Ozonolyses of Acetylenes: Trapping of α-Oxo Carbonyl Oxides by Carbonyl Compounds and Stabilization of α-Oxo Ozonides by Derivatizations

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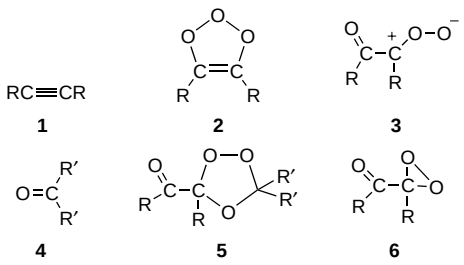
Ozonolyses of 2-butyne (**7**) or of 3-hexyne (**14**) in the presence of carbonyl compounds (aldehydes, ketones, acid derivatives) afforded the corresponding mostly labile monocyclic α-oxo ozonides (**9**, **13a**, **16**), which could be stabilized and, hence, isolated by subsequent conversion into α-methoximino derivatives. Ozonolyses of 1,4-diacyloxy-substituted (**19**) and 1-acyloxy-substituted 2-butynes (**27**) gave bicyclic ozonides (**22**, **31**) by intramolecular [3 + 2]-cycloadditions of the corresponding carbonyl oxide intermediates (**20**, **29**). These ozonides could also be stabilized by reactions with *O*-methylhydroxylamine to give *O*-methyloximes (**23c**, **32**) or with diazomethane to give epoxy ozonides (**25**, **34**).

Introduction

By analogy with the mechanism of ozone olefin reactions, ozonolyses of acetylenes (**1**) are postulated to proceed *via* intermediates of types **2** and **3**.[1a] However, while carbonyl oxide intermediates generated by ozonolyses of olefins undergo facile cycloadditions with carbonyl compounds to give ozonides, we are not aware of any ozonides of type **5**, derived from reactions of intermediates of type **3** with carbonyl compounds of type **4**, although carbonyl compounds are produced as anomalous ozonolysis products of acetylenes[2] and are, thus, present during such ozonolysis reactions. The fact that no ozonides **5** have been found in ozonolyses of acetylenes (**1**) could be due either to special properties of α-oxo carbonyl oxides (**3**), such as isomerizations to give the corresponding α-oxo 1,2-dioxiranes (**6**)[3] or premature decompositions by free radical pathways,[4] or to the known instability of α-oxo ozonides of type **5**.[1b,5]

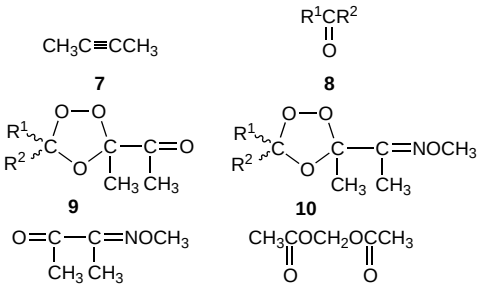


1 **2** **3**

4 **5** **6**

In this investigation, we have tried to get answers to these questions by ozonizing acetylenes (**1**) in the presence of added carbonyl compounds (**4**) and by stabilization of the anticipated α-oxo ozonides **5** by converting their α-oxo groups into the less destabilizing[6] methoximino groups (methoxyimino, CH_3ON═). To this end, 1:1 mixtures of an acetylene and of a carbonyl compound in CH_2Cl_2 were treated with ozone at low temperatures, and the cold crude reaction products were immediately admixed with a precooled solution of *O*-methylhydroxylamine in methanol.

Chart 1



7 **8** **9** **10** **11** **12**

	R^1	R^2	**9**(%)	**10**(%)[b]
a	H	H	nd	9
b	H	C_6H_5	nd	12
c	H	CH_3	17[a]	6
d	CH_3	CH_3	17[a]	6
e	CH_3	CH_2Cl	12[a]	15
f	CH_3	CF_3	42[a]	9
g	$(CH_2)_5$		8[a]	5
h	CH_3	CN	37[a]	14
i	H	OCH_3	23[a] 12[b]	7
j	H	OC_2H_5	29[a] 14[b]	9

[a]Determined in the product mixture by ^{1}HNMR analysis. [b]Yield of isolated products. nd = not detected.

Results

Ozonolyses of 2-butyne (**7**) in the presence of the aldehydes **8a**−**c**, of the ketones **8d**−**g**, of the acyl cyanide **8h**, and of the esters **8i** and **8j** followed by treatment with *O*-methylhydroxylamine gave the corresponding stable ozonides **10**, which were isolated in the yields shown (Chart 1). On the basis of the similarity of the ^{1}H NMR

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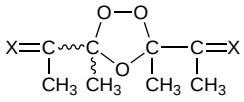
shift values of respective groups of corresponding ozonides of types **9** and **10**, ozonides **9c**−**j** could be also detected by ^{1}H NMR analysis of the crude ozonolysis products prior to the derivatization reactions. However, of these ozonides only **9i** and **9j** could be isolated, whereas **9c**−**h** decomposed during the attempted isolation. In the crude products derived from the ozonolysis of **7** in the presence of formaldehyde (**8a**) or benzaldehyde (**8b**), the corresponding ozonides **9a** and **9b** could not be detected, despite the fact that the corresponding derivatives **10a** and **10b** were formed. This apparent discrepancy is ascribed to decompositions of **9a** and **9b** during the solvent evaporation prior to the ^{1}H NMR analysis. One of the decomposition products of **9a** was its acyclic, nonperoxidic isomer **12** (7%), which had been also obtained previously as a product of the ozonolysis of the parent olefin of **9a**, *viz.* 2-methyl-1-buten-3-one.[3]

All of the stable ozonides (**10a**−**j**) have been characterized by positive peroxide tests, satisfactory elemental analyses, and their ^{1}H, ^{13}C, and ^{17}O NMR spectra. Reductions of ozonides **10a**−**j** gave the corresponding compounds of types **8** and **11** in nearly equimolar amounts. Of the possible *cis*,*trans*-ozonides **10b**, **10c**, **10e**, **10f**, **10h**, **10i**, and **10j**, only one isomer has been obtained in each case, but unambiguous stereochemical assignments could not be made on the basis of the available data.

Ozonolysis of **7** in the presence of butanedione followed by derivatization with *O*-methylhydroxylamine provided ozonide **13b** of unknown stereochemical identity. It was isolated in 10% yield and characterized as described above; its reduction gave 2 molar equiv of **11**. Although the corresponding ozonide **13a** could not be detected, the formation of **13b** provides evidence for its transient existence.

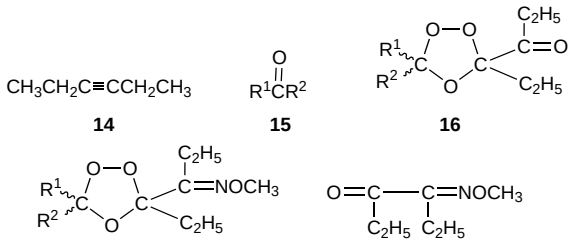


13

	a	b
X	O	$NOCH_3$

Ozonolyses of 3-hexyne (**14**) in the presence of one of the carbonyl compounds **15a**−**f** followed by treatment with *O*-methylhydroxylamine gave the corresponding stable ozonides **17** (Chart 2). They were isolated in the yields shown and characterized by the methods described above, including reduction to give the corresponding products **15** and **18**. Ozonolysis of **14** in the presence of acetaldehyde (**15a**) gave two isomeric ozonides **17a** of unknown stereochemistry, whereas of the ozonides **17d**−**f** only one isomer, each of unknown stereochemistry, was obtained. ^{1}H NMR analyses of the crude product mixtures prior to the derivatization step showed the presence of ozonides **16b**−**f**, of which only **16e** and **16f** could be isolated. Ozonide **16a** was not detected.

Chart 2



14 **15** **16** **17** **18**

	a	b	c	d	e	f
R^1	H	CH_3	$(CH_2)_5$	CH_3	H	H
R^2	CH_3	CH_3		CN	OCH_3	OC_2H_5
16(%)	nd	71[a]	45[a]	52[a]	79[a] 43[b]	70[a] 36[b]
17(%)[b]	16[c]	24	25	3	18	16

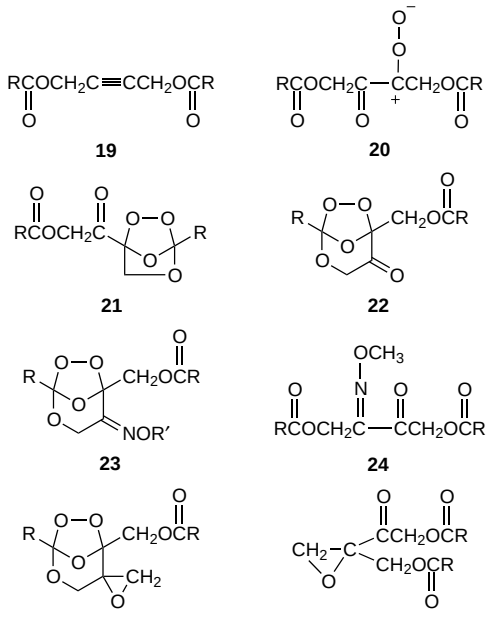
[a]Determined in the product mixture. [b]Yield of isolated product. nd = not detected. [c]Two stereoisomers in yields of 11% and 5%.

Ozonolyses of the acyloxy-substituted 2-butynes **19a** and **19b** in the presence of acetone did not provide the corresponding cross ozonides. Instead, we obtained ozonides which had the same molecular weights as the expected intermediates **20**. This, together with the fact that the same products were obtained by ozonolyses of **19a** and **19b** in the absence of acetone, was indicative of intramolecular [3 + 2]-cycloadditions between the carbonyl oxide moieties and the ester carbonyl groups in intermediates **20**. *A priori*, such intramolecular cycloadditions could provide two types of bicyclic ozonides, *viz.* **21** and **22**, depending on which of the two ester carbonyl groups in **20** reacts with the carbonyl oxide moiety. However, the chemical and structural evidence provided below shows that only the ozonides **22a** and **22b** with a [3.2.1] bicyclic ring structures have been selectively obtained. The formation of the isomeric ozonides **21a** and **21b** is most likely to be precluded by the higher degree of ring strain in the transition state leading to the [2.2.1] bicyclic ring system.

Ozonides **22a** and **22b** could be isolated in yields of 70% and 58%, respectively, but they underwent gradual decomposition at room temperature. Treatment of the crude ozonolysis products of **19a** and **19b** with *O*-methylhydroxylamine gave the corresponding stable ozonides **23ac** (11%) and **23bc** (9%), which were characterized by the methods mentioned above, including reduction with triphenylphosphine to give **24a** and **24b**, respectively. Treatment of the crude ozonolysis products of **19a** and **19b** with hydroxylamine gave the oximes **23ad** (4%) and **24bd** (10%), respectively. In contrast to the monocyclic α-oxo ozonides of types **9** and **16**, the bicyclic ozonides **22** reacted also with diazomethane to give the stable epoxy ozonides **25a** (42%) and **25b** (38%), respectively. Reductions of these ozonides with triphenylphosphine gave the expected epoxides **26a** and **26b**, respectively.

The unambiguous structural assignment of ozonide **22a** is based on X-ray diffraction analysis of the related crystalline epoxy ozonide **25a** (Figure 1).[7] The structural parameters obtained for **25a** suggest that the bicyclic ring system is rigid but relatively strain-free, with the 1,2,4-trioxolane ring being constrained to an envelope conformation. The configuration of the epoxy ring, which is clearly attached to the bicyclic ring system, is consistent with the required methylene group having been delivered to the carbonyl group in **22a** from the less hindered *exo*-face.

The X-ray crystallographic study of oxime derivative **23bd** (Figure 2) confirms the general structural features of the bicyclic ozonide. There is generally good agreement between corresponding structural parameters in **23bd** and **25a**.[8] The hydroxyimino group at C(2) in **23b** has the *E*-configuration, thereby minimizing steric interactions with the adjacent bridgehead acetoxymethyl group.



a, R = C_6H_5; **b**, R = CH_3; **c**, R′ = CH_3; **d**, R′ = H

Ozonolyses of the acyloxy-substituted 2-butynes **27a** and **27b** in the presence of acetone also did not provide the corresponding cross ozonides. Instead, we obtained the same bicyclic ozonides which were produced by ozonolyses of **27a** and **27b** in the absence of acetone, *viz.* **31a** and **31b**. They were obviously formed *via* intermediates **29**. Although, as evidenced by trapping with methanol,[9] intermediates **28** were also produced in roughly the same amounts as intermediates **29**, there was no evidence for the formation of the isomeric ozonides **30**. This supports our view that the lack of formation of ozonides **21** was due to inherent ring strain in the bicyclic [2.2.1] ring system.

Bicyclic ozonides **31a** and **31b** were formed in yields of 55% and 38%, respectively, as shown by ^{1}H NMR analysis of the crude reaction products. They were less stable than ozonides **22a** and **22b** and, hence, were not isolated. However, treatment of the crude reaction products with *O*-methylhydroxylamine gave the stable ozonides **32a** (7%) and **32b** (13%), respectively, and treatment with diazomethane gave the stable ozonides **34a** (14%) and **34b** (13%), respectively.

The assignments of structures **31** as opposed to **30** are based on the fact that the signals for the CH_3 groups

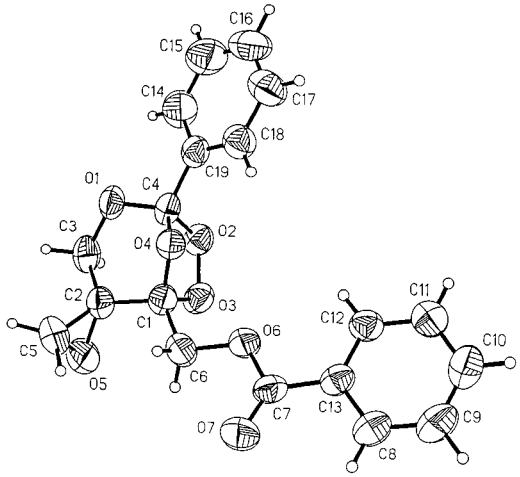
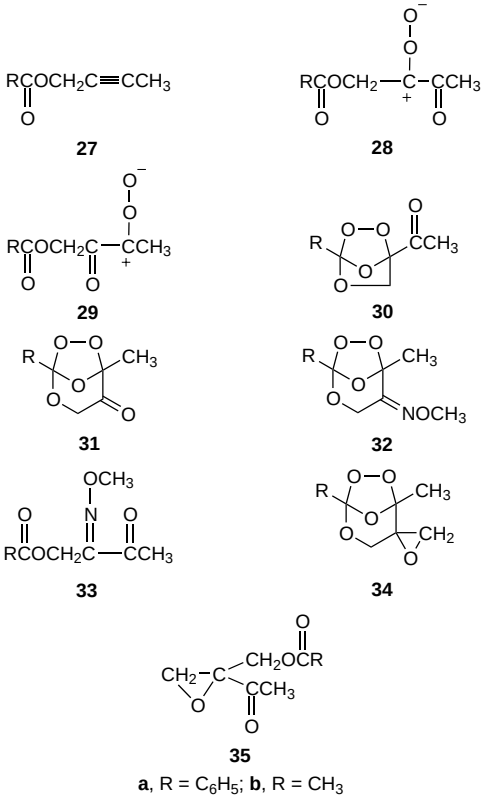


Figure 1. ORTEP diagram of the molecular structure of **25a** in the crystal. Only one of the two unique molecules is shown for clarity. All thermal ellipsoids for non-hydrogen atoms are represented at the 50% probability density level; hydrogen atoms are represented as open circles of arbitrary radius.

appeared in the range of δ 1.60−1.80 ppm and that there were no signals for CH_3CO groups in the range of δ 2.2−2.3 ppm. Ozonides **32** and **34** were characterized by the methods mentioned above, including reductions with triphenylphosphine to give **33** from **32** and **35** from **34**.



a, R = C_6H_5; **b**, R = CH_3

The results obtained in this study show that α-oxo carbonyl oxides **3** derived from ozonolysis of acetylenes **1** can be readily trapped by carbonyl compounds to give monocyclic α-oxo ozonides **5** and that this reaction competes favorably with the previously postulated formation of α-oxo dioxiranes **6**.[3] It appears even that α-oxo carbonyl oxides are more reactive in [3 + 2]-cycloadditions with carbonyl compounds than simple alkyl- or aryl-substituted carbonyl oxides derived from the ozonolysis

(7) Crystal data for **25a**: $C_{19}H_{16}O_7$, M = 356.32, colorless needles, monoclinic, space group $P2_1/c$ (No. 14), a = 14.5883(11), b = 23.755(2), and c = 9.7459(7) Å, β = 91.130(6)°, U 3376.7(4) Å^3, Z = 8, D_c = 1.402 g cm^{-3}, F(000) = 1488, μ(Mo Kα) = 0.108 mm^{-1}, graphite-monochromated Mo Kα λ = 0.71073 Å, T = 293 K. Data were collected on a Siemens P4 diffractometer, and the structure was solved by direct methods. Final discrepancy factors: R = 0.056 and R_w = 0.124. The crystal structure consists of two independent molecules per asymmetric unit which only differ significantly in the spatial orientation of the phenyl group at C(4).

(8) Crystal data for **23bd**: $C_8H_{11}NO_7$, M = 233.18, colorless needles, triclinic, space group $P1$ (No. 2), a = 7.2522(7), b = 8.8749(7), and c = 8.9885(8) Å, α = 109.534(6), β = 95.022(9), and γ = 111.235(5)°, U = 493.66(8) Å^3, Z = 2, D_c = 1.569 cm^{-3}, F(000) = 244, μ(Mo Kα) = 0.140 mm^{-1}, graphite-monochromated Mo Kα λ = 0.71073 Å, T = 293 K. Data were collected on a Siemens P4 diffractometer, and the structure was solved by direct methods. Final discrepancy factors: R = 0.037 and R_w = 0.097. The authors have deposited the atomic coordinates for the crystal structures of **25a** and **23bd** with the Cambridge Crystallographic Data Centre. The coordinates can be obtained, on request, from the Director, the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge, CB2 1EZ, U.K.

(9) Griesbaum, K.; Dong, Y. *Liebigs Ann.* **1997**, 753.

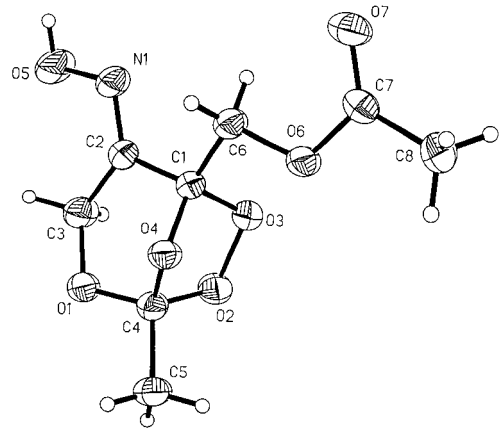


Figure 2. ORTEP diagram of the molecular structure of **23bd** in the crystal. All thermal ellipsoids for non-hydrogen atoms are represented at 50% probability density level; hydrogen atoms are represented as open circles of arbitrary radius.

of olefins, since the former react readily with nonactivated ketones while the latter generally do not form ozonides with ketones.[1c] From a preparative standpoint, ozonolyses of acetylenes in the presence of carbonyl compounds open a short-path, albeit low yield synthesis for α-oxo ozonides, since they obviate the synthesis of the parent α-oxo olefins. Furthermore, the in-situ stabilization of α-oxo ozonides by conversion of the α-oxo groups into *O*-methyl oximes or into epoxides allow the verification of the existence of elusive labile ozonides such as ozonides **9a**, **9b**, or **13a**, which could not be detected as such in the product mixtures.

Experimental Section

General. NMR spectra: Bruker AC-250. ^{1}H- and ^{13}C(BB) NMR spectra were obtained in $CDCl_3$ with TMS as internal reference and the ^{17}O NMR spectra in C_6D_6 by using H_2O as external reference. The conditions for recording the ^{17}O NMR spectra and the ^{17}O NMR data of **10c**−**f**, **10h**, and **10j** have been published elsewhere.[10] Chromatographic separations: flash chromatography on silica gel. HPLC separations: Merck-Hitachi 655 A-11; column 3.2 × 25 cm, Li Chrosorb Si 60.

Ozonolysis Procedure. A solution of the respective acetylene and carbonyl compound in dichloromethane was treated with ozone at low temperatures until the acetylenic substrate had disappeared. A sample of ca. 1 mL was removed, the solvent was evaporated at reduced pressure, and the residue was analyzed by ^{1}H NMR spectroscopy. The major part of the cold ozonolysis product was admixed with a solution of *O*-methylhydroxylamine and pyridine in methanol, which—unless mentioned otherwise—was precooled to −20 °C, and the mixture was kept at low temperature for several days. Then, the solvent was evaporated at room temperature and reduced pressure, the residue was admixed with water, and the mixture was extracted with dichloromethane. The extract was sequentially washed with 2 M aqueous hydrochloric acid and an aqueous solution of sodium bicarbonate, dried with $MgSO_4$, filtered, and concentrated by evaporation of the solvent at room temperature and reduced pressure. Unless mentioned otherwise, the ozonides were isolated by flash chromatography.

Caution! An attempt to ozonize 2-butyne in *pentane* and in the presence of acetone at −75 °C led to a violent explosion. Therefore, CH_2Cl_2 was used as solvent in all experiments. We assume that this prevents the precipitation of peroxidic byproducts.

2-Butyne (7) and Formaldehyde (8a). A solution of 1.17 g (21.7 mmol) of **7** and 2 mL of formaldehyde (freshly prepared by pyrolysis of paraformaldehyde) in 40 mL of CH_2Cl_2 was ozonized at −100 °C to give 71% of acetic anhydride (δ 2.23), 17% of acetic acid (δ 2.10), 5% of butanedione (δ 2.34), and 7% of **12** (δ 2.12, 5.73).[3] Derivatization at −75 °C for 5 d with 3.62 g (43.4 mmol) of *O*-methylhydroxylamine and 7 mL of pyridine in 30 mL of CH_3OH, precooled to −75 °C, gave 0.72 g of a residue, from which 0.30 g (9%) of **10a** was isolated (solvent: pentane/ether, 20:1).

3-(1-Methoximinoethyl)-3-methyl-1,2,4-trioxolane (10a): colorless liquid. ^{1}H NMR: δ 1.64 (s, 3 H), 1.87 (s, 3 H), 3.91 (s, 3 H), 5.19 (s, 1 H), 5.26 (s, 1 H). ^{13}C NMR: δ 9.76, 20.38, 62.11, 94.60, 107.26, 154.30. ^{17}O NMR: δ 103 (s, C−O−C), 157 (s, N−OCH_3), 283 (s) and 319 (s) (O−O). Anal. Calcd for $C_6H_{11}NO_4$ (161.2): C, 44.72; H, 6.88; N, 8.69. Found: C, 44.67; H, 6.65; N, 8.34.

2-Butyne (7) and Benzaldehyde (8b). A solution of 0.93 g (17.2 mmol) of **7** and 1.82 g (17.2 mmol) of **8b** in 50 mL of CH_2Cl_2 was ozonized at −100 °C to give 72% of acetic anhydride (δ 2.20), 19% of acetic acid (δ 2.08), and 9% of butanedione (δ 2.30). Derivatization at −75 °C for 5 d with 2.88 g (34.5 mmol) of *O*-methylhydroxylamine and 6 mL of pyridine in 30 mL of CH_3OH precooled to −75 °C gave 2.24 g of a residue, from which 0.49 g (12%) of **10b** was isolated (solvent: pentane/ether, 20:1).

3-(1-Methoximinoethyl)-3-methyl-5-phenyl-1,2,4-trioxolane (10b): colorless liquid. ^{1}H NMR: δ 1.75 (s, 3 H), 1.97 (s, 3 H), 3.94 (s, 3 H), 6.13 (s, 1 H), 7.40−7.60 (m, 5 H). ^{13}C NMR: δ 10.04, 20.56, 62.06, 104.15, 108.65, 128.10, 128.61, 130.69, 130.92, 155.59. ^{17}O NMR: δ 114 (s, C−O−C), 162 (s, N−OCH_3), 312 (s, O−O). Anal. Calcd for $C_{12}H_{15}NO_4$ (237.3): C, 60.75; H, 6.37; N, 5.90. Found: C, 60.42; H, 6.19; N, 6.15.

2-Butyne (7) and Acetaldehyde (8c). A solution of 1.20 g (22.2 mmol) of **7** and 0.98 g (22.3 mmol) of **8c** in 50 mL of CH_2Cl_2 was ozonized at −75 °C to give 17% of **9c** [δ 1.46 (d, J = 4.9 Hz, 3 H), 1.54 (s, 3 H), 2.29 (s, 3 H), 5.36 (q, J = 4.9 Hz, 1 H)]. Derivatization with 3.71 g (44.4 mmol) of *O*-methylhydroxylamine and 7 mL of pyridine in 40 mL of CH_3OH at −20 °C for 4 d gave 0.78 g of a residue, from which 0.25 g (6%) of **10c** was isolated (solvent: pentane/ether, 20:1).

3-(1-Methoximinoethyl)-3,5-dimethyl-1,2,4-trioxolane (10c): colorless liquid. ^{1}H NMR: δ 1.47 (d, J = 4.9 Hz, 3 H), 1.63 (s, 3 H), 1.89 (s, 3 H), 3.90 (s, 3 H), 5.36 (q, J = 4.9 Hz, 1 H). ^{13}C NMR: δ 9.67, 15.35, 20.14, 61.96, 101.48, 107.78, 155.74. ^{17}O NMR.[10] Anal. Calcd for $C_7H_{13}NO_4$ (175.2): C, 47.99; H, 7.48; N, 8.00. Found: C, 48.27; H, 7.31; N, 8.16.

2-Butyne (7) and Acetone (8d). A solution of 0.56 g (10.4 mmol) of **7** and 0.61 g (10.5 mmol) of **8d** in 40 mL of CH_2Cl_2 was ozonized at −75 °C to give 17% of **9d** [δ 1.49 (s), 1.51 (s), 1.54 (s), 2.29 (s)].[5] Derivatization with 1.73 g (20.7 mmol) of *O*-methylhydroxylamine and 4 mL of pyridine in 20 mL of CH_3OH at −20 °C for 4 d gave 0.35 g of a residue, from which 0.12 g (6%) of **10d** was isolated (solvent: pentane/ether, 20:1).

3-(1-Methoximinoethyl)-3,5,5-trimethyl-1,2,4-trioxolane (10d): colorless liquid. ^{1}H NMR: δ 1.52 (s), 1.53 (s), 1.61 (s, 3 H), 1.89 (s, 3 H), 3.91 (s, 3 H). ^{13}C NMR: δ 10.05, 21.25, 23.30, 25.51, 61.99, 107.60, 109.87, 155.53. ^{17}O NMR.[10] Anal. Calcd for $C_8H_{15}NO_4$ (189.2): C, 50.78; H, 7.99; N, 7.40. Found: C, 50.44; H, 8.01; N, 7.42.

2-Butyne (7) and Chloroacetone (8e). A solution of 1.12 g (20.7 mmol) of **7** and 1.88 g (20.3 mmol) of **8e** in 80 mL of CH_2Cl_2 was ozonized at −75 °C to give 12% of **9e** [δ 1.56 (s), 1.59 (s), 2.29 (s), 3.57, AB-system, δ_A 3.64, δ_B 3.50 (J = 11.9 Hz)]. Derivatization with 4.42 g (52.9 mmol) of *O*-methylhydroxylamine and 9 mL of pyridine in 50 mL of CH_3OH at −20 °C for 5 d gave 2.03 g of a residue, from which 0.68 g (15%) of **10e** was isolated (solvent: pentane/ether, 20:1).

5-(Chloromethyl)-3-(1-methoximinoethyl)-3,5-dimethyl-1,2,4-trioxolane (10e): colorless liquid. ^{1}H NMR: δ 1.59 (s, 3 H), 1.66 (s, 3 H), 1.90 (s, 3 H), 3.58, AB-system, δ_A 3.66, δ_B 3.50 (J = 11.6 Hz, 2 H), 3.92 (s, 3 H). ^{13}C NMR: δ 10.17, 18.34, 20.58, 46.42, 62.07, 108.21, 109.28, 155.47. ^{17}O NMR.[10] Anal. Calcd for $C_8H_{14}ClNO_4$ (223.7): C, 42.96; H, 6.31; N, 6.26. Found: C, 43.28; H, 6.27; N, 6.42.

2-Butyne (7) and Trifluoroacetone (8f). A solution of 1.01 g (18.7 mmol) of **7** and 2.08 g (18.5 mmol) of **8f** in 70 mL

(10) Hock, F.; Ball, V.; Dong, Y.; Gutsche, S.-H.; Hilss, M.; Schlindwein, K.; Griesbaum, K. *J. Magn. Reson.* **1994**, Ser. *A 111*, 150.

of CH_2Cl_2 was ozonized at −75 °C to give 42% of **9f** [δ 1.61 (q), 1.63 (s), 2.31 (s)]. Derivatization with 3.12 g (37.4 mmol) of *O*-methylhydroxylamine and 7 mL of pyridine in 30 mL of methanol at −20 °C for 5 d gave 0.73 g of a residue, from which 0.40 g (9%) of **10f** was isolated (solvent: pentane/ether, 20:1).

3-(1-Methoximinoethyl)-3,5-dimethyl-5-(trifluoromethyl)-1,2,4-trioxolane (10f): colorless liquid. ^{1}H NMR: δ 1.66 (s, 3 H), 1.67 (q, J = 1.3 Hz, 3 H), 1.89 (s, 3 H), 3.93 (s, 3 H). ^{13}C NMR: δ 10.30, 15.73, 19.10, 62.13, 104.53 (q, J = 34 Hz), 109.45, 121.75 (q, J = 289 Hz), 154.69. ^{17}O NMR.[10] Anal. Calcd for $C_8H_{12}F_3NO_4$ (243.2): C, 39.51; H, 4.97; N, 5.76. Found: C, 39.79; H, 4.92; N, 5.90.

2-Butyne (7) and Cyclohexanone (8g). A solution of 0.90 g (16.7 mmol) of **7** and 1.64 g (16.8 mmol) of **8g** in 60 mL of CH_2Cl_2 was ozonized at −75 °C to give 8% of **9g** [δ 1.53 (s), 1.2−2.0 (m), 2.29 (s)]. Derivatization with 1.40 g (16.8 mmol) of *O*-methylhydroxylamine and 5 mL of pyridine in 20 mL of methanol at −20 °C for 5 d gave 1.0 g of a residue, from which 0.19 g (5%) of **10g** was isolated (solvent: pentane/ether, 20:1).

3-(1-Methoximinoethyl)-3-methyl-1,2,4-trioxaspiro[4.5]decane (10g): colorless liquid. ^{1}H NMR: δ 1.61 (s, 3 H), 1.30−1.90 (m, 10 H), 1.90 (s, 3 H), 3.90 (s, 3 H). ^{13}C NMR: δ 10.01, 21.53, 23.72, 23.88, 24.91, 33.40, 34.99, 61.96, 107.28, 110.57, 155.55. ^{17}O NMR: δ 127 (s, C-O-C), 167 (s, N−OCH_3), 308 (s, O−O). Anal. Calcd for $C_{11}H_{19}NO_4$ (229.3): C, 57.63; H, 8.35; N, 6.11. Found: C, 57.50; H, 8.27; N, 6.31.

2-Butyne (7) and Acetyl Cyanide (8h). A solution of 0.60 g (11.1 mmol) of **7** and 0.76 g (11.0 mmol) of **8h** in 80 mL of CH_2Cl_2 was ozonized at −75 °C to give 37% of **9h** [δ 1.72 (s), 1.88 (s), 2.28 (s)]. Derivatization with 1.85 g (22.2 mmol) of *O*-methylhydroxylamine and 5 mL of pyridine in 20 mL of methanol at −20 °C for 5 d gave 0.41 g of a residue, from which 0.31 g (14%) of **10h** was isolated (solvent: pentane/ether, 10:1).

5-Cyano-3-(1-methoximinoethyl)-3,5-dimethyl-1,2,4-trioxolane (10h) : colorless liquid. ^{1}H NMR: δ 1.80 (s, 3 H), 1.86 (s, 3 H), 1.89 (s, 3 H), 3.90 (s, 3 H). ^{13}C NMR: δ 9.77, 19.56, 20.38, 62.13, 98.63, 110.42, 116.45, 153.86. ^{17}O NMR: δ 134 (s, C−O−C), 166 (s, N−OCH_3), 300 (s) and 322 (s) (O−O). Anal. Calcd for $C_8H_{12}N_2O_4$ (200.2): C, 48.00; H, 6.04; N, 13.99. Found: C, 48.30; H, 5.99; N, 13.83.

2-Butyne (7) and Methyl Formate (8i). (a) Isolation of 9i. A solution of 1.00 g (18.5 mmol) of **7** and 1.12 g (18.7 mmol) of **8i** in 60 mL of CH_2Cl_2 was ozonized at −75 °C to give 23% of **9i**. The solvent was distilled off at room temperature and reduced pressure, and from the residue (3 mL) 0.36 g (12%) of **9i** was isolated (solvent: pentane/ether, 5:1).

3-Acetyl-5-methoxy-3-methyl-1,2,4-trioxolane (9i): colorless liquid. ^{1}H NMR: δ 1.65 (s, 3 H), 2.29 (s, 3 H), 3.45 (s, 3 H), 6.02 (s, 1 H). ^{13}C NMR: δ 15.91, 24.99, 51.82, 107.60, 113.38, 203.57.

(b) Isolation of 10i. Ozonolysis of 1.24 g (23.0 mmol) of **7** and 1.38 g (23.0 mmol) of **8i** in 60 mL of CH_2Cl_2 at −75 °C, followed by derivatization with 1.92 g (23.0 mmol) of *O*-methylhydroxylamine and 4 mL of pyridine in 20 mL of CH_3OH at 0 °C for 4 d, gave 0.48 g of a residue, from which 0.30 g (7%) of **10i** was isolated (solvent: pentane/ether, 10:1).

3-(1-Methoximinoethyl)-5-methoxy-3-methyl-1,2,4-trioxolane (10i): colorless liquid. ^{1}H NMR: δ 1.71 (s, 3 H), 1.87 (s, 3 H), 3.45 (s, 3 H), 3.91 (s, 3 H), 6.06 (s, 1 H). ^{13}C NMR: δ 10.18, 18.93, 51.50, 62.10, 108.08, 113.61, 154.62. ^{17}O NMR: δ 37 (s, OCH_3), 126 (s, C−O−C), 160 (s, N−OCH_3), 303 (s, O−O). Anal. Calcd for $C_7H_{13}NO_5$ (191.2): C, 43.98; H, 6.85; N, 7.33. Found: C, 44.31; H, 6.65; N, 7.34.

2-Butyne (7) and Ethyl Formate (8j). (a) Isolation of 9j. A solution of 0.64 g (12.2 mmol) of **7** and 0.91 g (12.3 mmol) of **8j** in 40 mL of CH_2Cl_2 was ozonized at −75 °C and worked up as described for **9i** to give 0.30 g (14%) of **9j**.

3-Acetyl-5-ethoxy-3-methyl-1,2,4-trioxolane (9j): colorless liquid. ^{1}H NMR: δ 1.27 (t, J = 7.1 Hz, 3 H), 1.65 (s, 3 H), 2.28 (s, 3 H), 3.74 (m, 2 H), 6.05 (s, 1 H). ^{13}C NMR: δ 14.79, 16.00, 24.32, 60.97, 107.45, 112.97, 203.67.

(b) Isolation of 10j. Ozonolysis of 1.08 g (20.0 mmol) of **7** and 1.48 g (20.0 mmol) of **8j** in 60 mL of CH_2Cl_2 at −75 °C, followed by derivatization with 1.67 g (20.0 mmol) of *O*-methylhydroxylamine and 4 mL of pyridine in 20 mL of CH_3OH at 0 °C for 4 d, gave 1.35 g of a residue, from which 0.37 g (9%) of **10j** was isolated (solvent: pentane/ether, 20:1).

5-Ethoxy-3-(1-methoximinoethyl)-3-methyl-1,2,4-trioxolane (10j): colorless liquid. ^{1}H NMR: δ 1.27 (t, J = 7.1 Hz, 3 H), 1.71 (s, 3 H), 1.87 (s, 3 H), 3.74 (m, 2 H), 3.91 (s, 3 H), 6.08 (s, 1 H). ^{13}C NMR: δ 10.13, 14.91, 19.09, 60.60, 62.05, 107.95, 113.26, 154.68. ^{17}O NMR: δ 70 (s, OCH_2), 130 (s, C−O−C), 161 (s, N−OCH_3), 296 (s, O−O). Anal. Calcd for $C_8H_{15}NO_5$ (205.2): C, 46.82; H, 7.37; N, 6.83. Found: C, 46.98; H, 7.28; N, 6.96.

Reductions of Ozonides 10a−j. A solution of ca. 20 mg of one of the ozonides in 1 mL of $CDCl_3$ was admixed with excess TPP at room temperature. ^{1}H NMR analysis after 12 h showed in each case the presence of **11** [δ 1.90 (s, 3 H), 2.36 (s, 3 H), 4.04 (s, 3 H)] and of the corresponding carbonyl compound **8** in a ratio of ca. 1:1.

2-Butyne (7) and Butanedione. A solution of 1.28 g (23.7 mmol) of **7** and 2.03 g (23.6 mmol) of butanedione in 40 mL of CH_2Cl_2 was ozonized at −100 °C to give a mixture of acetic anhydride and acetic acid. Derivatization at −75 °C for 5 d with 3.96 g (47.4 mmol) of *O*-methylhydroxylamine and 8 mL of pyridine in 30 mL of CH_3OH precooled to −75 °C gave 2.80 g of a residue, from which 0.60 g (10%) of **13b** has been isolated by flash chromatography (solvent: pentane/ether, 10:1), followed by HPLC separation (solvent: pentane/ether, 92:8).

3,5-Bis(1-methoximinoethyl)-3,5-dimethyl-1,2,4-trioxolane (13b): colorless liquid. ^{1}H NMR: δ 1.65 (s, 3 H), 1.92 (s, 3 H), 3.91 (s, 3 H). ^{13}C NMR: δ 10.16, 20.07, 62.01, 108.39, 155.51. ^{17}O NMR: δ 118 (s, C−O−C), 170 (s, N−OCH_3), 305 (s, O−O). Anal. Calcd for $C_8H_{18}N_2O_5$ (246.3): C, 48.77; H, 7.37; N, 11.38. Found: C, 48.68; H, 7.27; N, 11.41.

Reduction of 13b. A solution of 20 mg of **13b** in 1 mL of $CDCl_3$ was admixed with excess TPP at room temperature. After 1 week, **11** was present as the only product of reduction.

3-Hexyne (14) and Acetaldehyde (15a). A solution of 1.07 g (13.1 mmol) of **14** and 0.57 g (13.0 mmol) of **15a** in 50 mL of CH_2Cl_2 was ozonized at −75 °C to give 35% of propionic anhydride [δ 1.19 (t, J = 7.4 Hz), 2.50 (q, J = 7.4 Hz)] and 65% of paraldehyde [δ 1.38 (d, J = 5.2 Hz), 5.06 (q, J = 5.2 Hz)]. Derivatization with 2.17 g (26.0 mmol) of *O*-methylhydroxylamine and 5 mL of pyridine in 50 mL of CH_3OH at 0 °C for 5 d gave 1.21 g of a residue, from which 0.12 g (5%) of **17a** (isomer I) and 0.30 g (11%) of **17a** (isomer II) were isolated (solvent: pentane/ether, 30:1).

3-Ethyl-3-(1-methoximinopropyl)-5-methyl-1,2,4-trioxolanes (17a). Isomer I: colorless liquid. ^{1}H NMR: δ 0.98 (t, J = 7.4 Hz, 3 H), 1.09 (t, J = 7.5 Hz, 3 H), 1.45 (d, J = 5.0 Hz, 3 H), 1.96 (m, 2 H), 2.31 (m, 2 H), 3.90 (s, 3 H), 5.45 (q, J = 5.0 Hz, 1 H). ^{13}C NMR: δ 7.81, 10.70, 17.51, 18.89, 28.26, 62.09, 102.20, 109.99, 157.82. ^{17}O NMR: δ 115 (s, C−O−C), 156 (s, N−OCH_3), 301 (s, O−O). Anal. Calcd for $C_9H_{17}NO_4$ (203.2): C, 53.19; H, 8.43; N, 6.89. Found: C, 53.47; H, 8.14; N, 6.83.

Isomer II: colorless liquid. ^{1}H NMR: δ 1.00 (t, J = 7.4 Hz, 3 H), 1.11 (t, J = 7.5 Hz, 3 H), 1.48 (d, J = 4.9 Hz, 3 H), 1.97 (m, 2 H), 2.34 (m, 2 H), 3.90 (s, 3 H), 5.35 (q, J = 4.9 Hz, 1 H). ^{13}C NMR: δ 7.40, 10.82, 15.52, 18.75, 27.09, 61.93, 102.16, 109.56, 160.02. ^{17}O NMR: δ 112 (s, C−O−C), 157 (s, N−OCH_3), 302 (s, O−O). Anal. Calcd for $C_9H_{17}NO_4$ (203.2): C, 53.19; H, 8.43; N, 6.89. Found: C, 52.79; H, 8.31; N, 6.94.

3-Hexyne (14) and Acetone (15b). A solution of 1.61 g (19.6 mmol) of **14** and 1.14 g (19.7 mmol) of **15b** in 80 mL of CH_2Cl_2 was ozonized at −75 °C to give 71% of **16b** [δ 0.98 (t, J = 7.5 Hz, 3 H), 1.07 (t, J = 7.2 Hz, 3 H), 1.47 (s, 3 H), 1.49 (s, 3 H), 1.86 (q, J = 7.5 Hz, 2 H), 2.67 (m, 2 H)] and propionic anhydride. Derivatization with 3.30 g (39.5 mmol) of *O*-methylhydroxylamine and 7 mL of pyridine in 30 mL of CH_3OH at 0 °C for 6 d gave 2.28 g of a residue, from which 1.01 g (24%) of **17b** was isolated (solvent: pentane/ether, 20:1).

3-Ethyl-3-(1-methoximinopropyl)-5,5-dimethyl-1,2,4-trioxolane (17b): colorless liquid. ^{1}H NMR: δ 1.05 (t, J = 7.5 Hz, 3 H), 1.10 (t, J = 7.5 Hz, 3 H), 1.49 (s, 3 H), 1.55 (s, 3 H), 1.90 (q, J = 7.5 Hz, 2 H), 2.32 (m, 2 H), 3.91 (s, 3 H). ^{13}C NMR: δ 7.68, 10.73, 19.12, 23.19, 25.75, 27.44, 62.00, 109.63,

109.84, 159.85. ^{17}O NMR: δ 122 (s, C−O−C), 163 (s, N−OCH_3), 304 (s, O−O). Anal. Calcd for $C_{10}H_{19}NO_4$ (217.3): C, 55.28; H, 8.81; N, 6.45. Found: C, 55.27; H, 8.68; N, 6.53.

3-Hexyne (14) and Cyclohexanone (15c). A solution of 1.49 g (18.2 mmol) of **14** and 1.78 g (18.2 mmol) of **15c** in 70 mL of CH_2Cl_2 was ozonized at −75 °C to give 45% of **16c** [δ 0.98 (t, J = 7.5 Hz, 3 H), 1.07 (t, J = 7.2 Hz, 3 H), 1.30−1.90 (m), 1.86 (q, J = 7.5 Hz, 2 H), 2.68 (m, 2 H)] and propionic anhydride. Derivatization with 3.03 g (36.3 mmol) of *O*-methylhydroxylamine and 6 mL of pyridine in 30 mL of CH_3OH at 0 °C for 6 d gave 2.87 g of a residue, from which 1.18 g (25%) of **17c** was isolated (solvent: pentane/ether, 20:1).

3-Ethyl-3-(1-methoximinopropyl)-1,2,4-trioxaspiro[4.5]decane (17c): colorless liquid. ^{1}H NMR: δ 0.99 (t, J = 7.5 Hz, 3 H), 1.11 (t, J = 7.5 Hz, 3 H), 1.30−1.90 (m, 10 H), 1.91 (q, J = 7.5 Hz, 2 H), 2.32 (m, 2 H), 3.90 (s, 3 H). ^{13}C NMR: δ 7.74, 10.76, 19.05, 23.66, 23.95, 24.90, 27.68, 33.42, 35.08, 61.95, 109.25, 110.47, 159.65. ^{17}O NMR: δ 120 (s, C−O−C), 160 (s, N−OCH_3), 319 (s, O−O). Anal. Calcd for $C_{13}H_{23}NO_4$ (257.3): C, 60.68; H, 9.01; N, 5.44. Found: C, 60.95; H, 8.82; N 5.74.

3-Hexyne (14) and Acetyl Cyanide (15d). A solution of 1.43 g (17.4 mmol) of **14** and 1.25 g (17.4 mmol) of **15d** in 80 mL of CH_2Cl_2 was ozonized at −75 °C to give 52% of **16d** [δ 1.08 (t, J = 7.3 Hz, 6 H), 1.86 (s, 3 H), 2.03 (q, J = 7.5 Hz, 2 H), 2.62 (m, 2 H)] and propionic anhydride. Derivatization with 2.91 g (34.9 mmol) of *O*-methylhydroxylamine and 5 mL of pyridine in 30 mL of CH_3OH at 0 °C for 6 d gave 0.56 g of a residue, from which 0.12 g (3%) of **17d** was isolated (solvent: pentane/ether, 20:1).

5-Cyano-3-ethyl-3-(1-methoximinopropyl)-5-methyl-1,2,4-trioxolane (17d): colorless liquid. ^{1}H NMR: δ 1.09 (t, J = 7.5 Hz, 6 H), 1.91 (s, 3 H), 2.07 (q, J = 7.5 Hz, 2 H), 2.29 (m, 2 H), 3.90 (s, 3 H). ^{13}C NMR: δ 7.35, 10.65, 19.09, 20.87, 26.40, 62.23, 99.19, 112.31, 116.57, 158.26. ^{17}O NMR: δ 111 (s, C−O−C), 152 (s, N−OCH_3), 316 (s, O−O). Anal. Calcd for $C_{10}H_{16}N_2O_4$ (228.3): C, 52.62; H, 7.07; N, 12.27. Found: C, 52.91; H, 7.02; N, 12.41.

3-Hexyne (14) and Methyl Formate (15e). (a) Isolation of 16e. A solution of 1.05 g (12.8 mmol) of **14** and 0.77 g (12.8 mmol) of **15e** in 60 mL of CH_2Cl_2 was ozonized at −75 °C to give 79% of **16e** and propionic anhydride. The solvent was distilled off at room temperature and reduced pressure, and from the residue (3 mL) 1.05 g (43%) of **16e** was isolated.

5-Methoxy-3-ethyl-3-propionyl-1,2,4-trioxolane (16e): colorless liquid. ^{1}H NMR: δ 1.03 (t, J = 7.6 Hz, 3 H), 1.08 (t, J = 7.2 Hz, 3 H), 1.98 (q, J = 7.6 Hz, 2 H), 2.65 (m, 2 H), 3.44 (s, 3 H), 5.98 (s, 1 H). ^{13}C NMR: δ 6.91, 7.09, 23.42, 30.52, 52.02, 109.76, 113.31, 206.93.

(b) Isolation of 17e. The above-described ozonolysis of **14** and **15e** was repeated. Derivatization with 1.02 g (12.2 mmol) of *O*-methylhydroxylamine and 2 mL of pyridine in 20 mL of CH_3OH at 0 °C for 6 d gave 1.23 g of a residue, from which 0.48 g (18%) of **17e** was isolated.

3-Ethyl-3-(1-methoximinopropyl)-5-methoxy-1,2,4-trioxolane (17e): colorless liquid. ^{1}H NMR: δ 1.05 (t, J = 7.6 Hz, 3 H), 1.10 (t, J = 7.5 Hz, 3 H), 2.00 (q, J = 7.5 Hz, 2 H), 2.28 (m, 2 H), 3.44 (s, 3 H), 3.91 (s, 3 H), 6.03 (s, 1 H). ^{13}C NMR: δ 7.49, 10.48, 19.17, 25.67, 51.68, 62.11, 110.12, 113.56, 158.62. ^{17}O NMR: δ 61 (s, C−OCH_3), 131 (s, N−OCH_3), 159 (s, C−O−C), 316 (s, O−O). Anal. Calcd for $C_9H_{17}NO_5$ (219.2): C, 49.31; H, 7.82; N, 6.39. Found: C, 49.38; H, 7.84; N, 6.51.

3-Hexyne (14) and Ethyl Formate (15f). (a) Isolation of 16f. A solution of 1.18 g (14.4 mmol) of **14** and 1.07 g (14.5 mmol) of **15f** in 60 mL of CH_2Cl_2 was ozonized at −75 °C to give 70% of **16f** and propionic anhydride. The solvent was distilled off at room temperature and reduced pressure, and from the residue (4 mL) 1.05 g (36%) of **16f** was isolated (solvent: pentane/ether, 6:1).

5-Ethoxy-3-ethyl-3-propionyl-1,2,4-trioxolane (16f): colorless liquid. ^{1}H NMR: δ 1.02 (t, J = 7.6 Hz, 3 H), 1.07 (t, J = 7.2 Hz, 3 H), 1.26 (t, J = 7.2 Hz, 3 H), 1.98 (q, J = 7.5 Hz, 2 H), 2.64 (m, 2 H), 3.74 (m, 2 H), 6.02 (s, 1 H). ^{13}C NMR: δ 6.98, 7.16, 14.83, 23.60, 30.59. 61.16, 109.72, 112.90, 207.13.

(b) Isolation of 17f. A solution of 1.69 g (20.6 mmol) of **14** and 1.53 g (20.7 mmol) of **15f** in 70 mL of CH_2Cl_2 was ozonized at −75 °C. Derivatization with 2.58 g (30.9 mmol) of *O*-methylhydroxylamine and 5 mL of pyridine in 30 mL of CH_3OH at 0 °C for 6 d gave 1.40 g of a residue, from which 0.78 g (16%) of **17f** was isolated (solvent: pentane/ether, 20:1).

5-Ethoxy-3-ethyl-3-(1-methoximinopropyl)-1,2,4-trioxolane (17f): colorless liquid. ^{1}H NMR: δ 1.05 (t, J = 7.5 Hz, 3 H), 1.10 (t, J = 7.5 Hz, 3 H), 1.26 (t, J = 7.1 Hz, 3 H), 1.97 (q, J = 7.4 Hz, 2 H), 2.28 (m, 2 H), 3.73 (m, 2 H), 3.91 (s, 3 H), 6.07 (s, 1 H). ^{13}C NMR: δ 7.52, 10.51, 14.93, 19.18, 25.79, 60.71, 62.10, 110.01, 113.14, 158.73. ^{17}O NMR: δ 69 (s, OCH_2), 134 (s, N−OCH_3), 173 (s, C−O−C), 304 (s, O−O). Anal. Calcd for $C_{10}H_{19}NO_5$ (233.3): C, 51.49; H, 8.21; N, 6.00. Found: C, 51.26; H, 8.19; N, 6.07.

Reductions of Ozonides 17a−f. A solution of ca. 20 mg of one of the ozonides in 1 mL of $CDCl_3$ was admixed with excess TPP at room temperature. ^{1}H NMR analyses after 6−12 h showed in each case the presence of **18** [δ 0.98 (t, J = 7.5 Hz, 3 H), 1.09 (t, J = 7.3 Hz, 3 H), 2.47 (q, J = 7.5 Hz, 2 H), 2.80 (q, J = 7.3 Hz, 2 H), 4.02 (s, 3 H)] and of the corresponding carbonyl compound **15** in a ratio of ca. 1:1.

Ozonolyses of 1,4-Dibenzoxy-2-butyne (19a). (a) In the Presence of Acetone. A solution of 0.25 g (0.9 mmol) of **19a** and 0.10 g (1.7 mmol) of acetone in 10 mL of CH_2Cl_2 was ozonized at −30 °C to give 56% of **22a**.

(b) In the Absence of Acetone. A solution of 1.96 g (6.7 mmol) of **19a** in 60 mL of CH_2Cl_2 was ozonized at −30 °C to give 94% of **22a**. The solvent was distilled off at room temperature and reduced pressure, and from the residue (4 mL) 1.60 g (70%) of **22a** was isolated.

5-(Benzoxymethyl)-4-oxo-1-phenyl-2,6,7,8-tetraoxabicyclo[3.2.1]octane (22a): colorless liquid. ^{1}H NMR: δ 4.70, AB-system, δ_A 4.82, δ_B 4.58 (J = 17.5 Hz, 2 H), 4.94, AB-system, δ_A 4.99, δ_B 4.89 (J = 13.2 Hz, 2 H), 7.30−8.20 (m, 10 H). ^{13}C NMR: δ 56.44, 67.89, 103.89, 119.20, 126.97, 128.45, 128.48, 129.04, 129.40, 129.92, 131.08, 133.51, 165.40, 193.33.

(c) In Dichloromethane Followed by Treatment with *O*-Methyl hydroxylamine. A solution of 3.26 g (11.1 mmol) of **19a** in 70 mL of CH_2Cl_2 was ozonized at −30 °C. Derivatization with 1.39 g (16.7 mmol) of *O*-methylhydroxylamine and 3 mL of pyridine in 20 mL of CH_3OH at 0 °C for 9 d gave 4.25 g of a residue, from which 0.47 g (11%) of **23ac** was isolated (solvent: pentane/ether, 9:1).

5-(Benzoxymethyl)-4-methoximino-1-phenyl-2,6,7,8-tetraoxabicyclo[3.2.1]octane (23ac): colorless solid; mp 96.5 °C. ^{1}H NMR: δ 3.92 (s, 3 H), 4.95, AB-system, δ_A 5.04, δ_B 4.86 (J = 16.4 Hz, 2 H), 5.05, AB-system, δ_A 5.09, δ_B 5.01 (J = 13.4 Hz, 2 H), 7.30−8.20 (m, 10 H). ^{13}C NMR: δ 57.65, 58.72, 62.95, 104.56, 118.90, 126.81, 128.32, 128.45, 129.53, 129.96, 130.71, 130.77, 133.34, 146.91, 165.68. Anal. Calcd for $C_{19}H_{17}NO_7$ (371.4): C, 61.45; H, 4.61; N, 3.77. Found: C, 61.68; H, 4.89; N, 3.96.

Reduction of 23ac. A solution of 20 mg of **23ac** in 1 mL of $CDCl_3$ was admixed with excess TPP at room temperature. ^{1}H NMR analysis after 2 d showed the presence of **24a** as the sole product of reduction [δ 4.14 (s, 3 H), 5.16 (s, 2 H), 5.45 (s, 2 H), 7.30−8.20 (m, 10 H).

(d) In Dichloromethane Followed by Treatment with Hydroxylamine. A solution of 2.92 g (9.9 mmol) of **19a** in 60 mL of CH_2Cl_2 was ozonized at −30 °C. Derivatization with 1.04 g (15.0 mmol) of $NH_2OH{\cdot}HCl$ and 3 mL of pyridine in 5 mL of H_2O and 30 mL of CH_3OH at 0 °C for 10 d gave 4.54 g of a residue, from which 0.15 g (4%) of **23ad** was isolated (solvent: pentane/ether, 4:1).

5-(Benzoxymethyl)-4-hydroximino-1-phenyl-2,6,7,8-tetraoxabicyclo[3.2.1]octane (23ad): colorless solid; mp 119 °C. ^{1}H NMR: δ 5.04, AB-system, δ_A 5.16, δ_B 4.92 (J = 16.0 Hz, 2 H), 5.06, AB-system, δ_A 5.09, δ_B 5.03 (J = 12.8 Hz, 2 H), 7.30−8.20 (m, 10 H). ^{13}C NMR: δ 57.88, 58.51, 104.64, 119.01, 126.86, 128.37, 128.53, 129.31, 130.07, 130.66, 130.80, 133.58, 148.43, 166.19. Anal. Calcd for $C_{18}H_{15}NO_7$ (357.3): C, 60.51; H, 4.23; N, 3.92. Found: C, 60.76; H, 4.51; N, 4.26.

(e) In Dichloromethane Followed by Treatment with Diazomethane. A solution of 4.27 g (14.5 mmol) of **19a** in

80 mL of CH_2Cl_2 was ozonized at −30 °C, and a solution of 2.8 g (66.7 mmol) of diazomethane in 200 mL of ether was dropwise added with stirring within 30 min. Stirring was continued for 2 h at room temperature. Then the solvent was evaporated at room temperature, and from the residue (6.8 g), 2.17 g (42%) of **25a** was isolated (solvent: pentane/ether, 6:1).

4-(Benzoxymethyl)-4,7-epoxy-7-phenyl-1,5,6,8-tetraoxaspiro[2.6]nonane (25a): colorless solid; mp 78 °C. ^{1}H NMR: δ 2.97 (d, J = 3.8 Hz, 1 H), 3.27 (dd, J = 3.8 and 1.9 Hz, 1 H), 3.76 (d, J = 11.2 Hz, 1 H), 4.82 (dd, J = 11.2 and 1.9 Hz, 1 H), 4.64, AB-system, δ_A 4.66, δ_B 4.62 (J = 12.8 Hz, 2 H), 7.30−8.20 (m, 10 H). ^{13}C NMR: δ 52.58, 54.54, 57.16, 64.29, 107.30, 118.92, 127.03, 128.34, 128.51, 129.15, 129.55, 129.89, 130.86, 133.48, 165.50. Anal. Calcd for $C_{19}H_{16}O_7$ (356.3): C, 64.04; H, 4.53. Found: C, 64.09; H, 4.56.

Reduction of 25a. A solution of 30 mg of **25a** in 1 mL of $CDCl_3$ was admixed with excess DMS at room temperature. ^{1}H NMR analysis after 2 h showed the presence of **26a** as the sole product of reduction [δ 3.28, AB-system, δ_A 3.33, δ_B 3.23 (J = 4.6 Hz, 2 H), 4.76, AB-system, δ_A 5.09, δ_B 4.43 (J = 12.5 Hz, 2 H), 4.99, AB-system, δ_A 5.05, δ_B 4.93 (J = 17.6 Hz, 2 H), 7.30−8.20 (m, 10 H)].

Ozonolyses of 1,4-Diacetoxy-2-butyne (19b). (a) In the Presence of Acetone. A solution of 0.50 g (2.9 mmol) of **19b** and 0.34 g (5.9 mmol) of acetone in 40 mL of CH_2Cl_2 was ozonized at −30 °C to give 70% of **22b**.

(b) In the Absence of Acetone. A solution of 0.94 g (5.5 mmol) of **19b** in 50 mL of CH_2Cl_2 was ozonized at −30 °C to give 81% of **22b**, of which 0.70 g (58%) was isolated (solvent: pentane/ether, 3:7).

5-(Acetoxymethyl)-1-methyl-4-oxo-2,6,7,8-tetraoxabicyclo[3.2.1]octane (22b): colorless liquid. ^{1}H NMR: δ 1.85 (s, 3 H), 2.14 (s, 3 H), 4.46, AB-system, δ_A 4.59, δ_B 4.33 (J = 17.5 Hz, 2 H), 4.58, AB-system, δ_A 4.65, δ_B 4.51 (J = 13.1 Hz, 2 H). ^{13}C NMR: δ 18.84, 20.44, 56.03, 67.45, 102.98, 120.33, 169.73, 193.28.

(c) In Dichloromethane Followed by Treatment with *O*-Methylhydroxylamine. A solution of 2.05 g (12.1 mmol) of **19b** in 60 mL of CH_2Cl_2 was ozonized at −30 °C. Derivatization with 1.51 g (18.1 mmol) of *O*-methylhydroxylamine and 3 mL of pyridine in 20 mL of CH_3OH at 0 °C for 5 d gave 1.14 g of a residue, from which 0.27 g (9%) of **23b** was isolated.

5-(Acetoxymethyl)-4-methoximino-1-methyl-2,6,7,8-tetraoxabicyclo[3.2.1]octane (23bc): colorless liquid. ^{1}H NMR: δ 1.76 (s, 3 H), 2.14 (s, 3 H), 3.88 (s, 3 H), 4.68, AB-system, δ_A 4.78, δ_B 4.58 (J = 16.4 Hz, 2 H), 4.70, AB-system, δ_A 4.75, δ_B 4.65 (J = 13.3 Hz, 2 H). ^{13}C NMR: δ 19.36, 20.53, 57.09, 58.13, 62.83, 103.59, 119.93, 146.84, 169.96. Anal. Calcd for $C_9H_{13}NO_7$ (247.2): C, 43.73; H, 5.30; N, 5.67. Found: C, 43.95; H, 5.33; N, 5.86.

Reduction of 23bc. A solution of 20 mg of **23bc** in 1 mL of $CDCl_3$ was admixed with an excess of TPP at room temperature. ^{1}H NMR analysis after 4 h showed the presence of **24b** as the sole product of reduction [δ 2.05 (s, 3 H), 2.19 (s, 3 H), 4.13 (s, 3 H), 4.88 (s, 2 H), 5.16 (s, 2 H)].

(d) In Dichloromethane Followed by Treatment with Hydroxylamine. A solution of 5.56 g (32.7 mmol) of **19b** in 100 mL of CH_2Cl_2 was ozonized at −30 °C. Derivatization with 3.40 g (48.9 mmol) of $H_2NOH{\cdot}HCl$ and 10 mL of pyridine in 20 mL of H_2O and 50 mL of CH_3OH at 0 °C for 6 d gave 1.71 g of a residue, from which 0.76 g (10%) of **23bd** was isolated (solvent: pentane/ether, 3:7).

5-(Acetoxymethyl)-4-hydroximino-1-methyl-2,6,7,8-tetraoxabicyclo[3.2.1]octane (23bd): colorless solid; mp 86.5 °C. ^{1}H NMR: δ 1.78 (s, 3 H), 2.16 (s, 3 H), 4.69, AB-system, δ_A 4.75, δ_B 4.63 (J = 13.2 Hz, 2 H), 4.78, AB-system, δ_A 4.90, δ_B 4.66 (J = 16.4 Hz, 2 H). ^{13}C NMR: δ 19.33, 20.63, 57.39, 57.89, 103.61, 120.04, 148.25, 170.56. Anal. Calcd for $C_8H_{11}NO_7$ (233.2): C, 41.21; H, 4.75; N, 6.01. Found: C, 41.07; H, 4.81; N, 6.04.

(e) In Dichloromethane Followed by Treatment with Diazomethane. A solution of 3.21 g (18.9 mmol) of **19b** in 80 mL of CH_2Cl_2 was ozonized at −30 °C, and a solution of 2.8 g (66.7 mmol) of diazomethane in 200 mL of ether was dropwise added with stirring within 30 min. Stirring was continued for 2 h at room temperature. Then the solvent was evaporated at room temperature, and from the residue (5.9 g), 1.67 g (38%) of **25b** was isolated (solvent: pentane/ether, 6:1).

4-(Acetoxymethyl)-4,7-epoxy-7-methyl-1,5,6,8-tetraoxaspiro[2.6]nonane (25b): colorless liquid. ^{1}H NMR: δ 1.76 (s, 3 H), 2.13 (s, 3 H), 2.90 (d, J = 3.9 Hz, 1 H), 3.16 (dd, J = 3.9 and 2.0 Hz, 1 H), 3.50 (d, J = 11.2 Hz, 1 H), 4.56 (dd, J = 11.2 and 2.0 Hz, 1 H), 4.30, AB-system, δ_A 4.35, δ_B 4.25 (J = 12.8 Hz, 2 H). ^{13}C NMR: δ 18.24, 20.45, 52.45, 54.20, 56.59, 63.84, 106.36, 119.90, 169.75. Anal. Calcd for $C_9H_{12}O_7$ (232.2): C, 46.56; H, 5.21. Found: C, 46.69; H, 5.24.

Reduction of 25b. A solution of 20 mg of **25b** in 1 mL of $CDCl_3$ was admixed with excess TPP at room temperature. ^{1}H NMR analysis after 6 h showed the presence of **26b** as the sole product of reduction [δ 2.07 (s, 3 H), 2.16 (s, 3 H), 3.15, AB-system, δ_A 3.19, δ_B 3.11 (J = 4.6 Hz, 2 H), 4.46, AB-system, δ_A 4.85, δ_B 4.07 (J = 12.4 Hz, 2 H), 4.70, AB-system, δ_A 4.77, δ_B 4.63 (J = 17.6 Hz, 2 H)].

Ozonolyses of 1-Benzoxy-2-butyne (27a). (a) In the Presence of Acetone. A solution of 0.15 g (0.9 mmol) of **27a** and 0.10 g (1.7 mmol) of acetone in 10 mL of CH_2Cl_2 was ozonized at −30 °C to give 44% of **31a**.

(b) In the Absence of Acetone. A solution of 2.67 g (15.3 mmol) of **27a** in 80 mL of CH_2Cl_2 was ozonized at −30 °C to give 55% of **31a** as shown by ^{1}H NMR analysis [δ 1.74 (s, 3 H), 4.65, AB-system, δ_A 4.76, δ_B 3.54 (J = 17.5 Hz, 2 H), 7.30−7.80 (m, 5 H)].

(c) In Dichloromethane Followed by Treatment with *O*-Methylhydroxylamine. The above experiment was repeated. Derivatization with 1.92 g (23.0 mmol) of *O*-methylhydroxylamine and 4 mL of pyridine in 30 mL of CH_3OH at 0 °C for 6 d gave 1.57 g of a residue, from which 0.23 g (7%) of **32a** was isolated (solvent: pentane/ether, 9:1).

4-Methoximino-5-methyl-1-phenyl-2,6,7,8-tetraoxabicyclo[3.2.1]octane (32a): colorless liquid. ^{1}H NMR: δ 1.85 (s, 3 H), 3.91 (s, 3 H), 4.90, AB-system, δ_A 4.99, δ_B 3.81 (J = 16.5 Hz, 2 H), 7.30−7.80 (m, 5 H). ^{13}C NMR: δ 14.98, 58.86, 62.66, 106.43, 111.85, 126.69, 128.32, 130.52, 131.52, 148.88. Anal. Calcd for $C_{12}H_{13}NO_5$ (251.2): C, 57.37; H, 5.22; N, 5.58. Found: C, 57.23; H, 5.45; N, 5.26.

Reduction of 32a. A solution of 20 mg of **32a** in 1 mL of $CDCl_3$ was admixed with excess TPP at room temperature. ^{1}H NMR analysis after 1 h showed the presence of **33a** as the sole product of reduction [δ 2.44 (s, 3 H), 4.11 (s, 3 H), 5.13 (s, 2 H), 7.30−8.10 (m, 5 H)].

(d) In Dichloromethane Followed by Treatment with Diazomethane. A solution of 3.91 g (22.5 mmol) of **27a** in 80 mL of CH_2Cl_2 was ozonized at −30 °C, and a solution of 2.8 g (66.7 mmol) of diazomethane in 200 mL of ether was added dropwise with stirring within 30 min. Stirring was continued for 2 h at room temperature. Then the solvent was evaporated at room temperature, and from the residue (5.20 g), 0.75 g (14%) of **34a** was isolated (solvent: pentane/ether, 9:1).

4,7-Epoxy-4-methyl-7-phenyl-1,5,6,8-tetraoxaspiro-[2.6]nonane (34a): colorless solid; mp 62 °C. ^{1}H NMR: δ 1.51 (s, 3 H), 2.89 (d, J = 4.2 Hz, 1 H), 3.03 (dd, J = 4.2 and 2.0 Hz, 1 H), 3.71 (d, J = 11.1 Hz, 1 H), 4.77 (dd, J = 11.1 and 2.0 Hz, 1 H), 7.30−7.80 (m, 5 H). ^{13}C NMR: δ 13.07, 52.79, 54.73, 64.00, 109.51, 118.65, 126.89, 128.34, 130.55, 130.67. ^{17}O NMR: δ −11 (s, epoxy-O), 73 (s, C−O−CH_2), 162 (s, C−O−C), 302 (s, O−O). Anal. Calcd for $C_{12}H_{12}O_5$ (236.2): C, 61.01; H, 5.12. Found: C, 60.85; H, 4.83.

Reduction of 34a. A solution of 20 mg of **34a** in 1 mL of $CDCl_3$ was admixed with excess TPP at room temperature. ^{1}H NMR analysis after 12 h showed the presence of **35a** as the sole product of reduction [δ 2.14 (s, 3 H), 3.11, AB-system, δ_A 3.13, δ_B 3.09 (J = 4.9 Hz, 2 H), 4.74, AB-system, δ_A 5.01, δ_B 4.47 (J = 12.4 Hz, 2 H), 7.40−8.10 (m, 5 H)].

Ozonolyses of 1-Acetoxy-2-butyne (27b). (a) In the Presence of Acetone. A solution of 0.20 g (1.8 mmol) of **27b** and 0.21 g (3.6 mmol) of acetone in 10 mL of CH_2Cl_2 was ozonized at −30 °C to give 20% of **31b**.

(b) In the Absence of Acetone. A solution of 1.98 g (17.7 mmol) of **27b** in 60 mL of CH_2Cl_2 was ozonized at −30 °C to

give 38% of **31b**, as shown by ^{1}H NMR analysis [δ 1.62 (s, 3 H), 1.80 (s, 3 H), 4.42, AB-system, δ_A 4.55, δ_B 4.29, J = 17.4 Hz)].

(c) In Dichloromethane Followed by Treatment with *O*-Methylhydroxylamine. The above experiment was repeated. Derivatization with 2.21 g (26.5 mmol) of *O*-methylhydroxylamine and 5 mL of pyridine in 50 mL of CH_3OH at −20 °C for 5 d gave 1.36 g of a residue, from which 0.43 g (13%) of **32b** was isolated (solvent: pentane/ether, 30:1).

4-Methoximino-1,5-dimethyl-2,6,7,8-tetraoxabicyclo-[3.2.1]octane (32b): colorless liquid. ^{1}H NMR: δ 1.72 (s, 3 H), 1.74 (s, 3 H), 3.88 (s, 3 H), 4.66, AB-system, δ_A 4.76, δ_B 4.56 (J = 16.4 Hz, 2 H). ^{13}C NMR: δ 14.79, 19.62, 58.22, 62.47, 105.51, 119.75, 148.86. ^{17}O NMR: δ 60 (s, C−O−CH_2), 156 (s, C−O−C and N−OCH_3), 296 (s, O−O). Anal. Calcd for $C_7H_{11}NO_5$ (189.2): C, 44.45; H, 5.86; N, 7.40. Found: C, 44.42; H, 5.79; N, 7.67.

Reduction of 32b. A solution of 20 mg of **32b** in 1 mL of $CDCl_3$ was admixed with an excess of TPP at room temperature. ^{1}H NMR analysis after 12 h showed the presence of **33b** as the sole product of reduction [δ 2.03 (s, 3 H), 2.39 (s, 3 H), 4.09 (s, 3 H), 4.89 (s, 2 H)].

(d) In Dichloromethane Followed by Treatment with Diazomethane. A solution of 2.85 g (25.5 mmol) of **27b** in 100 mL of CH_2Cl_2 was ozonized at −30 °C, and a solution of 2.8 g (66.7 mmol) of diazomethane in 200 mL of ether was added dropwise with stirring within 30 min. Stirring was continued for 2 h at room temperature, and from the residue (4.3 g), 0.56 g (13%) of **34b** was isolated (solvent: pentane/ether, 5:1).

4,7-Epoxy-4,7-dimethyl-1,5,6,8,-tetraoxaspiro[2.6]nonane (34b): colorless solid; mp 86.5 °C. ^{1}H NMR: δ 1.40 (s, 3 H), 1.72 (s, 3 H), 2.86 (d, J = 4.2 Hz, 1 H), 3.00 (dd, J = 4.2 and 2.0 Hz, 1 H), 3.48 (d, J = 11.1 Hz, 1 H), 4.54 (dd, J = 11.1 and 2.0 Hz, 1 H). ^{13}C NMR: δ 12.85, 18.55, 52.58, 54.47, 63.47, 108.63, 119.50. ^{17}O NMR: δ 2 (s, epoxy-O), 72 (s, C−O−CH_2), 159 (s, C−O−C), 312 (s, O−O). Anal. Calcd for $C_7H_{10}O_5$ (174.2): C, 48.28; H, 5.79. Found: C, 48.51; H, 5.68.

Reduction of 34b. A solution of 20 mg of **34b** in 1 mL of $CDCl_3$ was admixed with excess TPP at room temperature. ^{1}H NMR analysis after 1 h showed the presence of **35b** as the sole product of reduction [δ 2.07 (s, 3 H), 2.10 (s, 3 H), 3.07 (s, 2 H), 4.46, AB-system, δ_A 4.79, δ_B 4.13 (J = 12.4 Hz, 2 H)].

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