# Tandem Fragmentation of Cyclopropylcarbinyl/Oxiranylcarbinyl Radicals. On the Reversibility of Oxiranylcarbinyl/Allyloxyl Radical Formation

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The tandem radical fragmentation of four stereoisomeric epoxy thiocarbonates **7c–10c** has been investigated. In each instance a cyclopropylcarbinyl radical fragments to generate an oxiranylcarbinyl radical, which, in turn, undergoes fragmentation. The initially detected product is (*Z*)-allylic alcohol **23**, which isomerizes to (*E*)-allylic alcohol **24** under acid catalysis. The reversibility of allyloxyl radical formation is considered.

## Introduction

The mechanism and mode of fragmentation of monocyclic and bicyclic cyclopropylcarbinyl radicals of varying substitution patterns are well-understood owing to detailed studies over the past two decades. These reactions have been evaluated from both the mechanistic[1–15] and synthetic perspective.[16–18] More recently, the fragmentation of oxiranylcarbinyl radicals has been explored. These radicals undergo preferential C–O bond cleavage,[19–31] except in cases where the resultant carbon radical arising from oxirane cleavage is stabilized as a benzyl or allyl radical.[32–34] Cyclopropylcarbinyl radical has been trapped prior to fragmentation ($k_f = 1 \times 10^8\ s^{-1}$ at 25 °C);[13] the back reaction, the cyclization of allylcarbinyl radical, is significantly slower[13,35] than fragmentation ($k_c = 8 \times 10^3\ s^{-1}$ at 25 °C).[7,9,14] On the other hand, the oxiranylcarbinyl radical itself has neither been observed[36,37] nor trapped.[33] An ESR study has placed a lower limit of $k_f = 4 \times 10^8\ s^{-1}$ at 128 K on the rate of cleavage of the oxiranylcarbinyl radical.[37] In a competitive fragmentation of the thiocarbonylimidazolide of *erythro*-1-cyclopropyl-2,3-epoxypropan-1-ol in the presence of $Ph_3SnH$, exclusive C–O bond cleavage of the oxirane ring occurred.[38] A lower limit of $k_f = 10^{10}\ s^{-1}$ at 70 °C was established whereby the back reaction in this unsubstituted case (primary allyloxyl radical) was assumed to be comparatively slow. However, secondary allyloxyl radicals[39] and tertiary allyloxyl radicals[28,40–42] do undergo cyclization to oxiranylcarbinyl radicals.

This study was driven by an interest in the direction of fragmentation of the 2-oxobicyclo[3.1.0]hexanylcarbinyl radical **1**. The orbital bearing the unpaired electron is able to overlap with the ring fusion carbon–carbon bond. This rotamer can fragment to the secondary radical **2**, which, in the presence of a hydrogen atom donor, would provide unsaturated ketone **3** as an initial product. Fragmentation of the alternative cyclopropane bond leads to secondary radical **4**. This radical would be expected to fragment rapidly to allyloxyl radical **5**, which would abstract a hydrogen atom from an appropriate donor. Although both modes of fragmentation are known,[43–46] the latter mode of cyclopropane cleavage was anticipated

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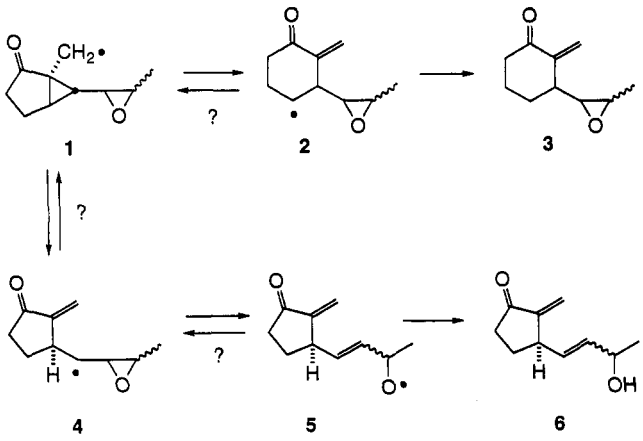
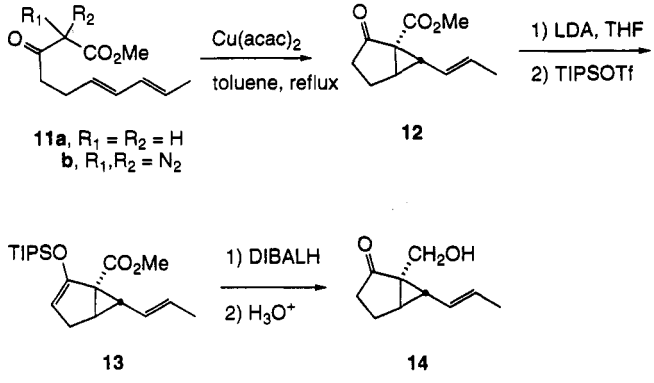
**Scheme 1**



**Scheme 2**



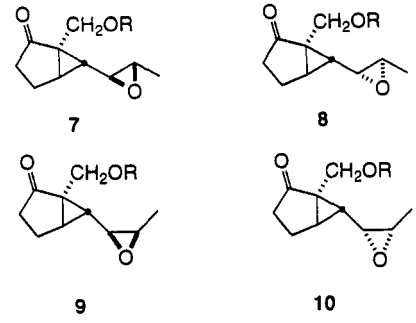
because the fragmenting bond maintains overlap with the carbonyl group.

The stereochemistry of the nonconjugated double bond in **6** and the stability of the enones in both **5** and **6** were at issue. Moreover, there was interest in determining whether or not the olefin stereochemistry of **6** would be influenced by the geometry of the epoxide in oxiranylcarbinyl radical **4**.

## Results

Exo-trans epoxides **7c** and **8c** and exo-cis epoxides **9c** and **10c** were prepared. The known β-keto ester **12** was synthesized from α-diazo-β-keto ester **11b** with minor variations of the Kondo procedure (Scheme 2).[47] Keto ester **11a** was prepared by γ-alkylation of methyl acetoacetate with sorbyl bromide.[48] Preparation of α-diazo-β-keto ester **11b** employed the Regitz protocol of diazo transfer with tosyl azide.[49]

The conversion of β-keto ester **12** to keto alcohol **14** via reduction of the lithium enolate of **12** with $LiAlH_4$ or DIBALH resulted in substantial overreduction.[50] An effective procedure involved in situ trapping of the enolate with triisopropylsilyl triflate as the TIPS enol ether.



a) R = H; b) R = C(O)$CF_3$; c) R = C(S)$OC_6F_5$

Reduction with DIBALH and subsequent hydrolysis with aqueous acetic acid provided keto alcohol **14** in 79% yield.

(*Z*)-Olefin **18** was prepared from β-keto ester **12** (Scheme 3). Ozonolysis of the (*E*)-olefin gave rise to aldehyde **15**,[51] which underwent selective olefination of the aldehyde function with ethyltriphenylphosphonium bromide and sodium hexamethyldisilazide (NaHMDS) in THF at 0 °C to afford an inseparable 4:1 mixture of (*Z*)- and (*E*)-olefins (**16** and **12**), respectively. The use of lower temperature or KHMDS in the Wittig reaction did not improve the selectivity. The mixture of isomers was converted into keto alcohols **18** and **14** via the TIPS enol ether protocol in 89% yield. The desired (*Z*)-isomer **18** was separated from the mixture by fractional crystallization.

The (*E*)-olefin **14** was epoxidized with urea–hydrogen peroxide complex/trifluoroacetic anhydride[52–54] to provide a 1:1 mixture of trans epoxy trifluoroacetates **7b** and **8b**. Removal of the trifluoroacetate group was accomplished by transesterification in methanol catalyzed by 3-Å molecular sieves to afford keto alcohols **7a** and **8a**. The isomeric epoxides were separated readily by radial chromatography. Similarly, (*Z*)-olefin **18** provided a 1:1 mixture of cis epoxides **9b** and **10b**. However, during the transesterification ~40% of cis epoxide **9a** underwent intramolecular opening of the epoxide ring to form tetrahydrofuran **21a**. This reaction was presumably initiated by traces of acid. Owing to the stereoselectivity of this ring opening process,[55] an opportunity to assign the relative stereochemistry of each of the four epoxy alcohols presented itself. Thus, independent exposure of epoxides **7a–10a** to catalytic trifluoroacetic acid (TFA) in $CH_2Cl_2$, followed by benzoylation of the secondary alcohols to facilitate $^1H$ NMR analysis, led to the four diastereomer benzoates **19b–22b**, respectively (Scheme 4).

(*E*)-Epoxide **7a** and (*Z*)-epoxide **9a** have the same relative stereochemistry at the oxirane carbon adjacent to the cyclopropane which translates into the same trans relationship of the methine hydrogens of the tetrahydrofuran rings of **19b** and **21b**. Both molecular models and MM2 calculations indicate a dihedral angle close to 90°, which is reflected in the lack of coupling between these protons in the $^1H$ NMR spectrum. Similarly, tricycles **20b** and **22b** reveal dihedral angles of ~35°, which correspond to coupling constants of ~3 Hz.

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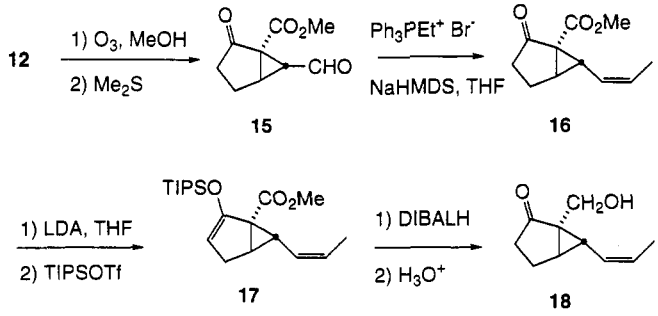
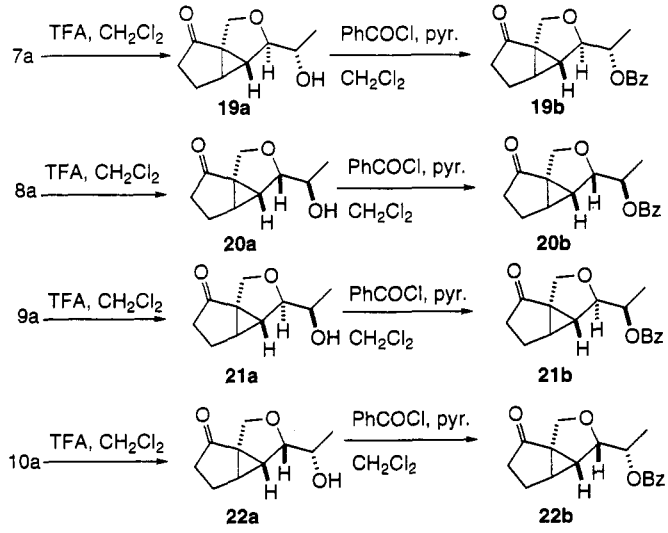
**Scheme 3**




**Scheme 4**




Alcohols **7a–10a** were converted into their respective pentafluorophenyl thiocarbonates **7c–10c**, derivatives that have high reactivity in radical deoxygenations.[56] The derivatization with *O*-pentafluorophenyl chlorothioformate (PFPTCl) required controlled conditions (pyr, PFPTCl; $CH_2Cl_2$; −78 °C) because the reaction mixtures were contaminated with cyclopropylcarbinyl chlorides when the acylations were run at higher temperatures. The reaction mixtures also contained a strong UV absorbing material, 5-isothiocyanatopenta-2,4-dienal, a known product derived from the cleavage of pyridine with thiophosgene.[57,58] These difficulties aside, the desired thiocarbonates could be isolated by radial chromatography in 50–60% yield.

Tri-*n*-butylstannane-promoted fragmentation of trans epoxides **7c** and **8c** under Nozaki conditions ($Et_3B$, $O_2$, rt)[51] provided ~25% yield of a 4:1 mixture of (*Z*)- and (*E*)-dienones **23** and **24**, respectively. No products of generic structure **6** were found. To shed light on the process at early conversion, the reactions of **7c** and **8c** in the presence of *n*-$Bu_3SnH$ (0.03 M) were studied by $^1H$ NMR in degassed benzene-$d_6$ at 75 °C. The only product observed upon monitoring the vinyl region during the consumption of the starting materials was (*Z*)-allylic alcohol **23**! In time, **23** gave rise to (*E*)-isomer **24**, a transformation seemingly catalyzed by tin salts. In addition, when a $CDCl_3$ NMR sample of purified (*Z*)-allylic alcohol **23** was allowed to stand at room temperature overnight, (*Z*)-isomer **23** isomerized to (*E*)-isomer **24** under the influence of trace acid present in the solvent. This

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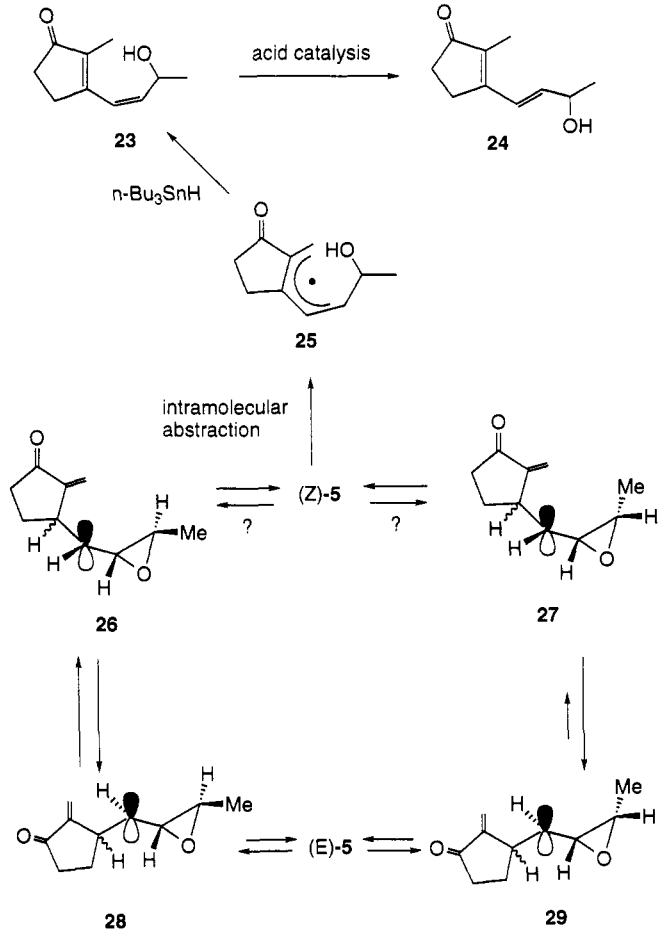
**Scheme 5**




conversion was readily monitored by observing the chemical shift and coupling constants of the vinyl protons in **23** and **24**.

In an effort to induce the formation of a product having the (*E*)-allylic alcohol configuration under radical conditions, cis epoxides **9c** and **10c** were subjected to the $^1H$ NMR study. The cis oxiranyl radical should favor rotamer **29**, which would lead to allyloxyl radical (*E*)-**5**, over its more sterically demanding rotameric counterpart **27**, which would give rise to allyloxyl radical (*Z*)-**5**. Again, the initial, observable product was (*Z*)-allylic alcohol **23**, which eventually isomerized to (*E*)-allylic alcohol **24**.

In a final series of experiments, addition of *n*-$Bu_3SnH$/AIBN over 2 h to each of the diastereomeric thiocarbonates **7c–10c** in toluene at 75 °C provided the (*E*)-allylic alcohol **24** *via* the (*Z*)-allylic alcohol **23** in ~50% isolated yield in each instance.

## Discussion

The results obtained under the Nozaki conditions suggested initially that oxiranyl radical **4** (Scheme 1) derived from trans epoxides **7c** and **8c** fragments through two rotameric transition states. First, cisoid conformation **26** fragments to provide alkoxyl radical (*Z*)-**5**, which, in turn, undergoes a 1,5-hydrogen atom shift. The resultant pentadienyl radical **25** (Scheme 5) terminates the process by abstracting a hydrogen atom from *n*-$Bu_3SnH$ to afford (*Z*)-allylic alcohol **23**. Because of the bis-allylic nature of the tertiary methine hydrogen in (*Z*)-**5**, the rate of the intramolecular hydrogen atom shift is expected to be accelerated over the shift of a non-allylic hydrogen atom.

The rate of intramolecular 1,5-H abstraction from an unactivated secondary carbon atom by an alkoxyl radical has been estimated at $6 \times 10^8$ s$^{-1}$ at 80 °C, albeit in water.[59] Secondly, transoid rotamer **28** was thought to lead to (*E*)-**5** and, ultimately, to **6** through intermolecular hydrogen atom abstraction by the alkoxyl radical.

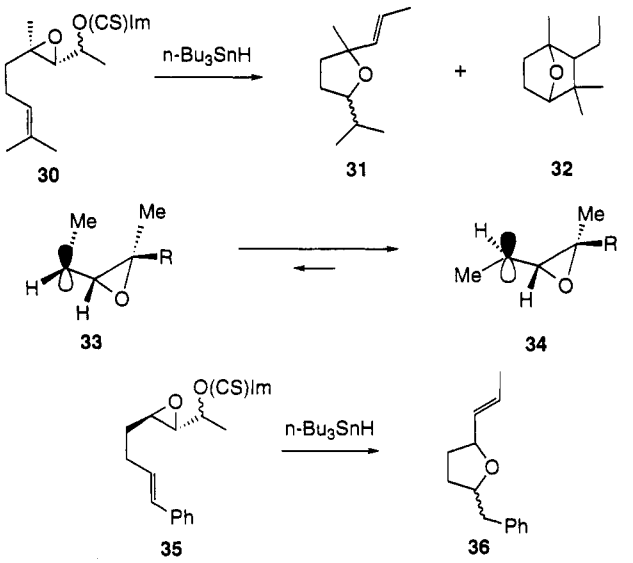
In light of the NMR study, one possibility for the lack of (*E*)-olefinic products derived from alkoxyl radical (*E*)-**5** is that this intermediate may lead to intractable material. However, no precipitate formed during the $^1$H NMR experiments; the reaction mixtures were homogeneous throughout the duration of the studies. Destruction of the (*E*)-double bond in (*E*)-**5** might be perceived as occurring by a formal 1,2-H atom shift from carbon to oxygen, which leads to a 1-hydroxyallyl radical that, upon reaction with a hydrogen atom donor, would be reduced to either an enol (ketone) or an allylic alcohol. Such intermolecular 1,2-H atom transfers are known to occur in hydroxylic solvent with saturated alkoxyl radicals wherein water acts as the hydrogen atom source.[59] In addition, 1-hydroxyallyl radical is the observable product in ESR studies on the fragmentation of oxiranylcarbinyl radical. The allyloxyl radical is converted by hydrogen atom abstraction to allyl alcohol, which in turn reacts with allyloxyl radical to form the observed species.

A second possibility is that (*E*)-**5**, and perhaps (*Z*)-**5**, is in equilibrium with oxiranylcarbinyl radical **4**, which fragments to (*Z*)-**5** through conformation **26** or **27** and then proceeds on to (*Z*)-allylic alcohol **23** (Scheme 5). As noted in the Introduction, there is evidence that tertiary and secondary allyloxyl radicals undergo ring closure to oxiranylcarbinyl radicals. No direct evidence is available in this regard for primary allyloxyl radicals. Certainly, (*E*)-**5** meets the criterion for a secondary allyloxyl radical.

The isolation of (*E*)-allylic alcohol **24** derived from **23** in nearly the same yields (58, 52, 49, and 45%) from compounds **7c–10c**, respectively, supports the possibility of an oxiranylcarbinyl/allyloxyl radical equilibration. In particular, conformation **27**, which is destabilized relative to rotamer **29**, would be expected to afford substantially less of the (*Z*)-allylic alcohol if the allyloxyl radical were not formed reversibly. The intramolecular hydrogen atom abstraction of (*Z*)-**5** is the irreversible step that shifts the equilibrium.

The literature contains several examples of related fragmentations. Murphy has conducted the reductive cyclization of thiocarbonylimidazolide **30** in the presence of *n*-$Bu_3SnH$.[22] In this instance a secondary oxiranylcarbinyl radical is generated wherein the β-carbon of the epoxide is disubstituted. A 6:1 ratio of trans/cis tetrahydrofurans **31** is formed (59% yield) in addition to 14% of bicyclic ether **32**, which is derived from the cis tertiary cyclized radical that leads to cis **31**. Any (*Z*)-olefin that may have been formed would have had to appear as bicyclic ether **32**. Given the substitution pattern of **30**, the formation of (*E*)-olefin in the isomers **31** under kinetic conditions is not surprising. Conformation **34**, which leads to (*E*)-olefin, would be expected to be favored over the eclipsed conformation **33**, which affords (*Z*)-olefin. This effect was not operative to any degree in our study.

On the other hand, Murphy has also investigated the fragmentation of **35**, the substitution pattern of which




closely mirrors the current study. The products of the reaction, tetrahydrofurans **36**, are formed in a 3:1 ratio (trans/cis) with formation of (*E*)-olefins (no (*Z*)-isomers were reported), an observation that is contrary to our results. This reaction was conducted by addition of the stannane to the substrate over 1 h in refluxing THF followed by heating for 15 h (<0.02 M *n*-$Bu_3SnH$), conditions that might suggest equilibration of the olefin prior to cyclization to the tetrahydrofurans.[60]

For thermodynamic control to exist and to produce (*E*)-olefins in the case of **30** and **35**, formation of the oxiranylcarbinyl radical from the allyloxyl radical must be greater than $6 \times 10^8$ s$^{-1}$, the rate for cyclization of 4-pentenyloxy radical at 80 °C.[61] Thus, the back reaction, (*E*)-**5** → **4** would have to be faster than the rate of irreversible tetrahydrofuran formation.

Gleicher's competitive fragmentation leads only to (*E*)-3-cyclopropyl-2-propen-1-ol in the presence of excess $Ph_3SnH$ (2.3 M). The slightly higher reactivity of this stannane over *n*-$Bu_3SnH$, the higher concentration of stannane, and the primary nature of the allyloxyl radical may argue for a kinetic process that leads to (*E*)-olefin. However, the slower fragmentation of 1-cyclopropyl-1-chloroethane gives a 2.2:1 mixture of (*E*)- and (*Z*)-2-pentene, respectively, upon reduction with *n*-$Bu_3SnH$, a ratio that reflects kinetic fragmentation.[7] Intuitively, the faster fragmentation of oxiranylcarbinyl radicals would be expected to give, at best, similar selectivity in the formation of olefins under kinetic conditions.

The formation of mixtures under conditions that are more amenable to kinetic control, *i.e.*, addition of the 2:1 mixture of steroidal epoxides **37** to *n*-$Bu_3SnH$, provides a 2:1 mixture of allylic alcohols **38a** and **38b**, respectively, a result that suggests little selectivity in the fragmentation.[20] Of course, the 2:1 ratios do not imply stereospecificity, *i.e.*, no rotation about the $C_{17}$–$C_{20}$ bond.

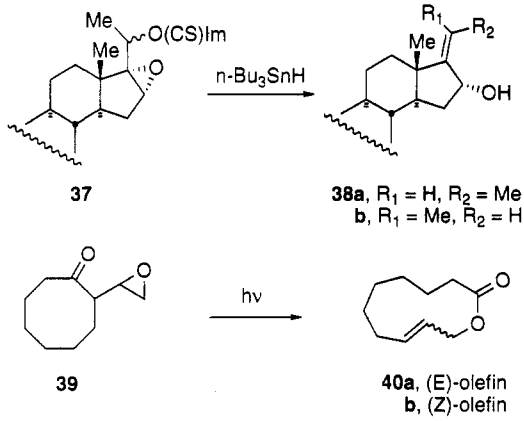
Secondary oxiranylcarbinyl radicals have been generated by photolysis of a series of 2-oxiranylcycloalkanones.[62] The cyclooctanone **39** affords both (*E*)- and (*Z*)-decenolides

(59) Gilbert, B. C.; Holmes, R. G. G.; Laue, H. A. H.; Norman, R. O. C. *J. Chem. Soc., Perkin Trans. 2* **1976**, 1047.

(60) A study by Marples in a related system suggests that the mode of addition of *n*-$Bu_3SnH$ may not be important. Corser, D. A.; Marples, B. A.; Dart, R. K. *Synlett* **1992**, 987.

(61) Beckwith, A. L. J.; Hay, B. P. *J. Am. Chem. Soc.* **1988**, *110*, 4415.

(62) Carlson, R. G.; Huber, J. H.-A.; Henton, D. E. *J. Chem. Soc., Chem. Commun.* **1973**, 223.




**40a** (36%) and **40b** (50%). The latter study parallels closely the substitution pattern of the oxiranylcarbinyl radicals generated in our investigation. The appearance of both (*E*)- and (*Z*)-olefins in the photochemical study does not distinguish between kinetic and thermodynamic formation of the allyloxyl radicals. In either case, the (*Z*)-isomer is trapped, regardless of its mode of formation.

A recent ab initio calculation by Lee and Jackson[63] at the PMP4/6-311G**//UMP2/6-31G* level vibrationally corrected to 298 K shows that cleavage of the C–O bond of the oxiranylcarbinyl radical is exothermic by 0.6 kcal/mol. Cleavage of the C–C bond is exothermic by 1.6 kcal/mol. However, the kinetic barrier for C–O bond cleavage (4.8 kcal/mol) lies substantially below the barrier for C–C bond cleavage (11.5 kcal/mol). These data provide strong evidence for a low barrier for the oxiranylcarbinyl–allyloxyl radical interconversion.

## Conclusion

The radical fragmentation of thiocarbonates **7c–10c** gives at least ~50% (*Z*)-allylic alcohol **23** as the first identifiable product. At this time we are not able to distinguish categorically between kinetic and thermodynamic fragmentation of the oxiranylcarbinyl radicals **4**. However, if allyloxyl radical (*Z*)-**5** is formed as a kinetic product, the observation brings into question whether or not the exclusive formation of (*E*)-olefins in the fragmentations studied by Murphy and Gleicher are kinetically controlled. At the other extreme, if allyloxyl radical (*E*)-**5** is the major isomer of kinetic fragmentation, then the (*Z*)-allyloxyl radical must have formed reversibly from (*E*)-**5**. In the current study, intramolecular hydrogen atom abstraction competes favorably with bimolecular abstraction to afford (*Z*)-allylic alcohol **23**.

## Experimental Section

All reactions were conducted in dry glassware under argon. Ether and THF were distilled from benzophenone ketyl under $N_2$. Benzene, $CH_2Cl_2$, i-$Pr_2NH$, hexanes, pyridine, toluene, and $Et_3N$ were distilled from $CaH_2$. Other solvents (A.C.S. spectrophotometric grade) were dried over 3-Å molecular sieves and were used without further purification. Alkyllithiums were titrated with diphenylacetic acid in THF.[64] Reaction mixtures submitted to homolytic conditions were purged with argon and degassed by the freeze-pump-thaw method prior to execution. Melting points are corrected. IR spectra were recorded in $CCl_4$ or $CHCl_3$ ($CHCl_3$, for alkenes). NMR spectra were recorded as follows: $^1H$ spectra in $CDCl_3$ or $CD_2Cl_2$ at 250 MHz; $^{13}C$ spectra in $CDCl_3$ ($\delta$ = 77.0 ppm) or $CD_2Cl_2$ ($\delta$ = 53.8 ppm) at 62.85 MHz; $^{19}F$ spectra at 282.6 MHz ($CCl_3F$ as external standard, $\delta \sim 0$). Low resolution mass spectra (MS) were run in the DCI mode (isobutane); high resolution mass spectra (HRMS) were conducted in the CI mode (methane) unless stated otherwise. Radial chromatography was conducted with a Chromatotron. Workup means drying organic extracts over anhydrous $MgSO_4$, filtration, and evaporation of solvents in vacuo.

**(*E,E*)-1-Bromo-2,4-hexadiene.** $CaH_2$ (9.66 g, 0.23 mol) was suspended in $Et_2O$ (250 mL) and cooled to −5 °C in an ice/salt-water bath. (*E,E*)-2,4-Hexadien-1-ol (15.0 g, 0.15 mol) at room temperature was added in one portion, and the mixture was recooled to −5 °C. A solution of $PBr_3$ (5.32 mL, 56.0 mmol) in $Et_2O$ (20 mL) was added to the stirred mixture over 30 min. After 1 h at −5 °C followed by 30 min at room temperature, MeOH (0.5 mL) was added and the suspension was filtered through Celite and concentrated to afford a yellow liquid (23.0 g) which was distilled immediately (bp 44–47 °C, 25 Torr) to give the desired product (18.5 g, 75%) as a mixture of isomers containing ~85% (*E,E*)-bromide as determined by $^1H$ NMR (partial):[48] $\delta$ 4.02 (d, $J$ = 7.5 Hz, 2 H), 1.77 (d, $J$ = 6.5 Hz, 3 H).

**4-Methylbenzenesulfonyl Azide.** $NaN_3$ (37.01 g, 0.57 mol) was dissolved in $H_2O$ (120 mL) and diluted with EtOH (200 mL, 95%) to saturation. 4-Methylbenzenesulfonyl chloride (94.20 g, 0.49 mol) was added in portions to the solution with vigorous stirring over a period of 30 min; stirring was continued for another 2 h. The mixture was diluted with $H_2O$ (600 mL). The lower layer was separated and washed with water (3 × 50 mL), dried with $Na_2SO_4$ (1 h), and filtered through a coarse sinter funnel. The resulting colorless oil (83.05 g, 85%) was stored over molecular sieves (3 Å) and shown to consist of pure 4-methylbenzenesulfonyl azide: $^1H$ NMR ($CDCl_3$) $\delta$ 7.84 (d, $J$ = 7.7 Hz, 2 H), 7.41 (d, $J$ = 7.7 Hz, 2 H), 2.48 (s, 3 H).[49]

**Methyl (1α,5α,6α)-6-Formyl-2-oxobicyclo[3.1.0]hexane-1-carboxylate (15).** Following the reported conditions,[51] the aldehyde was obtained as a pale yellow oil (5.34 g, 93%) after dry column chromatography (EtOAc/hexane): $^1H$ NMR ($CDCl_3$) $\delta$ 9.39 (d, $J$ = 4.81 Hz, 1 H), 3.80 (s, 3 H), 3.15 (t, $J$ = 4.81 Hz, 1 H), 2.43–2.15 (m, 5 H).

**Methyl (1*R**,5*S**,6*R**,*Z*)-2-Oxo-6-(1-propenyl)bicyclo-[3.1.0]hexane-1-carboxylate (16).** (Ethyl)triphenylphosphonium bromide (13.83 g, 37.26 mmol) was suspended in THF (260 mL), and NaHMDS (1.0 M in THF, 37.25 mmol) was added via syringe with stirring at rt. After 25 min the deep red suspension was added over 35 min to a solution of aldehyde **15** (4.85 g, 26.61 mmol) in THF (300 mL) cooled in ice/water to 0 °C. The reaction mixture was kept at ambient temperature for 20 min, and $H_2O$ (150 mL) and $Et_2O$ (100 mL) were added. Extraction, workup, and flash chromatography (EtOAc/hexane; 1:4) gave (3.17 g, 61%) of a 4:1 mixture of alkenes **16** and **12**, respectively: IR 1730, 1720 $cm^{-1}$; $^1H$ NMR ($CDCl_3$, **16**) $\delta$ 5.68 (ddq, $J$ = 10.68, 0.92, 6.95 Hz, 1 H), 5.20 (ddq, $J$ = 10.68, 9.05, 1.78 Hz, 1 H), 3.76 (s, 3 H), 2.67 (t, $J$ = 5.08 Hz, 1 H), 2.53 (dd, $J$ = 9.05, 5.45 Hz, 1 H), 2.38–2.04 (m, 4 H), 1.73 (dd, $J$ = 6.95, 1.78 Hz, 3 H); $^{13}C$ NMR ($CDCl_3$) $\delta$ 205.8, 166.5, 129.1, 123.8, 52.1, 45.3, 35.0, 33.5, 32.8, 20.9, 13.5; MS $m/z$ 195 (60, M + H), 163 (100, M + H − MeOH); HRMS calcd for $C_{11}H_{15}O_3$ $(M + H)^+$ 195.1021, found 195.1019.

**(1*R**,5*S**,6*R**,*E*)-1-(Hydroxymethyl)-2-oxo-6-(1-propenyl)-bicyclo[3.1.0]hexane (14).** *n*-BuLi (1.55 M in hexane, 23.3 mL, 36.1 mmol) was added dropwise to a stirred solution of i-$Pr_2NH$ (5.42 mL, 3.91 g, 38.7 mmol) in THF (240 mL) at −42 °C (acetonitrile/$CO_2$). After 30 min a solution of β-keto ester **12** (5.01 g, 0.026 mol) in THF (20 mL) was added over 10 min to create a clear yellow solution, which was treated with neat TIPSOTf (9.29 mL, 10.59 g, 33.53 mmol). After 13 min, the solution was treated over 30 min with DIBALH (1.0 M in hexane, 77.4 mL, 77.4 mmol). After another 10 min, the clear mixture was poured into $H_2O$ (250 mL, prechilled with ice), acidified with glacial HOAc (150 mL, 159 g, 2.6 mol), and stirred vigorously for 5 h. The mixture was neutralized with KOH (87%, 167 g, 2.6 mol) in $H_2O$ (150 mL) and extracted with $Et_2O$. Workup and flash chromatography (EtOAc/hexane; 1:1) gave keto alcohol **14** as a yellow oil (3.40 g, 79%): IR 3606, 1707 $cm^{-1}$; $^1H$ NMR ($CDCl_3$) $\delta$ 5.70 (dq, $J$ = 15.28, 6.57 Hz, 1 H), 5.24 (ddq, $J$ = 15.28, 7.29, 1.17 Hz, 1 H), 3.86 (d, $J$ = 3–4 Hz, 2 H, concentration dependent), 2.50 (t, $J$ = 3–4 Hz, 1 H, OH, concentration dependent), 2.30–

(63) Lee, M.; Jackson, J. E., personal communication.
(64) Kofron, W. G.; Baclawski, L. M. *J. Org. Chem.* **1976**, *41*, 1879.

2.00 (m, 6 H), 1.73 (dd, $J$ = 6.57, 1.17 Hz, 3 H); $^{13}$C NMR ($CDCl_3$) δ 215.7, 129.1, 125.4, 58.4, 44.7, 32.8, 32.6, 32.1, 22.0, 17.9; MS $m/z$ 167 (55, M + H), 149 (100, M + H - $H_2O$); HRMS calcd for $C_{10}H_{15}O_2$ (M + H)$^+$ 167.1072, found 167.1070. Anal. Calcd for $C_{10}H_{14}O_2$: C, 72.26; H, 8.49. Found: C, 72.28; H, 8.54.

A sample of the intermediate TIPS enol ether **13** was isolated and characterized. The sample was diluted with $H_2O$, extracted with $Et_2O$, worked up, and subjected to flash chromatography (EtOAc/hexane; 3:97) to yield a yellow oil: $^1$H NMR ($CDCl_3$) δ 5.69–5.50 (m, 2 H), 4.32 (dd, $J$ = 3.50, 1.96 Hz, 1 H), 3.69 (s, 3 H), 2.59 (ddd, $J$ = 16.46, 6.68, 1.96 Hz, 1 H), 2.23 (ddd, $J$ = 16.46, 3.50, 1.00 Hz, 1 H), 2.08 (ddd, $J$ = 6.68, 5.04, 1.00 Hz, 1 H), 1.75 (dd, $J$ = 8.85, 5.04 Hz, 1 H), 1.70 (d, $J$ = 5.03 Hz, 3 H), 1.15–1.05 (m, 21 H).

**(1*R**,5*S**,6*R**,*Z*)-1-(Hydroxymethyl)-2-oxo-6-(1-propenyl)-bicyclo[3.1.0]hexane (18).** Using the previous procedure, 80% pure β-keto ester **16** (1.56 g, 8.01 mmol) gave a mixture of keto alcohols **18** and **14** as a solid (1.18 g, 7.11 mmol, 89%) after flash chromatography. The crude material was recrystallized to afford pure **18** (0.75 g, 70%): mp 60.0–61.5 °C (EtOAc/hexane); IR 3602, 1708, 1655 (w) cm$^{-1}$; $^1$H NMR ($CDCl_3$) δ 5.68 (ddq, $J$ = 10.65, 0.97, 6.91 Hz, 1 H), 5.12 (ddq, $J$ = 10.65, 10.6, 1.74 Hz, 1 H), 3.90 (dd, $J_{AB}$ = 12.42, 6.57 Hz, 1 H), 3.80 (dd, $J_{AB}$ = 12.42, 6.17 Hz, 1 H), 2.39 (t, <$J$> = 6.4 (6.57 and 6.17) Hz, 1 H, OH), 2.28–2.06 (m, 6 H), 1.73 (dd, $J$ = 6.91, 1.74 Hz, 3 H); $^{13}$C NMR ($CDCl_3$) δ 215.6, 128.6, 124.9, 58.7, 44.7, 33.7, 32.9, 28.2, 22.2, 13.4; MS $m/z$ 167 (50, M + H), 149 (100, M + H - $H_2O$); HRMS calcd for $C_{10}H_{15}O_2$ (M + H)$^+$ 167.1072, found 167.1066. Anal. Calcd for $C_{10}H_{14}O_2$: C, 72.26; H, 8.49. Found: C, 72.32; H, 8.53.

**(1*R**,5*R**,6*R**)-1-(Hydroxymethyl)-6-[(2*S**,3*S**)-3-methyloxiran-2-yl]-2-oxobicyclo[3.1.0]hexane (7a) and (1*R**,5*R**,6*R**)-1-(Hydroxymethyl)-6-[(2*R**,3*R**)-3-methyloxiran-2-yl]-2-oxobicyclo[3.1.0]hexane (8a).** To a solution of keto alcohol **14** (1.56 g, 9.37 mmol) dissolved in $CH_2Cl_2$ (62 mL) at 0 °C were added $Na_2HPO_4$ (11.7 g, 82.0 mmol) and urea-$H_2O_2$ complex (8.8 g, 94.0 mmol) successively. Trifluoroacetic anhydride (3.3 mL, 4.9 g, 23.0 mmol) was added to the vigorously stirred 0 °C solution over a 10-min period. The cooling bath was removed and the reaction mixture was stirred an additional 30 min. Cold (0 °C), saturated $NaHCO_3$ (150 mL) was added cautiously to the reaction mixture. The layers were separated, back-extracted with $CH_2Cl_2$ and $Et_2O$, and washed with $H_2O$. Workup afforded a pale yellow oil (2.33 g, 89%) which was shown by $^1$H NMR integration to be a 1:1 mixture of trifluoroacetates **7b** and **8b**: MS $m/z$ 279 (20, M + H), 165 (100, M + H - $CF_3CO_2H$). The crude mixture was treated for 40 min with 3-Å molecular sieves (5 g) in methanol (100 mL). Filtration and concentration *in vacuo* (25 °C) left a colorless oil (1.55 g). Radial chromatography separated the two diastereomeric epoxides and afforded a colorless solid (0.53 g, 40%) which was recrystallized from to give pure **7a**: mp 70.5–71.0 °C (EtOAc/hexane); IR 3588, 1719 cm$^{-1}$; $^1$H NMR ($CD_2Cl_2$) δ 4.02 (dd, $J_{AB}$ = 12.34, 4.54 Hz, 1 H), 3.77 (dd, $J_{AB}$ = 12.34, 8.51 Hz, 1 H), 2.85 (dq, $J$ = 2.17, 5.09 Hz, 1 H), 2.82 (dd, $J$ = 2.4, 2.17 Hz, 1 H), 2.38 (dd, $J$ = 8.51, 4.54 Hz, 1 H, OH), 2.16–1.92 (m, 5 H), 1.59 (t, <$J$> = 3.4 (4.4 and 2.4) Hz, 1 H), 1.30 (d, $J$ = 5.09 Hz, 3 H); $^{13}$C NMR ($CD_2Cl_2$) δ 216.9, 59.8, 56.9, 55.6, 44.2, 34.4, 31.6, 29.9, 23.4, 18.6; MS $m/z$ 183 (10, M + H), 165 (100, M + H - $H_2O$); HRMS calcd for $C_{10}H_{15}O_3$ (M + H)$^+$ 183.1021, found 183.1020. Anal. Calcd for $C_{10}H_{14}O_3$: C, 65.92; H, 7.74. Found: C, 65.99; H, 7.76.

Epoxide **8a** was isolated as a colorless oil (0.58 g, 43%): IR 3630, 1723 cm$^{-1}$; $^1$H NMR ($CD_2Cl_2$) δ 3.97 (dd, $J_{AB}$ = 12.25, 6.68 Hz, 1 H), 3.86 (dd, $J_{AB}$ = 12.25, 6.19 Hz, 1 H), 2.99 (dq, $J$ = 2.12, 5.19 Hz, 1 H), 2.56 (dd, $J$ = 7.28, 2.12 Hz, 1 H), 2.38 (t, <$J$> = 6.44 (6.68 and 6.19) Hz, 1 H, OH), 2.18–1.98 (m, 5 H), 1.36 (dd, $J$ = 7.28, 4.4 Hz, 1 H), 1.31 (d, $J$ = 5.20 Hz, 3 H); $^{13}$C NMR ($CD_2Cl_2$) δ 215.8, 60.0, 59.1, 56.9, 44.6, 34.2, 32.1, 31.8, 23.3, 18.8; MS $m/z$ 183 (40, M + H), 165 (65, M + H - $H_2O$); HRMS calcd for $C_{10}H_{15}O_3$ (M + H)$^+$ 183.1021, found 183.1019. Anal. Calcd for $C_{10}H_{14}O_3$: C, 65.92; H, 7.74. Found: C, 66.01; H, 7.80. A mixed fraction (0.31 g, 18%) was collected and rechromatographed (combined yields given).

**(1*R**,5*R**,6*R**)-1-(Hydroxymethyl)-6-[(2*S**,3*R**)-3-methyloxiran-2-yl]-2-oxobicyclo[3.1.0]hexane (9a) and (1*R**,5*R**,6*R**)-1-(Hydroxymethyl)-6-[(2*R**,3*S**)-3-methyloxiran-2-yl]-2-oxobicyclo[3.1.0]hexane (10a).** Epoxidation of (*Z*)-keto alcohol **18** (401.4 mg, 2.41 mmol) was achieved as described for the epoxidation of (*E*)-keto alcohol **14**. This procedure gave the (*Z*)-epoxy trifluoroacetates (1:1) as an oil (0.620 g, 93%) as demonstrated by $^1$H NMR integration: MS $m/z$ 279 (85, M + H), 165 (100, M + H - $CF_3CO_2H$). Transesterification resulted in a colorless oil (450 mg) that was submitted to radial chromatography (EtOAc/hexane, 3:1) which led to successive fractions containing **9a** and alcohol **21a**, **9a** and **10a**, and pure **10a** (164 mg, 37%). The first fraction was not purified to obtain **9a**, but rather the mixture was used to form pure **9c** (vide infra): IR (**9a** and **21a**) 3550, 1723 cm$^{-1}$; $^{13}$C NMR (**9a**, by subtraction of pure **21a**; $CD_2Cl_2$) δ 216.9, 59.7, 55.1, 54.2, 43.7, 34.3, 31.9, 29.2, 23.1, 14.7; MS $m/z$ 183 (100, M + H); HRMS calcd for $C_{10}H_{15}O_3$ (M + H)$^+$ 183.1021, found 183.1023. Epoxide **10a** (150 mg, 34%) solidified upon standing and was recrystallized to yield white crystals: mp 96.5–97.5 °C (EtOAc/hexane); IR 3619, 1725 cm$^{-1}$; $^1$H NMR ($CD_2Cl_2$) δ 4.00 (dd, $J_{AB}$ = 12.08, 7.30 Hz, 1 H), 3.88 (dd, $J_{AB}$ = 12.08, 5.83 Hz, 1 H), 3.18 (dq, $J$ = 4.21, 5.47 Hz, 1 H), 2.73 (dd, $J$ = 8.47, 4.21 Hz, 1 H), 2.36 (dd, $J$ = 7.30, 5.83 Hz, 1 H, OH), 2.21–1.98 (m, 5 H), 1.38 (d, $J$ = 5.47 Hz, 3 H), 1.30 (dd, $J$ = 8.47, 3.64 Hz, 1 H); $^{13}$C NMR ($CD_2Cl_2$) δ 215.7, 60.0, 56.9, 54.9, 44.6, 34.3, 33.1, 28.3, 23.4, 15.2; MS $m/z$ 183 (12, M + H), 165 (30, M + H - $H_2O$), 123 (100); HRMS calcd for $C_{10}H_{15}O_3$ (M + H)$^+$ 183.1021, found 183.1021. Anal. Calcd for $C_{10}H_{14}O_3$: C, 65.92; H, 7.74. Found: C, 65.94; H, 7.77.

**(1*R**,5*R**,6*R**)-6-[(2*S**,3*S**)-3-Methyloxiran-2-yl]-2-oxo-1-[[[(pentafluorophenoxy)thiocarbonyl]oxy]methyl]bicyclo-[3.1.0]hexane (7c).** To a solution of epoxy alcohol **7a** (77 mg, 0.43 mmol) dissolved in $CH_2Cl_2$ (5 mL, 0.09 M) at −78 °C was added pyridine (0.069 mL, 0.85 mmol) followed by dropwise addition of neat *O*-pentafluorophenyl chlorothioformate (96%, 0.142 mL, 0.85 mmol). After 2 h, $H_2O$ (2.5 mL) was added, the aqueous fraction was extracted with $CH_2Cl_2$ and worked up, and the residue partially purified by flash chromatography to give an oil (183 mg). Further purification was accomplished by radial chromatography (EtOAc/hexane, 1:3) to afford a white solid (135 mg). Recrystallization (EtOAc/hexane) gave thiocarbonate **7c** (101 mg, 58%): mp 111.5–113.0 °C; IR 1737 cm$^{-1}$; $^1$H NMR ($CDCl_3$) δ 5.00 (d, $J_{AB}$ = 11.75 Hz, 1 H), 4.89 (d, $J_{AB}$ = 11.75 Hz, 1 H), 2.93 (dq, $J$ = 2.08, 5.19 Hz, 1 H), 2.84 (dd, $J$ = 3.13, 2.08 Hz, 1 H), 2.34 (dd, $J$ = 4.46, 4.4 Hz, 1 H), 2.28–1.99 (m, 4 H), 1.80 (dd, $J$ = 4.46, 3.13 Hz, 1 H), 1.36 (d, $J$ = 5.19 Hz, 3 H); $^{13}$C NMR ($CDCl_3$) δ 210.9, 191.6, 141.2 (dm, $J_{CF}$ = 243 Hz, 2 C, Ar-$C_2$), 140.2 (dm, $J_{CF}$ = 241 Hz, Ar-$C_4$), 138.1 (dm, $J_{CF}$ = 243 Hz, 2 C, Ar-$C_3$), 127.6 (m, Ar-$C_1$), 71.5, 54.8, 54.1, 39.0, 32.2, 30.7, 28.8, 21.4, 17.0; MS $m/z$ 409 (7, M + H), 165 (100, M + H - $C_6F_5OCSOH$); HRMS calcd for $C_{17}H_{14}F_5O_4S$ (M + H)$^+$ 409.0533, found 409.0523. Anal. Calcd for $C_{17}H_{13}F_5O_4S$: C, 50.00; H, 3.21; S, 7.85. Found: C, 49.89; H, 3.27; S, 7.93.

**(1*R**,5*R**,6*R**)-6-[(2*R**,3*R**)-3-Methyloxiran-2-yl]-2-oxo-1-[[[(pentafluorophenoxy)thiocarbonyl]oxy]methyl]bicyclo-[3.1.0]hexane (8c).** By the procedure described for the preparation of **7c**, **8a** (502 mg, 2.76 mmol) gave **8c** (733 mg, 65%): IR 1740 cm$^{-1}$; $^1$H NMR ($CDCl_3$) δ 5.33 (d, $J_{AB}$ = 12.15 Hz, 1 H), 4.82 (d, $J_{AB}$ = 12.15 Hz, 1 H), 3.02 (dq, $J$ = 2.02, 5.22 Hz, 1 H), 2.62 (dd, $J$ = 7.17, 2.02 Hz, 1 H), 2.41 (t, $J$ = 4.44 Hz, 1 H), 2.28–2.03 (m, 4 H), 1.51 (dd, $J$ = 7.17, 4.44 Hz, 1 H), 1.36 (d, $J$ = 5.22 Hz, 3 H); $^{13}$C NMR ($CD_2Cl_2$) δ 210.6, 192.3, 141.2 (dm, $J_{CF}$ = 243 Hz, 2 C, Ar-$C_2$), 140.2 (dm, $J_{CF}$ = 241 Hz, Ar-$C_4$), 138.1 (dm, $J_{CF}$ = 243 Hz, 2 C, Ar-$C_3$), 127.6 (m, Ar-$C_1$), 72.1, 57.4, 55.3, 40.1, 32.4, 31.9, 31.1, 21.9, 17.5; MS $m/z$ 409 (8, M + H), 165 (100, M + H - $C_6F_5OCSOH$); HRMS calcd for $C_{17}H_{14}F_5O_4S$ (M + H)$^+$ 409.0533, found 409.0523. Anal. Calcd for $C_{17}H_{13}F_5O_4S$: C, 50.00; H, 3.21; S, 7.85. Found: C, 50.08; H, 3.21; S, 7.94.

**(1*R**,5*R**,6*R**)-6-[(2*S**,3*R**)-3-Methyloxiran-2-yl]-2-oxo-1-[[[(pentafluorophenoxy)thiocarbonyl]oxy]methyl]bicyclo-[3.1.0]hexane (9c).** The above procedure was used for the conversion of ketol **9a** (40% **21a**, 47 mg, 0.26 mmol total) into **9c** (36.7 mg, 35%): IR 1737 cm$^{-1}$; $^1$H NMR ($CDCl_3$) δ 5.04 (d, $J_{AB}$ = 11.87 Hz, 1 H), 4.84 (d, $J_{AB}$ = 11.87 Hz, 1 H), 3.16 (dq, $J$ = 4.33, 5.43 Hz, 1 H), 3.04 (dd, $J$ = 4.33, 3.21 Hz, 1 H), 2.47 (dd, $J$ = 4.75, 3.89 Hz, 1 H), 2.29–2.03 (m, 4 H), 1.68 (dd, $J$ = 4.75, 3.21 Hz, 1 H), 1.40 (d, $J$ = 5.43 Hz, 3 H); $^{13}$C NMR ($CDCl_3$) δ 210.8, 191.6, 141.2 (dm, $J_{CF}$ = 243 Hz, 2 H, Ar-$C_2$), 139.8 (dm, $J_{CF}$ = 241 Hz, Ar-$C_4$), 138.0 (dm, $J_{CF}$ = 243 Hz, 2 C, Ar-$C_3$), 127.3 (m, Ar-$C_1$),

71.4, 53.3, 52.9, 38.5, 32.2, 31.0, 28.4, 21.2, 13.2; $^{19}$F NMR ($CDCl_3$) $\delta$ 131 (d, $J_{FF}$ = 20 Hz, 2 H, *o*-F), 126 (t, $J_{FF}$ = 20 Hz, 1 H, *p*-F), 121 (t, $J_{FF}$ = 20 Hz, 2 H, *m*-F); MS *m/z* 409 (5, M + H), 165 (100, M + H - $C_6F_5OCSOH$); HRMS calcd for $C_{17}H_{14}F_5O_4S$ (M + H)$^+$ 409.0533, found 409.0522. Anal. Calcd for $C_{17}H_{13}F_5O_4S$: C, 50.00; H, 3.21; S, 7.85. Found: C, 49.90; H, 3.18; S, 7.91.

**(1*R**,5*R**,6*R**)-6-[(2*R**,3*S**)-3-Methyloxiran-2-yl]-2-oxo-1-[[[(pentafluorophenoxy)thiocarbonyl]oxy]methyl]bicyclo-[3.1.0]hexane (10c).** The method described for the preparation of **7c** was employed in the conversion of **10a** (58.1 mg, 0.32 mmol) to **10c** (52%): IR 1740 cm$^{-1}$; $^1$H NMR ($CDCl_3$) $\delta$ 5.43 (d, $J_{AB}$ = 12.28 Hz, 1 H), 4.86 (d, $J_{AB}$ = 12.28 Hz, 1 H), 3.22 (dq, *J* = 4.22, 5.49 Hz, 1 H), 2.77 (dd, *J* = 8.64, 4.22 Hz, 1 H), 2.45 (dd, *J* = 4.25, 3.89 Hz, 1 H), 2.32–2.06 (m, 4 H), 1.42 (d, *J* = 5.49 Hz, 3 H), 1.41 (dd, *J* = 8.64, 4.25 Hz, 1 H); $^{13}$C NMR ($CDCl_3$) $\delta$ 210.2, 191.8, 141.4 (dm, $J_{CF}$ = 243 Hz, 2 C, Ar-$C_2$), 140.1 (dm, $J_{CF}$ = 241 Hz, Ar-$C_4$), 138.6 (dm, $J_{CF}$ = 243 Hz, 2 C, Ar-$C_3$), 127.5 (m, Ar-$C_1$), 71.1, 55.0, 53.0, 39.8, 32.0, 31.2, 28.1, 21.5, 13.8; $^{19}$F NMR ($CDCl_3$) $\delta$ 131 (d, $J_{FF}$ = 20 Hz, 2 H, *o*-F), 126 (t, $J_{FF}$ = 20 Hz, 1 H, *p*-F), 121 (t, $J_{FF}$ = 20 Hz, 2 H, *m*-F); MS *m/z* 409 (5, M + H), 165 (100, M + H - $C_6F_5OCSOH$); HRMS calcd for $C_{17}H_{14}F_5O_4S$ (M + H)$^+$ 409.0533, found 409.0531. Anal. Calcd for $C_{17}H_{13}F_5O_4S$: C, 50.00; H, 3.21; S, 7.85. Found: C, 50.01; H, 3.23; S, 7.92.

**(3*R**,3a*R**,3b*R**,6a*R**)-3,3a,3b,4,5,6-Hexahydro-3-[(1*S**)-1-hydroxyethyl]-6-oxo-1*H*-cyclopenta[1,3]cyclopropa[1,2-*c*]-furan (19a).** Epoxy ketol **7a** (100 mg, 0.55 mmol) was dissolved in 10 mL of 1% trifluoroacetic acid (TFA) in $CH_2Cl_2$ and stirred at room temperature for 15 h. Evaporation of the solvent gave a colorless oil (100 mg, 0.55 mmol, 100%) which solidified. Recrystallization (EtOAc/hexane) gave pure material: mp 71–72 °C; IR 3630, 3476, 1724 cm$^{-1}$; $^1$H NMR ($CDCl_3$) $\delta$ 4.30 (d, $J_{AB}$ = 8.83 Hz, 1 H), 3.85 (d, $J_{AB}$ = 8.83 Hz, 1 H), 3.80–3.70 (m, 2 H), 2.28–2.01 (m, 6 H), 1.75 (br s, 1 H, OH), 1.23 (d, *J* = 6.20 Hz, 3 H); $^{13}$C NMR ($CDCl_3$) $\delta$ 209.6, 84.7, 69.2, 66.3, 46.4, 36.1, 34.1, 32.4, 20.9, 19.6; MS *m/z* 183 (100, M + H), 165 (45, M + H - $H_2O$); HRMS calcd for $C_{10}H_{15}O_3$ (M + H)$^+$ 183.1021, found 183.1020. Anal. Calcd for $C_{10}H_{14}O_3$: C, 65.92; H, 7.74. Found: C, 66.02; H, 7.78.

**(3*S**,3a*R**,3b*R**,6a*R**)-3,3a,3b,4,5,6-Hexahydro-3-[(1*R**)-1-hydroxyethyl]-6-oxo-1*H*-cyclopenta[1,3]cyclopropa[1,2-*c*]-furan (20a).** Cyclization of **8a** (29 mg, 0.16 mmol) as described above led to **20a** as an oil. Traces of acid were removed by flash chromatography (EtOAc/hexane): IR 3240, 1724 cm$^{-1}$; $^1$H NMR ($CDCl_3$) $\delta$ 4.19 (d, $J_{AB}$ = 8.99 Hz, 1 H), 3.93 (d, $J_{AB}$ = 8.99 Hz, 1 H), 3.90–3.82 (m, 2 H), 2.42 (t, <*J*> = 4.2 (4.6 and 3.8) Hz, 1 H), 2.24–1.95 (m, 4 H), 2.00 (t, <*J*> = 3.4 (3.8 and 3.0) Hz, 1 H), 1.68 (br s, 1 H, OH), 1.27 (d, *J* = 6.07 Hz, 3 H); $^{13}$C NMR ($CDCl_3$) $\delta$ 210.3, 82.9, 68.0, 66.6, 45.0, 35.3, 34.2, 28.1, 20.6, 19.9; MS *m/z* 183 (100, M + H), 165 (30, M + H - $H_2O$). Anal. Calcd for $C_{10}H_{14}O_3$: C, 65.92; H, 7.74. Found: C, 66.00; H, 7.77.

**(3*R**,3a*R**,3b*R**,6a*R**)-3,3a,3b,4,5,6-Hexahydro-3-[(1*R**)-1-hydroxyethyl]-6-oxo-1*H*-cyclopenta[1,3]cyclopropa[1,2-*c*]-furan (21a).** Transformation of **9a** (containing ~40% **21a**, 44 mg, 0.24 mmol) into pure **21a** was accomplished quantitatively by the method described above. Flash chromatography (EtOAc/hexane) gave solid material that was recrystallized (EtOAc/hexane): mp 93.5–94.7 °C; IR 3577, 1726 cm$^{-1}$; $^1$H NMR ($CDCl_3$) $\delta$ 4.26 (d, $J_{AB}$ = 8.95 Hz, 1 H), 3.87 (d, $J_{AB}$ = 8.95 Hz, 1 H), 3.73–3.60 (m, 2 H), 2.35 (s, 1 H, OH), 2.28–1.98 (m, 5 H), 1.84 (d, *J* = 3.11 Hz, 1 H), 1.20 (d, *J* = 5.55 Hz, 3 H); $^{13}$C NMR ($CDCl_3$) $\delta$ 209.5, 84.9, 67.8, 65.0, 46.0, 35.5, 34.1, 31.5, 20.7, 18.1; MS *m/z* 183 (100, M + H), 165 (50, M + H - $H_2O$), 123 (60). Anal. Calcd for $C_{10}H_{14}O_3$: C, 65.92; H, 7.74. Found: C, 65.63; H, 7.83.

**(3*S**,3a*R**,3b*R**,6a*R**)-3,3a,3b,4,5,6-Hexahydro-3-[(1*S**)-1-hydroxyethyl]-6-oxo-1*H*-cyclopenta[1,3]cyclopropa[1,2-*c*]-furan (22a).** The above procedure was employed with ketol **10a** (21 mg, 0.12 mmol). The crude product was passed through $SiO_2$ (EtOAc) and then submitted to radial chromatography (EtOAc/hexane = 3:1). This procedure gave a slightly impure white solid (4.3 mg, 68%), which was recrystallized from EtOAc/hexane to give pure material: mp 81.5–83.0 °C; IR 1715 cm$^{-1}$; $^1$H NMR ($CDCl_3$) $\delta$ 4.18 (d, $J_{AB}$ = 9.10 Hz, 1 H), 3.92 (d, $J_{AB}$ = 9.10 Hz, 1 H), 3.82 (dd, *J* = 7.68, 3.37 Hz, 1 H), 3.73 (br dq, *J* = 7.68, 6.13 Hz, 1 H), 2.28–1.93 (m, 5 H), 1.89 (t, <*J*> = 3.26 Hz (3.37 and 3.14), 1 H), 1.54 (s, 1 H, OH), 1.23 (d, *J* = 6.13 Hz, 3 H); $^{13}$C NMR ($CDCl_3$) $\delta$ 209.8, 83.9, 69.1, 66.4, 45.5, 35.3, 34.2, 27.4, 20.5, 19.3; MS *m/z* 183 (100, M + H), 165 (50, M + H - $H_2O$), 137 (30, M + H - $CH_3CHOH_2$); HRMS calcd for $C_{10}H_{15}O_3$ (M + H)$^+$ 183.1021, found 183.1023.

**(3*R**,3a*R**,3b*R**,6a*R**)-3,3a,3b,4,5,6-Hexahydro-3-[(1*S**)-1-benzoxyethyl]-6-oxo-1*H*-cyclopenta[1,3]cyclopropa[1,2-*c*]-furan (19b).** Alcohol **19a** (111 mg, 0.61 mmol) and pyridine (98 mL, 96 mg, 1.22 mmol) in $CH_2Cl_2$ (3 mL) at room temperature was treated dropwise with benzoyl chloride (171 mg, 1.22 mmol). After 4 h, water (3 mL) was added and the mixture was stirred for another 4 h. Extraction with $CH_2Cl_2$ and workup gave a colorless oil, which was purified by flash chromatography (EtOAc/hexane). The resulting solid (137 mg, 78%) was recrystallized from EtOH: mp 105.0–106.5 °C; IR 1725 cm$^{-1}$; $^1$H NMR ($CDCl_3$) $\delta$ 8.05 (dm, *J* = 6.7 Hz, 2 H), 7.58 (tt, *J* = 7.0, 1.4 Hz, 1 H), 7.46 (br t, <*J*> = 6.9 Hz (6.7 and 7.0), 2 H), 5.16 (dq, *J* = 4.82, 6.45 Hz, 1 H), 4.35 (d, $J_{AB}$ = 8.71 Hz, 1 H), 4.08 (d, *J* = 4.82 Hz, 1 H), 3.89 (d, $J_{AB}$ = 8.71 Hz, 1 H), 2.30–2.00 (m, 5 H), 2.10 (d, *J* = 3.15 Hz, 1 H), 1.38 (d, *J* = 6.45 Hz, 3 H); $^{13}$C NMR ($CDCl_3$) $\delta$ 209.3, 165.8, 133.1, 130.2, 129.8 (2), 128.4 (2), 82.3, 73.1, 66.7, 46.3, 35.3, 34.3, 31.6, 20.8, 16.2; MS *m/z* 287 (100, M + H), 165 (60, M + H - PhCOOH); HRMS calcd for $C_{17}H_{19}O_4$ (M + H)$^+$ 287.1283, found 287.1277. Anal. Calcd for $C_{17}H_{18}O_4$: C, 71.31; H, 6.34. Found: C, 71.39; H, 6.37.

**(3*S**,3a*R**,3b*R**,6a*R**)-3,3a,3b,4,5,6-Hexahydro-3-[(1*R**)-1-benzoxyethyl]-6-oxo-1*H*-cyclopenta[1,3]cyclopropa[1,2-*c*]-furan (20b).** Alcohol **20a** (88 mg, 0.48 mmol) gave crystalline benzoate **20b** (77%) by the above procedure. Recrystallization was accomplished with difficulty from EtOH/$H_2O$: mp 60.5–63.0 °C; IR 1724 cm$^{-1}$; $^1$H NMR ($CDCl_3$) $\delta$ 8.05 (dm, *J* = 6.7 Hz, 2 H), 7.58 (tt, *J* = 7.0, 1.4 Hz, 1 H), 7.46 (br t, <*J*> = 6.9 Hz (6.7 and 7.0), 2 H), 5.19 (dq, *J* = 7.36, 6.31 Hz, 1 H), 4.21 (d, $J_{AB}$ = 9.04 Hz, 1 H), 4.11 (dd, *J* = 7.36, 3.29 Hz, 1 H), 3.96 (d, $J_{AB}$ = 9.04 Hz, 1 H), 2.36 (br t, <*J*> = 3.4 Hz, 1 H), 2.25–1.85 (m, 4 H), 2.02 (t, <*J*> = 3.36 Hz (3.43 and 3.29), 1 H), 1.43 (d, *J* = 6.31 Hz, 3 H); $^{13}$C NMR ($CDCl_3$) $\delta$ 210.0, 165.5, 133.1, 130.4, 129.6 (2), 128.5 (2), 81.3, 70.8, 66.7, 45.6, 36.0, 34.3, 28.1, 20.5, 17.8; MS *m/z* 287 (100, M + H), 165 (70, M + H - PhCOOH); HRMS calcd for $C_{17}H_{19}O_4$ (M + H)$^+$ 287.1283, found 287.1279. Anal. Calcd for $C_{17}H_{18}O_4$: C, 71.31; H, 6.34. Found: C, 71.41; H, 6.39.

**(3*R**,3a*R**,3b*R**,6a*R**)-3,3a,3b,4,5,6-Hexahydro-3-[(1*R**)-1-benzoxyethyl]-6-oxo-1*H*-cyclopenta[1,3]cyclopropa[1,2-*c*]-furan (21b).** Alcohol **21a** (31 mg, 0.17 mmol) gave crystalline benzoate **21b** by the above procedure. Recrystallization (EtOH) gave pure material (81%): mp 83.0–84.0 °C; IR 1723 cm$^{-1}$; $^1$H NMR ($CDCl_3$) $\delta$ 8.05 (dm, *J* = 6.7 Hz, 2 H), 7.58 (tt, *J* = 7.0, 1.4 Hz, 1 H), 7.46 (br t, <*J*> = 6.9 Hz (6.7 and 7.0), 2 H), 5.25 (dq, *J* = 3.50, 6.47 Hz, 1 H), 4.49 (d, $J_{AB}$ = 8.57 Hz, 1 H), 4.08 (d, *J* = 3.50 Hz, 1 H), 3.92 (d, $J_{AB}$ = 8.57 Hz, 1 H), 2.21 (br t, <*J*> = 2.3 Hz, 1 H), 2.18–1.98 (m, 4 H), 1.95 (d, *J* = 3.06 Hz, 1 H), 1.40 (d, *J* = 6.47 Hz, 3 H); $^{13}$C NMR ($CDCl_3$) $\delta$ 209.1, 166.2, 133.1, 130.0, 129.7 (2), 128.4 (2), 81.9, 72.6, 66.6, 46.1, 35.8, 34.1, 31.2, 20.8, 16.2; MS *m/z* 287 (100, M + H), 165 (45, M + H - PhCOOH); HRMS calcd for $C_{17}H_{19}O_4$ (M + H)$^+$ 287.1283, found 287.1277. Anal. Calcd for $C_{17}H_{18}O_4$: C, 71.31; H, 6.34. Found: C, 70.70 (0.61% low); H, 6.31.

**(3*S**,3a*R**,3b*R**,6a*R**)-3,3a,3b,4,5,6-Hexahydro-3-[(1*S**)-1-benzoxyethyl]-6-oxo-1*H*-cyclopenta[1,3]cyclopropa[1,2-*c*]-furan (22b).** Alcohol **22a** (15.6 mg, 0.09 mmol) gave benzoate **22b** by the above procedure as an oil (62%): IR 1724 cm$^{-1}$; $^1$H NMR ($CDCl_3$) $\delta$ 8.04 (dm, *J* = 6.7 Hz, 2 H), 7.54 (tt, *J* = 7.0, 1.4 Hz, 1 H), 7.42 (br t, <*J*> = 6.9 Hz (6.7 and 7.0), 2 H), 5.24 (dq, *J* = 6.63, 6.54 Hz, 1 H), 4.16 (d, $J_{AB}$ = 9.34 Hz, 1 H), 4.17 (dd, *J* = 6.63, 3.35 Hz, 1 H), 3.94 (d, $J_{AB}$ = 9.34 Hz, 1 H), 2.32 (br dd, *J* = 5.26, 3.47 Hz, 1 H), 2.25–1.83 (m, 4 H), 1.96 (t, <*J*> = 3.41 Hz (3.47 and 3.35), 1 H), 1.42 (d, *J* = 6.54 Hz, 3 H); $^{13}$C NMR ($CDCl_3$) $\delta$ 209.9, 166.0, 133.1, 130.4, 129.7 (2), 128.3 (2), 81.1, 71.4, 66.5, 45.0, 35.5, 34.3, 27.5, 20.5, 17.3; MS *m/z* 287 (100, M + H), 165 (35, M + H - PhCOOH). Anal. Calcd for $C_{17}H_{18}O_4$: C, 71.31; H, 6.34. Found: C, 71.14; H, 6.27.

**(*E*)-3-(3-Hydroxy-1-butenyl)-2-methyl-2-cyclopenten-1-one (24). General Procedure for the Fragmentation of Thiocarbonates 7c–10c.** A degassed solution of *n*-$BuSn_3H$ (0.175 mL, 0.189 g, 0.65 mmol) and 1,1'-azobis(isobutyronitrile) (AIBN) (56 mg, 0.34 mmol) in toluene (2.5 mL) was added via a syringe-pump to a degassed solution of thiocarbonate (133 mg, 0.33 mmol) in toluene (5.7 mL) at 75 °C over a period of 2 h. ($^1$H

NMR experiments were conducted at the same concentrations; however, reagents were premixed with the starting material and $^1H$ NMR spectra were recorded after heating at 75 °C for various lengths of time.) The solvent was evaporated in vacuo and the oily residue was dissolved in wet $Et_2O$ (8 mL), DBU (0.10 mL, 102 mg, 0.67 mmol) was added, and the resulting milky solution was titrated with a solution of $I_2/Et_2O$ (saturated, 3 mL), until a yellow precipitate formed.[65] Back titration with 5% $NaHSO_3$ (5 mL), filtration of the $Et_2O$ solution through $SiO_2$, and workup gave a yellow, semisolid material. Flash chromatography (EtOAc/hexane) gave dienone **24** as a pure oil (31.5 mg, 58%): IR 3609, 3400, 1685 $cm^{-1}$; $^1H$ NMR ($CD_2Cl_2$) $\delta$ 6.79 (br d, $J$ = 15.75 Hz, 1 H), 6.29 (dd, $J$ = 15.75, 5.60 Hz, 1 H), 4.50 (dq, $J$ = 5.60, 6.50 Hz, 1 H), 2.63 (m, 2 H), 2.37 (m, 2 H), 2.14 (br s, 1 H, OH), 1.76 (t, $J$ = 1.90 Hz, 3 H), 1.34 (d, $J$ = 6.50 Hz, 3 H); $^{13}C$ NMR ($CD_2Cl_2$) $\delta$ 209.6, 163.3, 141.7, 137.2, 123.5, 68.6, 34.1, 26.1, 23.6, 8.3; MS (DEI) $m/z$ 166 (25, M), 148 (20, M − $H_2O$), 123 (85); HRMS calcd for $C_{10}H_{15}O_2$ (M + H)$^+$ 167.1072, found 167.1068.

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**Supplementary Material Available:** Copies of $^1H$ and $^{13}C$ NMR spectra of **16**, **21b**, **22a**, and **24** (8 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.