β-Stannyl Allylic Alcohols through Photooxygenation (Schenck Reaction) of Vinylstannanes and Reduction of the Resulting Allylic Hydroperoxides: Synthesis and Selected Transformations

Waldemar Adam* and Peter Klug

Institute of Organic Chemistry, University of Würzburg, Am Hubland, D-97074 Würzburg, Germany

Received December 21, 1993®

β-Stannyl allylic alcohols **2** were prepared regioselectively by photooxygenation (Schenck reaction) of the vinylstannanes **1** and subsequent reduction of the resulting allylic hydroperoxides by sodium borohydride. This novel methodology makes the hitherto unknown oxyfunctionalized cyclic vinylstannanes conveniently accessible, which constitute valuable building blocks in organic synthesis. For example, palladium-catalyzed coupling of these vinylstannanes **2** with allylic and vinylic halides produced the β-substituted allylic alcohols **3** in good yields. Tin–lithium exchange directly on the oxyfunctionalized vinylstannanes **2** afforded the corresponding lithio dianions, which on reaction with aldehydes led to the allylic diols **4**. Furthermore, iododestannylation of the β-stannyl allylic alcohols **2** gave the respective vinyl iodides **5**.

Introduction

The singlet oxygen ene reaction (the Schenck reaction[1]) has been shown to be a powerful method for the allylic oxyfunctionalization of alkenes. Unfortunately, the low regioselectivity, especially for alkyl-substituted olefins, which leads to difficult-to-separate isomeric hydroperoxides, encumbers severely the preparative utility of this method. This problem can in part be avoided by attaching steering groups to the olefinic double bond, as it has been demonstrated for a variety of electron-withdrawing groups.[2] Such acceptor-substituted alkenes generally give high *gem* selectivity in the photooxygenation reaction, but at the price of substantial loss of reactivity in view of the electrophilic nature of singlet oxygen.

Alternatively, the electron-rich vinylsilanes exhibit high *gem* selectivity,[3] with the advantage that they react smoothly with singlet oxygen. This approach was recently extended to the photooxygenation of vinylstannanes,[4] which affords regio- and stereoselectively β-stannyl allylic hydroperoxides (Scheme 1). Although smaller amounts of α,β-enones and trialkyltin hydroxide are also produced from decomposition of the labile, nongeminal, regioisomeric α-stannyl allylic hydroperoxides, these side products are easily removed.

Since allylic hydroperoxides are readily reduced to the corresponding alcohols, the reduction of the vinylstannane hydroperoxides should constitute a versatile synthesis for β-stannyl allylic alcohols. The latter have previously been prepared by hydrostannation[5] of or the addition of stannyl cuprates[6] to alkynes and applied for the synthesis of chiral allenes.[5a] However, this approach is limited to acyclic derivatives, due to the lack of the cyclic acetylenic precursors with ring systems smaller than eight members. Additionally, terminal alkynes often give rise to regioisomeric products,[5b,c] which are difficult to separate.

Herein we report that the regioselective photooxygenation of vinylstannanes, followed by reduction of the resulting β-stannyl allylic hydroperoxides, constitutes a new, general, and convenient sequence for the preparation of cyclic and terminal β-stannyl allylic alcohols, which complements existing methods. Additionally, the synthetic utility of these building blocks is demonstrated in the preparation of β-functionalized allylic alcohols by tin-lithium exchange[7] and the well-known palladium coupling reaction.[8] The latter has not been efficiently achieved as yet for β-hydroxy-substituted vinylstannanes.[9]

Results

The required vinylstannanes **1** were prepared, as previously reported,[4] in one or two steps from cheap and readily available starting materials. Derivatives **1a,b** were obtained from commercial 2-bromo-2-butene and the corresponding Grignard reagent. The Shapiro reaction,[10] which yields regioselectively the least substituted double bond in **1d**, was the source of vinylstannanes **1c,d**. Stannylation of 1-lithiocyclohexene[11] derived from 1-chlorocyclohexene afforded derivative **1e**.

The photooxygenation of the vinylstannanes **1** was conducted in an immersion lamp apparatus,[21] with Rose Bengal (RB) in methanol (**1a**) or ethanol (**1b–e**) at −20 °C, which afforded the corresponding β-stannyl allylic hydroperoxides (Scheme 1). Also smaller amounts of α,β-enones, derived from the decomposition of the regioiso-

® Abstract published in *Advance ACS Abstracts,* April 15, 1994.

(1) (a) Schenck, G. O.; Eggert, H.; Denk, W. *Liebigs Ann. Chem.* **1953**, *584*, 177–198. (b) Frimer, A. A.; Stephenson, L. M. In *Singlet Oxygen*; Frimer, A. A., Ed.; CRC Press Inc.: Boca Raton, 1985; Vol. II, p 67–92. (c) Ohloff, G. *Pure Appl. Chem.* **1975**, *43*, 481–502. (d) Wasserman, H. H.; Ives, J. L. *Tetrahedron* **1981**, *37*, 1825–1852.

(2) (a) Adam, W.; Griesbeck, A. *Synthesis* **1986**, 1050–1052. (b) Ensley, H. E. *Adv. Oxygenated Processes* **1990**, *2*, 181–201. (c) Akasaka, T.; Takeuchi, K.; Ando, W. *Tetrahedron Lett.* **1987**, *28*, 6633–6636.

(3) (a) Fristad, W. E.; Bailey, T. R.; Paquette, L. A.; Gleiter, R.; Böhm, M. C. *J. Am. Chem. Soc.* **1979**, *101*, 4420–4423. (b) Fristad, W. E.; Bailey, T. R.; Paquette, L. A. *J. Org. Chem.* **1980**, *45*, 3028–3037. (c) Adam, W.; Richter, M.; *J. Am. Chem. Soc.* **1994**, in press.

(4) Adam, W.; Klug, P. *J. Org. Chem.* **1993**, *58*, 3416–3420.

(5) (a) Konoike, T.; Araki, Y. *Tetrahedron Lett.* **1992**, *33*, 5093–5096. (b) Jung, M. E.; Light, L. A. *Tetrahedron Lett.* **1982**, *23*, 3851–3854. (c) Zhang, H. X.; Guibé, F.; Balavoine, G. *J. Org. Chem.* **1990**, *55*, 1957–1967. (d) Ensley, H. E.; Buescher, R. R.; Lee, K. *J. Org. Chem.* **1982**, *47*, 404–408.

(6) Lipshutz, B. H.; Ellsworth, E. L.; Dimock, S. H.; Reuter, D. C. *Tetrahedron Lett.* **1989**, *30*, 2065–2068.

(7) Seyferth, D.; Weiner, M. A. *J. Org. Chem.* **1959**, *24*, 1395–1396.

(8) (a) Stille, J. K. *Angew. Chem., Int. Ed. Engl.* **1986**, *25*, 508–523. (b) Mitchell, T. N. *Synthesis* **1992**, 803–815.

(9) Mitchell, T. N.; Wickenkamp, R.; Amamria, A.; Dicke, R.; Schneider, U. *J. Org. Chem.* **1987**, *52*, 4868–4874.

(10) Chamberlin, A. R.; Stemke, J. E.; Bond, F. T. *J. Org. Chem.* **1978**, *43*, 147–154.

(11) Braude, E. A.; Coles, J. A. *J. Chem. Soc.* **1950**, 2014–2019.

0022-3263/94/1959-2695$04.50/0

Scheme 1

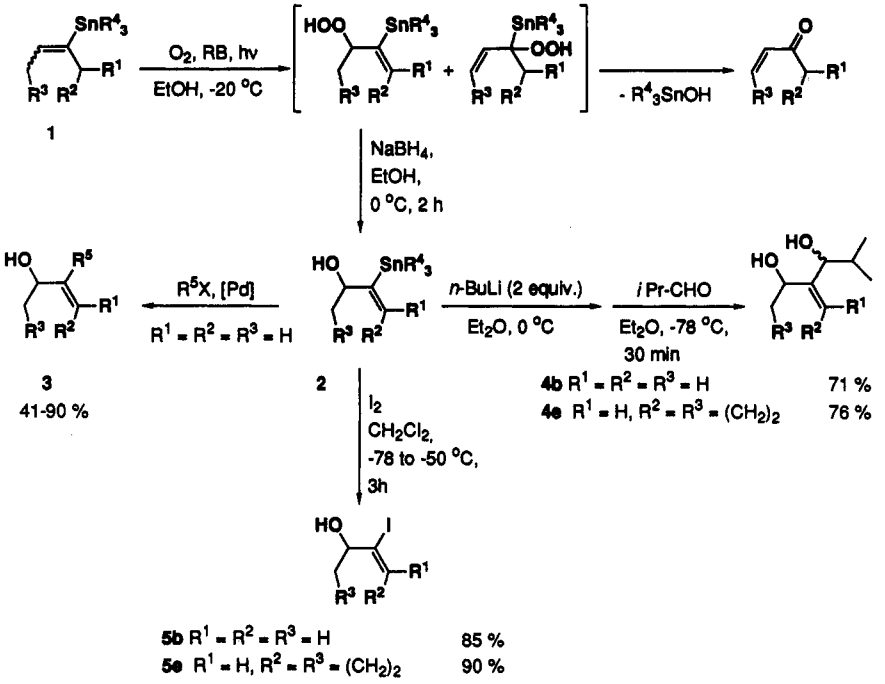


Table 1. β-Stannyl Allylic Alcohols 2 Prepared by Photooxygenation (Schenck reaction) of Vinylstannanes 1

vinylstannane	R^1	R^2	R^3	R^4	time[a] (h)	yield (%)
1a[b]	H	H	H	Me	8.5	45
1b[c]	H	H	H	*n*-Bu	8	54
1c	H	CH_2		*n*-Bu	1.5	73
1d	Me	CH_2		*n*-Bu	1.5	54
1e	H	$(CH_2)_2$		*n*-Bu	27	50

[a] Photooxygenation at −20 °C with Rose Bengal (RB) as sensitizer in MeOH for 1a and in EtOH for 1b–e conversion >95%. [b] (*Z*)-1a:(*E*)-1a = 82:18. [c] (*Z*)-1b:(*E*)-1b = 75:25.

meric ene product, were obtained. The crude reaction mixture was directly reduced at 0 °C with an excess of sodium borohydride to yield, after aqueous workup and flash chromatography, the desired β-stannyl allylic alcohols **2** in moderate to good yields (45–73%, Scheme 1, Table 1). Less advantageous is triphenylphosphine reduction, since the product **2** cannot be efficiently removed by flash chromatography from the excess triphenylphosphine.

The further functionalization of the stannyl allylic alcohols **2a,b** by palladium-catalyzed coupling[8] with allylic and vinylic halides (Scheme 1) afforded the respective 2-alkyl allylic alcohols **3** in moderate to excellent yields (41–90%, Table 2). For example, reaction of **2a** with allyl bromide (Table 2, entry 1) or **2b** with ethyl α-bromomethacrylate[12] (Table 2, entry 3) proceeded smoothly with 2% of $PdCl_2(CH_3CN)_2$ or $Pd(dba)_2$ as catalyst to yield the coupling products **3a,c**. The coupling of **2b** with 1-bromo-3-methyl-2-butene[13] (Table 2, entry 2) required longer reaction times, for which $Pd(dba)_2$ in THF proved to be the best conditions to produce **3b** in excellent yield. In contrast, the reaction between **2b** and (*E*)-1-iodohexene[14] (Table 2, entry 4) needed to be carried out in the aprotic solvent DMF with $Pd(PPh_3)_4$ (3%) as catalyst, which afforded the 1,3-diene **3d** in only 41% yield.

(12) Villieras, J.; Rambaud, M. *Synthesis* **1982**, 924–926.
(13) Simon, H. L.; Kaufmann, A.; Schinz, H. *Helv. Chim. Acta* **1946**, *29*, 1133–1144.
(14) Stille, J. K.; Simpson, J. H. *J. Am. Chem. Soc.* **1987**, *109*, 2138–2152.

Tin–lithium exchange was performed on the β-stannyl allylic alcohol **2b** and the cyclic derivative **2e** (Scheme 1). The corresponding lithio dianions were obtained by treating substrates **2b,e** with 2 equiv of *n*-butyllithium in ether at −78 to 0 °C. These intermediates were allowed to react with isobutyraldehyde at −78 °C to yield diastereoisomeric mixtures of allylic diols, which were isolated in 71% (dr = 61:39) for **4b** and 76% (dr = 55:45) for **4e**.

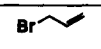
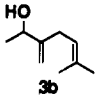
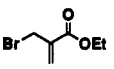
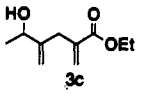
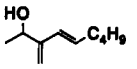
Finally, iododestannylation of the vinylstannanes **2b,e** (Scheme 1) with iodine afforded cleanly the corresponding hydroxyvinyl iodides **5b,e**, which were isolated by flash chromatography in 85 and 90% yields.

Discussion

The regioselective photoxygenation (Schenck reaction) of vinylstannanes **1** and subsequent reduction of the resulting hydroperoxides generates the corresponding β-stannyl allylic alcohols **2** in good yields. Most significant are the cyclic systems **2c–e**, which cannot be prepared by conventional hydrostannation techniques[5,6] but have now become accessible by this convenient one-pot process. A practical advantage is the fact that the isolation of the potentially hazardous hydroperoxides is avoided.

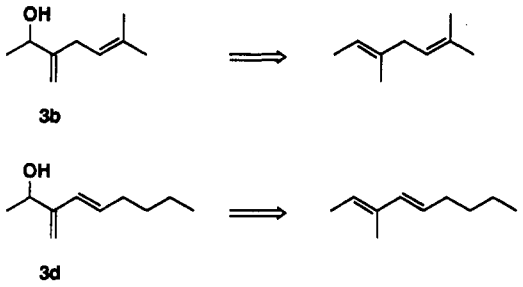
The palladium-catalyzed coupling between **2a,b** and unsubstituted (Table 2, entry 1) or 2-substituted allylic halides (Table 2, entry 3) proceeded swiftly. The coupling reaction between **2b** and the 3,3-disubstituted allylic bromide (Table 2, entry 2) was more sluggish, presumably the result of slow formation of the π-allyl palladium intermediate due to increased steric hindrance. Nevertheless, the reaction proceeded in excellent overall yield. The fact that the δ-hydroxy ester **3c** was obtained in high yield without cyclization to the corresponding δ-lactone is significant for synthetic purposes. Furthermore, in all cases studied, no complications through competitive reaction at the allyl system in the vinyltin derivative **2** were observed. As expected, the allylic hydroxy functionality is a very poor leaving group in the palladium-catalyzed process.

Table 2. Palladium-Catalyzed Coupling of β-Stannyl Allylic Alcohols 2

entry	alcohol	R	electrophile R^5X	catalyst[a]	time (h)	product	yield[b] (%)
1	**2a**	Me		A	1.5	 **3a**	89
2	**2b**	*n*-Bu		B	77	 **3b**	90
3	**2b**	*n*-Bu		B	3	 **3c**	79
4	**2b**	*n*-Bu		C	5	 **3d**	41

[a] A = $PdCl_2(CH_3CN)_2$ in DMF, 70 °C; B = $Pd(dba)_2$ in THF, 55 °C; C = $Pd(PPh_3)_4$ in DMF, 70 °C. [b] Yield of isolated material by flash chromatography.

Scheme 2



The overall synthetic sequence of transforming vinylstannanes **1** to the allylic alcohols **3** and **4** (Scheme 1) nicely demonstrates the synthetic value of the present methodology. For example, due to regioselectivity problems, the allylic alcohol **3b** cannot be prepared directly by the Schenck reaction on 2,5-dimethyl-2,5-heptadiene and subsequent reduction of the resulting allylic hydroperoxide (Scheme 2). The singlet oxygen ene reaction of both trisubstituted double bonds will take place and as many as five regioisomeric allylic hydroperoxides may result.

For the allylic alcohol **3d** , the appropriate dienic precursor would be 3-methyl-2,4-nonadiene (Scheme 2), for which [4 + 2] cycloaddition would definitely win over ene reaction at the required 3-methylallylic site. Besides this mode selectivity problem, three regioisomeric allyl hydroperoxides must be counted as products of the Schenck reaction. Therefore, the readily available vinylstannane **1b**, for which the stannyl functionality acts as a *gem*-directing group in the photooxygenation step and cleanly provides the corresponding β-hydroxy-substituted vinylstannane **2b** after reduction, constitutes an attractive starting material to circumvent the regio- and mode-selectivity problems of the tempting direct reaction of singlet oxygen. The modest price to pay, however, is the introduction of the remaining alkyl chain through the subsequent palladium-catalyzed C–C coupling reaction (Scheme 1).

Also tin–iodine exchange of the stannyl allylic alcohols **2b,e** is of synthetic value, since the desirable iodo allylic alcohols **5b,e** are obtained in high yields (Scheme 1). Such useful synthetic building blocks have previously been prepared mainly from propargyl alcohols by hydrometalation[15] and subsequent iodination or by reaction of trimethylsilyl iodide[16] with these precursors, followed by hydrolysis of the resulting silyl ether. Alternatively, iodides **5** can also be obtained by formal addition of HOI to allenes,[17] which is of low preparative scope, however. As demonstrated for derivative **5e** , our new methodology makes available the previously unknown cyclic derivatives.

In summary, the sequence described herein (Scheme 1) allows the regioselective synthesis of oxyfunctionalized vinylstannanes from the readily available tin-substituted olefins. The present approach is applicable also to cyclic systems, a method which is complementary to the existing procedures. The resulting β-stannyl allylic alcohols **2** are versatile synthetic building blocks for the preparation of highly substituted and functionalized 2-alkyl allylic alcohols, as demonstrated by palladium-catalyzed C–C coupling reactions, tin–lithium exchange followed by the addition of carbonyl-containig electrophiles, and by metal–halogen exchange to hydroxy vinyl iodides **5**. In view of the broad synthetic scope of functionalized vinylstannanes, we expect that this novel and convenient methodology will prove useful in organic synthesis.

Experimental Section

General Methods. All melting points and boiling points are uncorrected. Solvents were purified according to standard literature procedures. TLC was performed on Polygram Sil G UV (40 × 80 mm), Macherey & Nagel. Silica gel (32–64 μm) from Woelm was used for flash chromatography. Elemental analyses were obtained in-house. IR spectra were recorded on a Perkin Elmer Model 1420 instrument. ^1H NMR spectra were obtained in $CDCl_3$ solution at 250 MHz on a Bruker AC 250 or at 200 MHz on a Bruker AC 200 instrument with $CDCl_3$ (δ 7.26) as internal standard. ^{13}C NMR spectra were recorded on a Bruker AC 250 or a Bruker AC 200 instrument at 69.3 or 50.3 MHz with $CDCl_3$ (δ 77.0) as internal standard. The separate J (^{117}SnH) and J (^{119}SnH) values of the alkenylstannanes were reported when the satellite peaks were clearly distinct; otherwise the indicated J_{HSn} values represent approximate mean values of J (^{117}SnH) and J (^{119}SnH).

The vinylstannanes **1a–e** were made as previously reported.[4] $Pd(CH_3CN)_2$,[18] $Pd(PPh_3)_4$,[19] and $Pd(dba)_2$[20] were prepared according to literature procedures.

(15) (a) Marshall, J. A.; DuBay, W. J. *J. Org. Chem.* **1993**, *58*, 3435–3443. (b) Tolstikov, G. A.; Miftakhov, M. S.; Danilova, N. A.; Vel'der, Y. L. *Synthesis* **1986**, 496–499. (c) Corey, E. J.; Kirst, H. A.; Katzenellenbogen, J. A. *J. Am. Chem. Soc.* **1970**, *92*, 6314–6319. (d) Cowell, A.; Stille, J. K. *Tetrahedron Lett.* **1979**, 133–136.

(16) Gras, J. L.; Kong Win Chang, Y. Y.; Bertrand, M. *Tetrahedron Lett.* **1982**, *23*, 3571–3572.

(17) (a) Coulomb, F.; Roumestant, M.-L.; Gore, J. *Bull. Chim. Soc. Fr.* **1973**, *12*, 3352–3359. (b) Georgoulis, C.; Smadja, W.; Valery, J. M. *Synthesis* **1981**, 572–574.

(18) Parker, K. A.; O'Fee, R. P. *J. Org. Chem.* **1983**, *48*, 1547–1550.

General Procedure for the Preparation of β-Stannyl Allylic Alcohols 2. A solution of 8.08–14.5 mmol of the corresponding vinylstannane 1 and 50 mg of Rose Bengal in 125 mL of methanol (for **1a**) or ethanol (for **1b–e**) was photooxygenated at −20 °C in an immersion lamp apparatus[21] (equipped with a Osram Vialox NAV-TS 250-W sodium lamp) by passing a slow stream of dry oxygen gas through the solution until complete conversion of the starting material (TLC monitoring). The crude photooxygenate was transferred to a 250-mL, round-bottomed flask and was treated at 0 °C with an excess (40–80 mmol) of sodium borohydride and stirred for 2 h at 0 °C and for 10 h at 25 °C. Water (100 mL) was added and the solution was extracted with ether (3 × 50 mL). The combined organic layers were washed with water (50 mL) and brine (50 mL) and dried ($MgSO_4$), and the solvent was removed (20 °C at 20 Torr). From the resulting crude oil, the β-stannyl allylic alcohols **2** were obtained by flash chromatography on silica gel (50 g), besides smaller amounts of tri-*n*-butyltin hydride, which eluted considerably faster in the chromatography.

3-(Trimethylstannyl)-3-buten-2-ol (2a). Photooxygenation of 2.00 g (9.14 mmol) of vinylstannane **1a** in methanol for 8 h and subsequent $NaBH_4$ reduction yielded 969 mg (45%) of a colorless liquid after silica gel flash chromatography [6:1 petroleum ether (30–50 °C)/ether as eluent]: ^{1}H NMR (200 MHz) δ 0.17 (s, J_{HSn} = 52.5/54.9 Hz, 9H), 1.24 (d, J = 6.4 Hz, 3H), 1.77 (d, J = 2.5 Hz, 1H), 4.44 (m, J_{HSn} = 49 Hz, 1H), 5.19 (dd, J = 2.1, 1.2 Hz, J_{HSn} = 69.5 Hz, 1H), 5.75 (dd, J = 2.0, 1.4 Hz, J_{HSn} = 145 Hz, 1H); ^{13}C NMR (50 MHz) δ −8.6 (q), 24.2 (q), 74.9 (q), 122.6 (t), 160.7 (s); IR (neat) ν 3700–3100, 3040, 920 cm^{-1}. Anal. Calcd for C_7H_{16}OSn (234.9): C, 35.79; H, 6.87. Found: C, 35.44; H, 6.58.

3-(Tri-*n*-butylstannyl)-3-buten-2-ol (2b). Photooxygenation of 5.00 g (14.5 mmol) of vinylstannane **1b** in ethanol for 8 h and subsequent $NaBH_4$ reduction yielded 3.34 g (54%) of a colorless oil after flash chromatography on silica gel [10:1 to 3:1 petroleum ether (30–50 °C)/ether as eluent]: ^{1}H NMR (200 MHz) δ 0.80–1.10 (m, 15H), 1.24 (d, J = 6.4 Hz, 3H), 1.25–1.65 (m, 13H), 4.42 (m, 1H), 5.16 (dd, J = 2.1, 1.3 Hz, J_{HSn} = 52.6 Hz, 1H), 5.79 (dd, J = 2.1, 1.4 Hz, J_{HSn} = 132 Hz, 1H); ^{13}C NMR (63 MHz) δ 10.1 (t), 13.7 (q), 24.1 (q), 27.4 (t), 29.1 (t), 74.8 (d), 122.8 (t), 160.4 (s); IR (neat) ν 3700–3140, 3085, 933 cm^{-1}. Anal. Calcd for $C_{16}H_{34}$OSn (361.2): C, 53.21; H, 9.49. Found: C, 53.48; H, 9.79.

2-(Tri-*n*-butylstannyl)-2-cyclopenten-1-ol (2c). From the photooxygenation of 3.01 g (8.45 mmol) of vinylstannane **1c** in ethanol for 1.5 h and subsequent $NaBH_4$ reduction was obtained 2.30 g (73%) of a colorless oil after flash chromatography on silica gel [8:1 petroleum ether (30–50 °C)/ether as eluent]: ^{1}H NMR (200 MHz) δ 0.78–1.02 (m, 15H), 1.18 (d, J = 8.3 Hz, 1H), 1.22–1.72 (m, 13H), 2.15–2.65 (m, 3H), 4.86 (m, 1H), 6.05 (m, J_{HSn} = 28 Hz, 1H); ^{13}C NMR (50 MHz) δ 9.5 (t), 13.7 (q), 27.3 (t), 29.2 (t), 33.3 (t), 33.9 (t), 83.4 (d), 144.3 (d), 147.5 (s); IR (neat) ν 3580–3200, 3030, 1570 cm^{-1}. Anal. Calcd for $C_{17}H_{34}$OSn (373.1): C, 54.72; H, 9.18. Found: C, 54.96; H, 9.10.

2-(Tri-*n*-butylstannyl)-3-methyl-2-cyclopenten-1-ol (2d). From the photooxygenation of 3.05 g (8.21 mmol) of vinylstannane **1d** in ethanol for 1.5 h and subsequent $NaBH_4$ reduction was obtained 1.70 g (54%) of a colorless oil after flash chromatography on silica gel [8:1 petroleum ether (30–50 °C)/ether as eluent]: ^{1}H NMR (200 MHz) δ 0.79–1.02 (m, 15H), 1.11 (d, J = 6.9 Hz, 1H), 1.22–1.74 (m, 13H), 1.81 (d, J = 1.2 Hz, 3H), 2.16–2.61 (m, 3H), 4.79 (m, 1H); ^{13}C NMR (50 MHz) δ 9.7 (t), 13.7 (q), 18.8 (q), 27.4 (t), 29.8 (t), 35.0 (t), 37.5 (t), 84.0 (d), 140.0 (s), 153.8 (s); IR (neat) ν 3580–3200, 1620 cm^{-1}. Anal. Calcd for $C_{18}H_{36}$OSn (387.2): C, 55.84; H, 9.37. Found: C, 55.69; H, 9.85.

2-(Tri-*n*-butylstannyl)-2-cyclohexen-1-ol (2e). Photooxygenation of 3.00 g (8.08 mmol) of vinylstannane **1e** in ethanol for 27 h and subsequent $NaBH_4$ reduction yielded 1.55 g (50%) of a colorless oil after flash chromatography on silica gel [10:1 petroleum ether (30–50 °C)/ether as eluent]: ^{1}H NMR (250 MHz) δ 0.75–1.05 (m, 15H), 1.20–1.70 (m, 15H), 1.70–2.10 (m, 4H), 4.16 (m, 1H), 5.87 (m, J_{HSn} = 65.3 Hz, 1H); ^{13}C NMR (63 MHz) δ 9.7 (t), 13.7 (q), 19.8 (t), 27.1 (t), 27.4 (t), 29.2 (t), 33.1 (t), 70.9 (d), 138.7 (d), 145.7 (s); IR (neat) ν 3600–3140, 1603 cm^{-1}. Anal. Calcd for $C_{18}H_{36}$OSn (387.2): C, 55.84; H, 9.37. Found: C, 55.69; H, 9.85.

3-Methylene-5-hexen-2-ol (3a).[22] To a solution of 130 mg (1.07 mmol) of allyl bromide and 5.0 mg (19.0 μmol, 2%) of $PdCl_2(CH_3CN)_2$[18] in 5 mL of dry dimethylformamide was added 235 mg (1.00 mmol) of stannyl alcohol **2a** and stirred at 70 °C for 1.5 h. Water (20 mL) was added and the mixture was extracted with ether (5 × 10 mL). The combined organic layers were washed with brine (10 mL) and the solvent was removed by distillation at atmospheric pressure. Flash chromatography of the remaining residue on silica gel [3:1 petroleum ether (30–50 °C)/ether as eluent] and removal of the solvent at 0 °C and 20 Torr afforded 100 mg (89%) of a colorless liquid: ^{1}H NMR (250 MHz) δ 1.29 (d, J = 6.5 Hz, 3H), 1.75 (s, 1H), 2.82 (m, 2H), 4.27 (br q, J = 6.5 Hz, 1H), 4.83 (m, 1H), 5.04–5.12 (m, 3H), 5.75–5.91 (m, 1H); ^{13}C NMR (50 MHz) δ 22.0 (q), 36.3 (t), 70.7 (d), 109.8 (t), 116.4 (t), 136.2 (d), 151.4 (s); IR (neat) ν 3700–3100, 3080, 1638, 911, 901 cm^{-1}.

6-Methyl-3-methylene-5-hepten-2-ol (3b).[23] A solution of 149 mg (1.00 mmol) of 1-bromo-3-methyl-2-butene[13] and 12.0 mg (20.0 μmol, 2%) $Pd(dba)_2$[20] was prepared in 3 mL of dry THF under an argon gas atmosphere, whereby the color of the mixture turned from violet to yellow. Then was added a solution of 361 mg (1.00 mmol) of stannyl alcohol **2b** in 2 mL of THF and stirred at 55 °C for 77 h. The solvent was evaporated (0 °C at 20 Torr) to about 1 mL and the residue purified by flash chromatography on 50 g of silica gel [6:1 petroleum ether (30–50 °C)/ether as eluent] to yield 126 mg (90%) of a colorless liquid: ^{1}H NMR (200 MHz) δ 1.30 (d, J = 6.5 Hz, 3H), 1.62 (m, 4H), 1.73 (m, 3H), 2.77 (m, 2H), 4.28 (m, 1H), 4.80 (m, 1H), 5.02 (m, 1H), 5.19 (m, 1H); ^{13}C NMR (50 MHz) δ 17.6 (q), 22.1 (q), 25.7 (q), 30.7 (t), 70.8 (d), 108.7 (t), 121.6 (d), 133.3 (s), 152.4 (s); IR (neat) ν 3700–3100, 3080, 910 cm^{-1}.

Ethyl-5-Hydroxy-2,4-dimethylenehexanoate (3c). Analogous to the above procedure at 55 °C for 3 h, from 193 mg (1.00 mmol) of ethyl α-bromomethacrylate,[12] 12.0 mg (20.0 μmol, 2%) of $Pd(dba)_2$,[20] and 361 mg (1.00 mmol) of **2b** was obtained after flash chromatography on 50 g of silica gel [3:1 petroleum ether (30–50 °C)/ether as eluent] 145 mg (79%) of a colorless liquid: ^{1}H NMR (200 MHz) δ 1.28 (t, J = 7.0 Hz, 3H), 1.30 (d, J = 7.2 Hz, 3H), 2.31 (d, J = 3.7 Hz, 1H, OH), 3.20 (AB-system, J_{AB} = 15.9 Hz, 2H), 4.18 (q, J = 7.1 Hz, 2H), 4.29 (m, 1H), 4.78 (d, J = 1.2 Hz, 1H), 5.09 (m, 1H), 5.62 (q, J = 1.3 Hz, 1H), 6.24 (d, J = 1.5 Hz, 1H); ^{13}C NMR (50 MHz) δ 14.1 (q), 21.8 (q), 33.6 (t), 60.9 (t), 70.8 (d), 110.7 (t), 126.7 (t), 138.8 (s), 150.4 (s), 167.1 (s); IR (neat) ν 3750–3160, 3015, 1736, 1650, 915 cm^{-1}. Anal. Calcd for $C_{10}H_{16}O_3$ (184.2): C, 65.19; H, 8.75. Found: C, 64.95; H, 9.07.

(*E*)-3-Methylene-4-nonen-2-ol (3d). To a solution of 210 mg (1.00 mmol) of (*E*)-1-iodohexene[14] and 35.0 mg (3.03 μmol, 3%) of $Pd(PPh_3)_4$[19] in 5 mL of dry DMF was added 361 mg (1.00 mg) of stannyl alcohol **2b** under an argon gas atmosphere, and the resulting mixture was heated at 70 °C while stirring for 5 h. After cooling to room temperature, 5 mL of water were added and the reaction mixture was extracted with ether (5 × 10 mL). The combined organic layers were dried ($MgSO_4$) and the solvent evaporated (0 °C at 20 Torr). Flash chromatography of the resulting residue on 50 g of silica gel [3:1 petroleum ether (30–50 °C)/ether as eluent] yielded 64.0 mg (41%) of a colorless liquid: ^{1}H NMR (250 MHz) δ 0.89 (m, 3H), 1.20–1.45 (m, 7H), 1.67 (d, J = 3.4 Hz, 1H, OH), 2.10 (q, J = 6.5 Hz, 2H), 4.56 (m, 1H), 4.98 (s, 1H), 5.12 (s, 1H), 5.80 (dt, J = 16.0, 6.8 Hz, 1H), 6.02 (d, J = 16.4 Hz, 1H); ^{13}C NMR (63 MHz) δ 13.9 (q), 22.2 (t), 22.8 (q), 31.4 (t), 32.8 (t), 67.7 (d), 110.6 (t), 129.1 (d), 131.4 (d), 150.3 (s); IR (neat) ν 3600–3100, 3070, 1710, 1628, 1590, 890 cm^{-1}. Anal. Calcd for $C_{10}H_{18}O$ (154.3): C, 77.87; H, 11.76. Found: C, 78.07; H, 11.83.

5-Methyl-3-methylenehexane-2,4-diol (4b). To a solution of 722 mg (2.00 mmol) of stannyl alcohol **2b** in 20 mL of dry ether was added 3.2 mL of a 1.55 M solution of *n*-BuLi (in hexane) at −78 °C. This solution was stirred at this temperature for 30

(19) Coulson, D. R. *Inorg. Synth.* **1972**, *13*, 121–124.
(20) Takahashi, Y.; Ito, T.; Sakai, S.; Ishii, Y. *Chem. Commun.* **1970**, 1065–1066.
(21) Denny, R. W.; Nickon, A. *Org. React.* **1973**, *20*, 133–336.
(22) Yanagisawa, A.; Nomura, N.; Habaue, S.; Yamamoto, H. *Tetrahedron Lett.* **1989**, *30*, 6409–6412.
(23) Pattenden, G.; Storer, R. *J. Chem. Soc., Perkin Trans. 1* **1974**, 1603–1606.

min and further 5 h at 0 °C until transmetalation was complete (TLC monitoring). The reaction mixture was cooled to −78 °C and 720 mg (0.91 mL, 10.0 mmol) of isobutyraldehyde was added. Stirring was continued for 10 min and the solution was allowed to warm up to room temperature. Water (1 mL) was added and the organic layer washed with brine (20 mL), dried ($MgSO_4$), and evaporated (20 °C at 20 Torr). Flash chromatography on 50 g of silica gel [1:2 petroleum ether (30–50 °C)/ether as eluent] afforded, besides tetrabutyltin (R_f = 0.9), 125 mg (43%) of a colorless liquid (R_f = 0.26, isomer A) and 81.0 mg (28%) of a colorless liquid (R_f = 0.19, isomer B).

Isomer A: ^{1}H NMR (200 MHz) δ 0.81 (d, J = 6.8 Hz, 3H), 1.01 (d, J = 6.5 Hz, 3H), 1.34 (d, J = 6.4 Hz, 3H), 1.87 (m, 1H), 2.85 (br s, 2H, OH), 3.80 (d, J = 8.2 Hz, 1H), 4.42 (br q, J = 6.4 Hz, 1H), 5.04 (s, 1H), 5.17 (m, 1H); ^{13}C NMR (50 MHz) δ 18.5 (q), 19.5 (q), 21.6 (q), 31.9 (d), 67.6 (d), 81.3 (d), 112.2 (t), 151.9 (s); IR (neat) ν 3600–3050, 3060, 1628, 910 cm^{-1}. Anal. Calcd for $C_8H_{16}O_2$ (144.3): C, 66.63; H, 11.18. Found: C, 66.86; H, 11.51.

Isomer B: ^{1}H NMR (200 MHz) δ 0.91 (d, J = 6.8 Hz, 3H), 0.96 (d, J = 6.6 Hz, 3H), 1.38 (d, J = 6.5 Hz, 3H), 1.93 (m, 1H), 2.08 (br s, 2H, OH), 3.91 (d, J = 7.1 Hz, 1H), 4.37 (br q, J = 6.4 Hz, 1H), 5.08 (s, 1H), 5.20 (m, 1H); ^{13}C NMR (50 MHz) δ 17.6 (q), 19.9 (q), 23.0 (q), 31.9 (d), 69.0 (d), 79.2 (d), 111.2 (t), 153.6 (s); IR (neat) ν 3600–3050, 3070, 1628, 910 cm^{-1}. Anal. Calcd for $C_8H_{16}O_2$ (144.3): C, 66.63; H, 11.18. Found: C, 66.92; H, 11.59.

2-(1-Hydroxy-2-methylpropyl)-2-cyclohexen-1-ol (4e). Analogous to the above procedure, 425 mg (1.10 mmol) of stannyl alcohol **2e** was treated with 2.0 mL of a 1.30 M solution of *n*-BuLi (in hexane) in 10 mL of ether for 30 min at −78 °C and 30 min at 0 °C. After addition of 300 mg (4.16 mmol) of isobutyraldehyde, aqueous workup, and flash chromatography on 50 g of silica gel [1:1 petroleum ether (30–50 °C)/ methyl *tert*-butyl ether as eluent], there were obtained 347 mg (91%) of tetrabutyltin, 79.0 mg (42%) of a colorless liquid (R_f = 0.35, isomer A), and 64.0 mg (34%) of colorless needles, mp 97.5–98.5 °C (R_f = 0.18, isomer B).

Isomer A: ^{1}H NMR (200 MHz) δ 0.71 (d, J = 6.8 Hz, 3H), 1.03 (d, J = 6.5 Hz, 3H), 1.40–2.10 (m, 7H), 3.10–3.55 (br s, 2H, OH), 3.58 (d, J = 9.5 Hz, 1H), 4.33 (t, J = 4.2 Hz, 1H), 5.69 (t, J = 3.8 Hz, 1H); ^{13}C NMR (50 MHz) δ 17.9 (t), 19.4 (q), 19.5 (q), 25.2 (t), 31.5 (t), 31.9 (d), 64.9 (d), 84.6 (d), 129.5 (d), 138.3 (s); IR (CCl_4) ν 3650–3100, 1663 cm^{-1}. Anal. Calcd for $C_{10}H_{18}O_2$ (170.3): C, 70.55; H, 10.66. Found: C, 70.14; H, 10.56.

Isomer B: ^{1}H NMR (200 MHz) δ 0.90 (d, J = 6.8 Hz, 3H), 0.91 (d, J = 6.7 Hz, 3H), 1.45–1.82 (m, 4H), 1.90 (hept, J = 6.7 Hz, 1H), 1.97–2.22 (m, 2H), 2.39 (d, J = 4.3 Hz, 1H, OH), 2.52 (d, J = 5.8 Hz, 1H, OH), 3.88 (m, 1H), 4.13 (m, 1H), 5.80 (t, J = 3.5 Hz, 1H); ^{13}C NMR (50 MHz) δ 17.1 (t), 17.4 (q), 19.8 (q), 25.1 (t), 31.8 (t), 32.1 (d), 66.3 (d), 78.4 (d), 126.1 (d), 140.5 (s); IR (CCl_4) ν 3650–3150, 3625, 3640 cm^{-1}. Anal. Calcd for $C_{10}H_{18}O_2$ (170.3): C, 70.55; H, 10.66. Found: C, 70.03; H, 11.21.

3-Iodo-3-buten-2-ol (5b).[16] To a solution of 772 mg (2.14 mmol) of alcohol **2b** , dissolved in 50 mL of CH_2Cl_2 at −78 °C, was added dropwise a solution of 571 mg (2.25 mmol) of iodine under an argon gas atmosphere. Within 3 h, the reaction mixture was allowed to warm up to −50 °C. At this temperature 1 mL of concd aqueous $NaSO_3$ solution was added and the mixture allowed to warm up to room temperature. The solvent was evaporated at 0 °C/20 Torr and the residue directly purified by flash chromatography on 50 g of silica gel [1:1 petroleum ether (30–50 °C)/ether as eluent] to yield 360 mg (85%) of a pale yellow liquid: ^{1}H NMR (200 MHz) δ 1.30 (d, J = 6.3 Hz, 3H), 2.07 (d, J = 5.3 Hz, 1H), 3.92 (m, 1H), 5.81 (dd, J = 1.8, 1.1 Hz, 1H), 6.36 (dd, J = 1.8, 0.3 Hz, 1H); ^{13}C NMR (50 MHz) δ 23.1 (q), 74.2 (d), 199.5 (s), 124.4 (t); IR (neat) ν 3650–3050, 1608, 905 cm^{-1}.

2-Iodo-2-cyclohexen-1-ol (5e). According to the above procedure, from 810 mg (2.09 mmol) of stannyl alcohol **2e** and 556 mg (2.19 mmol) of iodine wase obtained after flash chromatography on 50 g of silica gel [2:1 petroleum ether (30–50 °C)/ether as eluent] and recrystallization from this solvent 421 mg (90%) of colorless cubes: mp 44–45 °C; ^{1}H NMR (200 MHz) δ 1.50–2.15 (m, 6H), 2.18 (d, J = 5.0 Hz, 1H), 4.18 (m, 1H), 6.49 (t, J = 3.9 Hz, 1H); ^{13}C NMR (50 MHz) δ 17.6 (t), 29.3 (t), 31.9 (t), 72.0 (d), 103.6 (s), 141.0 (d); IR (CCl_4) ν 3700–3100, 3580, 3030, 1620 cm^{-1}. Anal. Calcd for C_6H_9IO (224.0): C, 32.17; H, 4.05. Found: C, 31.96; H, 4.02.

Acknowledgment. Financial support by the Deutsche Forschungsgemeinschaft (SFB 347 "Selektive Reaktionen Metall-aktivierter Moleküle") is gratefully appreciated. P.K. thanks the Fonds der Chemischen Industrie for a doctoral fellowship (1992–94).