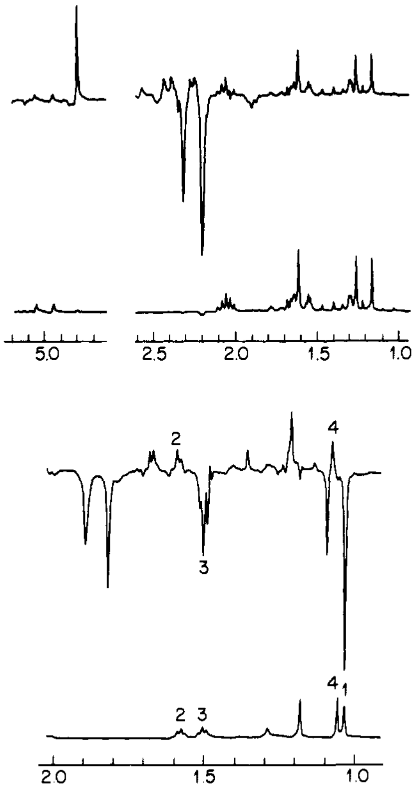

Figure 1. (Upper section) ^{1}H NMR spectra (90 MHz) of 0.02 M chloranil solutions in acetone-d_6 containing 0.02 M 6-chloro-5-methylene-1,2,3,4,6-pentamethylbicyclo[2.2.0]hex-2-ene (**1a**) in the dark (bottom) and during UV irradiation showing the formation of polarized pentamethylbenzyl chloride (top). (Lower section) ^{1}H NMR spectra (90 MHz) of 0.02 M chloranil solutions in acetone-d_6 containing 0.02 M 6-methoxy-5-methylene-1,2,3,4,6-pentamethylbicyclo[2.2.0]hex-2-ene (**1b**) in the dark (bottom) and during UV irradiation (top).

the other hand, indicates that the stabilization of the cationic allyl fragment by the methoxy group may partially compensate for the presence of the more highly strained cyclobutenyl fragment.

Registry No. 1a, 91281-46-8; **1b**, 91281-47-9; chloranil, 118-75-2.

Synthesis of Doubly Orthogonal Hexa-1,3,5-trienes: 11,12-Dimethylbicyclo[5.3.2]dodeca-1,6,11-triene

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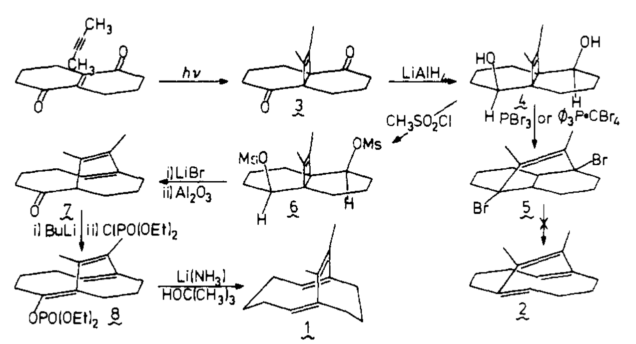
A fundamental property of butadiene and its higher vinylogues relates to changes in energy as the planes of two adjacent double bonds are twisted from 0° (s-trans) to 180° (s-cis). Extensive theoretical[1] and experimental[2] investigations over many years attest to the significance attached to the problem.

The present purpose is the first synthesis of a structure containing conjugated double bonds permanently fixed at nearly right angles to each other. To construct such a permanently orthogonal butadiene, so much structural complexity is required that it is just as easy to incorporate a doubly orthogonal hexatriene unit, which has the virtue of amplifying any thermochemical differences associated with orthogonality.

Scheme I



Triene **1**, for example, may be viewed as a near model of the transition state for the disrotatory interconversion of the s-trans,s-trans conformation of hexa-1,3,5-triene into its hypothetical s-cis,s-cis conformation, whereas triene **2** represents a model of the corresponding conrotatory transition state.

The first two steps toward a synthesis of the original target, **2**, proceeded smoothly. Reduction of the known[3] tricyclic dione **3** gave a mixture of diols. The major isomer, mp 171-174 °C, was assigned structure **4** of C_{2v} symmetry on the basis of a proton-decoupled ^{13}C NMR having seven instead of 14 peaks. The suggested configuration of the hydroxyl groups was based on steric considerations of hydride delivery. Attempted conversion to the corresponding dibromide led via profound rearrangement to **5**, the structure of which was determined by X-ray crystallographic analysis (details to be published elsewhere). Although **5** can still be imagined to give **2** by fragmentation of the Grob type, all efforts to realize that transformation failed.

In an attempt to prepare unrearranged dibromide, the mixture of diols **4** was converted to dimesylate **6**, which was treated with LiBr/THF. The resulting mixture afforded **7**, mp 68.5-70.0 °C, by chromatography on basic alumina. Its structure was deduced by spectral analysis[4] and confirmed by X-ray analysis[5] to be 11,12-dimethylbicyclo[5.3.2]dodeca-1,11-dien-6-one. The unanticipated formation of **7** opened the way to **1**, a target closely related in structure to **2** but, according to molecular mechanical calculations (MMPI),[6] even more closely approaching the desired ideal model (dihedral angles calculated for **1**, 87.5°, for **2**, 76°).

Base-catalyzed, deuterium exchange of **7** (0.048 M **7**, 0.48 M NaOCH$_3$, MeOD, 22 °C, 22 h) resulted in greater than 95% exchange at the bridgehead (C-7) hydrogen atom.[7] Advantage was taken of this unexpected behavior by converting **7** to its bridgehead enolate with butyllithium, trapping with diethyl chlorophosphate to give enol phosphate **8**,[8] and reduction of **8** with lithium in liquid ammonia. This sequence generated triene **1**, mp 36-38 °C, 78% theoretical yield based on **7** (Scheme I). Assignment of structure followed from the presence of two vinyl

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(1) Two recent theoretical papers also serve as a source of earlier references: (a) Breulet, J.; Schaefer, H. F., III. *J. Am. Chem. Soc.*, in press. (b) Bock, C. W.; George, P.; Trachtman, M. *Theor. Chim. Acta* (*Berlin*) **1984**, *64*, 292-311.

(2) (a) Squillacote, M. E.; Sheridan, R. S.; Chapman, O. L.; Anet, F. A. L. *J. Am. Chem. Soc.* **1979**, *101*, 3657-3659. (b) Carreira, L. A. *J. Chem. Phys.* **1979**, *62*, 3851-3854.

(3) Peet, N. P.; Cargill, R. L. *J. Org. Chem.* **1973**, *38*, 4281-4285.

(4) IR (film) 1695 (C=O) cm^{-1}; ^{1}H NMR (CDCl$_3$, 270 MHz) δ 5.14 (t, 1 H, J = 4.0 Hz), 2.46-2.55 (m, 3 H), 2.17-2.24 (m, 4 H), 1.85 (q, 3 H, J = 0.99 Hz), 1.79 (q, 3 H, J = 0.99 Hz), 1.76-2.06 (m, 2 H), 1.50-1.59 (m, 2 H), 1.32-1.41 (m, 2 H); ^{13}C NMR (CDCl$_3$) 213.7 (s), 144.0 (s), 134.5 (s), 129.1 (s), 127.4 (d), 58.1 (d), 39.4 (t), 31.5 (t), 31.1 (t), 29.4 (t), 24.6 (t), 22.7 (t), 20.1 (q), 17.3 (q); ms, *m/e* 204 (calcd for $C_{14}H_{20}O$ 204).

(5) Crystal data for **7**: $C_{14}H_{20}O$, M_r = 204.34; monoclinic, space group $P2_1/n$, a = 8.122 (7) Å, b = 12.071 (4) Å, c = 12.574 (8) Å, β = 105.21 (1)°, V = 1190 (7) Å^3, D_c = 1.140, Z = 4, λ(Mo Kα) (graphite monochromator) = 0.71073 Å. The intensity data were measured on a Nicolet R3M diffractometer using a crystal, with approximate dimensions of 0.42 × 0.35 × 0.30 mm, mounted in a sealed capillary. From a total of 2040 unique reflections ($3.0 \leq 2\theta \leq 48.0°$) measured, 1221 ($I > 2\sigma(I)$) were used to solve (Oxford CRYSTALS package) and refine (SHELXTL) the structure to give final results R = 0.0872 and R_w = 0.1003. All bond lengths and angles are reasonable with the exception of those involving the bridgehead double bond, which differ from expected values, apparently due to minor disorder. The final difference map has no peaks greater than ±1 e Å^{-3}.

(6) Allinger, N. L.; Sprague, J. T. *J. Am. Chem. Soc.* **1973**, *95*, 3893-3907.

(7) ^{1}H NMR shows simplification of the multiplet at 2.46-2.55 ppm, while ^{13}C NMR shows loss of intensity at 58.1 ppm. Mass spectrographic analysis indicates d_0 0.6%, d_1 91.9%, d_2 6.2%, d_3 0.9%, and d_4 0.4%.

(8) Ireland, R. E.; Muchmore, D. C.; Hengartner, U. *J. Am. Chem. Soc.* **1972**, *94*, 5098-5100.

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hydrogen atoms in the ^{1}H NMR and the presence of the eight required resonance absorptions in the ^{13}C NMR.[9]

The ultraviolet spectrum has no maximum above 200 nm (λ 230 nm: $\epsilon = 1160$ in acetonitrile).[10] The photoelectron spectrum shows three ionization bands at 8.1_5, 8.3_5, and 9.2 eV, closely spaced in comparison to those shown by *trans*-hexa-1,3,5-triene (8.3, 10.2_5, and 11.9 eV).[11] Both observations are in excellent agreement with the prediction that **1** is close to being a "perpendicular triene".

For the purpose of assessing the thermochemical consequences of orthogonality by studying heats of hydrogenation, the parent hydrocarbon bicyclo[5.3.2]dodeca-1,6,11-triene has the advantage of giving only a single perhydro derivative. This triene has now been prepared following closely the scheme developed for **1**, starting with acetylene instead of dimethylacetylene in the photochemical step. Support for its structure comes from the ^{1}H NMR spectrum, in which two new vinyl hydrogen atoms appear as a singlet [6.38 (s, 2 H)] in place of the two methyl groups of **1**[12] while the rest of the spectrum remains essentially unchanged.

Acknowledgment. We express our deep appreciation to Dr. James K. Bashkin and Jeremy M. Berg of this department for their skillful assistance in resolving the X-ray crystallographic data for **7** and our gratitude to the Norman Fund in Organic Chemistry for its support of J.C.S. in this work.

Supplementary Material Available: Thermal ellipsoid diagram, crystallographic data, and bond lengths and angles for compound **7** (5 pages). Ordering information is given on any current masthead page.

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[9] IR (film) 3030 (C—H), 1660 (C=C) cm^{-1}; ^{1}H NMR (CDCl$_3$, 270 MHz) δ 5.18 (dd, 2 H, $J = 5.5$, 10.2 Hz), 1.79–2.26 (m, 9 H), 1.76 (s, 6 H), 1.56–1.70 (m, 1 H), 1.42–1.53 (m, 1 H), 1.00–1.12 (m, 1 H); ^{13}C NMR (CDCl$_3$) δ 145.5 (s), 133.2 (s), 124.5 (d), 33.8 (t), 31.5 (t), 30.2 (t), 24.4 (t), 15.6 (q); ms, *m/e* 188.15649 (*m/e* calcd for $C_{14}H_{20}$ 188.15649).

[10] For comparison (*Z*,*Z*,*Z*)-1,3,5-cyclononatriene has λ_{max} 296 nm (ϵ = 4010, cyclohexane) [Glass, D. S.; Watthey, J. W. H.; Winstein, S. *Tetrahedron Lett.* **1965**, 377–383].

[11] The details of the PES will be published elsewhere by Professor Edgar Heilbronner to whom we express our gratitude for his active interest.

[12] IR (film) 3020 (C—H), 1650 (C=C) cm^{-1}; ^{1}H NMR (CDCl$_3$, 270 MHz) δ 6.38 (s, 2 H), 5.39 (dd, 2 H, $J = 5.2$, 10.6 Hz), 2.27–2.41 (m, 2 H), 2.10–2.18 (m, 2 H), 1.87–2.01 (m, 5 H), 1.11–1.71 (m, 3 H); ms, *m/e* 160 (calcd for $C_{12}H_{16}$ 160).

Erythrolides: Unique Marine Diterpenoids Interrelated by a Naturally Occurring Di-π-methane Rearrangement

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As part of a research program emphasizing the characterization of biologically active, novel compounds from marine sea fans and whips (Cnidaria, Octocorallia), we have recently concluded an investigation of the encrusting Caribbean octocoral *Erythropodium caribaeorum* (Duchassaing and Michelotti) (family Anthothelidae).[1,2] Unlike other organisms within this group, *E. caribaeorum* lacks the characteristic fan or tree shape of related octocorals and grows in shallow-water reef habitats as encrusting sheets exposed on rock and coral surfaces.[2] In this communication, we report the structures of two new chlorinated diterpenoids, **1** and **2**, from this source. Erythrolide A (**1**) appears to be produced in nature from diterpenoid **2** by a di-π-methane rearrangement.[3] This is the first observation of this photochemical rearrangement in the production of natural products.[4]

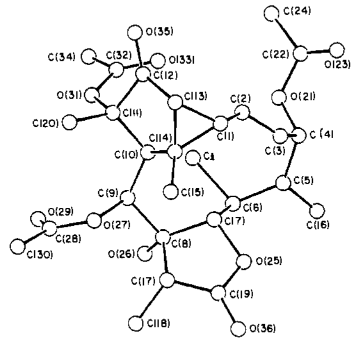
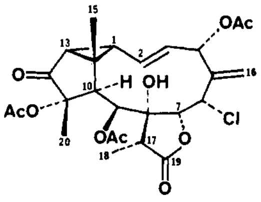
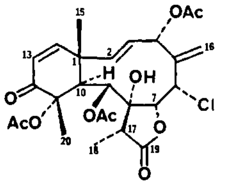


Figure 1. A computer-generated perspective drawing of erythrolide A. The absolute stereochemistry is C-1 *S*, C-4 *S*, C-6 *S*, C-7 *R*, C-8 *R*, C-9 *S*, C-10 *S*, C-11 *S*, C-13 *R*, C-14 *R*, and C-17 *R*.

Conventional chromatographic methods yielded pure samples of erythrolide A (**1**),[5] and erythrolide B (**2**),[6] from the CHCl$_3$ extract of *E. caribaeorum*. Erythrolide A was analyzed for $C_{26}H_{31}O_{10}Cl$ by high-resolution mass spectrometry, and its spectral properties suggested a structural similarity with the briarein diterpenoids recently reported from sea pens and other related octocorals.[7] The combined spectral data for **1** indicated the presence of three acetates, one ketone, a γ-lactone, two double bonds, and a single chlorine. These data combined with the molecular formula of **1** required erythrolide A to have a tricyclic carbon skeleton.



1



2

Insight into the gross structure of **1** was gained by a close examination of ^{13}C NMR data. A shielded quaternary carbon was observed at δ 28.7, suggesting the presence of a cyclopropane ring. From a gated decoupling experiment two signals at δ 37.4 (d) and 39.8 (d) were confidently assigned to a cyclopropane on the basis of their characteristically large J_{CH} values of 158.9 and 164.3 Hz. ^{1}H NMR experiments at 360 MHz yielded connectivity data for carbons 13 and 1, 1–7, and 9 and 10. On the basis of this information, structure **1**, without stereochemistry, was proposed for erythrolide A.

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[1] This organism was collected (–20 m) at Carrie Bow Cay, Belize, in March, 1980, and April, 1981.

[2] Bayer, F. M. "The Shallow Water Octocorallia of the West Indian Region"; Nijhoff: The Hague, 1961.

[3] For a review, see: Hixon, S. S.; Mariano, P. S.; Zimmerman, H. E. *Chem. Rev.* **1973**, *73*, 531.

[4] Pettus and Moore have pointed out (Pettus, J. A., Jr.; Moore, R. E. *J. Am. Chem. Soc.* **1971**, *93*, 3087–3088 and references therein) that dictyopterene A could plausibly have been formed by a di-π-methane rearrangement of *cis,trans*-1,4,6-undecatriene. However, this precursor has not been reported from *Dictyopteris*, nor have photochemical experiments been reported.

[5] Spectral data for Erythrolide A have been deposited as supplementary material.

[6] Spectral data for Erythrolide B have been deposited as supplementary material.

[7] (a) Burks, J. E.; van der Helm, D.; Chang, C. Y.; Ciereszko, L. S. *Acta Crystallogr. Sect. B.* **1977**, *B33*, 704. (b) Wratten, S. J.; Fenical, W.; Faulkner, D. J.; Wekel, J. C. *Tetrahedron Lett.* **1977**, *18*, 1559. (c) Wratten, S. J.; Faulkner, D. J.; Hirotsu, K.; Clardy, J. *J. Am. Chem. Soc.* **1977**, *99*, 2824. (d) Grode, S. H.; James, T. R.; Cardellina, J. H., II. *Tetrahedron Lett.* **1983**, *24*, 691. (e) Ravi, B. N.; Marwood, J. F.; Wells, R. J. *Aust. J. Chem.* **1980**, *33*, 2307. (f) Grode, S. H.; James, T. R.; Cardellina, J. H., II. *J. Org. Chem.* **1983**, *48*, 5203.

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