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Dodecahedrane. Improved Synthetic Access to, and Monofunctionalization of, the Spherical Hydrocarbon. Spectral Properties of the Derivatives

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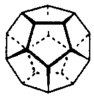
Abstract: Initially described are several notable improvements in the synthesis of dodecahedrane. The principal modifications involve the domino Diels–Alder reaction, utilization of ethyl ester derivatives while progressing to bis(lactone) **10**, peripheral bond construction during the late stages of sphere construction, and the final dehydrogenation. In the latter transformation, the use of 5% platinum on alumina alone is shown to constitute the most feasible and efficient preparative procedure for obtaining the $C_{20}H_{20}$ hydrocarbon. Next, methods for the successful monohalogenation, carboxylation, oxygenation, arylation, amidation, and methylation of dodecahedrane are described. Very significant differences were found between the reactivity of dodecahedrane and adamantane. Finally, ^1H and ^{13}C chemical shifts within the various monofunctionalized dodecahedranes are correlated with acyclic and cyclic compounds that have previously been scrutinized and for which detailed information is available.

In view of its lofty position as the most complex of the structurally intriguing C_nH_n hydrocarbons whose carbon frameworks define regular polyhedrons, the pentagonal dodecahedrane molecule unquestionably merits close scrutiny as a starting point for exploratory synthetic and physical-organic investigation. Although total synthesis of this rigid, topologically spherical hydrocarbon has been successfully realized,[2,3] the problem of gaining access to dodecahedrane in amounts useful for extensive study of its chemical reactivity had first to be addressed.

We begin herein by describing those modifications of our original synthesis of **1** that now make possible its acquisition in 25–50-mg lots as described. A major consequence of these improvements is to remove dodecahedrane from the realm of aesthetically pleasing structures that, while known, remain obscure and generally unavailable for advancing our knowledge of their physical properties and reactivity. The broad range of studies completed by us within the last several months[4-9] aptly documents the fact that the availability of **1** is no longer a deterrent to progress in the dodecahedrane area.



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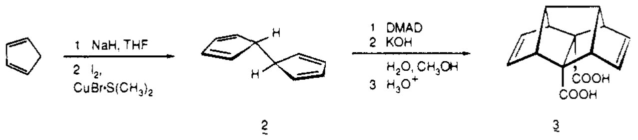
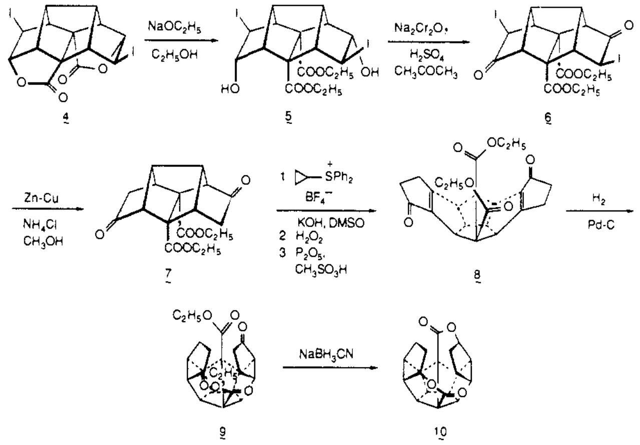
The conditions developed for the successful monohalogenation, carboxylation, oxygenation, arylation, amidation, and methylation of dodecahedrane are next detailed. The very significant differences found between the reactivity of **1** and adamantane are made evident where this is relevant. The likely factors underlying the appreciable modulation of response to electrophilic reagents are discussed.

Finally, the spectral properties of the resultant monosubstituted dodecahedranes are closely examined. In particular, the protons β to the pendant group are seen to be responsive to substituent electronegativity, their shifts correlating well with σ_I values. Additionally, the chemical shifts of all quaternary carbons correlate well with data derived from *tert*-butyl systems. In contrast, the shielding effects exerted on the γ-carbons happen to be at odds with the behavior previously reported for monosubstituted cyclohexyl and 1-adamantyl systems.

Scheme I



Scheme II



Synthetic Improvements. A. Domino Diels–Alder Reaction. In the original development of Scheme I,[10,11] the principal concern was to generate colorless sodium cyclopentadienide in an anaerobic atmosphere such that it could be oxidatively coupled in good yield at low temperature to deliver 9,10-dihydrofulvalene (**2**). Recourse was made to those conditions involving the use of finely divided sodium on alumina that were earlier developed and refined by Matzner.[12] However, this method of generating the anion mandated laborious filtration in the absence of air prior to exposure

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[1] The Ohio State University Postdoctoral Fellow, 1986–1988.

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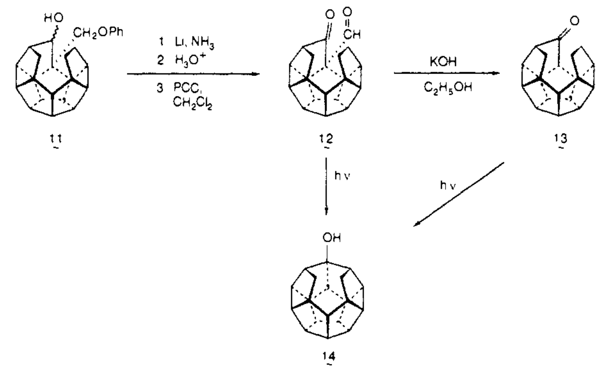
Scheme III



to 0.5 equiv of iodine. Although efficiency levels of 70–80% are routinely realized,[10,13] the preparation of 40–50-g lots of diacid **3** invariably took 3 days.[10] Because the major time commitment was associated with the anion-transfer process, other methods were early examined and found to be less workable.[14] In particular, the potassium and lithium cyclopentadienides were determined to be less conducive to smooth reaction with iodine.

The more recent commercial availability of *oil-free* sodium hydride has prompted examination of its suitability for this particular cyclocondensation process.[15] Detailed in the Experimental Section is a modified procedure for the preparation of **3** that makes use of this base, requires no transfer step, and is accomplished with greater efficiency and in much less time than heretofore.[16] Practically translated, 600-g quantities of **3** can now be prepared in 2 weeks rather than the former 2-month period.

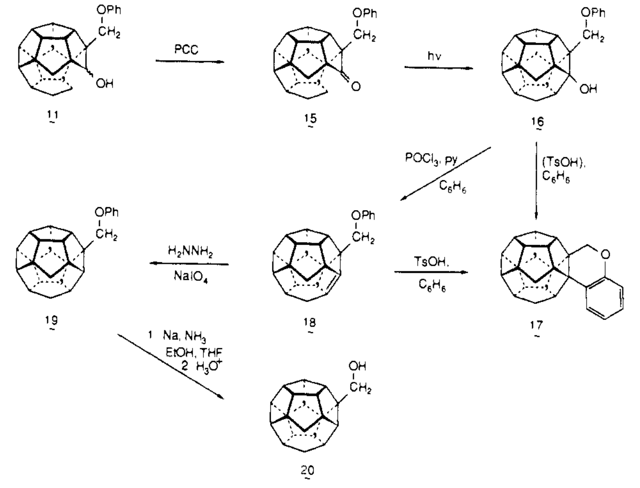
B. Ethyl Ester Route. An additional relevant modification was uncovered when suitable comparison of the dimethyl diester sequence deployed earlier[17] was made with that involving the diethyl homologues (Scheme II). Usefully, intermediates **5**–**9** are highly crystalline colorless solids with better solubility characteristics. As a consequence, the *isolated* yields at each stage are higher, and efficiency is enhanced throughout. Thus, **7** is obtained in 73% overall yield from **4**. Furthermore, the triad of subsequent steps that achieves 2-fold cyclopentenone annulation as in **8** with maintenance of C_2 symmetry is also more efficacious (59%).

C. Late Stages of Sphere Construction. Originally, the phenoxymethyl substituent in **11** was excised by sequential Birch reduction, acidic hydrolysis, oxidation to **12**, and reverse Claisen reaction of **12** in alkaline solution to give **13** (Scheme III).[2] Yields in the last step are vexatiously low and variable (20–48%). Although adequate amounts of **13** were prepared by Ternansky to complete his original synthesis of **1**, there existed a clear need to upgrade the crucial elaboration of secododecahedranol (**14**) or an equivalent advanced intermediate.

Two pathways have been devised to skirt the inefficient deformylation process. The first consists simply in the direct irradiation of **12** (Scheme III). In line with expectation, excited-state decarbonylation proceeds more rapidly than homo-Norrish cyclization. After 23 h of irradiation, **14** can be isolated quantitatively or dehydrated directly to secododecahedrene in 65% overall yield. The advantages offered by this modification are obvious.

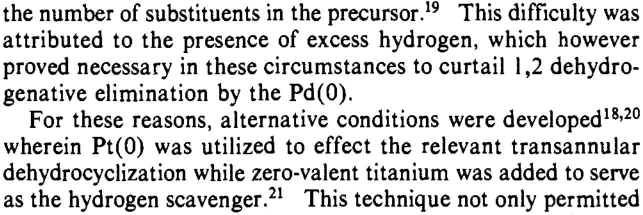
Alternatively, the side chain in **11** need not be immediately removed. Instead, this alcohol can be oxidized to diseco ketone **15**, photocyclization of which provides **16** in 72% yield (Scheme IV). When dehydration of **16** was attempted under the usual acidic conditions, cyclic ether **17** materialized as the result of intramolecular Friedel–Crafts alkylation.[18] That **18** is produced efficiently in the presence of phosphorus oxychloride and pyridine is noteworthy, since subsequent double-bond saturation with diimide and Birch reduction combine to make **20** readily available (85% overall). This primary carbinol is directly transformable into dodecahedrane (vide infra).

Scheme IV



D. Dehydrogenation of Secododecahedrane Derivatives. The final step in the synthetic pathway has posed somewhat of a different problem. Initially, installation of the final carbon–carbon bond consisted of heating an intimate mixture of secododecahedrane with hydrogen-presaturated 10% palladium on carbon at 250 °C for several hours.[2] However, this dehydrogenative process proved highly intolerant of pendant groups. In the examples studied, reductive dealkylation occurred to give **1** irrespective of the number of substituents in the precursor.[19] This difficulty was attributed to the presence of excess hydrogen, which however proved necessary in these circumstances to curtail 1,2 dehydrogenative elimination by the Pd(0).

For these reasons, alternative conditions were developed[18,20] wherein Pt(0) was utilized to effect the relevant transannular dehydrocyclization while zero-valent titanium was added to serve as the hydrogen scavenger.[21] This technique not only permitted access to di- and trimethyldodecahedranes but also made feasible as well the possibility of stepwise dehydrogenation,[22] as exemplified by the conversion of **21** to benzyldodecahedrane (**22**) at 200 °C and to **23** at somewhat higher temperatures.[18,20]



Despite this improvement, concurrent dealkylation was noted to persist (10–25%). Application of the methodology to the newly

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(15) This innovation was pioneered by R. T. Taylor and M. W. Pelter (Miami University), whom we thank.

(16) The combined experiences of P. Galatsis, T. Vandenheste, and D. Lagerwall in these laboratories.

(17) 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.

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(19) The hydrogenolytic removal of methyl groups from adamantanes and related molecules has been described: (a) Maier, W. F.; Grubmüller, P.; Thies, I.; Stein, P. M.; McKervey, M. A.; Schleyer, P. v. R. *Angew. Chem., Int. Ed. Engl.* **1979**, *18*, 939. (b) Grumbmüller, P.; Maier, W. F.; Schleyer, P. v. R.; McKervey, M. A.; Rooney, J. J. *Chem. Ber.* **1980**, *11*, 1989.

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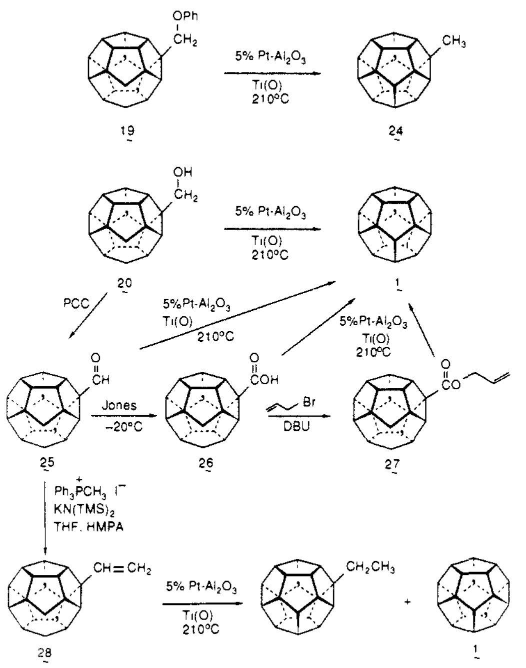
(22) For a leading reference to the mechanism of C–H activation on platinum, consult: Lebilla, C. B.; Maier, W. F. *J. Am. Chem. Soc.* **1986**, *108*, 1606.

Scheme V



available secododecahedranes **19** and **20** gave rise to methyldodecahedrane (**24**) and the parent hydrocarbon, respectively (Scheme V). Therefore, to the extent that this was to be a viable synthetic entry to functionalized derivatives, reductive cleavage had to be more stringently curtailed.

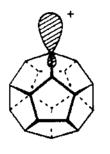
When the conversion of **20** to **1** was arrested at various points short of completion, (hydroxymethyl)dodecahedrane could not be detected. Enhancement of the oxidation level of the substituent as in **25** or **26** expectedly facilitated loss of the functional group. In the latter two examples, it is likely that the platinum preferentially abstracts a hydrogen atom from the aldehyde and carboxyl groups to liberate CO and CO_2 first.

The range of observations associated with use of the mixed-catalyst system prompted us to question how effectively the finely divided titanium was serving as hydrogen scavenger. Secododecahedranes **27** and **28** were viewed as suitable test systems since their unsaturated centers were expected to provide sites for the ready uptake of that hydrogen liberated during the dehydrocyclization step. Since the stoichiometry is balanced, either molecule should serve as its own "hydrogen sponge" and thereby curtail hydrogenolysis. Notwithstanding, allyl ester **27** continued to prove too fragile under the conventional dehydrogenation conditions, giving rise to dodecahedrane as the sole observable product. The second series of experiments involving **28** were more rewarding. In this case, ethyldodecahedrane was formed with less than 10% contamination by dodecahedrane.

Repetition of these ring closures with omission of the finely divided Ti(0) was found to give virtually identical results! In actuality, the absence of titanium has had no obvious deleterious effects on the response of any secododecahedrane yet examined. Therefore, in our more recent work, this reagent has been omitted. Two advantages accrue. The necessity to maintain the Ti(0) in an inert atmosphere at all times in order to guarantee against deactivation by reaction with air proved awkward and was scale-limiting. Physical implementation of a dehydrogenation is thereby facilitated and a reasonable increase in scale becomes possible.

Although alkyl groups remain largely unaffected during dehydrogenation, most heteroatom substituents are seen to suffer reductive cleavage at those elevated temperatures necessary for closing the sphere. In light of these failures, attention was directed to gaining access to monosubstituted dodecahedranes by functionalization of **1**.

Direct Functionalization of Dodecahedrane. At first glance, an obvious prototype for the response of **1** to electrophilic and free-radical reagents is adamantane, the chemistry of which has been very extensively studied during the past two decades.[23] However, this pair of hydrocarbons differs very significantly in many ways, although they may be loosely grouped together as globular entities. In terms of specific structural features alone, the unique geometry[8,24,25] and rigid conformational features[26] of dodecahedrane require virtually ideal sp^3 hybridization at carbon. Our expectation was that any consistuent ring atom in the framework of **1** would not readily accommodate planarity as positive charge began to develop there. More importantly, the dodecahedryl cation is clearly devoid of the normal stabilizing effect of alkyl substitution.[27] In **29**, no C–C (or C–H) bond can be oriented trans to the vacant orbital that is strongly directed to the molecular exterior. This is clearly not the case in **30**, where the strongly stabilizing triad of C–C bonds is depicted in bold lines. The situation in **29** is, in fact, akin to that in the 10-perhydrotriquinacenyl cation (**31**). The tosylate precursor to **31** experiences a 10^9-fold rate retardation in solvolysis[28] relative to the norm.[29] These properties are quite unlike the high solvolytic reactivity of *tert*-adamantyl derivatives[23,30] and directly reflect the substantive reactivity differences between **30** and **31**, and by extrapolation between **29** and **30**.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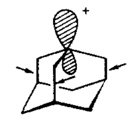
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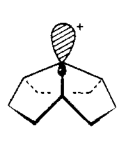
31

Where adamantane is concerned, ionic processes have shown impressive site selectivity.[23] On heating adamantane in neat bromine at the reflux temperature, the 1-bromo derivative is produced very efficiently.[31] This reaction is catalyzed by Lewis acids, thereby indicating its ionic nature. With the proper choice of catalyst and conditions, one to four bromines can be introduced sequentially into the molecule. Substitution occurs only at the tertiary carbon atoms and each bromine is in turn more difficult to introduce than the last. The cause of this increasingly attenuated reactivity is the inductive effect that the bromine atom(s) exert(s) on the other positions. With the second reactive site never more than two atoms removed, the electron-withdrawing capacity of each additional bromine atom lessens the likelihood of electrophilic attack and attendant formation of a carbocationic center. This effect is obviously very pronounced within adamantane, but can it be expected to control the regioselectivity of substitution in dodecahedrane?

In **1**, introduction of a single bromine atom would likewise impart an inductive effect that would undoubtedly be felt at all of the remaining unsubstituted centers. However, the position most remote from the seat of substitution is now five atoms removed. The electronegativity effect would be proportionately lessened,[32] but to what degree? When **1** was stirred in liquid

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(28) Bingham, R. C.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1971**, *93*, 3189.

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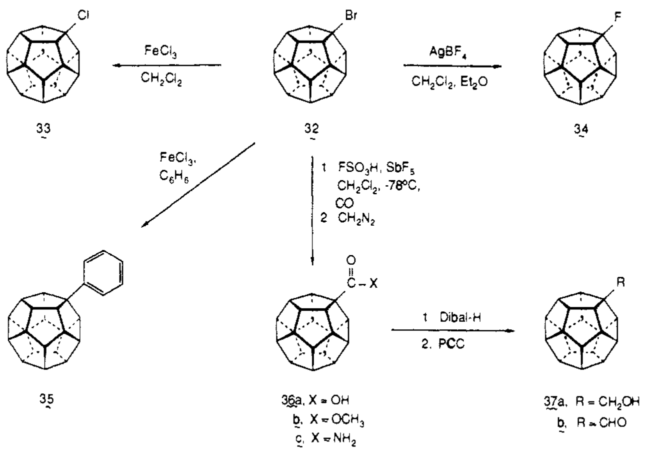
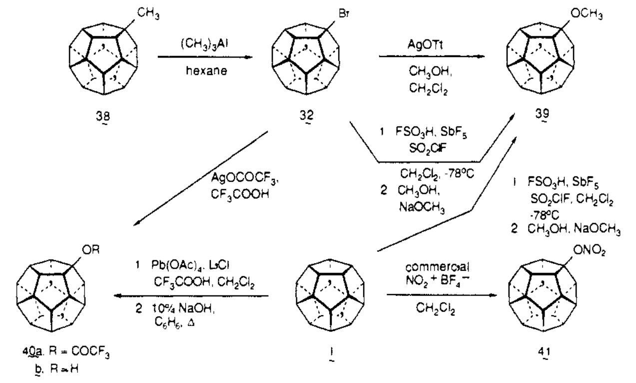
Scheme VI



Scheme VII



bromine at room temperature overnight, monobromide **32** was produced quantitatively. Close examination of such reaction mixtures gave no evidence for the formation of secondary products.

With **32** readily available, halogen exchange was made possible. Thus, chlorododecahedrane (**33**) was formed in high yield when **32** was exposed to ferric chloride in an inert solvent such as dichloromethane (Scheme VI). Use of benzene as the reaction medium offers the opportunity for electrophilic capture of the solvent and leads conveniently to the phenyl derivative **35**. Recourse to stronger Lewis acids such as $AlCl_3$ and $AlBr_3$ only induced decomposition. Despite the disclosure of effective results in the adamantane series,[33] **32** could not be transformed into the nitrile by reaction with stannic chloride and trimethylsilyl cyanide. The standard Ritter conditions[31,34] also proved ineffective. However, it was possible through the agency of silver tetrafluoroborate in dichloromethane[35] to gain access cleanly to the monofluoro derivative **34**.

When attempted Koch–Haaf carboxylation[36] of hydrocarbon **1** and bromide **32** resulted only in recovery of starting material, somewhat more forcing conditions were seen to be necessary for transient cation generation. Carboxylic acids have been prepared by exposing magic acid solutions of alkanes to carbon monoxide at low temperature.[37] In an adaptation of this protocol, **32** was dissolved at −78 °C in magic acid and carbon monoxide was bubbled through this solution. Eventual pouring into water afforded **36a**. For purification purposes, this acid was converted to methyl ester **36b**, the structural features of which have been established by X-ray crystallographic analysis.[8] Yields of **36b** approached 60% after chromatography. At this point, direct conversion to amide **36c**,[9] alcohol **37a**, and aldehyde **37b** was achieved, conventionally.

Table I. Proton NMR Chemical Shifts for Monosubstituted Dodecahedranes (300 MHz, $CDCl_3$, δ)

subst	proton type β	γ	δ, ϵ, ζ
CH_3	2.92	3.36	3.36
OH	3.23	3.55	3.35
NHCOO-*t*-Bu	3.23	3.53	3.36
$NHCOCH_3$	3.32	3.55	3.37
F	3.37	3.55	3.37
H	3.38		
OCH_3	3.49	3.37	3.37
ONO_2	3.56	3.56	3.40
Cl	3.72	3.61	3.38
COOMe	3.73	3.50	3.41
$CONH_2$	3.74	3.53	3.42
CN	3.80	3.59	3.42
Br	3.94	3.60	3.38

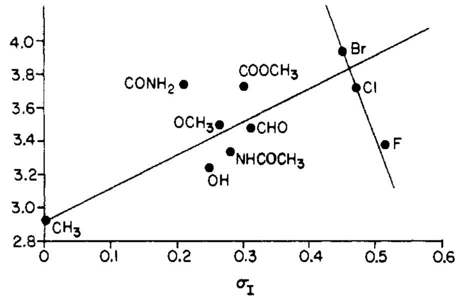


Figure 1. Correlation of β protons in monosubstituted dodecahedranes with σ_I.

Bromododecahedrane could also be transformed efficiently (90%) into the known methyl derivative (**38**)[38] by reaction with trimethylaluminum in hexane (Scheme VII).[39] Preparation of methyl ether **39** took advantage once again of the ability of silver(I) ion to induce the ionization of **32**. Addition of silver triflate to a solution of the bromide in methanol–dichloromethane (1:1) at room temperature gave **39** (71%). Alternatively, dissolution of **1** in magic acid at −78 °C and quenching of the cation solution in cold methanol containing sodium methoxide[40] delivered **39** with almost equal efficiency (61%).

Investigation of the controlled oxygenation of **1** was successful from several directions. Dodecahedranol (**40b**) was obtained in 76% yield by treatment of the hydrocarbon and lead tetraacetate in a trifluoroacetic acid–dichloromethane solvent system containing lithium chloride[41] followed directly by saponification of the trifluoroacetate **40a**. Alternatively, **40a** was made available by reaction of **32** with silver trifluoroacetate in trifluoroacetic acid at room temperature.

In the presence of *commercial* nitronium tetrafluoroborate,[42,43] solutions of dodecahedrane in chloroform furnished the nitrate

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[32] For a discussion of the effect of remote substituents on select electrophilic processes in nonspherical molecules, consult: (a) Peterson, P. E.; Allen, G. *J. Am. Chem. Soc.* **1963**, *85*, 3608. (b) Peterson, P. E.; Casey, C. *Tetrahedron Lett.* **1963**, 1569. (c) Peterson, P. E.; Casey, C.; Tao, E. V. P.; Agtarap, A.; Thompson, G. *J. Am. Chem. Soc.* **1965**, *87*, 5163. (d) Peterson, P. E.; Bopp, R. J.; Chevli, D. M.; Curran, E. L.; Dillard, D. E.; Kamat, R. J. *Ibid.* **1967**, *89*, 5902. (e) Peterson, P. E.; Chevli, D. M. *J. Org. Chem.* **1974**, *39*, 3684, and relevant references cited in these papers. For spherical molecules, the relative importance of through-space interactions also requires consideration. We hope to be in a position to report on the global impact of these electronic forces in the context of dodecahedrane chemistry at a future date.

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Table II. Carbon NMR Chemical Shifts for Monosubstituted Dodecahedranes (125 or 75 MHz, $CDCl_3$, ppm)

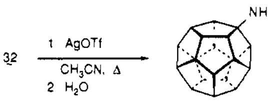
subst	carbon type					
	α	β	γ	δ	ϵ	ζ
Br	96.98	79.98	65.67	66.53	66.09	66.87
Cl	104.39	78.40	65.81	66.66	66.00	66.89
F	137.64	71.26	65.16	66.76	65.56	*a*
OH	115.99	74.95	65.71	66.99	65.71	66.89
OMe	*a*	68.90	65.47	66.98	65.77	66.79
ONO_2	129.89	70.33	65.19	66.47	65.94	66.67
$OCOCF_3$	*a*	71.65	65.34	66.51	65.90	66.69
CH_3	75.55	74.67	67.17	66.74	66.39	67.06
CH_2OH	81.86	68.91	67.10	66.54	66.56	67.02
CHO	90.00	67.23	66.96	66.86	66.91	67.11
CO_2Me	84.54	70.97	66.92	66.86	66.86	66.99
$CONH_2$	85.61	71.19	66.98	66.98	66.75	*a*
CN	*a*	73.91	67.03	66.67	66.87	*a*
Ph	84.42	75.15	67.19	67.06	66.71	*a*
$NHCOCH_3$	95.77	74.21	66.06	66.68	66.16	66.80
H	66.93					

[a] Signal not observed.

Table III. ^{13}C Substituent Effect for Monosubstituted Dodecahedranes ($\Delta\delta$, ppm for $CDCl_3$ Solutions)

subst	carbon type					
	α	β	γ	δ	ϵ	ζ
Br	30.05	12.99	−1.26	−0.40	−0.84	−0.06
Cl	37.46	11.47	−1.12	−0.27	−0.93	−0.04
F	70.71	4.33	−1.77	−0.17	−1.37	
OH	49.06	8.02	−1.22	0.06	−1.22	−0.04
OMe		1.97	−1.46	0.05	−1.16	−0.14
ONO_2	62.96	3.40	−1.74	−0.46	−0.99	−0.26
$OCOCF_3$		4.72	−1.59	−0.42	−1.03	−0.24
CH_3	8.62	7.74	0.24	−0.19	−0.54	0.13
CH_2OH	14.93	1.98	0.17	−0.39	−0.37	0.07
CHO	23.07	0.30	0.03	−0.07	−0.02	0.18
CO_2Me	17.61	4.04	−0.01	−0.07	−0.07	0.06
$CONH_2$	18.68	4.26	0.05	0.03	−0.18	
CN		6.98	0.10	−0.26	−0.06	
Ph	17.49	8.22	0.26	0.13	−0.22	
$NHCOCH_3$	28.84	7.28	−0.87	−0.25	−0.77	−0.13

ester **41** in 84% yield. Finally, formation of *N*-dodecahedrylacetamide (**42**) was ultimately achieved by again making recourse to the triflate.[44] Suspension of bromide **32** and silver triflate in hot acetonitrile followed by hydration made **42** available in quantitative yield.



42

Spectral Characteristics of the Monosubstituted Dodecahedranes. The availability of the functionalized dodecahedranes described earlier has made possible a comprehensive analysis of general trends in their ^1H and ^{13}C NMR spectra. These data have significance since no closely comparable prototypes have previously been examined. In addition, since the dodecahedrane framework is extremely rigid and substituents do little to alter the 0° dihedral angle between vicinal protons,[8,24,35] the interrelationship between the several types of all-eclipsed protons and the observed chemical shifts (also coupling constants when measurable) are of more than passing theoretical interest.

The signals attributable to the β-, γ-, and δ–ζ-hydrogens in the monosubstituted dodecahedranes are usually well separated (Table I). The β protons are expectedly most responsive to substituent electronegativity and correlate well with σ_I values,[45] although a separate line is needed for the halogen substituents[46] (Figure 1). Although the halogen effect may seem unusual, the response of monohalogenated adamantanes is rather comparable. Comparison with Figure 11 of ref 46 is recommended.

To achieve proper interpretation of the ^{13}C NMR spectra, 2D C–H correlations were performed on select dodecahedranes within each substitution class. Striking trends are observed. Whereas halogens and other heteroatomic groups (as **32**–**34** and **42**) exert a modest shielding effect on the β-carbons, the same atoms in the C–C-bonded examples **35**–**38** are downfield shifted (Tables II and III). These effects are at odds relative to those found earlier for monosubstituted cyclohexyl[47a] and 1-adamantyl systems,[47b] where paramagnetic shielding universally operates. The chemical shifts of all quaternary carbons correlate particularly well with corresponding data derived from *tert*-butyl systems[46] (Figure 2). Since the β-carbon shifts also show a trend correlatable with the methyl group signals of $(CH_3)_3C–X$,[48] steric and electronic effects at this level appear comparable. A more detailed explication of these findings awaits additional work currently in progress.

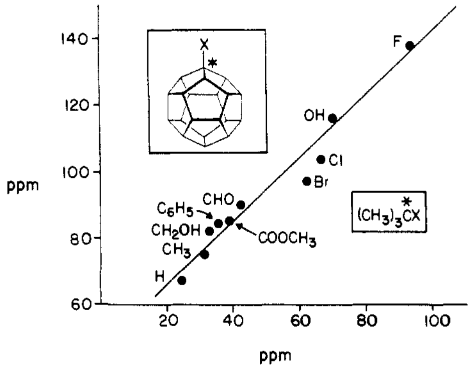


Figure 2. Correlation of ^{13}C chemical shifts of the quaternary carbons in monosubstituted dodecahedranes and *tert*-butyl derivatives.

In aliphatic compounds, no substituent effect on δ-carbons is usually observed. The C-4 atoms of cyclohexyl derivatives are shifted to high field by as much as 2 ppm when a strongly electronegative group resides at C-1.[47a] An analogous situation is observed in adamantyl derivatives, again with shifts up to 2.3 ppm.[47b] As concerns dodecahedranes, the $\Delta\delta$ values fluctuate from upfield to downfield depending on the substituent (Tables II and III). Only a very small shift is observed throughout the entire series, the maximum amounting to only 0.46 ppm. Accordingly, the effect on the δ-carbons of monofunctionalized dodecahedranes is very small and nonunidirectional relative to cyclohexyl-derived models.

Experimental Section

9,10-Dihydrofulvalene (2). A 5-L three-necked flask was fitted with a Hirschberg stirrer, gas inlet, and septum, flame-dried under vacuum, and allowed to cool to room temperature under a positive pressure of dry, oxygen-free argon. Dry sodium hydride (100 g, 4.17 mol) was introduced, and anhydrous tetrahydrofuran was added via cannula under argon pressure. The stirred suspension was cooled in an ice bath while cold (−78 °C), freshly distilled cyclopentadiene (275 g, 4.17 mol) was likewise transferred dropwise over 30–40 min via cannula. Upon completion of the addition, the cooling bath was removed and the reaction mixture was stirred at room temperature for 1 h. Cuprous bromide–dimethyl sulfide complex was added, the anion solution was cooled to −78 °C, and a solution of sublimed iodine (530 g, 2.08 mol) in 500 mL of anhydrous tetrahydrofuran was introduced to the cold slurry during 90 min.

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Domino Diels–Alder Reaction. The preceding solution was stirred for 15 min at −78 °C and treated with dimethyl acetylenedicarboxylate (330 g, 2.32 mol) via cannula over 10 min. After 30 min, the cooling bath was removed and stirring was maintained for 4 h. The subsequent workup and partial saponification was performed as previously described[10] to give diacid **3** in 8–13% yield (42–74.5 g).

Diethyl Decahydro-1,5-*endo*,*endo*-dihydroxy-2,6-*exo*,*exo*-diiodo-3,4,6-metheno-7*H*-cyclopenta[*a*]pentalene-7,8-dicarboxylate (5). A dry and well-powdered sample of iodolactone **4** (72.7 g, 0.147 mol) was suspended in absolute ethanol (300 mL). With good mechanical stirring, sodium ethoxide solution (3 mL, obtained by dissolving 0.5 g of sodium in 20 mL of absolute ethanol) was added dropwise until a pH of 9–10 was arrived at. Within 10 min, a color change from yellow to brown occurred with evolution of heat. After 2 h of stirring, the solvent was removed on a rotary evaporator. The residue was dissolved in dichloromethane (400 mL) and filtered. The filtrate was washed with sodium thiosulfate solution and water, dried, and evaporated. Trituration with ethanol gave 82.7 g (95.9%) of **5** as colorless crystals: mp 136.0–136.5 °C dec (from ethanol); IR (KBr) 3430, 3240, 2970, 1738, 1691, 1299, 1291, 1100, 1093 cm^{-1}; ^{1}H NMR (300 MHz, CDCl$_3$) δ 4.72 (d, J = 4.1 Hz, 2 H), 4.33 (d, J = 3.9 Hz, 2 H), 4.26 (q, J = 7.2 Hz, 4 H), 4.03 (br s, 2 H), 2.942 (s, 2 H), 2.937 (s, 2 H), 2.63 (narrow m, 2 H), 1.32 (t, J = 7.2 Hz, 6 H); ^{13}C NMR (20 MHz, CDCl$_3$) 172.61, 84.78, 67.34, 62.29, 62.10, 59.16, 45.36, 27.03, 13.98 ppm; MS, m/z (M$^+$) calcd 587.9509, obsd 587.9497. Anal. Calcd for C$_{18}$H$_{22}$I$_2$O$_6$: C, 36.76; H, 3.77. Found: C, 36.91; H, 3.90.

Diethyl Decahydro-1,5-*exo*,*exo*-diiodo-2,6-dioxo-3,4,7-metheno-7*H*-cyclopenta[*a*]pentalene-7,8-dicarboxylate (6). A cold (5 °C), stirred solution of **5** (79.0 g, 0.134 mol) in acetone (1000 mL) was treated dropwise with 400 mL of a stock solution prepared from 200 g of sodium dichromate dihydrate, 272 g of concentrated sufuric acid, and 600 mL of water. The rate of addition was controlled so that the temperature did not rise above 5 °C during the entire 2-h period. The reaction mixture was stirred at room temperature for 30 min, at which point the acetone solution was decanted from the chromium salts. Most of the acetone was evaporated under reduced pressure, and the residue was partitioned between water and dichloromethane (300 mL). The aqueous phase was extracted with dichloromethane (3 × 100 mL), and the combined organic phases were washed twice with water, dried, and evaporated. Recrystallization of the resulting solid from ethanol gave **6** as white crystals: mp 167.0–167.5 °C (73.1 g, 91.9%); IR (KBr) 2980, 1755, 1720, 1370, 1315, 1165, 1100 cm^{-1}; ^{1}H NMR (300 MHz, CDCl$_3$) δ 4.95 (s, 2 H), 4.07 (q, J = 7.2 Hz, 4 H), 3.21 (narrow m, 2 H), 3.12 (narrow m, 2 H), 3.03 (narrow m, 2 H), 1.16 (t, J = 7.2 Hz, 6 H); ^{13}C NMR (20 MHz. CDCl$_3$) 205.06, 167.50, 67.98, 62.80, 62.10, 60.37, 46.90, 20.45, 13.74 ppm; MS, m/z (M$^+$ − I) calcd 457.0150, obsd 457.0171. Anal. Calcd for C$_{18}$H$_{18}$I$_2$O$_6$: C, 37.01; H, 3.10. Found: C, 37.16; H, 3.18.

Diethyl Decahydro-1,5-dioxo-3,4,7-metheno-7*H*-cyclopenta[*a*]pentalene-7,8-dicarboxylate (7). In a 5-L three-necked reaction flask, copper(II) acetate monohydrate (5.88 g) was dissolved in acetic acid (300 mL) under an inert atmosphere. Zinc dust (88.4 g) was added with vigorous stirring. The greenish-blue color of the solution faded quickly, and the warm reaction mixture was filtered under a nitrogen stream. The couple was washed well with acetic acid (2 × 200 mL), ether (6 × 200 mL), and finally methanol (3 × 200 mL). To a suspension of this material in methanol (3 mL) was added **6** (122.6 g, 0.21 mol) and ammonium chloride (104.7 g). The heterogeneous mixture was stirred for 6 h under nitrogen. The supernatant solution was decanted and concentrated. The residual metal and salts were washed with dichloromethane (600 mL), and the washings were combined with the concentrate. This solution was washed with saturated ammonium chloride solution (2×) and water (1×) prior to drying. Solvent evaporation and crystallization from ethanol gave **7** as colorless prisms: mp 155.0–155.5 °C (58.2 g, 83.2%); IR (KBr) 2990, 1748, 1720, 1400, 1370, 1310, 1140 cm^{-1}; ^{1}H NMR (300 MHz, CDCl$_3$) δ 4.05 (q, J = 7.2 Hz, 4 H), 2.98 (narrow m, 4 H), 2.90 (s, 2 H), 2.76 ($^{1}/_{2}$AB d, J = 19.4 Hz, 2 H), 2.23 ($^{1}/_{2}$AB d, J = 19.4 Hz, 2 H), 1.18 (q, J = 7.2 Hz, 6 H); ^{13}C NMR (20 MHz, CDCl$_3$) 211.26, 168.72, 68.74, 61.40, 60.69, 52.90, 47.85, 36.80, 13.76 ppm; MS, m/z (M$^+$) calcd 332.1260, obsd 332.1246. Anal. Calcd for C$_{18}$H$_{20}$O$_6$: C, 65.05; H, 6.07. Found: C, 64.94; H, 6.07.

Diethyl 1,2,3,3b,4a,5,6,6,8,8a,8b,9-Dodecahydro-1,5-dioxo-4,8,9-metheno-4*H*-cyclopenta[1,2-*a*:4,3-*a*′]dipentalene-4,10-dicarboxylate (8). A solution of **7** (17.5 g, 0.0527 mol) and cyclopropyldiphenylsulfonium tetrafluoroborate (136.0 g, 0.432 mol) in anhydrous dimethyl sulfoxide (400 mL) was prepared under argon in a 1-L three-necked flask. Powdered potassium hydroxide (11.6 g of 85% purity, 0.176 mol) was introduced. The red color that was immediately generated gradually faded to yellow. The reaction mixture was stirred magnetically for 2 days at room temperature. At this point, aqueous fluoroboric acid (45 g of 50% HBF$_4$ diluted to 250 mL) was added. After an additional hour of stirring, the solution was diluted with water (650 mL) and the acidic mixture was extracted with dichloromethane (2 × 300 mL, 4 × 200 mL). The combined organic layers were washed with water (2 × 300 mL), dried, filtered, and evaporated. The crystalline solid that materialized was separated by filtration and washed with ethanol (2 × 50 mL). The recovered sulfonium fluoroborate weighed 89 g.

The filtrates from two reactions as above were combined, diluted with methylene chloride (400 mL), and adsorbed onto silica gel (150 g). This material was placed atop a column of fine silica gel (TLC grade, 160 g). Initial elution with 10% ether in petroleum ether (2 L) removed sulfide impurities. The spirocyclobutanones were eluted with ethyl acetate (2 L) and obtained as a semisolid mixture (41.4 g) that was employed directly in the next step.

Dissolution of this semisolid in methanol (800 mL) was followed by addition of 30% hydrogen peroxide (50 g) and sodium hydroxide solution (18.6 mL of 10 N) at room temperature. Following the exothermic reaction that occurs, the reaction mixture was stirred at room temperature for 2 h and treated with dilute hydrochloric acid (50 mL of concentrated acid with 1 L of water). The product was extracted into dichloromethane (6 × 300 mL), and the combined organic phases were washed with water (2 × 300 mL), dried, and concentrated to a volume of ca. 100 mL on a rotary evaporator.

Into a 3-L Morton flask equipped with an efficient stirrer, thermometer, and nitrogen inlet was placed 1200 mL of freshly distilled methanesulfonic acid. With stirring, the acid was heated to 50 °C, phosphorus pentoxide (180 g) was introduced, and the mixture was stirred at 50 °C under a nitrogen atmosphere for 1 day. The above bis(spirolactone) solution was added portionwise over 10 min, and stirring at the same temperature was resumed for 2 days. After being cooled, the reaction mixture was added slowly to ice water (3.5 L) with occasional swirling. The aqueous phase was extracted with dichloromethane (6 × 300 mL), and the combined organic layers were washed with water and saturated sodium bicarbonate solution prior to drying. The dichloromethane solution was filtered through a column of silica gel (55 × 300 mm). Elution with ethyl acetate and concentration afforded 25.3 g (58.5% overall) of **8** as colorless plates: mp 203.5–204.5 °C (from ethanol); IR (KBr) 2970, 1724, 1685, 1623, 1395, 1294, 1090 cm^{-1}; ^{1}H NMR (300 MHz, CDCl$_3$) δ 3.93 (m, 4 H), 3.611 (s, 2 H), 3.606 (s, 2 H), 3.13 (narrow m, 2 H), 2.9–2.5 (m, 8 H), 1.08 (t, J = 7.2 Hz, 6 H); ^{13}C NMR (75 MHz, CDCl$_3$) 202.12, 185.45, 169.99, 147.12, 70.85, 63.50, 62.87, 61.14, 59.42, 39.74, 25.94, 13.68 ppm; MS, m/z (M$^+$) calcd 408.1573, obsd 408.1570. Anal. Calcd for C$_{24}$H$_{24}$O$_6$: C, 70.58; H, 5.92. Found: C, 70.57; H, 5.93.

Diethyl Hexadecahydro-1,5-dioxo-4,8,9-methenocyclopenta[1,2-*a*:4,3-*a*′]pentalene-4,10-dicarboxylate (9). Bis(cyclopentenone) **8** (15.0 g, 36.7 mmol) was dissolved in a mixture of ethanol (130 mL) and ethyl acetate (40 mL) with warming. Palladium on carbon (1.0 g of 10%) was added, and hydrogenation was effected on a Paar apparatus at an initial pressure of 50 psi for 6 h. The catalyst was removed by filtration, and the filtrate was concentrated and allowed to crystallize to give 14.6 g (96.6%) of **9** as colorless prisms: mp 148.5–150 °C (from ethanol); IR (KBr) 2960, 1725, 1366, 1297, 1283, 1220, 1134, 1100, 1092 cm^{-1}; ^{1}H NMR (300 MHz, CDCl$_3$) δ 4.09 (q, J = 7.2 Hz, 4 H), 2.09 (br d, 2 H), 2.81 (m, 4 H), 2.69 (br d, 2 H), 2.65 (br s, 2 H), 2.5–1.9 (series of m, 8 H), 1.25 (t, J = 7.2 Hz, 6 H); ^{13}C NMR (75 MHz, CDCl$_3$) 217.01, 171.27, 62.23, 61.20, 60.44, 57.05, 53.03, 51.88, 43.25, 38.91, 24.67, 13.87 ppm; MS, m/z (M$^+$) calcd 412.1890, obsd 412.1900. Anal. Calcd for C$_{24}$H$_{28}$O$_6$: C, 69.89; H, 6.84. Found: C, 69.95; H, 6.82.

Tetradecahydro-5*H*,6*H*-1,5b,12:5a,10,11-dimethenodicyclopenta[*e*,*e*′]benzo[2,1-*c*:3,4-*c*′]dipyran-5,6-dione (10). To a solution of **9** (18.2 g, 44.1 mmol) in 400 mL of methanol was added bromocresol green and sodium cyanoborohydride (11.0 g). As the resulting blue reaction mixture was stirred, 2 N methanolic hydrogen chloride was introduced dropwise to maintain a yellow titration point. After ~8 h and addition of 75 mL of acid, reduction was judged complete on the basis of the persistence of the yellow color and the cessation of hydrogen evolution. A final 25 mL of acid was added, and the solution was stirred an additional 2 h before solvent evaporation. The residue was treated with water, and the product was extracted into dichloromethane (1 × 300 mL, 4 × 100 mL). The combined organic layers were washed with water, dried, and evaporated. To complete the lactonization process, the semisolid was dissolved in benzene (700 mL) containing *p*-toluenesulfonic acid (10 mg) and this solution was heated at reflux for 8 h with periodic removal of small volumes of distillate. A total of 100 mL was collected in this fashion. On cooling, colorless needles of **10** formed. Further concentration of the filtrate gave additional bis(lactone). The total weight was 12.70 g (88.8%), and the spectra were identical to those reported earlier.[17]

Direct Irradiation of 12. A solution of **12** (58 mg, 0.19 mmol) in 4:1 benzene–*tert*-butyl alcohol (10 mL) containing 3 drops of triethylamine was deoxygenated with argon and irradiated with a 450-W Hanovia lamp through a Pyrex filter for 23 h. The solution was concentrated to give secododecahedranol **14** quantitatively.

Routinely, this alcohol was heated with a few crystals of *p*-toluenesulfonic acid in benzene for 4 h. These conditions furnished secododecahedrene in 65% yield after chromatography on silica gel.

Octadecahydro-7f-(phenoxymethyl)-1,6,7-metheno-1*H*-cyclopenta[3,4]pentaleno[2,1,6-*gha*]pentaleno[1,2,3-*cd*]pentalen-2-one (15). A mixture of epimeric alcohols **11** (345.4 mg, 0.89 mmol) in dry dichloromethane (5 mL) was rapidly added dropwise to a suspension of pyridinium chlorochromate (481 mg, 2.23 mmol), dry sodium acetate (367 mg, 4.47 mmol), and dry Celite (400 mg) in the same solvent (10 mL) and stirred for 5 h under an argon atmosphere. Ether (50 mL) was added dropwise to precipitate the inorganic salts, and the mixture was passed through a silica gel plug (elution with dichloromethane). Concentration gave ketone **15** as a white foam, which was normally used without further purification. Purification for spectral data was achieved by MPLC (85% petroleum ether–7.5% ethyl ether–7.5% dichloromethane elution). Recrystallization from acetone yielded colorless crystals: mp 61–63 °C; IR ($\mathrm{CHCl_3}$) 2970, 1720, 1600, 1580, 1490, 1450, 1370, 1210, 1040 cm^{-1}; ^{1}H NMR (300 MHz, $\mathrm{CDCl_3}$) δ 7.26–7.21 (m, 2 H), 6.93–6.79 (m, 3 H), 4.18 (d, $J = 7.7$ Hz, 1 H), 3.63 (d, $J = 7.7$ Hz, 1 H), 3.63–1.50 (series of m, 21 H); ^{13}C NMR (75 MHz, $\mathrm{CDCl_3}$) 226.03, 158.96, 129.15, 120.69, 114.80, 76.73, 69.38, 67.62, 67.50, 67.29, 67.07, 64.95, 62.22, 61.35, 59.97, 58.39, 58.11, 53.87, 51.98, 51.81, 50.73, 49.56, 36.66, 30.79, 27.31 ppm; MS, *m/z* (M$^+$) calcd 384.2090, obsd 384.2132.

Hexadecahydro-7-(phenoxymethyl)-1,6,2,5-ethanediylidenecyclopenta[3,4]pentaleno[2,1,6-*cde*]pentaleno[2,1,6-*gha*]pentalen-3b(1*H*)-ol (16). Unpurified ketone **15** was taken up in a benzene–*tert*-butyl alcohol solution (20 mL, 4:1 volume), and triethylamine (20 drops) was added. The solution was deoxygenated with argon for 30 min and irradiated with a 450-W Hanovia lamp for 13 h. Evaporation and purification by MPLC (elution with 85% petroleum ether–7.5% dichloromethane–7.5% ether) gave 246.7 mg (71.8% overall) of **16** as colorless crystals: mp 111–113 °C (from acetone); IR ($\mathrm{CHCl_3}$) 3540, 3000, 2930, 2860, 1595, 1580, 1485, 1230, 1025 cm^{-1}; ^{1}H NMR (300 MHz, $\mathrm{CDCl_3}$) δ 7.31–7.28 (m, 2 H), 6.98–6.92 (m, 3 H), 4.00 (s, 2 H), 3.56–2.89 (series of m, 19 H), 1.67–1.60 (m, 2 H); ^{13}C NMR (75 MHz, $\mathrm{CDCl_3}$) 158.70, 129.35, 121.06, 114.87, 97.20, 82.24, 73.97, 69.08, 67.55, 65.57, 64.90, 64.19, 60.91, 60.88, 52.98, 48.94, 32.08 ppm (one signal not observed); MS, *m/z* (M$^+$) calcd 384.2089, obsd 384.2122.

Acid-Catalyzed Dehydration of 16. *p*-Toluenesulfonic acid (6 mg) was added to a solution of **17** (25.1 mg, 0.07 mmol) in dry benzene (3 mL), and the reaction mixture was heated at 70 °C under argon for 3 h. Evaporation of solvent from the cooled reaction mixture left a pale yellow solid which was taken up in dichloromethane and passed through a short silica gel column. There was isolated 24.5 mg (98%) of **17**: ^{1}H NMR (300 MHz, $\mathrm{CDCl_3}$) δ 7.28–7.25 (m, 1 H), 7.04–6.95 (m, 2 H), 6.87–6.84 (m, 1 H), 3.74 (s, 2 H), 3.61–3.44 (m, 5 H), 3.27–2.95 (m, 13 H), 1.73–1.57 (m, 2 H); ^{13}C NMR (75 MHz, $\mathrm{CDCl_3}$) 153.17, 145.68, 126.94, 124.99, 122.56, 116.88, 82.79, 69.35, 67.70, 66.93 (2 C), 66.07 (2 C), 64.60 (2 C), 63.25 (2 C), 61.85 (2 C), 60.56, 53.10 (2 C), 49.38, 32.66 (2 C) ppm; MS, *m/z* (M$^+$) calcd 366.1983, obsd 366.1967.

1,1a,1b,2,3,3a,4,5,5a,6,6a,6b,6c,6d,6e,6f-Hexadecahydro-7-(phenoxymethyl)-1,6,2,5-ethanediylidenecyclopenta[3,4]pentaleno[2,1,6-*cde*]pentaleno[2,1,6-*gha*]pentalene (18). Alcohol **16** (238.4 mg, 0.620 mmol) was dissolved in dry benzene (35 mL) and dry pyridine (15 mL). This solution was treated with distilled phosphorus oxychloride (4 mL) and heated at 55 °C for 10 h under an argon atmosphere. The solution was carefully poured onto cold dilute hydrochloric acid (20 mL) and extracted with methylene chloride (3 × 100 mL). The organic extracts were washed with brine and dried. Filtration and solvent removal gave an oil which was customarily used without further purification. Recrystallization from acetone for spectral analysis afforded colorless crystals: mp 106–109 °C; IR ($\mathrm{CHCl_3}$) 3000, 2940, 2860, 1700, 1595, 1580, 1440, 1290, 1240, 1030 cm^{-1}; ^{1}H NMR (300 MHz, $\mathrm{CDCl_3}$) δ 7.28–7.22 (m, 2 H), 6.93–6.88 (m, 3 H), 3.92 (s, 2 H), 3.50–2.86 (m, 16 H), 1.96–1.92 (m, 1 H), 1.63–1.55 (m, 2 H); ^{13}C NMR (75 MHz, $\mathrm{CDCl_3}$) 159.68, 143.40, 141.85, 129.16, 120.19, 114.65, 82.34, 73.60, 66.98, 66.95, 66.45, 64.06, 63.86, 62.12, 61.21, 60.35, 60.30, 59.24, 59.09, 52.63, 51.83, 50.79, 48.08, 33.12, 30.45 ppm; MS, *m/z* (M$^+$) calcd 366.1983, obsd 366.1947.

Octadecahydro-7-(phenoxymethyl)-1,6,2,5-ethanediylidenecyclopenta[3,4]pentaleno[2,1,6-*cde*]pentaleno[2,1,6-*gha*]pentalene (19). The secododecahedrene from above was dissolved in dry tetrahydrofuran (90 mL), and glacial acetic acid (4 drops), saturated copper sulfate solution (4 drops), and hydrazine hydrate (1.41 g, 28.2 mmol, 1.37 mL) were added. The mixture was vigorously stirred under argon while a solution of sodium periodate (753 mg, 3.52 mmol) in water (4 mL) was added over a 1-h period and stirred for an additional hour. The reaction mixture was diluted with water (100 mL) and extracted with dichloromethane (3 × 150 mL). The organic layers were washed once with brine and dried. Evaporation and recrystallization from acetone gave 206.1 mg (90.2% overall from **16**) of **19** as colorless crystals: mp 94–95 °C; IR ($\mathrm{CHCl_3}$) 3000, 2830, 1595, 1590, 1485, 1410, 1360, 1220, 1085, 1030 cm^{-1}; ^{1}H NMR (300 MHz, $\mathrm{CDCl_3}$) δ 7.28–7.22 (m, 2 H), 6.93–6.88 (m, 3 H), 3.73 (s, 2 H), 3.57–2.86 (series of m, 19 H), 1.61–1.51 (m, 2 H); ^{13}C NMR (75 MHz, $\mathrm{CDCl_3}$) 159.77, 129.22, 120.20, 114.62, 82.65, 76.64, 69.26, 67.73, 65.86, 65.68, 64.72, 61.97, 53.24, 52.83, 52.60, 49.87, 32.17 ppm; MS, *m/z* (M$^+$) calcd 368.2140, obsd 368.2164. Anal. Calcd for $\mathrm{C_{27}H_{28}O}$: C, 88.00; H, 7.66. Found: C, 87.57; H, 7.70.

Octadecahydro-1,6,2,5-ethanediylidenecyclopenta[3,4]pentaleno[2,1,6-*cde*]pentaleno[2,1,6-*gha*]pentalene-7-methanol (20). A solution of **19** (206.1 mg, 0.559 mmol) in dry tetrahydrofuran (80 mL) was added to anhydrous ammonia (80 mL) at the reflux temperature. Absolute ethanol (8 mL) was introduced, followed by the portionwise addition of sodium metal (643 mg, 28.0 mmol). The ammonia was allowed to evaporate, and the mixture was diluted with water (100 mL) and extracted with dichloromethane (3 × 100 mL). The combined extracts were washed with water and dried. Evaporation gave the dienol ether which was taken up in tetrahydrofuran (10 mL) and treated with 3 M hydrochloric acid (4 mL). The solution was stirred overnight (16 h), diluted with dichloromethane (20 mL), and washed with water and saturated sodium bicarbonate solution. Drying and evaporation yielded a white solid which was chromatographed over silica gel (elution with 10% ethyl acetate in petroleum ether) to give pure **19** (152.5 mg, 93.3%) as a white solid: mp >240 °C (from acetone); IR ($\mathrm{CHCl_3}$) 3350, 3005, 2910, 2840 cm^{-1}; ^{1}H NMR (300 MHz, $\mathrm{CDCl_3}$) δ 3.54–2.69 (series of m, 22 H), 1.57–1.45 (m, 2 H); ^{13}C NMR (75 MHz, $\mathrm{CDCl_3}$) 84.70, 71.81, 69.27, 67.88, 65.79, 65.67, 64.15, 62.05, 52.95, 52.85, 52.71, 49.94, 32.25 ppm; MS, *m/z* (M$^+$ – $\mathrm{H_2O}$) calcd 274.1722, obsd 274.1756.

Secododecahedrane-7-carboxaldehyde (25). Alcohol **20** (30.7 mg, 0.105 mmol) in dry dichloromethane (3 mL) was added dropwise to a suspension of pyridinium chlorochromate (40.7 mg, 0.189 mmol), dry sodium acetate (25 mg, 0.305 mmol), and dry Celite (60 mg) in the same solvent (3 mL), and the resultant mixture was stirred at room temperature for 3 h. Ether (10 mL) was added, and the mixture was passed through a silica gel plug (elution with 10% ethyl acetate in petroleum ether) to give 27.9 mg (91.5%) of **25** as a white solid: mp >240 °C (from acetone); IR ($\mathrm{CHCl_3}$) 3030, 2940, 2880, 2700, 1700 cm^{-1}; ^{1}H NMR (300 MHz, $\mathrm{CDCl_3}$) δ 9.47 (s, 1 H), 3.60–3.03 (series of m, 19 H), 1.63–1.53 (m, 2H); ^{13}C NMR (75 MHz, $\mathrm{CDCl_3}$) 201.32, 92.56, 69.43, 68.28, 65.86, 65.68, 62.62, 61.86, 53.16, 52.88, 50.17, 49.86, 32.10 ppm; MS, *m/z* (M$^+$) calcd 290.1670, obsd 290.1654.

Secododecahedrane-7-carboxylic Acid (26). Aldehyde **25** (19.0 mg, 0.065 mmol) was suspended in acetone (3 mL) at room temperature, and dry tetrahydrofuran (3 mL) was added until dissolution of the aldehyde was complete. The solution was cooled to –45 °C, and Jones reagent (1 mL) was added. The reaction mixture was stirred for 1 h, quenched with excess isopropyl alcohol at –45 °C, allowed to warm to room temperature, and diluted with water (10 mL). The solution was extracted with ether (3 × 30 mL), and the combined extracts were washed with water and dried. Evaporation yielded 16.9 mg (84.5%) of **26** as a white solid: mp >240 °C (acetone); IR ($\mathrm{CHCl_3}$) 3400–2700 (br), 2930, 2860, 1680 cm^{-1}; ^{1}H NMR (300 MHz, $\mathrm{CDCl_3}$) δ 3.54–2.99 (series of m, 19 H), 1.59–1.54 (m, 2 H); ^{13}C NMR (75 MHz, $\mathrm{C_6D_6}$) 87.50, 69.52, 68.32, 66.53, 66.16, 65.92, 62.11, 55.54, 53.40, 53.14, 49.91, 32.10 ppm (carboxyl carbon not observed); MS, *m/z* (M$^+$) calcd 306.1620, obsd 306.1651.

7-Vinylsecododecahedrane (28). Methyltriphenylphosphonium iodide (197 mg, 0.487 mmol) was suspended in dry tetrahydrofuran (6 mL) and hexamethylphosphoramide (0.6 mL) under an argon atmosphere. To this mixture was added potassium hexamethyldisilazide (0.52 mL of 0.9 M in THF, 0.468 mmol) at room temperature. After 15 min of stirring, the bright yellow solution was cooled to –78 °C and **25** (28.3 mg, 0.0975 mmol) in dry tetrahydrofuran (5 mL) was added. The reaction mixture was allowed to warm to ambient temperature, stirred for an additional hour, quenched by the addition of sodium sulfate hexahydrate, and passed through a silica gel plug. Recrystallization from acetone yielded 24.8 mg (88.2%) as a colorless crystalline solid: mp >230 °C; IR ($\mathrm{CHCl_3}$) 2950, 1630, 905 cm^{-1}; ^{1}H NMR (300 MHz, $\mathrm{CDCl_3}$) δ 6.12 (dd, $J = 10.4$, 17.2 Hz, 1 H), 4.87 (d, $J = 17.2$ Hz, 1 H), 4.68 (d, $J = 11.1$ Hz, 1 H), 3.56–2.94 (series of m, 19 H), 1.57–1.52 (m, 2 H); ^{13}C NMR (75 MHz, $\mathrm{CDCl_3}$) 151.30, 104.33, 69.29, 67.87, 67.63, 65.97, 65.74, 62.01, 56.42, 53.41, 52.83, 52.40, 49.93, 32.22 ppm; MS, *m/z* (M$^+$) calcd 288.1878, obsd 288.1908.

Allyl Secododecahedrane-7-carboxylate (27). A solution of **26** (10.6 mg, 0.0346 mmol) in dry benzene (1 mL) was treated with 1,8-diazabicyclo[5.4.0]undec-7-ene (2 drops). The mixture was stirred vigorously at room temperature under argon for 1 h, at which time the mixture was passed through a silica gel column (elution with 10% ethyl acetate in petroleum ether) to give 11.7 mg of a white solid. Recrystallization from acetone yielded 10.6 mg (88.3%) of **27** as colorless crystals: mp 124.0–124.5 °C; IR ($CHCl_3$) 2930, 2860, 1740, 1100 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.98–5.86 (m, 1 H), 5.35–5.18 (m, 2 H), 4.56 (d, J = 5.4 Hz, 2 H), 3.57–2.98 (series of m, 19 H), 1.61–1.51 (m, 2 H); ^{13}C NMR (75 MHz, $CDCl_3$) 178.95, 132.74, 117.10, 87.27, 69.36, 67.99, 66.19, 65.74, 65.69, 64.86, 61.88, 55.21, 53.98, 52.93, 49.75, 31.95 ppm; MS, m/z (M^+) calcd 346.1933, obsd 346.1922.

Prototypical Reductive Catalytic Dehydrogenations. A. Dodecahedrane. Alcohol **20** (23.2 mg, 0.079 mmol) and 5% platinum on alumina (420 mg) were distributed equitably among four 7-mm Pyrex tubes. Each tube was sealed under high vacuum to a length of ~5 cm. The four reaction vessels were vigorously shaken, wrapped in aluminum foil, and immersed in a silicone oil bath at 210 °C. Heating was maintained for 8 h with interruption every 2 h for physical mixing of the contents. The cooled tubes were opened, and the solid was placed directly on top of a silica gel plug. Elution with benzene (50 mL) gave a white solid which was washed twice with ether to give pure **1** (11.5 mg, 55.6%).

B. Ethyldodecahedrane.[49] A mixture of **28** (11.0 mg, 0.0382 mmol) and 5% platinum on alumina (620 mg) was placed in a Pyrex tube and sealed under high vacuum. The contents were mixed, and the tube was submersed in a silicone oil bath at 210 °C for 7 h. The tube was cooled, the powder was placed atop a silica gel column, and the products were eluted with benzene. Trituration of the residue with acetone afforded 10.0 mg (90.0%) of an 8.7:1 mixture of ethyldodecahedrane and **1** (capillary GC analysis). For ethyldodecahedrane: IR ($CHCl_3$) 2940, 1180, 910 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 3.37 (s, 16 H), 3.01 (br s, 3 H), 1.38 (q, J = 7.3 Hz, 2 H), 0.84 (t, J = 7.3 Hz, 3 H); ^{13}C NMR (75 MHz, $CDCl_3$) 80.51, 71.23, 67.19, 67.02, 66.64, 66.52, 35.99, 10.09 ppm; MS, m/z (M^+) calcd 288.1859, obsd 288.1878.

Bromododecahedrane (32).[49] Dodecahedrane (12.7 mg, 0.488 mmol) was dissolved in neat bromine (3 mL) and stirred at room temperature for 24 h. After this time, the excess bromine was evaporated under a stream of argon and the resultant solid was taken up in dichloromethane. The solution was swirled with powdered sodium thiosulfate until colorless, dried by addition of anhydrous magnesium sulfate, and passed through a short silica gel column (elution with dichloromethane). Solvent removal and recrystallization from ethanol yielded **32** (15.7 mg, 95.2%) as colorless needles: mp >240 °C (sealed tube); ^1H NMR (300 MHz, $CDCl_3$) δ 3.99–3.91 (m, 3 H), 3.60 (br s, 6 H), 3.38 (s, 10 H); ^{13}C NMR (75 MHz, $CDCl_3$) 96.98, 79.98, 66.87, 66.53, 66.09, 65.67 ppm; MS, m/z (M^+) calcd 340.0650, obsd 340.0628.

Chlorododecahedrane (33).[49] A solution of bromide **32** (11.2 mg, 0.033 mmol) in dichloromethane (10 mL) was stirred at room temperature for 4 h in the presence of anhydrous ferric chloride (40 mg). The solution was transferred to a separatory funnel and washed with water prior to drying. Filtration and solvent removal gave a white solid which was passed through a plug of silica gel. Elution with benzene furnished 8.8 mg (90.7%) of **33**: mp >280 °C (from benzene–hexane 1:3); IR ($CHCl_3$) 2940, 1300, 1295, 870 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 3.79–3.71 (m, 3 H), 3.62 (br s, 6 H), 3.38 (s, 10 H); ^{13}C NMR (75 MHz, $CDCl_3$) 104.39, 78.40, 66.89, 66.66, 66.01, 65.81 ppm; MS, m/z (M^+) calcd 294.1175, obsd 294.1140.

Fluorododecahedrane (34).[49] To bromide **32** (7.0 mg, 0.021 mmol) in methylene chloride (2 mL) and ether (2 mL) was added silver tetrafluoroborate (20 mg). The mixture was stirred for 20 h in the dark, after which time ether (5 mL) was added. The organic layer was washed twice with water and dried. Filtration and concentration yielded a solid which was passed through a plug of silica gel. Elution with benzene gave 5.1 mg (89.5%) of **34** as a white solid: mp >260 °C (from chloroform); IR ($CHCl_3$) 2950, 1340, 1300 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 3.55 (br s, 9 H), 3.37 (br s, 10 H), ^{13}C NMR (125 MHz, $CDCl_3$) 137.64 (d, J = 192.9 Hz), 71.26 (d, J = 23.6 Hz), 66.76, 65.68, 65.56, 65.17 (d, J = 3.0 Hz) ppm; ^{19}F NMR (75 MHz, $CDCl_3$) 121.92 ppm; MS, m/z (M^+) calcd 278.1487, obsd 278.1476.

Phenyldodecahedrane (35).[49] Bromododecahedrane (**32**; 4.0 mg, 0.0118 mmol) was dissolved in warm benzene (ca. 32 °C) under an argon atmosphere and treated with anhydrous ferric chloride (~2 mg). The solution, which turned orange immediately, was stirred for 3 h. The mixture was diluted with ether (40 mL), washed with water and saturated sodium bicarbonate solution, and then dried. Filtration and solvent removal yielded 3.75 mg (93.8%) of **35** as a colorless solid: mp 200–201 °C (from ethyl acetate in acetone); IR ($CHCl_3$) 2950, 2860, 1600, 1495, 1300 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.74–7.28 (m, 4 H), 7.15–7.09 (m, 1 H), 3.81–3.57 (m, 2 H), 3.44 (br s, 10 H); ^{13}C NMR (75 MHz, $CDCl_3$) 154.28, 128.20, 124.80, 124.68, 84.42, 75.15, 67.19, 67.06, 66.71 ppm (1 C not observed); MS, m/z (M^+) calcd 336.1870, obsd 336.1874.

Methyl Dodecahedranecarboxylate (36b).[49] Bromide **32** (4.4 mg, 0.013 mmol) was dissolved in methylene chloride (2 mL) and cooled to −78 °C. Fluorosulfonic acid (10 drops) was added followed by ca. 4 mg of antimony pentafluoride. The resulting yellow mixture was stirred for 15 min, and carbon monoxide gas was then bubbled through the solution for 30 min at −78 °C. The mixture was stirred for an additional 15 min, poured onto ice water, and extracted with methylene chloride (3 × 30 mL). The combined extracts were washed with brine and dried. The filtrate was concentrated to a volume of ~10 mL, diluted with ether (50 mL), and treated with excess diazomethane. After 1 h, the excess diazomethane was carefully destroyed with acetic acid and the solution was diluted with water, saturated sodium bicarbonate solution, and brine prior to drying. Filtration and solvent removal gave the crude ester as a white solid. A total of 11.4 mg of **32** was treated in this manner, and the combined products were submitted to MPLC purification. Elution with 2% ethyl acetate in petroleum ether yielded 6.3 mg (59.8%) of pure **36b**: mp 192–193 °C (from ethyl acetate); IR ($CHCl_3$) 2940, 2860, 1715, 1430, 1285 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 3.77–3.66 (m, 3 H), 3.67 (s, 3 H), 3.50 (br s, 6 H), 3.41 (br s, 10 H); ^{13}C NMR (75 MHz, $CDCl_3$) 179.29, 84.54, 70.97, 66.99, 66.92, 66.86 (2 C), 51.99 ppm; MS (CI) m/z ($M^+ - 1$) 319 (100).

Dodecahedranecarboxylic Acid (36a). Ester **36b** (6.3 mg, 0.020 mmol) was dissolved in methanol (5 mL) with the aid of gentle heating. A solution of sodium hydroxide (0.4 g) in water (2 mL) was added, and the resultant mixture was stirred at room temperature for 18 h. The solution was acidified with 6 M hydrochloric acid, diluted with water (20 mL), and extracted with methylene chloride (4 × 30 mL). The combined extracts were washed with brine and dried. Filtration and solvent removal yielded a white solid which was triturated twice with ether to give pure **36a** (5.7 mg, 95.0%): mp >250 °C; ^1H NMR (300 MHz, $CDCl_3$–DMSO-d_6) δ 3.22–3.20 (m, 3 H), 2.97–2.94 (m, 6 H), 2.88 (br s, 10 H); ^{13}C NMR (75 MHz, $CDCl_3$–DMSO-d_6) 179.23, 83.14, 69.52, 65.52, 65.47 ppm (two signals not observed); MS, m/z (M^+) calcd 304.1463, obsd 304.1449.

(Hydroxymethyl)dodedahedrane (37a).[49] A solution of **36b** (5.3 mg, 0.017 mmol) in dry benzene (2 mL) was treated with diisobutylaluminum hydride (15 drops). The solution was stirred for 23 h under an argon atmosphere, after which time excess hydride was destroyed by the addition of methanol. The mixture was diluted with 1 N hydrochloric acid (5 mL) and extracted with methylene chloride (3 × 20 mL). The combined extracts were washed with brine and dried. Filtration and solvent removal afforded a white solid which was triturated with hexane (2×) leaving 3.5 mg (72.9%) of **37a**: mp >250 °C; IR ($CHCl_3$) 3500 (br), 2960, 1300 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 3.40 and 3.39 (two s, total of 18 Hh), 3.08 (br s, 3 H); ^{13}C NMR (125 MHz, $CDCl_3$) 81.86, 71.06, 68.91, 67.10, 67.02, 66.56, 65.54 ppm; MS, m/z (M^+) calcd 290.1681, obsd 290.1659.

Dodecahedranecarboxaldehyde (37b).[49] To a suspension of pyridinium chlorochromate (10 mg), sodium acetate (10 mg), and Celite (10 mg) in dry methylene chloride was added alcohol **37a** (7.2 mg, 0.0248 mmol) in the same solvent (2 mL). The reaction mixture was stirred at room temperature for 1 h, diluted with ether (5 mL), and passed through a plug of silica gel (elution with dichloromethane). Concentration yielded a white solid which was purified by trituration with hexane to give 4.7 mg (66.2%) of **37b**: mp >250 °C; IR ($CHCl_3$) 2940, 2800, 2700, 1695, 1300, 905, 720 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 9.48 (s, 1 H), 3.58 (br s, 3 H), 3.44 (s, 16 H); ^{13}C NMR (125 MHz, $CDCl_3$) 201.49, 90.00, 67.23, 67.11, 66.96, 66.91, 66.86 ppm; MS, m/z (M^+) calcd 288.1514, obsd 288.1519.

Methyldodecahedrane (38).[49] Bromide **32** (7.0 mg, 0.021 mmol) was dissolved in hexane (5 mL) and treated with neat trimethylaluminum (10 drops) at room temperature for 24 h. The excess reagent was quenched by careful addition of methanol with cooling. The mixture was diluted with benzene and 3 N hydrochloric acid. The layers were separated, and the organic phase was washed with water and dried. The resultant residue was passed through a silica gel plug (elution with benzene). Concentration gave 5.1 mg (90.1%) of **38** as a white solid: ^1H NMR (300 MHz, $CDCl_3$) δ 3.38 (br s, 16 H), 2.92 (m, 3 H), 1.14 (s, 3 H); ^{13}C NMR (75 MHz, $CDCl_3$) 77.55, 74.67, 67.17, 67.06, 66.74, 66.39, 32.60 ppm.

Methoxydodecahedrane (39).[49] **A. Treatment of 32 with Magic Acid and Methanol Quench.** Bromide **32** (4.2 mg, 0.0124 mmol) was dissolved in deuteriated chloroform (0.5 mL) and cooled to −78 °C under an argon atmosphere. Sulfuryl chloride fluoride (1 mL) was added followed by

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(49) Microanalytical data are not available for the monosubstituted dodecahedranes because of our desire to maximize the utilization of all amounts of the derivatives produced during this study. However, all spectral data on each derivative suitably referenced were recorded on material previously shown to be constitutionally pure by capillary VPC. As a result, the possibility that extraneous peaks have been recorded and consequently complicated the chemical shift correlations is extremely remote.

fluorosulfonic acid (4 drops) and ca. 4 mg of antimony pentafluoride. The yellow solution was stirred at −78 °C for 15 min and then poured into a solution of sodium methoxide in methanol at −78 °C. The solution was allowed to warm to room temperature, diluted with water, and extracted with methylene chloride (3 × 30 mL). The dried extracts were concentrated and purified by preparative thin-layer chromatography (elution with 5% ethyl acetate in petroleum ether). There was isolated 0.4 mg (12%) of **32** and 2.2 mg (61%) of **39**: IR ($CHCl_3$) 2930, 1270, 910, 900 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 3.50–3.37 (m, 16 H), 3.37 (s, 3 H), 3.24 (s, 3 H); ^{13}C NMR (125 MHz, $CDCl_3$) 68.90, 66.90, 66.79, 65.77, 65.48, 51.19 ppm (1 C not observed); MS, *m/z*/(M^+) calcd 290.1670, obsd 290.1678.

B. Treatment of 32 with Silver Triflate in the Presence of Methanol. Bromide **32** (1.0 mg, 0.0030 mmol) was dissolved in methylene chloride (2 mL) and methanol (2 mL) and treated with silver trifluoromethanesulfonate (5.0 mg, 0.023 mmol). The mixture was stirred at ambient temperature in the dark for 18 h. Methylene chloride (15 mL) was added, and the organic phase was washed with water (2×) and dried. The solid obtained after concentration was purified by preparative TLC. Elution with 5% ethyl acetate in petroleum ether afforded **39** (0.6 mg, 69.8%), identical in all respects to the material obtained in part A.

Dodecahedranol (40b).[49] To **1** (3.9 mg, 0.015 mmol) dissolved in dry dichloromethane (1 mL) was added an excess amount of lead tetraacetate (ca. 10 mg) followed by trifluoroacetic acid (1 mL) and a small amount of dry lithium chloride. The resulting suspension was stirred in the dark for 24 h at room temperature. The reaction mixture was diluted with ether (20 mL) and water (5 mL), the layers were separated, and the aqueous phase was further extracted with ether (3 × 20 mL). The combined organic phases were washed with water (2×) and saturated sodium bicarbonate solution (1×) prior to drying. Filtration and solvent removal gave trifluoroacetate **40a** which was taken up in benzene (2 mL) and heated to 100 °C for 2 h in the presence of 10% sodium hydroxide solution (2 mL). The cooled mixture was diluted with water (10 mL) and extracted with dichloromethane (3 × 30 mL). The combined extracts were washed with water and dried. Solvent removal gave a white solid which was triturated with ether (2×) leaving pure **40b** (3.1 mg, 75.6%): mp >250 °C (sealed tube); ^1H NMR (300 MHz, $CDCl_3$) δ 3.55 (br s, 6 H), 3.35 (br s, 10 H), 3.26–3.20 (m, 3 H), 1.76 (s, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$) 115.99, 74.95, 66.97, 66.89, 65.71 (2 C) ppm; MS, *m/z* (M^+) calcd 276.1515, obsd 276.1482.

Alternative Synthesis of (Trifluoroacetoxy)dodecahedrane (40a).[49] Bromododecahedrane (**32**; 9.0 mg, 0.027 mmol) was dissolved in trifluoroacetic acid (5 mL), treated with silver trifluoroacetate (20 mg, 0.09 mmol), and stirred at room temperature for 20 h. The trifluoroacetic acid was evaporated in vacuo, and dichloromethane (15 mL) was added to the residue. The organic phase was washed with water (2×) and brine (1×) prior to drying. Solvent removal yielded a solid which was passed through a short silica gel column. Elution with benzene furnished 7.9 mg (84.0%) of **40a** as a white solid: mp 183–185 °C, dec 220 °C (from hexane); IR ($CHCl_3$) 2940, 1730, 1355, 1340, 1305, 1300, 1230, 1160 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 3.58 (br s, 9 H), 3.40 (s, 10 H); ^{13}C NMR (75 MHz, $CDCl_3$) 126.47, 71.65, 66.69, 66.51, 65.90, 65.34 ppm (2 C of ester group not observed); MS, *m/z* ($M^+ - CF_3CO_2H$) calcd 258.1408, obsd 258.1407.

Dodecahedryl Nitrate (41). Dodecahedrane (3.4 mg, 0.013 mmol) was taken up in deuteriochloroform (3 mL) under an argon atmosphere and treated with an excess of commercial nitronium tetrafluoroborate. The heterogeneous mixture was stirred vigorously for 68 h and then diluted with dichloromethane and water. The layers were separated, and the aqueous phase was further extracted with dichloromethane (3 × 20 mL). The combined organic extracts were washed with brine and dried. Filtration and removal of solvent gave a yellow solid which was passed through a plug of silica gel (elution with dichloromethane). Recrystallization from ethyl acetate yielded 3.5 mg (83.5%) of **41** as colorless crystals: mp 220 °C dec; IR ($CHCl_3$) 3060, 2950, 1615, 1300, 1270 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) 129.89, 70.33, 66.67, 66.47, 65.94, 65.19 ppm; MS (CI) *m/z* 320 ($M^+ - 1$, 1.57), 275 ($M^+ - NO_2$, 10.45), 259 ($M^+ - ONO_2$, 100).

***N*-Dodecahedrylacetamide (42).**[49] Bromododecahedrane (**32**; 10.3 mg, 0.0304 mmol) was heated at reflux in acetonitrile (10 mL) containing silver trifluoromethanesulfonate (150 mg) in the dark for 20 h. After cooling, water (10 mL) was added and the solution was stirred for 15 min prior to extraction with dichloromethane (3 × 30 mL). The combined extracts were washed with brine and dried. Filtration and solvent removal gave 9.6 mg (99.6%) of **42** as a white solid: mp >250 °C (from ethyl acetate); IR ($CHCl_3$ 2950, 1660, 1490 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.81 (br s, 1 H), 3.55 (br s, 6 H), 3.37 (s, 3 H), 3.37–3.28 (m, 10 H), 1.92 (s, 3 H); ^{13}C NMR (125 MHz, $CDCl_3$) 168.95, 95.77, 74.21, 66.80, 66.80, 66.68, 66.16, 66.07, 23.80 ppm; MS, *m/z* (M^+) calcd 317.1780, obsd 317.1772.

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The Dodecahedryl Cation and 1,16-Dodecahedryl Dication. ^1H and ^{13}C NMR Spectroscopic Studies and Theoretical Investigations[1a]

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Abstract: Ionization of dodecahedryl derivatives (**4**, X = Cl, OH) as well as of the parent hydrocarbon **1** itself under superacidic conditions (SbF_5/SO_2ClF) gave the dodecahedryl cation, **2**, which was found to be a static ion with no tendency to undergo degenerate hydrogen scrambling (on the NMR time scale) up to 0 °C. The unique ion **2** was characterized by ^1H and ^{13}C NMR spectroscopy. Upon prolonged exposure to the superacidic medium, the dodecahedryl cation was irreversibly transformed into the **1**,16-dodecahedryl dication, **3**, which opens up the possibility for regioselective difunctionalization of the dodecahedrane sphere. According to semiempirical SCF-MO calculations, the dodecahedrane skeleton is incapable of accommodating a planar cation geometry. This situation is still more acute in dication **3**, which is considered to constitute the first true sp^3-hybridized carbocation. Likewise, the static nature of these cations is shown to be due to unfavorable bending in the transition state for intramolecular 1,2-hydride shifts on the convex surface of the cage.

The formidable challenge[2] of synthesizing the pentagonal dodecahedrane **1**, a $C_{20}H_{20}$ hydrocarbon of spherical polycyclopentanoid topology (composed of 12 five-membered rings) with the highest possible point group symmetry (I_h, icosahedral), has been successfully met in two laboratories.[3,4] As more practical

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[1] (a) Considered as Stable Carbocations, Part 275, at the University of Southern California. (b) The Ohio State University Postdoctoral Fellow, 1986–1988.

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