereochemistry. After having found that **1** is formed in a reaction obeying a second-order rate law, it was important to determine the stereochemistry of the ring cleavage. The epoxides *cis*- and *trans*-2-butylene oxide as well as cyclohexene oxide [which proved to react similarly to ethylene and propylene oxide (vide infra)] were reacted with chromyl chloride at −50 °C on a preparative scale. Their cleavages produce *two* stereocenters, and accordingly diastereomers rather than enantiomers have to be distinguished. The reaction mixtures obtained were quenched by water and the resulting chlorohydrins extracted and identified by means of IR and NMR spectroscopy, respectively. Gas chromatography provided additional information concerning type and relative yields of the chlorohydrin stereoisomers (and consequently about the stereochemistry of the ring-opening). Reference spectra and retention times were obtained by performing measurements with authentic samples which had been prepared independently. A *trans*-cleavage by chromyl chloride can, for instance, be simulated by HCl which adds selectively *trans* to epoxides[24] as shown in Scheme 5. It turned out that the chlorohydrins isolated from the chromyl chloride cleavage reactions had all selectively [90% (hexene oxide) and 99% (butylene oxides)] been formed via *trans*-opening of the epoxides; i.e., *trans*-butylene oxide gave the *threo*-, *cis*-butylene oxide and the *erythro*-chorohydrin, which is in good agreement with the bimolecular mechanism postu-

(22) (a) Marsden, C. J.; Hedberg, L.; Hedberg, K. *Inorg. Chem.* **1982**, *21*, 1115. (b) Flesch, G. D.; Svec, H. J. *J. Am. Chem. Soc.* **1959**, *81*, 1787. (c) Akena, A. M.; Brown, D. S.; Tuck, D. G. *Can. J. Chem.* **1971**, *49*, 1505.

(23) To be accurate, all equilibria **2** is involved in would have to be considered, but in agreement with the experimental results it can be assumed that these quickly adjust and also that **2** is a major compound in solution. Moreover, neither reaction ii nor the decomposition processes were considered, but this should be appropriate for the first periods of the reactions.

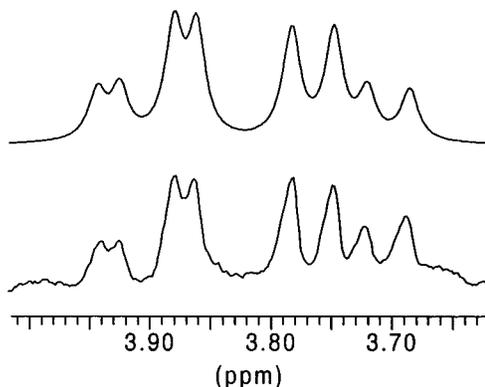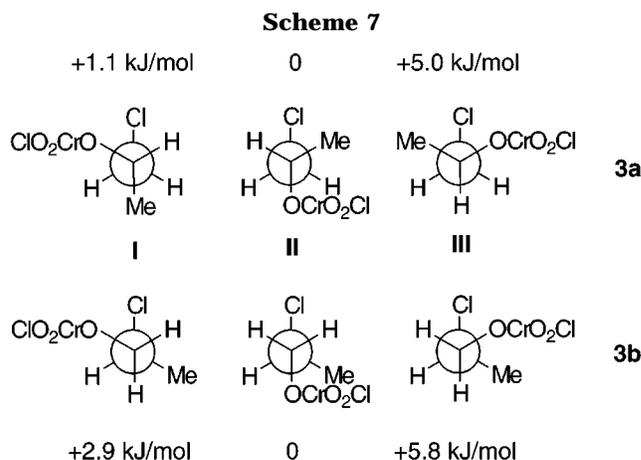(24) Bartlett, P. J. *J. Am. Chem. Soc.* **1935**, *57*, 224.

Scheme 6

Figure 3. Experimental (lower trace) and calculated (upper trace; line width 3.5 Hz, *R* factor 9.48, standard deviation 1.31) ^{1}H NMR spectrum for the methylene unit of **3a**.

Scheme 7

lated in Scheme 4. This finding may have an impact on the results K. B. Sharpless et al. obtained investigating olefin oxidations by chromyl chloride. It had been observed[25] that the chlorohydrins isolated after aqueous workup of the reaction mixtures had mainly been produced in a *cis*-addition of the components of HOCl to the olefins, but that a small fraction had also formed in a *trans*-addition. Since the second type of main product occurring in such oxidations is represented by epoxides (compare Scheme 6), Sharpless also investigated the behavior of epoxides in the presence of chromyl chloride at −80 °C. While he could not detect any reaction between these compounds at that temperature, he found that *trans*-opening of epoxides did occur when they were present in the reaction mixture while another olefin was being oxidized. He therefore "felt that epoxides undergo sufficient *trans* opening to chlorohydrins to completely account for the *trans* addition of HOCl observed in olefin oxidations". The findings presented here prove that this statement is right. Although no reactions involving epoxides (apart from complexation) will have occurred at −80 °C, on quenching the mixture will eventually have reached temperatures where *trans*-cleavages of epoxides by chromyl chloride occur.

Spectroscopic Properties of the O$_2$Cr(OCR^{1}R^{2}CR^3-R^{4}Cl)Cl Products and Their Structure in Solution. The ^{1}H NMR spectra of **1** and **3** give rise to some thoughts concerning the solution structure of those compounds. While the pseudotriplets (compare Figure 1) obtained for the methylene groups of **1** after ring-opening of ethylene oxide by chromyl chloride are not unusual (XCH$_2$CH$_2$Y moieties can in principle yield spectra of higher order),[26] the multiplet observed for the methylene group of Cl-(O=)$_2$Cr−O−(CH$_3$)CH−CH$_2$−Cl, **3a**, on employment of propylene oxide can only be explained in terms of one special geometry being preferred in solution: The two protons are diastereotopic and accordingly form a priori two doublets (^2J(HH) = 12.6 Hz). Remarkably and as becomes obvious from Figure 3, they are coupled with different constants to the methine proton of the neighbor carbon [^3J(HH) = 7.2 and 3.6 Hz as determined by simulation (δ_A = 3.90, δ_B = 3.74 ppm)]; i.e., in solution mainly a structure is adopted in which (according to Karplus)[26] they show different torsion angles with respect to this methine proton. For **3a** three staggered conformations shown in Scheme 7 exist.[27] According to the ^{1}H NMR data, a structure similar to either **3a$_I$** or **3a$_{II}$** must be predominantly present in solution, since only those would yield one large (*trans*) and one small (*cis*) coupling

(25) Sharpless, K. B.; Teranishi, A. Y.; Bäckvall, J.-E. *J. Am. Chem. Soc.* **1977**, *99*, 3120.

(26) Fribolin, H. *Ein- und Zweidimensionale NMR−Spektroskopie*; VCH: Weinheim, 1988.

(27) Plus enantiomers, which also form as the propylene oxide employed was not enantiomerically pure, but these of course have identical NMR properties.

constant. Comparing **3a$_I$** and **3a$_{II}$** individually to **3a$_{III}$**, this appears to be reasonable on the basis of simple arguments considering sterically unfavorable *gauche*-interactions of ligands at the central C−C bond. However, only one of the structures, **3a$_I$** or **3a$_{II}$**, is adopted in solution as indicated by the two markedly different coupling constants (note, that−on the appropriate assumption[26] of a fast rotation around the C−C bond at −50 °C−in the case of an equal population of **3a$_I$** and **3a$_{II}$** two identical coupling constants ^3J(HH) should be found for each of the diastereotopic protons due to averaging!), and responsible is possibly the "anti-periplanar effect": in **3a$_I$** the high-lying $\sigma_{C−CH_3}$ bond orbital can delocalize into the low-lying $\sigma^*_{C−Cl}$ orbital, and the same is possible for $\sigma_{C−H}$ and $\sigma^*_{C−O}$. In **3a$_{II}$** no such interaction is possible so that **3a$_I$** will be the more favorable conformation. By analogy the spectrum of the regioisomer Cl(O=)$_2$Cr−O−CH$_2$−CH(CH$_3$)−Cl, **3b**, can be assigned: A simulation showed that the couplings, which could be deduced from the spectrum of **3b**, are in excellent agreement with those of **3a** and that therefore also in the case of **3b** one of the conformations (**3b$_I$** or **3b$_{II}$**) should be significantly more stable than the other one. Applying similar arguments as above, it has to be concluded that **3b$_I$** is more favorable than **3b$_{II}$**. DFT calculations (LANL2DZ, B3LYP) did not reveal any other structure-determining forces such as for instance interactions between the Cr=O groups and α-, β-, or γ-hydrogens, or between the Cr centers and the Cl atoms of the alkoxy arms. Starting geometries suitable to develop contacts as those mentioned above during the optimiza-

Scheme 8
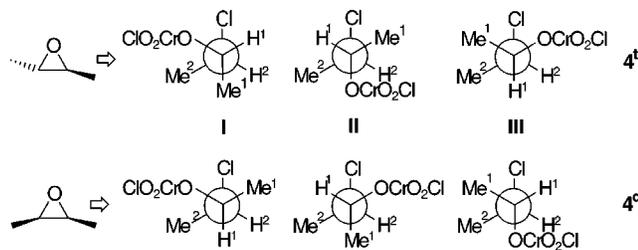
Table 1.   ¹H and ¹³C NMR Data for 4ᶜ and 4ᵗ

$^3J_{(MeCH)} = 6.2$ Hz	$\delta_C(\mathbf{4^t})$/ppm	$\delta_H(\mathbf{4^t})$/ppm	$\delta_C(\mathbf{4^c})$/ppm	$\delta_H(\mathbf{4^c})$/ppm
(CH)¹	102.76	6.05	102.33	6.01
Me¹	20.30	1.66	21.86	1.69
(CH)²	61.33	4.33	61.70	4.21
Me²	19.32	1.51	20.70	1.56

tion procedure were employed, but neither Cr⋯Cl (the Cr⋯Cl distances amounted to ca. 4.2 Å) nor Cr=O⋯H interactions became apparent. However, this can simply be due to the well-known difficulties for DFT methods to describe weak interactions.[28] As the differences in energies computed for the pairs of conformers under discussion are negligible (see Scheme 7) and even suggest that the conformers lacking an anti-periplanar effect should be slightly more stable, it has to be concluded that the latter has not been considered appropriately in these calculations, either.

It was therefore attempted to accumulate additional evidence in a comparative study. Should the above arguments hold, then the products obtained after employment of *cis-* and *trans*-butylene oxide should show unusual coupling constants, too. Making use of the finding that the epoxide rings are attacked from their backsides, the possible staggered conformations for the products resulting from the reaction of chromyl chloride with *trans-* and *cis*-butylene oxide can be formulated as in Scheme 8 (the corresponding enantiomers are omitted). It should be obvious that in the absence of any additional effects the conformations **II** where unfavorable *gauche*-interactions are minimized should be the most stable ones. In this case the ^3J(HH) coupling constants measured for **4ᵗ** and **4ᶜ** should be almost equal and amount to ca. 8 Hz, which is the lower limit for the *trans* coupling constant predicted according to the findings made for **3a** and **3b**. As already mentioned above, it was found that analogously to oxirane *trans-* and *cis*-butylene oxide also formally inserted into one Cr−Cl bond of chromyl chloride, yielding (as can be deduced from the results of the previous section) exclusively *threo* (**4ᵗ**) and *erythro* (**4ᶜ**) O₂CrCl(OC¹H¹Me¹C²H²Me²Cl), respectively (compare Scheme 8; the NMR data are summarized in Table 1). In the spectra of **4ᶜ** there was no sign of **4ᵗ** and vice versa, which additionally proves that the reactions proceed selectively with defined stereochemistry.[29]

For the above reasons the determination of the ^3J(H¹H²) coupling constants of **4ᵗ** and **4ᶜ** were of interest, and for this purpose selective decoupling experiments were per-

formed. Decoupling with the ¹H frequency of Me² in **4ᶜ** converted the H² multiplet into a doublet with ^3J(H¹H²) = 4.3 Hz. When the same procedure was performed for a sample of **4ᵗ**, no coupling could be resolved, which means that with respect to the experimental conditions and the typical line widths the ^3J(H¹H²) of **4ᵗ** must be below 2 Hz. These findings exclude the conformations **II** as the preferred conformation in solution for both cases, although intuitively (considering *gauche*-interactions) they would have been expected to represent the most stable ones (in the case of **4cᵢᵢ** the anti-periplanar effect should even lead to an additional stabilization). To decide between the remaining alternatives **I** and **III**, NOESY spectra were recorded: For **4ᵗ** intense cross-peaks for Me¹/H¹ and Me²/H² as well as a weaker cross-peak for Me²/H¹ appeared (a peak for Me¹/H² was found, too, but far less pronounced) as expected for conformation **4ᵗᵢᵢᵢ**. In the case of **4ᶜ** both Me groups showed one strong and one weaker cross-peak, which is only in agreement with a conformation **4cᵢ**.[30] These results cannot be understood solely on the basis of arguments comparable to those used in the case of **3**. Unfortunately no NOE distances could be determined due to the short lifetimes of the samples, confining the interpretation to this qualitative assignment.

In summary all NMR data provide evidence that each of the compounds **3−4** adopts a certain conformation in solution, being the result of a minimization of destabilizing effects (like *gauche*-interactions) and a maximization of favorable interactions (like the anti-periplanar effect or other forces which have their origin in the −O−Cr-(O)₂Cl moiety at the central C−C bond). The discovery that **4ᵗᵢᵢᵢ** and **4cᵢ** are preferred over the other two possible staggered conformations still supports the idea of Cr⋯Cl contacts, which, however, eluded detection in DFT calculations.

Thermodynamics. The structures of relevant compounds were optimized in various conformations (compare Figure 4) with the aid of DFT calculations using the B3LYP functional and LANL2DZ basis sets, which had yielded good results concerning high oxidation state oxochromium chloride systems previously.[31] The comparison of the energies obtained, of course, does not provide any information about the probability or rate of a certain step to occur, as the corresponding barriers are unknown, but they provide an idea about the location of the minima on the potential energy surface and therefore about the feasibility of the proposed mechanism on thermodynamic grounds. The formation energy of **2** was calculated to be −35.4 kJ/mol, which corroborates a positioning of the equilibrium in eq 1 far on the right side, as had already been concluded from NMR spectroscopic investigations under variation of the oxirane concentration.[15a] Furthermore, it had been deduced that **1** is capable of coordinating a second oxirane molecule, and this was supported by the calculations, too. Reaction iii (Scheme 9) was found to release −57.9 kJ/mol, and it is therefore even more exothermic than the coordination of the first ethylene oxide molecule. This is understandable, as Cr(VI) centers prefer the coordination number

(28) Kristyán, S.; Pulay, P. *Chem. Phys. Lett.* **1994**, *229*, 175. Wright, T. C. *J. Chem. Phys.* **1996**, *105*, 7579. Pérez-Jordà, J. M.; Becke, A. D. *Chem. Phys. Lett* **1995**, *233*, 134. Ruiz, E.; Salahub, D. R.; Vela, A. *J. Phys. Chem.* **1996**, *100*, 12265. García, A.; Cruz, E. M.; Sarasola; C.; Ugalde, J. M. *J. Phys. Chem. A* **1997**, *101*, 3021.

(29) There are two enantiomers existent for *trans*-butylene oxide, and these produce **4ᵗ** in the form of two enantiomers which, however, naturally show the same NMR spectra.

(30) At the same time both compounds **4ᵗ** and **4ᶜ** showed contacts between H² and H¹, but it would not be appropriate to try to deduce any information from their intensities.

(31) Limberg, C.; Köppe, R.; Schnöckel, H. *Angew. Chem.* **1998**, 110, 512−515; *Angew. Chem., Int. Ed. Engl.* **1998**, 37, 496−499. Limberg, C.; Köppe, R. *Inorg. Chem.* **1999**, *38*, 2106−2116.
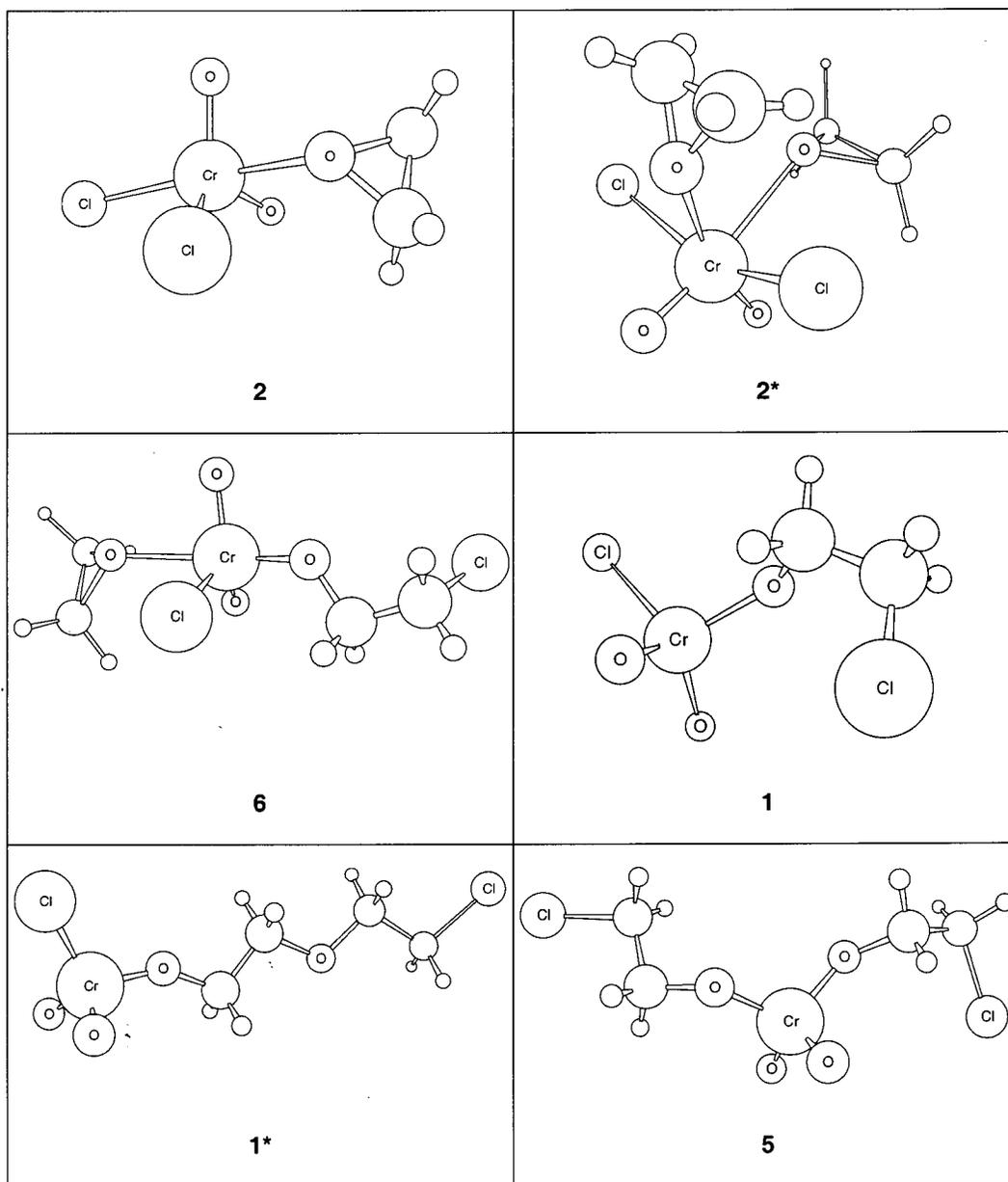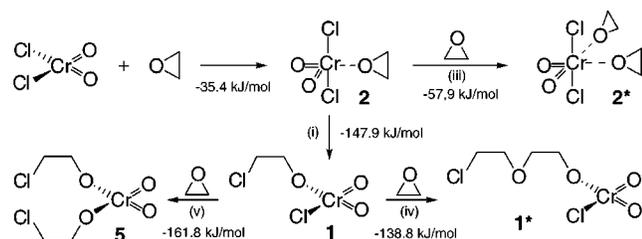
Figure 4. Optimized structures (B3LYP, LanL2dz) for **1**, **1***, **2**, **2***, **5**, and **6**.

Scheme 9

4, but since they are electron deficient at the same time, energy is released on coordination of a suitable (σ-donating) fifth ligand. The changes occurring on going from a 5- to a 6-fold coordination are not that pronounced, so that—if entropy changes are not considered—a sixth ligand entering the coordination sphere just has the positive effect of providing even more electrons, provided that it fits into the coordination sphere. Not only does this allow the formation of **2*** in a reaction of chromyl

chloride with 2 equiv of ethylene oxide, it could also give rise to a 6-fold rather than a 5-fold coordination in the intermediates proposed in Scheme 4. However, on the basis of the calculated energies, **2*** would be expected to represent the sole product of an equimolar reaction between chromyl chloride and oxirane at −80 °C. On the other hand, the results of the kinetic investigation require that two molecules of an ethylene oxide complex are consumed to give two molecules of **1**, and there is no way to achieve this starting from **2*** rather than from **2** (compare the effect of the aforementioned lowering of the rate on addition of an excess of oxirane). Moreover, no (E=)$_2$Cr^{VI} compound (E = O or NR) with an octahedral

(32) Danopoulos, A. A.; Leung, Wa-Hung; Wilkinson, G.; Hussain-Bates, B.; Hursthouse, M. B. *Polyhedron* **1990**, *9*, 2625. Lam, Hon-Wah, Wilkinson, G.; Hussain-Bates, B.; Hursthouse, M. B. *J. Chem. Soc., Dalton Trans.* **1993**, 781. Cles, M. P. Dalby, C. I.; Gibson, V. C.; Clegg, W.; Elsegood, M. R. J. *J. Chem. Soc., Chem. Commun.* **1995**, 1709. Leung, Wah-Hung; Wu, Man-Ching; Lau, Tai-Chu; Wong, Wing-Tak *Inorg. Chem.* **1995**, *34*, 4271. Meijboom, N.; Schaverien, C. J.; Orpen, A. G. *Organometallics* **1990**, *9*, 774.

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coordination sphere has been structurally characterized so far, while pentacoordinated compounds are known.[12,32] Consequently, a complex **2*** may not be as favorable as the calculation of its energy suggests. First of all, entropy changes have to be considered: Cr[VI] is very small, and while a fifth ligand still has a lot of freedom (the structures of three different conformational isomers were optimized for **2**, and their energy differences were not higher than 2 kJ/mol), a sixth one certainly does not. Frequency calculations allowed the determination of the entropies, leading to a ΔG_{208} value of only −16 kJ/mol for the reaction of two molecules of **1** to **2*** and CrO$_2$Cl$_2$. This would still lead to considerable disproportion, but the error of these calculations has to be considered at that stage: the ΔG value is the result of three structure optimizations and three frequency calculations. Bearing in mind the results obtained with the same method for the conformers of **3a**, it is easy to imagine that the error for the ΔG value mentioned above can fall into a region which is decisive for the positioning of the corresponding equilibrium. We therefore still consider **2** as the major species in solution before the actual reaction, in agreement with the experimental findings. However, as already suggested by those, the calculations support the relevance of **2*** for the consideration of the equilibria in solution. The same is true for an oxirane complex of **1** (**6**), the structure of which was optimized, too. A complexation energy of −29.2 kJ/mol was deduced,[33] which is naturally less negative than the one found for chromyl chloride as the alkoxide ligand lowers the Lewis acidity of the chromium center. The energy of reaction i was calculated to amount to −147.9 kJ/mol (the most stable conformation of **1** calculated was considered), which is a reasonable driving force for it to proceed even at very low temperatures. Surprisingly, reaction v (Scheme 9) was found to be more exothermic (−161.8 kJ/mol) than reaction iv (−138.8 kJ/mol), so that for purely thermodynamic reasons the formation of the chromatdiester (O=)$_2$Cr(OCH$_2$CH$_2$Cl)$_2$, **5**, should have been expected. The reason for reaction v not being observed must therefore have its origin in the kinetics. There are some transition states which dependent on Scheme 4 would lead to **5**, and it is easy to find reasons why these should not be formed. However, as such a discussion would be purely speculative, we will refrain from going into detail here.

In conclusion the mechanism depicted in Scheme 4 is in good agreement with all experimental findings and therefore provides a picture explaining the observations made and elucidating the critical features of the mechanism for ring-opening of epoxides by chromyl chloride at low temperatures. Current research concerns the synthesis of stable derivatives of **1**, making use of the information gained in the present study, as such compounds are expected to show a higher selectivity in oxidation reactions than chromyl chloride.

(33) The formation of **6** will also contribute to the deviations found for the later periods of the kinetic investigations.

(34) Gaussian 94, Revision E.2: Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Gill, P. M. W.; Johnson, B. G.; Robb, M. A.; Cheeseman, J. R.; Keith, T.; Petersson, G. A.; Montgomery, J. A.; Raghavachari, K.; Al-Laham, M. A.; Zakrzewski, V. G.; Ortiz, J. V.; Foresman, J. B.; Peng, C. Y.; Ayala, P. Y.; Chen, Wong, W. M. W.; Andres, J. L.; Replogle, E. S.; Gomperts, R.; Martin, R. L.; Fox, D. J.; Binkley, J. S.; Defrees, D. J.; Baker, J.; Stewart, J. P.; Head- Gordon, M.; Gonzalez, C.; Pople, J. A. Gaussian, Inc., Pittsburgh, PA, 1995.

Experimental and Computational Details

Computational Method. Density functional calculations were carried out with the Gaussian/DFT[34] series of programs. The structures were optimized with the LanL2DZ basis set using in each case the B3LYP formulation of density functional theory, i.e., Becke's three-parameter exchange functional and the Lee−Yang−Parr correlation functional. The simulations of the NMR spectra of **3a** and **3b** were performed using Win Daisy.

Experimental Procedure. NMR spectra of solutions were recorded using a Bruker AC 200 instrument operating at 200 MHz. CrO$_2$Cl$_2$ (99.99% pure), propylene oxide (99% pure), and *cis*- and *trans*-2-butylene (96% pure) were supplied by Aldrich, and ethylene oxide (99.8%) was supplied by Fluka. The reagents were further purified by fractional distillation in vacuo by passage through traps maintained at successively lower temperatures prior to use. The traps were cooled by immersion in liquid nitrogen, acetone/dry ice, or "slush" baths each composed of a suitable organic material in solid−liquid equilibrium.

The NMR samples were prepared by means of a vacuum line (at a background pressure of <10^{-3} mbar). Chromyl chloride dissolves in, and reacts with, hydrocarbon-based greases, and so recourse was made to a combination of Young's greaseless valves and ground-glass joints lubricated typically with Voltalef fluorocarbon grease. Since all reactants employed were sufficiently volatile, their stoichiometries could be adjusted with use of standard manometric techniques. Typically the epoxide was allowed to enter the line at a certain pressure and was then condensed at the bottom of a Pyrex NMR tube. The appropriate amount of CD$_2$Cl$_2$ was distilled on top of it. Subsequently the line was filled with chromyl chloride at the pressure required, and this quantity was added to the NMR tube via condensation, too. The latter was flame sealed and placed in a −90 °C slush where it was allowed to anneal to that temperature. After its contents had liquefied, they were mixed by shaking of the tube at that temperature, and the tube was quickly transferred into the NMR spectrometer which had been precooled to −95 °C. Subsequently the temperature was adjusted to −80 °C and the first spectrum recorded.

For clarification of the stereochemistry of the cleavages, typically 1 mmol of epoxide and 1 mmol of chromyl chloride were co-condensed together with dichloromethane (20 cm³), and the mixture was warmed to −50 °C and allowed to stir for 2 h. Subsequently 10 cm³ of water was added at that temperature by means of a syringe and the whole mixture annealed to room temperature under constant shaking of the reaction vessel. The layers were separated, and the aqueous one was extracted three times with 5 cm³ of diethyl ether. All organic phases were combined and investigated by gas chromatography on a Chrompack CP 9002. Evaporation of the solvents yielded the chlorohydrins which could be investigated spectroscopically. Authentic samples were prepared by co-condensing stoichiometric amounts of the epoxides in diethyl ether with gaseous HCl, which had been dried over H$_2$SO$_4$. After 1 h of reaction time at −30 °C the mixtures were annealed to room temperature and investigated as described above.

Supporting Information Available: Structural and spectroscopic data concerning the optimized structures in Figure 4. This material is available free of charge via the Internet at http://pubs.acs.org.

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