

# Trimethyl Phosphite as a Trap for Alkoxy Radicals Formed from the Ring Opening of Oxiranylcarbinyll Radicals. Conversion to Alkenes. Mechanistic Applications to the Study of C–C versus C–O Ring Cleavage

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**Abstract:** Trimethyl phosphite,  $(\text{MeO})_3\text{P}$ , is introduced as an efficient and selective trap in oxiranylcarbinyll radical (**2**) systems, formed from haloepoxides **8–13** under thermal AIBN/ $n\text{-Bu}_3\text{SnH}$  conditions at about 80 °C. Initially, the transformations of **8–13**, in the absence of phosphite, to allyl alcohol **7** and/or vinyl ether **5** were measured quantitatively (Table 1). Structural variations in the intermediate oxiranylcarbinyll radical (**2**), allyloxy (**3**), and vinyloxy carbinyll (**4**) radicals involve influences of the thermodynamics and kinetics of the C–O (**2**  $\rightarrow$  **3**,  $k_1$ ) and C–C (**2**  $\rightarrow$  **4**,  $k_2$ ) radical scission processes and readily account for the changes in the amounts of product vinyl ether (**5**) and allyl alcohol (**7**) formed. Added  $(\text{MeO})_3\text{P}$  is inert to vinyloxy carbinyll radical **4** and selectively and rapidly traps allyloxy radical **3**, diverting it to trimethyl phosphate and allyl radical **6**. Allyl radicals (**6**) dimerize or are trapped by  $n\text{-Bu}_3\text{SnH}$  to give alkenes, formed from haloepoxides **8**, **9**, and **13** in 69–95% yields. Intermediate vinyloxy carbinyll radicals (**4**), in the presence or absence of  $(\text{MeO})_3\text{P}$ , are trapped by  $n\text{-Bu}_3\text{SnH}$  to give vinyl ethers (**5**). The concentrations of  $(\text{MeO})_3\text{P}$  and  $n\text{-Bu}_3\text{SnH}$  were varied independently, and the amounts of phosphate, vinyl ether (**5**), and/or alkene from haloepoxides **10**, **11**, and **13** were carefully monitored. The results reflect readily understood influences of changes in the structures of radicals **2–4**, particularly as they influence the C–O ( $k_1$ ) and C–C ( $k_2$ ) cleavages of intermediate oxiranylcarbinyll radical **2** and their reverse ( $k_{-1}$ ,  $k_{-2}$ ). Diversion by  $(\text{MeO})_3\text{P}$  of allyloxy radicals (**3**) from haloepoxides **11** and **12** fulfills a prior prediction that under conditions closer to kinetic control, products of C–O scission, not just those of C–C scission, may result. Thus, for oxiranylcarbinyll radicals from haloepoxides **11**, **12**, and **13**, C–O scission ( $k_1$ , **2**  $\rightarrow$  **3**) competes readily with C–C cleavage ( $k_2$ , **2**  $\rightarrow$  **4**), even though C–C scission is favored thermodynamically.

## Introduction

The differences in reactivities of free radicals toward tri-coordinate phosphorus ( $\text{Z}_3\text{P}$ ) have been used effectively in the preparation of vinylphosphonates from 6-bromo-1-alkynes<sup>1</sup> and substituted cyclopentanes and cyclohexanes from 5- and 6-bromoaldehydes.<sup>2</sup> In both cases, an alkyl radical, essentially unreactive toward  $\text{Z}_3\text{P}$ , was allowed to cyclize to a very reactive species, a vinyl<sup>1</sup> or alkoxy<sup>2</sup> radical, which was then rapidly trapped by  $\text{Z}_3\text{P}$  to give a preparatively useful product.

More specifically, alkoxy radicals ( $\text{RO}^\bullet$ ) react at near diffusion controlled rates with trialkyl phosphites to give phosphoranyl radicals  $[\text{ROP}(\text{OR}')_3]^\bullet$  that typically are rapidly deoxygenated to generate alkyl radicals ( $\text{R}^\bullet$ ) and phosphate  $[\text{OP}(\text{OR}')_3]$ .<sup>3</sup> In

contrast, primary and secondary alkyl radicals ( $\text{R}^\bullet$ ) react reversibly with trialkyl phosphites  $[(\text{R}'\text{O})_3\text{P}]$  to form phosphoranyl radicals  $[\text{R}''\text{-P}(\text{OR}')_3]^\bullet$ . These intermediates only form product when the intermediate has available a very rapid, product-forming  $\beta$ -scission step to give a relatively stable radical,  $\text{R}^\bullet$ , such as benzyl, and a product alkylphosphonate,  $\text{R-P}(\text{O})(\text{OR}')_2$ . We report here the use of these reactivity differences, under typical thermal AIBN/ $\text{Bu}_3\text{SnH}$  conditions in the presence of  $(\text{MeO})_3\text{P}$ , to effect the conversion of bromoepoxides **8**, **9**, and **13** to the corresponding alkenes: indene (**17**), 3-phenylpropene (**23**), and isomeric indenenes **45** and **46**.

Because these transformations defunctionalize **8**, **9**, and **13**, they likely are of more mechanistic (Scheme 1) than methodological interest. In this regard,  $(\text{MeO})_3\text{P}$  is found to be a very reactive and selective trap for the allyloxy radical (**3**) of mechanistic Scheme 1. Previously, hydrogen-donors  $\text{PhSH}^4$  and  $n\text{-Bu}_3\text{SnH}^5$  have been used in mechanistic studies to trap free radical intermediates, **2–4**. Trimethyl phosphite has the advantage that it selectively traps intermediate **3**, but not **2** or **4**, and,

(1) Kim, S.; Oh, D. H. *Synlett* **1998**, 525.

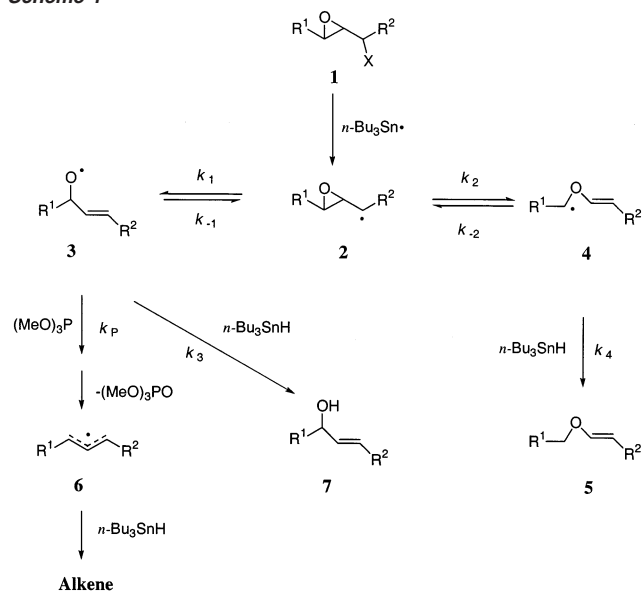
(2) Jiao, X.-Y.; Bentrude, W. G. *J. Am. Chem. Soc.* **1999**, *121*, 6088.

(3) For reviews of the chemistry of phosphoranyl radicals, see: (a) Bentrude, W. G. In *The Chemistry of Organophosphorus Compounds*; Hartley, F. R., Ed.; Wiley: Sussex, 1990; Vol. 1, p 531. (b) Bentrude, W. G. In *Reactive Intermediates*; Abramovitch, R. A., Ed.; Plenum: London, 1983; Vol. 3, p 199. (c) Bentrude, W. G. *Acc. Chem. Res.* **1982**, *15*, 117. (d) Roberts, B. P. In *Advances in Free Radical Chemistry*; Williams, G. H., Ed.; Heyden and Sons: London, 1980; Vol. 6, p 225. Schipper, P.; Janzen, E. H. J. M.; Buck, H. M. *Top. Phosphorus Chem.* **1977**, *191*, 407. Bentrude, W. G. In *Free Radicals*; Kochi, J. K., Ed.; Wiley-Interscience: New York, 1973; p 54.

(4) Krishnamurthy, V.; Rawal, V. H. *J. Org. Chem.* **1997**, *62*, 1572. For a lower limit of the rate constant for C–O scission (Scheme 1) of  $1 \times 10^{10} \text{ s}^{-1}$  at 70 °C, see: Krosley, K. W.; Gleicher, G. J. **1993**, *6*, 228.

(5) Ziegler, F. E.; Petersen, A. K. *J. Org. Chem.* **1995**, *60*, 2666.

Scheme 1

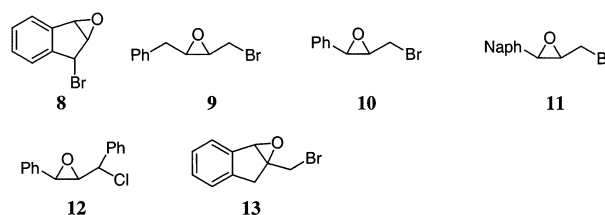


as we show, it can be used in conjunction with *n*-Bu<sub>3</sub>SnH in experiments in which the concentrations of the two traps are varied independently. In fact, both (MeO)<sub>3</sub>P and *n*-Bu<sub>3</sub>SnH react with allyloxy radical **3**. However, the phosphite, a volatile liquid, can be used as solvent (8 M). Even at equal concentrations, the phosphite is considerably more reactive than *n*-Bu<sub>3</sub>SnH ( $k_p/k_H$  ca. 8, Scheme 1, see Discussion). Moreover, *n*-Bu<sub>3</sub>SnH is normally used at concentrations less than 1 M, which makes trimethyl phosphite the essentially exclusive trap for allyloxy radical **3**, while vinyloxy radical **4** is trapped only by *n*-Bu<sub>3</sub>SnH.<sup>6</sup>

The kinetics and thermodynamics of the competition between C–C and C–O bond cleavage for oxiranylcarbinyl radicals (Scheme 1), generated under thermal AIBN/*n*-Bu<sub>3</sub>SnH conditions, have received extensive recent study. For haloepoxide **1** with R<sup>1</sup> = H or Ph and R<sup>2</sup> = H or alkyl, the formation from **2** of allyloxy radical **3** instead of C–C scission product **4** has been found both experimentally<sup>5,9</sup> and theoretically<sup>10,11</sup> to be kinetically favored. Carbon–carbon scission gives the thermodynamically more stable radical **4**.<sup>5,9–11</sup> Under kinetic product

control conditions, allyl alcohol **7** is formed (R<sup>1</sup> = H or Ph; R<sup>2</sup> = H or alkyl). Radicals **3** and **4** are readily reclosed to oxiranylcarbinyl radical **2**, and, ultimately, an equilibrium ratio of **4/3**, determined primarily by the influence of R<sup>1</sup> and R<sup>2</sup> on the stabilities of radicals **3** and **4**, potentially can be established. Thus, for bromoepoxide **10** (R<sup>1</sup> = Ph, R<sup>2</sup> = H), at relatively low concentrations of *n*-Bu<sub>3</sub>SnH, close to thermodynamic control conditions prevail,<sup>5</sup> and allyl ether **24** (R<sup>1</sup> = Ph, R<sup>2</sup> = H) is the dominant product.<sup>5</sup> Conversely, at high *n*-Bu<sub>3</sub>SnH concentrations, nearly kinetic control is operative, which gives predominantly allyl alcohol (**7**, R<sup>1</sup> = Ph, R<sup>2</sup> = H).

The thermal AIBN/*n*-Bu<sub>3</sub>SnH-induced rearrangements of all but bromoepoxide **9** have been investigated previously; yet, except for bromoepoxide **10**, careful quantitative studies of product distributions have not been reported. We have examined the product distribution from haloepoxide radical precursors **8–13** with and without added trimethyl phosphite and find that trimethyl phosphite at high concentrations traps allyloxy radical **3** in competition with its reclosure to intermediate **2** with formation of alkene (or allyl radical dimers), instead of alcohol **7**, along with trimethyl phosphate. Moreover, the equilibrium of Scheme 1 can be shifted by phosphite strongly in the direction of **3** to give a reduced yield of vinyl ether **5** along with phosphate.



Furthermore, changes in *n*-Bu<sub>3</sub>SnH and phosphite concentrations strongly affect product distributions and provide useful insights into the effects of variations in the structure of the oxiranylcarbinyl radical (**2**) on the kinetic array represented by Scheme 1. In this regard, it was suggested in the pivotal work of Ziegler and Petersen<sup>5</sup> that under conditions of kinetic control, products from C–O cleavage of radical **2** (Scheme 1), rather than the reported products of C–C scission, might be observed for haloepoxides **11**<sup>12</sup> (R<sup>1</sup> = R<sup>2</sup> = Ph) and **12**<sup>12</sup> (R<sup>1</sup> = 1-naphthyl, R<sup>2</sup> = H), just as they had seen with **10**.<sup>5,12</sup> Indeed, we confirm that at low *n*-Bu<sub>3</sub>SnH concentrations in the absence of phosphite, haloepoxides **11**, **12**, and also **13**<sup>13</sup> give the thermodynamic product, allyl ether **5**, exclusively or very predominantly (Table 1). However, with 5 M (MeO)<sub>3</sub>P present (conditions which are closer to kinetic control), the reactions of haloepoxides **11–13** result in deoxygenation of allyloxy radical **3**, to yield (MeO)<sub>3</sub>PO in 52, 49, and 70% yields, respectively (Table 1). Consequent reductions in vinyl ether **5** yields are noted along with the formation of alkenes (Scheme 1). The deoxygenation of **3** from **12** (R<sup>1</sup> = R<sup>2</sup> = Ph) occurs, although when R<sup>2</sup> is phenyl (radicals from chloroepoxide **12**), ring reclosure of **3** to the resonance stabilized oxiranylcarbinyl radical (**2**) should be strongly favored both kinetically and thermodynamically (see Discussion). For **1** with R<sup>1</sup> = Ph, R<sup>2</sup> = H (compound **10**) at high trimethyl phosphite concentrations,

(6) Neat *n*-Bu<sub>3</sub>SnH corresponds to a 3.7 M concentration, while neat (MeO)<sub>3</sub>P is 8.5 M in phosphite. At the same time, the first-order rate constant<sup>7</sup> for abstraction of hydrogen from Bu<sub>3</sub>SnH ( $k_H$ ) by *tert*-butoxy radical at 22 °C is  $2.0 \times 10^8 \text{ s}^{-1} \text{ M}^{-1}$ . For reaction of the same radical with (EtO)<sub>3</sub>P,  $k_p$  at 28 °C is measured<sup>8</sup> to be  $1.7 \times 10^9 \text{ s}^{-1} \text{ M}^{-1}$ . (MeO)<sub>3</sub>P is generally somewhat more reactive than (EtO)<sub>3</sub>P toward free radicals.<sup>3</sup> This makes neat (MeO)<sub>3</sub>P at least an order of magnitude more reactive than neat *n*-Bu<sub>3</sub>SnH toward *tert*-butoxy radical. Moreover, the deoxygenation experiments of Tables 1 and 2, where deoxygenation of **3** is maximized, were run at (MeO)<sub>3</sub>P/*n*-Bu<sub>3</sub>SnH ratios of 500 and 400, respectively.

(7) Scaiano, J. C. *J. Am. Chem. Soc.* **1980**, *102*, 5399.

(8) Griller, D.; Ingold, K. U.; Patterson, L. K.; Scaiano, J. C.; Small, R. D., Jr. *J. Am. Chem. Soc.* **1979**, *101*, 3780. Roberts, B. P.; Scaiano, J. C. *J. Chem. Soc., Perkin Trans. 2* **1981**, 905.

(9) Without resonance stabilization of **4**, alcohol from allyloxy radicals (**3**) is formed exclusively. See, for example: Edwards, A. J.; Hird, N. W.; Marples, B. A.; Rudderman, J. A.; Slawin, A. M. *Z. Tetrahedron Lett.* **1997**, *38*, 3599. Rawal, W. H.; Zhong, H. M. *Tetrahedron Lett.* **1993**, *55*, 5181. Breen, A. P.; Murphy, J. A. *J. Chem. Soc., Chem. Commun.* **1993**, 191. Barton, D. H. R.; Motherwell, R. S. H.; Motherwell, W. B. *J. Chem. Soc., Perkin Trans. 1* **1981**, 2363. Johns, A.; Murphy, J. *Tetrahedron Lett.* **1988**, 837. Davies, A. G.; Muggleton, B. J. *J. Am. Chem. Soc.* **1979**, *101*, 9. Davies, A. G.; Tse, M. W. *J. Organomet. Chem.* **1978**, *155*, 25. Dobbs, A. J.; Gilbert, B. C.; Laue, H. A.; Norman, R. O. C. *J. Chem. Soc., Perkin Trans. 2* **1976**, 1044.

(10) Pasto, D. J. *J. Org. Chem.* **1996**, *61*, 252.

(11) Smith, D. M.; Nicolaides, A.; Golding, B. T.; Radom, L. *J. Am. Chem. Soc.* **1998**, *120*, 10223.

(12) Dickinson, J. M.; Murphy, J. A.; Patterson, C. W. Wooster, N. F. *J. Chem. Soc., Perkin Trans. 1* **1990**, 1179.

(13) Murphy, J. A.; Patterson, C. W. *J. Chem. Soc., Perkin Trans. 1* **1993**, 405.

**Table 1.** Summary of Effects of Trimethyl Phosphite on Reactions of **8–13**, One-Pot Conditions<sup>a</sup>

| reactant | yield of alcohol             |                           | yield of vinyl ether         |                           | yield of alkene           | yield of (MeO) <sub>3</sub> PO |
|----------|------------------------------|---------------------------|------------------------------|---------------------------|---------------------------|--------------------------------|
|          | without (MeO) <sub>3</sub> P | with (MeO) <sub>3</sub> P | without (MeO) <sub>3</sub> P | with (MeO) <sub>3</sub> P |                           |                                |
| 8        | 15, 91 <sup>b</sup>          | 4 <sup>b</sup>            | 14, 0                        | 0                         | 17, 73                    | 89                             |
| 9        | 21, 93                       | <1 <sup>d</sup>           | 22, 0                        | 0                         | 23a,b,c, 95 <sup>hi</sup> | 97                             |
| 10       | 25, 4                        | 0                         | 24, 89                       | 13                        | 27, 33 <sup>f</sup>       | 82                             |
| 11       | 34, 0 <sup>e</sup>           | 0                         | 33, 92 <sup>e</sup>          | 43                        | 35–37, <sup>m</sup> 16    | 52                             |
| 12       | 31, 0                        | 0                         | 30, 93 <sup>j</sup>          | 52 <sup>k</sup>           | 32, <sup>n</sup> 34       | 49                             |
| 13       | 40, 12 <sup>d,e</sup>        | 4 <sup>c,d</sup>          | 41, 42, 84 <sup>e,l</sup>    | 10                        | 45, 46, 69 <sup>g</sup>   | 70                             |

<sup>a</sup> Unless otherwise indicated, reactions were run by Method B at 0.01 M substrate, 0.02 M *n*-Bu<sub>3</sub>SnH, 5 M (MeO)<sub>3</sub>P, (*n*-PrO)<sub>3</sub>PO internal standard. Reactions without phosphite were run at the same concentrations of tin hydride (except for **11**<sup>e</sup> and **13**<sup>e</sup>), substrate, and AIBN in benzene solvent.

<sup>b</sup> As 1-indanone. <sup>c</sup> As 2-methyl-1-indanone. <sup>d</sup> Detected by GC, estimated by comparison to 1% stock solution of **21**. <sup>e</sup> At 0.005 M *n*-Bu<sub>3</sub>SnH. <sup>f</sup> Cinnamyl radical dimers also formed (**28** and **29**), 42% total yield. <sup>g</sup> Total 2-methylindene (**45**) plus 2-methyleneindane (**46**); ratio **45/46** = 1.5. <sup>h</sup> Combined yield of three isomers; 21% *trans*-4-phenyl-2-propene (**23b**); 54% *cis*-**23a**; 20% 4-phenyl-1-propene (**23c**). <sup>i</sup> At 0.02 M (TMS)<sub>3</sub>SiH, 92% **23a**. <sup>j</sup> 52% *cis*-**30**, 41% *trans*-**30**. <sup>k</sup> **30**, *cis* plus *trans*. <sup>l</sup> 46% **41**, 38% **42**. <sup>m</sup> GC yields: **35** (3%), **36** (6%), **37** (7%). <sup>n</sup> *Cis* plus *trans*.

**Table 2.** Summary of Effects of Trimethyl Phosphite on Reactions of **8–13**, Syringe Pump Method<sup>a</sup>

| substrates                   | 8                  | 10      | 11      | 12      | 13                   |
|------------------------------|--------------------|---------|---------|---------|----------------------|
| yield of vinyl ether         | 0 (0) <sup>b</sup> | 8 (13)  | 34 (43) | 42 (52) | 23 <sup>c</sup> (10) |
| yield of trimethyl phosphate | 96 (89)            | 85 (82) | 58 (52) | 42 (49) | 69 (70)              |

<sup>a</sup> Method A. Addition of 0.04 M *n*-Bu<sub>3</sub>SnH and AIBN (6 mg) to neat (MeO)<sub>3</sub>P (ca. 8 M) containing 0.01 M substrate at 80 °C; (*n*-PrO)<sub>3</sub>PO internal standard. <sup>b</sup> Numbers in parentheses are from Table 1. <sup>c</sup> Combined yield of **41** plus **42**.

and with sufficient amounts of added radical trap *n*-Bu<sub>3</sub>SnH, the C–C and C–O scission steps appear to become close to being irreversible. From the ratio of phosphate to vinyl ether, an estimation of  $k_1/k_2$  (5.8) is obtained that is similar to the value reported for oxiranylcarbiny radical **2** from **10** previously ( $k_1/k_2 = 4.2$ ),<sup>5</sup> with *n*-Bu<sub>3</sub>SnH as the sole radical trap for both **3** and **4**. For **11** and **13**,  $k_1/k_2$  evidently is closer to one.

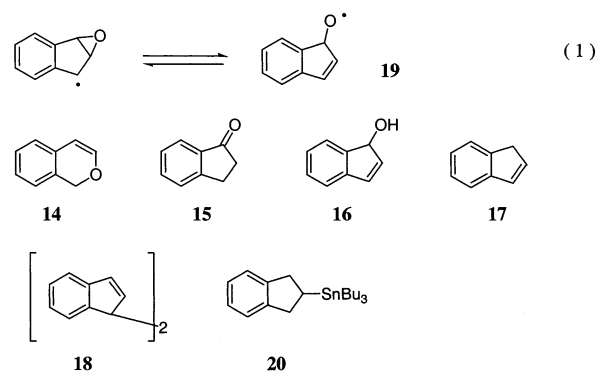
## Results

The reactions of halooxides are reported in the order **8–13** which, except for **13**, reflects decreasing amounts of trimethyl phosphite formation. All reactions with trimethyl phosphite present were run with exclusion of oxygen. Phosphate yields recorded (Tables 1 and 2), therefore, contain at most 1–2% of material from air oxidation of the phosphite (phosphate yield based on starting halooxide; see control reactions in the Experimental Section).

**Debromodeoxygenations of Bromoepoxides 8 and 9.** These are reported together because in both cases phosphite brings about total deoxygenation of allyloxy radical intermediate **3** and formation of reasonably high yields of alkene. In the absence of (MeO)<sub>3</sub>P, the conversion of bromoepoxide **8** to 1-indanone is readily accomplished, as reported previously.<sup>13</sup> Thus, syringe-pump addition under argon of a benzene solution of *n*-Bu<sub>3</sub>SnH (0.05 M) and AIBN (0.003 M) to a refluxed 0.03 M benzene solution of **8** over a 5 h period, followed by a further 2 h reflux, gave none of the thermodynamic C–C cleavage product, vinyl ether **14** (GC). The primary product, 1-indanone (**15**), presumably formed from the initial C–O scission product, 1-indenol

(**16**), was isolated in 70% yield. The formation of **15** by rearrangement of alcohol **16** under free radical (thermal AIBN/*n*-Bu<sub>3</sub>SnH), thermal, or weakly basic conditions is well documented.<sup>14</sup> The high yield of 1-indanone (**15**) was verified in a separate syringe-pump reaction (87% GC yield) and in a one-pot reaction (Method B without phosphite, 91% GC yield, Table 1).

In contrast, addition via syringe pump of *n*-Bu<sub>3</sub>SnH (0.04 M) and AIBN to bromoepoxide **8** (0.02 M) in refluxed benzene that contained only modest amounts of (MeO)<sub>3</sub>P (ca 0.4 M) resulted in a greatly reduced yield of 1-indanone, **15** (5%), which was replaced by indene, **17** (67%), and 1-indenyl radical dimer, **18** (9%), all quantified by GC analysis. Evidently, the kinetically favored (eq 1) allyloxy radical **19** (radical **3** of Scheme 1) is deoxygenated ( $k_p = 1.7 \times 10^9 \text{ s}^{-1} \text{ M}^{-1}$  for reaction of *tert*-butoxy radical with (EtO)<sub>3</sub>P at 28 °C<sup>8</sup>) to generate 1-indenyl radicals which are primarily reduced by *n*-Bu<sub>3</sub>SnH<sup>15</sup> to form indene (**17**). Use of an increased concentration of *n*-Bu<sub>3</sub>SnH in a one-pot reaction with higher phosphite concentration (5 M, Experimental Section, one pot – Method B, but with 0.6 M *n*-Bu<sub>3</sub>SnH) greatly reduced the yield of dimer **18** by trapping a higher percentage of 1-indenyl radicals. The amount of **15** (1%) formed was decreased. However, the net yield of indene (**17**, 74%) was not greatly increased, because side product **20**, from the free radical addition of *n*-Bu<sub>3</sub>SnH to indene (**17**), was formed in 11% yield (GC).



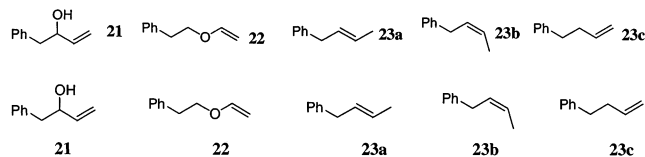
Under syringe-pump-addition conditions in the absence of (MeO)<sub>3</sub>P (low [*n*-Bu<sub>3</sub>SnH]), bromoepoxide **9** (**1**, R<sup>1</sup> = PhCH<sub>2</sub>, R<sup>2</sup> = H), which had not previously been studied, was converted exclusively (GC) to allyl alcohol (**21**) in 76% isolated yield, presumably via oxiranyl radical **2** (R<sup>1</sup> = PhCH<sub>2</sub>, R<sup>2</sup> = H) and allyloxy radical **3** (R<sup>1</sup> = PhCH<sub>2</sub>, R<sup>2</sup> = H). No peak assignable to allyl ether **22** (**5**, R<sup>1</sup> = PhCH<sub>2</sub>, R<sup>2</sup> = H) could be detected by GC/MS. In a carefully monitored one-pot reaction (Method B, but with no phosphite added, Table 1), the yield of allyl alcohol **21** was 93%.

Syringe-pump addition of a benzene solution of AIBN and *n*-Bu<sub>3</sub>SnH to a solution of bromoepoxide **9** in (MeO)<sub>3</sub>P as solvent (ca. 8 M) at 80 °C resulted in nearly quantitative deoxygenation of **3**. The resulting allyl radical **6** on reaction with *n*-Bu<sub>3</sub>SnH generated a mixture of isomeric alkenes (**23**)

- (14) Rearrangement of 1-indenol (**16**) to 1-indanone (**15**) has been previously reported under (1) weakly basic conditions: Friedrich, E. C.; Taggart, D. B. *J. Org. Chem.* **1975**, *40*, 720. Eisch, J. J.; Galle, J. E. *J. Org. Chem.* **1990**, *55*, 4835–4840; and (2) thermal and/or free radical conditions.<sup>13</sup>
- (15) Chatgililoglu, C.; Ingold, K. U.; Scaiano, J. C. *J. Am. Chem. Soc.* **1981**, *103*, 7739.



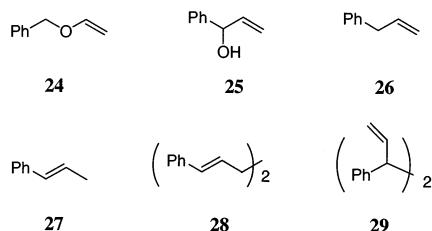
in high yield. In a one-pot version of the reaction (Method B, Table 1), a 95% total GC yield of three alkenes resulted (**23a**:**23b**:**23c** = 57:22:21). Alcohol **21** was present, but in less than 1% yield. Use of the sterically demanding H-transfer agent (TMS)<sub>3</sub>SiH afforded *trans*-**23** (**23a**) as the only alkene (92% GC yield) by regioselective reaction at the methylene terminus of the intermediate 1-methyl-4-phenylallyl radical (**6**, R<sup>1</sup> = PhCH<sub>2</sub>, R<sup>2</sup> = H).



For the reaction of bromoepoxide **8**, under conditions similar to those described for **9**, replacement of *n*-Bu<sub>3</sub>SnH by (TMS)<sub>3</sub>SiH (0.6 M) did not give an increased yield of indene (**17**, 46%). The yield of 1-indenyl radical dimer (**8**), however, was somewhat increased (47%).

**Debromodeoxygenation of Bromoepoxide 10.** In contrast to the exclusive formation of C–O scission products, **15** and **21**, from **8** and **9** in the absence of MeO<sub>3</sub>P, bromoepoxide **10** (R<sup>1</sup> = Ph, R<sup>2</sup> = H) was transformed under analogous syringe-pump-addition conditions almost exclusively to allyl ether **24** (R<sup>1</sup> = Ph, R<sup>2</sup> = H) in 85% isolated yield. In a parallel reaction (syringe pump) on a smaller scale, the yield of **24**, the thermodynamic C–C scission product, was 89% (GC). A minor amount of allyl alcohol **25** (4%) also was found. Nearly identical numbers were obtained in a one-pot variation of the reaction (Method B without phosphite, Table 1). The predominance of the C–C scission pathway in the reaction of **10** under similar, near-thermodynamic, thermal/AIBN conditions was reported previously in a very thorough study of this system.<sup>5</sup>

Added (MeO)<sub>3</sub>P (5 M) very rapidly traps intermediate **3** (R<sup>1</sup> = Ph, R<sup>2</sup> = H), formed by C–O scission of the intermediate oxiranylcarbiny radical **2** from **10**. (This scission has been clearly shown<sup>5</sup> to be the kinetically favored process for **2** with R<sup>1</sup> = Ph, R<sup>2</sup> = H; *k*<sub>1</sub>/*k*<sub>2</sub> = 4.2.<sup>5</sup>) Thus, a one-pot reaction of an argon-saturated benzene solution of **10** (0.015 M), *n*-Bu<sub>3</sub>SnH (0.03 M), a large excess of (MeO)<sub>3</sub>P (5 M), and a small amount of AIBN, heated at 80 °C until all bromoepoxide **10** was consumed (150 min), gave a much-reduced amount of vinyl ether **24** (18% vs 89% without phosphite, GC). Products that result from the *n*-Bu<sub>3</sub>SnH reduction or dimerization of allyl radical **26** (**6**, R<sup>1</sup> = Ph, R<sup>2</sup> = H) include (GC) alkene **27** (15%), and radical dimers **28** (41%) and **29** (14%). The trimethyl phosphite yield from a separate one-pot reaction (Method B, Table 1) was 82%. (See also Table 1 for yields of **24**, and **27**–**29**.)



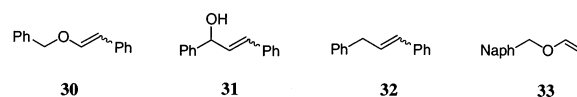
Attempts to maximize the yield of alkene **27** by increasing the concentrations of *n*-Bu<sub>3</sub>SnH (0.02, 0.04, 0.08 M) in one-

pot reactions at a high phosphite concentration (ca. 8 M) were unsuccessful. Dimer **28** was reduced in yield to 16%, but the yield of **27** did not exceed 13% (see Experimental Section).

**Dehalodeoxygenations of Haloepoxides 11, 12, and 13.** As noted above, it had been proposed earlier<sup>5</sup> that the reported<sup>12</sup> exclusive formation from certain other haloepoxides (**1**, R<sub>1</sub> = Ph, R<sub>2</sub> = Me; **11**, R<sup>1</sup> = 1-naphthyl, R<sup>2</sup> = H; and **12**, R<sub>1</sub> = R<sub>2</sub> = Ph) of the C–C scission product, that is, vinyl ether **5**, may be the result of working under close to thermodynamic conditions. Ziegler and Petersen further suggested<sup>5</sup> that under kinetic conditions, products from C–O cleavage might be encountered. *The above results indicate that (MeO)<sub>3</sub>P should be an excellent trap of intermediate 3 (Scheme 1) with which to test this postulate.*

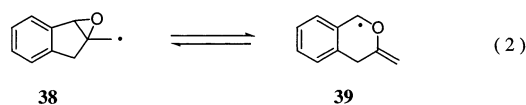
Under syringe-pump conditions in the absence of phosphite, slow addition of a 5 mL benzene solution of *n*-Bu<sub>3</sub>SnH (0.04 M) containing AIBN (6 mg) to 15 mL of a 7 mM solution of chloroepoxide **12** in benzene at reflux afforded vinyl ether **30** in 80% isolated yield as a mixture of two isomers in ratio 1.2/1.0. Alcohol **31** was not detected by GC analysis, a finding in agreement with an earlier report.<sup>12</sup> A one-pot reaction (Table 1, Method B, no phosphite) gave a 93% yield (GC) of vinyl ether **30** (*cis/trans* = 1.3). In contrast, when 5 mL of a 0.2 M benzene solution of *n*-Bu<sub>3</sub>SnH containing 6 mg of AIBN was added by syringe pump to 15 mL of a refluxed solution of **12** (7 mM) and excess (MeO)<sub>3</sub>P (2.6 M) in benzene, the isolated yield of vinyl ether **30** was reduced to 48%. In a GC-quantitated one-pot reaction with 5 M phosphite present (Table 1, Method B), GC yields for vinyl ether **30** were 23% *cis* and 29% *trans*. The deoxygenation product, alkene **32**, was formed in 34% GC yield (two isomers), along with a 49% yield of trimethyl phosphite.

In analogous fashion, in a one-pot reaction on a one millimole scale at the concentrations used for Method B (no phosphite), the previous report<sup>12</sup> that bromoepoxide **11** yields exclusively vinyl ether **33** (which we isolated in 73% yield) was confirmed. At low *n*-Bu<sub>3</sub>SnH concentration (0.005 M) in a smaller-scale one-pot reaction (Method B except for tin hydride concentration, no phosphite, Table 1), the GC yield of **33** was 92%. No GC/MS peak assignable to allyl alcohol **34** was seen.

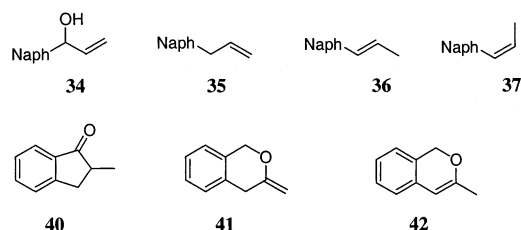


In the presence of 5 M trimethyl phosphite in a one-pot reaction (Method B, Table 1), the yield of vinyl ether (**33**) from bromoepoxide **11** was reduced to 43% (GC, Table 1). In addition, the three alkenes **35**, **36**, and **37** were seen but in only 3, 6, and 7% GC yields, respectively. Presumably, the low yields of alkenes are the result of the formation from the 1-naphthylpropenyl radical (**6**, R<sup>1</sup> = 1-naphthyl, R<sup>2</sup> = H) of large amounts of dimer, as is seen for the allyl radicals (**6**) from the parallel reaction of **10** (**28** and **29** formed). Such dimers from bromoepoxide **11** are no doubt too high boiling to be detected by gas chromatography.

Carbon–carbon scission (eq 2) of the oxiranylcarbiny radical (**38**) from bromoepoxide **13** (a bicyclic analogue of **10**) gives a methylene-bridged cyclic benzylic species (**39**) that is otherwise analogous to that from **10** (**4**, R<sup>1</sup> = Ph, R<sup>2</sup> = H). Column chromatography of a syringe-pump-addition reaction afforded

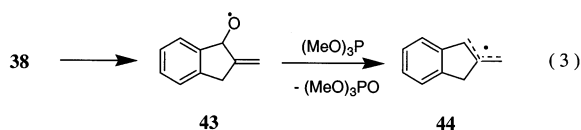


2-methyl-1-indanone (**40**) and vinyl ether **42** in 8 and 48% isolated yields, respectively. We determined in a quantitative one-pot reaction (no phosphite, Method B, but at low 0.005 M  $\text{Bu}_3\text{SnH}$ , Table 1) that indeed major amounts of two carbon-carbon scission products, vinyl ethers **41** (GC/MS evidence; 46%, GC) and **42** (38%, GC), were formed (Table 1). A lesser amount of C–O scission product, 2-methyl-1-indanone, **40** (12%, GC), that was not reported in the previous study,<sup>13</sup> also was seen. Vinyl ether **41** also was not found in the earlier research.<sup>13</sup> It seems likely that allyl ether **41** is formed initially and then is isomerized to **42** during isolation or otherwise destroyed, as **41** was not found on column chromatography.

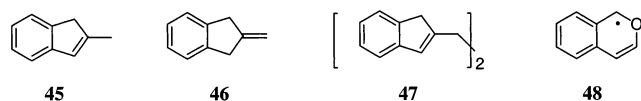


It had been suggested<sup>13</sup> that there is a 1,5-hydrogen shift in the benzylic allyloxycarbonyl radical precursor to vinyl ether **41** to form the isomeric allyl radical that yields vinyl ether **42**. Postulation of this unusual process appears to be unnecessary and unlikely in view of our finding that **41** is in fact formed. (See also Discussion.)

Excess  $(\text{MeO})_3\text{P}$  largely deoxygenates the allyloxy radicals, **43**, from **13** (eq 3). Alkenes **45** and **46** are the predominant



products from subsequent  $n\text{-Bu}_3\text{SnH}$  reduction of **44**. Thus, in a one-pot reaction (Method B, 0.02 M  $n\text{-Bu}_3\text{SnH}$ , Table 1), **45** and **46** were formed in 69% total GC yield ( $45/46 = 1.5$ ), along with about 1% of what appears to be **47** (GC/MS) generated by dimerization of the 2-methyl-1-indenyl radical (**44**, eq 3). Only 4% of 2-methyl-1-indanone (**40**) was formed. The combined yield of vinyl ethers **41** and **42** was reduced to 10% (83% overall product accountability). Presumably, terminal alkenes **41** and **46** would be found in somewhat higher amounts except for the relatively high concentrations of  $n\text{-Bu}_3\text{SnH}$  (0.02 M vs 0.005 M without phosphite) with which they most probably form adducts. Several unidentified side product peaks were seen by GC/MS.



#### Comparisons of Product Yields from Haloepoxides 8–13.

In Table 1, the yields of alcohol **3** and vinyl ether **5** from one-pot reactions, with and without trimethyl phosphite (Experimental Section, Method B), are compared for the series of

haloepoxides **8–13**. Also recorded are the yields of alkene **6** generated in the presence of 5 M phosphite. Table 2 lists yields of vinyl ether and phosphate from parallel reactions of haloepoxides **8**, **10**, and **11–13** under syringe-pump conditions with high concentrations of phosphite present (Experimental Section, Method A). In each table, all data are obtained at the same concentrations of reactants, except as noted.

Deoxygenation of allyloxymethyl radicals (**3**, Scheme 1) by trimethyl phosphite generates trimethyl phosphate and allyl radicals (**6**) that dimerize or are trapped by  $n\text{-Bu}_3\text{SnH}$  to give alkene. The yield of trimethyl phosphate formed should correspond to the fraction of **3** that is deoxygenated and be equal to the yield of alkene and other products of the allyl radical **6**. The yield of vinyl ether (**5**), in the absence of phosphite, measures the degree to which C–C scission occurs and the success of trapping of vinyloxy radical **4** by  $n\text{-Bu}_3\text{SnH}$  in competition with reformation of oxiranycarbonyl radical **2**. In theory, the yield of phosphate should equal the combined reduction in yields of vinyl ether **5** and allyl alcohol **7**. The total yield of phosphate plus **5** should be 100% if all **3** is trapped by high concentrations of phosphite such that no **7** is formed.

For Table 2, the sum of phosphate plus vinyl ether **5** ranges from 92 to 96%, except for the reaction of bromoepoxide **13**. Using the data in Table 1, we find that this quantity runs from 89 to 101%, except again for **13** which gives a sum of phosphate plus **5** (**41**, **42**) of 80%. As noted above, the yield of vinyl ether **41** from **13** was seen to be reduced at higher tin hydride concentrations, likely because of the susceptibility of the exocyclic double bond to radical addition reactions. The syringe-pump method keeps the tin hydride concentration very low and preserves a higher yield of vinyl ethers **41** and **42** (23% in Table 2), an effect noted in the earlier work<sup>5</sup> on the influence of  $n\text{-Bu}_3\text{SnH}$  concentration on the yields of products **24** and **25** from bromoepoxide **10**.

The phosphate and alkene yields in Table 1 are close to being equal for the reactions of bromoepoxides **9** and **13**. Moreover, if the yield of dimers is included for **10**, the yield of allyl radical **6** products rises to 75%, as compared to an 82% phosphate yield. For bromoepoxides **10** and **11**, as mentioned earlier, extensive allyl radical dimerization is expected, as is seen for **10**. Presumably, dimers abound for the allyl radicals from chloroepoxide **12** as well. As also noted above, in addition to indene (**17**) and 1-indenyl radical dimers **28** and **29**, **8** yields an indene/ $n\text{-Bu}_3\text{SnH}$  adduct (**20**) at higher concentrations of  $n\text{-Bu}_3\text{SnH}$ . Clearly, trimethyl phosphate yields are a much more reliable measure of the amount of deoxygenation of oxiranycarbonyl radical **3** than are the yields of alkene.

**Effects of Variations in  $n\text{-Bu}_3\text{SnH}$  and Phosphite Concentrations on Product Distributions.** The equilibria of Scheme 1, and the quantities of products formed thereby, may be strongly influenced by changes in concentrations of  $n\text{-Bu}_3\text{SnH}$  or  $(\text{MeO})_3\text{P}$  leading to variations in the yields of  $(\text{MeO})_3\text{PO}$ , vinyl ether **5**, and alcohol **7**. Differences in the effect of added phosphite from one haloepoxide to another (**10**, **11**, and **13**) may give insightful inferences concerning changes in the various rate constants of Scheme 1 as a function of structure.

(a) **Bromoepoxide 10.** In Table 3 are listed results that show the decrease in yield of vinyl ether **24** and parallel increase in phosphate yield with increased trimethyl phosphite concentration. The 0.04 M solution of  $n\text{-Bu}_3\text{SnH}$  was added under

**Table 3.** Effect of Trimethyl Phosphite Concentration on Formation of Vinyl Ether **24** and Trimethyl Phosphate on Debromodeoxygenation of **10** at 0.04 M *n*-Bu<sub>3</sub>SnH Concentration (Syringe-Pump Addition)<sup>a</sup>

| molar concentration of (MeO) <sub>3</sub> P | yield of <b>24</b> | yield of (MeO) <sub>3</sub> PO |
|---|--------------------|--------------------------------|
| 0   | 89                 | 0                              |
| 0.1   | 52                 | 17                             |
| 0.5   | 34                 | 50                             |
| 1.1   | 24                 | 57                             |
| 2.0   | 22                 | 66                             |
| 4.2   | 14                 | 72                             |
| 5.1   | 12                 | 76                             |
| 5.6   | 12                 | 81                             |
| 6.9   | 10                 | 82                             |
| 8.5   | 8                  | 82                             |

<sup>a</sup> Method C. 0.04 M *n*-Bu<sub>3</sub>SnH in benzene added to 0.02 M **10** in refluxed benzene containing trimethyl phosphite; (*n*-PrO)<sub>3</sub>PO internal standard.

syringe-pump-addition conditions to keep its concentration very low. The sum of the phosphate and vinyl ether **24** yields at 2.0 M phosphite concentrations and above is 86–92%. The continued increase in yield of **24** as phosphite concentration increases shows that the equilibrium of Scheme 1 continues to be drawn toward **3**.

In contrast, in one-pot reactions at a higher constant concentration of *n*-Bu<sub>3</sub>SnH (0.6 M), both phosphate (81%) and **24** (14%) yields become constant at 4.4 M phosphite concentrations and above (see Table 4, Supporting Information). Furthermore, at constant 5 M phosphite, no effect is seen of variation in *n*-Bu<sub>3</sub>SnH concentration in the range from 0.02 to 1.2 M (Table 5, Supporting Information; phosphate 81–82%, **24** 14–15%; sum 95–97%).

**(b) Bromoepoxide 11.** The phosphate and vinyl ether (**33**) yields from reaction of **11** at constant, 0.02 M *n*-Bu<sub>3</sub>SnH concentration in one-pot reactions with increasing phosphite concentrations also change dramatically (Table 6, Supporting Information). Phosphate yield gradually increases up to about 6 M phosphite (34% at 1.2 M, 55% at 6.2 and 7.8 M) along with a concomitant decrease from 84% in yield of **33** (56% at 1.2 M; 37% at 6.2 and 7.8 M). The yield of phosphate plus vinyl ether **33** is 90–93%.

Furthermore, with **11**, phosphate yields at high phosphite concentrations (7 M), over a 10-fold range (0.06–0.64 M) of concentration of *n*-Bu<sub>3</sub>SnH, remain constant (45–47%; Table 7, Supporting Information). The yield of vinyl ether **33**, however, decreases from 44 to 28%, most likely because of 1,2-addition of the hydride to **33**, and the combined yield of phosphate plus **33** decreases progressively from ca. 90% at 0.06 M *n*-Bu<sub>3</sub>SnH to 73% at 0.64 M tin hydride. Phosphite does not draw the equilibrium of Scheme 1 from **11** as far toward phosphate (45–47%) as it does the radical system from **10** (81–82% phosphate, Table 5 of Supporting Information).

**(c) Bromoepoxide 13.** The yields from bromoepoxide **13** of both phosphate (from 34 to 50%) and alkenes **45** and **46** (from 32 to 50%) increase on an increase in phosphite concentration (1.3–6.7 M) at a relatively high *n*-Bu<sub>3</sub>SnH concentration (0.06 M, Table 8 of Supporting Information; same conditions as for **10**, Table 4). A change in tin hydride concentration (0.02–0.60 M) at relatively high, 6.7 M phosphite decreases phosphate yield (70 to 50%), as well as the sum of **45** and **46** (69 to 50%); see Supporting Information, Table 9. Alkenes **45** and **46** were assayed, because vinyl ethers **41** and **42** are evidently consumed

by reaction with relatively high concentrations of tin hydride (see above, Table 8, Supporting Information). Thus, the combined yields of **41** and **42** are maximized at 84% in Table 1 in a reaction without phosphite that was run at low tin hydride (0.005 M). The yields of phosphate and alkene (Tables 8, 9 (Supporting Information)) are close to equal, as in theory they should be. The phosphate yields and combined yields of **45** and **46** from bromoepoxide **13**, at a relatively high tin hydride concentration (0.6 M), are nearly constant (47–50%) over the range 4.5–6.7 M phosphite. The same effect on phosphate and vinyl ether **24** yields was seen for **10** (Table 4, Supporting Information).

## Discussion

Except for **9**, the *n*-Bu<sub>3</sub>SnH/AIBN-initiated reactions of the haloepoxides (**8–13**) of this study have been investigated previously. However, only for **10** have quantitative investigations of products been carried out.<sup>5</sup> Also, as noted above, product indanone **40** from C–O scission of oxiranylcarbiny radical **38** was not found in the earlier study of the AIBN/*n*-Bu<sub>3</sub>SnH-initiated reaction of **13**<sup>13</sup> nor was allyl ether **41**. Furthermore, a systematic correlation of structure and product distribution (Tables 1 and 2) for the series **8** and **10–13** has not been attempted. The use of trimethyl phosphite as a trap for allyloxy radicals **3** is novel. Phosphite is shown to react rapidly enough with **3** from **11** and **12** to divert the equilibrium of Scheme 1 in favor of products of C–O scission as suggested previously<sup>5</sup> under conditions more nearly approaching kinetic control of product formation. The Results outlined above for haloepoxides **8–13**, including those for the new haloepoxide **9**, will be discussed in terms of the relation of product distribution to the energetics and rate constants of the reactions of Scheme 1.

Zeigler and Petersen<sup>5</sup> thoroughly examined the thermal *n*-Bu<sub>3</sub>SnH/AIBN-induced reaction of **10** (R<sup>1</sup> = Ph, R<sup>2</sup> = H) at various concentrations of tin hydride with *n*-Bu<sub>3</sub>SnH as sole trap of both radicals **3** and **4**. Their careful kinetic analysis, based on Scheme 1 (without phosphite), showed that the ratio of allyl alcohol (**7**) to vinyl ether (**5**) under conditions of thermodynamic control, that is, at very low tin hydride concentration, should correspond to the equation:

$$7/5 = (k_1/k_{-1})(k_{-2}/k_2)(k_3/k_4) \quad (4)$$

Expression (4) arises from simplification of the more general expression<sup>5</sup> (eq 5) under the assumptions  $[n\text{-Bu}_3\text{SnH}]k_3 \ll k_{-1}$  and  $[n\text{-Bu}_3\text{SnH}]k_4 \ll k_{-2}$ . Clearly, the ratio of products is

$$7/5 = (k_1k_3(k_{-2} + k_4[n\text{-Bu}_3\text{SnH}])) / (k_2k_4(k_{-1} + k_3[n\text{-Bu}_3\text{SnH}])) \quad (5)$$

affected by all six rate constants of Scheme 1. If, on the other hand, the concentration of *n*-Bu<sub>3</sub>SnH is such that  $[n\text{-Bu}_3\text{SnH}]k_3 \gg k_{-1}$  and  $[n\text{-Bu}_3\text{SnH}]k_4 \gg k_{-2}$ , the product ratio will be kinetically controlled, and eq 5 is simplified to eq 6.<sup>5</sup> However, as indicated below, purely kinetic or thermodynamic control

$$7/5 = k_1/k_2 \quad (6)$$

may not be operative for haloepoxides **8–13**.

With *n*-Bu<sub>3</sub>SnH as H-transfer agent,<sup>5</sup> the ratio  $k_3/k_4$  (Scheme 1) will be large in all cases, thus favoring formation of allyl alcohol **7**. This conclusion arises from the consideration of rate



constants for closely related reactions:  $k_3$  (*tert*-butoxy radical,  $2.2 \times 10^8 \text{ M}^{-1} \text{ s}^{-1}$  at 25 °C;  $4 \times 10^8 \text{ M}^{-1} \text{ s}^{-1}$  at 80 °C<sup>7</sup>); and  $k_4$  (at 20 °C, ethyl radical,<sup>15</sup>  $2.0 \times 10^6 \text{ M}^{-1} \text{ s}^{-1}$ ; benzyl radical,  $3.0 \times 10^5 \text{ M}^{-1} \text{ s}^{-1}$ ). In these systems, one moves toward nearly kinetic conditions by working at higher concentrations of *n*-Bu<sub>3</sub>SnH (eq 4) and/or (MeO)<sub>3</sub>P. However, strictly kinetic control (eq 6) was not observed in the kinetic study<sup>5</sup> of bromoepoxide **10**, even when the H-transfer agent *n*-Bu<sub>3</sub>SnH was used as solvent.

The success of trimethyl phosphite as a selective trap for allyloxy radicals (**3**, Scheme 1) is based on the fact that alkyl radicals, such as **4**, at best add reversibly to trimethyl phosphite to give phosphoranyl radical intermediates ([**4**-P(OMe)<sub>3</sub>]<sup>•</sup>) but fail to give product, because the subsequent β-scission of the phosphoranyl radical to yield product **4**-P(O)(OMe)<sub>2</sub> and methyl radical is too slow.<sup>3</sup> In contrast, alkoxy radicals, such as **3**, react by rapid, irreversible<sup>3</sup> addition to trimethyl phosphite (for *tert*-butoxy radical with (EtO)<sub>3</sub>P,  $k_p = 1.7 \times 10^9 \text{ M}^{-1} \text{ s}^{-1}$  at room temperature<sup>8</sup>). Deoxygenation of **3** occurs cleanly by subsequent irreversible β-scission of the phosphoranyl radical [**3**-P(OMe)<sub>3</sub>]<sup>•</sup> to give the relatively stable allyl radical **6** and highly stable trimethyl phosphate, readily assayed by GC. This reaction is severalfold faster than abstraction of hydrogen from *n*-Bu<sub>3</sub>SnH (for *tert*-ButO<sup>•</sup>,  $k_H = 2.0 \times 10^8 \text{ M}^{-1} \text{ s}^{-1}$  at 22 °C<sup>7</sup>). Furthermore, trimethyl phosphite is a relatively volatile liquid that even can be used neat as solvent (ca. 8 M). Thus, neat phosphate has a 30- to 1000-fold kinetic advantage in the interception of allyloxy radical **3** over tin hydride when the latter is present in the range of concentrations, 0.02–0.6 M, used in this research. Phosphate yields in these studies, therefore, account for essentially all of the trapping of **3** and need not be adjusted for alcohol formation. Control reactions showed at most 1–2% of phosphate to be formed in the absence of haloepoxide (see Results).

The results for **8**–**13** will be discussed in the order that allows them to be best correlated with the mechanism set forth in Scheme 1. Special emphasis is given to the first-time use of trimethyl phosphate as a trap of the allyloxy radical **3** (Scheme 1) and to the information gained thereby concerning the competition between the C–C and C–O scission for the series of oxiranylcarbinyl radicals (**2**) studied.

**Bromoepoxide 9.** Bromoepoxide **9** has not been studied previously. At modest *n*-Bu<sub>3</sub>SnH concentrations in the absence of (MeO)<sub>3</sub>P (Tables 1 and 2), bromoepoxide **9** (along with **8**) gives only the product of C–O scission of oxiranylcarbinyl radical **2**, that is, allyl alcohol **21**, in >90% yield. This outcome is predicted, on the basis of previous experimental studies<sup>5,9</sup> and calculations<sup>10,11</sup> for oxiranylcarbinyl radicals (**2**, R<sup>1</sup> = H or alkyl; R<sup>2</sup> = H or alkyl) that undergo potential scission to intermediates **3** and **4** when radical **4** is not resonance stabilized by a vinyl, naphthyl, or phenyl substituent. Calculated and experimentally estimated values for  $k_1$  near room temperature are in the range  $10^9$ – $10^{10} \text{ s}^{-1}$ . Thus, an experimental value for  $k_1$  of  $2 \times 10^{10} \text{ s}^{-1}$  at 25–30 °C has been measured for a case in which the carbinyl center of oxiranylcarbinyl radical **2** is tertiary.<sup>4</sup> It has been pointed out<sup>11,16</sup> that this value in fact may be low because  $k_1$  was determined under the assumption that step **2** → **3** (C–O scission) is irreversible, which has been shown generally not to be true.<sup>5,16–23</sup> For oxiranylcarbinyl radical **2**

with R<sup>1</sup> = R<sup>2</sup> = H, ab initio calculations<sup>11</sup> give at 25 °C:  $k_1 = 5.2 \times 10^9 \text{ s}^{-1}$  ( $E_a = 4.4 \text{ kcal/mol}$ );  $k_{-1} = 3.9 \times 10^8 \text{ s}^{-1}$  ( $E_a = 5.5 \text{ kcal/mol}$ );  $\Delta^\circ_{2-3} = -1.1 \text{ kcal/mol}$ ;  $k_2 = 1.5 \times 10^4 \text{ s}^{-1}$  ( $E_a = 12.1 \text{ kcal/mol}$ ); and, for  $k_{-2}$  ( $E_a = 15.9 \text{ kcal/mol}$ );  $\Delta^\circ_{2-4} = -3.8 \text{ kcal/mol}$ . At 70 °C, an experimental estimate<sup>5</sup> of  $k_{-1}$  (**3** → **2**) of  $2 \times 10^9 \text{ s}^{-1}$  has been made for the case R<sup>1</sup> = Ph, R<sup>2</sup> = H (radicals from **10**), which also is consistent with the reversibility of C–O scission (**2** ⇌ **3**). A phenyl R<sup>1</sup> substituent should not significantly perturb the value of  $k_1$ , which, therefore, should be applicable generally to cases, including **9**, where R<sup>1</sup> = H, alkyl, aryl and R<sup>2</sup> = H. For such cases, the C–O scission product, alcohol **21**, should be formed exclusively because  $k_1 \gg k_2$ .

It is arguable that for bromoepoxide **9**, C–C cleavage of oxiranylcarbinyl radical **2** occurs essentially irreversibly, because vinyloxy carbinyl radical **4**, once formed, is trapped by 0.02 M *n*-Bu<sub>3</sub>SnH. In contrast, trapping by 0.02 M *n*-Bu<sub>3</sub>SnH likely will not compete readily with reclosure of allyloxy radical **3** to **2**. Thus, theoretical calculations<sup>11</sup> for oxiranylcarbinyl radical **2** with R<sup>1</sup> = R<sup>2</sup> = H give  $k_2 = 1.5 \times 10^4 \text{ s}^{-1}$  ( $E_a = 12.1 \text{ kcal/mol}$ ). A value for  $k_{-2}$  ( $E_a = 15.9 \text{ kcal/mol}$ <sup>11</sup>) at 25 °C of  $30 \text{ s}^{-1}$  can be estimated from the difference (3.9 kcal/mol) in calculated<sup>11</sup>  $E_a$  values for  $k_2$  and  $k_{-2}$ , with the assumption that the preexponential  $A$  values are nearly the same for both processes. This means that at a concentration of *n*-Bu<sub>3</sub>SnH of 0.02 M (Table 1)  $k_4[n\text{-Bu}_3\text{SnH}] \gg k_{-2}$ , that is,  $(2 \times 10^6 \text{ M}^{-1} \text{ s}^{-1} \times (2 \times 10^{-2} \text{ M})) = 4 \times 10^4 \text{ s}^{-1} \gg 30 \text{ s}^{-1}$ , where  $k_H = 2 \times 10^6 \text{ M}^{-1} \text{ s}^{-1}$  is the rate constant for reaction of ethyl radical with *n*-Bu<sub>3</sub>SnH.<sup>15</sup> Furthermore, comparison of calculated and measured values of  $k_{-1}$  (calculated<sup>11</sup> for R<sup>1</sup> = R<sup>2</sup> = H,  $k_{-1} = 4 \times 10^8 \text{ M}^{-1} \text{ s}^{-1}$ ; experimentally estimated<sup>5</sup> for R<sup>1</sup> = Ph, R<sup>2</sup> = H,  $k_{-1} = 2 \times 10^9 \text{ M}^{-1} \text{ s}^{-1}$  at 70 °C) and  $k_3$  (calculated,<sup>11</sup>  $2 \times 10^8 \text{ M}^{-1} \text{ s}^{-1}$ ) shows that  $k_{-1} \gg k_3[n\text{-Bu}_3\text{SnH}]$ . Equation 5, therefore, is simplified at 0.02 M *n*-Bu<sub>3</sub>SnH to eq 7:

$$7/5 = k_1 k_3 [n\text{-Bu}_3\text{SnH}] / k_2 k_{-1} \quad (7)$$

Use of the calculated<sup>11</sup> rate constants listed above for R<sup>1</sup> = R<sup>2</sup> = H in eq 7 gives a predicted 7/5 ratio of  $>10^3$ , consistent with the exclusive formation of allyl alcohol **21** from bromoepoxide **9**.

It is intuitively obvious from the above considerations (Scheme 1;  $k_1 \gg k_2$ ,  $k_1 > k_{-1}$ ,  $k_2 \gg k_{-2}$ ) that trimethyl phosphite, especially at 1 M and above ( $k_p[\text{phosphite}] > k_{-1}$ ), should be an excellent trap for the allyloxy radicals **3** from bromoepoxide **9**. It is not surprising, therefore, that trimethyl phosphate is formed in high yields (Table 1, 5 M phosphite) to the near-exclusion of alcohol **21** and elimination of allyl ether **22**. At 5–8 M phosphite concentrations,  $k_p[(\text{MeO})_3\text{P}]$  is  $10^9$ – $10^{10} \text{ s}^{-1}$ , and deoxygenation should compete readily with reclosure of vinyloxy carbinyl radical **3** to allyloxy carbinyl radical **2** under conditions that begin to approach kinetic control. (As noted earlier, at room temperature, the rate of reaction<sup>5,6,8</sup> of *tert*-BuO<sup>•</sup> with (EtO)<sub>3</sub>P is  $k_p[(\text{EtO})_3\text{P}] = 5 \text{ M} \times 1.7 \times 10^9 \text{ M}^{-1} \text{ s}^{-1} = 8 \times 10^9 \text{ s}^{-1}$ , whereas the calculated<sup>11</sup>  $k_{-1} = 4 \times 10^8 \text{ s}^{-1}$  for R<sup>1</sup> = R<sup>2</sup> = H.)

(18) Nussbaum, A. L.; Wayne, R.; Yuan, E.; Zagmetko, O.; Oliveto, E. P. *J. Am. Chem. Soc.* **1962**, *84*, 1070.

(19) Rawal, V. H.; Iwasa, S. *Tetrahedron Lett.* **1992**, *33*, 4687.

(20) Galatsis, P.; Millan, S. D. *Tetrahedron Lett.* **1991**, *32*, 7493.

(21) Galatsis, P.; Millan, S. D.; Faber, T. *J. Org. Chem.* **1993**, *58*, 8, 1215.

(22) Sugimoto, H.; Wang, J. B. *J. Chem. Soc., Chem. Commun.* **1990**, 1629.

(23) Weinberg, J. S.; Miller, A. *J. Org. Chem.* **1979**, *44*, 4722.

(16) Ziegler, F. E.; Petersen, A. K. *J. Org. Chem.* **1995**, *60*, 2666.

(17) Amaudrut, J.; Wiest, O. *Org. Lett.* **2000**, *2*, 1251.

$n\text{-Bu}_3\text{SnH}$  at 0.02 M and greater should trap essentially all oxiranylcarbonyl radicals **2** that undergo C–C scission (see above). It is evident from the lack of formation of vinyl ether **22**, both with and without phosphite present, that C–C scission does not compete kinetically with C–O cleavage. This is as predicted by the calculated<sup>11</sup> ratio for  $k_1/k_2$  ( $>10^5$ ) for **2** with  $R^1 = R^2 = \text{H}$ .

**Haloepoxides 10 and 11.** These compounds differ from **9** in that the ring opening of **2** ( $R^1 = \text{Ph}$  or 1-naphthyl;  $R^2 = \text{H}$ ) by C–C scission yields a radical (**4**) which is stabilized by Ph or 1-naphthyl with potential kinetic and thermodynamic consequences. Compared to **9**, these compounds give reduced phosphate yields (**10**, 82%; **11**, 52%; 5 M phosphite, Table 1; **10**, 85%; **11**, 58%; 8 M phosphite, Table 2). This is in keeping with the formation from **10** and **11** in the absence of phosphite of very predominant amounts of vinyl ether (89% **24** from **10** and 92% **33** from **11**, Table 1), a process with which deoxygenation of **3** must compete when phosphite is added (Scheme 1). In the absence of phosphite, a small amount (4%) of alcohol **25** is formed from **10** which is consistent with earlier reports;<sup>5,17</sup> yet formation of alcohol **34** from **11** was not detected by GC/MS in our study or in the previous work.<sup>17</sup> Vinyl ether **33** formation from **11** in the absence of phosphite (Table 1) may have been enhanced by the very low  $n\text{-Bu}_3\text{SnH}$  concentrations (0.005 M) employed, which allows radical **3** ( $R^1 = 1\text{-naphthyl}$ ,  $R^2 = \text{H}$ ) of Scheme 1 to reclose to **2** to a greater extent than does its analogue from bromoepoxide **10**.

The changes in product distributions from **10** and **11**, as compared to those from **9**, can be readily understood in terms of the thermodynamics of the reactions of **2** and the rate constants of eq 7. For the oxiranylcarbonyl species (**2**) with  $R^1 = \text{H}$ ,  $R^2 = \text{Ph}$ , a stabilization of 5–7 kcal/mol has been calculated to be imparted by the phenyl group (benzylic type radical).<sup>16</sup> A similar stabilization is to be expected on phenyl substitution of the vinyloxymethyl radical **4** from **10** ( $R^1 = \text{Ph}$ ,  $R^2 = \text{H}$ ). The stabilization in **4** ( $R^1 = \text{Ph}$ ,  $R^2 = \text{H}$ ) will make the C–C scission for **2** → **4** about 10 kcal/mol exothermic ( $3.8^{11} + 6 = 10$  kcal/mol) and will necessarily result in a large decrease in the equilibrium expressed by  $k_{-2}/k_2$ . Moreover, the benzylic stabilization of **4** will be felt in the transition state for C–C scission greatly increasing  $k_2$ , but drastically reducing  $k_{-2}$ . The latter will compensate for a reduction in  $k_4$ , perhaps by a factor of 10 ( $k_{\text{H}}$  for reaction of benzyl radical with  $n\text{-Bu}_3\text{SnH}$ <sup>15</sup> is reduced to  $3.0 \times 10^5 \text{ M}^{-1} \text{ s}^{-1}$  at 20 °C), so that  $k_4[n\text{-Bu}_3\text{SnH}] \gg k_{-2}$ , as is required for eq 7 to be applicable. There should be little difference in  $k_1$  and  $k_{-1}$  for the radicals from **10** and **11** as compared to those from **9**. Thus,  $k_{-1} \gg k_3[n\text{-Bu}_3\text{SnH}]$ , which is the second requirement for eq 7 to apply.

The above makes understandable the difference in the calculated value<sup>11</sup> for  $k_1/k_2$  ( $3 \times 10^5$ ) for  $R^1 = R^2 = \text{H}$  (and presumably applicable to **9**) and  $k_1/k_2$  (4.2) determined experimentally<sup>5</sup> for **10** ( $R^1 = \text{Ph}$ ,  $R^2 = \text{H}$ ). Notably, radical **3** from **10** ( $R^1 = \text{Ph}$ ,  $R^2 = \text{H}$ ) still undergoes C–O scission several times more rapidly than it does C–C cleavage. Use of the experimental value<sup>5</sup> for  $k_1/k_2$  (4.2), along with the above estimated or calculated  $k_3$  and  $k_{-1}$  values and  $n\text{-Bu}_3\text{SnH}$  concentration of 0.02 M, allows calculation by eq 7 of **7/5** (**25/24**) percentage ratios of **7/93** and lower, depending on which of the temperature-dependent values of  $k_3$  and  $k_{-1}$  is used (based on *tert*-butoxy radical as a model: experimental<sup>15</sup>  $k_3$ ,  $2 \times 10^8$

$\text{M}^{-1} \text{ s}^{-1}$  at 22 °C;  $4 \times 10^8 \text{ M}^{-1} \text{ s}^{-1}$  at 80 °C; calculated<sup>11</sup> for **2** with  $R^1 = R^2 = \text{H}$   $k_{-1}$ ,  $4 \times 10^8 \text{ s}^{-1} \text{ M}^{-1} \text{ s}^{-1}$ ; experimental<sup>5</sup> for **2** with  $R^1 = \text{Ph}$ ,  $R^2 = \text{H}$   $k_{-1}$ ,  $2 \times 10^9 \text{ s}^{-1}$  at 70 °C). The value for **2** from **10** of  $k_1/k_2$  4.2 favors C–O cleavage. However, at the relatively low concentration of  $n\text{-Bu}_3\text{SnH}$  (0.02 M) of Table 1, conditions closer to thermodynamic control should prevail. The dominant amounts of allyl ether encountered in Table 1 and in previously reported research<sup>5</sup> are, therefore, predictable. Indeed, at closer to kinetic conditions (3.72 M  $\text{Bu}_3\text{SnH}$ ), a predominance of alcohol **25** (**7**) was reported (**25/24** = 1.94).<sup>5</sup>

In comparing the results from the reaction of **10** with those from **11**, it is significant that the 1-naphthylmethyl radical (1-naphthyl- $\text{CH}_2^*$ ) has been calculated<sup>24</sup> to be 14 kcal/mol more stable (resonance energy difference) than the benzyl radical. This energy difference can be applied to the oxiranylcarbonyl radicals, **2**, formed from bromoepoxide **11** (**4**,  $R^1 = 1\text{-naphthyl}$ ,  $R^2 = \text{H}$ ) and its benzylic counterpart from **10** (**4**,  $R^1 = \text{Ph}$ ,  $R^2 = \text{H}$ ). Consequently, for **2** from **11** ( $R^1 = 1\text{-naphthyl}$ ,  $R^2 = \text{H}$ ), C–C scission should be favored by about 18 kcal/mol ( $3.8^{11} + 14$  kcal/mol). The 1-naphthylmethyl-type radical (**4**) will be formed more rapidly as well (increased  $k_2$ ). Consequently,  $k_1/k_2$  will be decreased in the radical system from **11**, as compared to the 4.2 value<sup>5</sup> for **10**, as will  $k_{-2}/k_2$ . The greatly reduced value of  $k_{-2}$  will again make  $k_{-2} \ll k_4[n\text{-Bu}_3\text{SnH}]$  at 0.005 M  $n\text{-Bu}_3\text{SnH}$  (Table 1), even though  $k_4$  will doubtless be reduced from what it is with **2** from **10**. The condition  $k_{-1} \gg k_3[n\text{-Bu}_3\text{SnH}]$  will also apply, as will eq 7. The ring reclosures of the allyloxy radicals **3** from **10** and **11** (as well as from **9**) to regenerate **2** likely occur with very similar rate constants ( $k_{-1}$ ), as **2** is a primary radical in both instances. Together, these factors, and primarily an expected increase in  $k_2$  ( $k_1/k_2$  increased), account in terms of eq 7 for the now exclusive formation (Table 1) of vinyl ether **33** from **11**.

The ideas concerning the rate constants of Scheme 1 set forth in the preceding paragraphs are confirmed by the use of phosphite as a trap for radical **3** from **10** ( $R^1 = \text{Ph}$ ,  $R^2 = \text{H}$ ) and **11** ( $R^1 = 1\text{-naphthyl}$ ,  $R^2 = \text{H}$ ) and further illustrate its usefulness. Thus, at high concentrations of phosphite, large amounts of phosphate are encountered from **10** (82, 85%; Tables 1 and 2), although less than from **9**, and vinyl ether **24** is still formed (13, 8%; Tables 1 and 2). At a 5 M concentration of phosphite (Table 1), as stated above for **9**,  $k_{\text{p}}[\text{phosphite}] > k_{-1}$ , which also applies to **10** and **11**, because  $k_{-1}$  should be nearly the same for all three. Moreover, the reduced ratio of  $k_1/k_2$  for radical **2** from **10** ( $R^1 = \text{Ph}$ ,  $R^2 = \text{H}$ ) decreases the fraction of initial **2** that becomes available as **3** for deoxygenation by phosphite.

The equilibrium of Scheme 1 for the radicals from **11**, because of the stabilizing effect of the 1-naphthyl substituent on  $k_2$  and  $k_{-2}$ , lies even more in the direction of **4** than that from **10** and, therefore, is less readily diverted by phosphite toward phosphate formation. Consequently, at high phosphite concentrations, only moderate amounts of phosphate result from **11** (52, 58%; Tables 1, 2), which still affords a considerable yield of vinyl ether **33** (43, 34%; Tables 1 and 2).

**Haloepoxide 12.** The vinyloxy carbonyl radicals (**4**) from **10** ( $R^1 = \text{Ph}$ ,  $R^2 = \text{H}$ ) and **12** ( $R^1 = R^2 = \text{Ph}$ ), formed on C–C

(24) Calculated greater resonance energy of the 1-naphthylmethyl radical as compared to the benzyl radical: Herndon, W. C. *J. Org. Chem.* **1981**, *46*, 2119.



scission, possess essentially identical benzylic radical sites (Scheme 1). A key difference in these radical systems, however, is that for **12** the C–O scission of **2** to yield **3** sacrifices the benzylic resonance stabilization, which is then regained on presumably very rapid reclosure to **2** (increased  $k_{-1}$ ). As noted earlier, a recent calculation<sup>11</sup> predicts that phenyl substitution at the radical center of **2** with  $R^1 = H$ ,  $R^2 = Ph$  will stabilize **2** by 5–7 kcal/mol. This makes the conversion of **2** to **3** for the radical system from **12** ( $R^1 = R^2 = Ph$ ) endothermic by about 5 kcal/mol ( $\Delta H^\circ$  for  $2 \rightarrow 3$   $R^1 = R^2 = H$ , calculated<sup>11</sup> to be –1 kcal/mol) and renders  $(k_1/k_{-1}) < 1$ . However, conversion of **2** from **12** ( $R^1 = R^2 = Ph$ ) to **4** should still be favored by about 4 kcal/mol,<sup>25</sup> the same as is calculated<sup>11</sup> for the same interconversion with  $R^1 = R^2 = H$ , because a benzylic radical site is present in both **2** and **4** from **12**. Therefore,  $(k_{-2}/k_2) < 1$ .

Clearly, for **12**, the increase in  $k_{-1}$  in the now exothermic step  $3 \rightarrow 2$  renders  $k_{-1} \gg k_3[n\text{-Bu}_3\text{SnH}]$  at the concentration of  $n\text{-Bu}_3\text{SnH}$  of Table 1 (0.02 M). As for the allyloxy carbonyl radical **4** from bromoepoxide **10**,  $[n\text{-Bu}_3\text{SnH}]k_4 \gg k_{-2}$ . Therefore, eq 7 again applies. Under the conditions of Table 1, vinyl ether **30** (92%), not surprisingly, is the sole product. This is the result of (1) the very small value of  $k_1/k_{-1}$  (eq 7) associated with the favorable 5 kcal/mol exothermic step  $3 \rightarrow 2$ ; (2) little change in  $k_3$  from the other cases; and (3) a C–C scission step ( $k_2$ ) with energetics similar to those of  $2 \rightarrow 4$  for the radicals from **9**, but with increased  $k_2$  (resonance-stabilized transition state) such that the ratio  $k_1/k_2$  is reduced.

Because of the reduction in  $k_1$ ,  $k_1/k_{-1}$ , and  $k_1/k_2$  for **2** from **12**, as a result of the endothermicity of the formation of allyloxy radical **3**, not only is vinyl ether **30** the only product in the presence of  $n\text{-Bu}_3\text{SnH}$ , but, even at high concentrations, trimethyl phosphite will compete ( $[\text{phosphite}]k_p$ ) less well for radical **3** and its enhanced reclosure to **2** ( $k_{-1}$  increased). Most likely, the radical equilibrium of Scheme 1 ( $3 \rightleftharpoons 2 \rightleftharpoons 4$ ) lies in the direction of **4** and is not readily diverted toward deoxygenation of **3**. These factors result in the least efficient deoxygenation of **3** from **12** of the whole series of haloepoxides **8–13** (49% phosphate; 52% remaining vinyl ether **30**, Table 1; 42% phosphate, 42% **30**, Table 2). This contrasts, for example, to the very high diversion of **3** from **10** ( $R^1 = H$ ,  $R^2 = Ph$ ) to phosphate (82%) accompanied by much-reduced vinyl ether **24** (13%) formation (Table 1). As noted earlier, the rate constant ( $k_{-1}$ ) for reclosure of **3** to **2** has been measured<sup>5</sup> at 70 °C for the case  $R^1 = Ph$ ,  $R^2 = H$  ( $k_{-1} = 2 \times 10^9 \text{ s}^{-1}$ ) and calculated<sup>11</sup> for the case  $R^1 = R^2 = H$  ( $k_{-1} = 4 \times 10^8 \text{ s}^{-1}$ ). It seems likely that  $k_{-1}$  for **3** from **12**, as a result of the strong exothermicity of the process, may be on the order  $10^{10}–10^{11} \text{ s}^{-1}$ .

**Haloepoxide 13.** At first examination, the radical intermediates (Scheme 1) from **13** appear to be analogous to those from **10**, with **13** being merely a bicyclic version of **10**. Primary oxiranylcarbonyl radicals (**2**) are cleaved by C–O scission to allyloxy radicals (**3**) that are structurally analogous except for the cyclic nature of **43** from **13** (eq 3). Both oxiranylcarbonyl radicals (**2**) yield similar oxygen-substituted benzylic radicals, that is, **4** ( $R^1 = Ph$ ,  $R^2 = H$ ) from **10** and **39** from intermediate **38** (eq 2). Moreover, unlike C–C scission for **2** generated from **8** (see discussion of **8** to follow), there are no stereoelectronic

constraints on the C–C scission of radicals **2** from **10** or **13** (eq 2). Equation 7 would appear to apply to a discussion of product formation with both **10** and **13**. The products from **13**, formed at 0.005 M  $n\text{-Bu}_3\text{SnH}$  concentrations (Table 1), show a marginally larger proportion of C–O scission (12% vinyl alcohol-derived 2-methylindanone (**40**), 84% vinyl ethers **41** and **42**, 96% product accountability) as compared to those from **10** (4% alcohol **25** and 89% vinyl ether **24**, 94% product accountability). Furthermore, the formation of **41** and **42** (C–C scission) in the one-pot reaction of Table 1 from **13** is enhanced (eq 7) by the very low concentration of  $n\text{-Bu}_3\text{SnH}$  (0.005 M) employed. If run under the tin hydride concentration (0.02 M) conditions used for **10**, **13** likely would have given a greater amount of C–O scission product (**40**). The greater advantage of C–O scission with radical **2** from **10** is in fact seen in Table 2, where the syringe-pump addition technique keeps hydride concentration low in both cases with the vinyl ether yield (23%) from **13** being markedly greater than that from **10** (8%). The yields of phosphate follow those of the vinyl ethers.

Consistent with the above, deoxygenation of radical **3** ( $R^1 = Ph$ ,  $R^2 = H$ ) from **10** also is measurably easier than deoxygenation of **43** from **13** (eq 3), as judged by comparisons of the yields of phosphate (Tables 1 and, especially, 2). A possible explanation is that formation of **39** (eq 2) may be assisted somewhat kinetically by the fixed geometries about the developing benzylic radical center in **39** in which the benzene ring is optimally prealigned to conjugate with the developing carbon radical center. In contrast, phenyl stabilization of the C–C scission of **3** from **10** ( $R^1 = Ph$ ,  $R^2 = H$ ) requires a kinetically unfavorable loss of entropy (rotational freedom) in the transition state.

**Bromoepoxide 8.** The oxiranylcarbonyl radical **2** formed from **8** that opens to an allyloxy radical **19** (eq 1) that is benzylic and is likely stabilized by 5–7 kcal/mol, based on calculations noted earlier for the stabilization of the oxiranylcarbonyl radical with  $R^1 = H$ ,  $R^2 = Ph$ ,<sup>17</sup> just as is radical **2** ( $R^1 = R^2 = Ph$ ) from **12** ( $R^1 = R^2 = Ph$ ) discussed above. As with **2** from **12**, formation of **19** should be about 5 kcal/mol unfavorable because the benzylic stabilization is lost (eq 1). However, like the radical (**4**) from C–C scission of **2** from **12** ( $R^1 = R^2 = Ph$ ), **48** retains benzylic stabilization. Therefore, its formation from **2** should still be favored by about 4 kcal/mol, the energy change calculated<sup>11</sup> for unsubstituted **2** and **4** with  $R^1 = R^2 = H$  and, as stated above, assumed for  $2 \rightarrow 4$  for the radicals from **12** for which both **2** and **4** are phenyl-substituted ( $R^1 = R^2 = Ph$ ). This radical system at 0.02 M tin hydride concentrations, therefore, would be expected to behave like that from **12** (which gives only enol ether **30**) and yield exclusively enol ether **14**.

However, carbon–oxygen scission to give **19** (eq 1) and ultimately **15** (91%, Table 1, by rearrangement<sup>14</sup> of first-formed allyl alcohol **16**), although endothermic, occurs to the exclusion of vinyl ether **14**, as reported previously.<sup>13</sup> It has been suggested<sup>13</sup> that the thermodynamically favored ring-opening C–C cleavage of the oxiranylcarbonyl species (**2**) of eq 1 to benzylic radical **48** is disfavored kinetically by stereoelectronic factors ( $k_1 \gg k_2$ , Scheme 1). Thus, ring constraints prevent the proper alignment of the SOMO on carbon in **2** with the C–C bond to be cleaved, a geometric requirement also noted for the  $\beta$ -scission of other radicals.<sup>26</sup>

(25) The difference in energy between **2** with  $R^2 = H$  and **4** with  $R^1 = H$  is calculated to be about 4 kcal/mol.<sup>11</sup> This difference should remain when a phenyl group is substituted in place of hydrogen at the radical sites of **2** ( $R^2 = Ph$ ) and **4** ( $R^1 = Ph$ ), as it does in the radical system from **12**.

As a result, high activation energies should be associated with both  $k_2$  and  $k_{-2}$  for  $\mathbf{2} \rightleftharpoons \mathbf{48}$  as they are<sup>11</sup> for  $\mathbf{2} \rightleftharpoons \mathbf{4}$  from bromoepoxide  $\mathbf{9}$ . The latter is a C–C scission process for which the transition state is not resonance stabilized. In the absence of phosphite, eq 7 likely applies to the radicals from  $\mathbf{8}$ , as was argued earlier for those from  $\mathbf{9}$ . As with  $\mathbf{9}$ , kinetically favored C–O scission ( $k_1 > k_2$ ) to give  $\mathbf{19}$  (eq 1) is thermodynamically less favored than C–C scission to give  $\mathbf{48}$ .

However, unlike  $\mathbf{2} \rightleftharpoons \mathbf{3}$  for  $\mathbf{9}$  ( $R^1 = \text{PhCH}_2$ ,  $R^2 = \text{H}$ ), reformation of  $\mathbf{2}$  from  $\mathbf{19}$  (eq 1), following C–O scission, is both kinetically and thermodynamically favored ( $k_{-1} > k_1$ ). Trapping of  $\mathbf{19}$  by 0.02 M tin hydride (Table 1) to yield  $\mathbf{15}$  (from  $\mathbf{16}$ ), to the exclusion of vinyl ether  $\mathbf{14}$ , stems largely from the small value of  $k_2$  ( $k_1 \gg k_2$ , eq 7) and despite the fact that  $k_{-1} > k_1$  (eq 7).

Allyloxy radical  $\mathbf{19}$ , formed kinetically from radical  $\mathbf{2}$  from  $\mathbf{8}$  (eq 1), is also efficiently trapped by phosphite (Tables 1, 89%, and 2, 96%) such that  $\mathbf{8}$ , along with  $\mathbf{9}$ , affords trimethyl phosphate in the highest yields observed (Tables 1 and 2). As noted above, it is very likely that phosphite ( $k_p[\text{phosphite}]$ ) at 5–8 M concentrations (Tables 1 and 2) in many instances competes successfully with  $k_{-1}$  for reclosure of  $\mathbf{3}$  to give  $\mathbf{2}$  (Scheme 1). Moreover, the exothermic reclosure of  $\mathbf{19}$  (eq 1) should be even faster than that for  $\mathbf{3} \rightarrow \mathbf{2}$  for  $R^1 = \text{Ph}$ ,  $R^2 = \text{H}$  from bromoepoxide  $\mathbf{10}$ , which was found experimentally<sup>5</sup> to be  $2 \times 10^9 \text{ s}^{-1}$  at 70 °C. The high yield of phosphate from  $\mathbf{8}$  in both Tables 1 and 2 (like the high yield of  $\mathbf{15}$  in its absence) doubtless is in part dependent on the trapping of  $\mathbf{19}$  formed by reopening of oxiranycarbonyl radicals (eq 1).

Allyl radical reduction product indene ( $\mathbf{17}$ ) and indenyl radical dimer,  $\mathbf{18}$ , account for the majority of the radical products of deoxygenation of  $\mathbf{19}$ . The failure of phosphite to totally prevent formation of allyl alcohol  $\mathbf{15}$  (4%  $\mathbf{15}$ , Table 1) is likely the result of the rapid reclosure of  $\mathbf{19}$  to benzylic radical  $\mathbf{2}$  (eq 1;  $k_{-1}/k_1 > 1$ ) and its trapping by tin hydride.

**Effects of *n*-Bu<sub>3</sub>SnH and (MeO)<sub>3</sub>P Concentration Changes on Product Distribution.** Changes in product distributions from haloepoxides  $\mathbf{8}$ ,  $\mathbf{10}$ , and  $\mathbf{13}$  on increasing phosphite and/or *n*-Bu<sub>3</sub>SnH concentrations (Results and tables discussed therein) reflect readily understandable influences of structure on the radical equilibria of Scheme 1. In general, the ease of shift of products in the direction of deoxygenation by increased phosphite concentration is determined by the same rate constant scenario that leads to an increase in ratio  $\mathbf{7}/\mathbf{5}$ , (alcohol)/(vinyl ether), especially increased  $k_1$  and decreased  $k_2$ .

**(a) Bromoepoxide  $\mathbf{10}$ .** The extremely low effective concentration of hydride under syringe-pump addition conditions for  $\mathbf{10}$  (Table 3) likely does not prevent reclosure of  $\mathbf{4}$  and  $\mathbf{3}$  to  $\mathbf{2}$  ( $k_{-2} \gg k_4[n\text{-Bu}_3\text{SnH}]$ ;  $k_{-1} \gg k_3[n\text{-Bu}_3\text{SnH}]$ ). In the absence of phosphite, nearly thermodynamic control conditions (eq 4) for trapping of  $\mathbf{3}$  and  $\mathbf{4}$  by *n*-Bu<sub>3</sub>SnH apply with vinyl ether  $\mathbf{24}$  as the dominant product (89%) as found previously<sup>5</sup> at low tin hydride concentrations. The yield of vinyl ether  $\mathbf{24}$  decreases progressively from 89 to 8% in response to the presence of phosphite in increasing concentrations, as the equilibrium of Scheme 1 is drawn toward  $\mathbf{3}$  and its deoxygenation. Perhaps unexpectedly, the phosphate yield does eventually level off. At

a sufficient concentration of both phosphite (4.4 M or greater) and tin hydride (0.02 M or greater) in one-pot reactions, the amounts of vinyl ether  $\mathbf{24}$  and trimethyl phosphate reach constant values and high accountabilities, 14 and 81%, respectively (Tables 4 and 5, Supporting Information).

The ratio of (phosphate)/(vinyl ether  $\mathbf{24}$ ),  $81/14 = 5.8$ , is reasonably close to the ratio of  $k_1/k_2$  (4.2) reported earlier,<sup>5</sup> which was based on a careful kinetic analysis of the variation in allyl alcohol/vinyl ether ( $\mathbf{25}/\mathbf{24}$ ) with concentrations of *n*-Bu<sub>3</sub>SnH. In the range of concentrations of tin hydride employed in the published report (0.06–3.7 M),<sup>5</sup> the  $\mathbf{25}/\mathbf{24}$  ratio did not become constant but was maximized at 1.94. Clearly, the conversion from thermodynamic control of the competition (eq 4) to kinetic control (eq 6) in which reversal of both C–C and C–O scission no longer occurs ( $k_3[n\text{-Bu}_3\text{SnH}] \gg k_{-1}$ ;  $k_4[n\text{-Bu}_3\text{SnH}] \gg k_{-2}$ ) had not been accomplished<sup>5</sup> at 3.7 M *n*-Bu<sub>3</sub>SnH concentration ( $(\mathbf{25})/(\mathbf{24}) = 1.9$  vs  $k_1/k_2 = 4.2$  for kinetic control). The asymptotic approach to constant (phosphate)/ $\mathbf{24}$  seen at high concentrations of phosphite and tin hydride (Tables 4 and 5, Supporting Information) suggests that both  $\mathbf{3}$  and  $\mathbf{4}$  become efficiently and near-irreversibly trapped, and more than coincidentally the ratio (phosphate)/ $\mathbf{24}$  of 5.8 approximates the previous value for  $k_1/k_2$  (4.2). Clearly, the data of this paper show C–O scission ( $k_1$ ) to be kinetically favored over the C–C ( $k_2$ ) process, as previously determined.<sup>5</sup>

It should be reiterated that  $k_{-1}$  for the conversion  $\mathbf{2} \rightarrow \mathbf{3}$  for bromoepoxide  $\mathbf{10}$  ( $R^1 = \text{Ph}$ ,  $R^2 = \text{H}$ ) has been estimated experimentally<sup>5</sup> to be  $2 \times 10^9 \text{ s}^{-1}$  at 70 °C. Furthermore,  $k_p$  experimental<sup>8</sup> for reaction of (EtO)<sub>3</sub>P with *tert*-BuO• at room temperature is  $1.7 \times 10^9 \text{ M}^{-1} \text{ s}^{-1}$ , making the rate of deoxygenation with 6–8 M phosphite at 80 °C  $> 10^{10} \text{ s}^{-1}$ . Arguments for the irreversible trapping of the benzylic type radical  $\mathbf{4}$  from  $\mathbf{10}$  ( $R^1 = \text{Ph}$ ,  $R^2 = \text{H}$ ) by *n*-Bu<sub>3</sub>SnH at concentrations 0.02 M and above were made earlier in this paper.

**(b) Bromoepoxide  $\mathbf{11}$ .** At a constant tin hydride concentration of 0.02 M (Table 6, Supporting Information), the yield of phosphate levels out on increase in phosphite concentration at about 55% at ca. 6 M phosphite concentration, a comparatively smaller number than what was seen with  $\mathbf{10}$  (82%) at 0.02 M *n*-Bu<sub>3</sub>SnH and above (Table 5). Furthermore, to attain a constant phosphate yield (45%) from  $\mathbf{11}$  at 7 M phosphite, on increasing tin hydride concentration, the latter must be 0.06 M or greater (Table 7), somewhat higher than that required for the radical system from  $\mathbf{10}$  (0.02 M, Table 5).

As noted above, the expected increased  $k_2$  and reduced  $k_{-2}$  values for the intermediates from  $\mathbf{11}$ , as compared to those from  $\mathbf{10}$ , account for the exclusive formation from  $\mathbf{11}$  of vinyl ether  $\mathbf{33}$  (92%, Table 1) at low tin hydride concentration (eqs 4 and 7) in the absence of phosphite. They also predict that, as observed, the radical system (Scheme 1) from  $\mathbf{11}$  should be less readily perturbed away from formation of vinyl ether  $\mathbf{33}$  toward  $\mathbf{3}$  and its deoxygenation by increasing concentrations of phosphite. The data for  $\mathbf{11}$  are less-well behaved than those for  $\mathbf{10}$  (Tables 3–5). Nonetheless, it is clear that radical  $\mathbf{2}$  ( $R^1 = 1\text{-naphthyl}$ ,  $R^2 = \text{H}$ ) from  $\mathbf{11}$  gives a considerably larger proportion of initial C–C cleavage than does  $\mathbf{2}$  ( $R^1 = \text{Ph}$ ,  $R^2 = \text{H}$ ) from  $\mathbf{10}$ , that is,  $k_2(\mathbf{11}) > k_2(\mathbf{10})$ . If trapping of  $\mathbf{3}$  and  $\mathbf{4}$  from  $\mathbf{11}$  approaches irreversibility (kinetic control), the data

(26) Beckwith, A. L. J.; Easton, C. J.; Serlis, A. K. *J. Chem. Soc., Chem. Commun.* **1980**, 482. Friedrich, E. C.; Holmstead, R. L. *J. Org. Chem.* **1972**, *37*, 2550. Dauben, W. G.; Wolf, R. E.; Deviny, E. J. *J. Org. Chem.* **1969**, *34*, 2512.

suggest that  $k_1/k_2$  is closer to 1, rather than the 4.2 ratio found<sup>5</sup> for the radicals from **10**.

The suggestion of Ziegler and Petersen<sup>5</sup> that C–O cleavage products from **11** and **12** might be seen under conditions that approach kinetic control is in fact realized for the first time in our studies of **11** and **12** at high phosphite concentrations. However, unlike what is seen with **10**, the predominance of the reaction of **11** or **12** (Tables 1 and 2), via **3** and its deoxygenation, is not observed, even at highest phosphite concentrations.

(c) **Bromoepoxide 13**. The effects of increasingly high phosphite or *n*-Bu<sub>3</sub>SnH concentrations on the reaction of **13** parallel what is seen with **10** (Tables 8 and 9, Supporting Information). However, the asymptotic phosphate yield from **10** was about 80% as compared to the 50% value for **13**. Following the arguments made earlier for **10** and **11**, it appears that  $k_1/k_2$  for the radicals from **13** may be reasonably close to 1, similar to that for **11**. This is consistent with the arguments made above that rationalize the somewhat greater propensity of oxiranylcarbonyl radical **38** to isomerize to **39** (eq 2) than that of the analogous radical **2** ( $R^1 = \text{Ph}$ ,  $R^2 = \text{H}$ ) from **10** to undergo C–C scission to its vinyloxy carbonyl radical **4**. It appears that being closer to kinetic control is realized in the system from **13** (i.e., irreversible trapping of radicals from C–C and C–O scission) at high concentrations of both phosphite and 0.6 M tin hydride than when the *n*-Bu<sub>3</sub>BuH concentration is only 0.02 M, even at high concentrations of phosphite.

**Alkenes from Haloepoxides 8–13**. Precursors **8**, **9**, and **13** give the highest yields of alkenes: 73, 95, and 69%, respectively (Table 1), which is in line with the accompanying high yields of trimethyl phosphate found, especially for **8** and **9**. Although the defunctionalization of a haloepoxide to form an alkene would likely be of synthetic use only in highly specialized instances, the yield from **9** of **23** as a single, regio-, and stereoisomer (*trans*-**23a**), when (TMS)<sub>3</sub>SiH is employed,<sup>27</sup> is high (92%). Evidently, the sterically highly hindered silane transfers hydrogen to allyl radical **6** ( $R^1 = \text{PhCH}_2$ ,  $R^2 = \text{H}$ ) at the primary carbon terminus in a fashion to generate only the *trans* 2-alkene.

As indicated by the reactions of the other haloepoxides of this study, regioselective, high-yield formation of alkene will occur only when allyloxy radical **3** is the kinetically favored scission product from oxiranylcarbonyl radical **2**, and the allyl radical **6** is sufficiently reactive to be rapidly trapped by the sterically hindered silane ((TMS)<sub>3</sub>SiH). In this regard, the 1-indenyl radical, generated in the radical system from **8**, is evidently too stable to be readily reduced to indene (**17**) by (TMS)<sub>3</sub>SiH (indene yield 47%, see Results), although 0.02 M *n*-Bu<sub>3</sub>SnH (Table 1) gives a reasonably good yield of indene (73%). However, indene yields at high concentrations of tin hydride, as noted earlier, are reduced by the formation of tin hydride-indene adduct **20**.

Bromoepoxide **13** also yields a relatively large amount of alkene (**45**, **46**, 69%, Table 1) in the presence of phosphite at 0.02 M *n*-Bu<sub>3</sub>SnH concentration. (TMS)<sub>3</sub>SiH was not employed in this system but would be expected to react regioselectively with radical **44** to give 2-methylindene (**45**). However, allyl radical **44** (eq 3) may not react sufficiently rapidly with the silane to give a high yield of **45**.

## Conclusions

Quantitative product studies for the thermal AIBN/*n*-Bu<sub>3</sub>SnH-induced radical reactions of **8**, **9**, **11**, and **13** at low concentrations of tin hydride are reported (Table 1) for the first time. Consideration of the potential effects of variation in the structure ( $R^1$  and  $R^2$ ) of intermediates **2–4** on the thermodynamics and kinetics (eqs 4–7) of the reactions of Scheme 1 leads to reasonable structure/product correlations. The formation of **40** and **41** from **13** had not previously been reported. It is proposed that **41** is isomerized to **42** under the reaction conditions which avoid the unusual rearrangement of radical **39** previously proposed.

Trimethyl phosphite is found to be a very efficient and selective trap for the allyloxy radicals (**3**) of Scheme 1 to divert the equilibria of Scheme 1 toward the deoxygenation ( $k_p$ ) of **3** to give allyl radical **6** and trimethyl phosphate. Radical **6** dimerizes or is trapped by *n*-Bu<sub>3</sub>SnH to form alkenes. The dehalodeoxygenations of **8**, **9**, and **13** afford alkenes in 73, 95, and 69% yields, respectively (Table 1), along with 89, 97, and 70% yields of trimethyl phosphate. Yields of vinyl ethers (**5**) formed from haloepoxides **10–13** also are markedly diminished by added phosphite. The amounts of trimethyl phosphate, **5**, and **7** (Tables 1 and 2), formed at high concentrations of phosphite, vary systematically with changes in radical structure in a fashion consistent with predictable trends in the rate constants and thermodynamics for the individual reactions of Scheme 1. This is particularly true for the C–O ( $k_1$ ) and C–C ( $k_2$ ) cleavages of intermediate **2**, to form radicals **3** and **4**, and their reversal to regenerate **2**. Deoxygenation of **3** is especially efficient for the radical systems from **8** and **9** which give alcohol **7** to the exclusion of allyl ether **5** in the absence of phosphite. Notably, the diversion and deoxygenation of the allyloxy radicals **3** from **11** and **12** by trimethyl phosphite fulfill the prediction of Ziegler and Petersen<sup>5</sup> that, under conditions closer to kinetic control, **11** and **12** may afford products of C–O scission. Use of varying amounts of trimethyl phosphite and *n*-Bu<sub>3</sub>SnH with **10** gave product trends (phosphate/vinyl ether) consistent with a  $k_1/k_2$  ratio of approximately 5.8, which is reasonably consistent with the reported value of 4.2<sup>5</sup> determined with *n*-Bu<sub>3</sub>SnH alone as a radical trap. For **2** from **11** and **13**,  $k_1$  and  $k_2$  appear to be nearly equal. Nonetheless, even when intermediate **4** is stabilized by a 1-naphthyl substituent (**4** from **12**), C–O scission is kinetically at least competitive with C–C scission, as revealed by trapping of **3** by trimethyl phosphite.

## Experimental Section

**General.** Reactions were performed under Ar or N<sub>2</sub> atmosphere. For air-sensitive compounds, standard Schlenk techniques were used. Chemicals were obtained from Fluka, Aldrich, and ARCOS and used as purchased. All solvents were dried according to literature methods. Silica gel (Gel 60, 230–400 mesh ASTM) for column chromatography was purchased from EM Science. GC analyses were performed on a temperature-programmed, FID-equipped Hewlett-Packard HP 5890 instrument with a DB-1 Ultra capillary column. NMR spectra were recorded on Varian XL300 and XVR300 spectrometers [<sup>1</sup>H, 300 MHz; <sup>13</sup>C, 75 MHz]. <sup>1</sup>H and <sup>13</sup>C chemical shifts are given in  $\delta$  (ppm) relative to internal Si(CH<sub>3</sub>)<sub>4</sub>  $\delta$  (0.00 ppm). Electron ionization (70 eV) GC/MS data were acquired on a Hewlett-Packard 5971A Mass Selective Detector model 5971A instrument, equipped with an HP 5890 Series II gas chromatograph. Melting points were measured on a Thomas-Hoover apparatus and are uncorrected.

(27)  $k_H$  for (Me<sub>3</sub>Si)<sub>3</sub>SiH at 24 °C is  $1.1 \times 10^8$ . Chatgililoglu, C.; Rossini, S. *Bull. Soc. Chim. Fr.* **1988**, 298.



**Systematic Study of Dehalodeoxygenation of Oxiranylcarbinyl Radicals by (MeO)<sub>3</sub>P, Method A.** A solution of tributyltin hydride (58 mg, 0.20 mmol), internal standard (*n*-PrO)<sub>3</sub>P(O) (0.1 mmol), and AIBN (6 mg) in 5 mL of benzene (deoxygenated by purging with Ar for 20 min) was added by a syringe pump into a solution of a haloepoxide (0.1 mmol) in neat trimethyl phosphite (10 mL, 80 mmol) over a 5 h period. (The phosphite had been carefully distilled just before use to remove all phosphate, GC evidence.) Reflux was continued for another 2 h, after which the yields of trimethyl phosphate and vinyl ether were measured by GC. An otherwise identical control reaction without added tin hydride produced only a 1–2% yield of trimethyl phosphate, based on haloepoxide.

**Systematic Study of Dehalodeoxygenation of Oxiranylcarbinyl Radicals by (MeO)<sub>3</sub>P, Method B.** Under argon, *n*-Bu<sub>3</sub>SnH (58 mg, 0.20 mmol, 0.020 M), AIBN (7 mg), trimethyl phosphite (5 M final concentration), the haloepoxide (0.1 mmol), and internal standard (*n*-C<sub>3</sub>H<sub>7</sub>O)<sub>3</sub>PO, 1 mL, 0.1 M solution) were added to a volumetric flask and then diluted with benzene to 10 mL. (The phosphite had been carefully distilled before use to remove all phosphate, GC evidence.) The solution was transferred to an ampule, subjected to four freeze–thaw vacuum degassings (high vacuum/liquid nitrogen), flame-sealed, and then held at 80 °C for at least 5 h and sometimes overnight. The yields of trimethyl phosphate, alkene, vinyl ether, and/or allyl alcohol were determined by GC. A control reaction run under the same conditions but without substrate gave a yield of trimethyl phosphate of 1–2% based on haloepoxide.

**Debromodeoxygenation of 10 at Different Phosphite Concentrations, Syringe-Pump Addition, Method C.** A 5 mL solution of *n*-Bu<sub>3</sub>SnH (58 mg, 0.20 mmol), AIBN (6 mg), tri-*n*-propyl phosphate (1 mL of 0.1 M solution, 0.1 mmol), and a known amount of trimethyl phosphite was added by a syringe pump to a refluxed, 5 mL solution of **10** (21 mg, 0.10 mmol) in benzene containing the same concentration of trimethyl phosphite. The yields of **24** and trimethyl phosphate were determined by GC analysis. A control reaction, run under identical conditions, but without substrate **10**, gave a 1–2% phosphate yield.

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**Supporting Information Available:** Preparations of **9**, **18**, **20**. Rearrangements of haloepoxides **8–13**. Deoxyhalogenations of **8–13**. Product identification and quantitation for Tables 1–3, one-pot and syringe-pump conditions. Quantitative effects of (MeO)<sub>3</sub>P and *n*-Bu<sub>3</sub>SnH concentrations (Tables 4–9). Methods A–F (PDF). This material is available free of charge via the Internet at <http://pubs.acs.org>.

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