An Expedient Synthesis of 1,16-Dimethyldodecahedrane

Leo A. Paquette* and Douglas W. Balogh[1]

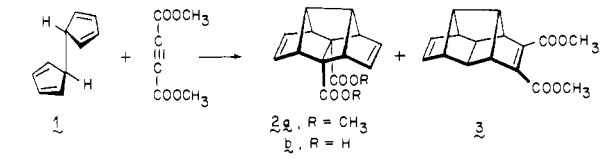
Contribution from the Evans Chemical Laboratories, The Ohio State University, Columbus, Ohio 43210. *Received May 11, 1981*

Abstract: 9,10-Dihydrofulvalene, prepared by the oxidative coupling of sodium cyclopentadienide with iodine, was subjected to domino Diels-Alder reaction with dimethyl acetylenedicarboxylate. The resulting C_{2v} symmetric diester (**2a**) was transformed to the C_2 symmetric diketo diester **5** by two routes. Condensation of **5** with cyclopropyldiphenylsulfonium ylide, Baeyer-Villiger ring expansion, acid-catalyzed rearrangement, and catalytic hydrogenation yielded diketo diester **12** which already carries ten cis-locked methine hydrogens. Sequential sodium borohydride reduction and ring opening with anhydrous HCl in methanol delivered dichloro diester **17**, whose dissolving metal reduction and subsequent dimethylation afforded keto ester **28**. This key intermediate was then transformed to triseco diester **32b** in a three-step sequence consisting of excited-state homo-Norrish cyclization, dehydration, and diimide reduction. The carbomethoxy group in **32b** was converted to an aldehydo function, and this aldehyde (**38**) was subjected to the same triad of steps. While the resulting monosecododecahedrane (**42**) could not be induced to eliminate molecular hydrogen, its alcohol (**40**) and olefin (**41**) precursors were readily cyclized to 1,16-dimethyldodecahedrane (**43**) under strongly acidic conditions. The possible significance of the Wagner-Meerwein methyl shift which operates is discussed. Those chemical and physical properties of **43** which are presently known are described.

Dodecahedrane! Little did Plato realize in 400-350 B.C. when he composed his *Timaeus* that the most complex of the five regular polyhedra described therein was to evolve as a major synthetic challenge of organic chemistry late in the twentieth century. So enthralled were the ancient Greeks by the mathematical elegance of this elaborate convex polyhedron that they sought to equate it in their mind's eye with the sphere of the universe. The chemist's fascination with this $(CH)_{20}$ hydrocarbon arises from its spherical superpolycyclopentanoid topology[2] which comprises the highest known point group symmetry (I_h, icosahedral), its unique encapsulation of a cavity incapable of solvation, its negligible angle strain but unparalleled high torsional strain,[3] the spectral consequences of its 20 symmetry-equivalent methine units, the existing absence of structurally allied substances, and much more.[4] Actually, the physical and chemical properties (e.g., melting point, volatility, low viscosity, etc.) of dodecahedrane have been shrouded in a sort of mystique which, although addressed to some degree from the theoretical vantage point,[3,5-8] necessarily awaited the successful synthesis of the hydrocarbon, or a simple derivative thereof, for ultimate clarification.

From the first, we considered the existing armamentarium of synthetic methodology adequately equipped for an attack on so formidable a target objective. The difficulty of the challenge was clearly apparent from the limited progress achieved on the attainment of this elusive hydrocarbon since Woodward's[9] and Jacobson's[10] first reference to a triquinacene coupling strategy in the 1960s.[11] Among the more notable accomplishments during the intervening period can be cited the successful preparation of peristylane,[12] *dl*-bivalvane,[13] C_{16}-hexaquinacene,[14] and a (C_2)-dioxatrisecododecahedrane.[15] To us, the lure of Plato's hydrocarbon took on an added sense of fascination with the advent of ^{13}C NMR spectroscopy. Through proper use of this magnificent new tool, the opportunity was provided for advantage to be taken of dodecahedrane's symmetry through deployment of a synthetic scheme mediated, where feasible, by intermediates endowed with a plane or axis of symmetry. In this fashion, we had visions of expediting our synthesis to an extent that would deliver the C_{20} nucleus in a sequence of steps not exceeding in number the sum of the framework carbon atoms. This self-imposed goal has satisfyingly been realized,[16] and the full details of our remarkably short 19-step synthesis of 1,16-dimethyldodecahedrane are herein presented.

Scheme I

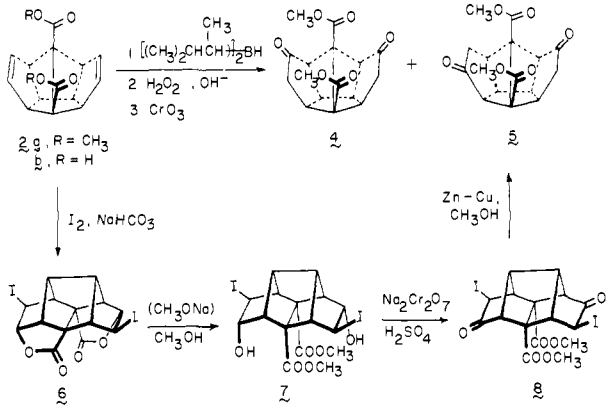


Highly pertinent to any projected synthesis of pentagonal dodecahedranes is a detailed concern for the efficient control of stereochemistry at every stage of development. Thus, the spherical contour of the ring system requires that installation of every methine carbon be accomplished in contrathermodynamic fashion, i.e., with the much smaller hydrogen atom oriented outward to the exterior and the larger functional group projected within the interior of the sphere. As imposing as this may appear at first glance, we viewed this feature as a potential asset at the later stages of molecular development, where reagent approach from the

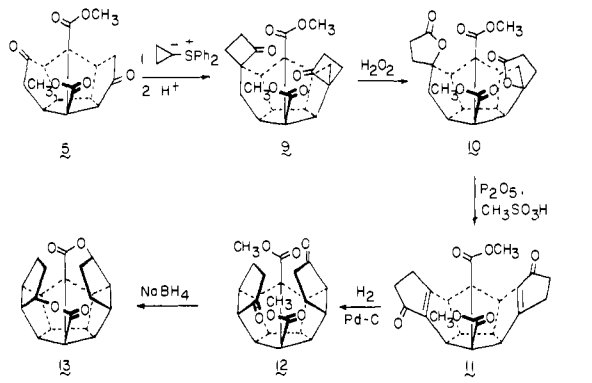
(1) Presidential Fellow, The Ohio State University, 1979-1980.
(2) Mehta, G. *J. Sci. Ind. Res.* **1978**, *37*, 256.
(3) Ermer, O. *Angew. Chem., Int. Ed. Engl.* **1977**, *16*, 411.
(4) The possibility that dodecahedrane deserves to be viewed as a diterpene hypothetically derivable by proper biogenetic-like fusion of four isoprene units has also been considered: St. Pyrek, J. *Pol. J. Chem.* **1979**, *53*, 1557.
(5) Schultz, H. P. *J. Org. Chem.* **1965**, *30*, 1361.
(6) Engler, E. M.; Andose, J. D.; Schleyer, P. von R. *J. Am. Chem. Soc.* **1973**, *95*, 8005.
(7) (a) Schulman, J. M.; Venanzi, T.; Disch, R. L. *J. Am. Chem. Soc.* **1975**, *97*, 5335. (b) Schulman, J. M.; Disch, R. L. *Ibid.* **1978**, *100*, 5677.
(8) (a) Clark, T.; Knox, T. McO.; Mackle, H.; McKervey, M. A. *J. Chem. Soc., Chem. Commun.* **1975**, 666. (b) Clark, T.; Knox, T. McO.; McKervey, M. A.; Mackle, H.; Rooney, J. J. *J. Am. Chem. Soc.* **1979**, *101*, 2404.
(9) (a) Woodward, R. B.; Fukunaga, T.; Kelly, R. C. *J. Am. Chem. Soc.* **1964**, *86*, 3162. (b) Repic, O. Ph.D. Dissertation, Harvard University, 1976.
(10) Jacobson, I. T. *Acta Chem. Scand.* **1967**, *21*, 2235.
(11) Eaton, P. E. *Tetrahedron* **1979**, *35*, 2189.
(12) (a) Eaton, P. E.; Mueller, R. H. *J. Am. Chem. Soc.* **1972**, *94*, 1014. (b) Eaton, P. E.; Mueller, R. H.; Carlson, G. R.; Cullison, D. A.; Cooper, G. F.; Chou, T.-C.; Krebs, E.-P. *Ibid.* **1977**, *99*, 2751. (c) Eaton, P. E.; Andrews, G. D.; Krebs, E.-P.; Kunai, A. *J. Org. Chem.* **1979**, *44*, 2824.
(13) (a) Paquette, L. A.; Farnham, W. B.; Ley, S. V. *J. Am. Chem. Soc.* **1975**, *97*, 7273. (b) Paquette, L. A.; Itoh, I.; Farnham, W. B. *Ibid.* **1975**, *97*, 7280. (c) Paquette, L. A.; Itoh, I.; Lipkowitz, K. *J. Org. Chem.* **1976**, *41*, 3524. (d) Clardy, J.; Solheim, B. A.; Springer, J. P.; Itoh, I.; Paquette, L. A. *J. Chem. Soc. Perkin Trans. 2* **1979**, 296.
(14) (a) Paquette, L. A.; Snow, R. A.; Muthard, J. L.; Cynkowski, T. *J. Am. Chem. Soc.* **1978**, *100*, 1600. (b) *Ibid.* **1979**, *101*, 6991.
(15) (a) Balogh, D.; Begley, W. J.; Bremner, D.; Wyvratt, M. J.; Paquette, L. A. *J. Am. Chem. Soc.* **1979**, *101*, 749. (b) Paquette, L. A.; Begley, W. J.; Balogh, D.; Wyvratt, M. J.; Bremner. D *J. Org. Chem.* **1979**, *44*, 3630. (c) Paquette, L. A.; Balogh, D.; Engel, P. *Heterocycles* **1981**, 271.
(16) A preliminary communication describing some of our findings has appeared: Paquette, L. A.; Balogh, D. W.; Usha, R.; Kountz, D.; Christoph, G. G. *Science (Washington, D.C.)* **1981**, *211*, 575.

0002-7863/82/1504-0774$01.25/0

Scheme II



Scheme III



convex surface could be essentially guaranteed because of prevailing steric conditions. Our immediate objective, then, was to juxtapose as many cis-locked methine groups as possible, while simultaneously accommodating our earlier considerations of symmetry, so as to set the stage for later transformations of this type.

The domino Diels–Alder reaction of 9,10-dihydrofulvalene (**1**),[17] prepared by the coupling of sodium cyclopentadienide with iodine,[17a] with dimethyl acetylenedicarboxylate[18,19] served our needs admirably. Not only was the desired adduct readily separated from unwanted isomer **3**, but also it could be obtained directly either as the diester (**2a**) or the diacid (**2b**) depending upon workup conditions (Scheme I).[20] Although the isolated yields of these materials ranged only from 10 to 15%, it will be noted that their structure already contains four of the requisite cyclopentane rings and *six* cis-locked methine hydrogens, as well as pairs of felicitiously placed carboxyl groups and double bonds which are interrelated on the basis of the intrinsic C_{2v} symmetry and well positioned for the contemplated introduction of additional carbon atoms. In point of fact, **2a**, whose role it was to serve as the cornerstone of the dodecahedrane, had become available in a single laboratory operation.

Although the added central bond within **2** can readily be cleaved at this stage as a consequence of its positional relationship to the two carbonyl groups,[20] the decision was made to retain this linkage until a later time, in order to take advantage of the norbornenyl character that it provides to the two halves of the molecule, thereby guaranteeing excellent stereochemical control in certain ensuing steps. Consequently, we had now to face the prospect of reducing the symmetry level within **2** in a controlled manner such that a simple C_2 molecular axis would exist in the intermediates to follow. More specifically, the task we set for ourselves was to transform **2** into diketo diester **5**. Two protocols were developed (Scheme II). The first consisted in the reaction of **2a** with disiamylborane followed by sequential alkaline peroxide and Jones oxidation. This simply executed procedure gave rise to the anticipated two products (**4** and **5**). Although the unwanted C_s isomer was invariably produced in higher proportion (49%) relative to **5** (30% isolated), their separation could be achieved chromatographically. Alternatively, **5** could be produced in isomerically pure form and highly efficient fashion (80% overall yield) by iodolactonization of **2b**, cleavage of **6** to the iodohydrin **7** with sodium methoxide in methanol at room temperature, Jones oxidation to deliver **8**, and reductive removal of the iodine atoms with zinc–copper couple and ammonium chloride in methanol solution.[21,22] Satisfyingly, this four-step sequence proved particularly amenable to scale-up without loss of efficiency.

A relatively simple, although expensive method for homologating **5** involved exposure to 5 molar equiv of Trost's diphenylcyclopropylsulfonium ylide. Coupling this modification to an acid workup procedure in order to isomerize the initially formed oxaspiropentanes afforded bis(spirocyclobutanone) **9** in 77% yield (Scheme III).[22] At this point, let us recognize explicitly the fact that this transformation achieves the twofold addition of three carbon atoms to a preexisting C_{14} framework (the hydrolyzable methyl ester groups are discounted) and consequently delivers an axially symmetric product having a carbon content already equal to that of the target nucleus. Moreover, this diketo diester has been made available in either four or six steps, depending upon the pathway selected. In principle, therefore, no additional carbon atoms need be introduced and the further chemical modification of **9** is limited to the construction of new five-membered rings through suitable deployment of the existing framework.

Next, the bis(spirocyclobutanone) **9** was converted quantitatively into dilactone diester **10** by the action of hydrogen peroxide. The expectation that the spirocyclic functionality within **10** could be transposed into laterally fused cyclopentenone rings as in **11** was met without incident (83%). As an important practical point, it may be noted that our arrival at **11** now set the stage for proper positioning, on the exterior of the developing sphere, of four additional methine hydrogens by means of catalytic hydrogenation. Further, the attack of sodium borohydride on **12**, while sterically impeded from the concave direction, can deliver hydride from the convex surface without constraint and lead ultimately through additional cyclization to the "closed" dilactone **13**.[22] Not only does **13** possess 12 of the necessary 20 stereochemical centers, but also its topology was expected to relegate all reagents used hereafter to convex approach. Clearly, our strategem had so far proceeded very directly toward our objective.

Now we were to embark on various synthetic excursions, the outcome of which necessitated major tactical changes in our original plans. The attractiveness of **13** as a valuable intermediate stems from its C_2 symmetry, low level of functionality, and particularly the 1,4-relationship of its two carbonyl groups which are seen to be geometrically oriented with stereoelectronic features quite suitable for reductive cleavage of the internal bond. In actuality, the reductive cleavage of **13** to **14a** was easily brought about.[22] Disappointingly, however, **14a** proved to be so highly susceptible to symmetry-destroying transannular cyclization under both alkaline and acidic conditions that work with this "open" dilactone ultimately had to be abandoned.

For the above reasons, we were led to block the enolizable centers in **14a** and it was found to be a simple matter to exhaustively methylate the dianion of **14a**, prepared by sodium–liquid ammonia reduction of **13**.[21,22] It will be easily imagined that the ^{1}H NMR spectra of our molecules are characterized by enor-

(17) (a) Doering, W. von E. In "Theoretical Organic Chemistry-The Kekule Symposium"; Butterworth: London, 1959; p 45. Matzner, E. A. Ph.D. Thesis, Yale University, 1958. (b) Hedaya, E.; McNeil, D. W.; Schissel, P.; McAdoo, D. J. *J. Am. Chem. Soc.* **1968**, *90*, 5284. (c) Shen, K. *Ibid.* **1971**, *93*, 3064.

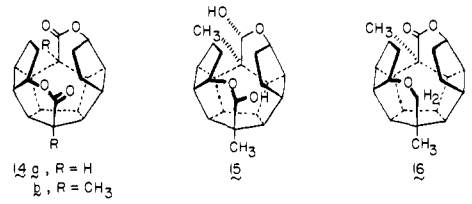
(18) McNeil, D.; Vogt, B. R.; Sudol, J. J.; Theodoropulos, S.; Hedaya, E. *J. Am. Chem. Soc.* **1974**, *96*, 4673.

(19) Paquette, L. A.; Wyvratt, M. J. *J. Am. Chem. Soc.* **1974**, *96*, 4671.

(20) Paquette, L. A.; Wyvratt, M. J.; Berk, H. C.; Moerck, R. E. *J. Am. Chem. Soc.* **1978**, *100*, 5845.

(21) Paquette, L. A.; Wyvratt, M. J.; Schallner, O.; Schneider, D. F.; Begley, W. J.; Blankenship, R. M. *J. Am. Chem. Soc.* **1976**, *98*, 6744.

(22) Paquette, L. A.; Wyvratt, M. J.; Schallner, O.; Muthard, J. L.; Begley, W. J.; Blankenship, R. M.; Balogh, D. *J. Org. Chem.* **1979**, *44*, 3616.



14 a, R = H
b, R = CH3

15 16

mously complex upfield regions. However, the singlet absorption due to the pair of methyl groups in **14b** stands out as a beacon signalling the C_2 symmetric nature of the molecule. Because this phenomenon subsequently allowed us to perform many diagnostic experiments on a few milligrams, this substitution pattern was gainfully deployed in the ensuing investigation.

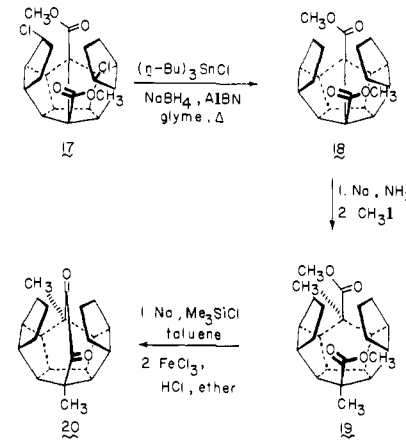
The dialkylation just described now permitted direct chemical manipulation of the lactone rings. In planning our program, we had supposed that we might be able to take advantage of an intramolecular Prins reaction sequence if and when the proper diene dialdehyde came to hand. Toward this end, **15b** was reduced to dilactol **15** (isolated as the thermodynamically more stable isomer illustrated) and the potential of this substance for twofold dehydration with ring opening was examined.[23] Our standing concern for transannular reactions within this series was justified in that all experiments directed toward the dehydration of **15** uniformly resulted in smooth conversion to **16**.[23] All attempts to modify conditions had the invariant result of driving the system inexorably to this unsymmetrical product of intramolecular oxidation–reduction. Regrettably, no transformations involving **15** and its derivatives, interesting as they might be in themselves, led in the desired direction.

Unquestionably, success in the construction of additional peripheral bonds was attendant upon new approaches which would effectively bypass the use of carbocation intermediates or, for that matter, the deployment of any reaction whose transition state is characterized by rather stringent geometry demands, e.g., S_N2 displacement. Various experimental designs had revealed unequivocally that such hemispherical molecules as are described here are generally not adequately flexible to allow for intramolecular trajectories of this sort.[24]

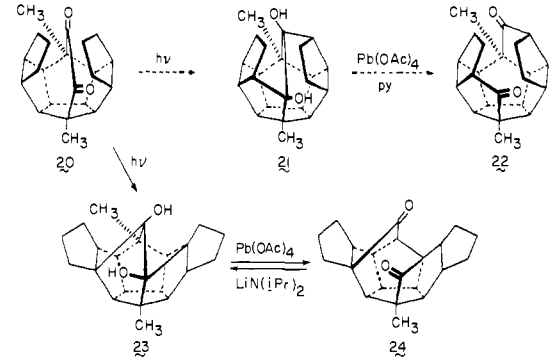
We therefore made the decision to examine the feasibility of excited-state homo-Norrish δ-hydrogen transfer[25] as a means of achieving proper carbon–carbon bond formation. Since such processes are mediated by biradical intermediates and their coupling is dependent chiefly upon proximity factors, we anticipated that our earlier difficulties might be duly resolved in this fashion.

Ester carbonyl groups are rarely photoactive and **5**, **12**, **13**, and **14** proved not to provide exceptions to this general rule. The task before us, then, was to transform **13** into a suitably photoreactive ketonic species, preferably by means of an appropriate intramolecular reductive coupling scheme. In considering those means available for cleavage of the oxygenated rings in the "closed" dilactone, one must give proper recognition to the fact that chemistry does not, of course, occur simultaneously at both carbonyl groups. Following attack at the first ester linkage, a ring vital to retention of spherical topology is ruptured and the molecule immediately flexes to minimize the many nonbonded interactions of its methylene hydrogens. This drastic modification of conformation so ameliorates the chemical reactivity of the second lactone carbonyl that it becomes generally unresponsive to

Scheme IV



Scheme V



chemical agents.[22] Consequently, it was a great advance when we discovered that hydrogen chloride in methanol behaves anomalously and transforms **13** to dichloro diester **17** in 62% yield at room temperature.[22] It will be noted that a minimum of nine steps is required to gain access to this pivotal molecule.

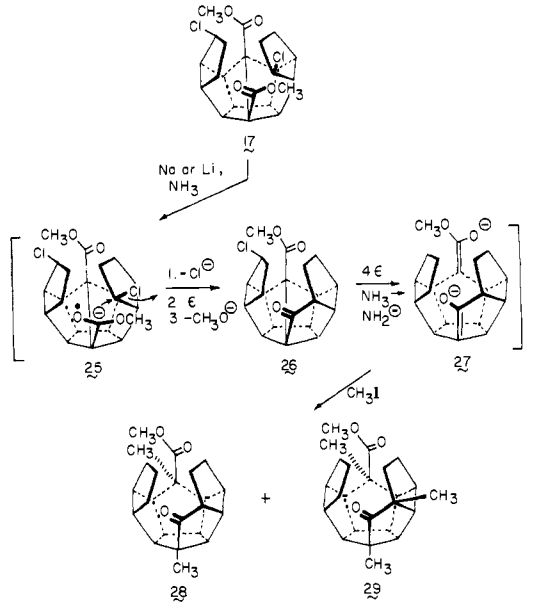
On treatment with tri-*n*-butyltin hydride, **17** was directly convertible to **18** which was reductively methylated to give **19** in the usual way (Scheme IV). The latter underwent sequential acyloin condensation and ferric chloride oxidation with exceptional ease.[26] Once the beautifully crystalline yellow ketone **20** had been obtained, we were in a position to test our expectation that its response to ultraviolet irradiation would be to form caged diol **21** (Scheme V). Although **21** does contain an interconnective σ bond improperly predisposed for our purposes, this diol should be particularly responsive to the action of lead tetraacetate and undergo cleavage to the very attractive triseco diketone **22**. Proper photochemical activation of **21** did give rise to a diol whose ^{13}C and ^{1}H NMR spectra revealed that twofold axial symmetry had been maintained. However, it was rapidly determined that all mechanistic precedence had been violated and that the rearranged isomer **23** had actually be produced instead.[26] Relevantly, all of the steps necessary to go from **20** to **23** are entirely unlikely, with the exception of the initial hydrogen abstraction. The unusual pathway which does materialize operates as the direct result of the prevailing steric congestion which is sufficiently extreme to force radical rearrangements to gain kinetic prominence. These same structural features are believed to underlie the extraordinary ease with which diketone **24** experiences unprecedented intramolecular pinacolization in the presence of a slight excess of lithium diisopropylamide.[26]

Although the aforementioned complications could not be surmounted, our quest for 1,16-dimethyldodecahedrane was, in fact, to be significantly advanced through the implementation of photochemistry. Our concern that the additional "staging" bond

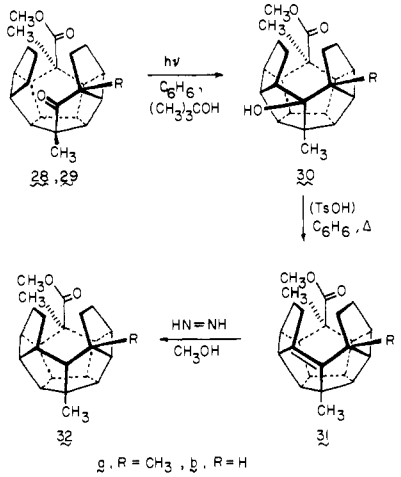
(23) Balogh, D. W.; Paquette, L. A. *J. Org. Chem.* **1980**, *45*, 3038.
(24) (a) Hales, N. J.; Paquette, L. A. *J. Org. Chem.* **1979**, *44*, 4603. (b) Sobczak, R. L.; Osborn, M. E.; Paquette, L. A. *Ibid.* **1979**, *44*, 4886. (c) Osborn, M. E.; Kuroda, S.; Muthard, J. L.; Kramer, J. D.; Engel, P.; Paquette, L. A. *Ibid.* **1981**, *46*, 3379.
(25) (a) Wagner, P. J.; Kemppainen, A. E. *J. Am. Chem. Soc.* **1972**, *94*, 7495. (b) Wagner, P. J.; Kelso, P. A.; Kemppainen, A. E.; Zepp, R. G. *Ibid.* **1972**, *94*, 7500. (c) O'Connell, F. J. *Ibid.* **1968**, *90*, 6550. (d) Yang, N. C.; Jorgenson, M. J. *Tetrahedron Lett.* **1964**, 1203. (e) Hamer, N. K. *J. Chem. Soc., Perkin Trans. 1* **1979**, 1285 and appropriate references cited in these papers. (f) Empirical calculations concerning γ- vs. δ-hydrogen abstraction have been carried out by: Previtali, C. M.; Scaianno, J. C. *J. Photochem.* **1974**, *2*, 321.

(26) Balogh, D. W.; Paquette, L. A.; Engel, P.; Blount, J. F. *J. Am. Chem. Soc.* **1981**, *103*, 226.

Scheme VI



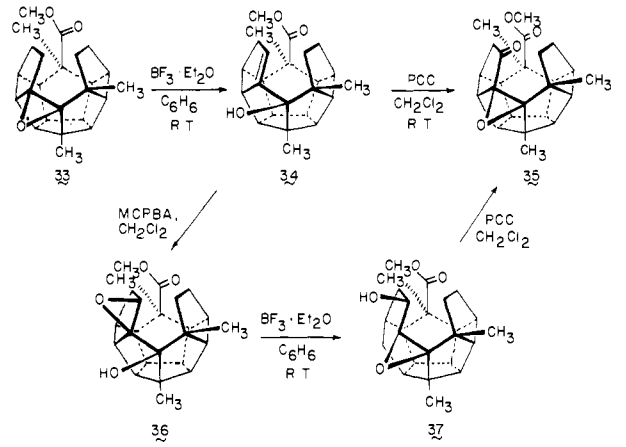
Scheme VII



in **20** may have been the principal steric impediment to appropriate homo-Norrish closure caused us to give attention to ketone candidates which lacked this complication. Much earlier, we had learned that **17** could not be enticed to undergo twofold cyclization via transient organometallic intermediates.[27] Since formation of carbanionic centers at the originally chlorinated carbon atoms in **17** led most frequently to simple reduction (formation of **18**), the alternate electronic process in which the ester functionalities are made to experience reduction first was examined.

At the mechanistic level, the dissolving metal reduction of **17** in liquid ammonia was perceived as a viable means of generating radical anion **25** via electron transfer to the most electropositive center. In our thinking, suitable stereoelecttronic overlap of the negatively charged carbon with the transannular carbonyl group was expected to be sufficiently disfavored on steric grounds to allow for intramolecular S_N2 displacement of chloride ion and formation of **26**. Continued reduction of the latter should, again on the basis of known typical half-wave potentials, involve attack at the ketone carbonyl and lead consequently to central bond cleavage. In view of the obvious inability of the resulting ester enolate to displace the second halogen via a cyclopentanoid transition state, this chlorine is ultimately subject to independent reductive cleavage. In the final analysis, a single cyclization can result from this procedure. In accordance with the preceding hypothesis, treatment of solutions generated in this manner with an excess of methyl iodide afforded mixtures of **28** and **29** in a combined yield in excess of 65% (Scheme VII).[28] Because **29** is formed

Scheme VIII



as a consequence of the alkalinity of the medium and the presence of excess alkylating agent, conditions could be controlled (chiefly by counterion effects) so as to allow **28** to predominate widely. This keto ester, obtainable in ten steps, clearly possesses many of the desirable structural features which were being sought.

The situation at this point may be summarized by depicting **28** and **29** as tetrasecododecahedranes, substances possessed of such high levels of nonbonded steric strain that our effects to coax both into additional peripheral bond formation should meet with success. Whereas the photocyclization of both keto esters proceeded without framework rearrangement to give **30a** and **30b** and these tertiary alcohols could be easily dehydrated to their olefinic counterparts **31**, labor was unsuccessfully expended in attempts to saturate these triseco intermediates by catalytic hydrogenation on a Parr apparatus. The low reactivity of these double bonds, a phenomenon encountered with each of the several molecules of this general type available to us (e.g., **41**), is interesting. It may reflect the fact that the strain inherent to the alkene fragment makes the formation constant for the M–alkene bond (on the metal surface) very high. Consequently, attaining the transition state for (H)M–‖ insertion becomes quite energy demanding, especially since a necessarily coplanar MCCH system seems difficult to arrive at. But this problem too was in the end surmounted when reduction with diimide, as generated from hydrogen peroxide and hydrazine delivered **32a** and **32b**. The X-ray crystal structure of the lesser symmetrical ester (**32a**)[28] indicated that the triseco level of development had been attained in only 13 steps.

A further point deserves special mention. Studies by Scheffer and Dzakpasu of the solid-state photochemistry of selected ketones have revealed that the distance requirement for intramolecular hydrogen abstraction by carbonyl oxygen via a six-membered transition state is ≤ca. 2.5 Å, provided that the hydrogen is less than 10° out of the carbonyl plane.[29] Furthermore, the radical recombination process generally was found to proceed without conformational isomerization at distances ≤ca. 3.5 Å. These structural guidelines are particularly well met by **28** and **29**, at least within the level of accuracy provided by Dreiding models.

It will be noticed that the opposed methylene groups in **32** are unfunctionalized. In a perhaps too brief effort to correct this situation, epoxide **33** was prepared. On exposure to boron trifluoride etherate, strikingly clean isomerization to **34** was observed. This tertiary allylic alcohol does not respond in typical fashion to chromium-based oxidants.[30] Rather than transmute into the 1,3-transposed enone, **34** gives rise to epoxy ketone **35**. While reactions of this type have seen precedent,[31] structural confirmation

(27) Wyvratt, M. J. Ph.D. Thesis, The Ohio State Univeristy, 1976.
(28) Paquette, L. A.; Balogh, D. W.; Blount, J. F. *J. Am. Chem. Soc.* **1981**, *103*, 228.
(29) Scheffer, J. R.; Dzakpasu, A. A. *J. Am. Chem. Soc.* **1978**, *100*, 2163.
(30) Dauben, W. G.; Michno, D. M. *J. Org. Chem.* **1977**, *42*, 682.

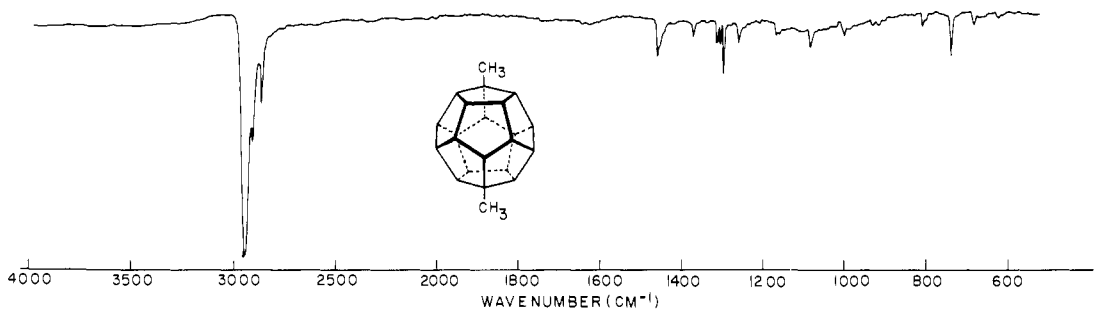
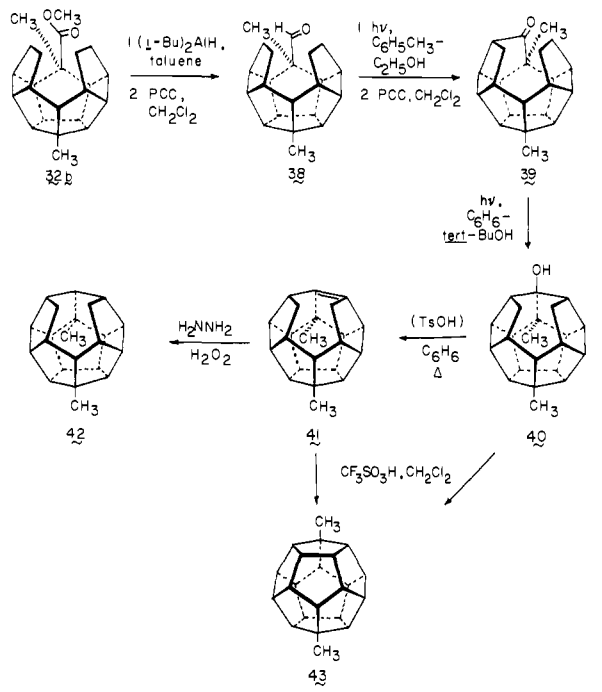


Figure 1. Infrared spectrum of **43** (KBr pellet).

was deemed necessary. To this end, **34** was epoxidized and caused to undergo an interesting and unusual epoxy alcohol–epoxy alcohol rearrangement. As usual for these molecules, the conversion of **36** to **37** is sterically driven. Whereas the three-membered ring appendage in **36** does little to alleviate the extent of nonbonded steric interactions in the gap, the pinching effect exerted by the epoxide ring in **17** serves to enlarge the open seam of the molecule. In these terms, the impetus underlying the all-frontside bond relocation[32] becomes clear. The subsequent oxidation of **37** also gave **35**. Because the carbonyl pπ orbitals in this epoxy ketone are held orthogonal to the epoxide C–O bond and rather rigidly so, stereoelectronic overlap is exceedingly poor and suitable cleavage of the linkage could not be achieved. Because of the structural distortion caused by the presence of the epoxide ring in **35**, the carbonyl oxygen is not adequately close to the transannular hydrogen and the molecule is not responsive to photoactivation.

Circumstances such as these caused us to defer consideration of this problem to a later stage of the synthesis. Consequently, the next immediate task before us was to engage the oxygenated carbon atom of **32b** into twofold cyclopentane ring formation. Because it was already obvious that the carbomethoxy group could not be enticed into chemical reaction by photochemical means, the decision was made to proceed with aldehyde **38**. The conversion of **32b** to **38** was an excellent one, but possible complications from the fact that the –CHO group was bonded to a fully substituted carbon now had to be contended with. The literature dealing with the photocyclization of aldehydes to cyclobutanols[33] leaves no doubt that these structural features are most conducive to decarbonylation. Suitable resolution of this difficulty came purely from the experimental side by taking advantage of certain observations made in the course of varying temperature and solvent. While **38** remained highly prone to carbon monoxide extrusion, a 29% yield of a "homo-Norrish" cyclopentanol could be realized by conducting the irradiation at −78 °C in deoxygenated toluene–ethanol (9:1) solution containing triethylamine (to ward off any potential development of acidity) (Scheme IX). With subsequent pyridinium chlorochromate oxidation, the desired diseco diketone **39** was obtained. Needless to say, we were delighted to find that **39** could be cyclized reproducibly in high yield and that removal of the tertiary hydroxyl group in **40** and saturation of the double bond in **49** were encouragingly simple and efficient steps.

Scheme IX



With arrival at the beautifully crystalline monosecododecahedrane **42**, a return to C_{2v} symmetry status materializes, a phenomenon reflected in the appearance of an eight line ^{13}C NMR spectrum. By every standard, the nonbonded interactions in **42** should provide a heightened level of steric congestion between the methylene groups. The manner and extent to which this compression is dissipated within the molecule can be inferred from the X-ray crystal structure analysis, details of which are presented in the ensuing paper.[34]

These very gratifying results were marred somewhat by our inability to effect the extrusion of molecular hydrogen from **42**. Because oxidative addition by various transition-metal reagents is likely relegated exclusively to the exo-C–H bonds of the two methylene groups, transannular cyclization is precluded despite a huge thermodynamic reward. It should be noted, however, that whereas **42** is an overreduced derivative of dimethyldodecahedrane, **41** is isomeric with **43**. Attempts to effect double-bond isomerization and transannular closure within **41** failed to cause any change whatsoever when a variety of protic acids were added.[35] It was found, however, that the powerful trifluoromethanesulfonic acid reagent[36] in dichloromethane solution at room temperature causes rapid (<10 min) disappearance of **41** to give presumably

(31) (a) Rosenheim, O.; King, H. *Nature (London)* **1937**, *139*, 1015. (b) Rosenheim, O.; Starling, W. W. *J. Chem. Soc.* **1937**, 377. (c) Petrow, V. A.; Starling, W. W. *Ibid.* **1940**, 60. (d) Lieberman, S.; Fukushima, D. K. *J. Am. Chem. Soc.* **1960**, *72*, 5211. (e) Glotter, E.; Greenfield, S.; Lavie, D. *J. Chem. Soc. C* **1968**, 1646 and references cited therein. (f) Glotter, E.; Rabinsohn, Y.; Ozan, Y. *J. Chem. Soc., Perkin Trans 1* **1975**, 2104. (g) Sundararaman, P.; Herz, W. *J. Org. Chem.* **1977**, *42*, 813. (h) Ellison, R. Ph.D. Dissertation, Northwestern University, 1976. (i) Shau, J.-H.; Reusch, W. *J. Org. Chem.* **1980**, *45*, 2013.

(32) The phenomenon of epoxide ring opening with retention of configuration has previously been reported: Wasserman, H. H.; Aubrey, N. E. *J. Am. Chem. Soc.* **1956**, *78*, 1726.

(33) (a) Orban, I.; Schaffner, K.; Jeger, O. *J. Am. Chem. Soc.* **1963**, *85*, 3033. (b) Schaffner, K. *Chimia* **1965**, *19*, 575. (c) Agosta, W. C.; Herron, D. K. *J. Am. Chem. Soc.* **1968**, *90*, 7025. (d) Coyle, J. D. *J. Chem. Soc. B* **1971**, 2254. (e) Lischewski, M.; Adam, G.; Serebryakov, E. P. *Tetrahedron Lett.* **1980**, 45

(34) Christoph, G. G.; Engel, P.; Usha, R.; Balogh, D. W.; Paquette, L. A., following paper in this issue.

(35) The fact that **41** is formed efficiently by heating **40** with *p*-toluenesulfonic acid in benzene provided an initial indication of the stability of this secododecahedrane to the more ordinary acidic reagents.

(36) (a) Takaishi, N.; Inamoto, Y.; Aigami, K.; Fujikura, Y.; Osawa, E.; Kawanisi, M.; Katsushima, T. *J. Org. Chem.* **1977**, *42*, 2041. (b) Inamoto, Y.; Aigami, K.; Takaishi, N.; Fujikura, Y.; Tsuchihashi, K.; Ikeda, H. *Ibid.* **1977**, *42*, 3833.

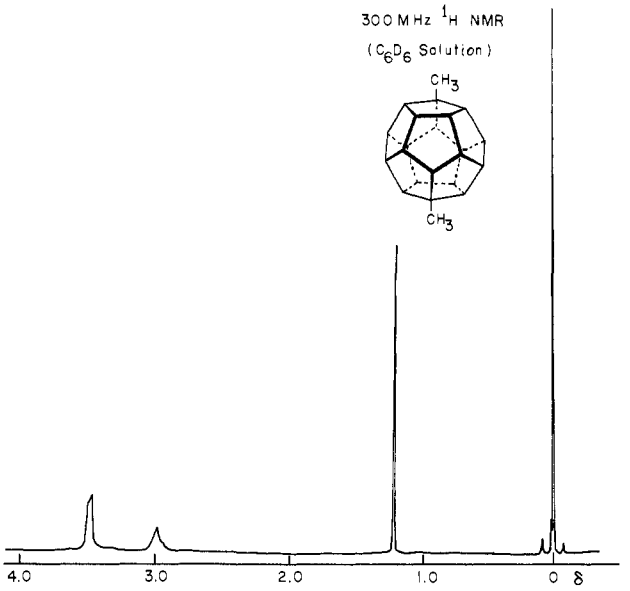


Figure 2. 300-MHz ^{1}H NMR spectrum of **43** (C_6D_6 solution).

Table I. ^{13}C NMR Chemical Shifts (δ_C) and ^{13}C–H Coupling Constants ($^1J_{CH}$) for Perhydrotriquinacene (**44**), Perhydro-C_{16}-hexaquinacene (**45**), and 1,16-Dimethyldodecahedrane (**43**)

compd	δ_C	$^1J_{CH}$, Hz	assignt
44[a]	54.84	137.0	apical (1 C)
	45.02	133.3	methine (3 C)
	31.89	127.8	methylene (6 C)
45	65.98	130.9	apical (1 C)
	54.47	131.9	methine (3 C)
	49.08	130.9	methine (6 C)
	30.25	128.5	methylene (6 C)
43	76.08		quaternary (2 C)
	74.57	131.2	methine (6 C)
	67.38	135.0	methine (12 C)
	32.82	123.9	methyl (2 C)

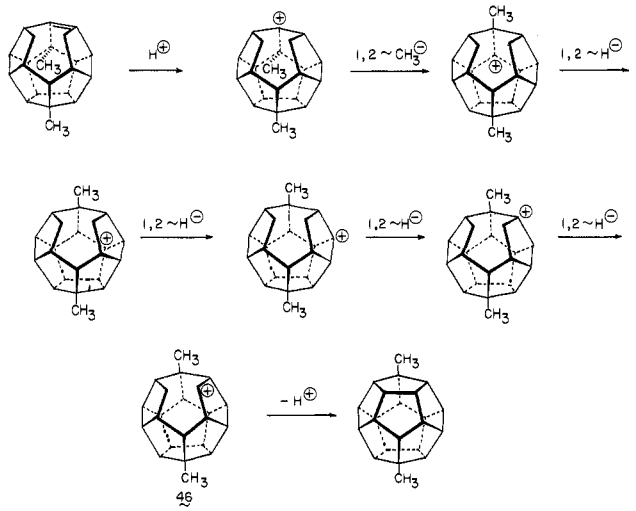
[a] Data of Professor G. R. Weisman (private communication, Sept 18, 1980).

a mixture of dimethyldodecahedranes from which the most highly symmetric isomer **43** could be crystallized in 27% yield. The same conversion materialized, although with lowered efficiency, when alcohol **40** was comparably treated.

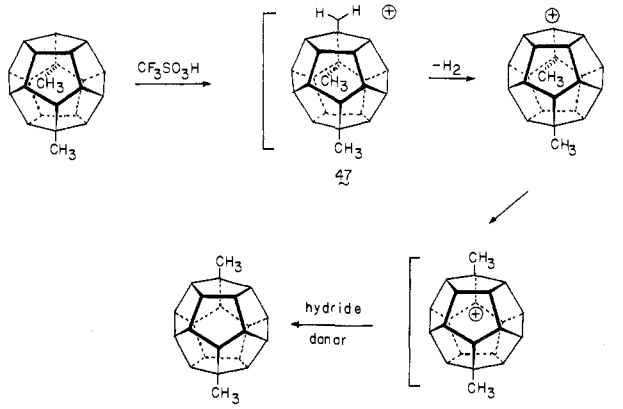
Indication that **43** had been obtained surfaced quickly. For example, a crystal contained in an evacuated sealed tube did not melt when heated as high as 420 °C.[37] This phenomenon might well derive from inherent structural rigidity which deprives the molecule of ready angle deformation and the like. The infrared spectrum (Figure 1) gives no evidence for the presence of a sight of unsaturation. The 70-eV mass spectrum shows only two intense peaks corresponding to the molecular ion (M^+) and to $M^+ - CH_3$. This unique behavior contrasts markedly with the fragmentation patterns encountered with **41** and **42**, adamantane and its derivatives,[38] diamantane,[39] and various pentacyclodecanes.[40]

Three widely separated resonances are observed in the 300-MHz ^{1}H NMR spectrum (C_6D_6 solution) at δ 3.44 (12 H), 2.93 (6 H), and 1.19 (6 H) (Figure 2). When it is recalled that the methine protons of admantane (δ 1.88),[41] diamantane (1.68),[39] and triamantane (1.82, 1.40)[42] all appear at significantly higher field,

Scheme X



Scheme XI



it is immediately apparent that C–C and C–H bond anisotropies lacking a simple alicyclic counterpart are at work. Downfield shifts approaching this magnitude for a saturated hydrocarbon have previously been encountered in the apical proton of perhydro-C_{16}-hexaquinacene[14] and more highly developed spherical polyquinane frameworks.[28] Consequently, the chemical shift of the parent dodecahedrane's single methine proton absorption can be projected with reasonable confidence to appear at δ 3.5–3.4.

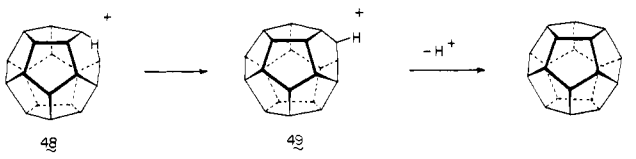
When the off-resonance decoupled ^{13}C NMR spectrum (C_6D_6 solution) was seen to consist of only four lines (Table I), it was made clearly apparent that the dodecahedrane had assumed D_{3d} symmetry and, therefore, that a 1,2-methyl shift had accompanied installation of the final bond. This conclusion was later supported by X-ray crystal structure studies.[16,34]

The precise timing of the alkyl migration remains to be established. Three reasonable possibilities present themselves. The first involves Wagner–Meerwein methyl shift prior to cyclization and requires the intervention of a host of cationic intermediates (Scheme X). Notably, all of the carbenium ions except **46** are required to be nonplanar, and their stability must be questioned in light of the known solvolytic reactivity of a 10-substituted perhydrotriquinacene[43] and the unusual stability of a structurally related tertiary perchlorate.[15b,44]

Methyl migration after the dodecahedrane ring system has been formed constitutes the second alternative (Scheme XI). Required

(37) Some coloration of the crystals begins at ca. 350 °C. At 410 °C, a dark brown coloration has materialized, but melting is never observed.
(38) Dolejšek, Z.; Hala, S.; Hanuš, V.; Landa, S. *Collect. Czech. Chem. Commun.* **1966**, *31*, 435.
(39) Cupas, C.; Schleyer, P. von R.; Trecker, D. J. *J. Am. Chem. Soc.* **1965**, *87*, 917.
(40) Dilling, W. L.; Braendlin, H. P.; McBee, E. T. *Tetrahedron* **1967**, *23*, 1211.
(41) Fort, R. C., Jr.; Schleyer, P. von R. *J. Org. Chem.* **1965**, *30*, 789.
(42) Williams, V. Z., Jr.; Schleyer, P. von R.; Gleicher, G. J.; Rodewald, L. B. *J. Am. Chem. Soc.* **1966**, *88*, 3862.
(43) Bingham, R. C.; Schleyer, P. von R. *J. am. Chem. Soc.* **1971**, *93*, 3189.
(44) The question of the stability of triquinacenyl cations has been addressed and these are considered to be stabilized relative to their perhydro counterparts because of substantive σ–π interaction: Bischof, P. *Angew. Chem., Int. Ed. Engl.* **1976**, *15*, 556. Bosse, D.; de Meijere, A. *Ibid.* **1976**, *15*, 557.

Scheme XII



by such a series of events would be an enhanced σ basicity of dodecahedrane C–H bonds which will allow for "closed" three-center, two-electron bonding[45] (see **47** where Olah's notation is used[46]). The ensuing loss of H_2 allows for cation formation and subsequent methyl (and/or hydride) shift along the perimeter of the sphere. In this event, the unusual stability of the dodecahedryl cation would necessarily serve as the driving force (recall the mass spectrum!). If complete reversibility prevailed, the distribution of isomers would be dictated by their individual relative energies. While theoretical calculations concerning these dimethyl isomers are not yet available, Schulman and Disch have utilized INDO approximate molecular orbital theory to determine the relative stabilities of five difluorododecahedranes: 1,16-F_2, 0; 1,6-F_2, 0.03; 1,7-F_2, 0.09; 1,4-F_2, 0.30; and 1,2-F_2, 3.5 kcal/mol.[7b] In the dimethyl series, the D_{3d} symmetric 1,16-disubstituted derivative can be logically expected to retain the position of more stable isomer.

Finally, migration could be initiated by protonation of a skeletal bond next to methyl. If the bridging proton were to exchange with methyl, the methyl (now bridging) could eventuate on the adjacent skeletal carbon.

While we hope to resolve some of these issues through further experimentation, the closure step in its own right is of considerable mechanistic interest when analyzed in the light of recent developments. Sorensen's study of a series of 1-substituted cyclooctyl cations has provided evidence for unsymmetrical μ-hydrido bridging between the tertiary and transannular secondary carbon ends.[47] When symmetry is present (either disecondary or ditertiary), a symmetrical "open" μ-hydrido-bridged cation forms.[48] Since secododecahedranes such as **40–42** in reality possess a highly embellished eight-membered ring, it would appear reasonable that a species such as **48** (methyl groups omitted for clarity) also intervenes in our cyclization reaction (Scheme XII). The simpler 1,5-μ-hydrido-bridged cyclooctyl cations, however, show no propensity for cyclization. In the case of **48**, the deep thermodynamic well in which the dodecahedrane ring system must sit could lower the energy for C–C σ-bond formation. In all likelihood, this event does not occur directly but is mediated by initial conversion to the closed μ-hydrido-bridged species **49** (contrast **47**) prior to loss of the proton.[46]

With the preparation of **43** successfully completed, one can now inquire of the future. First, there is the matter of gaining access to the monomethyl derivative and, ultimately, the parent hydrocarbon; azadodecahedrane holds equal fascination. Second, a rather detailed investigation of the physical and chemical properties of these exquisite molecules is mandated. While the magnitude of the synthetic challenges still to be met are not to be underestimated, we are confident that a solid basis for the ultimate resolution of these problems has now been built.

Experimental Section

Proton magnetic resonance spectra were obtained with Varian T-60, EM-360, and EM-390 spectrometers; apparent splittings are given in all cases. ^{13}C NMR spectra were recorded on Bruker WP-80, HX-90, and WM-300 spectrometers. Infrared spectra were determined on a Perkin-Elmer Model 467 instrument. Mass spectra were recorded on an AEI-MS9 spectrometer at an ionization potential of 70 eV. Elemental analyses were performed by the Scandinavian Microanalytical Laboratory, Herlev, Denmark.

Procedures for the preparation of the early intermediates utilized in this synthesis, if not described here, can be found in those earlier papers from this laboratory referred to in the text.

Dimethyl Hecadecahydro-4,8,9-metheno-4*H*-cyclopenta[1,2-*a*:4,3-*a'*]dipentalene-4,10-dicarboxylate (18). To a solution of dichloro diester **17** (520 mg, 1.23 mmol) in 25 mL of glyme was added tri-*n*-butyltin chloride (80 mg, 0.246 mmol), sodium borohydride (117 mg, 3.07 mmol), and AIBN (20 mg). The mixture was heated at the reflux temperature for 36 h. When cool, the solution was added to 500 mL of ether and the mixture washed with water, aqueous potassium fluoride solution, water, and brine. After being dried, the filtered solution was evaporated to dryness in vacuo, placed atop a silica gel column, and eluted with 5% ether in hexane. Early fractions contained alkane impurities. Continued elution gave pure diester **18** (407 mg, 97%) which was recrystallized from hexane: mp 122–122.5 °C; IR (KBr, cm^{-1}) 1757, 1738; ^1H NMR (δ, $CDCl_3$) 3.66 (s, 6 H), 2.80–2.23 (br m, 9 H), 2.17–1.78 (br m, 2 H), 1.75–1.26 (br m, 11 H); *m/e* calcd 356.1987, obsd 356.1991.

Anal. Calcd for $C_{22}H_{28}O_4$: C, 74.13; H, 7.92. Found: C, 74.03; H, 7.96.

Dimethyl Octadecahydro-4,8-dimethyldipentaleno[1,2,3-*cd*:1',2',3'-*gh*]pentalene-4,8-dicarboxylate (19). A solution of diester **18** (500 mg, 1.4 mmol) in 20 mL of tetrahydrofuran was added to a solution of distilled ammonia (250 mL) containing 50 mL of tetrahydrofuran and sodium (320 mg, 14 mmol) and the mixture stirred at −78 °C for 30 min. Methyl iodide (3 mL) was introduced, and the ammonia was evaporated. The remaining organic solution was added to 500 mL of ether and washed with sodium thiosulfate solution, water, and brine before drying. After filtration and evaporation of the solvent in vacuo, there was obtained 500 mg of crude crystalline diester. Recrystallization from ethyl acetate gave pure **19** (300 mg, 60%): mp 169–171 °C; IR (KBr, cm^{-1}) 1730, 1140, 1105; ^1H NMR (δ, $CDCl_3$) 3.9–0.8 (m, 22 H), 3.60 (s, 6 H), 1.40 (s, 6 H); ^{13}C NMR (ppm, $CDCl_3$) 176.96, 60.14, 57.83, 55.22, 51.58, 50.79, 39.93, 30.53, 29.98; *m/e* calcd 386.2457, obsd 386.2461.

Anal. Calcd for $C_{24}H_{34}O_4$: C, 74.58; H, 8.87. Found: C, 74.46; H, 8.79.

Octadecahydro-4,8-dimethyl-4,8-ethanodipentaleno[1,2,3-*cd*:1',2',3'-*gh*]pentalene-9,10-dione (20). To a dispersion of sodium (400 mg, 17.4 mmol) and potassium (400 mg, 10.3 mmol) in 175 mL of dry toluene was added trimethylsilyl chloride (5 mL, 39.0 mmol) followed dropwise by diester **19** (400 mg, 1.04 mmol) in 10 mL of toluene. The mixture was heated at the reflux temperature for 48 h under nitrogen, cooled, filtered through Celite, and concentrated in vacuo. The residue (which crystallized on standing) was redissolved in 10 mL of benzene and the solution added dropwise to a stirred solution of anhydrous ferric chloride (500 mg, 3.08 mmol) in 40 mL of dry ether containing 5 drops of concentrated hydrochloric acid. The solution was refluxed gently for 0.5 h and treated with 20 mL of saturated ammonium sulfate solution. The layers were separated, and the aqueous layer was extracted with ether (2 × 75 mL). The combined organic extracts were washed with water (2×) and brine before drying. The solution was filtered and freed of solvent to give 375 mg of a yellow oil which partially crystallized on standing. Chromatography on Florisil with 10% ether in hexane first gave an unidentified material (40 mg) followed by the yellow band of desired diketone **20** (180 mg, 55%). Recrystallization from ethyl acetate gave yellow prisms: mp 182–183 °C; IR (KBr, cm^{-1}) 2950, 1690, 1088, 965; UV (isooctane) 260 (ϵ 165), 310 (55), 430 nm (47); ^1H NMR (δ $CDCl_3$) 3.5–0.8 (m, 22 H), 1.32 (s, 6 H); ^{13}C NMR (ppm, $CDCl_3$) 201.96, 61.29, 60.08, 57.23, 48.91, 32.41, 26.03, 24.88; *m/e* calcd 324.2089, obsd 324.2094.

Anal. Calcd for $C_{22}H_{28}O_2$: C, 81.44; H, 8.70. Found: C, 81.18; H, 8.59.

Hexadecahydro-4,8-dimethyl-3a,8,4,7b-ethanediylidenedipentaleno-[1,2,3-*cd*:1',2',3'-*gh*]pentalene-9,10-diol (23). A. Photolysis of 20. Diketone **20** (100 mg, 0.31 mmol) was dissolved in 5 mL of a degassed solution of benzene, acetone, and *tert*-butyl alcohol in a 3:1:1 ratio. The mixture was irradiated with a 450-W Hanovia lamp for 10 h. The solvent was removed in vacuo, and the yellow residue was purified by preparative TLC (10% ether–10% methylene chloride–80% hexane) on silica gel to give 12 mg of diol **23** (R_f = 0.3), 15 mg of recovered **20** (R_f = 0.35), and 30 mg of monocyclized keto alcohol (R_f = 0.55). The latter two bands could be combined and irradiated again to give an additional 8 mg of diol, total yield 20 mg (20%). Recrystallization from ethyl acetate gave pure **23**: mp 142–143 °C; IR (KBr, cm^{-1}) 3360, 2950, 2925, 1168, 1098; ^1H NMR (δ, $CDCl_3$) 3.0–0.8 (m, 22 H), 1.16 (s, 6 H); ^{13}C NMR (ppm, $CDCl_3$) 96.37 (s), 71.85 (s), 65.54 (d), 60.87 (d), 60.56 (d), 59.17 (s), 55.41 (d), 32.10 (t), 23.91 (t), 23.73 (t), 20.63 (q); *m/e* calcd 324.2089, obsd 324.2097.

Anal. Calcd for $C_{22}H_{28}O_2$: C, 81.44; H, 8.70. Found: C, 81.33; H, 8.70.

(45) Kirchen, R. P.; Ranganayakulu, K.; Rauk, A.; Singh, B. P.; Sorensen, T. S. *J. Am. Chem. Soc.* **1981**, *103*, 588.

(46) (a) Olah, G. A.; Klopman, G.; Schlosberg, R. H. *J. am. Chem. Soc.* **1969**, *91*, 3261. (b) Olah, G. A.; Halpern, Y.; Shen, J.; Mo, Y. K. *Ibid.* **1971**, *93*, 1251.

(47) Kirchen, R. P.; Okasawa, N.; Ranganayakulu, K.; Rauk, A.; Sorensen, T. S. *J. Am. Chem. Soc.* **1981**, *103*, 597.

(48) Kirchen, R. P.; Ranganayakulu, K.; Singh, B. P.; Sorensen, T. S. *Can. J. Chem.*, in press (footnote 14 of ref 47).

B. Reduction of Diketone 24 with Lithium Diisopropylamide. A solution of LDA was prepared by dissolving diisopropylamine (0.56 mL, 4.4 mmol) in 3 mL of tetrahydrofuran. After cooling of the solution to −78 °C, *n*-butyllithium (3.33 mL, 4.0 mmol) was added via syringe. The cooling bath was removed, and the mixture was allowed to warm to 25 °C for 0.5 h. The LDA solution was now brought to 0 °C, and a solution of diketone **24** (120 mg, 0.373 mmol) in 5 mL of tetrahydrofuran was added. The solution was warmed to 25 °C and stirred for 6 h before being quenched with water and added to 75 mL of ether. The organic layer was washed with dilute hydrochloric acid solution (2×), water, and brine prior to drying. Removal of solvent gave 140 mg (97%) of diol which was recrystallized from ethyl acetate to give 90 mg of pure **23**.

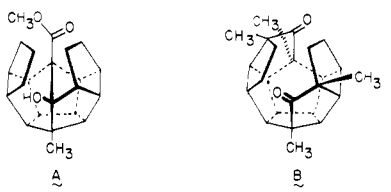
Hexadecahydro-4,8-dimethyl-4,8b:4a,8-dimethanodipentaleno[1,2,3-*cd*:1′,2′,3′-*gh*]pentalene-9,10-dione (24). Diol **23** (80 mg, 0.25 mmol) was dissolved in 12 mL of pyridine with stirring under nitrogen. Lead tetraacetate (400 mg, 0.9 mmol) was added and the resulting orange-red mixture was stirred at 25 °C for 1 h and then treated with oxalic acid (120 mg) and 4 drops of water. After being stirred for 5 min, the yellow mixture was filtered through Celite and the residue was rinsed with ether. The combined filtrates were concentrated under reduced pressure to give a gummy solid. Preparative TLC (10% ether–10% methylene chloride–80% hexane) on silica gel gave 72 mg (91%) of diketone **24**. Recrystallization from ethyl acetate gave pure **24**: mp 176–177.5 °C; IR (KBr, cm^{-1}) 2962, 2905, 1738, 1448, 952; ^1H NMR (δ, $CDCl_3$) 3.7–3.1 (m, 2 H), 3.1–0.8 (m, 18 H), 1.16 (s, 6 H); ^{13}C NMR (ppm, $CDCl_3$) 215.56 (s), 69.67 (s), 60.75 (d), 60.50 (d), 57.83 (d), 53.77 (d), 51.64 (s), 29.61 (t), 22.27, 22.15, 21.60; *m/e* calcd 322.1933, obsd 322.1939.

Anal. Calcd for $C_{22}H_{26}O_2$: C, 81.95; H, 8.13. Found: C, 81.85; H, 8.14.

Reductive Cyclization–Methylation of 17 in Sodium Liquid Ammonia. Dichloro diester **17** (800 mg, 1.89 mmol) was dissolved in 25 mL of tetrahydrofuran and added in rapid dropwise fashion to a stirred solution of sodium (800 mg, 34.8 mmol) in 250 mL of liquid ammonia and 50 mL of dry tetrahydrofuran cooled to −78 °C. After 15 min under nitrogen, methyl iodide (20 mL) was added at a rapid rate. The ammonia was allowed to evaporate and the remaining solution added to ether (700 mL). The organic phase was washed with water, sodium thiosulfate solution, water, and brine prior to drying. The solution was filtered and, upon removal of the solvent, keto ester **29** crystallized (300 mg, 45%). The mother liquors contained a mixture which was separated by preparative TLC on silica gel (10% dichloromethane–15% ether–75% hexane). Additional **29** (110 mg) was obtained at R_f = 0.3 thereby bringing the total yield of **29** to 410 mg (61%). Recrystallization from ethyl acetate gave the analytical material: mp 160–162 °C; IR (KBr, cm^{-1}) 1730, 1450, 1140, 1120; ^1H NMR (δ, $CDCl_3$) 4.4–0.8 (m, 20 H), 3.56 (s, 3 H), 1.36 (s, 3 H), 1.21 (s, 3 H), 1.10 (s, 3 H); ^{13}C NMR (ppm, $CDCl_3$) 231.30, 176.87, 65.15, 64.18, 62.02, 61.75, 61.38, 60.96, 59.41, 59.20, 56.68, 55.98, 53.16, 50.88 (2 C), 50.58, 43.24, 38.72, 34.98, 31.62, 31.31, 30.16, 27.85, 24.85; *m/e* calcd 368.2351, obsd 368.2340.

Anal. Calcd for $C_{24}H_{32}O_3$: C, 78.22; H, 8.75. Found: D, 77.97; H, 8.78.

At R_f = 0.5, the transannularly bonded hydroxy ester A (105 mg, 15%) was obtained. Recrystallization from ethyl acetate gave pure product: mp 108–109 °C; IR (KBr, cm^{-1}) 3480, 2950, 1700, 1190, 1115; ^1H NMR (δ, $CDCl_3$) 5.25 (s, 1 H), 3.60 (s, 3 H), 3.2–0.8 (m, 21 H), 1.15 (s, 3 H); ^{13}C NMR (ppm, $CDCl_3$) 178.71, 82.29, 60.88, 60.44, 59.52, 58.94, 58.36, 57.68, 57.04, 56.32, 51.46, 50.88, 49.47, 48.31 (2 C), 47.77, 32.77, 26.85, 26.02, 25.54, 24.22, 19.47; *m/e* calcd 340.2038, obsd 340.2046.



A B

Anal. Calcd for $C_{22}H_{28}O_3$: C, 77.61; H, 8.29. Found: C, 77.51; H, 8.30.

At R_f = 0.2, the tetramethylated diketone B was obtained (15 mg, 1.5%): ^1H NMR (δ, $CDCl_3$) 4.0–0.9 (m, 18 H), 1.23 (s, 6 H), 1.10 (s, 6 H); *m/e* calcd 350.2247; obsd 350.2253.

Reductive Cyclization of 17 in Lithium–Liquid Ammonia. Dichloro diester **17** (600 mg, 1.42 mmol) was dissolved in 25 mL of tetrahydrofuran and the solution added dropwise to 250 mL of liquid ammonia at −78 °C which contained lithium (150 mg, 21.4 mmol) and 50 mL of dry tetrahydrofuran. Upon completion of the addition of the diester, the reaction mixture was stirred at −78 °C for 10 additional min and then quenched by the rapid addition of methyl iodide (10 mL). The ammonia was allowed to evaporate, and the residual solution was immediately added to ether (500 mL). This solution was washed with water, sodium thiosulfate solution, water, and brine prior to drying. The solution was filtered, and the ether was removed to leave 560 mg of a clear oil. Preparative TLC (10% methylene chloride–15% ether75% hexane) gave keto ester **28** (R_f = 0.25, 260 mg, 52%). Recrystallization from ethyl acetate gave pure **28**: mp 179–180 °C; IR (KBr, cm^{-1}) 2950, 1730, 1720, 1271, 1130; ^1H NMR (δ, $CDCl_3$) 4.0–0.8 (m, 21 H), 3.62 (s, 3 H), 1.39 (s, 3 H), 1.21 (s, 3 H); ^{13}C NMR (ppm, $CDCl_3$) 228.73, 176.90, 64.51, 63.96, 63.72, 62.45, 59.47 (2 C), 56.62, 56.50, 55.95, 53.04, 52.86, 50.86 (2 C), 50.55, 38.90, 34.96, 34.04, 30.95, 30.71; *m/e* calcd 354.2195, obsd 354.2203.

Anal. Calcd for $C_{23}H_{30}O_3$: C, 77.93; H, 8.53. Found: C, 77.76; H, 8.53.

Also obtained from this reaction were keto ester **29** (R_f = 0.3, 100 mg, 19%) and hydroxy ester A (R_f = 0.5, 100 mg, 22%).

Methyl Octadecahydro-3b-hydroxy-3a,6d,7-trimethyl-1,6-methanocyclopenta[3,4]pentaleno[2,1,6-*cde*]pentaleno[2,1,6-*gha*]pentalene-7-carboxylate (30a). Keto ester **29** (100 mg, 0.28 mmol) was dissolved in 10 mL of dry deoxygenated benzene–*tert*-butyl alcohol solution (4:1) and irradiated with a 450-W Hanovia lamp for 16 h under nitrogen. The now slightly yellow solution was concentrated in vacuo to give 100 mg of crude crystalline **30a**. Recrystallization from ethyl acetate afforded 85 mg (85%) of pure **30a**: no melting point, gradual dec over 180 °C; IR (KBr, cm^{-1}) 3560, 3520, 2920, 1720, 1110; ^1H NMR (δ, $CDCl_3$) 4.0–0.8 (m, 20 H), 3.63 (s, 3 H), 1.31 (s, 3 H), 1.14 (s, 6 H); ^{13}C NMR (ppm, $CDCl_3$) 177.14, 98.25, 79.07, 69.24, 67.18, 65.96, 63.90, 63.48, 63.17 (2 C), 62.72, 59.47, 59.05, 57.59, 52.13, 50.98, 50.07, 41.51, 39.20, 31.62, 30.58, 30.16, 29.55, 28.70; *m/e* calcd for $M^+ - H_2O$ 350.2246, obsd 350.2253.

Methyl 1,1a,1b,2,3,3a,4,5,5a,6,6a,6b,6c,6d,6e,6f-Hexadecahydro-3a,6d,7-trimethyl-1,6-methanocyclopenta[3,4]pentaleno[2,1,6-*cde*]pentaleno[2,1,6-*gha*]pentalene-7-carboxylate (31a). Hydroxy ester **30a** (160 mg, 0.43 mmol) was dissolved in 15 mL of dry benzene, and *p*-toluenesulfonic acid (10 mg) was added. The mixture was heated at the reflux temperature with continuous removal of water for 6 h. The benzene was evaporated in vacuo to leave a yellow oil which crystallized upon standing. Preparative TLC (15% ether–hexane) of the mixture gave 140 mg (92%) of **31a**. Recrystallization from ethyl acetate gave analytically pure material: mp 141–142 °C; IR (KBr, cm^{-1}) 2920, 1730, 1260, 1110; ^1H NMR (δ, $CDCl_3$) 3.70–1.10 (m, 18 H), 3.64 (s, 3 H), 1.40 (s, 3 H), 1.36 (s, 3 H), 1.26 (s, 3 H); ^{13}C NMR (ppm, $CDCl_3$) 177.28, 142.47, 140.60, 79.84, 69.81, 67.14, 62.82, 62.55, 62.00, 59.62, 59.52, 58.94, 57.38, 53.72, 50.86, 50.03, 48.31, 40.83, 40.03, 29.03, 28.67, 28.47, 25.24, 24.78; *m/e* calcd 350.2246, obsd 350.2254.

Anal. Calcd for $C_{24}H_{30}O_2$: C, 82.24; H, 8.63. Found: C, 81.90; H, 8.56.

Methyl Octadecahydro-3a,6d,7-trimethyl-1,6-methanocyclopenta-[3,4]pentaleno[2,1,6-*cde*]pentaleno[2,1,6-*gha*]pentalene-7-carboxylate (32a). Ene ester **31a** (100 mg, 0.29 mmol) was dissolved in 10 mL of a mixture of methylene chloride–methanol (1:3). Hydrazine (97%, 600 μL) was added at −10 °C. Hydrogen peroxide (2.14 mL) was added dropwise to the cooled reaction mixture over a period of 45 min. The mixture was stirred at 0 °C for 2 h and at 25 °C for 12 h before being added to ether and washed with water (2×) and brine. After drying, filtration, and removal of solvent in vacuo gave 100 mg of a semicrystalline solid. Preparative TLC gave pure **32a**. Recrystallization from cold ethyl acetate gave the analytically pure material: mp 114–115 °C; IR (KBr, cm^{-1}) 2925, 1732, 1260, 1118, 1115; ^1H NMR (δ, $CDCl_3$) 3.7–0.70 (m, 20 H), 3.66 (s, 3 H), 1.31 (s, 3 H), 1.28 (s, 3 H), 1.12 (s, 3 H); ^{13}C NMR (ppm, $CDCl_3$) 177.45, 78.95, 72.76, 66.75 (2 C), 66.09, 65.72, 64.39, 63.60, 60.02, 59.84, 59.72, 57.71, 52.68, 51.95, 50.98, 50.62, 40.90, 39.08, 36.05, 34.89, 31.50, 30.53, 29.19; *m/e* calcd 352.2402, obsd 352.2409.

Anal. Calcd for $C_{24}H_{32}O_2$: C, 81.77; H, 9.15. Found: C, 81.47; H, 9.04.

Methyl Octadecahydro-3b-hydroxy-6d,7-dimethyl-1,6-methanocyclopenta[3,4]pentaleno[2,1,6-*cde*]pentaleno[2,1,6-*gha*]pentalene-7-carboxylate (30b). Keto ester **28** (100 mg, 0.3 mmol) was dissolved in 10 mL of a solution of 20% *tert*-butyl alcohol in benzene which was subsequently deoxygenated with nitrogen. Two drops of triethylamine were added, and the mixture was irradiated with a 450-W Hanovia lamp through Pyrex for 16 h. The solvent was removed in vacuo to leave crude crystalline hydroxy ester **30b** (100 mg). This material was not purified: IR (KBr, cm^{-1}) 3500, 1708, 1130, 1000; ^1H NMR (δ, $CDCl_3$) 4.0–0.8 (m, 21 H), 3.63 (s, 3 H), 1.38 (s, 3 H), 1.11 (s, 3 H); *m/e* 354.2195, obsd 354.2203.

Methyl 1,1a,1b,2,3,3a,4,5,5a,6,6a,6b,6c,6d,6e,6f-Hexadecahydro-6d,7-dimethyl-1,6-methanocyclopenta[3,4]pentaleno[2,1,6-*cde*]pentaleno-[2,1,6-*gha*]pentalene-7-carboxylate (31b). Crude hydroxy ester **30b** (100 mg, 0.28 mmol) was dissolved in 10 mL of benzene along with *p*-

toluenesulfonic acid (3 mg). The mixture was heated at 80 °C for 0.5 h then freed of solvent. Preparative TLC (10% ether in hexane) on silica gel gave 67 mg (71%) of pure **31b**. Recrystallization from ethyl acetate gave analytically pure material: mp 127–128 °C; IR (KBr, cm^{-1}) 1730, 1258, 1115; ^1H NMR (δ, $CDCl_3$) 3.7–0.6 (m, 19 H), 3.61 (s, 3 H), 1.36 (s, 3 H), 1.17 (s, 3 H); ^{13}C NMR (ppm, $CDCl_3$) 177.25, 140.36, 139.19, 79.57, 67.58, 62.73 (2 C), 62.34, 59.67 (2 C), 58.94, 57.00, 50.88, 48.84, 48.16, 45.54, 41.12, 30.25, 28.79, 28.35, 25.49, 24.37; *m/e* calcd 336.2089, obsd 366.2095.

Anal. Calcd for $C_{23}H_{28}O_2$: C, 82.10; H, 8.30. Found: C, 82.11; H, 8.47.

Methyl Hexadecahydro-6d,7-dimethyl-1,6-methanocyclopenta[3,4]pentaleno[2,1,6-*cde*]pentaleno[2,1,6-*gha*]pentalene-7-carboxylate (32b). To a solution of ethanol (10 mL) and tetrahydrofuran (2 mL) containing **31b** (100 mg, 0.3 mmol) was added hydrazine (800 μL, 25 mmol), and the mixture was cooled to 0 °C. Hydrogen peroxide (3.2 g of 30%) was added dropwise over a 45-min period, and the mixture was allowed to gradually warm to 25 °C where stirring was maintained for 6 h. The solution was added to ether (100 mL) and the mixture then washed with water (2 × 25 mL) and brine. The dried ether solution was filtered and evaporated in vacuo to give 100 mg (100%) of crude crystalline ester **32b**. Recrystallization from ethyl acetate gave pure ester: mp 138–140 °C; IR (KBr, cm^{-1}) 1725, 1130, 1118; ^1H NMR (δ, $CDCl_3$) 3.65 (s, 3 H), 3.7–0.7 (m, 21 H), 1.30 (s, 3 H), 1.18 (s, 3 H); ^{13}C NMR (ppm, $CDCl_3$) 177.40, 79.62, 66.61, 65.40, 64.08, 59.86, 58.70, 57.72, 52.14, 50.88 (2 C), 39.23, 33.64, 30.83, 30.68; *m/e* calcd 338.2246, obsd 338.2253.

Anal. Calcd for $C_{23}H_{30}O_2$: C, 81.61; H, 8.93. Found: C, 81.29; H, 8.90.

Methyl Hexadecahydro-4b,7d,8-trimethyl-1,7-methanocyclopenta[3′,4′]pentaleno[2′,1′,6′:1,6,5]pentaleno[6″,1″,2″:2,3,4]pentaleno[1,2-*b*]oxirene-8-carboxylate (33). Ene ester **31a** (190 mg, 0.54 mol) was dissolved in 15 mL of dry methylene chloride and *m*-chloroperbenzoic acid (115 mg of 85% purity, 0.56 mmol) was added with stirring. After 15 min, the mixture was added to 100 mL of ether and washed with sodium bisulfite solution, 10% sodium carbonate solution (2×), water, and brine prior to drying. After filtration and removal of solvent in vacuo, there was obtained 200 mg (100%) of crude epoxy ester **33**. Recrystallization from ethyl acetate gave the analytically pure material: mp 181–182 °C; IR (KBr, cm^{-1}) 2933, 1730, 1265, 1115; ^1H NMR (δ, $CDCl_3$) 4.0–1.0 (m, 18 H), 3.68 (s, 3 H), 1.40 (s, 3 H), 1.26 (s, 3 H), 1.21 (s, 3 H); ^{13}C NMR (ppm, $CDCl_3$) 176.96, 86.66, 83.56, 68.15, 66.21, 65.36, 63.30, 62.99, 59.78, 58.68 (2 C), 57.96, 57.71, 51.40, 51.04, 49.64, 48.06, 40.17, 38.23, 28.64, 27.37, 24.40 (2 C), 22.89; *m/e* calcd 366.2195, obsd 366.2201.

Anal. Calcd for $C_{24}H_{30}O_3$: C, 78.65; H, 8.25. Found: C, 78.29; H, 8.41.

Methyl 1,1a,1b,2,3,3a,3b,5,5a,6,6a,6b,6c,6d,6e,6f-Hexadecahydro-3b-hydroxy-3a,6d,7-trimethyl-1,6-methanocyclopenta[3,4]pentaleno[2,1,6-*cde*]pentaleno[2,1,6-*gha*]pentalene-7-carboxylate (34). Epoxy ester **33** (200 mg, 0.55 mmol) was dissolved in 15 mL of dry benzene. Boron trifluoride etherate (3 drops) was added, and the mixture was stirred at 25 °C for 8 h and added to 200 mL of ether and the solution washed with water (2×) and brine. After being dried, the solution was filtered and evaporated to leave 300 mg of a yellow oil. Preparative TLC on silica gel (50% ether–hexane) gave three bands. The first (R_f = 0.6) was a mixture of two unidentified compounds (30 mg). The second band (R_f = 0.4) was recovered epoxide (40 mg). The third band (R_f = 0.25) was the allylic alcohol (90 mg, 45%). The recovered starting material was recycled to give an additional 20 mg, thereby bringing the total yield of **34** to 110 mg (55%). Recrystallization from ethyl acetate gave the analytically pure material: mp 167–169 °C; IR (KBr, cm^{-1}) 3555, 2920, 1720, 1120; ^1H NMR (δ, $CDCl_3$) 5.30 (m, 1 H), 4.2–0.9 (m, 17 H), 3.60 (s, 3 H), 1.33 (s, 3 H), 1.20 (s, 3 H), 1.02 (s, 3 H); ^{13}C NMR (ppm, $CDCl_3$) 176.48, 156.81, 119.92, 97.00, 80.30, 69.42, 65.98, 65.44, 62.87, 62.29, 61.32, 60.20, 59.13, 58.45, 57.87, 52.82, 50.78, 47.43, 42.77, 40.68, 39.03, 31.70, 27.04, 18.25; *m/e* calcd 366.2195, obsd 366.2203.

Anal. Calcd for $C_{24}H_{30}O_3$: C, 78.65; H, 8.25. Found: C, 78.64; H, 8.29.

Methyl Hexadecahydro-4b,7d,8-trimethyl-3-oxo-1,7-methanocyclopenta[3′,4′]pentaleno[2′,1′,6′:1,6,5]pentaleno[6″,1″,2″:2,3,4]pentaleno[1,2-*b*]oxirene-8-carboxylate (35). A. Pyridinium Chlorochromate Oxidation of 34. Allylic alcohol **34** (100 mg, 0.33 mmol) was added as a solution in 5 mL of methylene chloride dropwise to a suspension of pyridinium chlorochromate (170 mg, 0.8 mmol) in 10 mL of methylene chloride. The mixture was stirred under nitrogen for 48 h. Ether was added to precipitate the chromium salts, and the solution was decanted from the brown salts. The salts were triturated with ether, and the combined ether extracts were washed with dilute hydrochloric acid, saturated sodium bicarbonate solution, water, and brine. After being dried over magnesium sulfate, the solution was filtered and evaporated in vacuo to give 75 mg of a yellow oil. Preparative TLC (50% ether–hexane) gave epoxy keto ester **35** (R_f = 0.2). Recrystallization from ethyl acetate gave pure **35** (54 mg, 53%): mp 196–197 °C; IR (KBr, cm^{-1}) 1732, 1718, 1118, 1108; ^1H NMR (δ, $CDCl_3$) 4.2–1.0 (m, 14 H), 3.70 (s, 3 H), 2.07 ($^1/_2$ABq, J_{AB} = 12 Hz, $\Delta\nu_{AB}$ = 8.1 Hz, 1 H), 1.98 ($^1/_2$ABq, J_{AB} = 12 Hz, $\Delta\nu_{AB}$ = 8.1 Hz, 1 H), 1.46 (s, 3 H), 1.28 (s, 3 H), 1.21 (s, 3 H); ^{13}C NMR (ppm, $CDCl_3$) 217.92, 176.66, 84.84, 84.11, 69.00, 64.69, 63.42, 62.51, 61.54, 61.35, 59.59 (2 C), 57.77, 57.65, 55.22, 51.34, 47.27, 40.96, 40.05, 39.57, 26.52, 24.64, 23.91, 16.08 *m/e* calcd 380.1987, obsd 380.1992.

Anal. Calcd for $C_{24}H_{28}O_4$: C, 75.76; H, 7.42. Found: C, 75.65; H, 7.41.

B. Dichromate Oxidation of 34. Allylic alcohol **33** (30 mg, 0.08 mmol) was dissolved in 5 mL of acetone and cooled to 0 °C. To this was added 280 mg of a stock solution of Jones reagent (prepared by adding 200 g of sodium dichromate dihydrate to 272 g of concentrated sulfuric acid and 600 mL of water) dropwise over a period of 0.5 h. The mixture was warmed to 25 °C and stirred an additional 2 h. The mixture was then added to water and extracted with methylene chloride (3×). The combined organic extracts were washed with saturated sodium bicarbonate solution, water, and brine. After being dried, the solution was filtered and the filtrate was concentrated in vacuo to give a pale yellow oil (25 mg). Preparative TLC (50% ether–hexane) gave 17 mg of pure **35** (55%).

C. Pyridinium Chlorochromate Oxidation of 37. Epoxy alcohol **37** (10 mg, 0.03 mmol) was dissolved in 1 mL of methylene chloride and added to a stirred suspension of pyridinium chlorochromate (20 mg) in 2 mL of methylene chloride. After 2.5 h, ether was added and the reaction worked up as before to give 10 mg of pure **37**.

D. Dichromate Oxidation of 36. Epoxy alcohol **36** (40 mg, 0.10 mmol) was dissolved in 5 mL of acetone and cooled to 0 °C in an ice bath. Jones reagent (10 drops, prepared as before) was added dropwise over a period of 20 min. After 2 h at 0 °C, the reaction was added to water and extracted with methylene chloride. Workup as before gave 35 mg of pure **35** (92%).

Methyl Hexadecahydro-3b-hydroxy-3c,6d,7-trimethyl-1,6-methano-1*H*-cyclopenta[3″,4″]pentaleno[2″,1″,6″:3′,4′,5′]pentaleno[6′,1′,2′:5,6,1]pentaleno[1,2-*b*]oxirene-7-carboxylate (36). Allylic alcohol **34** (60 mg, 0.16 mmol) was dissolved in 10 mL of methylene chloride with stirring under nitrogen. To this solution was added *m*-chloroperbenzoic acid (40 mg of 85% purity, 0.19 mmol), and the mixture was stirred for 10 min and added to 50 mL of methylene chloride and the solution washed with sodium thiosulfate solution, 10% sodium carbonate solution, water, and brine, dried, filtered, and evaporated in vacuo to give 60 mg of crystalline epoxy alcohol **36**: ^1H NMR (δ, $CDCl_3$) 4.09 (d, J = 4 Hz, 1 H), 4.0–0.9 (m, 20 H), 1.42 (s, 3 H), 1.24 (s, 3 H), 1.00 (s, 3 H); *m/e* 382.

Methyl Hexadecahydro-3-hydroxy-5b,7d,8-trimethyl-1,7-methanocyclopenta[3′,4′]pentaleno[2′,1′,6′:1,6,5]pentaleno[6″,1″,2″:2,3,4]pentaleno[1,2-*b*]oxirene-8-carboxylate (37). Epoxy alcohol **36** (20 mg, 0.05 mmol) was dissolved in 4 mL of dry benzene. Boron trifluoride etherate (1 drop) was added with stirring under nitrogen. After 1 h, the mixture was added to 30 mL of ether and this solution was washed with water (2×) and brine, dried, filtered, and concentrated to give 20 mg of a pale yellow oil. Preparative TLC (70% ether–hexane) gave 11 mg of pure **37** (R_f = 0.21, 55%): IR (KBr, cm^{-1}) 3500, 1720, 1270, 1115; ^1H NMR (δ, $CDCl_3$) 4.2–0.8 (m, 17 H), 4.0 (d, J_{AX} = 4.0 Hz, 1 H), 3.68 (s, 3 H), 1.37 (s, 3 H), 1.24 (s, 6 H).

Hexadecahydro-6d,7-dimethyl-1,6-methanocyclopenta[3,4]pentaleno[2,1,6-*cde*]pentaleno[2,1,6-*gha*]pentalene-7-carboxaldehyde (38). To a solution of ester **32b** (100 mg, 0.3 mmol) in toluene (10 mL) cooled to −78 °C was added diisobutyl aluminum hydride (1 M in hexane, 2 mL, 2.0 mmol) via a syringe. The mixture was stirred at −78 °C for 5 min, warmed gradually to 25 °C, and stirred for 3 h. The excess reagent was quenched with methanol, and the mixture was added to ether (100 mL). The ether solution was washed with dilute hydrochloric acid solution, saturated sodium bicarbonate solution, water, and brine. The dried solution was filtered and evaporated to dryness in vacuo to give 89 mg (97%) of the desired alcohol. Recrystallization from ethyl acetate gave pure product: mp 144–146 °C; IR (KBr, cm^{-1}) 3350, 1020, 1010; ^1H NMR (δ, $CDCl_3$) 4.20 (br s, 2 H), 3.9–0.8 (m, 22 H), 1.21 (s, 3 H), 1.13 (s, 3 H); ^{13}C NMR (ppm, $CDCl_3$) 79.52, 67.00, 65.35 (2 C), 65.20, 59.76, 58.79, 56.85, 51.61, 51.12, 38.11, 33.35, 31.17, 31.02 *m/e* calcd 310.2297, obsd 310.2305.

To a suspension of pyridinium chlorochromate (100 mg, 0.46 mmol) in dichloromethane (10 mL) was added a solution of the above alcohol (100 mg, 0.3 mmol) in dichloromethane (2 mL). The mixture was stirred for 1 h, and ether (15 mL) was added. The organic solution was decanted, and the salts were leached two additional times with ether. The combined ether layers were washed with dilute hydrochoric acid solution, saturated sodium bicarbonate solution, water, and brine, prior to drying. The filtered solution was evaporated to dryness in vacuo to leave 95 mg

of crude crystalline aldehyde **38**. Recrystallization from ethyl acetate gave pure aldehyde: mp 132–134 °C; IR (KBr, cm^{-1}) 2692, 1718, 1382; ^1H NMR (δ, $CDCl_3$) 9.98 (s, 1 H), 3.8–0.7 (m, 21 H), 1.20 (s, 3 H), 1.12 (s, 3 H); ^{13}C NMR (ppm, $CDCl_3$) 204.21, 79.44, 66.94, 65.66, 64.57, 64.14, 59.35, 58.93, 51.83, 50.43, 34.83, 33.56, 31.25.

Octadecahydro-3a,7-dimethyl-1,6,7-metheno-3*H*-cyclopenta[3,4]pentaleno[2,1,6-*gha*]pentaleno[1,2,3-*cd*]pentalen-3-one (39). Aldehyde **38** (100 mg, 0.3 mmol) was dissolved in 10 mL of a toluene–ethanol (9:1) solution. Triethylamine (0.25 mL) was added, and the solution was deoxygenated with nitrogen, cooled to −78 °C under nitrogen, and irradiated with a 450-W Hanovia lamp for 2 h through Pyrex. The mixture was warmed up 25 °C and concentrated in vacuo to give a crystalline solid. Preparative TLC on silica gel (10% ether–10% dichloromethane in hexane) gave three products. At R_f = 0.75, the decarbonylation products were obtained (45 mg). The structures of these products have not been determined. At R_f = 0.2, the endo alcohol was obtained (9 mg) while the exo alcohol materialized at R_f = 0.1 (12 mg). These two alcohols were combined to give 21 mg (21%) of total photocyclized product: IR ($CDCl_3$, cm^{-1}) 3380, 2920, 1445, 1010; *m/e* calcd 308.2140, obsd 308.2150.

The epimeric mixture of alcohols (21 mg, 0.068 mmol) was dissolved in 1 mL of dichloromethane and the solution added slowly to a suspension of pyridinium chlorochromate (20 mg, 0.093 mmol) in 5 mL of dichloromethane. The mixture was stirred for 2.5 h at 25 °C at which point ether (10 mL) was added and the organic solution decanted. The salts were leached two additional times with ether, and the combined organic layers were washed with dilute hydrochloric acid solution, saturated sodium bicarbonate solution, water, and brine prior to drying. The solution was filtered and evaporated to dryness in vacuo to give 19 mg (91%) of crude crystalline ketone **39**. Recrystallization from ethyl acetate gave pure material: mp 235–240 °C; IR (KBr, cm^{-1}) 2938, 1720, 1450, 1385; ^1H NMR (δ, $CDCl_3$) 3.9–0.8 (series of m, 20 H), 1.19 (s, 6 H); ^{13}C NMR (ppm, $CDCl_3$) 229.88, 78.22, 69.36, 68.33, 68.09, 67.42, 67.00, 66.57, 65.30 (2 C), 62.57, 59.11, 58.86, 53.52, 52.07, 56.34, 50.31, 36.90, 33.98, 33.13, 29.98, 28.34; *m/e* calcd 306.1984, obsd 306.1976.

Hexadecahydro-6d,7-dimethyl-1,6,2,5-ethanediylidenecyclopenta[3,4]pentaleno[2,1,6-*cde*]pentaleno[2,1,6-*gha*]pentalen-3b(1*H*)-ol (40). Ketone **39** (19 mg, 0.062 mmol) was dissolved in 5 mL of a solution containing 20% *tert*-butyl alcohol in benzene. After suitable deoxygenation with nitrogen, triethylamine (2 drops) was added and the mixture was irradiated with a 450-W Hanovia lamp through Pyrex under nitrogen for 16 h. The solvent was removed in vacuo to give crude cyclized alcohol **40** which was not routinely purified. Recrystallization from ethanol furnished colorless crystals: mp 243–250 °C; IR (KBr, cm^{-1}) 3400, 2935, 1020; ^1H NMR (δ, $CDCl_3$) 3.9–0.9 (m, 20 H), 1.18 (s, 3 H), 1.10 (s, 3 H); ^{13}C NMR (ppm, $CDCl_3$) 96.89, 78.23, 78.12, 70.14, 69.12, 68.23, 65.70, 64.54, 60.08, 58.03, 52.41, 41.33, 33.58, 32.45, 27.32; *m/e* calcd 306.1984, obsd 306.1976.

1,1a,1b,2,3,3a,4,5,5a,6,6a,6b,6c,6d,6e,6f-Hexadecahydro-6d,7-dimethyl-1,6,2,5-ethanodiylidenecyclopenta[3,4]pentaleno[2,1,6-*cde*]pentaleno[2,1,6-*gha*]pentalene (41). A sample of alcohol **40** (obtained from the photolysis withour purification, 19 mg, 0.062 mmol) was dissolved in 5 mL of benzene. A crystal of *p*-toluenesulfonic acid was added, and the mixture was heated to 80 °C. After 0.5 h, the mixture was cooled to 25 °C and concentrated in vacuo. The resulting yellow oil was subjected to preparative TLC on silica gel (hexane elution) to give 13 mg (73% overall) of olefin **41**: mp 218–221 °C (from hexane); IR (KBr, cm^{-1}) 3040, 2930, 1445, 1385; ^1H NMR (δ, $CDCl_3$) 4.0–0.6 (m, 18 H), 1.21 (s, 3 H), 1.11 (s, 3 H); ^{13}C NMR (ppm, $CDCl_3$) 145.99, 140.16, 68.60, 67.58, 67.43, 66.61, 65.74, 64.23, 63.99, 63.84, 62.09, 61.03, 60.78, 52.09, 50.44, 46.85, 33.60, 33.35, 30.29, 26.41 (2 carbons not observed); *m/e* 288.

Octadecahydro-6d,7-dimethyl-1,6,2,5-ethanediylidenecyclopenta[3,4]pentaleno[2,1,6-*cde*]pentaleno[2,1,6-*gha*]pentalene (42). A solution of olefin **41** (13 mg, 0.045 mmol) was dissolved in 5 mL of ethanol to which 1 mL of dichloromethane had been added to aid in the dissolution. The solution was cooled to −10 °C, and anhydrous hydrazine (200 μL, 6.25 mmol) was added. Chilled hydrogen peroxide (30%, 680 μL) was added dropwise over a period of 45 min, and the resulting solution was stirred for 6 h while warming to 25 °C. The reaction mixture was poured into water and extracted with ether (3×). The combined ether extracts were washed with water (2×) and brine. After being dried, the solution was filtered and concentrated in vacuo to give 12 mg (92%) of crystalline monosecododecahedrane **42**. Recrystallization from hexane (−10 °C) gave the analytically pure material: mp 235–250 °C; IR ($CDCl_3$, cm^{-1}) 3150, 2925, 1447, 1375; ^1H NMR (δ, $CDCl_3$) 3.8–0.7 (m, 20 H), 1.18 (s, 6 H); ^{13}C NMR (ppm, $CDCl_3$) 78.40 (s), 70.15 (d), 68.16 (d), 66.08 (d), 58.99 (d), 52.29 (d), 33.64 (d), 32.58 (t); *m/e* calcd 290.2034, obsd 290.2026.

1,16-Dimethyldodecahedrane (43). A. Dehydration of Alcohol 40. A solution of **40** (20 mg, 0.065 mmol) in 0.5 mL of dichloromethane was added to a solution of phosphorus pentoxide (20 mg, 0.14 mmol) and trifluoromethanesulfonic acid (4 drops) in 1 mL of the same solvent. This mixture was stirred at 25 °C under nitrogen for 30 min, treated with water (1 mL), and extracted with dichloromethane (20 mL). The organic phase was washed with water (5 mL), saturated sodium bicarbonate solution (5 mL), and brine (5 mL) prior to drying and concentration. Sublimation of the clear semicrystalline residue at 170 °C (1 mm) followed by recrystallization of the sublimate from benzene afforded 2 mg (11%) of **43** as colorless crystals, mp >420 °C; IR (KBr, cm^{-1}) 2938 (s), 2917 (m), 2852 (m), 1451 (w), 1291 (w), 735 (w); ^1H NMR (δ, C_6D_6) 3.49–3.40 (m, 12 H), 2.99–2.90 (m, 6 H), 1.19 (s, 6 H); ^{13}C NMR (ppm, C_6D_6) 76.08, 74.57, 67.38, 32.82; *m/e* calcd for $C_{22}H_{24}$ 288.1878, obsd 288.1871.

B. Isomerization of Olefin 41. To a stirred solution of **41** (15 mg, 0.05 mmol) in dichloromethane (3 mL) was added 1 drop of trifluoromethanesulfonic acid. After 10 min, water (1 mL) was added and the mixture was poured into 25 mL of hexane. The hexane layer was washed with water and brine, dried, and evaporated. The waxy residue was recrystallized from benzene to give 2 mg of **43**. Sublimation of the mother liquors at 180 °C (0.8 mm) gave a waxy solid from which an additional 2 mg of **43** could be obtained by crystallization from benzene (total yield of 27%).

Acknowledgment. We are indebted to the National Institutes of Health for their generous financial support of this research program (Grant AI-11490).

Registry No. 17, 71342-50-2; **18**, 71342-52-4; **19**, 80373-30-4; **20**, 80373-31-5; **23**, 76652-57-8; **24**, 80317-76-6; **28**, 80373-32-6; **29**, 80373-33-7; **30a**, 80373-34-8; **30b**, 76680-82-5; **31a**, 80373-35-9; **31b**, 76686-63-0; **32a**, 80373-36-0; **32b**, 76680-85-8; **33**, 80317-77-7; **34**, 80317-78-8; **35**, 80317-79-9; **36**, 80317-80-2; **37**, 80317-81-3; **38**, 76680-87-0; **39**, 80317-82-4; **40**, 76680-90-5; **41**, 80317-83-5; **42**, 76680-92-7; **43**, 77387-50-9; **A**, 80317-84-6; **B**, 80317-85-7; **39** endo alcohol, 80317-86-8; **39** exo alcohol, 80373-37-1.