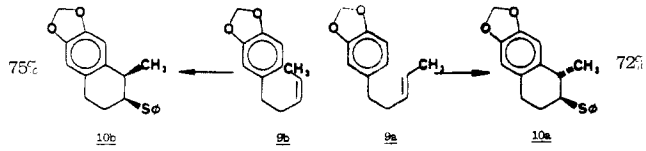
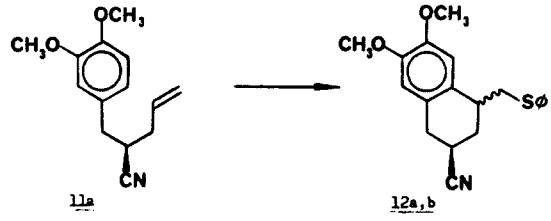
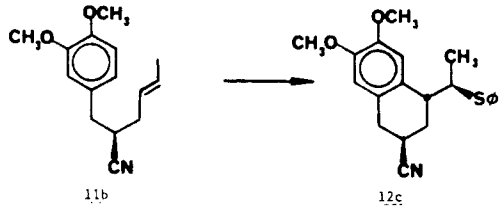
oxyphenyl)-3-pentene **9a** to a solution of $PhSOCH_3$ (1.05 equiv) and BF_3 (2.1 equiv, 0.8 M in CH_3NO_2) in CH_2Cl_2 [−78 °C (2 h) → −40 °C (2 h)] afforded the *trans*-tetralin derivative **10a** as the exclusive product in 75% chromatographed yield.[17] In complete accord with this observation the cyclization of the corresponding *Z* isomer **9b** gave only the cis adduct **10b** in 72% isolated



yield.[17] These results are consistent with the existance of bridged episulfonium ions as transient intermediates in the preceeding reactions.

A study to determine the exo/endo mode selectivity of cyclization (leading to six- or seven-membered rings, respectively) was carried out as follows. Exposure of the 2-(2-phenylethyl)pentenenitrile **11a** to $PhSOCH_3$ (1.05 equiv) and BF_3 (2.10 equiv, 0.8 M in CH_3NO_2) in CH_2Cl_2 [−78 °C (2 h) → −30 °C (10 h)] furnished the cyclized adducts **12a,b** (12b/12c: 1/1) in 52%





purified yield. Similarly, sulfenylative cyclization of **11b** [$PhSOCH_3$ (1.05 equiv), $SnCl_4$ (1.00 equiv), −78 °C (2 h) → −30 °C (10 h)] provided the tetralin derivative **12c** as the major diastereomer in 51% recrystallized yield.[18] In neither instance were products possessing seven-membered rings isolated.

The synthetic viability of sulfenium ion promoted carbocycle annulations reliant upon methyl benzenesulfenate–Lewis acid binary systems has been firmly established. Studies on the utility of this methodology for effecting polyene cyclizations as well as the development of a related procedure for the generation of episelenonium ions are currently under way. The application of these new methods for cationic annulation to the construction of naturally occurring ring systems will be described in future reports from these laboratories.

Acknowledgment. Support for this research by a grant from the National Institutes of Health (GM-32000) is gratefully acknowledged. This paper is dedicated to the memory of Professor Robert V. Stevens.

(17) Support for these stereochemical assignments was provided by 300-MHz NMR. Specifically, the quasi-equatorial methyl substituent of the trans derivative **10a** was deshielded (δ 1.38, d, J = 7.0 Hz) relative to the quasi-axial methyl (δ 1.29, d, J = 7.0 Hz) of the *cis*-tetralin **10b**. In consonance with this observation, the quasi-equatorial benzylic methine of cis **10b** was deshielded (δ 3.03) relative to its quasi-axial counterpart (δ 2.92) in trans **10a**.

(18) The stereochemistry of **12c** has been tentatively assigned on the basis of 300-MHz ^1H NMR spectral data. A definitive stereochemical assignment awaits single-crystal X-ray structure determination.

(Hydroxyacetyl)iridium and -rhodium Complexes: Model Compounds for CO Hydrogenation

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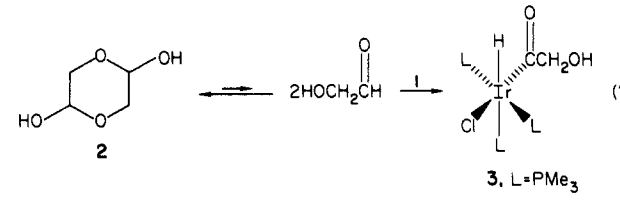
Hydroxyacetyl complexes are postulated as intermediates in the direct conversion of synthesis gas to oxygenated products[1] and in the hydroformylation of formaldehyde to glycolaldehyde, an ethylene glycol precursor[2] (Scheme I).

Whereas various hydroxymethyl complexes are now known, $Fe(COCH_2OH)[P(OMe)_3]_2(CO)Cl$[3] obtained as an isomeric mixture is the only hydroxyacetyl complex reported and no (hydroxyacetyl)metal hydrides are known. A chelate-stabilized hydroxyacyl complex has been reported very recently.[4] The lack of hydroxyacetyl complexes is perhaps due in part to difficulties in carbonylation of hydroxymethyl complexes.[5,6] We report here the synthesis of such complexes by oxidative addition reactions of 2,5-dihydroxy-1,4-dioxane (glycol aldehyde dimer) to Ir(I) and Rh(I) complexes, the reversal of the postulated product-forming step in formaldehyde hydroformylation. The thermally induced elimination modes of the rhodium complexes bear directly on the steps postulated in Scheme I.

Stirring a suspension containing equivalent amounts of $(C_8H_{14})Ir(PMe_3)_3Cl$ (**1**) (C_8H_{14} = cyclooctene) and 2,5-dihydroxy-1,4-dioxane (**2**) in toluene for 16 h under N_2, filtration, and evaporation of the solvent yield a yellow oil. Extraction of the oil with pentane and evaporation of the solvent yields the pure complex **3** as a light yellow solid in 60% yield (eq 1). The



(1)

structure of **3** is unambiguously assigned on the basis of ^1H NMR, ^{31}P NMR, and IR[7] and is confirmed by a single-crystal X-ray diffraction study (Figure 1).[8,9]

Complex **3** crystallizes in a $P\bar{1}$ space group with two molecules per asymmetric unit, for a total of four molecules per unit cell. Coordination about the iridium is octahedral with the expected distortion arising from the lack of steric bulk of the hydride ligand. The Ir–P trans to the hydride is 0.05 Å longer than the Ir–P bond

(1) (a) Rathke, J. W.; Feder, H. M. "Catalysis of Organic Reactions"; Moser, W. R., Ed.; Marcell Dekker: New York, 1981; p 219. (b) Fahey, D. R. *J. Am. Chem. Soc.* **1981**, *103*, 136. (c) Dombek, B. D. *Adv. Catal.* **1983**, *32*, 325.

(2) (a) Roth, J. A.; Orchin, M. *J. Organomet. Chem.* **1979**, *172*, C27. (b) Spencer, A. *Ibid.* **1980**, *194*, 113. (c) Chan, A. S. C.; Carroll, W. E.; Willis, W. E. *J. Mol. Catal.* **1983**, *19*, 377.

(3) Berke, H.; Huttner, G.; Weiler, G.; Zsolnai, L. *J. Organomet. Chem.* **1981**, *219*, 353.

(4) Vaughn, G. D.; Gladysz, J. A. *Organometallics* **1984**, *3*, 1596.

(5) Casey, C. P.; Andrews, M. A.; McAlister, D. R.; Jones, W. D.; Harsy, S. G. *J. Mol. Catal.* **1981**, *13*, 43.

(6) (a) Lin, Y. C.; Milstein, D.; Wreford, S. S. *Organometallics* **1983**, *2*, 1461. (b) Nelson, G. O. *Ibid.* **1983**, *2*, 1474.

(7) **3**: IR (Nujol) 3370 (m, ν_{OH}), 2025 (s, ν_{Ir-H}), 1588 (s, $\nu_{C=O}$), 1570 (s, $\nu_{C=O}$) (IR in solution shows only one band for $\nu_{C=O}$ at 1580 cm^{-1}); ^1H NMR (C_6D_6) δ 2.11 [t, $(J_{PH} + J_{P'H})/2$ = 3 Hz, 18 H, PMe_3)], 2.13 (d, J_{PH} = 8 Hz, 9 H, PMe_3), 4.36 (d, J = 3 Hz, 2 H, CH_2O), 4.68 (t, J = 3 Hz, 1 H, OH), −7.25 (d of t, J_{HP}(trans) = 128, J_{HP}(cis) = 17.8 Hz, 1 H, IrH); upon addition of D_2O the triplet at 4.68 disappears and the doublet at 4.36 becomes a singlet; $^{31}P\{^1H\}$ NMR (C_6D_6) δ 5.65 (t, J = 22.4 Hz, 1 P), 11.43 (d, J = 22.4 Hz, 2 P). Satisfactory C and H analyses were obtained for **3**, **4**, and **8**.

(8) X-ray quality crystals of **3** were obtained from a benzene solution by vapor diffusion of pentane.

(9) Crystal data for **3**: $IrC_{11}H_{31}P_3ClO_2$ space group $P\bar{1}$, No. 2, cell dimensions (−100 °C) a = 14.818 (2) Å, b = 15.150 (2) Å, c = 8.752 (1) Å, α = 93.55 (1)°, β = 95.17 (1)°, γ = 90.77 (1)°, λ = 0.71069 Å, V = 1952.7 Å^3, R = 0.036, R_w = 0.035. All details are included in the supplementary material.

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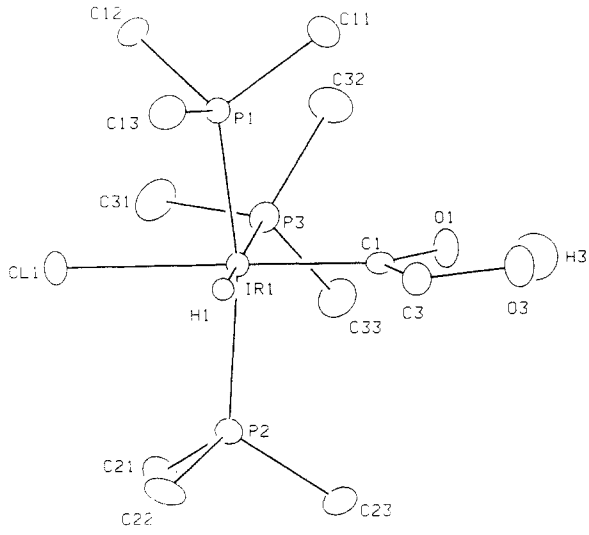
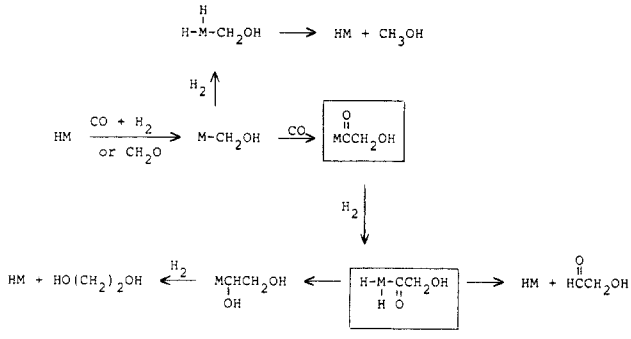


Figure 1. ORTEP drawing of a molecule of **3**. Selected bond distances (Å) and angles (deg): IR1–H1 1.632 (50); Ir1–P1 2.318 (2); Ir1–P2 2.316 (2); Ir1–P3 2.367 (2); Ir1–C11 2.518 (1); Ir1–C1 1.978 (6); O1–C1 1.237 (7); C1–C3 1.530 (8); C3–O3 1.423 (8); O3–H3 0.886 (90); O1–H3 1.914 (90); Ir1–C1–O1 127.5 (4); Ir1–C1–C3 119.0 (4); O1–C1–C3 113.5 (5); O3–C3–C1 111.6 (5); C3–O3–H3 100 (6).

Scheme I



cis to it, thus reflecting a large hydride trans influence. An important feature of this structure is the presence of an intramolecular hydrogen bond, C=O···H—O, as evidenced by the C3—O3—H3 angle of 100°, the distance H3—O1 of 1.914 Å, and the absence of any intermolecular hydrogen bonding in the crystal packing. Formation of a five-membered ring (Figure 2) is an obvious driving force for this interaction, persistence of which in solution is supported by the concentration independence of ν_{OH} in C_6D_6. Presence of such a hydrogen bond in metallacyclic (α-hydroxyacyl)manganese complex, postulated on the basis of spectroscopic data, was proposed to account for the rate increase in carbonylation of the corresponding α-hydroxyalkyl complex relative to its α-[(trimethylsilyl)oxy] analogue.[4] Intramolecular hydrogen bonding may very well be a general feature of (α-hydroxyacyl)metal complexes, suggesting that M–CH_2OH complexes generally have a higher aptitude for migratory insertion of CO than the corresponding, more readily available M–CH_2OR complexes.

It is noteworthy that O–H oxidative addition is not observed in the reaction of **1** with the alcohol **2**, although oxidative addition of alcohols to **1** is quite facile.[10] The large preference for C–H addition is probably thermodynamic in nature, reflecting the weaker formyl C–H bond.[11]

Complex **3** is quite thermally stable and does not undergo any decomposition upon extended heating at 100 °C. This is very likely a result of the tightness by which the PMe_3 ligands are bound to Ir(III). Ligand dissociation is a prerequisite in various elimination modes of Rh(III) and Ir(III) complexes.[12]

(10) Milstein, D., unpublished results.
(11) The Ir–O is probably also weaker than the corresponding Ir–C bond.

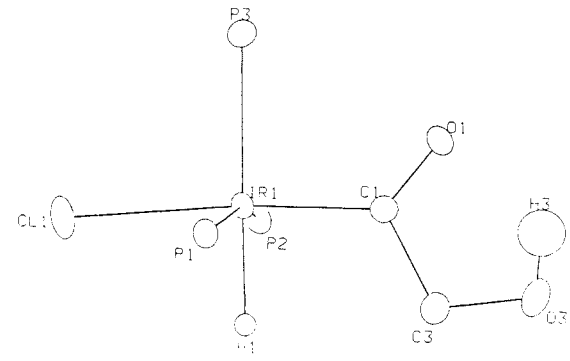
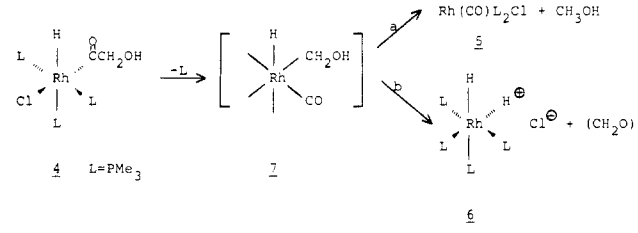


Figure 2. ORTEP drawing of a molecule of **3** showing the plane of the hydroxyacetyl ligand. CH_3 groups have been omitted for clarity.

Scheme II



An analogous (hydroxyacetyl)rhodium hydride complex, **4**, can be obtained similarly in 92% yield as light yellow needles after crystallization from toluene/pentane at −40 °C.[13] It is stable in the solid state at 25 °C but slowly decomposes in solution. Upon heating at 90 °C, migratory deinsertion takes place, followed by competing reductive elimination leading to complex **5** and methanol and β-elimination forming complex **6**[14] and formaldehyde, the latter process prevailing (Scheme II). Added PMe_3 retards the decomposition rate of **4**, consistent with phosphine dissociation being rate-determining, as observed with other *cis*-acylrhodium hydrides.[15] Both the reductive elimination process (a) and the β-hydride elimination (b) are essentially irreversible—no reactioin at 90 °C takes place between **5** and methanol and between **6** and formaldehyde. Reaction (a) represents a postulated but, to our knowledge, never observed product-forming step in the conversion of synthesis gas to methanol (Scheme I). A cationic hydrido(hydroxymethyl)iridium complex similar to **7** has been reported.[16] Process (b) is the reverse of the postulated hydroxymethyl ligand formation by formaldehyde reaction with a metal hydride complex. The reaction of $(C_6H_5)_2P(o\text{-}C_6H_4CHO)$ with $HMn(CO)_5$ is reported to yield a chelate-stabilized hydroxyalkyl complex.[17]

It is interesting to compare the elimination modes of **4** with those of the cis complex *mer*-$Rh(H)(COCH_2CH_2CH_3)(PMe_3)_3Cl$ (**8**),[18] obtained by oxidative addition of butyraldehyde to **2**. Here,

(12) Milstein, D. *Acc. Chem. Res.* **1984**, *17*, 221.
(13) **4**: IR (Nujol) 3395 (m, ν_{O-H}), 1910 (s, ν_{Rh-H}), 1630 (vs, $\nu_{C=O}$); ^1H NMR (C_6D_6) δ 1.13 (m, 27 H, 3 P), 3.95 (s, 2 H, CH_2O), −8.29 (d of d of t, J_{HP}(trans) = 188, J_{HP}(cis) = 16, J_{PRh} = 18 Hz, 1 H, RhH); the OH peak could not be observed; $^{31}P\{^1H\}$ NMR (C_6D_6) δ −7.53 (d of d, J_{RhP} = 109, J_{PP} = 31 Hz, 2 P), −22.91 (d of t, J_{RhP} = 91.5, J_{PP} = 31 Hz, 1 P).
(14) Complexes **5** and **6** were separated by fractional crystallization; IR, ^1H NMR, and ^{31}P NMR of the pure complexes are identical with those reported by: Jones, R. A.; Mayor Real, F.; Wilkinson, G.; Galas, A. M. R.; Hursthouse, M. B.; Abdul Malik, K. M. *J. Chem. Soc., Dalton Trans.* **1980**, 511.
(15) (a) Milstein, D. *Organometallics* **1982**, *1*, 1549. (b) Milstein D. *J. Chem. Soc., Chem. Commun.* **1982**, 1357.
(16) (a) Thorn, D. L. *Oranometallics* **1982**, *1*, 197. (b) Thorn, D. L.; Tulip, T. H. *Ibid.* **1982**, *1*, 1580. (c) Thorn, D. L.; Calabrese, J. C. *J. Organomet. Chem.* **1984**, *272*, 283.
(17) Vaughn, G. D.; Gladysz, J. A. *J. Am. Chem. Soc.* **1981**, *103*, 5608.
(18) **8**: Obtained as an off-white solid in 92% yield; IR (Nujol) 1950 cm^{-1} (s, ν_{Rh-H}), 1623 (vs, $\nu_{C=O}$); ^1H NMR (C_6D_6) δ 1.24 (d, J = 6.5 Hz, 9 H, PMe_3), 1.33 (t, $J_{PH} + J_{P'H})/2$ = 3.0 Hz, 18 H, 2 PMe_3), 1.54 (sextet, J = 7.0 Hz, 2 H, CH_2), 2.68 (t, J = 7.0 Hz, 2 H, CH_2CO), 0.94 (t, J = 7.0 Hz, 3 H, CH_3), −8.24 (d of d of t, J_{HP}(trans) = 188, J_{HP}(cis) = 15, J_{HRh} = 18 Hz, 1 H, RhH).

propane and **5**, as well as **2** and butyraldehyde, are formed at 90 °C (**5**/**2** = 10.5[19]), but propylene is not observed. This difference is consistent with an essentially irreversible formaldehyde elimination process compared with a reversible β-hydride elimination of an olefin, which ultimately leads to propane by irreversible C–H reductive elimination.

Further investigation of reactions of hydroxyacetyl complexes is now in progress.

Supplementary Material Available: Crystal structure analysis summary and tables of positional and thermal parameters of compound **3** (24 pages). Ordering information is given on any current masthead page.

(19) No attempt was made to remove the product aldehyde from the equilibrium mixture.

(20) **Note Added in Proof**: The octaethylporphyrin complex RhOEP-($COCH_2OH$) was reported after submittal of this article for publication: Van Voorhees, S. L.; Wayland, B. B. *Organometallics* **1985**, *4*, 1887.

Synthesis of Crystalline (±)-Fecapentaene

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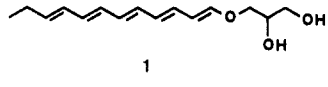
Received October 24, 1985

Since their discovery[1] and the structure elucidation[1,2] the fecapentaenes have gained worldwide scientific interest. These mutagenic glyceryl ether lipids can occur in trace amounts in the feces of people living in industrialized countries and are suspected to be a cause for colon cancer.[3]

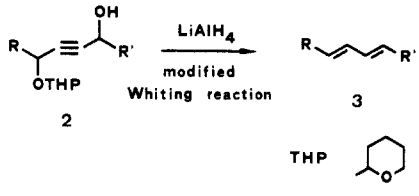
For the relevant carcinogenicity testing the mutagenic substances must be available in gram quantities, most desirably in pure form. Recently published syntheses[4] using Wittig and Horner–Wittig condensations to construct the polyene moiety lacked in stereochemical control and produced mixtures of cis–trans isomers which were extremely instable and difficult to handle.

We wish to communicate the first stereospecific route leading to the crystalline parent compound *all-trans*-fecapentaene-12 (**1**).



1

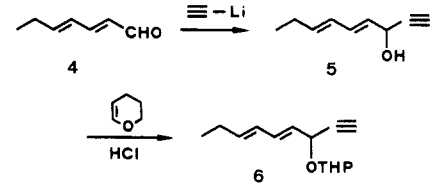
To avoid the difficulties encountered with the aforementioned nonselective preparations,[4] we chose an entirely different approach. In its key step, a modified[5] Whiting reaction[6] **2** → **3**, two of the



2 **3**

total five trans-oriented C=C double bonds in **1** are formed. This stereoselective reaction proceeds in one step starting with the precursor **2**, a derivative of an acetylenic diol.

According to a known method[7] lithium acetylide was added to *trans,trans*-hepta-2,4-dienal (**4**) to afford nona-4,6-dien-1-yn-3-ol (**5**) (bp 58–65 °C (0.01 mm), mp 8–10 °C, yield 67%), which in turn was transformed by 3,4-dihydro-2*H*-pyran together with a catalytic amount of hydrogen chloride to the tetrahydropyranyl derivative **6** (bp 108 °C (0.005 mm), yield 89%). Naturally, the

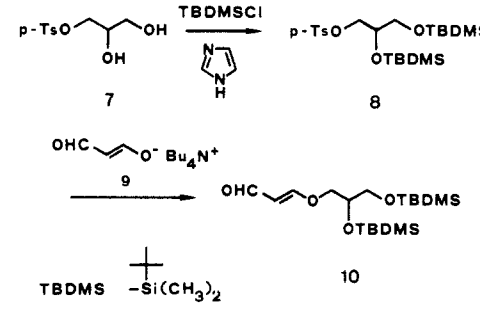


4 **5** **6**

trans-trans geometry of **4** was retained during these reactions. In the ^1H NMR spectrum of **6** no signals due to an isomer could be detected. Therefore **6** was most suitable to serve as the first building block in our synthesis.

To synthesize the other half of a precursor of the target molecule **1**, glyceryl *p*-toluenesulfonate (**7**) was protected[8] with *tert*-butyldimethylsilyl chloride and imidazol in dimethylformamide (room temperature, 6 h) to afford 2,3-bis(*tert*-butyldimethylsilyloxy)-propyl *p*-toluenesulfonate (**8**) in 91% yield after chromatography (silica gel, petroleum ether–ethyl acetate 98:2).

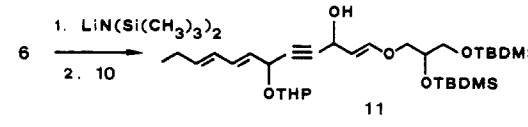
Up to now there existed no direct and convenient method[9] for the O-alkylation of malondialdehyde. We have found that the novel tetrabutylammonium salt **9** (mp 129–130 °C from glyme)—prepared in 67% yield from 1,1,3,3-tetraethoxypropane and 0.3 N aqueous hydrogen chloride (50 °C, 25 min) followed by addition of methanolic tetrabutylammonium hydroxide solution—easily reacted with the protected tosylate **8** (dry dimethylformamide, 1.5 equiv of **9**, concentrated solution, 50 °C, 22 h) to afford *trans*-3-[(2,3-bis[(*tert*-butyldimethylsilyl)oxy]-propyl)oxy]propenal (**10**) in 82% yield after chromatography



7 **8** **9** **10**

(silica gel, petroleum ether–ethyl acetate 9:1 and 4:1). Its ^1H NMR spectrum in CCl_4 showing a clean doublet of the —O—CH= resonance at 7.3 ppm with a coupling constant of 12.5 Hz revealed that the (oxopropenyl)oxy moiety had been linked with the complete trans stereoselectivity desired in the production of the second building block **10**.

At this stage the two units **6** and **10** were combined. Adding the preformed lithium derivative of **6**—prepared with 1.1 equiv of lithium bis(trimethylsilyl)amide (fresh colorless solution in tetrahydrofuran, −78 → 0 °C)—to the aldehyde **10** (−78 → −30 °C) furnished the liquid key compound **11**[10] in 72% yield after



11

(1) Bruce, W. R.; Varghese, A. J.; Furrer, R.; Land, P. C. *Cold Spring Harbor Conf. Cell Proliferation* **1977**, *3*, 1641–1646. Gupta, I.; Baptista, J.; Bruce, W. R.; Cho, C. T.; Furrer, R.; Gingerich, J. S.; Grey, A. A.; Marai, L.; Yates, P.; Krepinsky, J. J. *Biochemistry* **1983**, *22*, 241.

(2) Hirai, N.; Kingston, D. G. I.; Van Tassel, R. L.; Wilkins, T. D. *J. Am. Chem. Soc.* **1982**, *104*, 6149–6150.

(3) *Chem. Eng. News* **1982**, *60* (39), 22–23.

(4) (a) Gunatilaka, A. A. L.; Hirai, N.; Kingston, D. G. I. *Tetrahedron Lett.* **1983**, *24*, 5457–5460. (b) Nicolaou, K. C.; Zipkin, R.; Tanner, D. *J. Chem. Soc., Chem. Commun.* **1984**, 349–350. (c) De Wit, P. P.; Van Schaik, T. A. M.; Van Der Gen, A. *Recl. Trav. Chim. Pays-Bas* **1984**, *103*, 369–370.

(5) Claesson, A.; Bogentoft, C. *Acta Chem. Scand.* **1972**, *26*, 2540–2542.

(6) Nayler, P.; Whiting, M. C. *J. Chem. Soc.* **1954**, 4006–4009.

(7) (a) Midland, M. M. *J. Org. Chem.* **1975**, *40*, 2250–2252. (b) Cowie, J. S.; Landor, P. D.; Landor, S. R. *J. Chem. Soc., Perkin Trans. 1* **1973**, 720–724.

(8) Corey, E. J.; Venkateswarlu, A. *J. Am. Chem. Soc.* **1972**, *94*, 6190.

(9) (a) Klimko, V. T.; Protopopova, T. V.; Smirnova, N. V.; Skoldinov, A. P. *J. Gen. Chem. USSR (Engl. Transl.)* **1962**, *32*, 2913–2918. (b) Smithers, R. H. *J. Org. Chem.* **1978**, *43*, 2833–2838. (c) Maddaluno, J.; D'Angelo, J. *Tetrahedron Lett.* **1983**, *24*, 895–898.

(10) No attempts were made to separate the diastereomers or to determine their ratio.

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