449.7 nm is caused by internal scatter of the exciting laser line. It is present when the jet stream consists of distilled water but disappears when a 420-nm cutoff filter is placed in front of the entrance slit. The low-frequency peaks at 662 and 465 cm^{-1} are the M–C and M–N stretches, respectively.[9,10] The behavior of the 2148-cm^{-1} peak as a function of laser power is also shown in Figure 1. As the laser power decreases, the intensity of this peak decreases relative to that of the 449.7-nm scatter peak. A plot of the logarithm of the intensity of the Raman peak vs. the logarithm of the laser power gives a straight line with a slope of 2.3 ± 0.2, *proving that the 2148-cm^{-1} peak arises from an incoherent two-photon process.* The power dependences of the peaks in the metal–ligand stretching region could not be determined because of the background Raleigh scatter.[11]

The appearance of only one C–N mode in the excited-state Raman spectrum is probably a result of resonance enhancement of that mode in the excited state. In an attempt to observe other modes, both the 406- and 413-nm lines were used simultaneously with the goal of producing the excited state by absorption of the 406-nm line and observing resonance enhancement of other excited-state normal modes with the 413-nm line. The 2148-cm^{-1} C–N stretching mode was observed from both these laser lines, but no other normal modes were clearly detected. Apparently the 413-nm line is not different enough in frequency to provide resonance enhancement of any other modes. The technique of using several lines simultaneously is of great potential utility and is being explored further.

The C–N stretching frequency observed from the excited state of the complex is in the same region as those observed from the ground-state complex.[9-10] In order to assign the excited-state Raman peak, two orthogonal polarization direction were used. No readily distinguishable qualitative differences in the intensities were observed. These results must be interpreted with caution, because the intensities are extremely sensitive to small changes in the geometry, the position of the jet stream, etc. As a preliminary interpretation, the lack of a major intensity change under the two polarizations suggests that the excited-state Raman peak belongs to a nontotally symmetric normal mode. If this assignment is valid, the change in the stretching frequency between the ground and excited state is a maximum of only -6 cm^{-1}. If the excited state peak is the totally symmetric stretch, the shift would be a maximum of -14 cm^{-1}. In both cases, the shift is small.

The small shift is consistent both with the observed photochemical reactions[12] of the nitroprusside ion and with the molecular orbital interpretations of the bonding.[8] The primary photochemical reaction is loss of nitric oxide and aquation, yielding $Fe(CN)_5H_2O^{2-}$.[12] The metal–cyanide bonds are not broken. The excited-state Raman spectrum suggests that the metal–cyanide bonding is not strongly perturbed. The molecular orbital calculations show that the major cyanide component in the depopulated orbital is C–N *bonding* in character.[8] Thus depopulating this orbital should lead to C–N bond weakening and a Raman shift to lower frequencies. However, the populated orbital is mainly nitrosyl antibonding in character. Populating this orbital does not directly affect the C–N bond, but it indirectly changes the bonding by increasing the formal positive charge on the metal, decreasing the back-bonding to the cyanide, and thus strengthening the C–N bond leading to a Raman shift to higher frequency. The two effects occurring as a result of the electronic transition are thus in opposite directions and partially cancel, leading to only a small change in the C–N stretching frequency in the excited state.

Acknowledgment. We thank the National Science Foundation for financial support and Professor M. A. El-Sayed, J. Hsieh, and M. Nagumo for helpful discussions.

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[11] The dependence of the Raman signal intensity on the degree of focus provides a qualitative test of the origin of the signal. As expected, the intensity of the 2148-cm^{-1} peak increases as the focus is tightened. The peaks in the metal–ligand stretching region also exhibited this dependence on the focus, suggesting that they could also be excited-state Raman peaks. The qualitative nature of these observations prevents us from drawing quantitative conclusions.

[12] Wolfe, S. K.; Swinehart, J. H. *Inorg. Chem.* **1975**, *14*, 1049.

Neutral Alkylations via Palladium(0) Catalysis

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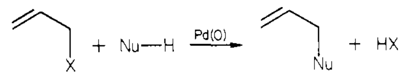
Received May 27, 1981

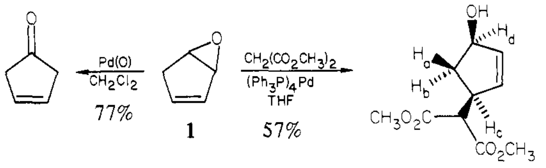
Alkylation reactions almost invariably involve either base or acid catalysis. Preclusion of such catalysts would generate one of the mildest ways to form C–C bonds. Palladium-catalyzed allylic alkylation[1] offers such an approach provided the leaving group X (eq 1) is sufficiently basic to remove a proton from Nu–H.



(1)

Unfortunately, an X^- which would be of sufficient basicity is normally too poor a leaving group in this reaction.[1b] In this paper, we wish to report that vinyl epoxides surprisingly offer a very nice solution to this problem and involve an unusual regioselectivity. Furthermore, the characteristics of the reaction indicate a fundamentally different reaction type than other reactions of vinyl epoxides.

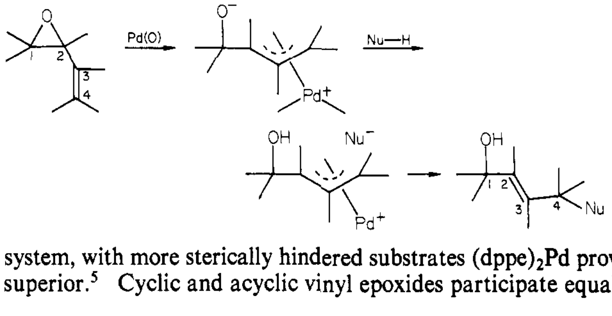
The recently reported palladium-catalyzed isomerization of vinyl epoxides to α,β-unsaturated ketones and/or dienols, which invoked an insertion of the palladium in the C–O bond, would appear to preclude their being substrates in allylic alkylation.[2] Nevertheless, while epoxide **1** is reported to isomerize to 3-cyclopenten-1-one with a Pd(0) catalyst, treatment of **1** with $(Ph_3P)_4Pd$ (**2**) in the presence of 1.2 equiv of malonic ester leads only to a single alkylation product **3**[3] (eq 2). Its regio- and stereochemistry is clearly assigned on the basis of the 270-MHz proton NMR spectrum where H_a (δ 1.58) couples with both H_c (δ 3.27) and H_d (δ 4.79) with similar couplings of J = 5.0 and 3.3 Hz, respectively, indicative of a trans orientation, and H_b (δ 2.56) couples with the same two hydrogens with appreciably larger couplings of J = 8.7 and 7.5 Hz, respectively, indicative of a cis relationship.[4]



1 **3**

(2)

Table I establishes the generality of the observation according to eq 3. While ~5 mol % of **2** generally serves as the catalytic system, with more sterically hindered substrates $(dppe)_2Pd$ proves superior.[5] Cyclic and acyclic vinyl epoxides participate equally



(3)

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[1] (a) For reviews, see: Trost, B. M. *Acc. Chem. Res.* **1980**, *13*, 385. *Tetrahedron* **1977**, *33*, 2615. (b) See: Tsuji, J.; Kobayashi, Y.; Kataoka, H.; Takahashi, T. *Tetrahedron Lett.* **1980**, 3393.

[2] Suzuki, M.; Oda, Y.; Noyori, R. *J. Am. Chem. Soc.* **1979**, *101*, 1623. Also see: Suzuki, M.; Watanabe, A.; Noyori, R. *Ibid.* **1980**, *102*, 2095.

[3] This compound has been fully characterized by spectral data and its elemental composition established by high-resolution mass spectroscopy and/or combustion analysis.

[4] Trost, B. M.; Verhoeven, T. R. *J. Am. Chem. Soc.* **1980**, *102*, 4730.

[5] Trost, B. M.; Runge, T. A.; Jungheim, L. N. *J. Am. Chem. Soc.* **1980**, *102*, 2840.

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Table I. Regioselective Neutral Alkylations of Vinyl Epoxides

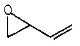
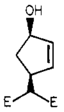
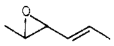
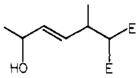
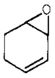
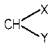
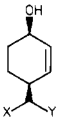
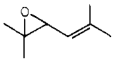
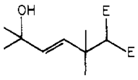
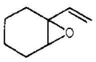
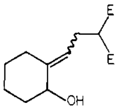
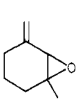
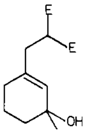
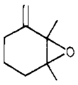
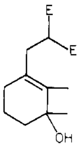
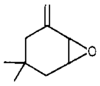
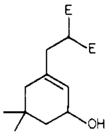
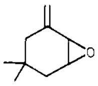
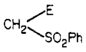
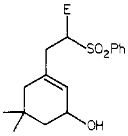
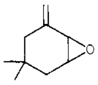
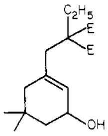
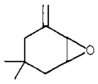
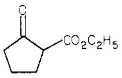
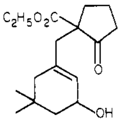
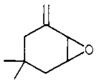
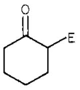
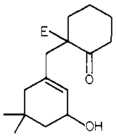
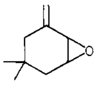
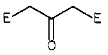
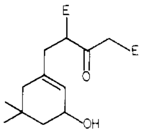
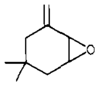
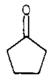
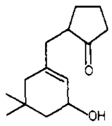
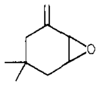
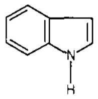
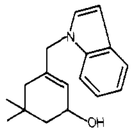
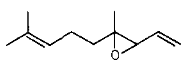
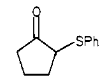
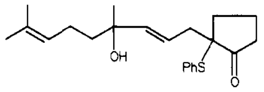
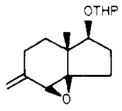
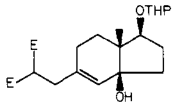
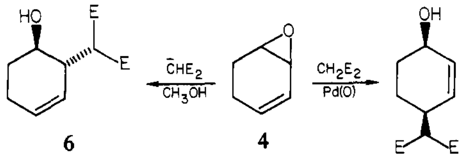
entry	vinyl epoxide	nucleophile[a]	product[a,c]	yield,[b] %
1		CH_2E_2		75
2		CH_2E_2		57
3		CH_2E_2		76
4				
		A, X = Y = E	X = Y = E	74
		B, X = E, Y = CO_2Ph	X = E, Y = CO_2Ph	61
		C, X = Y = $PhSO_2$	X = Y = $PhSO_2$	85
5		CH_2E_2		85
6		CH_2E_2		76
7		CH_2E_2		71
8		CH_2E_2		75
9		CH_2E_2		85
10				81
11		$C_2H_5CHE_2$		73
12				73
13				79
14				74

Table I (*Continued*)

entry	vinyl epoxide	nucleophile[a]	product[a,c]	yield,[b] %
15				29
16				62
17				72
18		CH_2E_2		87

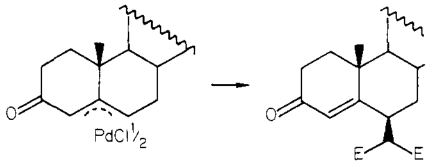
[a] The symbol E represents CO_2CH_3. [b] Isolated, pure products. [c] See ref 3.

well. The reaction proceeds with clean alkylation from the *same face as the oxygen of the epoxide and allyl inversion*—a fact which complements normal reactivity patterns. For example, vinyl epoxide **4** (eq 4) leads only to **5**[3] in the presence of Pd(0) but produces **6**, the product of direct substitution with inversion of configuration, under standard base-catalyzed conditions.[6] Substrate **7** (Table I, entries 9–16) was employed to examine the range of carbon acids that could be employed. Sterically hindered carbon acids (entries 4C, 11, 12, and 13) participate as effectively as their less hindered counterparts. It is most interesting to note that a simple ketone participated (entry 15), albeit in modest yield. Sulfenylated ketones are excellent partners (Table I, entry 17). The utility of β-ketosulfides in synthesis imparts special significance to this observation.[7] The stereochemistry of the resultant double bond in acyclic cases is predominantly (entry 1, ~5:1 *E*/*Z*) to exclusively (entries 3, 5, and 17) *E*. This feature reflects the general greater stability of the intermediate syn complexes compared to the anti isomers.[8]

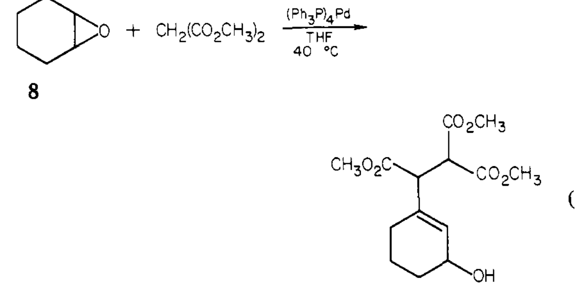


6 **4** **5** (4)

The total regiocontrol for formation of the new C–C bond distal to the hydroxyl group is extraordinary. From the present work and earlier observations[9,10] it appears that polar functional groups such as hydroxyl and carbonyl groups have a general directing effect in palladium-catalyzed alkylations. A substrate bearing an electron-withdrawing group directly on the double bond constitutes a specially interesting case since such groups are generally strong directors (cf. eq 5).[11] In the reaction of vinyl epoxide **8** where there is a direct competition of the two effects, the hydroxyl group still dominates (eq 6).

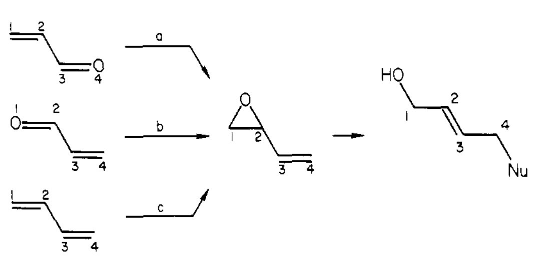


(5)



8 (6)

This approach to C–C bond formation provides an illustration of the ability of a transition metal to alter the normal rules of reactivity by allowing a totally neutral alkylation with completely different regio- and stereoselectivity. The general availability of vinyl epoxides further enhances its synthetic utility. For example, enones can be converted to vinyl epoxides by (a) olefin epoxidation,[12,13] followed by carbonyl olefination,[14] or (b) alkylidene transfer to the carbonyl group of an enone to form the epoxide.[15] In the former case, the overall alkylation involves inversion of the oxidation pattern by migrating the oxygen from C(3) to C(1) (eq 7, path a); in the latter case, the oxidation pattern is unchanged



(7)

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(6) Newman, M. S.; Vander Werf, C. A. *J. Am. Chem. Soc.* **1945**, *67*, 233.

(7) For reviews, see: Trost, B. M. *Acc. Chem. Res.* **1978**, *11*, 453. *Chem. Rev.* **1978**, *78*, 363.

(8) For example: Trost, B. M.; Verhoeven, T. R. *J. Am. Chem. Soc.* **1976**, *98*, 630; **1978**, *100*, 3435.

(9) See: Trost, B. M.; Klun, T. P. *J. Am. Chem. Soc.* **1979**, *101*, 6756. Klun, T. P., unpublished observations in these laboratories.

(10) Trost, B. M.; Schmuff, N. R.; Miller, M. J. *J. Am. Chem. Soc.* **1980**, *102*, 5979.

(11) Jackson, W. R.; Strauss, J. V. G. *Tetrahedron Lett.* **1975**, 2591. Collins, D. J.; Jackson, W. R.; Timms, R. N. *Ibid.* **1976**, 495. Jackson, W. R.; Strauss, J. V. *Aust. J. Chem.* **1977**, *30*, 2167. Collins, D. J.; Jackson, W. R.; Timms, R. N. *Ibid.* **1977**, *30*, 553.

(12) See: Wasson, R. L.; House, H. O. *Org. Synth. Collect. Vol. IV* **1963**, 552.

(13) Also epoxidation of an allyl alcohol followed by oxidation. For one example, see: Trost, B. M.; Salzmann, T. N. *J. Chem. Soc., Chem. Commun.* **1975**, 571. Trost, B. M.; Bogdanowicz, M. J.; Frazee, W. J.; Salzmann, T. N. *J. Am. Chem. Soc.* **1978**, *100*, 5512.

(14) Marino, J. P.; Abe, H. *Synthesis* **1980**, 872 and references therein.

(15) Trost, B. M.; Melvin, L. S. "Sulfur Ylides. Emerging Synthetic Intermediates"; Academic Press: New York, 1975.

(eq 7, path b). Alternatively, synthesis of the vinyl epoxide by selective epoxidation of a diene[16] translates into a 1,4 addition of the elements of OH and Nu across the termini of the diene (eq 7, path c). The characteristics of the reaction also clearly demonstrate that, in contrast to the reaction of vinyl epoxides with iron(0) complexes which involve C–O insertion[17] and in contrast to a similarly proposed pathway for the palladium-catalyzed isomerization,[2] this reaction presumably involves an ionization to a zwitterion with *inversion* in wh ich the epoxide oxygen serves as a leaving group (see eq 3). A new appreciation for the potential of transition-metal-catalyzed alkylations emerges from this reaction.

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Supplementary Material Available: Spectral and analytical data for compounds (3 pages). Ordering information is given on any current masthead page.

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(16) Potassium carbonate buffered MCPBA epoxidations were employed. See: Crandall, J. K.; Banks, D. B.; Colyer, R. A.; Watkins, R. J.; Arrington, J. P. *J. Org. Chem.* **1968**, *33*, 423.

(17) Aumann, R.; Fröhlich, K.; Ring, H. *Angew. Chem., Int. Ed. Engl.* **1974**, *13*, 275.

Regiochemistry of the Cycloaddition of a Substituted Trimethylenemethanepalladium Complex

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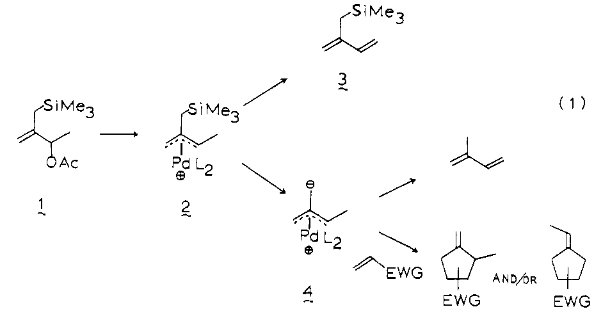
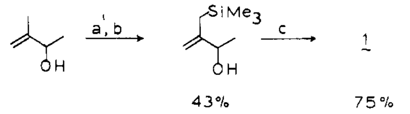
The utility of the cycloaddition of transition-metal complexed trimethylenemethanes in synthesis depends upon the availability of substituted systems.[1-3] However, substitution does not represent a simple structural change. Consider the case of introduction of a methyl group using the silicon based bifunctional conjunctive reagent **1** as the precursor (reaction 1). At the first intermediate **2**, competition exists between deprotonation[4] to form the stable molecule **3** and desilylation to form a reactive intermediate **4**. In the latter, a competition exists between simple tautomerism to isoprene vs. a bimolecular trapping to give the cycloadduct. For cycloaddition to be successful, it must compete with two apparently highly favorable reaction pathways. In addition, the question of regioselectivity of any cycloaddition exists.

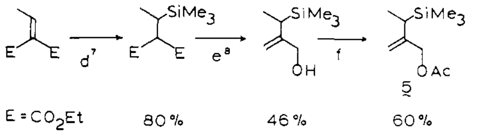


(1)

Two isomeric methyl substituted precursors **1**[5,6] [bp 70–73 °C (4.5 mm)] and **5**[5,6] [bp 70–75 °C (4.5 mm)] are available as summarized in reactions 2 and 3. For cycloaddition, we chose cyclopentenone as our key trap. With the parent TMM–PdL_2 and this enone, cycloaddition proceeds in 56% yield—a fact which can be contrasted with an unsuccessful attempt to synthesize the same adduct by a titanium tetrachloride catalyzed reaction of [2-(chloromethyl)allyl]silane with this trap.[9] As illustrated in reaction 4, not only did cycloaddition proceed—a fact that indicated our fears for competing reactions to be unwarranted—but essentially a single product **6**[5] (as a 1:1 stereoisomeric mixture) arises. By VPC and 270-MHz NMR analysis, very small amounts (<5%) of other products were observed, one of which appears to be a regioisomer of **6**.[10] Thus, in this case, the regioselectivity is >20:1. Mild acid-catalyzed double-bond migration converted **6** to **7**[5] and confirms the stereoisomeric nature of **6**.

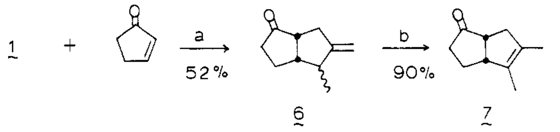


(2)



(3)

(a) *n*-BuLi, THF, ether, TMEDA, room temperature, then Me_3SiCl; (b) 1 N H_2SO_4, THF, room temperature; (c) AcCl, C_5H_5N, catalytic (dimethylamino)pyridine, 0 °C; (d) Me_3SiLi, HMPA, THF, −78 °C; (e) NaH, THF, then LAH, reflux; (f) AcCl, C_5H_5N, CH_2Cl_2, 0 °C



(4)

(a) 3.8 mol % $(Ph_3P)_4Pd$, 1.3 mol % Ph_3P, reflux; (b) 15 mol % $TsOH{\cdot}H_2O$, $CDCl_3$, 50 °C

While a detailed analysis of the Eu-induced shifts in the 270-MHz NMR spectrum initially allowed assignment of the regiochemistry, in order to confirm this critical assignment and illustrate the synthetic potential, we converted **6** into **8**, mp 57.5–58.0 °C (lit.[11] mp 58.5–59.0 °C) (reaction 5), a precursor of chrysomelidial **9**, the larval defensive secretion of a chrysomelide beetle.[12,13]

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† Standard Oil of Ohio Fellow, 1980.

(1) (a) Trost, B. M.; Chan, D. M. T. *J. Am. Chem. Soc.* **1979**, *101*, 6429, 6432. (b) Trost, B. M.; Chan, D. M. T. *Ibid.* **1980**, *102*, 6359.

(2) For codimerizations of olefins with methylenecyclopropanes, see: Binger, P. *Synthesis* **1973**, 427. Binger, P.; Schuchardt, U. *Angew. Chem., Int. Ed. Engl.* **1977**, *16*, 249. *Chem. Ber.* **1980**, *113*, 3334.

(3) Also see: Balavoine, G.; Eskenazi, C.; Guillemot, M. *J. Chem. Soc., Chem. Commun.* **1979**, 1109. Dallas, B. K.; Hughes, R. P. *J. Organomet. Chem.* **1980**, *184*, C67. Inoue, Y.; Hibi, T.; Kawashima, Y.; Hashimoto, H. *Chem. Lett.* **1980**, 1521.

(4) Pd-catalyzed elimination to dienes is well precedented. Trost, B. M.; Verhoeven, T. R.; Fortunak, J. *Tetrahedron Lett.* **1979**, 2301. Tsuji, J.; Yamakawa, T.; Kaito, M.; Mandai, T. *Ibid.* **1978**, 2075.

(5) This compound has been fully characterized by IR, NMR, and mass spectroscopy, and elemental composition established by high-resolution mass spectrometry and/or combustion analysis. Yields of adducts are normally based on recovered trap.

(6) **1**: IR (neat) 1739, 1637, 850 cm^{-1}; NMR (270 MHz, $CDCl_3$) δ 0.05 (s, 9 H), 1.31 (d, J = 6.6 Hz, 3 H), 1.46 (dd, J = 14.2, 1.1 Hz, 1 H), 1.60 (dd, J = 14.2, 1.1 Hz, 1 H), 2.06 (s, 3 H), 4.67 (br s, 1 H), 4.90 (t, J = 1.1 Hz, 1 H), 5.20 (q, J = 6.6 Hz, 1 H). **5**: IR (neat) 1745, 1640, 840 cm^{-1}; NMR (270 MHz, $CDCl_3$) δ 0.01 (s, 9 H), 1.14 (d, J = 7.5 Hz, 3 H), 1.56 (q, J = 7.5 Hz, 1 H), 2.09 (s, 3 H), 4.45 (dm, J = 13 Hz, 1 H), 4.46 (dm, J = 13 Hz, 1 H), 4.73 (m, 1 H), 4.97 (m, 1 H).

(7) Still, W. C. *J. Org. Chem.* **1976**, *41*, 3063.

(8) Marshall, J. A.; Andersen, N. H.; Hochstetler, A. R. *J. Org. Chem.* **1967**, *32*, 113.

(9) Knapp, S.; O'Connor, U.; Mobilio, D. *Tetrahedron Lett.* **1980**, 4557.

(10) A very small absorption at δ 1.56 (dm, J = 6.5 Hz) was assigned to an isomer of **6** bearing the methyl group on the double bond.

(11) Kon, K.; Isoe, S. *Tetrahedron Lett.* **1980**, 3399.

(12) Meinwald, J.; Hones, T. H.; Eisner, T.; Hicks, K. *Proc. Natl. Acad. Sci. U.S.A.* **1977**, *74*, 2189.

(13) Meinwald, J.; Johnes, T. H. *J. Am. Chem. Soc.* **1978**, *100*, 1883. Jones, T. H.; Blum, M. S.; Fales, H. M. *Tetrahedron Lett.* **1980**, 1701.

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