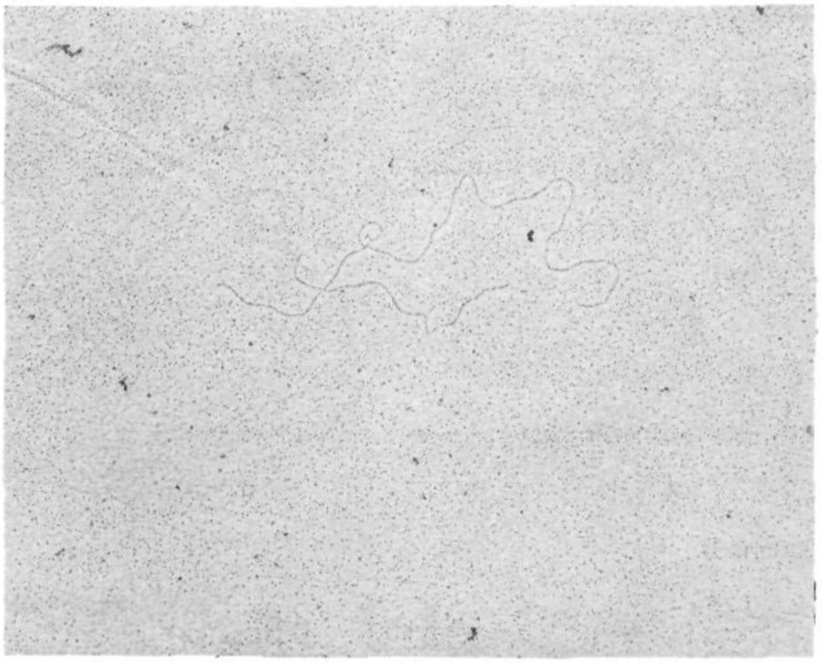

Figure 1. Cross of the 7 200 and 14 000 base pair restriction fragments from λ.[28]

dark.[15] This is irradiated in the visible (>400 nm) for 1 h.[17] The phage is burst with 1% SDS and treated with 1 mg/mL proteinase K at 37 °C for 4 h.[19] Gel electrophoresis[20] (0.3% agarose) of the BAMO/irradiated DNA (48 000 base pairs)[22] reveals higher mobility nucleic acid than the naked uncross-linked DNA. Examination of this "high mobility DNA" by electron microscopy reveals rosettes, tangled structures that may be the result of knotting.[23,25]

A protocol that affords structural data easier to interpret is shown in Scheme II. The bacteriophage λ (10^{-4} M in base pairs) is successively treated with BAMO (10^{-6} M), >400-nm light, and 1% SDS with 1 mg/mL proteinase K. The bacteriophage DNA is then purified by chromatography on Sepharose CL-2B,[26] dialyzed into an appropriate buffer,[27] treated with the restriction enzyme Mst II,[28] and spread for electron microscopy (EM).[23] Controls in the absence of cross-linker show 98% linear restriction fragments and 2% crossed structures.[30] Bacteriophage λ treated with BAMO reveal 17% crossed structures.[30] Using tritiated BAMO, we find that 6% of the reagent is covalently bound to the DNA after irradiation.[31] Because total cross-linker per DNA base pair is 0.01, an upper limit of 30 BAMO molecules/48 000 base pairs of DNA in bacteriophage λ affords the 17% "crossed" restriction fragments observed in the electron microscope (Figure 1). This suggests that BAMO is both an efficient reagent and a modest perturbation on the intact system.

One final piece of methodology will be needed before the assignment of the position of the interhelical crosslink is unique. The length of the four arms on a crossed structure can be experimentally measured from electron micrographs. Our choice of restriction enzymes and knowledge of the λ DNA restriction map, which is well documented,[29,33] allow identification of which final restriction fragments are cross-linked. However, the alignment of the crossed fragments remains to be resolved.[34] When this is accomplished, the structural data for interhelical nearest neighbors for packaged DNA will be available. Whether these "interhelical nearest neighbor" maps can be interpreted uniquely in light of conventional models for λ DNA packaging such as ball of yarn,[7,35] coaxial spool,[7,35] chain-folded structure,[7] or coil of coils[36] remains to be seen and will be reported in due course.

Acknowledgment. We are grateful to the National Institutes of Health (GM 22909) for generous support and to Professor Charles Cantor, Columbia University, for helpful discussions.

Registry No. 1, 82209-34-5; **2**, 52671-19-9; **3**, 82209-35-6; **4**, 3386-18-3; **5**, 82209-36-7.

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[15] Bacteriophage λ was produced by thermal induction of the lysogen w 3110 (λcI 857S7) and purified by CsCl density gradient centrifugation in 10 mM Tris HCl (pH 7.5) and 10 mM $MgSO_4$.[16] We thank B. Seed for assistance in the preparation of bacteriophage λ.

[16] Thomas, J. O. *J. Mol. Biol.* **1974**, *87*, 1–9.

[17] Photolysis was performed with a desk lamp equipped with two Westinghouse No. F15T8/CW light bulbs. The light was passed through a 5-cm 2.9 M aqueous sodium nitrite filter.[18]

[18] Bolton, P. H.; Kearns, D. R. *Nucleic Acids Res.* **1978**, *5*, 4891–4903.

[19] Proteinase K was obtained from Boehringer Mannheim Biochemicals.

[20] Agarose gels were poured and run on a horizontal gel apparatus similar to that of McDonnell et al.[21] with use of a buffer system consisting of 40 mM Tris, 5 mM sodium acetate, and 1 mM Na_2 EDTA adjusted to pH 7.8 with glacial acetic acid.

[21] McDonnell, M. W.; Simon, M. N.; Studier, F. W. *J. Mol. Biol.* **1977**, *110*, 119–146.

[22] Fiandt, M.; Honigman, A.; Rosenvold, E. C.; Szybalski, W. *Gene* **1977**, *2*, 289–293.

[23] DNA samples were spread for electron microscopy with use of the formamide modification of the Kleinschmidt technique.[24]

[24] Davis, R. W.; Simon, M. N., Davidson, N., *Meth. Enzymol. 21*, **1971**, 413–428.

[25] For examples of electron microscopy of bacteriophage λ DNA see (a) ref 16. (b) Chattoraj, D. K.; Inman, R. B. *J. Mol. Biol.* **1974**, *87*, 11–22.

[26] Sepharose CL-2B was obtained from Pharmacia Fine Chemicals.

[27] Buffer conditions for the enzyme Mst II are 6 mM Tris, 150 mM NaCl, 6 mM $MgCl_2$, (pH 7.4) with 6 mM 2-mercaptoethanol, and 100 μg/mL bovine serum albumin.

[28] Restriction endonuclease Mst II was obtained from New England Biolabs. Mst II cleaves λcI 857S7 DNA at two sites, approximately 26 400 and 33 600 bp from the left end of the genome, yielding three restriction fragments of lengths 26 400, bp, 7 200, and 14 400 bp.[29]

[29] Mst II cleavage map was obtained from New England Biolabs.

[30] A DNA species observed in the electron microscope was scored as a "linear restriction fragment" when it exhibited only two distinct ends. A DNA species was scored as a "crossed structure" when 2 N distinct ends (where *N* > 1) were continuously connected. A total of 500 DNA structures were counted for the BAMO-treated and control samples.

[31] Tritiated BAMO was synthesized according to Scheme I by using radiolabeled diamine **5**.[32] Specific activity is 1.1 Ci/mmol.

[32] Diamine **5** was custom labeled by New England Nuclear and redistilled (bulb to bulb, 230 °C at 5 μm) prior to use.

[33] Szybalski, E. H.; Szybalski, W. *Gene* **1979**, *7*, 217–270.

[34] Correct alignment of the crossed restriction fragments requires assignment of the directionality of each fragment (left to right).

[35] Richards, K.; Williams, R.; Calendar, R. *J. Mol. Biol.* **1973**, *78*, 255–259.

[36] Kilkson, R.; Maestre, M. F. *Nature (London)* **1962**, *195*, 494–495.

Cobalt Nitro Complexes as Oxygen Transfer Agents. 4.[1] Epoxidation of Olefins

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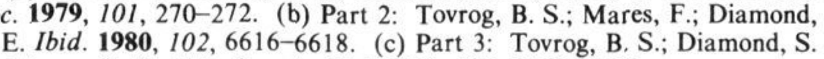
Epoxidation of propylene and higher olefins is one of the most important oxidation reactions in organic chemistry and in the chemical industry. With the exception of thallium(III),[2] all other oxidants capable of olefin epoxidation are peroxidic in nature.[3] They are obtained by reduction of molecular oxygen to hydrogen peroxide and by oxidation of alkanes to alkyl hydroperoxides or aldehydes to peracids. Under ideal conditions, only one oxygen atom of molecular oxygen is incorporated in the product epoxide while the other is utilized in the formation of side products. In the case of olefin oxidation by thallium(III) (eq 1) it is the en-



$$\mathrm{Tl(III)} + H_2O + RCH{=}CH_2 \rightarrow \mathrm{Tl(I)} + 2H^+ + \overset{O}{RCH{-}CH_2} \quad (1)$$

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[1] (a) Part 1: Tovrog, B. S.; Diamond, S. E.; Mares, F. *J. Am. Chem. Soc.* **1979**, *101*, 270–272. (b) Part 2: Tovrog, B. S.; Mares, F.; Diamond, S. E. *Ibid.* **1980**, *102*, 6616–6618. (c) Part 3: Tovrog, B. S.; Diamond, S. E.; Mares, F.; Szalkiewicz, A. *Ibid.* **1981**, *103*, 3522–3526.

[2] Brill, W. F. U.S. Patent 4 021 453, issued May 3, 1977 to Halcon International, Inc.

[3] Sheldon, R. A.; Kochi, J. K. "Metal Catalyzed Oxidations of Organic Compounds"; Academic Press: New York, 1981; Chapters 3 and 9 and references therein.

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Scheme I. Oxygen Transfer from Metal Nitro Complexes to Olefins Activated by Palladium(II)

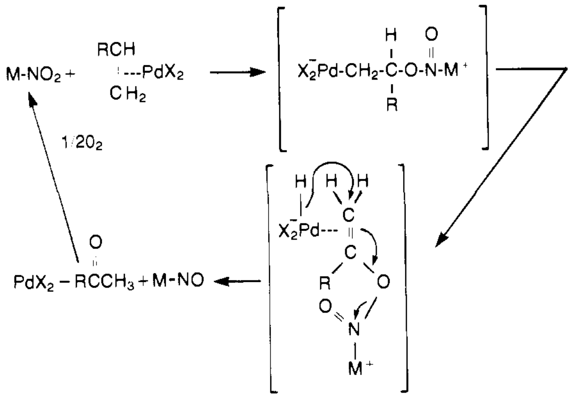
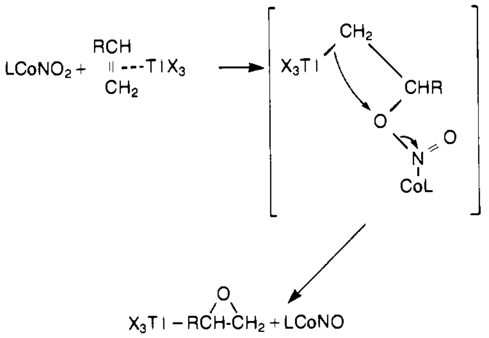


Table I. Oxidation of Olefins by a Bimetallic Cobalt–Thallium System[a]

substrate	cobalt, mmol	solvent	time, h	temp, °C	epoxide, mmol	ketone, mmol
1-octene	0.320	THF	5	60	0.165	tr
1-octene		THF	5	60	0.030	tr
1-octene	0.321	$CHCl_3$	2	RT[b]	0.176	0.097
1-octene		$CHCl_3$	3	RT	0.010	tr
propylene	0.317	THF	3	60	0.139	0.009
propylene		THF	3	60	0.010	tr
propylene	0.327	$CHCl_3$	1	RT	0.172	0.047
propylene		$CHCl_3$	1	RT	tr	tr

[a] In all cases the following materials were present in the reaction mixture: thallium benzoate (~1 g), benzoic acid (~650 mg), olefin (~1 g), solvent (~10 mL), and undecane (internal standard, ~75 mg). [b] Room temperature.

Scheme II. Oxygen Transfer from Metal Nitro Complexes to Olefin Activated by Thallium(III)



ergetically unfavorable reoxidation of thallium(I) to thallium(III) and the cumbersome recycle of thallium(III) that make the system impractical. Thus, there is a need for a different approach to olefin epoxidation by molecular oxygen.

Previously, we demonstrated a novel approach to specific oxidation of organic substrates that consists of oxygen transfer from the nitro ligand of a metal nitro complex to an organic substrate accompanied by the formation of the corresponding nitrosyl complex.[1] The catalytic cycle is then completed by reoxidation of the nitrosyl ligand by molecular oxygen. The system represented by py(saloph)$CoNO_2$ (**1**) or py(TPP)$CoNO_2$ (**2**) oxidized phosphines in slightly acidic media.[1a] Amplification of this mild solvent effect by employing strong Lewis acids allowed us to extend the use of nitro complexes to the oxidation of sulfides, alcohols, and 1,3-cyclohexadiene.[1c]

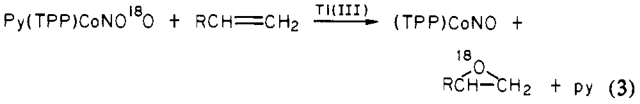
Recently, we utilized the fact that the nitro ligand can be regarded as a monoanionic oxygen-centered nucleophile. Thus, activation of olefins toward nucleophilic attack by π coordination to palladium(II) resulted in the oxidation of ethylene to acetaldehyde and of higher olefins to ketones as summarized in Scheme I.[1b]

It must be stressed that the formation of acetaldehyde and ketones is a consequence of β-hydride elimination and hydride transfer mediated by the olefin activator, palladium(II). This mechanism suggests that the use of olefin activators other than palladium(II), which are not capable of promoting the β-hydride elimination, may lead to epoxides. We now report our initial results in the area of olefin epoxidation which confirm that this postulate is indeed correct.

In the presence of water, oxidation of olefins by thallium(III) produces epoxides[2] (eq 1) rather than ketones, which are the normal products of olefin oxidation by palladium(II). This suggested that thallium(III) might possess the properties required for olefin epoxidation when coupled to the cobalt nitro complexes **1** or **2**. Indeed, in dry solvents such as tetrahydrofuran and chloroform, oxidation of olefins by **2** in the presence of thallium(III) benzoate results in moderate yields of epoxides (Table I). In tetrahydrofuran the oxidation of both 1-octene and propylene proceeds to approximately 50% completion after 5 h at 60 °C. Prolonged reaction times have little effect on the yields. The epoxide (either octene oxide or propylene oxide) was identified both by coinjection of an actual sample on a gas chromatograph and by gas chromatographic–mass spectroscopic analysis. Only a very small amount of ketone (2-octanone or acetone) was detected. These results are to be contrasted to those in chloroform. After approximately 2 h at room temperature, high yields of the products (based on **2**) are obtained. In these cases, the ratio of epoxide to ketone varies in the range of approximately 2:1 to 4:1.

A series of blank reactions was also carried out. Except for the absence of the cobalt nitro complex, these were identical with the above experiments. In all cases, small amounts of products were formed (table). This demonstrates the great sensitivity of thallium(III) to even traces of water present in the reagents and/or solvents. A partially labeled[4] cobalt nitro complex (44% ^{18}O) was prepared by oxidation of the corresponding unlabeled nitrosyl complex by oxygen-18 (eq 2). This complex was then utilized

$$(TPP)CoNO + py + {}^1/{}_2{}^{18}O_2 \rightarrow py(TPP)CoNO^{18}O \quad (2)$$



$$Py(TPP)CoNO^{18}O + RCH{=}CH_2 \xrightarrow{Tl(III)} (TPP)CoNO + RCH\overset{^{18}O}{-}CH_2 + py \quad (3)$$

for the oxidation of 1-octene mediated by thallium(III) (eq 3). Gas chromatographic–mass spectroscopic analysis of the product epoxide revealed approximately 44% of ^{18}O in the epoxide oxygen, in agreement with the theoretical value. At the conclusion of a reaction, in which anhydrous thallium(III) chloride[5] was used instead of a mixture of thallium(III) benzoate and benzoic acid, the cobalt complex was isolated and determined by IR to be a mixture of nitrosyl and nitro complexes, as expected.[6] These results demonstrate conclusively that the source of the oxygen in the product epoxides is the nitro ligand of the cobalt complex and suggest that the reaction mechanism can be represented by Scheme II. Importantly, during the epoxidation, thallium(III) should remain in the trivalent oxidation state. Thus, in theory, the stoichiometric epoxidation reaction in Scheme II may be converted into a catalytic system by the introduction of molecular oxygen as the oxidant. However, in the system studied thus far, a competing side reaction results in reduction of the thallium(III) cocatalyst. In analogy with eq 1, this reaction involves nucleophilic attack of benzoic acid on the thallium(III) coordinated olefin (eq 4). This leads to the formation of 2-octenylbenzoate, detected by gas chromatographic–mass spectroscopic analysis of the re-

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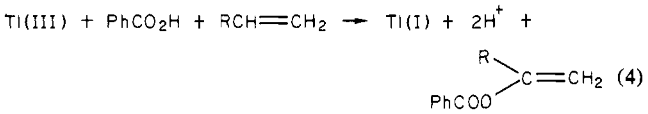
[4] The ^{18}O-labeled nitro complex of **2** was found to contain approximately 44% ^{18}O as determined by mass spectroscopic analysis. The fragments observed in the mass spectrometer probe correspond to pyridine, (TPP)Co, NO_2, and $NO^{18}O$.

[5] Prepared by oxidation of thallium(I) chloride by chlorine: Cotton, F. A.; Johnson, B. F. G.; Wing, R. M. *Inorg. Chem.* **1965**, *4*, 502–507.

[6] Thallium(III) benzoate was replaced by thallium(III) chloride since the carbonyl band of the benzoate obscures the nitrosyl band of reduced **2**. The amount of nitrosyl complex formed approximately parallels the amount of epoxide and ketone detected in the reaction mixture.



$$\mathrm{Tl(III)} + \mathrm{PhCO_2H} + \mathrm{RCH{=}CH_2} \rightarrow \mathrm{Tl(I)} + 2\mathrm{H}^+ + \mathrm{(R)(PhCOO)C{=}CH_2} \quad (4)$$

action mixture. Therefore, good yields of epoxides are formed only if excess thallium(III) relative to **2** is employed.

Our future work will be directed toward cocatalysts that avoid this side reaction and allow conversion of this stoichiometric epoxidation into a catalytic system.

Acknowledgment. We thank J. Smith, H. Njuguna, and E. McCarthy for GC-MS and MS analysis.

Registry No. 1-Octene, 111-66-0; propylene, 115-07-1; cobalt, 7440-48-4; thallium, 7440-28-0.

Epoxidation of Cyclic Alkenes by Bis(acetonitrile)chloronitropalladium(II): On the Role of Heterometallacyclopentanes and β-Hydrogen Elimination in the Catalytic Oxidation of Alkenes

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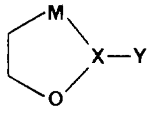
Selective (nonradical) alkene oxidation, epoxidation in particular, is a commercially important but technologically difficult procedure. Transition-metal dioxygen[1,2] and alkyl peroxide[3,4] complexes have been widely investigated in this regard, the latter being key intermediates in the Halcon propylene epoxidation process.[4b,d,5] Unsolved problems include the production of stoichiometric coproducts[6] and the lack of definitive mechanistic information due in large measure to the absence of detectable reaction intermediates. Catalysts based on the nitro–nitrosyl redox couple[7–9] offer a potential solution to the coproduct problem since symmetrical oxygen cleavage preceeds interaction with the substrate (eq 1 and 2). We report here the first example of the

$$\mathrm{M(NO)} + {}^1/{}_2\mathrm{O_2} \rightarrow \mathrm{M(NO_2)} \qquad (1)$$

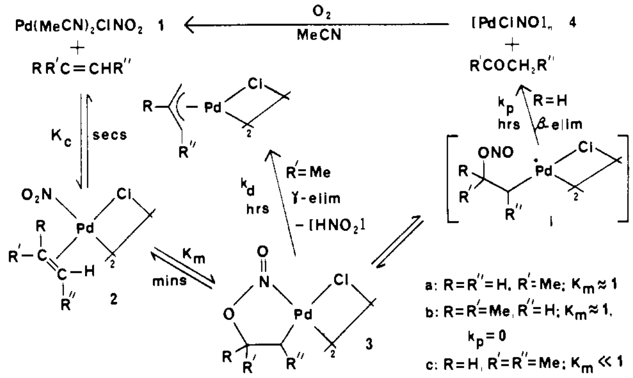
$$\mathrm{M(NO_2)} + \mathrm{L} \rightarrow \mathrm{M(NO)} + \mathrm{LO} \qquad (2)$$

application of this type of catalyst to alkene epoxidation,[10] together with the isolation and characterization of an intermediate heterometallacyclopentane of type Ia. Related metallacyclic intermediates Ib and Ic have been widely proposed without substantiation in the oxidation of unactivated alkenes by dioxygen[1a,b,2a,c,d] and alkyl peroxide[3a,b,4c] complexes, respectively.

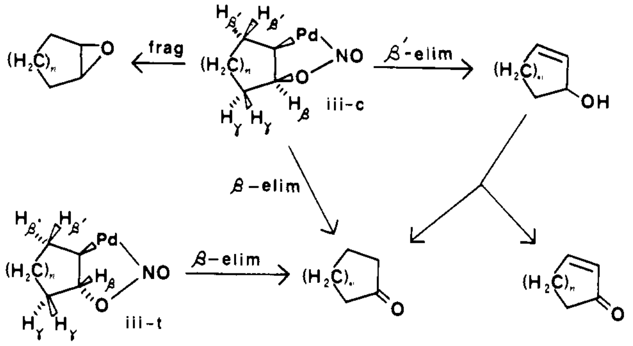


Ia: X=N, Y=O
Ib: X=O, Y=–
Ic: X=O, Y=R

Scheme I



Scheme II



We have shown that bis(acetonitrile)chloronitropalladium(II) (**1**) reacts with linear alkenes to give ketones via spectroscopically detectable alkene (**2**) and heterometallacyclopentane (**3**) complexes (Scheme I).[7] While complex **2** has precedent in the well-known dichloro analogue $[\mathrm{Pd(alkene)Cl_2}]_2$,[11] metallacycle **3** represents a new structural type.[12] Our attempts to isolate and fully characterize such a complex have been hampered by facile equilibria and decomposition reactions (Scheme I). Ketone formation may proceed via i, a ring-opened isomer of **3** (Scheme I),[13] where coordinative unsaturation[14] and of 0° Pd–C–C–H dihedral angle[14b] favorable to elimination are more readily accessible than in metallacycle **3** itself. This additional reaction path, which is not available to carbametallacyclopentanes, may account for the scarcity of heterometallacyclopentanes compared to their ubiquitous carbocyclic analogues.[14b,15]

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[2] Dioxygen complexes are implicated in a number of other systems: (a) Read, G.; Walker, P. J. C. *J. Chem. Soc., Dalton Trans.* **1977**, 883–888. (b) Holland, D.; Milner, D. J. *Ibid.* **1975**, 2440–2443. (c) Tang, R.; Mares, F.; Neary, N.; Smith, D. E. *J. Chem. Soc. Chem. Commun.* **1979**, 274–275. (d) Mimoun, H.; Perez Machirant, M. M.; Serēe de Roche, I. *J. Am. Chem. Soc.* **1978**, *100*, 5437–5444. (e) Nyberg, E. D.; Drago, R. S. *Ibid.* **1981**, *103*, 4966–4968.

[3] (a) Mimoun, H.; Charpentier, R.; Mitschler, A.; Fischer, J.; Weiss, R. *J. Am. Chem. Soc.* **1980**, *102*, 1047–1054. (b) Bregeault, J.-M.; Mimoun, H. *Nouv. J. Chim.* **1981**, *5*, 287–289. (c) Strukul, G.; Ros, R.; Michelin, R. A. *Inorg. Chem.* **1982**, *21*, 495–500.

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[5] Parshall, G. W. "Homogeneous Catalysis"; Wiley: New York, 1980; pp 115–117.

[6] Epoxidations based directly or indirectly on molecular oxygen, the reagent of choice, invariably lead to the loss of one oxygen atom per O_2 molecule to coproduct formation, e.g., alcohols or carbon dioxide and water.

[7] Andrews, M. A.; Kelly, K. P. *J. Am. Chem. Soc.* **1981**, *103*, 2894–2896.

[8] Tovrog, B. S.; Mares, F.; Diamond, S. E. *J. Am. Chem. Soc.* **1980**, *102*, 6616–6618.

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[10] Just prior to submission of this work, we learned of the demonstration of metal nitro catalyzed epoxidation of terminal alkenes: Diamond, S. E.; Mares, F.; Szalkiewicz, A.; Muccigrosso, D. A.; Solar, J. P. *J. Am. Chem. Soc.*, preceeding paper in this issue.

[11] Kharasch, M. S.; Seyler, R. C.; Mayo, F. R. *J. Am. Chem. Soc.* **1938**, *60*, 882–884.

[12] Two reports have described nonmetallacyclic alkyl nitrite complexes: (a) Read, C. A.; Roper, W. F. *J. Chem. Soc., Dalton Trans.* **1972**, 1243–1246. (b) Walsh, J. L.; Bullock, R. M.; Meyer, T. J. *Inorg. Chem.* **1980**, *19*, 865–869.

[13] The Pd–N bond in metallacycle **3** must be relatively weak since alkyl nitrites do not displace the labile acetonitrile ligands in bis(acetonitrile)dichloropalladium(II) (M.A.A., unpublished observation).

[14] (a) Reger, D. L.; Culbertson, E. C. *J. Am. Chem. Soc.* **1976**, *98*, 2789–2794. (b) McDermott, J. X.; White, J. F.; Whitesides, G. M. *Ibid.* **1976**, *98*, 6521–6528.

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