eluted with a linear gradient (400 + 400 mL, 0.25–1.0 M) of triethylammonium bicarbonate, pH 7.2. Fractions containing DAHP were pooled and passed down 350 mL of Dowex 50 (H^+). The resulting DAHP solution after degassing was neutralized with lithium hydroxide, evaporated to dryness, and stored at −20 °C. Purified DAHP was identical by ^1H and ^{13}C NMR with authentic material and was a substrate for the DAHP specific enzyme, dehydroquinate (DHQ) synthetase.[8,26a]

Conversion of Immobilized Enzyme Synthesis Produced DAHP to 3-Deoxy-D-*arabino*-heptulosonic Acid (DAH, 3). Supernatant (300 mL) from an enzyme reactor containing 0.90 g (3.12 mmol) of DAHP was made 10 mM in magnesium chloride and 1 mM in zinc chloride via addition of the appropriate amounts of inorganic salts. Immobilized alkaline phosphatase was added to the solution and stirred at 37 °C for 72 h. The pH of the solution, initially 7.3, was readjusted to this value at 12-h intervals. Reaction progress was monitored by TLC (2:1:1 1-butanol/water/acetic acid) and by the disappearance of DAHP as determined by DHQ synthetase assay.[26a] Upon completion, the gel was removed by centrifugation (3000 g for 10 min) and washed 4 times with 100 mL of water. The combined supernatant and washes were passed through Celite and loaded onto 400 mL of AG 1-X8 equilibrated with 50 mM sodium acetate, pH 5.0. The column was washed with 0.50 L of 50 mM sodium acetate, pH 5.0, and DAH eluted with a linear gradient (2.0 + 2.0 L, 50–400 mM) of sodium acetate, pH 5.0. Those fractions containing DAH were combined, passed down 0.5 L of Dowex 50 (H^+) at 4 °C, and eluted with 1.5 L of water. Concentration under vacuum yielded 0.50 g of DAH (2.40 mmol, 77%) as a hygroscopic white foam: ^1H NMR (D_2O) δ 1.83 (dd, J = 12, 12 Hz, 1 H), 2.28 (dd, J = 5, 8 Hz, 1 H), 3.43 (dd, J = 10, 10 Hz, 1 H), 3.79–3.86 (m, 3 H), 3.94–3.99 (m, 1 H); ^{13}C NMR (D_2O) δ 41.3, 63.3, 71.1, 73.3, 76.7, 97.8, 175.7.

Whole Cell Synthesis of 3-Deoxy-D-*arabino*-heptulosonic Acid (DAH, 3). A cell suspension (4.5 L) of *E. coli* JB-5 (obtained by using protocol II of Frost and Knowles[8]) was centrifuged at 14 000 G for 10 min and the clear-yellow supernatant passed through a column (1 L) of Dowex 50 (H^+) at 4 °C. After being concentrated on a rotary evaporator (keeping the temperature below 35 °C), the solution was adjusted to pH 8.0 with freshly prepared lithium hydroxide, and methanol (1 L) was added with vigorous stirring at 4 °C for 1 h. The precipitate which formed was removed by filtration and the resulting filtrate concentrated under reduced pressure. The residue was then taken up in 200 mL of distilled, deionized water and adjusted to pH 5.0. The solution was loaded on a column (0.50 L) of AG 1-X8 equilibrated with 0.10 N sodium acetate, pH 5.0. The column was washed with 0.50 L of 0.10 N sodium acetate, and DAH was eluted with a linear gradient (2.0 + 2.0 L, 0.10–0.60 N) of sodium acetate, pH 5.0. Column fractions were assayed, and those containing DAH were combined, passed down 0.5 L of Dowex 50 (H^+) at 4 °C, and eluted with 1.5 L of water. The solution was concentrated to yield 1.47 g (7.05 mmol) of DAH as a hygroscopic, white foam.

Conversion of DAH (3) into Methyl (Methyl 3-deoxy-D-*arabino*-heptulopyranosid)onate (4). DAH (3) (1.47 g, 7.05 mmol) was azeotroped 3 times with toluene, immediately dissolved in 60 mL of methanol which was 0.75 N in HCl, and then refluxed for 24 h. After cooling, the solution was neutralized with solid lead carbonate $(PbCO_3)_2{\cdot}Pb(OH)_2$. Excess lead carbonate was removed by filtration through Celite, and activated charcoal was added to the filtrate. The mixture was allowed to stand at room temperature for 1 h and filtered again through Celite. The filtrate was concentrated under reduced pressure to ~5 mL, and **4** crystallized upon standing at room temperature. The fine white needles were filtered and washed with dichloromethane, and a second crop was collected by storing the filtrate at −20 °C for a total yield of 0.95 g (4.02 mmol, 57%): IR (NaCl, neat) 3453, 3370–3280, 2964–2800, 1736, 1460, 1440, 1341, 1281, 1191, 1121, 1081 cm^{-1}; ^1H NMR (D_2O) δ 1.76 (dd, J = 12, 12 Hz, 1 H), 2.36 (dd, J = 5, 8 Hz, 1 H), 3.25 (s, 3 H), 3.42 (dd, J = 10, 10 Hz, 1 H), 3.57–3.63 (m, 1 H), 3.75–4.00 (m, 3 H), 3.87 (s, 3 H); MS, *m/e* (relative intensity) 177 (100), 141 (17), 129 (32), 127 (41), 117 (43); mp 138 °C, with decomposition at 145 °C. Anal. ($C_9H_{16}O_7$) C, H.

Acknowledgment. We thank Prof. K. M. Herrmann for permission to use HE 102 (pKB 45). Work was supported by a grant-in-aid from Chevron Corporation and a Du Pont Young Faculty Grant.

Registry No. 1, 105103-72-8; **2**, 2627-73-8; **3**, 56742-43-9; **4**, 85549-51-5; **5**, 57-48-7; **6**, 50-99-7; **7**, 154-17-6; **8**, 91294-63-2; **9**, 91294-64-3; **10**, 91294-65-4; **11**, 105103-73-9; **11** (unacetylated), 105103-77-3; **12**, 105103-74-0; **13**, 105103-75-1; **14**, 105103-76-2; PEP, 138-08-9; DHQ synthase, 37211-77-1; DAHP synthase, 9026-94-2; $BrSiMe_3$, 2857-97-8; $HS(CH_2)_3SH$, 109-80-8; hexokinase, 9001-51-8; transketolase, 9014-48-6; pyruvate kinase, 9001-59-6; alkaline phosphatase, 9001-78-9; triethyl phosphite, 122-52-1; D-fructose-6-phosphate, 643-13-0; D-erythrose-4-phosphate, 585-18-2.

General Transannulation Approach to Angular Triquinanes. Total Syntheses of (±)-Pentalenene and (±)-*epi*-Pentalenene

Goverdhan Mehta* and Kasibhatla Srinivas Rao

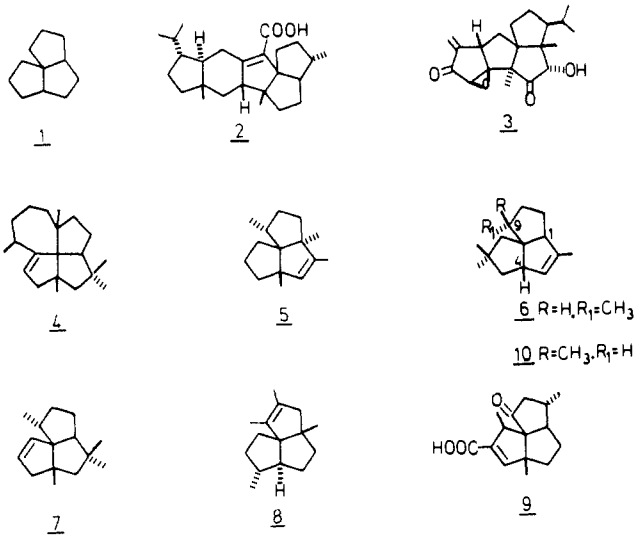
Contribution from the School of Chemistry, University of Hyderabad, Hyderabad 500 134, India.
Received May 19, 1986

Abstract: A short, general approach for the synthesis of angular triquinanes is delineated. The key element of this approach is the carbonium-ion-mediated transannulation in the bicyclo[6.3.0]undecane system. New syntheses of appropriately functionalized bicyclo[6.3.0]undecanes **11a** and **11b** from cheap, abundantly available 1,5-cyclooctadiene have been developed. These have been cyclized in formic acid and elaborated to tricyclo[6.3.0.$0^{4,8}$]undecane derivatives **23** and **28**, respectively. These observations have been further extended to stereoselective syntheses of sesquiterpene hydrocarbon (±)-pentalenene (**6**) and (±)-*epi*-pentalenene (**10**) from commercial 1,5-dimethyl-1,5-cyclooctadiene (**29**). Site-selective cyclopentannulation of **29** provided access to the bicyclo[6.3.0]undecane-based enones **35** and **36** which underwent facile and stereospecific cyclization to tricyclic C_{13}-ketones **37** and **39**, respectively. A three-step protocol transformed them to (±)-pentalenene (**6**) and its C_9-epimer **10**, respectively.

While the presence of the tricyclo[6.3.0.$0^{4,8}$]undecane (**1**, angular triquinane) moiety was first recognized as a part structure in the pentacyclic sesterterpene retigeranic acid (**2**)[1] in 1972 and subsequently in the novel diterpenoids laurenene (**4**)[2] and crinipellin (**3**),[3] it is among the sesquiterpenoids that the skeleta based on **1** are most abundant and diverse. Up to date, five different C_{15}-angular triquinane carbon frameworks represented here by isocomene (**5**),[4,5] pentalenene (**6**),[6] silphinene (**7**),[7] silphiperfolene

(1) Kaneda, M.; Takahashi, R.; Litake, Y.; Shibata, S. *Tetrahedron Lett.* **1972**, 4609.
(2) (a) Corbett, R. E.; Lauren, D. R.; Weavers, R. T. *J. Chem. Soc., Perkin Trans. 1* **1979**, 1774. (b) Corbett, R. E.; Couldwell, C. M.; Lauren, D. R.; Weavers, R. T. *J. Chem. Soc., Perkin Trans. 1* **1979**, 1791.
(3) Anke, T.; Heim, J.; Knoch, F.; Mocek, U.; Steffan, B.; Steglich, W. *Angew. Chem.* **1985**, 709.
(4) (a) Zalkow, L. H.; Harris, R. N., III; Van Derveer, D.; Bertrand, J. A. *J. Chem. Soc., Chem. Commun.* **1977**, 452. (b) Zalkow, L. H.; Harris, R. N., III; Burke, N. I. *J. Nat. Prod.* **1979**, 42, 96.
(5) Bohlmann, F.; Le Van, N.; Pickhardt, J. *Chem. Ber.* **1977**, *110*, 3777.

0002-7863/86/1508-8015$01.50/0



(**8**),[7] and subergorgic acid (**9**)[8] have been encountered in Nature from plant, marine, and microbial sources.[9] As the number of sesquiterpenoids based on these novel skeleta proliferated[10] in recent years, they began to capture the attention of synthetic chemists all around and have emerged as popular targets for the development of new cyclopentane annulation technologies.[11,12]

(6) (a) Seto, H.; Yonehara, H. *J. Antibiot.* **1980**, *33*, 92. (b) Cane, D. E.; Rossi, T.; Pachlatko, J. P. *Tetrahedron Lett.* **1979**, 3639.

(7) Bohlmann, F.; Jakupovic, J. *Phytochemistry* **1980**, *19*, 259.

(8) Groweiss, A.; Fanical, W.; Clardy, J.; Cun-heng, H.; Zhongde, W.; Zhongnian, Y.; Kanghou, L. *Tetrahedron Lett.* **1985**, 2379.

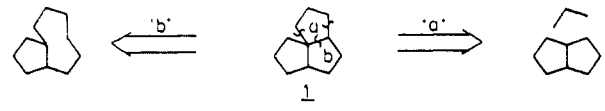
(9) Sesquiterpene hydrocarbon senoxydene from *Senecio oxyodontus* was earlier shown to possess an angular triquinane skeleton. However, recent synthetic studies have questioned its triquinane formulation; see: (a) Bohlmann, F.; Zdero, C. *Phytochemistry* **1979**, *18*, 1747. Paquette, L. A.; Galemmo, R. A., Jr.; Springer, J. P. *J. Am. Chem. Soc.* **1983**, *105*, 6975. Itô, S.; Kabasawa, Y.; Tsunoda, T. *Tetrahedron Lett.* **1984**, 773.

(10) An impressive number of oxygenated compounds based on angular triquinane skeleta have been isolated by Bohlmann and co-workers as well as others. Some of the leading references are as follows: Seto, H.; Sasaki, T.; Uzawa, J.; Takeuchi, S.; Yonehara, H. *Tetrahedron Lett.* **1978**, 4411. Takeuchi, S.; Uzawa, J.; Seto, H.; Yonehara, H. *Tetrahedron Lett.* **1977**, 2943. Bohlmann, F.; Suding, H.; Cuatrecasas, J.; Robinson, H.; King, R. M. *Phytochemistry* **1980**, 19, 2399. Bohlmann, F.; Zdero, C. *Phytochemistry* **1982**, *21*, 139. Bohlmann, F.; Zdero, C. *Phytochemistry* **1982**, *21*, 139. Bohlmann, F.; Zdero, C. *Phytochemistry* **1981**, *20*, 2529. Schmitz, R.; Frahm, A. W.; Kating, H. *Phytochemistry* **1980**, *19*, 1477.

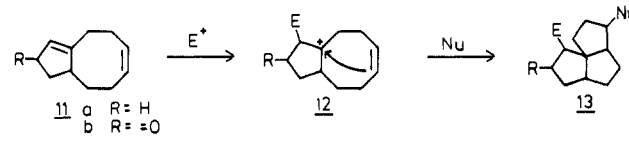
(11) For synthetic approaches to tricyclic[6.3.0.0^{4,8}]undecane systems, see: (a) Dauben, W. G.; Hart, D. J. *J. Org. Chem.* **1977**, *42*, 3787. (b) Knudsen, M. J.; Schore, N. E. *J. Org. Chem.* **1984**, *49*, 5025. (c) Dorsch, M.; Jager, V.; Spönlein, W. *Angew. Chem., Int. Ed. Engl.* **1984**, 23, 798. (d) Mehta, G.; Rao, K. S. *Tetrahedron Lett.* **1984**, *25*, 3481.

(12) Leading references for the total synthesis of triquinane natural products are as follows. Isocomene: (a) Paquette, L. A.; Han, Y. K. *J. Org. Chem.* **1979**, *44*, 4014; *J. Am. Chem. Soc.* **1981**, *103*, 1835. (b) Oppolzer, W.; Battig, K.; Hudlicky, T. *Helv. Chim. Acta* **1979**, *62*, 1493; *Tetrahedron* **1981**, *37*, 4359. (c) Pirrung, M. C. *J. Am. Chem. Soc.* **1979**, *101*, 7130; **1981**, *103*, 82. (d) Dauben, W. G.; Walker, D. M. *J. Org. Chem.* **1981**, *46*, 1103. (e) Wender, P. A.; Dreyer, G. B. *Tetrahedron* **1981**, *37*, 4445. (f) Wenkert, E.; Arrhenius, T. S. *J. Am. Chem. Soc.* **1983**, *105*, 2030. (g) Ranu, B. C.; Kavka, M.; Higgs, L. A.; Hudlicky, T. *Tetrahedron Lett.* **1984**, 2447. (h) Tobe, Y.; Yamashita, T.; Kakiuchi, K.; Odaira, Y. *J. Chem. Soc., Chem. Commun.* **1985**, 898. Pentalenene: (i) Ohfune, Y.; Shirahama, H.; Matsumoto, T. *Tetrahedron Lett.* **1976**, 2869. Misumi, S.; Ohtsuka, T.; Ohfune, Y.; Sugita, K.; Shirahama, H.; Matsumoto, T. *Tetrahedron Lett.* **1979**, 31. (j) Annis, G. D.; Paquette, L. A. *J. Am. Chem. Soc.* **1982**, *104*, 4504. (k) Piers, E.; Karunaratne, V. *J. Chem. Soc., Chem. Commun.* **1984**, 959. (l) Pattenden, G.; Teague, S. J. *Tetrahedron Lett.* **1984**, 3021. (m) Mehta, G.; Rao, K. S. *J. Chem. Soc., Chem. Commun.* **1985**, 1464. (n) Crimmins, M. T.; DeLoach, J. A. *J. Am. Chem. Soc.* **1986**, *108*, 800. (o) Crimmins, M. T.; Mascarella, S. W. *J. Am. Chem. Soc.* **1986**, *108*, 3435. Pentalenic acid: (p) Sakai, K.; Ohtsuka, T.; Misumi, S.; Shirahama, H.; Matsumoto, T. *Chem. Lett.* **1981**, 355. (q) Crimmins, M. T.; DeLoach, J. A. *J. Org. Chem.* **1984**, *49*, 2076. Silphinene: (r) Paquette, L. A.; Leone-Bay, A. *J. Am. Chem. Soc.* **1983**, *105*, 7352. (s) Tsunoda, T.; Kodama, M.; Itô, S. *Tetrahedron Lett.* **1983**, 83. (t) Sternbach, D. D.; Hughes, J. W.; Burdi, D. F.; Banks, B. A. *J. Am. Chem. Soc.* **1985**, *107*, 2149. (u) Wender, P. A.; Ternansky, R. J. *Tetrahedron Lett.* **1985**, 2625. (v) Hua, D. H. *J. Am. Chem. Soc.* **1986**, *108*, 3835. Silphiperfolene; oxasilphiperfolene: (w) Paquette, L. A.; Roberts, R. A.; Drtina, G. J. *J. Am. Chem. Soc.* **1984**, *106*, 6990. (x) Curran, D. P.; Kuo, S. C. *J. Am. Chem. Soc.* **1986**, *108*, 1106.

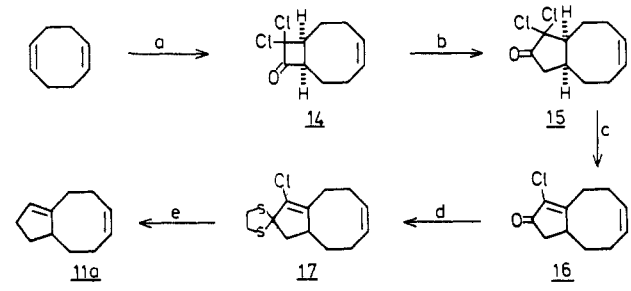
Scheme I



Scheme II

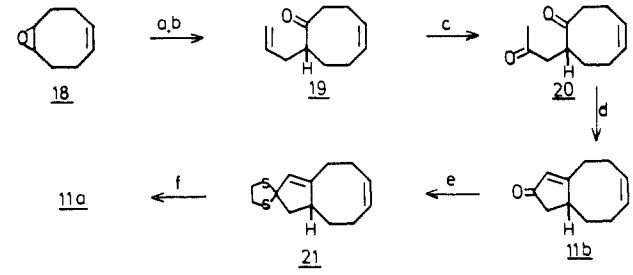


Scheme III



Reagents and yields: (a) CCl_2CO–Et_2O, 30 °C, 6 h, 60%; (b) CH_2N_2–Et_2O, MeOH, 5 °C, 1 h; (c) Li_2CO_3–DMF, 90 °C, 45 min, 70%; (d) $(CH_2SH)_2$–PTS–C_6H_6, reflux, 9 h, 82%; (e) Na–liquid NH_3–Et_2O, −40 °C, 2 h, 55%.

Scheme IV



Reagents and yields: (a) allyllithium–THF–Et_2O, room temperature, 5 h; (b) PCC–CH_2Cl_2, molecular sieves (4 Å), room temperature, 2 h, 80%; (c) $PdCl_2$, CuCl–DMF, H_2O, O_2, room temperature, 2 h, 85%; (d) NaH–toluene, 90 °C, 3 h, 70%; (e) $(CH_2SH)_2$–PTS–C_6H_6, 50 °C, 5 h, 80; (f) Na–liquid NH_3–Et_2O, −40 °C, 2 h, 60%.

Also adding to their synthetic appeal is the interesting biosynthetic origin of these compounds and the biological activity exhibited by some of them.

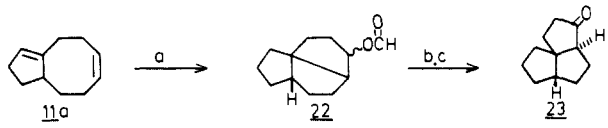
Although several imaginative solutions have been devised to achieve the syntheses of **5**–**8** and their oxygenated derivatives, these have been largely target-oriented efforts, and presently only limited methodologies are available for the rapid acquisition of the angular triquinane framework. We wish to describe here a general and flexible strategy for entry into the angular triquinanes via a carbonium-ion-mediated transannulation reaction in the bicyclo[6.3.0]undecane system. As an application of this theme, the total synthesis of the sesquiterpene hydrocarbon (±)-pentalenene (**6**) isolated from the culture broth of *Streptomyces griseochromogenes* and its C_9-epimer **10** is reported.[13]

General Strategy and Model Studies

As the main synthetic challenge of angular triquinane natural products resides in the construction of their tricyclic framework, control of stereochemistry on four contiguous asymmetric centers around the spiro carbon atom and installation of a network of methyl groups, the most commonly pursued approaches toward

(13) Portions of this work have been published in the form of a preliminary communication.[12m]

Scheme V



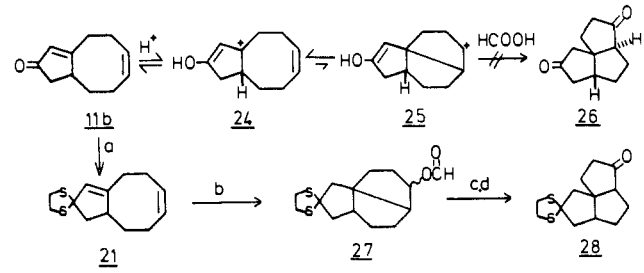
Reagents and yields: (a) 90% HCOOH, 80 °C, 3 h; (b) 10% KOH–MeOH, H_2O, reflux, 1.5 h; (c) Jones reagent–$(CH_3)_2CO$, 20 °C, 41% (from **11a**).

their syntheses have been conceived through a straightforward retrosynthetic analysis, pathway a, Scheme I, which simply involves cyclopentane annulation of preformed bicyclo[3.3.0]octane with concomitant generation of the spiro center. The ready availability of the latter[14] with varied functionalization and its known exo selectivity ensures the buildup of requisite methyl groups and control of stereochemistry. However, an obvious alternate mode of constructing angular triquinanes via the bicyclo[6.3.0]undecane system derived through bond disconnection b, Scheme I, offers[12i,l] new and interesting opportunities which have not been investigated. Interestingly, this pathway closely resembles the proposed biosynthetic route to angular triquinanes. Taking cognisance of the marked propensity of the cyclooctyl derivatives toward transannular cationic cyclizations,[15] we decided to explore the bicyclo[6.3.0]octane approach as outlined in Scheme II, with the bridgehead olefin **11** serving as the model system and precursor of the key carbonium ion **12** for cyclization to the angular triquinane derivative **13**. This required ready access to compounds like **11a** and **11b**. But at this stage, we also realized that the methodology for the preparation of suitably functionalized bicyclo[6.3.0]undecanes was not available in the literature, and therefore our first task was to develop short and general approaches to this system from abundantly available starting materials.

Two syntheses of the bicyclic diene **11a** from readily available 1,5-cyclooctadiene (COD) were developed and are presented in Schemes III and IV. In the first approach, 1,5-COD was cyclopentannulated through dichloroketene addition to give the monoadduct **14** followed by diazomethane ring expansion to **15**.[16] Dehydrochlorination of **15** furnished the chloroenone **16** which was converted to its ethylene thioacetal **17**, and then both the vinylic halogen and the thioacetal moieities were removed in a single step employing metal–ammonia reduction to give **11a** in 20% overall yield from 1,5-COD. The diolefin **11a** was duly characterized; and its ^{13}C NMR exhibited four resonances due to sp^2 carbon atoms at δ 127.5, 129.5, 130.2, and 149.4, with the last one being attributable to the bridgehead quaternary carbon. The second route to **11a**, Scheme IV, was through the 1,5-COD monoepoxide **18** which was opened with allyllithium reagent[17] and oxidized to give the ketone **19**. Tsuji-type oxidation[18] and the allyl group generated the acetonyl side chain, and the resulting diketone **20** was cyclized with NaH in boiling toluene to deliver the bicyclic enone **11b**. Deoxygenation via the ethylene thioacetal **21** and metal–ammonia reduction yielded the diolefin **11a** in satisfactory yield. With the assured availability of **11a**, the key transannular cyclization step was now attempted.

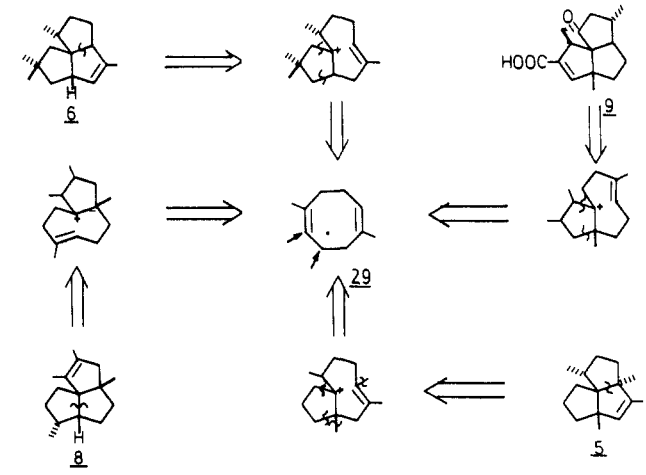
In the choice of the reaction conditions for effecting the cationic cyclization of **11a**, we opted for the formolysis reaction, so very effectively employed by Cope during his seminal studies of the transannular reactions in cyclooctyl systems.[15,19] Thus, exposure of **11a** to 90% formic acid smoothly transformed it into the formate ester **22** (IR: 1720, 1180 cm^{-1}). The crude **22** was not characterized any further but hydrolyzed and oxidized to a single ketone **23**, Scheme V. That it had the desired tricyclic structure was

Scheme VI



Reagents and yields: (a) $(CH_2SH)_2$–PTS–C_6H_6, 50 °C, 5 h, 80%; (b) 85% HCOOH, 80 °C, 3 h, 55%; (c) 10% KOH–MeOH, H_2O, reflux, 1 h; (d) PDC–CH_2Cl_2, room temperature, 2 h, 70% (from **27**).

Scheme VII



established through its IR spectrum (1740 cm^{-1}) and absence of unsaturation in its ^1H and ^{13}C NMR spectra. More importantly, the ^{13}C NMR displayed a quaternary carbon resonance at δ 59.2, diagnostic of angular triquinanes. To further extend the scope of this transannular cyclization, we sought to explore if a bicyclo[6.3.0]undecane derivative like **11b** could be induced to deliver bifunctional triquinane dione **26**, Scheme VI. However, repeated exposure of **11b** to a variety of protic acids (formic, trifluoroacetic, trifluoromethanesulfonic, etc.) or Lewis acids ($SnCl_4$, BF_3, Me_3SiI, etc.) drew a blank, and more stringent conditions or use of nucleophilic media gave only wayward products. It appeared reasonable to attribute the failure of **11b** to cyclize to the unfavorable equilibrium concentration of the tricyclic secondary carbonium ion **25** compared to the allylic carbonium ion **24** derived through the protonation of the enone **11b**. We therefore thought that masking of the carbonyl in the enone **11b** might eventuate in the transannular cyclization like **11a** and still provide access to a bifunctional triquinane. This indeed turned out to be the case. The ethylene thioacetal **21** derived from enone **11b** when subjected to formolysis furnished a 2:3 mixture of the formate ester **27** and the enone **11b**, respectively, the latter being obtained through competitive dethioacetalization in the reaction medium. The tricyclic formate ester **27** was hydrolyzed and oxidized to give **28** in modest yield. The IR spectrum (1720 cm^{-1}) as well as ^1H and ^{13}C NMR parameters (vide experimental) secured its formulation. Having demonstrated the transannular cyclization route to angular triquinanes **23** and **28**, effort was switched toward adopting this theme to the natural product synthesis.

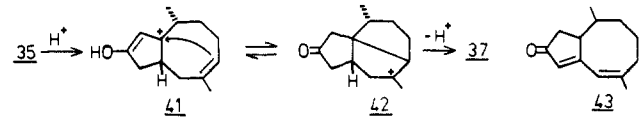
(±)-Pentalenene (6) and (±)-9-*epi*-Pentalenene (10). As already indicated we selected (±)-pentalenene (**6**) as the target molecule among other triquinanes mainly because of its importance as the biosynthetic precursor of the pentalenolactone family of antibiotics.[20] Retrosynthetic analysis of **6**, bearing in mind the synthetic methodology to angular triquinanes unfolded above, led to the identification of 1,5-dimethyl-1,5-cyclooctadiene **29** as the

(14) Kubiak, G.; Cook, J. M. *J. Org. Chem.* **1984**, *49*, 561, Venkatachalam, M.; Despande, M. N.; Jawdosiuk, M.; Kubiak, G.; Wehrli, S.; Cook, J. M.; Weiss, U. *Tetrahedron* **1986**, *42*, 1597.
(15) Cope, A. C.; Martin, M. M.; McKervey, M. A. *Q. Rev., Chem. Soc.* **1986**, *20*, 119.
(16) (a) Mehta, G.; Padma, S.; Rao, K. S. *Synth. Commun.* **1985**, *15*, 1137. (b) Mehta, G.; Rao, H. S. P. *Synth. Commun.* **1985**, *15*, 991.
(17) (a) Eisch, J. J.; Jacobs, A. M. *J. Org. Chem.* **1963**, *28*, 2145. (b) Apparu, M.; Barrelle, M. *Tetrahedron* **1978**, *34*, 1817.
(18) Tsuji, J.; Shimizu, I.; Yamamoto, K. *Tetrahedron Lett.* **1976**, 2975.
(19) Cope, A. C.; Kinnel, R. B. *J. Am. Chem. Soc.* **1966**, *88*, 752.
(20) (a) Cane, D. E.; Abell, C.; Tillman, A. M. *Bioorg. Chem.* **1984**, *12*, 312. (b) Cane, D. E.; Tillman, A. M. *J. Am. Chem. Soc.* **1983**, *105*, 122.

starting material, Scheme VII. Indeed, commercially available **29** could serve as the common precursor for various triquinane skeleta through the transannulation protocol, as all of them have methyl groups disposed in the 1,5-position like in **29**. Thus, with the simple expedient of altering the sites of cyclopentannulation and transannulation cyclization on **29**, it should be possible to design all triquinane natural products, Scheme VII. However, here we only outline the elaboration of 1,5-dimethyl-1,5-cyclooctadiene to (±)-pentalenene (**6**) and (±)-*epi*-pentalenene (**10**), which required cyclopentannulation at the positions marked with arrows on **29**. To achieve this, the following sequence was adopted.

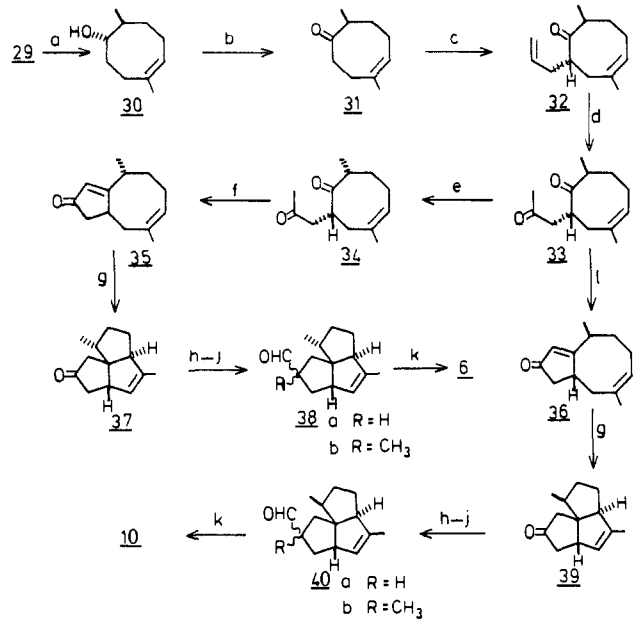
Selective hydroboration of **29** with 9-BBN and oxidation furnished the cyclooctenol **30** which on PCC oxidation gave cyclooctenone **31**. Kinetically controlled allylation of **31** with LiHMDS led exclusively to the trans product **32** in accordance with the recent results of Clark Still[21] on the stereo- and regioselective alkylations of cyclooctanone derivatives. The allyl group was now oxidized with Pd^{2+}–O_2 to the required acetonyl side chain following the procedure developed by Tsuji,[18] and diketone **33** was realized. At this stage, it was essential to secure the correct relative stereochemistry at the secondary carbon atoms bearing the methyl and the acetonyl side chains so as to correspond with that present in pentalenene. Consequently, diketone **33** was equilibrated with methonolic KOH, and a 1:4 mixture of **33** and its epimer **34**, respectively, was obtained. The formation of the new, desired epimer **34** with cis-alkyl groups was expected in view of the previous observations[21] on model cyclooctyl systems and was further supported by the incisive analysis of the ^1H and ^{13}C NMR data. Internal aldol cyclization in **34** was smoothly effected with NaH in THF, and the bicyclic enones **35** and **36** were realized in a ratio of 4:1. Obviously, some competitive epimerization of the tertiary methyl center had also occurred. The structures of enones **35** and **36** followed readily from their spectral properties but more explicitly from their ^{13}C NMR spectra, which exhibited resonances at δ 128.8, 192.3, 208.5 and δ 131.4, 188.4, 208.4 respectively, diagnostic of the 2-cyclopentenone moiety.

Attention was not turned toward the key transannular cyclization step. Although the enone–olefin cyclization did not succeed in the case of **11b** to **26** (vide supra), we were quite optimistic in the present case that the cyclization of the bicyclic cation **41** to a stabilized tertiary carbonium ion **42** would tilt the balance in favor of the latter. Indeed, transannular cyclization of **35**



proved to be quite facile and could be effected with *p*-toluenesulfonic acid, BF_3–etherate, Nafion-H, etc., but competitive formation of dienone **43** through double-bond isomerization was a serious irritant and had to be eliminated. After many trial-and-error runs, we found that formic acid in the presence of BF_3–etherate effected the cyclization of **35** almost exclusively to **37** in 55% isolated yield. The stereospecific formation of angular triquinane **37** was confirmed by the presence of a cyclopentanone moiety (IR: 1730 cm^{-1}) and a quaternary carbon center (δ 62.1, s) in the ^{13}C NMR spectrum. Thus, the tricyclic framework, all four stereocenters and 13 of the 15 carbon atoms of pentalenene **6** could be assembled in only 7 steps from 1,5-dimethyl-1,5-cyclooctadiene. The final task enroute to **6** now was the geminal dimethylation of the C_6-carbonyl group, and at first, direct, one-step procedures based on Reetz dimethyltitanium dichloride reagent[22] and the Russian workers tetramethylsilane–$AlCl_3$ reagent[23] were attempted. In both of these cases, complex mixtures of C_{14}- and C_{15}-alkenes and chloroalkanes were obtained, and although GC/MS analyses indicated the presence of pentalenene **6** in trace amounts, the methodologies were preparatively unsuitable despite their brevity. A more circuitous approach to **6** was therefore undertaken.

Scheme VIII



Reagents and yields: (a) 9-BBN–THF, room temperature, (b) PCC–CH_2Cl_2, molecular sieves (4 Å), 63% (from **29**); (c) LiHMDS–THF, allyl bromide, −78 °C; 75%; (d) $PdCl_2$–CuCl–DMF, H_2O, O_2, room temperature, 1 h, 80%; (e) 2% KOH–MeOH, reflux, 4 h, 82%; (f) NaH–THF, 70 °C, 3.5 h, 70%; (g) 85% HCOOH–BF_3–etherate, 90 °C, 2 h, 55%; (h) $Ph_3P^+Cl^-CH_2OMe$-*t*-$C_5H_{11}O^-Na^+$–Et_2O, room temperature; (i) 35% $HClO_4$–Et_2O, room temperature, 18 h, 80% (from **37** or **39**); (j) KH–THF, MeI, 0–10 °C, 4 h, 63%; (k) N_2H_4–$(HOCH_2CH_2)_2O$–$(HOCH_2)_2$, Na, 33%; (l) NaH–THF, 70 °C, 30 min.

Wittig olefination of **37** with (methoxymethyl)triphenylphosphonium chloride and the mild hydrolysis of the product gave the C_{14}-aldehyde **38a**. The labile aldehyde was immediately methylated with methyl iodide employing KH as the base in THF medium to establish the second quaternary carbon center at C_6. The resulting C_{15}-aldehyde **38b** (IR: 1720, 2700 cm^{-1}. ^1H NMR: δ 9.41, s) was subjected to Wolff-Kishner reduction to furnish (±)-pentalenene (**6**), which was found identical (^1H and ^{13}C NMR) with the natural product (Scheme VIII).

Since the trans-diketone **33** was readily available and in quantity, it too was subjected to a parallel series of reactions to deliver stereoselectively (±)-*epi*-pentalenene (**10**), Scheme VIII. The epimeric series of compounds obtained in this sequence proved useful for spectral comparisons and structural assignments. Aldol cyclization of **33** provided a 4:1 mixture of enones **36** and **35**, respectively. Transannular cyclization of **36** with formic acid–BF_3–etherate was stereospecific, and triquinane **39** was readily obtained. Geminal dialkylation of the carbonyl group was once again achieved through methoxy olefination, acid hydrolysis to C_{14}-aldehyde **40a**, methylation with KH–CH_3I to **40b**, and Wolff–Kishner reduction sequence. The resulting hydrocarbon (±)-*epi*-pentalenene (**10**) was found identical with the sample synthesized earlier by Paquette and co-workers.[12j]

In summary, a simple but conceptually new approach to angular triquinane natural products based on carbonium-ion-mediated transannulation reaction in bicyclo[6.3.0]undecanes has been outlined. The generality of the approach has been demonstrated through the synthesis of some model triquinanes of the sesquiterpene hydrocarbon (±)-pentalenene (**6**) and its C_9-epimer **10**. This accomplishment, to date, represents the shortest route to this natural product. Through tactical adjustments of substituents and functionality, the protocol developed here can lead to all angular triquinane skeleta from cheap, commercial precursors.

Experimental Section[24]

11-Chloro-10,10-(ethylenedithio)bicyclo[6.3.0]undeca-1(11),4-diene (17). A solution of the monochloro enone **16**[16a] (500 mg, 2.54 mmol),

(21) Clark Still, W.; Galynker, I. *Tetrahedron* **1981**, *37*, 3981.
(22) Reetz, M. T. *Top. Curr. Chem.* **1982**, *106*, 1.
(23) Parnes, Z. N.; Bolestova, G. I.; Akhrem, I. S.; Vol'pin. M. E.; Kursanov, D. N. *J. Chem. Soc., Chem. Commun.* **1980**, 748.

(24) For a general writeup, see: Mehta, G.; Rao, K. S. *J. Org. Chem.* **1985**, *50*, 5537.

ethanedithiol (0.5 mL), and a catalytic amount of *p*-toluenesulfonic acid in 20 mL of dry benzene was heated at reflux for 9 h. The organic layer was washed with water and 5% $NaHCO_3$ and dried. Removal of solvent gave 760 mg of crude compound which was charged on a silica gel (10 g) column. Elution with 10% benzene–petroleum ether furnished the thioacetal **17**: 560 mg (82%); IR (neat) ν_{max} 3010, 2950, 1620, 1420 cm^{-1}; ^1H NMR (100 MHz, $CDCl_3$) δ 5.6 (2 H, t), 3.38 (4 H, m), 3.0–1.2 (11 H, series of m). Anal. Calcd for $C_{13}H_{17}ClS_2$: C, 57.76; H, 6.24. Found: C, 57.51; H, 6.39.

Bicyclo[6.3.0]undeca-1(11),4-diene (11a). To a vigorously stirred mixture of 30 mL of liquid NH_3 and sodium (230 mg, 10 mmol) kept at −40 °C was carefully added chloro thioacetal **17** (550 mg, 2.0 mmol) in 3 mL of ether. The stirring was continued for 2 h at the same temperature, and then the reaction mixture was quenched with ethanol, ammonia was allowed to evaporate, and the mixture was brought to room temperature. The residue was dissolved in pentane (30 mL), and the organic layer was washed and dried. The oily residue obtained after removal of solvent was filtered through a silica gel (5 g column). Elution with pentane furnished the bicyclic hydrocarbon **11a**: 165 mg (55%); IR (neat) ν_{max} 3025, 1660, 720 cm^{-1}; ^1H NMR (100 MHz, $CDCl_3$) δ 5.7–5.4 (2 H, m), 5.36 (1 H, s), 2.8–1.3 (13 H, m); ^{13}C NMR (25.0 MHz, $CDCl_3$) δ 149.4 (s), 130.2 (d), 129.5 (d), 127.5 (d), 45.7 (d), 35.2 (t), 33.9 (t), 32.5 (t), 29.7 (t), 25.9 (t), 25.6 (t).

Tricyclo[6.3.0.0^{4,8}]undecan-5-one (23). The diene **11a** (120 mg, 0.81 mmol) was taken into 2 mL of 90% HCOOH and was heated at 80 °C for 3 h. The reaction mixture was poured into ice-cold water and was extracted with ether (3 × 10 mL). The ethereal layer was washed with 5% $NaHCO_3$ and dried, and removal of solvent gave 140 mg of formate ester **22** (IR: ν_{max} 1720, 1180 cm^{-1}). The crude formate ester was dissolved in 3 mL of 10% methanolic KOH, diluted with 3 drops of H_2O, and refluxed for 1.5 h. The reaction mixture was diluted with water and extracted with ether (4 × 20 mL). The ethereal layer was washed and dried, and removal of solvent gave 140 mg of tricyclic hydroxy compound. The hydroxy compound was dissolved in acetone, and Jones reagent was added dropwise at 20 °C until the orange color persisted. The acetone was removed under reduced pressure, and the residue was extracted with ether (3 × 20 mL). The ethereal layer was washed and dried, and removal of solvent gave 100 mg of the tricyclic ketone **23** which was charged on a silica gel (10 g) column. Elution with 20% benzene–petroleum ether furnished pure tricyclic ketone **23**, 55 mg (41% from **11a**), which was bulb-to-bulb distilled at 120 °C/0.4 torr; IR (neat) ν_{max} 1740 cm^{-1}; ^1H NMR (100 MHz, $CDCl_3$) δ 2.4–1.24 (16 H, m); ^{13}C NMR (25.0 MHz, $CDCl_3$) δ 223.5 (s), 60.5 (d), 59.2 (s), 51.5 (d), 41.0 (t), 39.6 (t), 35.0 (t), 34.5 (t), 34.3 (t), 30.7 (t), 26.9 (t). Anal. Calcd for $C_{11}H_{16}O$: C, 80.44; H, 9.81. Found: C, 80.32; H, 10.24.

8-Allylcyclooct-4-en-1-one (19). 1,5-Cyclooctadiene monoepoxide **18**[25] (12 g, 96.7 mmol) was dissolved in a mixture of 50 mL of dry THF and 25 mL of dry ether, and 200 mL of allyllithium (~0.6 mmol in THF and ether) was added through a pressure-equalizing addition funnel at 0 °C. After the completion of the addition, the red reaction mixture was stirred at room temperature for 5 h. The reaction mixture was carefully quenched with water and extracted with ether (4 × 50 mL). The ethereal layer was washed and dried, and removal of solvent furnished 17 g of crude allylated alcohol which was used as such for the next step.

The above compound was dissolved in 20 mL of dry dichloromethane and added to a solution of pyridinium chlorochromate (35 g) in 200 mL of dry dichloromethane containing 40 g of activated molecular sieves (4 Å). The reactants were stirred for 2 h and diluted with 50 mL of dry ether. The resulting solution was filtered through a Florisil pad and repeatedly washed with dichloromethane. Removal of solvent left a dark residue which was distilled at 110 °C/0.5 torr: 12 g (75%); IR (neat) ν_{max} 3075, 3025, 2950, 1700, 1640, 910, 720 cm^{-1}; ^1H NMR (100 MHz, $CDCl_3$) δ 5.8–5.2 (3 H, m), 5.0–4.7 (2 H, m), 3.0–1.6 (9 H, m), 1.6–1.0 (2 H, m); ^{13}C NMR (25.0 MHz, $CDCl_3$) δ 215.5, 135.2, 130.3, 129.4, 116.3, 49.2, 47.0, 37.5, 30.0, 25.1, 21.5. Anal. Calcd for $C_{11}H_{16}O$: C, 80.44; H, 9.83. Found: C, 80.43; H, 9.81.

8-(2-Oxopropyl)cyclooct-4-en-1-one (20). Into a 250-mL pressure bottle, $PdCl_2$ (1.1 g), cuprous chloride (9 g), 30 mL of DMF, and 8 mL of H_2O were taken and preactivated by shaking under an O_2 blanket for 1 h. A solution of **19** (5 g, 30.5 mmol) in 10 mL of DMF was added, and the contents were shaken for 2 h at room temperature in an O_2 atmosphere. The reaction mixture was quenched with 10% HCl and was extracted with ether (4 × 40 mL). The ethereal solution was washed and dried, and the solvent was removed to give 6 g of crude product which was purified through chromatography on an alumina (120 g) column. Elution with 10% ethyl acetate–petroleum ether furnished the diketone **20**: 4.66 g (85%); bp 130 °C/0.3 torr; IR (neat) ν_{max} 3020, 2950, 1700, 720 cm^{-1}; ^1H NMR (100 MHz, $CDCl_3$) δ 5.9–5.4 (2 H, m), 3.4–1.9 (9 H, m), 2.0 (3 H, s), 1.5–1.1 (2 H, m); ^{13}C NMR (25.0 MHz, $CDCl_3$) δ 215.7, 206.7, 130.1, 129.6, 48.9, 46.3, 43.7, 29.6, 29.0, 24.8, 21.5. Anal. Calcd for $C_{11}H_{16}O_2$: C, 73.30; H, 8.95. Found: C, 73.17; H, 8.99.

Bicyclo[6.3.0]undeca-1(11),4-dien-10-one (11b). Sodium hydride (400 mg, 8.33 mmol) was placed in a 100-mL three-necked flask equipped with magnetic pellet, dry N_2 inlet, condenser with mercury seal, and a septum. The mineral oil was removed by washing twice with dry petroleum ether, and the residue was suspended in 15 mL of dry toluene. A solution of diketone **20** (500 mg, 2.77 mmol) in 5 mL of dry toluene was added dropwise. The reaction mixture was heated at 90 °C for 3 h and then quenched with 5% HCl and extracted with ether (3 × 25 mL). The ethereal solution was washed and dried, and the solvent was removed to give 500 mg of bicyclic enone **11b**: 315 mg (70%); bp 130 °C/0.3 torr; IR (neat) ν_{max} 3070, 3030, 2950, 1700, 1600, 900 cm^{-1}; ^1H NMR (100 MHz, $CDCl_3$) δ 5.88 (1 H, br s), 5.8–5.4 (2 H, m), 3.4–1.8 (9 H, m), 1.8–1.2 (2 H, m); ^{13}C NMR (25.0 MHz, $CDCl_3$) δ 208.6, 186.2, 132.4, 128.9, 128.6, 44.6, 42.0, 34.6, 33.3, 25.7, 25.0. Anal. Calcd for $C_{11}H_{14}O$: C, 81.44; H, 8.70. Found: C, 81.38; H, 8.61.

10,10-(Ethylenedithio)bicyclo[6.3.0]undeca-1(11),4-diene (21). A solution of the enone **11b** (1 g, 6.17 mmol), ethanedithiol, and a catalytic amount of *p*-toluenesulfonic acid in 40 mL of dry benzene was heated at 50 °C for 5 h. The organic layer was washed with water and 5% $NaHCO_3$ and dried. Removal of solvent gave 1.5 g of crude compound which was charged on a silica gel (30 g) column. Elution with 10% benzene–petroleum ether furnished the thioacetal **21**: 1.17 g (80%) IR (neat) ν_{max} 3030, 2950, 1630, 740 cm^{-1}.

6,6-(Ethylenedithio)tricyclo[6.3.0.0^{4,8}]undecan-11-one (28). The thioacetal **21** (300 mg, 1.1 mmol) was taken into 5 mL of 85% HCOOH and was heated at 80 °C for 3 h. The reaction mixture was poured into ice-cold water and was extracted with ether (2 × 20 mL). The ethereal layer was washed with 5% $NaHCO_3$ and dried, and removal of solvent gave 280 mg of a 3:2 mixture of **11b** and **27**, which was charged on a silica gel (5 g) column. Elution with 30% benzene–petroleum ether furnished the formate ester **27** (epimeric mixture): 78 mg; IR (neat) ν_{max} 2950, 1720, 1440, 730 cm^{-1}; ^1H NMR (100 MHz, $CDCl_3$) δ 8.07 (1 H, s), 8.0 (1 H, s), 3.30 (8 H, br s), 3.3–1.0 (28 H, m). Further elution of the column with benzene furnished the enone **11b**, 118 mg, bp 130 °C/0.3 torr, identical with the sample obtained in the previous experiment.

Formate ester **27** (80 mg) was taken into 4 mL of 10% methanolic KOH, diluted with 3 drops of H_2O, and refluxed for 1 h. The reaction mixture was diluted with water and extracted with ether (2 × 20 mL). The ethereal layer was washed and dried, and removal of solvent gave 70 mg of the tricyclic hydroxy compound. The hydroxy compound was dissolved in 2 mL of dry dichloromethane and was added to a solution of 160 mg of pyridinium chlorochromate in 8 mL of dry dichloromethane containing 200 mg of activated molecular sieves (4 Å). The reactants were stirred for 2 h and diluted with 5 mL of dry ether. The resulting dark-brown solution was filtered through a Florisil pad and repeatedly washed with dichloromethane. Removal of solvent left a dark residue which was charged on a silica gel (5 g) column. Elution of the column with benzene furnished the keto thioacetal **28**: 50 mg (70% from **27**); IR (neat) ν_{max} 2950, 1740, 1460, 1160 cm^{-1}; ^1H NMR (100 MHz, $CDCl_3$): δ 3.33 (4 H, s), 2.6–1.0 (14 H, m); ^{13}C NMR (25.0 MHz, $CDCl_3$) δ 216.2, 77.0, 76.8 59.9, 58.2, 56.5, 52.1, 39.9, 39.5, 39.3, 35.9, 32.0, 29.5; exact mass calcd (M^+) 254.0784, found 254.0784.

4,8-Dimethylcyclooct-4-en-1-one (31). 1,5-Dimethyl-1,5-cyclooctadiene (10 g, 74.6 mmol) in 40 mL of dry THF was taken in a 250-mL, three-necked, round-bottomed flask fitted with dry N_2 inlet. To this solution, 9-BBN (10 g, 81.9 mmol) in 75 mL of dry THF was added (1 h) dropwise through a pressure equalizing addition funnel at 25 °C, and the reaction mixture was stirred for 4 h. The round-bottomed flask was then placed in an ice bath, and 10 mL of 6 M NaOH followed by 8 mL of 30% H_2O_2 was added through a pressure-equalizing addition funnel. After the completion of the addition, the flask was brought to room temperature and stirred for an additional 6 h. The reaction mixture was diluted with water and extracted with ether (4 × 50 mL). The ethereal solution was washed and dried, and the solvent was removed to give 11 g of crude hydroxy olefin **30** (IR: 3600 cm^{-1}) which was used as such for the next reaction.

The crude product obtained above was dissolved in 20 mL of dry dichloromethane and was added to a solution of 20 g of pyridinium chlorochromate in 150 mL of dry dichloromethane containing 25 g of activated molecular sieves (4 Å). The reactants were stirred for 3 h and diluted with 50 mL of dry ether. The resulting dark-brown solution was filtered through a Florisil pad and repeatedly washed with dichloromethane. Removal of solvent left a dark residue which was charged on a silica gel (200 g) column. Elution of the column with benzene furnished the keto olefin **31**: 7 g (63%); bp 80 °C/0.5 torr; IR (neat) ν_{max} 2930, 1700, 1440 cm^{-1}; ^1H NMR (100 MHz, $CDCl_3$) δ 5.8 (1 H, t), 2.92–1.12 (9 H, m), 1.64 (3 H, br s), 0.92 (3 H, d, J = 7 Hz); ^{13}C NMR (25.0 MHz, $CDCl_3$) δ 215.7, 136.9, 124.5, 44.9, 43.7, 34.0, 26.5 (2c), 22.8,

(25) Barrele, M.; Apparu, M. *Bull. Soc. Chim. Fr.* **1972**, 2016.

17.9. Anal. Calcd for $C_{10}H_{16}O$: C, 78.89; H, 10.58. Found: C, 78.62; H, 10.73.

2β-Allyl-4,8α-dimethylcyclooct-4-en-1-one (32). Into a 100-mL, three-necked flask fitted with a dry N_2 inlet, septum, and mercury seal was introduced *n*-butyllithium (20 mL, 20 mmol in hexane), and the flask was cooled to −78 °C. Hexamethyldisilazane (5.26 mL, 25 mmol) was carefully injected, the resulting slurry was stirred for 45 min, and 20 mL of dry THF was added. A solution of keto olefin **30** (3 g, 20 mmol) in 20 mL of dry THF was then slowly added through a syringe. The resulting enolate solution was stirred for 30 min and quenched with freshly distilled allyl bromide (2.2 mL, 25 mmol). The reaction mixture was maintained at −78 °C for 30 min and then brought to room temperature. After further stirring for 30 min, the reaction mixture was quenched with water and extracted with ether (4 × 50 mL). The ethereal solution was washed and dried, and the solvent was removed to give 5 g of crude product which was charged on a silica gel (100 g) column. Elution with 80% benzene–petroleum ether furnished the allylated ketone **32**: 2.88 g (75%); bp 120 °C/0.3 torr; IR (neat) ν_{max} 3030, 2950, 1710, 1640 cm^{-1}; ^1H NMR (100 MHz, $CDCl_3$) δ 6.12–5.44 (1 H, m), 5.44–5.16 (1 H, t), 5.16–4.84 (2 H, m), 3.04–1.04 (10 H, series of m), 1.68 (3 H, br s), 0.96 (3 H, d, J = 7 Hz); ^{13}C NMR (25.0 MHz, $CDCl_3$) δ 216.9, 136.5, 135.3, 125.5, 116.6, 56.1, 41.0, 36.0 (2c), 33.0, 27.4, 23.4, 19.1. Anal. Calcd for $C_{13}H_{20}O$: C, 81.20; H, 10.48. Found: C, 81.52; H, 10.51.

2β-(2-Oxopropyl)-4,8α-dimethylcyclooct-4-en-1-one (33). Palladium chloride (1.1 g), cuprous chloride (9 g), 30 mL of DMF, and 8 mL of H_2O were taken into a 250-mL pressure bottle and preactivated by shaking under an O_2 blanket for 1 h. A solution of **32** (5 g, 26 mmol) in 10 mL of DMF was added, and the contents were shaken for 1 h at room temperature in an O_2 atmosphere. The reaction mixture was quenched with 10% HCl and was extracted with ether (4 × 50 mL). The ethereal solution was washed and dried, and the solvent was removed to give 6 g of crude product which was purified through chromatography on an alumina (120 g) column. Elution with 10% ethyl acetate–petroleum ether furnished the trans-diketone **33**, 4.3 g (80%), which was distilled at 120 °C/0.2 torr: IR (neat) ν_{max} 2930, 1700, 1460, 1370 cm^{-1}; ^1H NMR (100 MHz, $CDCl_3$) δ 5.36 (1 H, t), 3.16–2.36 (4 H, m), 2.36–1.84 (4 H, m), 2.15 (3 H, s), 1.6–1.12 (2 H, m), 1.69 (3 H, br s), 1.0 (3 H, d, J = 7 Hz); ^{13}C NMR (25.0 MHz, $CDCl_3$) δ 218.9, 205.3, 136.2, 126.0, 51.0, 45.2, 41.7, 35.5, 32.9, 29.9, 27.1, 23.8, 19.1. Anal. Calcd for $C_{13}H_{20}O_2$: C, 74.96; H, 9.68. Found: C, 74.86; H, 9.94.

2β-(2-Oxopropyl)-4,8β-dimethylcyclooct-4-en-1-one (34). Trans-diketone (4 g, 19.2 mmol) was dissolved in 50 mL of 2% methanolic KOH solution and refluxed for 4 h. The methanol was removed under reduced pressure, and the residue was taken into ether (60 mL). The ethereal solution was washed with 5% HCl and water and dried. On removal of the solvent, 4 g of a 4:1 mixture of **34** and **33** was obtained. This was charged on a silica gel (80 g) column. Elution with 10% ethyl acetate–petroleum ether furnished first the major cis-diketone **34**: 2.63 g; bp 120 °C/0.2 torr; IR (neat) ν_{max} 2940, 1700, 830 cm^{-1}; ^1H NMR (100 MHz, $CDCl_3$) δ 5.28 (1 H, t), 3.24–1.0 (10 H, series of m), 2.0 (3 H, s), 1.68 (3 H, br s), 0.88 (3 H, d, J = 7 Hz); ^{13}C NMR (25.0 MHz, $CDCl_3$) δ 217.6, 206.8, 135.3, 125.1, 49.1, 45.2, 44.5, 33.8, 31.5, 30.0, 26.1, 25.1, 17.6. Anal. Calcd for $C_{13}H_{20}O_2$: C, 74.96; H, 9.68. Found: C, 74.33; H, 9.92. Further elution of the column with the same solvent gave the minor trans-diketone **33**, bp 120 °C/0.2 torr, identical with the sample obtained in the previous experiment.

2β,6-Dimethylbicyclo[6.3.0]undeca-1(11),5-dien-10-one (35). Sodium hydride (700 mg as 50% dispersion in oil, 14.5 mmol) was placed in a 100-mL, three-necked flask equipped with a magnetic pellet, dry N_2 inlet, condenser with mercury seal, and septum. The mineral oil was twice washed with dry petroleum ether, and the residue was suspended in 20 mL of dry THF. A solution of cis-diketone **34** (1.2 g, 5.77 mmol) in 10 mL of dry THF was added dropwise. The resulting light-yellow solution was heated for 3.5 h at 70 °C, after which it was quenched with 5% HCl and extracted with ether (4 × 25 mL). The ethereal solution was washed and dried and the solvent removed to give 1.2 g of a crude 4:1 mixture of **35** and **36** in 70% yield. This mixture was charged on a silica gel (20 g) column. Elution with 10% ethyl acetate–petroleum ether furnished the major enone **35**: 600 mg; bp 130 °C/0.2 torr; IR (neat) ν_{max} 2900, 1670, 1595, 860 cm^{-1}; ^1H NMR (100 MHz, $CDCl_3$) δ 5.9 (1 H, br s), 5.32 (1 H, t), 3.12–1.2 (10 H, series of m), 1.8 (3 H, br s), 1.1 (3 H, d, J = 7 Hz); ^{13}C NMR (25.0 MHz, $CDCl_3$) δ 208.5, 192.3, 135.3, 128.8, 125.1, 44.0, 43.3, 38.1, 35.9, 35.2, 26.0, 25.0, 21.8. Anal. Calcd for $C_{13}H_{18}O$: C, 82.05; H, 9.53. Found: C, 82.26; H, 9.63. Further elution of the column gave the minor enone **36**: bp 130 °C/0.2 torr; IR (neat) ν_{max} 3050, 2900, 1680, 1590, 730 cm^{-1}; ^1H NMR (100 MHz, $CDCl_3$) δ 6.0 (1 H, br s), 5.48 (1 H, t), 3.6–1.6 (10 H, m), 1.72 (3 H, br s), 1.27 (3 H, d, J = 7 Hz); ^{13}C NMR (25.0 MHz, $CDCl_3$) δ 208.4, 188.4, 134.0, 131.4, 125.8, 43.7, 41.7, 36.4, 36.1, 34.4, 27.1, 24.6, 18.1. Anal. Calcd for $C_{13}H_{18}O$: C, 82.05; H, 9.53. Found: C, 82.17; H, 9.57.

2,9β-Dimethyltricyclo[6.3.0.0^{4,8}]undec-2-en-6-one (37). To a solution of the enone **35** (420 mg, 2.21 mmol) in 5 mL of 85% formic acid, BF_3–etherate (0.2 mL) was added, and the solution was heated for 2 h at 90 °C. The reaction mixture was cooled, slowly poured into ice-cold water, and extracted with ether (3 × 20 mL). The ethereal solution was washed with 5% $NaHCO_3$ and dried, and the solvent was removed to give 400 mg of oily residue which was charged on a silica gel (10 g) column. Elution with 2% ethyl acetate–petroleum ether furnished the tricyclic ketone **37**, 230 mg (55%), which was distilled at 120 °C/0.3 torr: IR (neat) ν_{max} 3030, 2950, 1730 cm^{-1}; ^1H NMR (100 MHz, $CDCl_3$) δ 5.08 (1 H, br s), 3.28–1.12 (11 H, series of m), 1.64 (3 H, br s), 0.92 (3 H, d, J = 7 Hz); ^{13}C NMR (25.0 MHz, $CDCl_3$) δ 219.0, 144.0, 126.8, 62.1, 60.2, 51.6, 45.9, 43.6, 43.0, 34.8, 28.7, 15.8, 15.2. Anal. Calcd for $C_{13}H_{18}O$: C, 82.06; H, 9.54. Found: C, 82.14; H, 9.60.

2,9β-Dimethyltricyclo[6.3.0.0^{4,8}]undec-2-ene-6-carboxaldehyde (38a). Into a 50-mL, three-necked round-bottomed flask fitted with dry N_2 inlet, septum, reflux condenser, and mercury seal was placed (methoxymethyl)triphenylphosphonium chloride (2 g, 6 mmol). The solid was suspended in 15 mL of dry ether, and freshly sublimed sodium *tert*-amyl oxide (430 mg, 3.9 mmol) in 5 mL of dry ether was added. The dark-red reaction mixture was stirred for 45 min at room temperature, to this the tricyclic ketone **37** (280 mg, 1.3 mmol) in 5 mL of dry ether was introduced, and the reactants were stirred for 1 h. The reaction mixture was quenched with water and extracted with ether (4 × 20 mL). The ethereal layer was washed and dried, and the solvent was removed. The crude reaction mixture was used as such for the next step.

The crude reaction mixture obtained above was dissolved in 10 mL of ether, and to this were added 8–10 drops of 35% perchloric acid (ice bath). The reaction mixture was stirred for 18 h at room temperature, diluted with ether, and quenched with 5% $NaHCO_3$. The ethereal layer was washed and dried. The residue obtained after removal of the solvent was filtered through a silica gel (10 g) column. Elution with petroleum ether resulted in the removal of triphenylphosphine-derived impurities, and further elution with 25% benzene–petroleum ether furnished the aldehyde **38a** (mixture of aldehyde epimers): 214 mg (80%); IR (neat) ν_{max} 3030, 2950, 2700, 1720 cm^{-1}; ^1H NMR (100 MHz, $CDCl_3$) δ 10.14 (1 H, s), 10.08 (1 H, s), 5.34 (1 H, br s), 5.22 (1 H, br s), 3.18–2.28 (6 H, m), 2.28–1.02 (24 H, m), 0.98 (6 H, d); exact mass calcd (M^+) 204.27, found 204.2.

2,6,9β-Trimethyltricyclo[6.3.0.0^{4,8}]undec-2-ene-6-carboxaldehyde (38b). Potassium hydride (120 mg, 24% wt dispersion in oil, 0.75 mmol) was placed in a 25-mL, three-necked flask equipped with a magnetic pellet, dry N_2 inlet, and septum. The mineral oil was twice washed with dry petroleum ether and the residue suspended in 2 mL of dry THF. A solution of aldehyde **38a** (100 mg, 0.49 mmol) in 2 mL of dry THF was added dropwise at −5 °C. After 2 min the reaction was quenched with MeI (0.1 mL, freshly distilled over $CaCl_2$) and further stirred for 4 h at 5–10 °C. The reaction mixture was diluted with water and extracted with ether (3 × 10 mL). The ethereal extract was washed and dried, and removal of solvent gave crude C_{15}-aldehyde **38b**, 100 mg. Filtration through a silica gel (10 g) column with 50% benzene–petroleum ether furnished the C_{15}-aldehyde **38b** (mixture of aldehyde epimers): 67 mg (63%); IR (neat) ν_{max} 3030, 2950, 2700, 1720 cm^{-1}; ^1H NMR (100 MHz, $CDCl_3$) δ 9.41 (2 H, br s), 5.21 (1 H, br s), 4.96 (1 H, br s), 2.8–2.2 (4 H, m), 2.2–1.25 (24 H, m), 1.05 (6 H, s), 0.88 (6 H, d); exact mass calcd (M^+) 218.29, found 218.3.

(±)-Pentalenene (6). A mixture of C_{15}-aldehyde **38b** (40 mg, 0.18 mmol), 1.5 mL of ethylene glycol, 6 mL of diethylene glycol, and hydrazine hydrate (20 mg, 99%, 0.4 mmol) was heated to 180 °C for 1.5 h. After the mixture cooled to 70 °C, sodium (10 mg, 0.45 mmol) in 1 mL of diethylene glycol was added and the reaction mixture was heated under reflux for 4 h. The reaction mixture was poured into ice-cold water and extracted with pentane (4 × 10 mL). The pentane layer was washed and dried. The residue obtained after removal of solvent was filtered through a silica gel (5 g) column. Elution with pentane furnished pentalenene (**6**): 13 mg (33%); IR (neat) ν_{max} 3040, 2950, 1640, 1460, 1380 cm^{-1}; ^1H NMR (270 MHz, $CDCl_3$) δ 5.14 (1 H, br s), 2.65 (1 H, m), 2.53 (1 H, d), 2.0–1.1 (9 H, series of m), 1.62 (3 H, m), 0.98 (6 H, s), 0.89 (3 H, d, J = 7 Hz); ^{13}C NMR (25.0 MHz, $CDCl_3$) δ 140.6, 129.6, 64.8, 62.1, 59.4, 49.0, 46.9, 44.7, 40.6, 33.6, 30.0, 29.2, 27.7, 17.1, 15.5. The ^1H and ^{13}C spectra were found identical with the authentic spectra provided by Profs. Paquette and Pattenden.

2α,6-Dimethylbicyclo[6.3.0]undeca-1(11),5-dien-10-one (36). Sodium hydride (600 mg as 50% dispersion in oil, 12.4 mmol) was placed in a 100-mL, three-necked flask equipped with a magnetic pellet, dry N_2 inlet, condenser with mercury seal, and septum. The mineral oil was twice washed with dry petroleum ether, and the residue was suspended in 20 mL of dry THF. A solution of trans-diketone **33** (1.0 g, 4.8 mmol) in 10 mL of dry THF was added dropwise. The resulting light-yellow solution was heated for 30 min at 70 °C after which it was quenched with 5% HCl and extracted with ether (4 × 25 mL). The ethereal solution

was washed and dried and the solvent removed to give 1.0 g of a crude 4:1 mixture of **36** and **35** which was obtained in 70% yield. This mixture was charged on a silica gel (20 g) column. Elution with 10% ethyl acetate-petroleum ether furnished the major enone **36**, 460 mg, bp 130 °C/0.2 torr, identical with the sample obtained in the previous experiment. Further elution of the column gave the minor enone **35**, 116 mg, bp 130 °C/0.2 torr, identical with the sample obtained in the previous experiment.

2,9α-Dimethyltricyclo[6.3.0.0^{4,8}]undec-2-en-6-one (39). To a solution of the enone **36** (350 mg, 2.0 mmol) in 4 mL of 85% formic acid, BF_3-etherate (0.2 mL) was added and the solution was heated for 2 h at 90 °C. The reaction mixture was cooled, slowly poured into ice-cold water, and extracted with ether (3 × 20 mL). The ethereal solution was washed with 5% $NaHCO_3$ and dried, and the solvent was removed to give 350 mg of oily residue which was charged on a silica gel (10 g) column. Elution with 2% ethyl acetate-petroleum ether furnished the tricyclic ketone **39**, 192 mg (55%), which distilled at 120 °C/0.3 torr: IR (neat) ν_{max} 3030, 2950, 1740, 920, 730 cm^{-1}; ^{1}H NMR (100 MHz, $CDCl_3$) δ 5.16 (1 H, br s), 3.32-2.96 (1 H, m), 2.9-1.12 (10 H, m), 1.68 (3 H, br s), 1.0 (3 H, d, J = 7 Hz). Anal. Calcd for $C_{13}H_{18}O$: C, 82.06; H, 9.54. Found: C, 82.01; H, 9.62.

2,9α-Dimethyltricyclo[6.3.0.0^{4,8}]undec-2-ene-6-carboxaldehyde (40a). Into a 50-mL, three-necked, round-bottomed flask fitted with a dry N_2 inlet, septum, reflux condenser, and mercury seal was placed (methoxymethyl)triphenylphosphonium chloride (2 g, 6 mmol). The solid was suspended in 15 mL of dry ether, and freshly sublimed sodium *tert*-amyl oxide (430 mg, 3.9 mmol) in 5 mL of dry ether was added. The dark-red reaction mixture was stirred for 45 min at room temperature, to this the tricyclic ketone **39** (250 mg, 1.3 mmol) in 5 mL of dry ether was introduced, and reactants were stirred for 1 h. The reaction mixture was quenched with water and extracted with ether (4 × 20 mL). The ethereal layer was washed and dried, and the solvent was removed. The crude reaction mixture was used as such for the next step.

The crude reaction mixture obtained above was dissolved in 10 mL of ether, and to this 8-10 drops of 35% perchloric acid (ice bath) were added. The reaction mixture was stirred for 18 h at room temperature, diluted with ether, and quenched with 5% $NaHCO_3$. The ethereal layer was washed and dried. The residue obtained after removal of the solvent was filtered through a silica gel (10 g) column. Elution with petroleum ether resulted in the removal of triphenylphosphine-derived impurities, and further elution with 25% benzene-petroleum ether furnished the aldehyde **40a** (mixture of aldehyde epimers): 208 mg (80%); IR (neat) ν_{max} 3030, 2950, 2700, 1720, 1440 cm^{-1}; ^{1}H NMR (100 MHz, $CDCl_3$) δ 9.53 (1 H, br s), 4.98 (1 H, br s), 3.3-1.2 (12 H, series of m), 1.53 (3 H, m), 0.93 (3 H, d): exact mass calcd (M^+) 204.27, found 204.0.

2,6,9α-Trimethyltricyclo[6.3.0.0^{4,8}]undec-2-ene-6-carboxaldehyde (40b). Potassium hydride (140 mg, 24% wt dispersion in oil, 0.87 mmol) was placed in a 25-mL, three-necked flask equipped with a magnetic pellet, dry N_2 inlet, and septum. The mineral oil was twice washed with dry petroleum ether and the residue suspended in 2 mL of dry THF. A solution of aldehyde **40a** (120 mg, 0.58 mmol) in 2 mL of dry THF was added dropwise at -5 °C. After 2 min the reaction was quenched with MeI (0.1 mL, freshly distilled over $CaCl_2$) and further stirred for 4 h at 5-10 °C. The reaction mixture was diluted with water and extracted with ether (3 × 10 mL). The ethereal extract was washed and dried, and removal of solvent gave crude cis-aldehyde **40b**, 133 mg. Filtration through a silica gel (10 g) column, with 50% benzene-petroleum ether furnished the C_{15}-aldehyde **40b** (mixture of aldehyde epimers): 79 mg (63%); IR (neat) ν_{max} 3030, 2950, 2700, 1720 cm^{-1}; ^{1}H NMR (100 MHz, $CDCl_3$) δ 9.51 (2 H, br s), 4.96 (2 H, br s), 3.13-1.25 (28 H, series of m), 1.0-0.9 (12 H, m); exact mass calcd (M^+) 218.29, found 218.0.

(±)-*epi*-Pentalenene (10). A mixture of C_{15}-aldehyde **40b** (36 mg, 0.16 mmol), 1.5 mL of ethylene glycol, 6 mL of diethylene glycol, and hydrazine hydrate (20 mg, 99%, 0.4 mmol) was heated to 180 °C for 1.5 h. After the mixture cooled to 70 °C, sodium (10 mg, 0.45 mmol) in 1 mL of diethylene glycol was added, and the reaction mixture was heated under reflux for 4 h. The reaction mixture was poured into ice-cold water and extracted with pentane (4 × 10 mL). The pentane layer was washed and dried. The residue obtained after removal of solvent was filtered through a silica gel (5 g) column. Elution with pentane furnished *epi*-pentalenene (**10**): 12 mg (33%); ^{1}H NMR (100 MHz, $CDCl_3$) δ 5.14 (1 H, br s), 2.86 (1 H, m), 2.58 (1 H, m), 1.6 (3 H, m), 1.73-0.86 (18 H, series of m); ^{13}C NMR (25.0 MHz, $CDCl_3$) δ 140.6, 131.3, 63.4, 54.7, 50.5, 46.1, 45.0, 39.6, 32.9, 31.4, 28.5, 29.2, 15.3, 13.5. This was found identical with the comparison spectra provided by Prof. Paquette.

Acknowledgment. K.S.R. gratefully acknowledges receipt of a fellowship from CSIR, New Delhi, India. We thank the UGC for a special assistance program in Organic Chemistry and for COSIST support. We also thank Prof. L. A. Paquette, Ohio State University, and Prof. G. Pattenden, University of Nottingham, for providing the ^{1}H NMR spectra of pentalenene and *epi*-pentalenene.

Registry No. (±)-**6**, 82442-49-7; (±)-**10**, 82398-57-0; (±)-**11a**, 104762-08-5; (±)-**11b**, 104762-13-2; (±)-**16**, 104762-06-3; (±)-**17**, 104762-07-4; **18**, 637-90-1; (±)-**19**, 104762-11-0; **19**-ol, 104762-10-9; (±)-**20**, 104762-12-1; (±)-**21**, 104762-14-3; **22**, 92590-08-4; (±)-**23**, 104833-04-7; **23**-ol, 104762-09-6; (±)-**27** (isomer 1), 104762-15-4; (±)-**27** (isomer 2), 104833-05-8; **28**-ol, 104762-16-5; **28**, 104762-17-6; (±)-**30**, 104762-18-7; (±)-**31**, 104762-19-8; (±)-**32**, 101366-64-7; (±)-**33**, 101366-65-8; (±)-**34**, 101366-66-9; (±)-**35**, 101366-67-0; (±)-**36**, 101366-68-1; (±)-**37**, 101383-50-0; (±)-**37** (methoxymethylene derivative), 104762-20-1; (±)-**38a** (isomer 1), 104833-06-9; (±)-**38a** (isomer 2), 104833-07-0; (±)-**38b** (isomer 1), 104833-08-1; (±)-**38b** (isomer 2), 104833-09-2; (±)-**39**, 104833-10-5; (±)-**39** (methoxymethylene derivative), 104833-11-6; (±)-**40a** (isomer 1), 104833-12-7; (±)-**40a** (isomer 2), 104833-13-8; (±)-**40b** (isomer 1), 104833-14-9; (±)-**40b** (isomer 2), 104833-15-0; 1,5-dimethyl-1,5-cyclooctadiene, 3760-14-3; allyl lithium, 3052-45-7.

The Triplex Diels-Alder Reaction of Indene and Cyclic Dienes

Glenn C. Calhoun and Gary B. Schuster*

Contribution from the Department of Chemistry, Roger Adams Laboratory, University of Illinois, Urbana, Illinois 61801-3731. *Received June 30, 1986*

Abstract: Irradiation of 1,4-dicyanonaphthalene or 9,10-dicyanoanthracene in benzene solution containing indene and a cyclic 1,3-diene leads to isolation of Diels-Alder adducts in several cases. The mechanism of this reaction is proposed to proceed through formation of an intermediate exciplex of the dicyanoarene and indene. The exciplex combines with the diene to form a ternary complex (triplex) that leads eventually to the isolated cycloaddition products. This triplex reaction is compared with the recently popular radical cation and the well-known Lewis acid catalyzed Diels-Alder reactions.

The Diels-Alder reaction is one of the most important methods available for creation of carbon-carbon bonds and the formation of six-membered rings.[1] In the most favorable circumstances, when the diene and dienophile have strongly opposite electronic character, the reaction proceeds under mild conditions in excellent yield. In contrast, the Diels-Alder reaction of partners with similar electronic character often requires forcing conditions (high temperature or pressure) and usually results in only a poor to fair yield of the desired product. Recognition of this difficulty has led to the popularization of catalysis by Lewis acids in suitable cases[2] and to several attempts to find new ways to accelerate normally sluggish reactions.

(1) Brieger, G.; Bennet, J. N. *Chem. Rev.* **1980**, *80*, 63.

(2) (a) Yates, P.; Eaton, P. *J. Am. Chem. Soc.* **1960**, *82*, 4436. (b) Sauer, J. *Angew. Chem., Int. Ed. Engl.* **1967**, *6*, 16.

0002-7863/86/1508-8021$01.50/0