A General Approach to Linearly Fused Triquinane Natural Products. Total Syntheses of (±)-Hirsutene, (±)-Coriolin, and (±)-Capnellene

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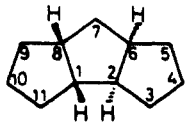
Abstract: A short, general protocol for the synthesis of linear triquinane natural products is delineated. The key element of this approach is the stepwise (photothermal) metathesis of Diels–Alder adducts derived from substituted 1,3-cyclopentadiene and *p*-benzoquinone. The methodology has been applied to the total synthesis of sesquiterpene hydrocarbons (±)-hirsutene **2**, (±)-capnellene **3**, and the antitumor compound, (±)-coriolin **5**. Thus, 1,3-cyclopentadiene and 2,5-dimethyl-*p*-benzoquinone furnish the C_{13}-bisenone **12** bearing 13 of the 15 carbon atoms of hirsutene and coriolin in only three steps. A series of regio- and chemoselective operations were performed on **12** to deliver **2** and **5** in 10 and 17 steps, respectively. Similarly, 1-methylcyclopentadiene and *p*-benzoquinone were employed as synthons for two syntheses of marine natural product capnellene **3** in 9 and 13 steps, respectively.

Despite their belated discovery in Nature, polyquinane natural products have rapidly proliferated and elicited widespread interest from synthetic chemists in recent years, primarily on account of the diverse and architecturally unique assembly of five-membered rings present in them and the promising biological activity exhibited by some members of this family.[1] Among the various polyquinanes, the linearly fused tricyclopentanoids (triquinanes) bearing the *cis,anti,cis*-tricyclo[6.3.0.$0^{2,6}$]undecane moiety **1** as the fundamental ring system are the most widely distributed and have provided a very popular testing ground for the development of new cyclopentanone annulation technologies as well as strategies for the rapid and simultaneous creation of two or more five-membered rings.[1,2] Three carbocyclic skeletons based on **1** and



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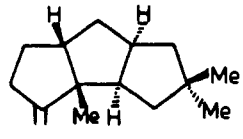

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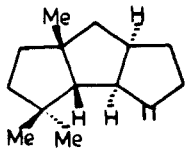

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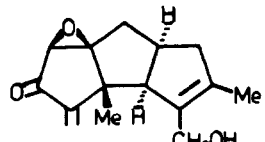

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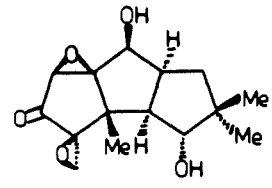
represented here by hirsutene **2** (from the fermentation broth of *Coriolus consors*),[3] capnellene **3** (from the soft coral *Capnella imbricata*),[4,5] and pleurotellol **4** (from *Pleurotellus hypnophilus*)[6] have been encountered so far. Some of the more prominent triquinane-based natural products that have received the attention of synthetic chemists due to their biological activity and the challenge posed by the high degree of functionalization with attendent stereochemical intricacies are coriolin **5** which cooccurs[7]



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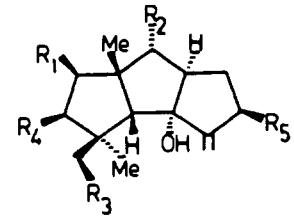

6. a. $R_1=R_2=R_3=H$, $R_4=R_5=OH$
   b. $R_1=R_3=H$, $R_2=R_4=R_5=OH$
   c. $R_2=R_3=R_4=H$, $R_1=R_5=OH$
   d. $R_2=R_4=H$, $R_1=R_3=R_5=OH$
   e. $R_1=R_3=R_4=H$, $R_2=R_5=OH$

with hirsutene **2** and capnellanols **6a–e**, the polyhydroxylated derivatives of **3**.[8] We wish to describe here the total syntheses of (±)-hirsutene **2**, (±)-coriolin **5**, and (±)-capnellene **3** by a common, flexible strategy. While an impressive number of imaginative syntheses[10–12] of **2**, **3**, and **5** have appeared in literature

(1) (a) Mehta, G. *J. Sci. Res. (Inda)* **1978**, *37*, 256. (b) Paquette, L. A. *Top. Curr. Chem.* **1979**; *79*, 43; (c) **1984**, *119*, 1.

(2) Vandewalle, M.; Declercq, P. *Tetrahedron* **1985**, *41*, 1767.

(3) Nozoe, S.; Furukawa, J.; Sankawa, U.; Shibata, S. *Tetrahedron Lett.* **1976**, 195.

(4) Ayanoglu, E.; Gebreyesus, T.; Beechan, C. M.; Djerassi, C. *Tetrahedron Lett.* **1978**, 1671.

(5) The hydrocarbon **3** has always been referred to as $\Delta^{9(12)}$-capnellene in literature. However, as **3** is the only known natural hydrocarbon of this type, we prefer to refer it as simply capnellene, like hirsutene, etc.

(6) Kupka, J.; Anke, T.; Giannetti, B. M.; Steglich, W. *Arch. Microbiol.* **1981**, *130*, 223. Steglich, W. *Pure Appl. Chem.* **1981**, *53*, 1233.

(7) Takahashi, S.; Naganawa, H.; Iinuma, H.; Takita, T.; Maeda, K.; Umezawa, H. *Tetrahedron Lett.* **1971**, 1955.

(8) Sheikh, Y. M.; Singy, G.; Kaisin, M.; Eggert, H.; Djerassi, C. *Tetrahedron Lett.* **1976**, 1171. Sheikh, Y. M.; Djerassi, C. *Tetrahedron* **1977**, *33*, 2115.

(9) Portions of the synthesis of (±)-hirsutene, (±)-coriolin and (±)-capnellene reported here have been published in the form of preliminary communications.[10d,11f,12g] However, the hirsutene synthesis described here is a shorter, modified version leading directly to the natural product. Similarly, an alternate route to (±)-capnellene which can be readily adapted to the synthesis of capnellanols **6** along with the earlier synthesis is described here.

(10) Syntheses of hirsutene **2**. (a) Tatsuta, K.; Akimoto, K.; Kinoshita, M. *J. Am. Chem. Soc.* **1979**, *101*, 6116. (b) Hudlicky, T.; Kuchan, T. M.; Wilson, S. R.; Mao, D. T. *J. Am. Chem. Soc.* **1980**, *102*, 6351. (c) Greene, A. E. *Tetrahedron Lett.* **1980**, 3059. (d) Mehta, G.; Reddy, A. V. *J. Chem. Soc., Chem. Commun.* **1981**, 756. (e) Little, R. D.; Muller, G. W. *J. Am. Chem. Soc.* **1981**, *103*, 2744. (f) Hayano, K.; Ohfune, Y.; Shirahama, H.; Matsumoto, T. *Helv. Chim. Acta* **1981**, *64*, 1347. (g) Misumi, S.; Matsushima, H.; Shirahama, H.; Matsumoto, T. *Chem. Lett.* **1982**, 855. (h) Ley, S. V.; Murray, P. J. *J. Chem. Soc., Chem. Commun.* **1982**, 1252. (i) Wender, P. A.; Howbert, J. J. *Tetrahedron Lett.* **1982**, 3983. (j) Funk, R. L.; Bolton, G. L. *J. Org. Chem.* **1984**, *49*, 5021. (k) Dawson, B. A.; Ghosh, A. K.; Jurlina, J. L.; Ragauskas, A. J.; Stothers, J. B. *Can. J. Chem.* **1984**, *62*, 2521. (l) Magnus, P.; Quagliato, D. *J. Org. Chem.* **1985**, *50*, 1621. (m) Hua, D. H.; Sinai-Zingde, G.: Venkataraman, S. *J. Am. Chem. Soc.* **1985**, *107*, 4088.

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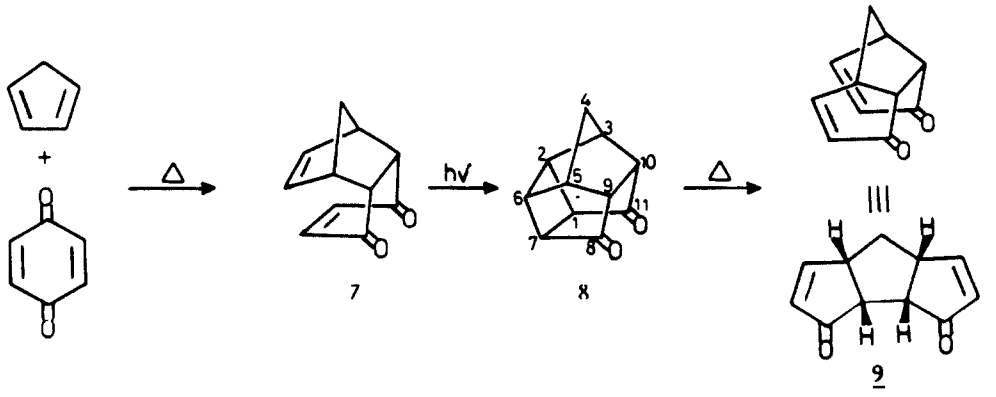
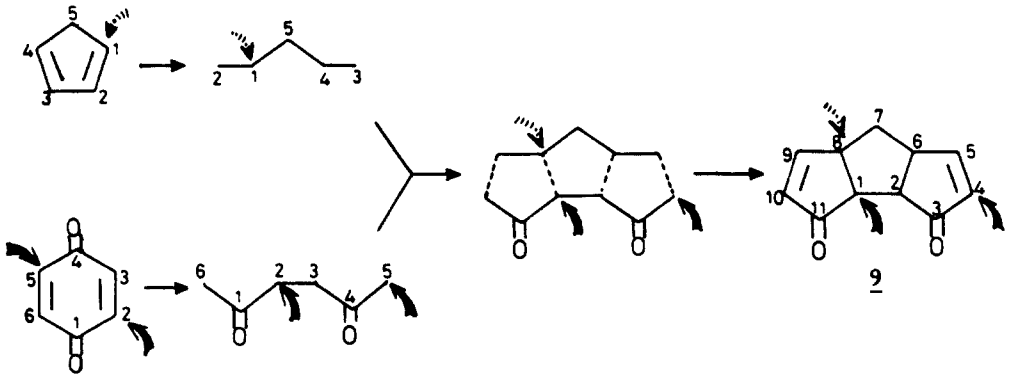
Scheme I



Scheme II



during the past 5 years, we believe that our approach to these sesquiterpenoids is notable for its generality, preparative simplicity, and conceptual novelty.

General Strategy

The cornerstone of our synthetic scheme was the recognition that the pentacyclo[5.4.0.0^{2,6}.0^{3,10}.5^{5,9}]undeca-8,11-dione (Cookson's caged dione **8**),[13a] readily available from 1,3-cyclopentadiene and *p*-benzoquinone in two high yielding steps, is a rich repository of five-membered rings which can be extracted through a thermally induced regioselective cyclobutane fragmentation (C_1–C_7 and C_2–C_6 cleavage) to furnish *cis,syn,cis*-triquinane bis-enone **9** (Scheme I).[13b] Quite remarkably, commercially available cyclopentadiene and *p*-benzoquinone can be transformed in three steps into three linearly fused five-membered rings using only heat, light, and heat, respectively, as the reagents. The key chemical change involved in this approach is the stepwise (photothermal) metathesis of the Diels–Alder adducts **7**–**9**. Adaptation of Scheme I to the synthesis of triquinane natural products requires installation of appropriate methyl substituents on the carbocyclic framework, change of cis,syn,cis stereochemistry of the triquinane to the desired cis,anti,cis pattern, and functional group adjustments.

A scrutiny of the origin of the carbon atoms of the triquinane system **9** from its precursors revealed that its top half (C_5–C_9) was derived from 1,3-cyclopentadiene and the bottom half (C_{10}, C_{11}, C_1–C_4) from *p*-benzoquinone, as shown in Scheme II. This provided direct, more or less unlimited scope for the induction of methyl or other groups on the carbocyclic framework, particularly at quaternary centers. For example, the methyl groups at C_1 and C_4 (dark arrows) required to generate the hirsutene **2** skeleton could be readily traced to the 2,5-positions of *p*-benzoquinone. Similarly, the methyl group at C_8 (dotted arrow) required to construct the capnellene **3** skeleton could be built into the complementary C_1 position of the starting 1,3-cyclopentadiene. The stereochemical problem could be readily sorted out as the *cis,syn,cis*-triquinane system **9** has a folded shape and is sterically crowded; it should be amenable to epimerization of the less hindered and thermodynamically more stable cis,anti,cis form of natural products either directly or through transposition of the enone double bond to the tetrasubstituted position and sterose-lective reduction. Finally, the bis-enone moieties on the triquinane framework constituted excellent functionalities with desirable location and oxidation level for further manipulation. Thus, a protocol for the synthesis of all triquinane natural products emerged. However, we selected hirsutene **2**, capnellene **3**, and coriolin **5** as the objectives to test our strategy, and their realization is described below.

(±)-Hirsutene 2 and (±)-Coriolin 5

Since **2** and **5** have the same carbon skeleton, it was decided at the outset that a common intermediate like **16** would be serviceable for the synthesis of both and a parting of ways should only occur at the stage of building up the requisite functionality. As indicated above, the components for constructing the triquinane framework of hirsutene and coriolin were identified as 1,3-cyclopentadiene and 2,5-dimethyl-*p*-benzoquinone. Diels–Alder cycloaddition between them finished the known adduct **10** in >90%

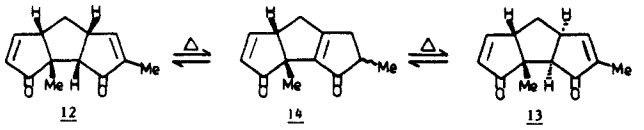
(11) Synthesis of coriolin **5**: (a) Nishimura, Y.; Koyama, Y.; Umezawa, S.; Takeuchi, T.; Ishizaka, M.; Umezawa, H. *J. Antibiot.* **1980**, *33*, 404. (b) Tatsuta, K.; Akimota, K.; Kinoshita, M. *Tetrahedron* **1981**, *37*, 4365. (c) Danishefsky, S.; Zamboni, R.; Kahn, H.; Etheredge, S. J. *J. Am. Chem. Soc.* **1981**, *103*, 3460. (d) Shibasaki, M.; Iseki, K.; Ikegami, S. *Tetrahedron* **1981**, *37*, 4411. (e) Trost, B. M.; Curran, D. P. *J. Am. Chem. Soc.* **1981**, *103*, 7380. (f) Mehta, G.; Reddy, A. V.; Murty, A. N.; Reddy, D. S. K. *J. Chem. Soc., Chem. Commun.* **1982**, 540. (g) Exon, C.; Magnus, P. *J. Am. Chem. Soc.* **1983**, *105*, 2477. (h) Wender, P. A.; Howbert, J. J. *Tetrahedron Lett.* **1983**, 5325. (i) Koreeda, M.; Mislankar, S. G. *J. Am. Chem. Soc.* **1983**, *105*, 7203. (j) Ito, T.; Tomiyoshi, N.; Nakamura, K.; Azuma, S.; Izawa, M.; Maruyama, F.; Yanagiya, M.; Shirahama, H.; Matsumoto, T. *Tetrahedron* **1984**, *40*, 241. (k) Schuda, P. F.; Heimann, M. R. *Tetrahedron* **1984**, *40*, 2365. (l) Demuth, M.; Ritterskamp, P.; Schaffner, K. *Helv. Chim. Acta* **1984**, *67*, 2023.

(12) Syntheses of capnellene **3**: (a) Huguet, J.; Karpf, M.; Dreiding, A. S. *Helv. Chim. Acta* **1982**, *65*, 2413. (b) Oppolzer, W.; Battig, K. *Tetrahedron Lett.* **1982**, 4669. (c) Fujita, T.; Ohtsuka, T.; Shirahama, H.; Matsumoto, T. *Tetrahedron Lett.* **1982**, 4091. (d) Birch, A. M.; Pattenden, G. *Tetrahedron Lett.* **1982**, 991. (e) Little, R. D.; Carroll, G. L.; Peterson, J. L. *J. Am. Chem. Soc.* **1983**, *105*, 928. (f) Paquette, L. A.; Stevens, K. E. *Can. J. Chem.* **1984**, *62*, 2415. (g) Mehta, G.; Reddy, D. S. K.; Murty, A. N. *J. Chem. Soc., Chem. Commun.* **1983**, 824. (h) Piers, E.; Karunaratne, V. *Can. J. Chem.* **1984**, *62*, 629. (i) Crisp, G. T.; Scott, W. J.; Stille, J. K. *J. Am. Chem. Soc.* **1984**, *106*, 7500.

(13) (a) Cookson, R. C.; Crundwell, E.; Hill, R. R.; Hudec, J. *J. Chem. Soc.* **1964**, 3062. (b) Metha, G.; Reddy, A. V.; Srikrishna, A.; Nair, M. S. *Tetrahedron* **1981**, *37*, 4543.

yield. Exposure of an ethyl acetate solution of the endo adduct **10** to irradiation from a 450-W UV lamp or sunlight, through Pyrex filter, resulted in a smooth intramolecular $\pi_s^2 + \pi_s^2$ cycloaddition to the crystalline pentacyclic dione **11** in high yield. The key step involving the uncaging of the caged dione was effected by employing the flash vacuum pyrolysis (FVP) technique. Sublimation of **11** through a quartz column filled with quartz chips at 500 °C (0.1 torr) led to its near quantitative conversion to the triquinane bis-enone **12**, mp 113 °C, through regioselective cyclobutane fragmentation. The structure of **12** was fully consonant with its UV spectrum (λ_{max}^{MeOH} 224 nm) and IR spectrum (1720, 1700, 1640, 1580 cm^{-1}) as well as ^1H and ^{13}C NMR parameters (vide Experimental Section). The cis,syn,cis stereochemistry of **12** followed from its genesis, and in conformity with this it underwent quantitative photocycloaddition to **11**. Thus, bis-enone **12** bearing 13 of 15 carbon atoms of hirsutene and coriolin could be readily made in 10–15-g lots through FVP, required no separation manoeuvre, and was obtained pure from the pyrolysate simply by direct crystallization!

In accordance with our plan, we had reached the stage for inversion of stereochemistry at one of the ring junctions in **12** to generate the requisite cis,anti,cis system **13**. Toward this end, the reaction of all *cis*-**11** with a variety of bases ($NaOCH_3$, DBU, K^+-*t*-BuO^-, etc.) and metal catalysts ($RhCl_3 \cdot 3H_2O$) was investigated. Although, there were definite indications about the formation of the transposed bis-enone **14**, the reactions were disappointing from preparative considerations. Recourse was then taken to thermal isomerization of the double bond in **12**, and this proved to be unexpectedly rewarding. When a solution of *cis,syn,cis*-**12** was refluxed in benzyl benzoate for 12 min, a 1:3:3.5 equilibrium mixture, readily separable by column chromatography, was obtained. While the minor component of the mixture was



12 14 13

the starting **12**, the two major products were easily recognized as the transposed bis-enone **14** and the required cis,anti,cis-bis-enone **13** on the basis of ^1H and ^{13}C NMR data. As expected, the *cis,anti,cis* isomer **13** on exposure to UV light did not revert back to the caged dione **11**. Although, the required *cis,anti,cis*-**13** was obtained in only 35–40% isolated yield from the thermal equilibrium mixture, in practical sense, these yields were quite satisfactory as the recovered **12**, and **14** could be recycled by reestablishing the thermal equilibrium.

Having secured the required stereochemistry in **13**, the next task was the installation of the C_4-*gem*-dimethyl group to reach the common intermediate **16** for hirsutene and coriolin. Catalytic hydrogenation of **13** over Pd/C furnished the tetrahydro derivative **15** (mixture of C_4-epimers). Alkylation of **15** with methyl iodide in the presence of either NaH or K^+-*t*-BuO^- proceeded with good regioselectivity, and the crystalline dione **16**, mp 64–65 °C, was obtained in moderate yield. The conversion of dione **16** to (±)-hirsutene necessitated methylenation of the C_{11}-carbonyl and removal of the C_3-carbonyl group, and this was achieved in a straightforward manner without recourse to any protective groups.[15] Wittig olefination of **16** with the ylide derived from triphenylmethylphosphonium bromide–sodium *tert*-amyloxide proceeded selectively at the less hindered C_{11}-carbonyl group, and **17** was realized in 84% yield. Removal of the C_3-carbonyl was accomplished via the Barton procedure[16] and involved LAH reduction to the hydroxyolefin **18**, one-pot conversion to *S*-methyl dithiocarbonate derivative **19**, and reduction with tri-*n*-butyltin hydride to furnish the hydrocarbon **2** found identical with the natural product[17] through direct spectral comparison (Scheme III).

Attention was now turned toward the more challenging coriolin **5** which required considerable elaboration of functionality with stereochemical control. Through retrosynthetic analysis shown in Scheme IV, we identified hydroxydienone **24** and hydroxyketone **22** as the main intermediate enroute to **5** from the C_{14}-dione **16** already in hand. Transformation of **16** to the hydroxy ketone **23** required an alkylative carbonyl transposition at C_{11} and stereoselective carbonyl reduction at C_3. This was achieved in a short, clean sequence, and once again our strategy was to rely on chemodifferentiation of functionality engendered by the prevailing steric environment around them rather than deploy any protective groups, Scheme V. Addition of methylmagnesium iodide occurred exclusively at the less hindered C_{11} in **16**, and dehydration of the resulting tertiary alcohol furnished the keto olefin **20**. Reduction of **20** with Li in liquid NH_3 proceeded stereoselectivity, and formation of the thermodynamically more stable hydroxyolefin **21** (^1H NMR: δ 3.52 (1 H, d, J = 8 Hz) secured the stereochemistry at this newly generated fifth chiral center. The olefinic moiety in **21** was carefully epoxidized with *m*-chloroperbenzoic acid, and the crude epoxide was rearranged with BF_3 etherate to furnish the crystalline hydroxy ketone **22**, mp 162 °C, in good yield. Only the C_{11}-β-methyl isomer was formed in the sequence due to the attack of the peracid from the convex face of hydroxyolefin **21** and subsequent stereoselective rearrangement. However, the stereochemistry at C_4 was not crucial, as it was to be compromised and destroyed with the introduction of double bonds in the later steps.

Attainment of the hydroxydienone **24** from **22** meant sequential installation of two double bonds in conjugation with the carbonyl group. The C_8–C_9 double bond was first introduced by capturing the kinetic enolate of **22** with TMSCl and subjecting the derived trimethylsilyl enol ether to palladium acetate mediated dehydrosilylation using Saegusa's procedure.[18] The C_3-hydroxy group was automatically protected as trimethylsilyl ether during the reaction. The derived hydroxyenone **23** (UV: 225 nm. IR: 1690, 1630 cm^{-1}) was then transformed into the cross-conjugated dienone **24** through a phenylselenylation–selenoxide elimination sequence.[19] Kinetic deprotonation of **23** with a 2-fold excess of LDA and treatment with phenylselenyl bromide furnished the intermediate α-phenylselenylenone, which was directly oxidized with 30% H_2O_2 to furnish the hydroxydienone **24** found identical with the compound recently described in the literature.[11d] Since, Ikegami et al.[11d] have converted **24** into coriolin **5** in a neat four-step sequence, our arrival at **24** completes a formal total synthesis of the natural product.

Another short entry to coriolin **5** through one of the advanced intermediates in Danishefsky's synthesis[11c] was explored. The keto olefin **20** described above was treated with *m*-chloroperbenzoic acid, and the resulting epoxy ketone was rearranged with BF_3 etherate to give the dione **25**. On deprotonation with LDA and quenching with TMSCl, dione **25** was transformed regioselectively to the trimethylsilyl enol ether. Dehydrosilylation with palladium acetate yielded the C_{11}–epimeric mixture of enones **26a,b**, readily separable by chromatography in 65% yield. Both **26a** and **26b** were found identical with the two epimers reported[11c] recently by Danishefsky by direct spectral comparison. Our synthesis of enones **26a,b** therefore constitutes an alternate route to (±)-coriolin **5**, Scheme V.

(±)-Capnellene 3

Our synthetic efforts toward the complex capnellanols **6** first focused on the presumed, biogenetic precursor of these polyoxygenated marine sesquiterpenoids and the simplest member of

(14) For the sake of convenience and commonality, we have used the tricyclo[6.3.0.0^{2,6}]undecane **1** numbering throughout this paper.

(15) An examination of the models clearly reveals that the C_3-carbonyl is sterically shielded by the C_1-methyl as well as the C_4-*gem*-dimethyl group. This enables chemoselective reactions on the C_{11}-carbonyl group. We have attempted to exploit these subtle steric differences in preference to the use of protective groups in all our functional group alterations.

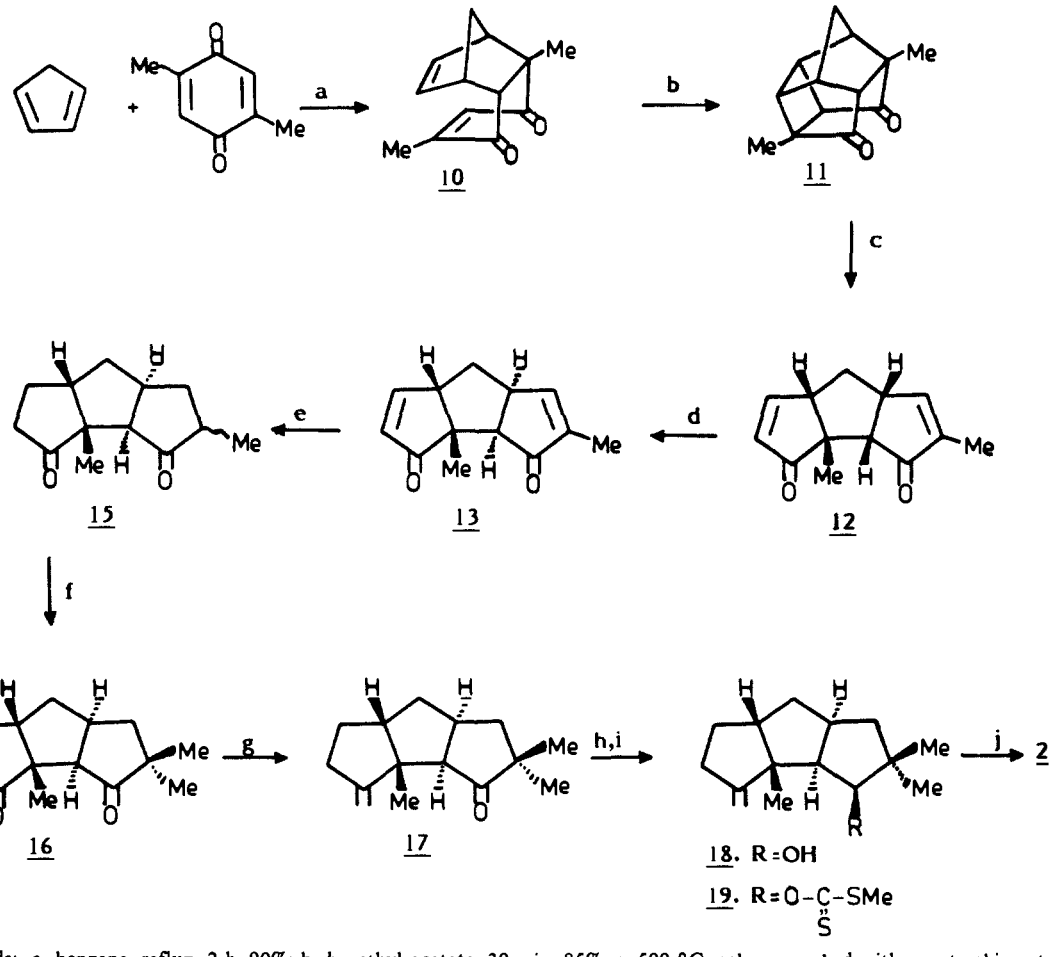
(16) Barton, D. H. R; McCombie, S. W. *J. Chem. Soc., Perkin Trans. 1* **1975**, 1574.

(17) The comparison spectra of hirsutene were kindly supplied by Prof. K. Tatsuta.

(18) Ito, Y.; Hirao, T.; Saegusa, T. *J. Org. Chem.* **1978**, *43*, 1011.

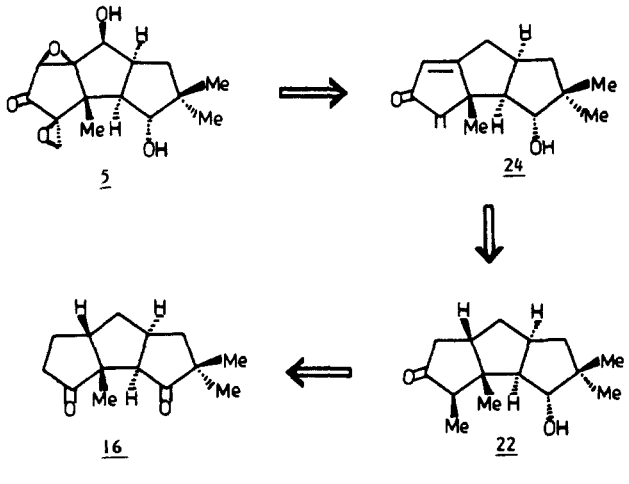
(19) Reich, H. J.; Renga, J. M.; Reich, I. L. *J. Am. Chem. Soc.* **1975**, *97*, 5434.

Scheme III



Reagents and yields: a, benzene, reflux, 2 h, 90%; b, *hν*, ethyl acetate, 30 min, 85%; c, 500 °C, column packed with quartz chips at 0.1 torr, quantitative; d, benzylbenzoate, 317 °C, 12 min, 37%; e, H_2–10% Pd/C in ethyl acetate, 20 min, 95%; f, NaH–THF, MeI, reflux, 65%; g, $Ph_3P{:}CH_2$–toluene, reflux, 3 h, 84%; h, LAH–Et_2O, room temperature, 30 min, 90%; i, NaH–THF–imidazole–CS_2–MeI, reflux, 88%; j, $(n\text{-Bu})_3SnH$– toluene, reflux, 6 h, 19%.

Scheme IV



the family, the hydrocarbon capnellene **3**. On the basis of the strategic analysis discussed earlier, 1-methylcyclopentadiene and *p*-benzoquinone were selected as the starting synthons for building the capnellane-type triquinane framework. Diels–Alder reaction between the two furnished a 60:40 mixture of regioisomeric endo adducts **27a,b** from which the requisite **27a** was obtained pure through fractional crystallization.[20] Irradiation of **27a** in ethyl acetate in a Pyrex vessel with a 450-W lamp furnished the pentacyclic dione **28a**, mp 176 °C, through intramolecular $\pi_s^2 + \pi_s^2$ photocycloaddition. FVP of **28a** through a quartz column at 530 °C (0.1 torr) gave the cis,syn,cis-bis-enone **29**, mp 93–94 °C, in near quantitative yield. The structure of **29** was secured through its diagnostic ^1H NMR (δ 1.30, 3 H, S)) and ^{13}C NMR data. Although, we demonstrated the sequence from **27a** to **29** using pure **27a**, the loss of material during purification of **27a** by fractional crystallization was too severe, and therefore, in practice, we carried the mixture of **27a** and **27b** to the FVP stage through **28a** and **28b**, where the bis-enones **29** and **30** were readily separable by column chromatography. Brief exposure of **29** to DBU resulted in a smooth relocation of the double bond, and the transposed bis-enone **31**, mp 97–98 °C, was formed in high yield.

Further elaboration of **31** bearing 12 of the 15 carbon atoms of the capnellane framework to the natural product **3** required creation of the cis,anti,cis stereochemical pattern as well as chemo- and regioselective geminal dimethylation and Wittig methylenation of the carbonyl groups. These objectives were successfully achieved following two different approaches summarized in Scheme VI. In the first series of transformations, the transposed bis-enone **31** was partially hydrogenated, and the resulting saturated carbonyl group underwent chemoselective Wittig olefination with the ylide derived from triphenylmethylphosphonium bromide and sodium *tert*-amyloxide to give **32**. Simmons–Smith cyclopropanation[21] of the terminal olefinic bond furnished the spiro-fused tetracyclic enone **33**. Catalytic hydrogenation of **33** over PtO_2 unravelled the C_{11}-*gem*-dimethyl group and simultaneously reduced the double bond to directly give norcapnellanone **34**. The presence of alkyl substitution at C_{11} provided the control element for the stereoselective reduction of the tetrasubstituted double bond to

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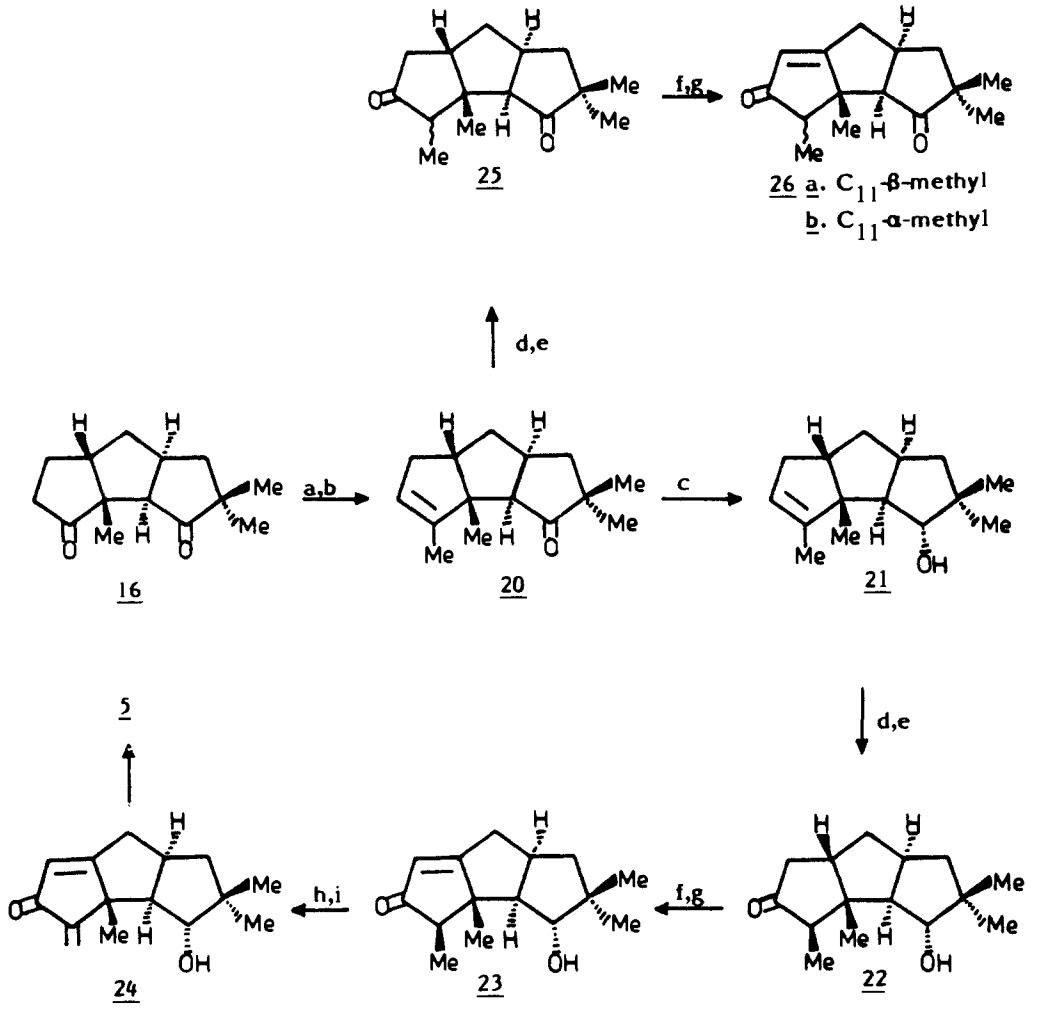
Scheme V



Reagents and yields: a, MeMgI–Et_2O, room temperature, 30 min, 90%; b, $POCl_3$–Py, room temperature, 14 h, 75%; c, Li–liquid NH_3–MeOH, 63%; d, *m*-CPBA–CH_2Cl_2, room temperature, 30 min, quantitative; e, BF_3 etherate–CH_2Cl_2, 0–5 °C, 5 min, 80%; f, LDA–THF, –78 °C, TMSCl; g, $Pd(OAC)_2$–MeCN, room temperature, 4 h, and aqueous THF–MeCOOH, 90%; h, LDA–THF, –78 °C, PhSeBr; i, MeCOOH–H_2O_2–THF, 30 min, 35%.

generate the less crowded cis,anti,cis stereochemistry. Since **34** has been previously converted[12e] to capnellene **3** in one step, our synthesis of **34** and its direct comparison with the spectra provided by Prof. Little completed the synthesis of the natural product.

In the second route toward **3**, we employed an alkylative enone transposition[22]–dimethyl cuprate addition sequence to generate the C_{11}-*gem*-dimethyl group. We selected this methodology as it generated an additional oxygen functionality at C_9 and renders this route amenable for adaptation to the complex capnellanols **6**. Consequently, bis-enone **31** was treated with methylmagnesium iodide and the resulting product directly oxidized with pyridinium chlorochromate molecular sieves.[23] Careful column chromatography of the product mixture provided the new alkylated bis-enone **35** in 40% yield. Controlled sodium borohydride reduction of **35** at –10 °C produced the 1,4-reduction product **36** as the major product of the reaction. Addition of lithium dimethyl cuprate to **36** in the presence[24] of BF_3–etherate proceeded smoothly and in good yield to deliver the geminal dimethylated compound **37** in 88% yield. Pyridinium chlorochromate oxidation of **37** followed by Wittig methylenation (triphenylmethylphosphonium bromide–sodium *tert*-amyloxide) of the less hindered carbonyl furnished the C_{15}-keto olefin **38**. The last stage in the synthesis was the removal of the C_9-carbonyl group, and this was realized by employing the Barton deoxygenation methodology.[16] LAH reduction of **38** gave the corresponding hydroxyolefin, which was directly transformed to *S*-methyldithiocarbonate and further reduced with tri-*n*-butyltin hydride to give the hydrocarbon **3** found identical with the natural product.

In summation, an exceptionally simple protocol for triquinane natural products based on photothermal olefin metathesis of readily available Diels–Alder adducts has been outlined. Since the requisite triquinane framework with its pendant methyl substitution can be readily constructed by building the complementary substitution pattern into the precursor 1,3-cyclopentadiene and *p*-benzoquinone, the task of synthesizing natural product of this family is reduced to functional group alterations. We have taken advantage of the geometry of the *cis,anti,cis*-triquinane framework and presence of bis-enone functionality to carry out several regio- and chemoselective reactions leading to the total synthesis of (±)-hirsutene **2** (10 steps), (±)-coriolin **5** (17 steps), and (±)-capnellene **3** (9 and 13 steps).

Experimental Section

1,4-Dimethyltricyclo[6.3.0.0^{2,6}]undeca-4,9-diene-3,11-dione (12). Pentacyclic dione **11**,[13b] 2.01 g (0.01 mol), was sublimed at 110 °C/0.1 torr through a quartz column [1.5 × 30 cm, connected to a vacuum line and provided with a collection flask and liquid nitrogen trap. The quartz tube was heated with a nichrome wire wound around it and was insulated with asbestos padding. The temperature was controlled by a Variac and was measured by a Chromel–Alumel thermocouple on a Keithley digital multimeter. The quartz tube was preheated and equilibrated at 500 °C]. The pyrolyzed product was directly crystallized from dichloromethane–petroleum ether, 2 g (quantitative). mp 113 °C. UV λ_{max}^{MeOH}: 224 nm (ϵ = 7500). IR (KBr): 1720, 1700, 1640, 1580 cm^{-1}. ^{1}H NMR (100 MHz, $CDCl_3$): δ 1.4 (3 H, s), 1.6 (3 H, s), 1.93 (1 H, $^1/_2$AB, J = 14

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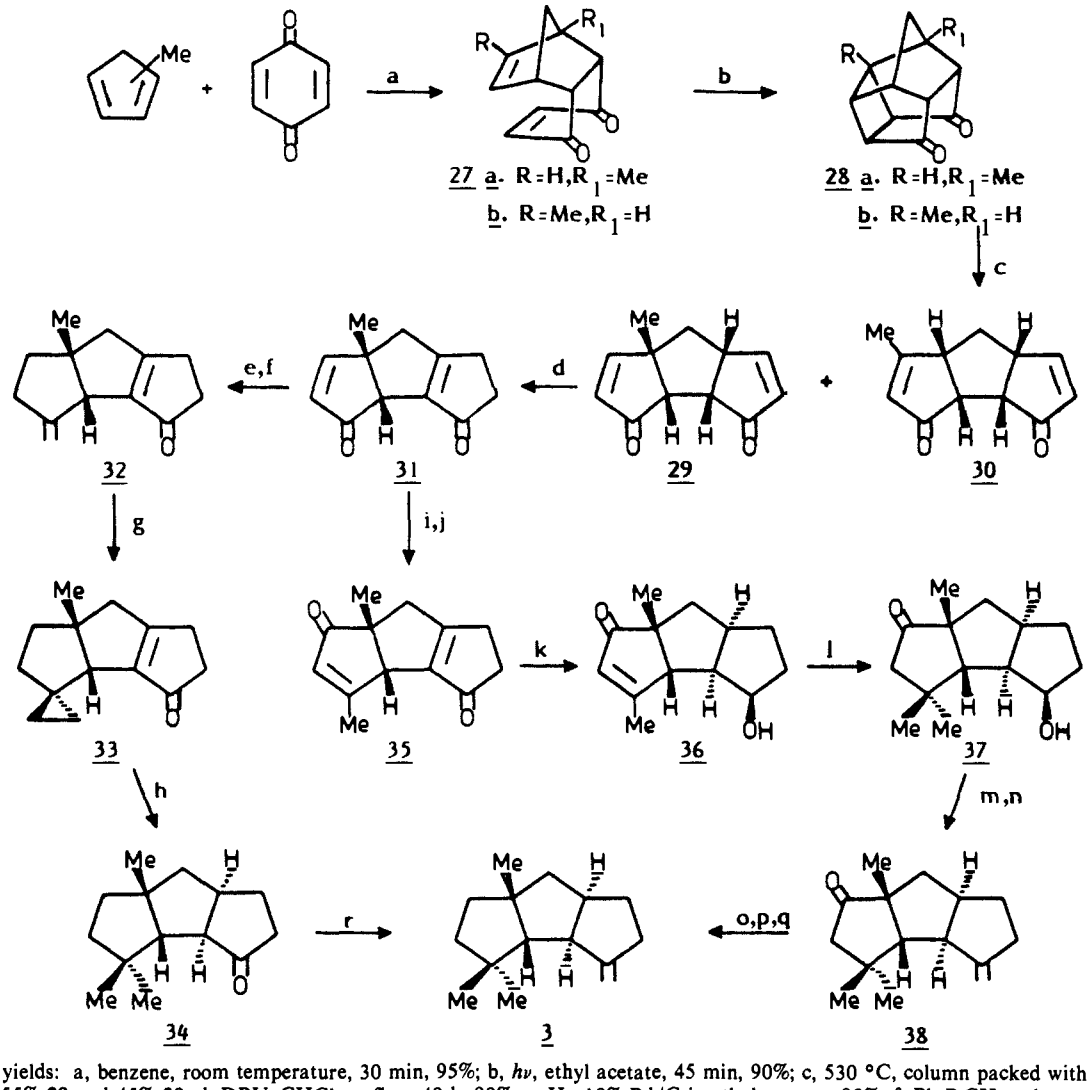
(23) Corey, E. J.; Suggs, J. W. *Tetrahedron Lett.* **1975**, 2647.
(24) Yamamoto, Y.; Maruyama, K. *J. Am. Chem. Soc.* **1978**, *100*, 3240.

Scheme VI



Reagents and yields: a, benzene, room temperature, 30 min, 95%; b, *hν*, ethyl acetate, 45 min, 90%; c, 530 °C, column packed with quartz chips at 0.1 torr, 55% **29** and 45% **30**; d, DBU–$CHCl_2$, reflux, 40 h, 90%; e, H_2–10% Pd/C in ethyl acetate, 80%; f, Ph_3P:CH_2–toluene, reflux, 3 h, 80%; g, CH_2I_2–Zn/Cu couple–Et_2O, 50 h, 50%; h, H_2–PtO_2 in MeCOOH, 3 atm, 30 h, 60%; i, MeMgI–Et_2O, room temperature, 1 h; j, PCC–CH_2Cl_2, 1.5 h, 40%; k, $NaBH_4$–MeOH, −10 °C, 45%; l, $LiMe_2Cu$–BF_3 etherate–Et_2O, 88%; m, PCC–CH_2Cl_2, 30 min, 88%; n, Ph_3P:CH_2–toluene, reflux, 2.5 h, 90%; o, LAH–Et_2O, room temperature 30 min, 80%; p, NaH–THF–imidazole–CS_2–MeI, reflux, 88%; q, $(n\text{-Bu})_3SnH$–toluene, reflux, 4 h, 53%; r, ref 12e.

Hz), 2.36 (1 H, td, J_1 = 14, J_2 = 10 Hz), 2.68 (1 H, d, J = 6 Hz), 3.03 (1 H, d, J = 10 Hz), 3.48 (1 H, br s), 5.84 (1 H, dd, J_1 = 6, J_2 = 2 Hz), 7.12 (1 H, br, s), 7.38 (1 H, dd, J_1 = 6, J_2 = 2 Hz). ^{13}C NMR (25.0 MHz, $CDCl_3$): δ 208.9 (s), 207.6 (s), 164.1 (d), 159.7 (d), 141.2 (s), 131.5 (d), 60.7 (d), 59.5 (s), 57.5 (d), 47.3 (d), 30.9 (t), 21.6 (q), 10.1 (q). Anal. Calcd for $C_{13}H_{14}O_2$: C, 77.2; H, 6.98. Found: C, 76.98; H, 6.95.

Sunlight Photocyclization of 12. The bis-enone **12**-20 mg (0.1 mmol), was dissolved in 10 mL of acetone in a Corning round-bottomed flask. The solution was flushed with nitrogen and was kept in sunlight for 5 h. The TLC, IR, and ^1H NMR of the product after removal of solvent were identical with the pentacyclic dione **11**.

Photocyclization of 12 using a UV Lamp. A solution of **12**, 202 mg (1 mmol), in 180 mL of nitrogen-purged ethyl acetate was irradiated by using a Hanovia 450-W medium-pressure mercury vapor lamp in a quartz immersion well with a Pyrex filter for 20 min. The TLC, IR, and ^1H NMR of the product after removal of solvent was identical with the pentacyclic dione **11**.

Thermal Equilibration of 1,4-Dimethyltricyclo[6.3.0.0^{2,6}]undeca-4,9-diene-3,11-dione (12). A benzyl benzoate (15 mL) solution of cis,syn,-cis-bis-enone **12**, 2.02 g (10 mmol), was refluxed (317 °C) for 12 min. GLC analysis of the total mixture indicated three components in the ratio 1:3:3.5. The reaction mixture was diluted with dichloromethane (20 mL) and chromatographed on a silica gel (50 g) column. Benzyl benzoate was removed by eluting the column with dichloromethane. Elution with 5% ethyl acetate–benzene furnished 740 mg (37%) of the cis,anti,cis compound **13**, which was bulb-to-bulb distilled (150 °C/0.4 torr) and crystallized as colorless plates from an ether–petroleum ether mixture. mp 65–66 °C. UV, λ_{max}^{MeOH}: 228 nm (ε 10140). IR (KBr): 1710, 1640, 1585 cm^{-1}. ^1H NMR (100 MHz, $CDCl_3$) δ 1.17 (3 H, s), 1.75 (3 H, dd, J = 1.5 Hz), 1.92 (1 H, dd, J_1 = 8, J_2 = 5 Hz), 2.0 (1 H, dd, J = 8, J_2 = 5 Hz), 2.82 (1 H, d, J = 6 Hz), 3.1 (1 H, t, J = 6 Hz), 3.32 (1 H, br s), 6.03 (1 H, dd, J_1 = 6, J_2 = 2 Hz), 7.27 (1 H, q, J = 1.5 Hz), 7.68 (1 H, dd, J_1 = 6, J_2 = 3 Hz). ^{13}C NMR (25.0 MHz, $CDCl_3$): δ 211.7 (s), 207 (s), 165.5 (d), 159.5 (s), 140.2 (s), 129.6 (s), 57.1 (d), 56.5 (s), 53.5 (d), 46.5 (d), 34.9 (t), 19.0 (q), 9.7 (q). Anal. Calcd for $C_{13}H_{14}O_2$: C, 77.20; H, 6.97. Found: C, 76.91; H, 7.09.

Further careful elution of the column with 30% ethyl acetate–benzene gave 320 mg (14%) of the starting material **12**, which was identified by TLC, GLC, and IR comparisons. Finally, elution of the column with 40% ethyl acetate–benzene furnished 940 mg (49%) of 1,4-dimethyltricyclo[6.3.0.0^{2,6}]undeca-2(6),9(10)-diene-3,11-dione (**14**) as an epimeric mixture which was distilled at 150 °C/0.4 torr. UV, λ_{max}^{MeOH}: 245 (ε 4811), 218 nm (ε 12300). IR (neat): 1715, 1635, 1590 cm^{-1}. ^1H NMR (100 MHz, $CDCl_3$ as an epimeric mixture at C_4): δ 1.16 (3 H, d, J = 7 Hz), 1.20 (3 H, d, J_1 = 7 Hz), 1.42 (3 H, s), 1.48–3.7 (1 H, m), 6.08 (1 H, dd, J_1 = 6, J_2 = 2 Hz), 7.5 (1 H, dd, J_1 = 6, J_2 = 3 Hz). ^{13}C NMR (25.0 MHz, $CDCl_3$ as an epimeric mixture at C_4): δ 207.9 (s), 204.4 (s), 182.1 (s), 181.8 (s), 163.6 (d), 163.5 (d), 145.7 (s), 131.1 (s), 57.7 (d), 56.0 (d), 46.6 (d), 34.7 (t), 34.3 (t), 18.4 (q), 16.8 (q), 16.4 (q).

1β,4-Dimethyl-*cis*,*anti*,*cis*-tricyclo[6.3.0.0^{2,6}]undecane-3,11-dione (15). Cis,anti,cis-bis-enone **13**, 505 mg (2.5 mmol), was taken in 30 mL of ethyl acetate and hydrogenated in a Parr hydrogenation apparatus over 50 mg of 10% Pd/C catalyst at 20-psi pressure. After 20 min, no more consumption of hydrogen was noticeable. The catalyst was filtered, and the solvent was removed to give 500 mg of the product (>95%). Bulb-

to-bulb distillation a 120 °C/0.8 torr furnished a colorless oil which solidified on refrigeration. Trituration with petroleum ether furnished small rectangular plates. mp 55–57 °C. IR (neat): 1740 cm^{-1}. ^1H NMR (100 MHz, $CDCl_3$): δ 1.0 (3 H, s), 1.08 (3 H, d, J = 6 Hz), 1.2–3.0 (12 H, en). ^{13}C NMR (25.0 MHz, $CDCl_3$ as an epimeric mixture); δ 221.3, 219.9, 60.1, 55.3, 54.2, 47.2, 46.2, 44.0, 43.4, 38.0, 34.2, 33.7, 33.0, 23.0, 21.5, 19.9, 18.2, 12.6. Anal. Calcd for $C_{13}H_{18}O_2$: C, 75.69; H, 8.80. Found: C, 75.47; H, 8.85.

1β,4,4′-Trimethyl-*cis*,*anti*,*cis*-tricyclo[6.3.0.0^{2,6}]undecane-3,11-dione (16). Freshly sublimed potassium *tert*-butoxide, 173 mg, (1.5 mmol), was placed in a 50-mL round-bottomed flask equipped with a dry nitrogen gas inlet, condenser with mercury seal and rubber septum, and covered with 5 mL of dry THF. The reaction flask was kept at 0 °C, and the diketone **15**, 300 mg (1.46 mmol), in 5 mL of THF was slowly injected. The reaction mixture was stirred for 10 min, and methyl iodide, 400 mg (3 mmol), in 1 mL of THF was added to the enolate. The reaction mixture was stirred for additional 15 min, and most of the THF was removed under reduced pressure. The residue was diluted with water (10 mL) and extracted with ether (3 × 15 mL). The ethereal layer was washed and dried and the solvent removed to furnish 290 mg of crude methylated product. The crude product was charged on a silica gel (10 g) column and chromatographed. Careful elution with benzene removed most of the minor products formed in the reaction. Elution with 2% ethyl acetate–benzene gave 150 mg (50%) of **16** which was crystallized from petroleum ether, mp 64–65 °C, as white cubic plates. IR (KBr): 1735, 1385 cm^{-1}. ^1H NMR (100 MHz, $CDCl_3$): δ 1.02 (9 H, s), 1.16–3.0 (11 H, m), 3.75, (1 H, Br s). ^{13}C NMR (25.0 MHz, $CDCl_3$): δ 222.7 (s), 221.6 (s), 60.0 (s), 55.3 (d), 48.0 (s), 47.2 (d), 43.4 (t), 38.0 (d), 36.2 (t), 33.0 (t), 25.1 (q), 23.0 (q), 21.5 (t), 18.2 (q). Anal. Calcd for $C_{14}H_{20}O_2$: C, 76.33; H, 9.15. Found: C, 75.95; H, 9.25.

The above reaction could also be carried out using NaH. NaH (800 mg, 16.7 mmol, 50% dispersion in oil) was placed in a 250-mL three-necked flask equipped with magnetic pellet, dry nitrogen gas inlet, condenser with mercury seal, and rubber septum. The mineral oil was washed off with dry petroleum ether (60–80 °C) 3 times, and NaH was covered with 10 mL of dry THF. The rubber septum was now quickly replaced by a pressure-equilizing separatory funnel containing diketone **15**, 3 g (14.6 mmol) in 40 mL of THF, and was slowly added to the stirred NaH dispersion. After the addition of **15** was complete, the solution was refluxed for 30 min and cooled to 10 °C (ice–water bath). Methyl iodide, 4 g (28.2 mmol) in 5 mL of THF, was now added to the enolate. The whole mixture was stirred for 30 min, and THF was removed under reduced pressure. The reaction mixture was quenched with water and extracted with ether (2 × 50 mL). The ethereal solution was dried, and the solvent was removed to give 2.6 g of crude oily product. The mixture was charged on a silica gel (70 g) column and chromatographed. Careful elution with benzene removed all the minor products and impurities. Elution with 2% ethyl acetate in benzene gave 2 g (65%) of the methylated product and was crystallized from petroleum ether, mp 64–65 °C. This was identical with the sample of **16** obtained in the above experiment.

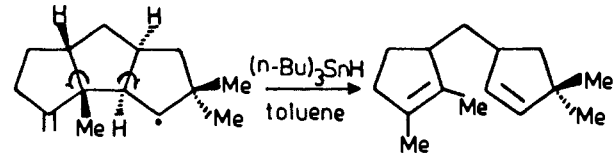
1β,4,4′-Trimethyl-*cis*,*anti*,*cis*-tricyclo[6.3.0.0^{2,6}]dodeca-11(12)-en-3-one (17). In to a 25-mL three-necked, round-bottomed flask fitted with dry nitrogen inlet, septum, reflux condensor, and mercury seal, triphenylmethylphosphonium bromide, 997 mg (2.79 mmol), was introduced with an addition funnel, and the solid was suspended in dry toluene (5 mL). To this suspension was added sodium *tert*-amyloxide, 246 mg (2.23 mmol), in dry toluene (5 mL). The yellow reaction mixture was stirred at ~40 °C for 5 min and then the diketone **16**, 410 mg (1.86 mmol), in dry toluene (5 mL) was introduced at once. The reaction mixture was refluxed for 3 h and then diluted with benzene (10 mL) and brine (15 mL). The organic layer was separated, washed, and dried. Removal of solvent gave an oily residue which was charged on a silica gel (25 g) column. Elution with petroleum ether removed the triphenylphosphine-derived impurities. Further elution with 50% benzene–petroleum ether furnished the terminal olefinic compound **17**, 340 mg (84%), which was bulb-to-bulb distilled at 90 °C/0.4 torr. IR (neat): 3100, 2950, 1740, 1660, 1460, 1380, 1140, 1100, 890 cm^{-1}. ^1H NMR (100 MHz, $CDCl_3$): δ 1.04 (3 H, s), 1.06 (3 H, s), 1.08 (3 H, s), 1.24–2.6 (9 H, m), 2.8 (2 H, br s), 4.92 (1 H, t, J = 2 Hz), 5.0 (1 H, t, J = 2 Hz). Exact mass calcd for $C_{15}H_{22}O$ m/e 218.1671, found m/e 218.1671.

1β,4,4′-Trimethyl-*cis*,*anti*,*cis*-tricyclo[6.3.0.0^{2,6}]dodeca-11(12)-en-3β-ol (18). In to a two-necked, 25-mL, round-bottomed flask fitted with a rubber septum and mercury seal was placed LAH, 20 mg (excess), in dry ether (10 mL). To this suspension, olefin **17**, 50 mg (0.23 mmol), in dry ether (10 mL) was slowly added through a syringe. After the solution stirred for 45 min, a few drops of ethyl acetate was added to destroy excess hydride. The reaction mixture was diluted with water and extracted with ether (3 × 10 mL). The ethereal layer was washed and dried. Removal of solvent gave hydroxyolefin **18**, 100 mg (90%), as a single epimer, which was crystallized from petroleum ether as white needles. mp 58 °C. IR (neat): 3450, 3100, 2950, 1660, 1470, 1390, 1080, 880 cm^{-1}. ^1H NMR (100 MHz, $CDCl_3$): δ 0.92 (3 H, s), 1.04 (3 H, s), 1.14 (3 H, s), 1.24–2.6 (12 H, m), 3.5 (1 H, d, J = 8 Hz), 4.84 (2 H, d, J = 4 Hz). Exact mass calcd for $C_{15}H_{24}O$ m/e 220.1827, found m/e 220.1827.

1β,4,4′-Trimethyl-*cis*,*anti*,*cis*-tricyclo[6.3.0.0^{2,6}]dodeca-11(12)-enyl 3-*S*-methyldithiocarbonate (19). A mixture of 100 mg (0.45 mmol) of hydroxyolefin **18**, NaH, 65 mg (1.35 mmol–50% dispersion in oil), and imidazole (5 mg) in dry THF (5 mL) in a 25-mL, three-necked flask was refluxed with stirring for 3 h under nitrogen. Carbon disulfide (1 mL) in THF (2 mL) was then added to the reaction mixture. After refluxing for a further 45 min, methyl iodide (1 mL) was added and refluxing continued for another 30 min. Reaction mixture was quenched with acetic acid (0.3 mL), diluted with water, and extracted with ether (3 × 10 mL). The ethereal layer was washed and dried. The crude product was charged on a silica gel (5 g) column. Elution with petroleum ether removed nonpolar impurities, and further elution with 10% benzene–petroleum ether furnished the *S*-methyldithiocarbonate derivative **19**, 125 mg (88%). IR (neat): 3100, 2950, 1660, 1470, 1220, 1060, 880 cm^{-1}. ^1H NMR (100 MHz, $CDCl_3$): δ 1.03 (3 H, s), 1.05 (3 H, s), 1.1 (3 H, s), 1.2–2.96 (11 H, m), 2.6 (3 H, s), 4.84 (2 H, m), 5.86 (1 H, d, J = 8 Hz).

(±)-Hirsutene (2). In to a 25-mL, three-necked, round-bottomed flask fitted with an argon inlet, reflux condensor, septum, and mercury seal was taken tri-*n*-butyltin hydride, 188 mg (0.65 mmol), in dry toluene (3 mL). The reaction mixture was heated to reflux during which the *S*-methyldithiocarbonate **19**, 100 mg (0.32 mmol), in dry toluene (2 mL) was slowly injected. After the mixture was refluxed for 6 h, toluene was removed under vacuum and the residual oil was charged on an $AgNO_3$ impegnated silica gel (10 g) column. Elution with petroleum ether removed the organotin impurities. Further elution with 5% benzene–petroleum ether furnished the hydrocarbon **2**, 12 mg (19%). IR (neat): 3080, 2950, 1650, 1460, 1370, 875 cm^{-1}. ^1H NMR [(CCl_4): δ 0.92 (6 H, s), 1.04 (3 H, s), 1.12–1.72 (10 H, m), 1.92–1.84 (1 H, m), 2.24–2.64 (4 H, m), 4.7 (2 H, br s). This hydrocarbon was found identical (IR and ^1H NMR) with hirsutene **2** through spectral comparison.[17]

Continued elution with 50% benzene–petroleum ether furnished another hydrocarbon, 12 mg (19%), tentatively identified as (ii) derived through reductive fragmentation of the intermediate homoallylic radical (i). IR (neat): 3050, 2900, 1455, 1380, 1360, 750 cm^{-1}. ^1H NMR (100 MHz, $CDCl_3$): δ 1.04 (3 H, s), 1.12 (3 H, s), 1.16–1.48 (6 H, m), 1.56 (3 H, s), 1.66 (3 H, s), 2.76–3.04 (4 H, m), 5.4 (2 H, s). ^{13}C NMR (25.0 MHz, $CDCl_3$): δ 140.9, 134.3, 133.3, 130.9, 48.5, 46.6, 45.1, 43.9, 41.4, 36.9, 30.2, 29.0, 28.7, 14.0, 12.2. Exact mass calcd for $C_{15}H_{24}$ m/e 204.1877, found m/e 204.1873.



(i) (ii)

1β,4,4′,11-Tetramethyl-*cis*,*anti*,*cis*-tricyclo[6.3.0.0^{2,6}]undeca-10-en-3-one (20). To a magnetically stirred suspension of magnesium (145 mg, 6 mmol) in 10 mL of dry ether was added methyl iodide (3 mL, excess) in 10 mL of dry ether. The mixture was stirred until all the magnesium had reacted. A solution of the diketone **16**, 1 g (4.55 mmol), in 15 mL of dry ether was added to it at a time. The reaction mixture was stirred at room temperature for 30 min and then quenched by the careful addition of saturated NH_4Cl solution. The organic layer was separated and the aqueous layer extracted with ether (2 × 40 mL). The combined organic extracts were washed and dried. Evaporation of the solvent furnished 1.06 g of tertiary alcohol (>95%). ^1H NMR (100 MHz, $CDCl_3$): δ 0.84 (3 H, s), 1.04 (6 H, s), 1.18 (3 H, s), 1.2–3.5 (12 H, m). Tertiary alcohol (1.06 g) obtained above (4.5 mmol) in 10 mL of dry pyridine was placed in a 50-mL round-bottomed flask fitted with a drying tube. To this stirred solution, 2 mL of phosphorus oxychloride was added at 0–5 °C, and the mixture was stirred overnight (14 h) at room temperature (35 °C). The reaction mixture was diluted with petroleum ether (20 mL) and slowly quenched with water (10 mL) to hydrolyze the excess phosphorus oxychloride. Extraction with petroleum ether (3 × 30 mL) and washing with dilute hydrochloric acid (20%, 3 × 20 mL) followed by brine and removal of solvent gave 800 mg of crude olefin **20**. This material was charged on a small silica gel (20 g) column. Elution with petroleum ether removed the impurities. Elution with 50% benzene–petroleum ether gave 700 mg of the desired olefin **20** (75%). It was

distilled at 140 °C/1 torr to furnish a colorless pleasant smelling oil. IR (neat): 3050, 1740, 1650 cm^{-1}. ^1H NMR (100 MHz, $CDCl_3$): δ 0.92 (3 H, s), 1.0 (3 H, s), 1.03 (3 H, s), 1.1–1.6 (3 H, m), 1.68 (3 H, br s), 1.72–2.9 (6 H, m), 5.02 (1 H, br s). ^{13}C NMR (25.0 MHz, $CDCl_3$): δ 223.4 (s), 145.8 (s), 120.4 (d), 61.7 (s), 57.6 (d), 49.3 (d), 47.4 (s), 42.6 (t), 39.8 (d), 38.0 (t), 35.4 (t), 25.0 (q), 23.2 (q), 23.0 (q), 12.1 (q). Anal. Calcd for $C_{15}H_{24}O$: C, 81.76; H, 10.98. Found: C, 81.48, H, 10.95.

1β,4,4′,11-Tetramethyl-*cis*,*anti*,*cis*-tricyclo[6.3.0.0^{2,6}]undeca-10-en-3α-ol (21). A solution of 500 mg (2.3 mmol) of the keto olefin **20** in 10 mL of THF was added to liquid ammonia (75 mL) followed by 6 mL of methanol. To this stirred solution, 500 mg of freshly cut lithium metal was carefully added, piece by piece, and allowed to stir further for 20 min. The reaction mixture was quenched with solid ammonium chloride and the ammonia evaporated off. The residue was extracted with ether (3 × 25 mL).

The combined organic layers were washed and dried, and the solvent was removed to furnish 480 mg of crude product which was charged on a silica gel (15 g) column. Elution with 50% benzene–petroleum ether removed some minor impurities. Further elution with benzene gave 316 mg of alcohol **21** (63%) which was crystallized from hot petroleum ether. mp 57–58 °C. IR (KBr): 3350, 1640, 795 cm^{-1}. ^1H NMR (100 MHz, $CDCl_3$): δ 0.9 (3 H, s), 1.16 (3 H, s), 1.1–1.6 (3 H, m), 1.63 (3 H, d, J = 1 Hz), 1.7–2.6 (6 H, m), 3.52 (1 H, d, J = 8 Hz), 5.08 (1 H, s). ^{13}C NMR (25.0 MHz, $CDCl_3$): δ 147.5 (s), 122.3 (d), 82.0 (d), 59.1 (s), 56.2 (d), 50.4 (d), 45.6 (t), 43.1 (s), 41.0 (t), 38.4 (d), 36.7 (t), 27.3 (q), 20.6 (q), 19.8 (q), 13.0 (q). Anal. Calcd for $C_{15}H_{24}O$: C, 81.76; H, 10.98. Found: C, 81.48, H, 10.95.

1β,4,4′,11-Tetramethyl-10-oxo-*cis*,*anti*,*cis*-tricyclo[6.3.0.0^{2,6}]undecan-3α-ol (22). Hydroxyolefin **21**, 600 mg (2.7 mmol), was dissolved in 10 mL of dry dichloromethane in a 50-mL round-bottomed flask, and 700 mg of anhydrous sodium carbonate was suspended in it. *m*-Chloroperbenzoic acid, 600 mg (80%, 3.48 mmol), was then added at 0 °C, and the mixture was stirred at room temperature for 30 min. The reaction mixture was quenched by the addition of sodium bicarbonate solution and was stirred for another 30 min. Extracting with dichloromethane (2 × 20 mL), washing, drying, and removing of solvent furnished 600 mg of crude epoxide, and it was used as such for further reaction.

To a cooled solution (0–5 °C) of the epoxide, 600 mg (2.7 mmol), in 10 mL of dry dichloromethane was added freshly distilled boron trifluoride etherate (0.1 mL). After stirring for about 5 min, the reaction mixture was quenched with saturated sodium bicarbonate solution and extracted with dichloromethane (2 × 20 mL). The dichloromethane extract was washed and dried. Removal of solvent furnished 550 mg (80%) of hydroxy ketone **22** and was crystallized from petroleum ether–dichloromethane. mp 162 °C. IR (KBr): 3510, 3475, 1730 cm^{-1}. ^1H NMR (100 MHz, $CDCl_3$): δ 0.9 (3 H, s), 0.97 (3 H, d, J = 6 Hz), 1.0 (3 H, s), 1.04 (3 H, s), 1.1–2.9 (11 H, en), 3.5 (1 H, J = 8 Hz). ^{13}C NMR (25.0 MHz, $CDCl_3$): δ 221.0 (s), 81.7 (d), 57.1 (d), 51.8 (s), 51.7 (d), 45.9 (t), 43.3 (s), 42.6 (t), 41.2 (t), 39.2 (d), 37.3 (d), 26.4 (q), 19.5 (q), 16.4 (q), 7.9 (q). Anal. Calcd for $C_{15}H_{24}O_2$: C, 76.23; H, 10.24. Found: C, 76.48; H, 10.13.

1β-4,4′,11-Tetramethyl-10-oxo-2α,6α-tricyclo[6.3.0.0^{2,6}]undeca-8-(9)-en-3α-ol (23). Into a 50-mL, three-necked flask fitted with dry nitrogen gas inlet, septrum, and mercury seal, 5 mL of dry THF was introduced. It was cooled to −78 °C, and 0.2 mL (1.2 mmol) of diisopropylamine was introduced followed by *n*-butyllithium (1.0 mmol) in ether (1 mL). A solution of hydroxy ketone **22**, 50 mg (0.2 mmol), in 2 mL of dry THF was added from a syringe, and the solution was stirred for 30 min and then brought to 0 °C. Trimethylsilyl chloride, 50 mg (0.5 mmol), in 1 mL of dry THF was introduced rapidly to the enolate solution, and the reaction mixture was stirred for 15 min. Saturated sodium bicarbonate solution was added to the reaction mixture, and the silyl enol ether was extracted with ether (3 × 20 mL). The ethereal layer was washed, dried, and evaporated to give an oily residue.

The above silyl enol ether was dissolved in 4 mL of dry acetonitrile; palladium acetate, 25 mg (0.1 mmol), and *p*-benzoquinone, 11 mg (0.1 mmol) were added to it.[18] The reaction mixture was stirred at ambient temperature for 2 h and then filtered through neutral alumina (5 g) column, using 5% ethyl acetate–benzene to remove palladium metal and other insoluble impurities. Removal of solvent furnished enone-*O*-silyl ether as an oily residue.

The silyl ether functionality was hydrolyzed by using a mixture of acetic acid–water–THF (3:1:1) and stirring over a period of 20 min. The reaction mixture was carefully quenched into a saturated sodium bicarbonate solution (5 mL) and extracted with ether (3 × 20 mL). The ethereal layer was washed, dried, and freed of solvent to furnish crude **23**. The crude product was applied to a short silica gel (10 g) column, and elution with 5% ethyl acetate–benzene gave first the starting hydroxy ketone **22** (10 mg). Further elution with 10% ethyl acetate–benzene gave hydroxyenone **23**, 40 mg (90% based on recovered starting material). On distillation at 140 °C/0.5 torr, **22** was obtained as a colorless oil. UV, λ_{max}^{MeOH}: 225 nm (ϵ 15 700). IR (neat), 3420, 1690, 1630 cm^{-1}. ^1H NMR (100 MHz, $CDCl_3$)b δ 0.96 (3 H, s), 1.05 (3 H, s), 1.08 (3 H, s), 1.14 (3 H, d, J = 7 Hz), 1.2–3.0 (8 H, en), 3.75 (1 H, d, J = 8 Hz), 5.7 (1 H, d, J = 1 Hz).

1β,4,4′-Trimethyl-10-oxo-2α,6α-tricyclo[6.3,0.0^{2,6}]undeca-8(9),11-(12)-dien-3α-ol (24). Into a 25-mL, three-necked flask fitted with dry nitrogen gas inlet, septum, and mercury seal, 5 mL of dry THF was introduced. It was cooled to −78 °C, and 0.2 mL (1.2 mmol) of diisopropylamine was introduced followed by *n*-butylithium (1.0 mmol) in ether (1 mL). A solution of hydroxyenone **23**, 10 mg (0.043 mmol), in 1 mL of dry THF was added from a syringe, and the solution was stirred for 30 min at the same temperature. Phenylselenyl bromide, 40 mg (0.12 mmol), in 1 mL of dry THF was introduced rapidly to the enolate solution, and the reaction mixture was stirred for 15 min. The cold reaction mixture was poured into 10 mL of 0.5 N hydrochloric acid and the α-(phenylseleno)enone was extracted with ether (3 × 20 mL). The ethereal layer was washed, dried, and evaporated to give a dark-brown oily residue.

The above α-(phenylseleno)enone was dissolved in 2 mL of THF containing glacial acetic acid (1 μL), 0.01 mL of 30% H_2O_2 was gradually added, and the solution was stirred at 0 °C for 1 h.[19] Saturated sodium bicarbonate solution was added to the reaction mixture and extracted with ether (3 × 10 mL). The ethereal layer was washed, dried, and evaporated to furnish crude **24** as an oily residue.

The crude dienone **24** was passed through a small silica gel (5 g) column, using 5% ethyl acetate–benzene as eluent to remove minor impurities. Removal of solvent furnished the dienone **24** as colorless oil, 4 mg (35%). IR (neat): 1687, 1620, 940 cm^{-1}. ^1H NMR (100 MHz, $CDCl_3$): δ 0.92 (3 H, s), 1.09 (3 H, s), 1.28 (3 H, s), 1.36–3.6 (7 H, en), 3.88 (1 H, d, J = 8 Hz), 5.35 (1 H, s), 5.92 (2 H, s). The comparison of IR and ^1H NMR spectra of **24** with the authentic spectra[11d] supplied by Prof. Ikegami established their complete identity.

Continued elution of the column with the same solvent gave the starting hydroxyenone **23** (2 mg), which could be conveniently recycled.

1β,4,4′,11-Tetramethyl-*cis*,*anti*,*cis*-tricyclo[6.3.0.0^{2,6}]undecane-3,10-dione (25). Ketoolefin **20**, 600 mg (2.7 mmol), was dissolved in 10 mL of dry dichloromethane in a 50-mL, round-bottomed flask, and 700 mg of anhydrous sodium carbonate was suspended in it. *m*-Chloroperbenzoic acid, 600 mg (80%, 3.48 mmol), was then added at 0 °C, and the contents were stirred at room temperature for 30 min. The reaction mixture was quenched by the addition of sodium bicarbonate solution and the heterogeneous mixture stirred for another 30 min to remove *m*-chlorobenzoic acid. Extracting with dichloromethane (2 × 20 mL), washing, drying, and removing of solvent furnished 600 mg of crude epoxide, and it was used as such for the next step.

To a cooled solution (0–5 °C) of the epoxide, 600 mg (2.7 mmol), in 10 mL of dry dichloromethane was added freshly distilled boron trifluoride etherate (0.1 mL). After stirring for about 5 min, the reaction mixture was quenched with saturated sodium bicarbonate solution and extracted with dichloromethane (2 × 20 mL). The dichloromethane extract was washed with brine and dried. Removal of solvent furnished 420 mg (65%) of diketone **25** as light-brown oil and was shown (TLC, ^1H NMR) to be a mixture of C_{11}-epimers with one epimer predominating. Distillation at 150 °C/1 torr furnished a colorless oil. IR (neat): 1740 cm^{-1}. Anal. Calcd for $C_{15}H_{22}O_2$: C, 76.88; H, 9.46. Found: C, 76.58; H, 9.23.

1β,4,4′,11-Tetramethyl-2α,6α-tricyclo[6.3.0.0^{2,6}]undeca-8(9)-ene-3,10-dione (26a and 26b). In to a 50-mL, three-necked flask fitted with dry nitrogen gas inlet, septum, and mercury seal, 5 mL of dry THF was introduced. It was cooled to −78 °C, and 0.2 mL (1.2 mmol) of diisopropylamine was introduced followed by *n*-butyllithium (1.0 mmol, which was estimated by Shapiro's method) in ether (1 mL). A solution of dione **25**, 50 mg (0.5 mmol), in 2 mL of dry THF was added from a syringe, the solution was stirred for 30 min, and the reaction mixture was brought to 0 °C. Trimethylsilyl chloride, 50 mg (0.5 mmol), in 1 mL of dry THF was introduced rapidly to the enolate solution, and the reaction mixture was stirred for 15 min. Saturated sodium bicarbonate solution was added to the reaction mixture and the silyl enol ether was extracted with ether (3 × 20 mL). The ethereal layer was washed, dried, and evaporated to give an oily residue.

The above silyl enol ether was dissolved in 4 mL of dry acetonitrile; palladium acetate, 25 mg (0.1 mmol), and *p*-benzoquinone, 11 mg (0.1 mmol), were added to it. The reaction mixture was stirred at ambient temperature for 2 h and then filtered through a neutral alumina (5 g) column, using benzene as the solvent to remove palladium metal and other insoluble impurities. Removal of solvent furnished a mixture containing **25** and **26a** and **26b**.

The mixture was applied to a short silica gel (10 g) column, and elution with benzene gave first the starting dione **25** (10 mg). Further elution with 5% ethyl acetate–benzene gave enone **26**, 30 mg (60%), as a mixture of C_{11}-epimers. Trituration of the mixture with petroleum ether gave 5 mg of one of the epimers **26a** or **26b** as a white crystalline solid. mp 94 °C [lit.[11c] mp 93–95 °C]. UV, λ_{max}^{MeOH}: 225 nm (ϵ 12100). IR: 1730, 1704, 1640 cm^{-1}. ^1H NMR (100 MHz, $CDCl_3$): δ 0.9 (3 H, s), 1.1 (6 H, s), 1.18 (3 H, d, J = 7 Hz), 1.3–3.3 (6 H, en), 5.81 (1 H, br s). The spectral characteristics of the other epimeric enone **26a** or **26b** were taken after the purification of the mother liquor of the above enone. UV, λ_{max}^{MeOH}: 228 nm (ϵ 10000). IR (CH_2Cl_2): 1730, 1700, 1640 cm^{-1}. ^1H NMR (100 MHz, $CDCl_3$): δ 1.08 (9 H, s), 1.16 (3 H, d, J = 7 Hz), 1.3–3.2 (6 H, en), 5.68 (1 H, d, J = 6 Hz). The ^1H NMR spectra of both **26a** and **26b** were superimposable with the authentic spectra of enone epimers provided by Prof. Danishefsky.[11c]

8-Methyl-*endo*-tricyclo[6.2.0.0^{2,7}]undeca-4,9-diene-3,6-dione (27a and 27b). To an ice-cooled solution of *p*-benzoquinone, 16.2 g (0.15 mol), in 200 mL of benzene was added at once 12 g (0.15 mol) of freshly cracked methylcyclopentadiene in 10 mL of benzene. The mixture was stirred for 30 min at ambient temperature, and the solvent was removed. The solid residue on crystallization from petroleum ether furnished **27a** and **27b** as yellow needles, 26 g (45% of methyl epimers, 60:40, respectively); while this adduct mixture was used as such for the subsequent steps, pure **27a** was obtained for characterization purposes through repeated crystallizations from methanol as pale-yellow needles. mp 115 °C [lit.[20] 116–117 °C). IR (KBr): 2950, 1670, 1600, 1300, 860, 740 cm^{-1}. ^1H NMR (100 MHz, $CDCl_3$): δ 1.40 (3 H, s), 1.56 (3 H, s), 2.9 (1 H, d, J = 8 Hz), 3.4 (2 H, m), 5.98 (2 H, ABq, J_{AB} = 6 Hz), 6.53 (2 H, s). ^{13}C NMR (25.0 MHz, $CDCl_3$): δ 199.3 (s), 198.7 (s), 142.1 (d), 141.7 (d), 139.0 (d), 134.9 (d), 57.8 (s), 55.4 (t), 52.7 (d), 50.9 (d), 49.2 (d), 17.5 (q).

Methylpentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undeca-8,11-dione (28a and 28b). The above adduct mixture, 20 g (0.106 mol), in 750 mL of nitrogen-purged ethyl acetate was irradiated with a Hanowia 450-W medium-pressure mercury vapor lamp in a quartz immersion well through Pyrex filter for 45 min. Removal of solvent and crystallization gave a mixture of pentacyclic diones, 18 g (90%). The mixture was used as such for the next step. However, for characterization purposes, an analytically pure sample of pentacyclic dione **28a** was prepared through repeated crystallizations of the mixture from acetone, colorless needles, mp 176 °C [lit.[20] mp 175 °C]. IR (KBr): 2950, 1760, 1730, 1460, 1060 cm^{-1}. ^1H NMR (100 MHz, $CDCl_3$): δ 1.20 (3 H, s), 1.95 (2 H, ABq, J_{AB} = 11 Hz), 2.23–3.55 (7 H, m). ^{13}C NMR (25.0 MHz, $CDCl_3$): δ 211.8 (s), 211.1 (s), 60.0 (d), 55.5 (d), 52.4 (d), 45.9 (t), 44.4 (2c, d), 44.2 (d), 42.9 (d), 39.6 (d), 15.7 (q). Anal. Calcd for $C_{12}H_{12}O_2$: C, 76.57; H, 6.43. Found: C, 76.42; H, 6.45.

Methyl-*cis,syn,cis*-tricyclo[6.3.0.0^{2,6}]undeca-4,9-diene-3,11-dione (29 and 30). The mixture of pentacyclic diones (60:40), 2.0 g (0.01 mol), was sublimed at 130 °C/0.3 mm through a quartz column [1.5 × 30 cm, connected to a vacuum line and provided with a collection flask and liquid nitrogen trap. The quartz tube was heated with a nichrome wire wound around it and was insulated with asbestos padding. The temperature was controlled by a Variac and was measured by a Chromel–Alumel thermocouple on a Keithley digital multimeter. The quartz tube was preheated and equilibrated at 530 °C]. The pyrolyzed product from the collection flask was charged on a silica gel column (50 g). Elution with 50% ethyl acetate–benzene furnished 1.1 g (55%) of **29**, which was crystallized from benzene–petroleum ether as colorless plates. mp 93–94 °C. UV, λ_{max}^{MeOH}: 216 nm (ϵ 11650). IR (KBr): 3100, 2950, 1730, 1600, 1470, 1350, 1200, 840 cm^{-1}. ^1H NMR (100 MHz, $CDCl_3$): δ 1.30 (3 H, s), 2.08 (2 H, d, J = 8 Hz), 2.80 (1 H, d, J = 12 Hz), 3.28 (1 H, dd, J_1 = 12, J_2 = 6 Hz), 3.60 (1 H, m), 5.72 (1 H, d, J = 6 Hz), 5.84 (1 H, dd, J_1 = 6, J_2 = 3 Hz), 7.40 (1 H, d, J = 6 Hz), 7.48 (1 H, dd, J_1 = 6, J_2 = 3 Hz). ^{13}C NMR (25.0 MHz, $CDCl_3$): δ 207.7 (s), 207.6 (s), 170.7 (d), 166.2 (d), 133.3 (d), 130.8 (d), 60.4 (d), 57.0 (s), 53.1 (d), 50.0 (d), 38.8 (t), 27.2 (q). Anal. Calcd for $C_{12}H_{12}O_2$: C, 76.57; H, 6.43. Found: C, 76.67; H, 6.48.

Further elution with 60% ethyl acetate–benzene furnished **30**, 800 mg (40%), which was crystallized from benzene–petroleum ether as microcrystals. mp 115 °C. UV, λ_{max}^{MeOH}: 222, 217 (ϵ 12400, 10950). IR (KBr): 3080, 2950, 1720, 1620, 1600, 1420, 1200, 860, 760 cm^{-1}. ^1H NMR (100 MHz, MHz, $CDCl_3$): δ 2.08 (3 H, s), 2.10–2.40 (1 H, m), 3.10–3.68 (5 H, m), 5.60 (1 H, s), 5.88 (1 H, dd, J_1 = 8, J_2 = 4 Hz), 7.44 (1 H, dd, J_1 = 8, J_2 = 4 Hz). ^{13}C NMR (25.0 MHz, $CDCl_3$): δ 207.4 (s), 206.2 (s), 178.5 (s), 165.3 (d), 133.2 (d), 129.7 (d), 54.3 (d), 53.3 (d), 52.4 (d), 50.2 (d), 29.5 (t), 17.3 (q). Anal. Calcd for $C_{12}H_{12}O_2$: C, 76.57; H, 6.43. Found: C, 76.59; H, 6.43.

8β-Methyltricyclo[6.3.0.0^{2,6}]undeca-2,9-diene-3,11-dione (31). Bis-enone **29**, 1 g (5.31 mmol), and DBU (1 g) in dichloromethane (25 mL) were refluxed for 40 h in a round-bottomed flask fitted with a reflux condensor. The reaction mixture was diluted with dichloromethane (20 mL) and washed with 30% HCl (3 × 25 mL). The organic phase was washed and dried. Removal of solvent gave tetrasubstituted bis-enone **31**, 900 mg (90%). Crystallization of **31** from acetone–petroleum ether yielded colorless cubic crystals. mp 97–98 °C. UV, λ_{max}^{MeOH}: 244, 214 (ϵ 5350, 16150). IR (KBr): 3080, 2950, 1720, 1640, 1590, 1430, 1200, 1040, 780 cm^{-1}. ^1H NMR (100 MHz, $CDCl_3$): δ 1.48 (3 H, s), 2.40–2.76 (6 H, m), 3.16 (1 H, s), 5.98 (1 H, d, J = 8 Hz), 7.5 (1 H, d, J = 8 Hz). ^{13}C NMR (25.0 MHz, $CDCl_3$): δ 204.7 (s), 201.2 (s), 183.8 (s), 168.9 (d), 147.6 (s), 129.8 (d), 57.5 (s), 57.2 (d), 42.6 (t), 39.6 (t), 25.3 (t), 25.0 (q). Anal. Calcd for $C_{12}H_{12}O_2$: C, 76.57; H, 6.43. Found: C, 76.22; H, 6.32.

8β-Methyltricyclo[6.3.0.0^{2,6}]dodeca-2(6),11(12)-dien-3-one (32). Tetrasubstituted bis-enone **31**, 500 mg (2.65 mmol), was hydrogenated over 50 mg of 10% Pd/C catalyst in ethyl acetate (30 mL). After the consumption of approximately 1 mol of hydrogen, the catalyst was filtered and the solvent was removed. The residue was filtered through a silica gel column (20 g) to give 400 mg (80%) of the dihydro compound, along with some perhydro impurity. The sample of dihydro compound on crystallization from carbon tetrachloride–petroleum ether furnished colorless cubes. mp 83–84 °C. UV, λ_{max}^{MeOH}: 242 (ϵ 7650). IR (KBr): 2950, 1740, 1700, 1630, 1440, 1160, 800, 690 cm^{-1}. ^1H NMR (100 MHz, $CDCl_3$): δ 1.36 (3 H, s), 1.80–2.74 (10 H, m), 2.94 (1 H, br s). ^{13}C NMR (25.0 MHz, $CDCl_3$): δ 214.2 (s), 202.2 (s), 186.9 (s), 143.4 (s), 59.1 (d), 53.7 (s), 45.9 (t), 40.4 (t), 37.9 (t), 35.0 (t), 27.0 (q), 25.9 (t). Exact mass calcd for $C_{12}H_{14}O_2$ m/e 190.0944, found m/e 190.0999.

Into a 25-mL, three-necked, round-bottomed flask fitted with dry nitrogen gas inlet, septum, reflux condensor, and mercury seal, triphenylmethylphosphorium bromide, 1.40 g (3.95 mmol), was introduced with an addition funnel. Dry toluene (3 mL) was added, and the rsulting suspension was stirred vigorously. To this suspension was injected sodium *tert*-amyloxide, 3.47 mg (3.16 mmol), in dry toluene (3 mL) and stirred at ~40 °C for 5 min. Dihydro compound, 500 mg (2.63 mmol), in dry toluene (5 mL) was introduced at once and the mixture refluxed for 3 h. The reaction mixture was diluted with benzene (10 mL) and quenched with water. The organic layer was separated, washed, and dried. The residue obtained after removal of the solvent was charged on a silica gel column (25 g). Elution with petroleum ether resulted in the removal of triphenylphosphine-derived impurities, and further elution with benzene furnished the terminal methylene compound **32**, 395 mg (80%), which was bulb-to-bulb distilled at 135 °C/0.3 torr. UV, λ_{max}^{MeOH}: 236 (ϵ 10950). IR (neat): 3100, 2950, 1700, 1640, 1440, 1380, 1230, 1040, 880 cm^{-1}. ^1H NMR (100 MHz, $CDCl_3$): δ 1.24 (3 H, s), 1.60–1.90 (2 H, m), 2.20–2.80 (8 H, m), 3.20 (1 H, br s), 4.96 (1 H, br s), 5.20 (1 H, br s). ^{13}C NMR (25.0 MHz, $CDCl_3$): δ 203.3, 183.3, 152.1, 148.6, 107.9, 56.6, 55.9, 46.4, 40.8, 40.4, 33.5, 27.7, 25.7. Exact mass calcd for $C_{13}H_{16}O$ m/e 188.1201, found m/e 188.1202.

11-Cyclopropyl-8β-methyltricyclo[6.3.0.0^{2,6}]dodeca-2(6)-en-3-one (33). A mixture of zinc–copper couple, 1.8 g (0.027 g-atom),[21] in dry ether (15 mL) and a solution of methylene iodide, 8.57 g (0.032 mol), in dry ether (5 mL) was refluxed for 30 min with stirring. To this mixture, olefin **32**, 100 mg (0.053 mmol), in dry ether (5 mL) was slowly added under reflux. After the mixture refluxed for 50 h, the ethereal layer was decanted and washed with cold 1 N HCl (3 × 10 mL) and water (3 × 10 mL) and dried. The crude product obtained after the removal of the solvent, was charged on a silica gel column (15 g). Elution with 50% benzene–petroleum ether removed unreacted methylene iodide, and further elution with benzene furnished the spiro compound **33**, 53 mg (50%). bp 140 °C/0.3 torr. UV, λ_{max}^{MeOH}: 240 (ϵ 8720). IR (neat): 3075, 2950, 1700, 1640, 1430, 1380, 1240, 1040 cm^{-1}; ^1H NMR (100 MHz, $CDCl_3$): δ 0.34–0.7 (2 H, m), 0.8–1.0 (2 H, m), 1.30 (3 H, s), 1.74 (4 H, br s), 2.2–2.8 (7 H, m). ^{13}C NMR (25.0 MHz, $CDCl_3$): δ 204.9, 184.6, 147.8, 58.4, 57.5, 47.6, 41.8, 40.7, 35.9, 29.3, 26.9, 25.8, 21.0, 14.9. Exact mass calcd for $C_{14}H_{18}O$ m/e 202.1357, found m/e 202.1357.

8β,11,11′-Trimethyl-*cis,anti,cis*-tricyclo[6.3.0.0^{2,6}]undecan-3-one (34). The spiro compound **33**, 20 mg (0.098 mmol), in 3 mL of acetic acid was hydrogenated over PtO_2 (5 mg, preactivated) catalyst in a Parr hydrogenation apparatus at 3-atm pressure for 36 h. The reaction mixture was diluted with ether, filtered, washed, and dried. Removal of solvent yielded a crude product mixture which was purified on a silica gel (5 g) column to give norcapnellanone **34**, 12 mg (60%), along with another compound, probably its cis,syn,cis isomer. Comparison of the IR and ^1H NMR spectra of **34** with the authentic spectra[12e] supplied by Prof. R. D. Little established their identity.

8β,11-Dimethyltricyclo[6.3.0.0^{2,6}]undeca-2,10-diene-3,9-dione (35). In to a 100-mL, three-necked, round-bottomed flask fitted with dry nitrogen gas inlet, reflux condensor, pressure equilized addition funnel, and mercury seal, 155 mg (6.38 mmol) of magnesium turnings was taken an dry ether (20 mL) was introduced. To this mixture methyl iodide (0.5

mL, excess) was slowly added, and stirring continued until all the magnesium dissolved. The Grignard reagent was cooled to −10 °C and bis-enone **31**, 1 g (5.31 mmol), in cold THF (10 mL) was introduced. The reaction mixture was slowly brought to room temperature and further stirred for 1 h. Quenching with cold saturated NH_4Cl solution (25 mL) and extraction with ether (3 × 50 mL) gave 1.1 g of crude tertiary allylic alcohol containing some unreacted bis-enone **31**.

The crude reaction mixture obtained above was dissolved in dry dichloromethane (20 mL) and added to a solution of pyridinium chlorochromate,[23] 1.5 g, in dry dichloromethane (20 mL) containing 2.0 g of activated molecular seives (4 Å). The reactants were stirred for 1.5 h and diluted with dry ether (30 mL). The resulting solution was filtered through a small Florisil pad and repeatedly washed with dichloromethane. Removal of solvent left a dark semisolid residue which was charged on a silica gel (50 g) column. Elution with 50% ethyl acetate–benzene furnished the transposed bis-enone[22] **35**, 300 mg (40% based on starting material recovery), which was bulb-to-bulb distilled at 150 °C/0.4 torr. UV, λ_{max}^{MeOH}: 223, 216 (ε 20 551, 15 770). IR (neat): 3075, 2950, 1700, 1630, 1420, 1380, 1220, 860 cm^{-1}. ^1H NMR (100 MHz, $CDCl_3$): δ 1.32 (3 H, s), 2.24, (3 H, s), 2.4–3.0 (6 H, m), 3.48 (1 H, br s), 5.76 (1 H, s). ^{13}C NMR (25.0 MHz, $CDCl_3$): δ 212.1 (s), 202.8 (s), 185.4 (s), 178.9 (s), 146.1 (s), 127.8 (d), 60.7 (s), 58.6 (d), 41.5 (t), 40.3 (t), 25.9 (t), 23.2 (q), 19.3 (q).

Further elution of the column with 65% ethyl acetate–benzene furnished starting bis-enone **31** (300 mg).

8β,11-Dimethyl-9-oxo-*cis*,*anti*,*cis*-tricyclo[6.3.0.0^{2,6}]undeca-10-en-3β-ol (36). Sodium borohydride, ~150 mg (4.0 mmol), was added in small lots to a solution of transposed enone **35**, 1 g (4.95 mmol), in absolute methanol at −10 °C until the starting material was completely consumed. Acetone (10 mL) was added to the reaction mixture to destroy excess sodium borohydride, and solvents were completely removed under reduced pressure. The residue was dissolved in ethyl acetate, washed, and dried. Removal of the solvent gave crude material (1 g) which was charged on a silica gel (25 g) column and eluted with 30% ethyl acetate–benzene to furnish *cis*,*anti*,*cis*-hydroxyenone **36**, 450 mg (44.5%), which was crystallized from benzene–petroleum ether as colorless prisms. mp 121–122 °C. UV, λ_{max}^{MeOH}: 232 (ε 11 680). IR (KBr): 3400, 3100, 1700, 1620, 1450, 1020, 860 m^{-1}. ^1H NMR (100 MHz, $CDCl_3$): δ 1.2 (3 H, s), 1.24–2.0 (8 H, m), 2.12 (3 H, s), 2.28 (1 H, s), 2.95 (1 H, s), 4.22 (1 H, m), 5.80 (1 H, s), ^{13}C NMR (25.0 MHz, $CDCl_3$): δ 214.1 (s), 180.9 (s), 127.6 (d), 73.9(d), 59.7 (s), 58.3 (d), 53.8 (d), 44.0 (t), 42.7 (d), 36.0 (t), 28.5 (t), 22.2 (q), 18.3 (q).

Further elution of the column gave other reduction products, but these were not characterized.

8β,11,11′-Trimethyl-9-oxo-*cis*,*anti*,*cis*-tricyclo[6.3.0.0^{2,6}]undecan-3β-ol (37). To a stirred solutin of CuI, 900 mg (4.7 mmol), in dry ether (6 mL) at −10 °C, methyllithium (2 mL 9.4 mmol) in ether was slowly added until the yellow color persisted. To this mixture, BF_3 etherate (0.4 mL excess) was added[24] followed by the addition of the hydroxyenone **36**, 50 mg (0.24 mmol) in dry ether (5 mL). The reaction was then brought to room temperature and stirred for 1 h. The reaction was quenched with saturated NH_4Cl and NH_4OH solutions (~pH 8) and then extracted with ether (3 × 10 mL). The ethereal layer was washed and dried. Removal of the solvent gave crude product (55 mg) which was purified on a silica gel (10 g) column to get the geminal dimethylated hydroxy ketone **37**, 40 mg (88%), and was bulb-to-bulb distilled at 130 °C/0.4 torr. IR (CH_2Cl_2): 3600, 2950, 1730, 1440, 1060 cm^{-1}. ^1H NMR (100 MHz, $CDCl_3$): δ 1.16 (6 H, s), 1.30 (3 H, s), 1.4–2.6 (12 H, m), 4.18 (1 H, m). ^{13}C NMR (25.0 MHz, $CDCl_3$): δ 225.1, 75.0, 60.9, 58.0, 53.5, 52.9, 48.8, 43.4, 36.6, 36.0, 30.8, 29.6, 26.0, 24.9. Anal. Calcd for $C_{14}H_{22}O_2$: C, 75.63; H, 9.97. Found: C, 75.12; H, 9.90.

8β,11,11′-Trimethyl-*cis*,*anti*,*cis*-tricyclo[6.3.0.0^{2,6}]dodeca-3(12)-en-9-one (38). To a solution of pyridinium chlorochromate[23] (40 mg) in dry dichloromethane (10 mL) containing activated molecular sieves (4 Å) was added hydroxy ketone **37**, 50 mg (0.225 mmol). The reaction mixture was stirred for 30 min and diluted with dry ether (10 mL). Filtration through a small Florisil column and evaporation of solvent furnished the diketone, 44 mg (88%), which was directly crystallized from petroleum ether as colorless needles. mp 78–79 °C. IR (neat): 2950, 1730, 1460, 1400, 1260, 1180, 660 cm^{-1}. ^1H NMR (100 MHz, $CDCl_3$): δ 1.05 (3 H, s), 1.09 (3 H, s), 1.17 (3 H, s), 1.48–2.48 (13 H, m).

Into a 25-mL, three-necked, round-bottomed flask fitted with dry nitrogen gas inlet, septum, reflux condensor, and mercury seal, triphenylmethylphosphorium bromide, 96 mg (0.27 mmol), was introduced with an addition funnel. The solid was suspended in dry toluene (2 mL), and sodium *tert*-amyloxide, 24 mg (0.22 mmol), in dry toluene (3 mL) was added. The yellow reaction mixture was stirred at ~40 °C for 5 min, and then the diketone, 40 mg (0.18 mmol), in dry toluene (3 mL) was introduced at once, and reactants were refluxed for 2.5 h. The reaction mixture was diluted with benzene (5 mL) and quenched with water. The organic layer was separated, washed, and dried. The crude product obtained, after removing the solvent, was chromatographed on a silica gel (25 g) column. Elution with petroleum other removed the triphenylphosphine-derived impurities, and further elution with 50% benzene–petroleum ether furnished the terminal olefinic compound **38**, 36 mg (90%), which was bulb-to-bulb distilled at 125 °C/0.5 torr. IR (neat): 3050, 2950, 1740, 1450, 1280, 1120, 870 cm^{-1}. ^1H NMR (100 MHz, $CDCl_3$): δ 1.09 (6 H, s), 1.12 (3 H, s), 1.13–2.04 (8 H, m), 2.08–2.38 (2 H, m), 2.58–2.84 (1 H, m), 4.74 (1 H, br s), 4.85 (1 H, br s).

$\Delta^{9(12)}$-Capnellene (3). In to a two-necked, 25-mL, round-bottomed flask fitted with a rubber septum and mercury seal was placed LAH, 10 mg (excess), in dry ether (5 mL). To this suspension, olefinic compound **38**, 50 mg (0.23 mmol), in dry ether (5 mL) was slowly added through a syringe. The reaction mixture was stirred for 30 min. A few drops of ethyl acetate were then added to destroy excess hydride. The reaction mixture was diluted with water and extracted with ether (3 × 10 mL). The ethereal layer was washed and dried. Removal of solvent gave hydroxyolefin, 40 mg (80%, as 1:1 mixture of hydroxy epimers). IR (neat): 3375, 2950, 1650, 1460, 1360, 1050, 870 cm^{-1}. ^1H NMR (100 MHz, $CDCl_3$): δ 0.91 (3 H, s), 0.95 (3 Hs, s), 0.98 (3 H, s), 0.99 (3 H, s), 1.05 (3 Hs, s), 1.13 (3 H, s), 1.23–1.82 (18 H, m), 1.90–2.68 (6 H, m), 3.78 (1 H, d, J = 6 Hz), 3.88 (1 H, d, J = 6 Hz), 4.72 (2 H, br s), 4.85 (2 H, br s).

Hydroxyolefin (epimeric mixture), 20 mg (0.09 mmol), NaH, 13 mg (50% dispersion in oil, 0.27 mmol), and imidazole (2 mg) in dry THF (5 mL) was refluxed in a 25-mL, three-necked, round-bottomed flask with stirring for 3 h under nitrogen. Carbon disulfide (0.5 mL) in THF (1 mL) was then added to the reactive mixture. After refluxing for further 30 min, methyl iodide (0.5 mL) was added in THF (1 mL) and refluxing continued for another 30 min. The reaction mixture was quenched with acetic acid (0.2 mL), diluted with water, and extracted with ether (3 × 10 mL). The ethreal layer was washed and dried. The crude product was charged on a silica gel (5 g) column. Elution with petroleum ether removed nonpolar impurities and further elution with 5% benzene–petroleum ether gave the *S*-methyldithiocarbonate, 25 mg (88%), as a mixture of epimers. IR (neat): 3075, 2950, 1660, 1460, 1220, 1060, 870 cm^{-1}. ^1H NMR (100 MHz, $CDCl_3$): δ 0.93 (3 H, s), 0.99 (3 H, s), 1.07 (6 H, s), 1.09 (3 H, s), 1.17 (3 H, s), 1.53–2.38 (20 H, m), 2.40 (3 H, s), 2.44 (3 H, s), 2.45–2.78 (2 H, m), 4.64 (2 H, br s), 4.8 (2 H, br s), 5.62 (2 H, ABq, J_{AB} = 6 Hz).

Into a 25-mL, three-necked, round-bottomed flask fitted with an argon gas inlet, reflux condensor, septum, and mercury seal was taken tri-*n*-butyltin hydride, 40 mg (0.13 mmol), in dry toluene (3 mL). The mixture was heated to reflux during which the *S*-methyldithiocarbonate, 20 mg (0.067 mmol), in dry toluene (2 mL) was slowly injected. After the mixture refluxed for 4 h, toluene was removed under vacuum, and the concentrate was charged on $AgNO_3$ impregnated silica gel (15 g) column. Elution with petroleum ether removed the organotin impurities and further elution with 10% benzene–petroleum ether furnished the hydrocarbon **3**, 7 mg (53%), which was found identical [IR (neat): 3060, 2930, 1640, 1460, 1380, 870 cm^{-1}. ^1H NMR NMR (100 MHz, $CDCl_3$): δ 0.98 (3 H, s), 1.05 (3 H, s), 1.14 (3 H, s), 1.18–1.8 (9 H, m), 2.38–2.4 (4 H, m), 4.8 (1 H, br s), 4.9 (1 H, br s)] with the naturally occurring $\Delta^{9(12)}$-capnellene.

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