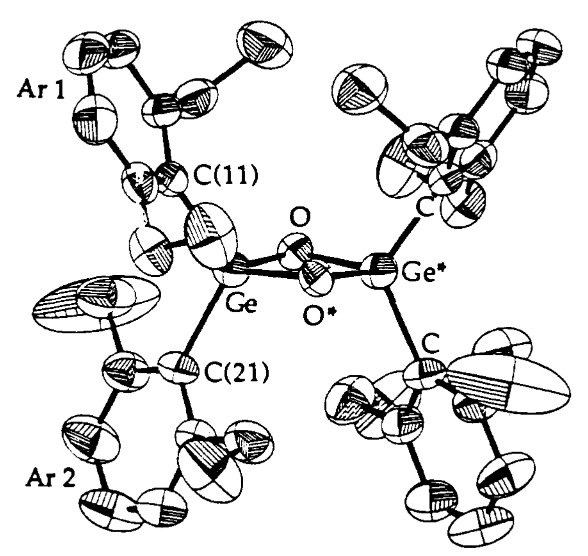

Figure 2. ORTEP diagram of **3**. Selected bond distances and angles are ass follows: Ge–O = Ge*–O* 1.820 (2) Å; Ge–O* = Ge*–O 1.814 (2) Å; Ge–Ar 1.951 Å and 1.956 Å; Ge–O–Ge* = Ge–O*–Ge 92.1 (1)°; O–Ge–O* = O–Ge*–O* 87.6 (1)°. Ge,Ge* distance 2.617 (1) Å.

lengths (2.46 Å),[9] while the Ge–O bond length is somewhat longer than others recorded (1.77 Å).[9] These deviations may be due to the constraint in forming the strained ring system. All of the four bulky 2,6-diethylphenyl groups lie below the Ge–Ge* side of the trapezoidal core. The lone pair–lone pair repulsion of the dioxetane oxygens and possibly minimization of the steric congestion of the aryl groups may lead to puckering of the four-membered ring. The aryl groups occupy a roughly helical arrangement about each germanium atom: the dihedral angles between the aryl planes and the C(11)–Ge–C(21) plane are 65.5° (for aryl group 1) and 61.2° (for aryl group 2).

Crystallographic Analysis of 3.[4,10] The crystal structure of **3** possesses a crystallographic 2-fold axis bisecting an approximately square but slightly puckered cyclodigermoxane ring with Ge–O distances and angles shown in Figure 2.[9] The dihedral angles between the two Ge–Ge*–O planes and between the two O–Ge–O* planes are 8.8 (2)° and 8.4 (1)°, respectively. The C(11)–Ge–C(21) plane is roughly orthogonal to the cyclodigermoxane ring with a slight twist angle of 9.5 (1)° along the Ge–Ge* axis. The aryl rings are attached to the cyclogermoxane ring in a roughly helical fashion and intersect the C–Ge–C plane with dihedral angles of 60.8° (for aryl 1) and 63.9° (for aryl 2).

A brief comment appears appropriate on the crystal structure of **3** in comparison with the silicon analogue **7** and other cyclodisiloxanes which were found earlier to possess silicon, silicon *distances* which are normal for, or even shorter than, a Si–Si *bond* length (2.34–2.35 Å).[3b] Both the cyclodigermoxane and cyclodisiloxane rings are nearly square. In the former (**3**) the Ge–O bond length (1.857 Å) is long enough to accommodate the two germanium atoms with a Ge,Ge distance of 2.617 (1) Å, well beyond a Ge–Ge normal bond length (2.46 Å), leading to the straightforward formulation that the cyclodigermoxane ring is constructed with four equivalent localized Ge–O bonds. In contrast, the Si–O bonds (1.66–1.68 Å), comparatively shorter than Ge–O, may in effect be "squeezing" the two silicon atoms together to minimize internal strains elsewhere in the molecule including the O,O repulsion. It is interesting to note that a normal Si–Si bond length is not significantly different from a Ge–Ge length.

Supplementary Material Available: Listings of atom coordinates and temperature factors, bond lengths, bond angles, and anisotrophic temperature factors of compounds **2** and **3** as well as physical properties (mp, UV, ^{1}H NMR) of new compounds (26 pages). Ordering information is given on any current masthead page.

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(8) Sheldrick, G. N. In *Crystallographic Computing 3*; Sheldrick, G. N., Kruger, C., Goddard, R. Eds.; Oxford University: New York, 1985; p 175.

(9) (a) Ross, L.; Dräger, M. *J. Organomet. Chem.* **1980**, *199*, 195. (b) Dräger, M.; Ross, L. Z. *Anorg. Allg. Chem.* **1981**, *476*, 95. (c) Jensen, W.; Jacobson, R. *Cryst. Struct. Commun.* **1975**, *4*, 299. (d) Glidewell, C.; Liles, D. C. *Acta Crystallogr.* **1978**, *B34*, 119. (e) Glidewell, C.; Rankin, W. H.; Robiette, A. G.; Sheldrick, G. M.; Beagley, B.; Cradock, S. *J. Chem. Soc. A* **1970**, 315.

(10) Compound **3**: $C_{40}H_{52}Ge_2O_2$, $M = 710.0$ g/mol, orthorhombic, $a = 19.362$ (7) Å, $b = 19.454$ (5) Å, $c = 9.638$ (1) Å, $V = 3630$ (3), space group *Pnab* $Z = 4$, $D_{calcd} = 1.30$ g cm^{-1}. Data were collected at room temperature by using Cu Kα radiation (graphite monochromator $\lambda = 1.5405$ Å) on a Rigaku AFC-5 diffractometer: 2627 unique, observed $[F > 3\sigma(F)]$ with $2\theta \leq 126°$. Data were corrected for Lorentz polarization effects but not for absorption. Structure solved by direct methods.[11] Convergence at $R = 0.068$ and $R_w = 0.1060$ ($p = 0.01$).

(11) Main, P.; Fiske, S. J.; Hull, S. E.; Lessinger, L.; Germain, G.; Declercq, J. P.; Woolfson, M. M. MULTAN 80, University of York, England, and Louvain-la-Neuve, Belgium, 1980.

A New Mode of Carbene Reactivity: Coupling with Two Alkynes To Generate Highly Substituted Cyclopentadiene Products

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The metal-mediated coupling of two alkynes with a carbene to generate five-membered carbocycles has not previously been realized, in part due to competitive reactions such as alkyne polymerization[1] or CO incorporation into the cyclized products.[2] A potential method for circumventing these competitive reactions is to introduce the carbene moiety at the metal center subsequent to alkyne complexation. Our approach to this problem therefore involves the intermediacy of a metallacycle, generated from two alkynes, which is then converted to a carbocycle, possibly via a metallacycle–carbene species.[3] An advantage of this route lies in the large number of metal complexes which readily form metallacycles upon reaction with alkynes and the observation that these metallacycles often react with a variety of cycloaddends to form carbocycles or heterocycles.[4] Employment of a carbene cycloaddend, in contrast to CO,[4c] would allow for direct introduction of an sp^3 carbon center into the five-membered ring product. Herein we report the successful metal-mediated cyclization of two different alkynes and a carbene to generate substituted η^4-cyclopentadiene cobalt products, with a high degree of regio- and stereoselectivity.

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(1) (a) Katz, T. J.; Hacker, S. M.; Kendrick, R. D.; Yannoni, C. S. *J. Am. Chem. Soc.* **1985**, *107*, 2182 and references therein. (b) Landon, S. J.; Shulman, P. M.; Geoffroy, G. L. *J. Am. Chem. Soc.* **1985**, *107*, 6739. (c) Schrock, R. R. *Acc. Chem. Res.* **1986**, *19*, 342.

(2) (a) Dötz, K. H.; Fischer, H.; Hofmann, P.; Kreissl, F. R.; Schubert, U.; Weiss, K. *Transition Metal Carbene Complexes*; Verlag Chemie: Deerfield Beach, FL, 1984. (b) Wulff, W. D. In *Advances in Metal-Organic Chemistry*; Liebeskind, L. S., Ed.; JAI: Greenwich, CT, 1987; Vol. 1. (c) Collman, J. P.; Hegedus, L. S.; Norton, J. R.; Finke, R. G. *Principles and Applications of Organotransition Metal Chemistry*; University Science Books: Mill Valley, CA 1987; pp 783–800.

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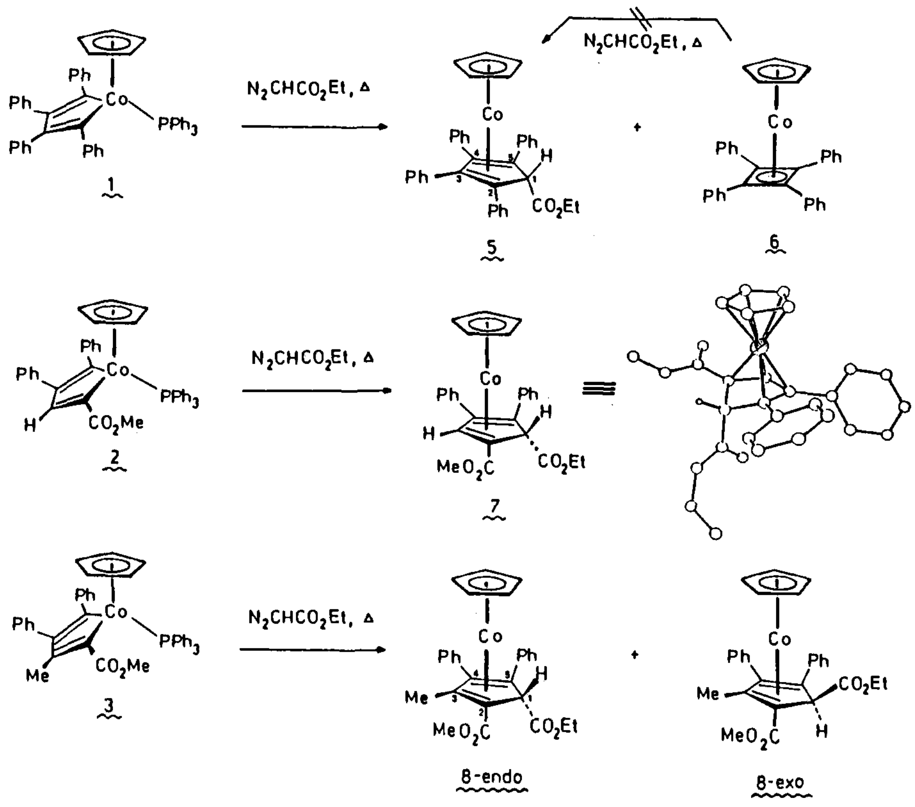
0002-7863/89/1511-1889$01.50/0

Scheme I



Following the procedure of Yamazaki, the cobaltacyclopentadiene complexes (η^5-C_5H_5)Co(PPh$_3$)(C(Ph)=C(Ph)C(Ph)=C(Ph)), **1**, and (η^5-C_5H_5)Co(PPh$_3$)(C(Ph)=C(Ph)C(R)=C(CO$_2$CH$_3$)), **2** (R = H), **3** (R = CH$_3$), were isolated as single regioisomers by reaction of (η^5-C_5H_5)Co(PPh$_3$)$_2$, **4**, with diphenylacetylene and a second alkyne.[5] When a benzene solution of **1** (779 mg, 1 mmol, 0.007 M) and ethyl diazoacetate (1.65 mL, 1.79 g, 15.8 mmol) is heated at 80 °C for 4 h, followed by chromatographic workup (−30 °C, 10% ethyl acetate/hexane, silica gel), a red solid, **5**, is isolated in 39% yield.[6] ^{1}H NMR spectroscopy (C_6D_6) indicates that **5** has incorporated a carbene fragment, :CH(CO$_2$CH$_2$CH$_3$) (δ 4.14, s, 1 H; 4.0, q, J = 7 Hz, 2 H; 0.87, t, J = 7 Hz, 3 H). The ^{13}C{^{1}H} NMR spectrum supports the η^4-cyclopentadiene ligand formulation in which the ring hydrogen remains on the carbon bearing the ethoxycarbonyl substituent. Resonances at δ 52.8 and 95.1 are assigned to C(2,5) and C(3,4), respectively, and a resonance at δ 65.5 ($^1J_{CH}$ = 132 Hz) is assigned to C(1).[7] The stereochemistry at C-1 of the diene ligand in **5** is tentatively assigned as that with hydrogen endo to the metal by analogy with the related η^4-cyclopentadiene complexes reported herein.[8]

When the reaction of **1** and ethyl diazoacetate is followed by ^{1}H NMR spectroscopy (C_6D_6, 1,4-bis(trimethylsilyl)benzene as internal standard), there are no identifiable intermediates, and η^4-cyclopentadiene complex **5** is formed in 41% yield as a single isomer. Reactions in which lower concentrations of ethyl diazoacetate are employed lead to formation of the η^4-cyclobutadiene complex (η^4-C_4Ph_4)Co(η^5-C_5H_5), **6**,[9] as a side product. Isolated **6** does not react with ethyl diazoacetate to give **5** under the reaction conditions.

The unsymmetrical metallacycle **2** reacts with ethyl diazoacetate, under similar conditions, over the course of 4 days to give the η^4-cyclopentadiene product **7** as a single isomer in 77% yield.[6] A single-crystal X-ray diffraction study unambiguously determined the relative stereochemistry in **7** as that with H-endo to the metal (Scheme I).[10] In contrast to **2**, when the closely related metallacycle **3** and ethyl diazoacetate are heated at 85 °C in C_6D_6, slow conversion (7 days) to a 1:1 ratio of **8-endo** and **8-exo** in 40% combined yield is observed. Repeated chromatography of the **8-endo**/**8-exo** mixture in the air leads to selective decomposition of **8-exo** and isolation of pure **8-endo**.[6] The endo configuration at C-1 is supported by a resonance in the ^{1}H NMR spectrum (CDCl$_3$) at δ 4.27 (s, 1 H).[11] For **8-exo**, a resonance at δ 3.50 is assigned to the ring hydrogen.[12] Photolysis of **3** and ethyl diazoacetate in C_6D_6 at 23 °C leads to decomposition of the ethyl diazoacetate, with no change in the ^{1}H NMR resonances of **3**.

Addition of Fe(NO$_3$)$_3$·9H$_2$O (244 mg, 0.60 mmol) to a wet CH$_2$Cl$_2$ solution of **8-endo** (30.5 mg, 0.063 mmol, ~0.003 M) at 23 °C (~16 h) liberates the diene ligand from cobalt as a single

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(5) Yamazaki, H.; Wakatsuki, Y. *J. Organomet. Chem.* **1977**, *139*, 157.

(6) Characterization data for complexes, **5**,**7**,**8-endo**, **8-exo**, and **9** is provided as Supplementary Material.

(7) Mann, B. E.; Taylor, B. F. ^{13}C NMR *Data for Organometallic Compounds*; Academic Press: New York, 1981.

(8) In the IR spectrum of **5**, no absorption band is observed near 2750 cm^{-1}; such a band would support an exo hydrogen assignment: Moseley, K.; Maitlis, P. M. *J. Chem. Soc., Chem. Commun.* **1969**, 616.

(9) Rausch, M. D.; Genetti, R. A. *J. Org. Chem.* **1970**, *35*, 3888. Nakamura, A.; Hagihara, N. *Bull. Chem. Soc. Jpn.* **1961**, *34*, 452.

(10) $C_{27}H_{25}O_4Co$: monoclinic, $P2_1/c$, a = 8.619 (5) Å, b = 29.18 (2) Å, c = 9.677 (6) Å, β = 109.97 (4)°, $V \approx$ 2287 (2) Å^3, Z = 4, μ = 7.76 cm^{-1}, Mo Kα (λ = 0.71073 Å), D_{calcd} = 1.37 g cm^{-3}, 23 °C, Nicolet R3m/μ diffractometer with graphite monochromator, deep red plates (0.15 × 0.30 × 0.40 mm) mounted on glass fiber. All specimens examined diffracted weakly. Of 2719 reflections collected ($4 \le 2\theta \le 42°$), 2467 were independent (R_{int} = 2.56%), and 1475 were observed with $F_o \ge 3\sigma(F_o)$. Intensity data were empirically corrected for absorption. Solution by Patterson map located Co atom, non-hydrogen atoms anisotropically refined, hydrogen atoms (except for H(9) which was located and refined) isotropic (fixed and idealized, dC–H = 0.960 Å, U = 1.2 U attached C atom), $R(F)$ = 7.65%, R(wF) = 6.64%, GOF = 1.275, and $\Delta\rho$ max = 0.49 e$^-$ Å^{-3} (between O(3)/O(4)).

(11) (a) Selective heteronuclear decoupling NMR experiments indicate that the ring hydrogen has remained on the carbon bearing the ethoxycarbonyl substituent, i.e., [1,5]-hydrogen shifts have not isomerized the complexed diene ligand in **8-endo**. (b) Similar NMR decoupling experiments on the mixture of exo and endo isomers as well as pure **9** support the proposed formulations for **8-exo** and **9**. See Supplementary Material for details.

(12) Although the relative chemical shift method for assigning stereochemistry is normally reliable, exceptions are known: Davies, S. G.; Moon, S. D.; Simpson, S. J.; Thomas, S. E. *J. Chem. Soc., Dalton Trans.* **1983**, 1805.

cyclopentadiene regioisomer, $\overline{C(H)(CO_2CH_2CH_3)C(CO_2CH_3)=C(CH_3)C(Ph)=C}(Ph)$, **9**, in 70% isolated yield.[6,11b] The overall transformation represents the metal-mediated cyclization of two different alkynes and a carbene to generate a highly substituted cyclopentadiene product. The further scope as well as the mechanism of this novel cyclopentadiene methodology is currently under exploration.

Acknowledgment. Support from the National Science Foundation (CHE-8721344) is gratefully acknowledged. We thank Professor David Macomber for helpful discussions and for suggesting the use of ethyl diazoacetate as a carbene source.

Supplementary Material Available: Tables of atomic coordinates, complete bond lengths and angles, and anisotropic thermal parameters for $C_{27}H_{25}O_4Co$, and characterization of all new compounds (6 pages); tables of observed and calculated structure factors for $C_{27}H_{25}O_4Co$ (9 pages). Ordering information is given on any current masthead page.

Formation of an Allene Oxide from (8*R*)-8-Hydroperoxyeicosatetraenoic Acid in the Coral *Plexaura homomalla*

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It has been known for two decades that the gorgonian coral *Plexaura homomalla* contains large amounts of prostaglandins of the A and E series,[1] yet the mechanism of biosynthesis of these compounds remains unresolved. There is strong circumstantial evidence that an allene oxide is formed via an (8*R*)-lipoxygenase pathway of arachidonic acid metabolism in *P. homomalla*[2-4] and that this transformation is a key step in the biosynthesis of the prostaglandins. This report describes the preparation of this unstable intermediate and establishes the structure as **2**.

In our initial investigations[3] we reported that the primary arachidonic acid metabolite (8*R*)-8-hydroperoxyeicosatetraenoic acid (8*R*-HPETE, **1**) is converted to a cyclopentenone **3** which had been detected previously in the coral *Clavularia viridis*[2] and to an α-ketol **4** (Scheme I). The α-ketol appears to be a hydrolysis product of the putative allene oxide, while the cyclic product is formed by a spontaneous rearrangement and ring closure. Notably, the cyclopentenone we isolated from incubations of *P. homomalla* has side chains in the cis configuration and is racemic,[3] and thus it is unlikely to be involved in the route to the prostaglandins.[5]

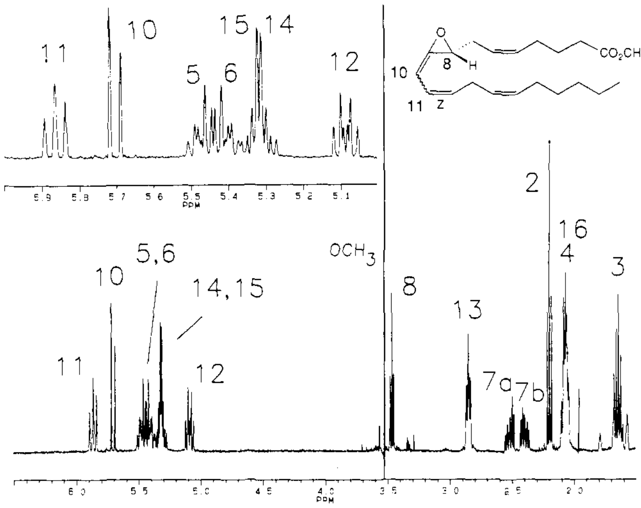
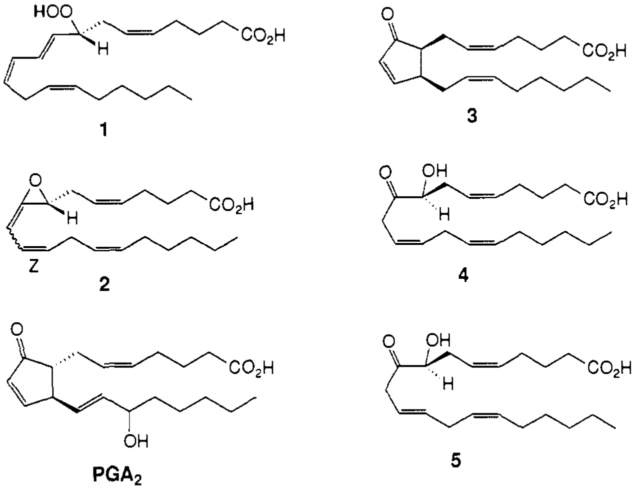


Figure 1. ¹H NMR (400 MHz) of **2**, methyl ester, in hexane-d_{14} at −50 °C.

Scheme I



The first attempts to isolate **2** using acetone powder of coral were foiled by the comparatively low rate of conversion of 8*R*-HPETE. It was reasoned that a more prolonged reaction time was required than the 5 s used with related transformations in flaxseed,[6] and yet the rapid hydrolysis of the allene oxide ($t_{1/2}$ ≈ 15 s at 0 °C, pH 7.4)[7] had to be prevented. These conditions were attained by conducting the enzymic transformation at pH 6, 0 °C for 2 min, while vortexing the solution with pentane.[8] Under these circumstances the 8*R*-HPETE is metabolized, and nonpolar product(s) are extracted into the cold organic phase and protected from hydrolysis.

Normal phase HPLC of the extract at −15 °C revealed a single main nonpolar product.[9] The structure was assigned from (i) the conjugated diene chromophore (λ_{max} 239 nm in hexane), (ii) the ¹H NMR spectrum of the methyl ester derivative, and (iii) the rapid cyclization and hydrolysis of the product to cyclopentenone **3** and α-ketol **4**. The NMR data are particularly diagnostic (Figure 1),[10] the spectrum having many features in

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[1] Weinheimer, A. J.; Spraggins, R. L. *Tetrahedron Lett.* **1969**, *59*, 5185-5188. Light, R. J.; Samuelsson, B. *Eur. J. Biochem.* **1972**, *28*, 232-240. Schneider, W. P.; Hamilton, R. D.; Rhuland, L. E. *J. Am. Chem. Soc.* **1972**, *94*, 2122-2123.

[2] Corey, E. J.; Lansbury, P. T., Jr.; Yamada, Y. *Tetrahedron Lett.* **1985**, *26*, 4171-4174. Corey, E. J.; d'Alarcao, M.; Matsuda, S. P. T.; Lansbury, P. T., Jr. *J. Am. Chem. Soc.* **1987**, *109*, 289-290. Corey, E. J.; Matsuda, S. P. T. *Tetrahedron Lett.* **1987**, *28*, 4247-4250. Corey, E. J.; Matsuda, S. P. T.; Nagata, R.; Cleaver, M. B. *Ibid.* **1988**, 2555-2558.

[3] Brash, A. R.; Baertschi, S. W.; Ingram, C. D.; Harris, T. M. *J. Biol. Chem.* **1987**, *262*, 15829-15839.

[4] For references to analogous reactions in plants, see: Hamberg, M. *Biochim. Biophys. Acta* **1987**, *920*, 76-84. Baertschi, S. W.; Ingram, C. D.; Harris, T. M.; Brash, A. R. *Biochemistry* **1988**, *27*, 18-24. Crombie, L.; Morgan, D. O. *J. Chem. Soc., Chem. Commun.* **1988**, 558-560.

[5] The cyclopentenone product **3** from *Clavularia viridis* and other sources is named pre-clavulone A by Professor Corey and co-workers,[2] although there is not yet evidence for the precursor-product relationship.

[6] Brash, A. R.; Baertschi, S. W.; Ingram, C. D.; Harris, T. M. *Proc. Natl. Acad. Sci. U.S.A.* **1988**, *85*, 3382-3386.

[7] This is an estimate, based on the measured half-life of (9*Z*,13*S*,15*Z*)-12,13-epoxy-9,11,15-octadecatrienoic acid ($t_{1/2}$ = 16 s at 0 °C, pH 7.4).[6]

[8] Conditions for 1 mL incubation: to *P. homomalla* acetone powder, 10 mg/mL in pH 6 phosphate at 0 °C, is added 8*R*-HPETE (200 μg in 20 μL EtOH), with vortexing for 2 min with 2 mL of pentane, centrifugation for 2 min at 10000 g, and collection of ≈ 1 mL of pentane (yield of **2**: ≈ 5-10%).

[9] Altex Ultrasphere silica column (4.5 × 0.46 cm), solvent system: hexane/diethyl ether/glacial acetic acid (100/10/0.01 by vol) for **2** and hexane/diethyl ether (100:3 v/v) for the methyl ester derivative. Temperature, −15 °C; flow rate, 3 mL/min; retention time ≈ 1.5 min.