Influence of Alkyl Substitution on the Intramolecular Ionic Diels–Alder Reaction of Tetraenes

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Fifteen tetraenes, comprised primarily of methylated analogs of (3*E*,8*E*)-1,3,8,10-undecatetraene, were synthesized and treated with acid to study the influence of alkyl substitution on the intramolecular ionic Diels–Alder reaction. Depending on methyl substitution patterns of these tetraenes, bicyclo[4.3.0]nonyl, bicyclo[4.4.0]decyl, and bicyclo[5.4.0]undecyl ring systems were produced. For two tetraenes, the ring preference between two different Diels–Alder-derived ring skeletons could be controlled using different temperatures and acid catalysts. Mechanistically, a stepwise process was postulated for at least some of these Diels–Alder reactions. The irreversible and stereoselective formation of the same Diels–Alder product from two noninterconverting tetraenes, which differed only by the *cis–trans* relationship of a terminal methyl group, was best explained by a stepwise process. A stepwise process was best demonstrated when intermediate triene products isolated from a reaction mixture irreversibly cyclized to Diels–Alder products when resubmitted to the reaction conditions. Although several of the tetraenes failed to give significant amounts of Diels–Alder products, certain alkyl substitution patterns were identified which generally led to high yields of cyclized products.

Introduction

Since its discovery over 65 years ago, the Diels–Alder reaction has been widely employed in synthesis and today remains among the most useful organic reactions.[3] Previously, it has been shown that tetraenes can undergo intramolecular Diels–Alder reactions in the presence of strong acids such as trifluoromethanesulfonic acid.[4] We now report further studies of this transformation utilizing fifteen tetraenes, comprised primarily of methylated analogs of (3*E*,8*E*)-1,3,8,10-undecatetraene. Depending on methyl substitution patterns of these tetraenes, changes in protonation and cyclization behavior are observed for tetraenes **1–15** (Table 1).

Results and Discussion

a. General Synthesis of Tetraenes.[5] Tetraenes **1–14** were synthesized starting from glutaraldehyde. Tetraene substrate **15** was synthesized starting with the ozonolysis of cyclohexene. Via Wittig reactions, ylides stabilized by groups such as an α-ester, α-ketone, or α-aldehyde were allowed to react with glutaraldehyde or other aldehyde intermediates to give the *trans* double bonds[6] connected by a three- or four-carbon chain. For ester groups, reduction with diisobutylaluminum hydride followed by oxidation with pyridinium dichromate gave the corresponding aldehyde. The double bonds furthest from the tethering chain were formed by Wittig reactions between aldehyde or ketone intermediates and ylides derived from the corresponding alkyl phosphonium salt and methyllithium.

b. Stereochemical Trends of Diels–Alder Products. Reaction of tetraenes **1–15** resulted in products **16–36** (Table 1).[7] For products arising from intramolecular ionic Diels–Alder reactions, bicyclo[4.3.0]nonyl, bicyclo[4.4.0]decyl, and bicyclo[5.4.0]undecyl ring systems were produced.

Prior descriptions are available regarding transition state structures and stereochemical trends of various intramolecular Diels–Alder reactions.[8] For intramolecular ionic Diels–Alder reactions, secondary orbital interactions between an electrophilic dienophile and a diene lead to a preference for *endo* transition states in the absence of overriding steric interactions. For tetraenes **1–15**, upon protonation, the resulting allyl cation should act as a strongly electrophilic dienophile. For these systems, an *endo* transition state can result in *cis* or *trans* ring fusion, depending on which end of the allyl cation cyclizes (Scheme 1). If the end closest to the tethering chain cyclizes (path a), R_2 and R_3 will be *trans* in the *endo* transition state, leading to *trans*-fused products. These trends were generally observed for products containing the bicyclo[4.3.0]nonyl and the bicyclo[4.4.0]decyl ring systems. If cyclization occurs from the outermost end of the allyl cation (path b), R_1 and R_3 will be *cis* in the *endo* transition state, leading to *cis*-fused products. This trend was observed for products containing the bicyclo[5.4.0]-undecyl ring system.

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(2) Deceased April 21, 1993. This paper is dedicated to the memory of P.G.G. by D.B.G.

(3) For selected reviews of the Diels–Alder reaction, see: (a) Pindur, U.; Lutz, G.; Otto, C. *Chem. Rev.* **1993**, *93*, 741. (b) Kagan, H. B.; Riant, O. *Chem. Rev.* **1992**, *92*, 1007. (c) Desimoni, G.; Tacconi, G. *Chem. Rev.* **1975**, *75*, 651. (d) Wasserman, A. *Diels-Alder Reactions*; Elsevier: New York, 1965. (e) Holmes, H. L. *Org. React.* **1948**, *4*, 60.

(4) (a) Gassman, P. G.; Singleton, D. A. *J. Am. Chem. Soc.* **1984**, *106*, 6085. (b) Gassman, P. G.; Gorman, D. B. *J. Am. Chem. Soc.* **1990**, *112*, 8623. (c) Gassman, P. G.; Gorman, D. B. *J. Am. Chem. Soc.* **1990**, *112*, 8624.

(5) The complete syntheses of **1–15**, along with experimental and characterization data for all intermediates, are included in the supplementary material.

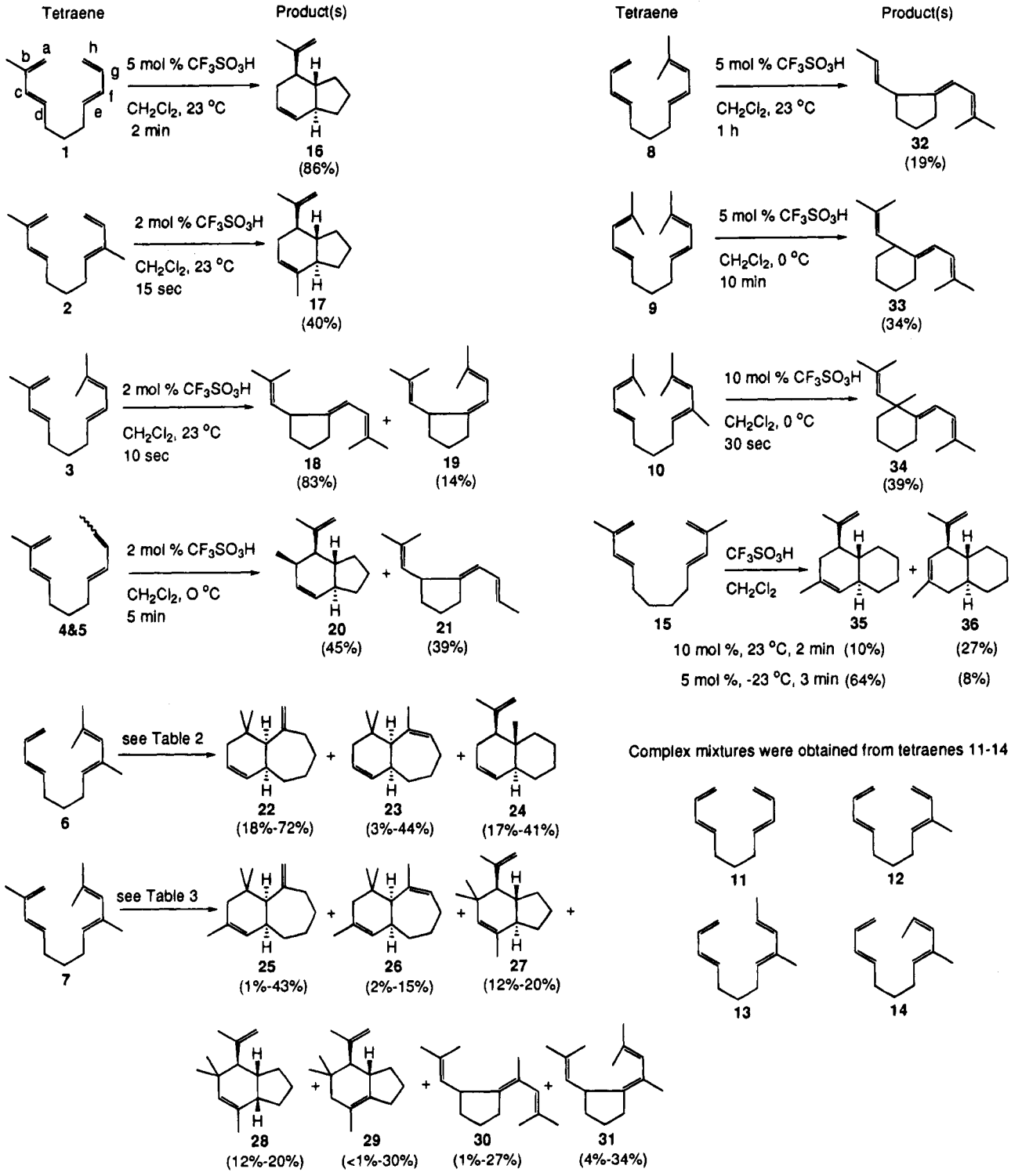
(6) Maercker, A. *Org. React.* **1965**, *14*, 270.

(7) Satisfactory elemental analyses and exact mass molecular weights were obtained for **1–36**. All compounds had ^{13}C NMR, ^{1}H NMR, and IR spectra which were consistent with the assigned structures. Skeletal and stereochemical assignments were based on ^{1}H NMR, ^{13}C NMR, DEPT, COSY, and HETCOR spectra. In addition, compounds **22** and **24** were treated with excess dichlorocarbene to give crystalline adducts, whose structures were confirmed by X-ray crystallography. Complete spectral data for all compounds, including stereochemical assignments, are available in the supplementary material.

(8) (a) Craig, D. *Chem Soc. Rev.* **1987**, *16*, 187. (b) Fallis, A. G. *Can. J. Chem.* **1984**, *62*, 183.

0022-3263/95/1960-0977$09.00/0

Table 1. Product/GLC Yield Summary. Acid-Catalyzed Cyclization Reactions of Alkyl-Substituted Tetraenes

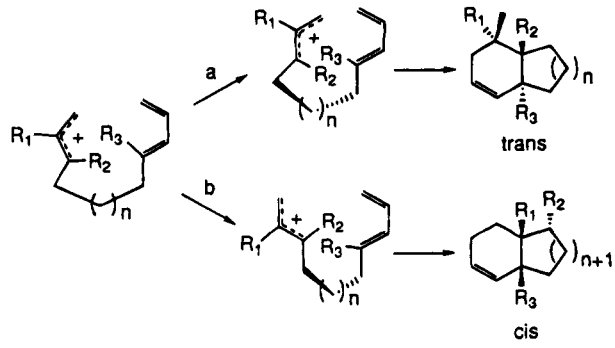


An exception to these stereochemical trends was found with tetraene **7**. The competitve formation of the *cis*- and *trans*-fused bicyclo[4.3.0]nonyl ring system from **7** is explained by examining *endo* versus *exo* transition states (Scheme 2). Upon protonation of **7** at C_a, the *endo* transition state leading to *trans*-fused **27** reveals a steric interaction between methyl groups at C_b and C_h of **37a**. This interaction is less severe in the *exo* transition state **37b**, which may have led to the competitive formation of *cis*-fused **28**.

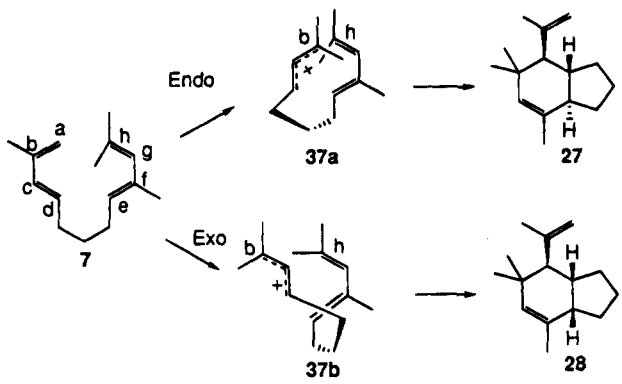
c. Reaction of Tetraenes. Products **16**–**36** (Table 1) may be rationalized as the result of different steric and electronic effects from intramolecular reactions of tetraenes **1**–**15** in the presence of acid.

The reaction of **1** with 5 mol % of trifluoromethanesulfonic acid (CF_3SO_3H) at 23 °C for 2 min produced **16** in 86% yield by GLC. Protonation at C_a to generate an allyl cation, followed by cyclization across C_d–C_e and C_c–C_h, gives the indene ring system. Subsequent deprotonation gives **16**. No other products were formed in appreciable quantities (>3%) in this reaction, including products arising from protonation of the other diene unit. The yield of **16** remained constant over a time period of 30 s to 1 h 50 min.

Scheme 1



Scheme 2

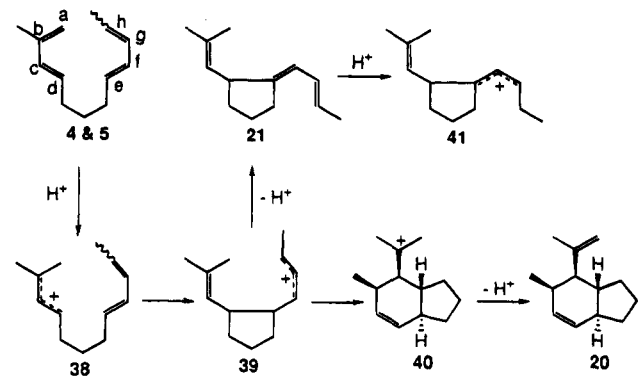


For **16** and the other bicyclo[4.3.0]nonyl products containing an isopropylidene group, deprotonation occurs to give the less-substituted terminal alkene, rather than the tetrasubstituted alkene incorporating the six-membered ring. Placing the double bond toward the ring restricts rotational freedom of the isopropylidene group and limits conformational freedom of the bicyclo[4.3.0]-nonyl ring system. This is expected to give a less stable product than when the isopropylidene group can rotate freely and the bicyclo[4.3.0]nonyl ring system can assume pseudoboat and pseudochair conformations to minimize steric interactions. For these systems, kinetic deprotonation also could be taking place. Particularly if the acid counterion stays associated with the carbocation, the proton whose abstraction would give the more highly substituted alkene may be sterically less accessible.

Substituting a methyl group for hydrogen at C_f led to a lower yield of Diels–Alder product for **2** vs **1**. Using optimized reaction conditions, **2** cyclized to **17** in 40% yield via protonation at C_a in only 15 s using 2 mol % of CF_3SO_3H at 23 °C. From GLC traces, **17** was the only major product formed in this reaction, with approximately 10% of **2** remaining. Lower yields at longer reaction times may have been due to the extra methyl group facilitating isomerization of the double bond in the six-membered ring of **17** toward the ring junction over time. Similar behavior was observed with tetraene **7** and is described later.

Tetraene **3**, which differed from **1** by placement of a terminal *gem*-dimethyl group at C_h, did not give any Diels–Alder products upon treatment with acid. Using 2 mol % of CF_3SO_3H at 23 °C, trienes **18** and **19** were produced in 97% yield after 10 s as an 86:14 ratio, respectively. Longer reaction times lead to lower yields without detectable formation of Diels–Alder products. Both **18** and **19** can arise from protonation at C_a to generate an allyl cation, followed by cyclization across C_d–C_e only, followed by deprotonation. The presence of the terminal *gem*-dimethyl group appears to create enough steric interference to inhibit cyclization to Diels–Alder products. On the basis of the high yield of **18** and **19**, and results from tetraene **15** described later, highly selective protonation at C_a appears to be occurring. Surprisingly, protonation of **3** at C_e instead of C_a apparently is not competitive, despite the similarities of the allyl cations expected from protonation of either C_a or C_e. Both allyl cations are delocalized between a secondary and a tertiary site, yet only products from protonation at C_a were observed. One possible explanation is that the energy barrier to protonation of each diene is different, with the barrier for protonation at C_a being lower than that for C_e. The possibility of kinetic protonation also cannot be ruled out, since protonation is observed at the readily accessible, primary position of C_a instead of the more hindered, secondary position of C_e.

Scheme 3



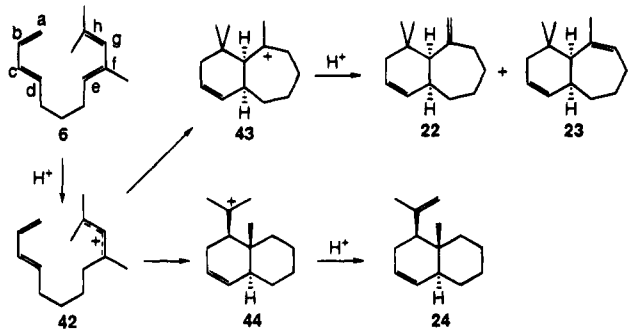
Separate acid reprotonation studies of **18** and **19**, using 2 mol % of CF_3SO_3H at 23 °C, showed negligible interconversion between **18** and **19**. Although a colored solution was produced, indicating the formation of a cationic species, no additional products were observed after 46 h. Reprotonation of these trienes may have occurred preferentially at a different site than deprotonation, explaining why little isomerization was observed.

Tetraenes **4** or **5** differed from each other only by the *cis–trans* relationship of one terminal methyl group on the diene unit not acting as the initial allyl cation. The acid-catalyzed reaction of either **4** or **5** produced the same Diels–Alder product **20** and triene **21**. Using 2 mol % of CF_3SO_3H at 0 °C, **20** and **21** were produced in 84% yield after 5 min as a 54:46 ratio, respectively. From carefully monitoring separate reactions of **4** and **5**, no interconversion of starting material, either **4** to **5** or **5** to **4**, was observed over 25 min. When **5** was used as the starting material, isomerization of the terminal methyl group on the diene unit of **21** occurred to give the more stable *E* double bond. If the formation of the Diels–Alder product was concerted, different stereochemistries would be expected for the Diels–Alder products from **4** or **5**, which was not observed. Since the starting material did not isomerize and it is unlikely that the methyl group on the six-membered ring of **20** would have isomerized quickly and independently of a detectable double bond migration, a stepwise process best explains the formation of **20** from **4** or **5**. The proposed pathway (Scheme 3) would have the allyl cation **38**, formed by protonation at C_a, cyclize across C_d–C_e to give the allyl cation **39**. A simple bond rotation of **39**, followed by deprotonation, would give **21**. Alternatively, **39** could cyclize further to give cation **40**, which upon deprotonation would give **20**. Resubmitting **21** to 2 mol % of CF_3SO_3H at 0 °C gave

Table 2. Optimization of Products from Tetraene 6. GLC Yields (%)

reaction conditions	22	23	24
10 mol % of CF_3SO_3H/−23 °C/20 min	72	4	25
100 mol % of CH_3SO_3H/−23 °C/2 min	18	44	17
100 mol % *p*-TsOH/+23 °C/40 min	27	3	41

Scheme 4



polymer over time. Reprotonation of **21** may have given the more highly substituted allyl cation **41** vs **39**, which could not cyclize directly to **20**.

Treatment of tetraene **6** under various acidic conditions gave **22**–**24**, products which contained either the bicyclo[5.4.0]undecyl or bicyclo[4.4.0]decyl ring system. The product distribution was sensitive to different reaction conditions, particularly the choice of acid catalyst (Table 2). Each product could be optimized by using CF_3SO_3H (72% of **22**), CH_3SO_3H (44% of **23**), or *p*-toluenesulfonic acid (*p*-TsOH) (41% of **24**) as the catalyst. All three products can form from the common allyl cation, **42** (Scheme 4). If cyclization occurs across C_a–C_h and C_d–C_g, **22** and **23** are produced from **43**. If cyclization occurs across C_a–C_g and C_d–C_f, **24** can form from **44**. Although the formation of **24** should be favored entropically since ring closure produces a six-membered ring versus seven-membered rings for **22** and **23**, the formation of **22** and **23** predominated, particularly at lower temperatures. When 10 mol % CF_3SO_3H was used, the ratio of (**22** + **23**)/**24** increased from 1.9 at 23 °C to 4.7 at −78 °C. When 100 mol % CH_3SO_3H was used, the ratio of (**22** + **23**)/**24** increased from 0.8 at 40 °C to 3.6 at −23 °C.[9]

Since different acids gave different results with tetraene **6**, the strength and/or the size of individual acids appear to play a role. Regarding the strength of individual acids, pK_a values are reported by Guthrie[10] to be −1.92 for both methanesulfonic acid (CH_3SO_3H) and *p*-toluenesulfonic acid (*p*-TsOH) and −5.9 for CF_3SO_3H. Assuming CH_3SO_3H and *p*-TsOH have equal pK_a values, the size of the acid appears to have some importance in determining which cyclization pathway is preferred. How differences in acid size would affect cyclization behavior is not clear, but lower yields of **22** and **23** were observed when *p*-TsOH was used versus the less bulky CH_3SO_3H. Factors favoring longer-lived allyl cations, low temperature (−23 °C) and a strong acid (CF_3SO_3H), were used to optimize the high yield of bicyclo[5.4.0]undecane ring product **22**. For **6**, ring closure to form the bicyclo[4.4.0]decyl ring system, though kinetically favored, may have a higher energy transition state than ring closure

(9) The ratio of (**22** + **23**)/**24** varied little over time for individual reactions, although individual yields of **22**–**24** did vary over time. Individual yields for **22**–**24** across several different times under several additional reaction conditions are available in the supplementary material.

(10) Guthrie, J. P. *Can. J. Chem.* **1978**, *56*, 2342.

Scheme 5

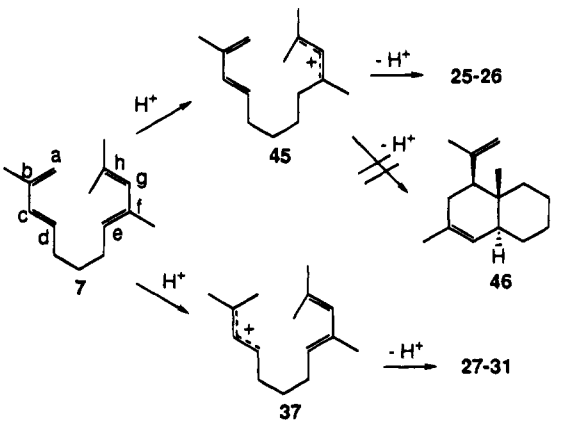


Table 3. Optimization of Products from Tetraene 7. GLC Yields (%)

reaction conditions	25	26	27 and 28[a]	29	30	31
10 mol % of CF_3SO_3H/ −23 °C/2 min	43	5	30	14	1	4
2 × 5 mol % of CF_3SO_3H/ −78 °C/1.5 h	21	15	24	<1	2	4
40 mol % of *p*-TsOH/ +23 °C/1 h	4	2	40	30	2	5
10 mol % of *p*-TsOH/ +23 °C/30 min	1	2	24	1	27	34

[a] Compounds **27** and **28** were not separated by GLC. The yield reflects the total of both compounds and assumes a 1:1 ratio.

to the bicyclo[5.4.0]undecane ring system. At lower temperatures with longer-lived allyl cations, this energy difference may be more important than the entropic favorability of forming a six-membered versus a seven-membered ring.

Treatment of tetraene **7** with acid gave products **25**–**31**.[11] Product formation can be explained by competitive protonation at C_a and C_e (Scheme 5). Products **25** and **26** can arise from allyl cation **45**, derived from protonation at C_e. Products **27**–**31** can be explained as arising from the alternative allyl cation **37**, derived from protonation at C_a. Given the similarity of tetraenes **6** and **7**, it was surprising that **46**, an analog of **24**, was not detected. As with **6**, different reaction conditions were used to optimize the yields of individual products from **7** (Table 3). In general, CF_3SO_3H and sub-zero temperatures were used to optimize yields of the bicyclo[5.4.0]-undecyl ring products **25** and **26**, while *p*-TsOH at 23 °C gave optimized yields of bicyclo[4.3.0]nonyl ring products **27**–**31**.

For **7**, the more highly substituted allyl cation **45** should be more stable than **37**,[12] yet competitive protonation takes place at C_a and C_e. If an acid behaves as a tight ion pair, a large, bulky counterion might inhibit protonation at the less accessible C_e versus C_a of **7**, leading to greater formation of **37** versus **45**, leading to products **27**–**31**. Greater formation of products **27**–**31** was observed when *p*-TsOH was used, while products **25** and **26** were formed preferentially from **45** when the stronger CF_3SO_3H was used. As a stronger acid, CF_3SO_3H should be more fully dissociated and less likely to form a tight ion pair than *p*-toluenesulfonic acid, which could lead to greater protonation at C_e. At higher

(11) Compounds **27** and **28** were not completely resolved by GLC or HPLC but appeared to form in about a 1:1 ratio.

(12) Deno, N. C. In *Carbonium Ions*; Olah, G. A., Schleyer, P. v. R., Eds.; Wiley-Interscience: New York, 1970; Vol. II, pp 790–791.

temperatures, the energy difference between **45** and **37** may be small enough relative to acid strength that protonation is influenced by steric factors, causing the rate of protonation at the more accessible C_a to be competitive with the rate of protonation at C_e. At lower temperatures, the energy difference between **45** and **37** may be large enough relative to acid strength to lead to a decrease in the rate of protonation at C_a versus C_e. As was observed with tetraene **6**, factors leading to longer-lived allyl cations (stronger acid and lower temperature), increased the preference for **7** to form products containing the bicyclo[5.4.0]undecyl ring system.

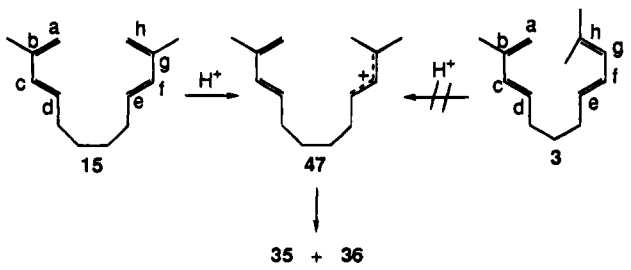
Products **30** and **31** from tetraene **7** were isolated from a reaction mixture containing 40 mol % of *p*-TsOH at 23 °C. When either triene **30** or **31** were resubmitted to these same reaction conditions, appreciable formation of Diels–Alder products **27–29** was observed. After 1 h, **30** gave 21% of **27** + **28** and 58% of **29**, while **31** gave 41% of **27** + **28** and 33% of **29**.

The interrelationship of products **27–29** was shown through acid reprotonation studies. Treatment of either **27** or **28** with 10 mol % of *p*-TsOH at 23 °C led to formation of **29**, though this conversion was much slower for **28** than **27**. For **27**, after 22.5 h the yields of **27** and **29** were 15 and 60%, respectively. For **28**, after 22.5 h the yields of **28** and **29** were 85 and 11%, respectively. Through a similar reprotonation study of **29**, reversible formation of neither **27** nor **28** was observed over 6 h. A stepwise pathway has been postulated to explain these results.[4c]

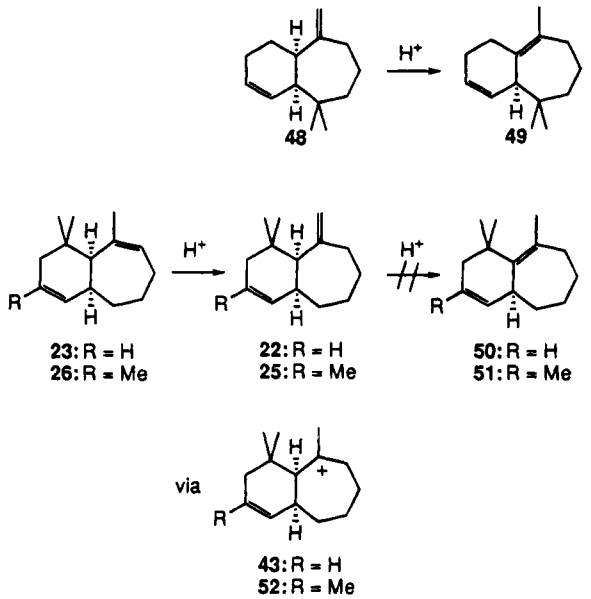
Tetraenes **8–14** all gave several products in low yield. As with tetraene **3**, the presence of terminal *gem*-dimethyl groups with **8–10** may have created steric interference which inhibited cyclization to Diels–Alder products, giving low yields of **32** (19%),[13] **33** (34%), and **34** (39%), respectively. Tetraenes **11–14** reacted sluggishly, giving complex reaction mixtures, including polymerization. As a result, no products could be purified and positively identified from reactions with these tetraenes.[14]

Tetraene **15**, which differs from **1–14** due to a four- vs a three-carbon tethering chain, gave two major products, **35** and **36**, arising from protonation at C_h to give allyl cation **47** (Scheme 6). This is the same allyl cation which would be derived from protonation of **3** at C_e, which was not observed for **3**. A maximum yield of 64% of **35** was obtained using 5 mol % of CF_3SO_3H at −23 °C for 3 min.[15] Minor product **36** was optimized to 27% using 10 mol % of CF_3SO_3H at 23 °C for 2 min. Compound **35** is the normal Diels–Alder product, with **36** being a Diels–Alder product where an additional double bond isomerization has taken place. Upon reprotonation, **35** could be converted to **36**, although complete isomerization was not observed, suggesting an equilibrium between the two products. At −23 °C, the ratio of **36** to **35** was maximized at 3:1, respectively, decreasing over time as polymerization occurred.

Scheme 6

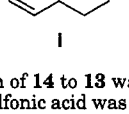


Scheme 7



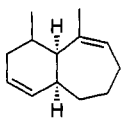
d. Himachalene Analogs. Products **22**, **23**, **25**, and **26**, which contain the bicyclo[5.4.0]undecane ring system, are structurally of interest since they are similar to naturally occurring himachalenes **48** and **49**,[16] differing primarily by the placement of the *gem*-dimethyl groups (Scheme 7). In a prior study, *cis*-α-himachalene (**48**) isomerized to β-himachalene (**49**) under acidic conditions.[17] When the analogous compounds **22** and **25** were treated with CF_3SO_3H, no isomerization was observed

(13) A second product was detected in roughly an equal amount to **32**, but could not be purified beyond 89% by GLC. On the basis of the ^1H NMR, ^{13}C NMR, and DEPT spectra, it was assigned the tentative structure **i**. Since it could not be purified, neither an isolated yield nor a GLC yield are reported.



i

(14) Partial isomerization of **14** to **13** was observed by GLC when 2 mol % of trifluoromethanesulfonic acid was added at room temperature. A similar isomerization of **13** to **14** was not observed under similar conditions. Using reaction conditions of 10 mol % of CF_3SO_3H at 23 °C for 1 min, one major product, estimated at 30–40%, was formed. This product could not be purified to greater than 90% purity. On the basis of ^1H NMR, ^{13}C NMR, and DEPT spectra, as well as comparison with the spectra for **23** and **26**, this product was tentatively identified as **ii**. Since it could not be purified, neither an isolated yield nor a GLC yield are reported.



ii

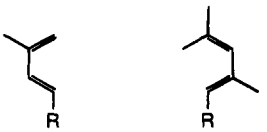
(15) Tetraene **15** was very sensitive to small changes in the strength of trifluoromethanesulfonic acid, making reproducibility somewhat difficult. Small differences in the amount of acid in each ampule, relative humidity, and dryness of solvents caused different results from reaction to reaction. A reaction color change from colorless to orange was the most reliable indicator that the reaction was complete, as defined as the disappearance of starting material.

(16) Joseph, T. C.; Dev, S. *Tetrahedron Lett.* **1961**, 216.
(17) Challand, B. D.; Hikinko, H.; Kornis, G.; Lange, G.; de Mayo, P. *J. Org. Chem.* **1969**, *34*, 794.

for either **22** or **25** to **50** or **51**, respectively. Although a colored solution was produced, indicating the formation of a cationic species, no reaction was observed at −23 °C. When the solution was warmed to room temperature, polymerization of starting material occurred over time. However, **23** and **26** isomerized at −23 °C to **22** and **25**, respectively. In this case, cation **43** or **52** was formed in which the double bond could be isomerized toward the ring junction upon deprotonation. Instead, the exocyclic double bond was formed, giving **22** or **25**. The exocyclic double bond may be favored due to partial eclipsing between the corresponding methyl group and the *gem*-dimethyl group when the double bond is toward the ring junction. The methylene group containing the exocyclic double bond is expected to bisect the *gem*-dimethyl group, minimizing any steric interaction between these groups.

e. Summary of Trends. Depending on methyl substitution patterns of tetraenes, bicyclo[4.3.0]nonyl, bicyclo[4.4.0]decyl, and bicyclo[5.4.0]undecyl ring systems have been produced. For tetraenes **6** and **7**, the ring preference between two different Diels–Alder-derived ring skeletons was controlled using different temperatures and CF_3SO_3H or *p*-TsOH as the acid catalyst. For the fifteen tetraenes studied, terminal methyl groups often led to incomplete cyclization, possibly due to steric interference caused by the methyl groups. Tetraenes **3**–**10**, **13**, and **14** all contain at least one terminal methyl group. Tetraenes **13** and **14** failed to give appreciable amounts of any products, including Diels–Alder products. Tetraenes **3**, **9**, and **10** gave only triene products instead of Diels–Alder products. In these three tetraenes, the products observed suggest that a diene unit with a terminal *gem*-dimethyl group was not reacting as an allyl cation or dienophile. Triene products from **4**, **5**, **7**, and **8** can be rationalized in the same fashion, though Diels–Alder products were also formed. For **4** and **5**, cyclization to a Diels–Alder product was competitive with formation of a triene product, possibly due to less steric interference from one terminal methyl group vs two methyl groups for **3**. Again, the diene with a terminal methyl group was not acting as the dienophile. For **7**, the diene unit possessing the terminal *gem*-dimethyl group functioned as either the diene or the dienophile, resulting in both triene and Diels–Alder products. For **6**, where the diene bearing terminal *gem*-dimethyl groups acted only as the dienophile, only Diels–Alder products were obtained. In only one case, **7**, were Diels–Alder products obtained from a tetraene when the diene unit containing a terminal *gem*-dimethyl group did not act as the dienophile. In this case, the triene products also observed were shown to cyclize further to these Diels–Alder products.

Two alkyl substitution patterns, **53** and **54**, generated allyl cations which generally led to high overall yields of cyclization products. Total yields of reported cyclized products for tetraenes containing **53** and/or **54** were 86% for **1**, 97% for **3**, 84% for **4** and **5**, 72% for **15**, 97% for **6**, and quantitative for **7**. None of the other tetraenes studied gave overall yields comparable with these tetraenes.



53 **54**

Mechanistically, a stepwise process is favored for at least some of the Diels–Alder reactions. A product progression can be seen from substrates such as **3**, which gave only triene products, to substrates such as **1** and **6**, which gave only Diels–Alder products. Tetraenes **4**, **5**, and **7**, which gave both triene products and Diels–Alder products, provide strong evidence for stepwise formation of Diels–Alder products. For **4** and **5**, the irreversible stereoselective formation of **20** from either **4** or **5**, which did not interconvert, is best explained by a stepwise process. A stepwise process is best demonstrated with **7**, where triene products irreversibly cyclized to Diels–Alder products when resubmitted to the reaction conditions.

Conclusion

On the basis of the fifteen tetraene systems studied, by a careful choice of alkyl substitution patterns of substrates, bicyclo[4.3.0]nonyl, bicyclo[4.4.0]decyl, and bicyclo[5.4.0]undecyl ring systems can be produced via intramolecular ionic Diels–Alder reactions of tetraenes. In some cases, the ring preference between two different Diels–Alder-derived ring skeletons can be controlled using different temperatures and acid catalysts. Terminal methyl groups often lead to incomplete cyclization, particularly when the diene unit containing a terminal *gem*-dimethyl group does not react as an allyl cation or dienophile. Two alkyl substitution patterns, **53** and **54**, generate allyl cations which generally lead to high overall yields of cyclization products. Although many of these tetraenes have limited synthetic utility, proper alkene substitution patterns, combined with a careful choice of reaction conditions, can reward the experimenter with high yields of stereoselective products. Some of these products, particularly the bicyclo[5.4.0]undecanes, are not readily available. Mechanistically, a stepwise process is favored for at least some of these Diels–Alder reactions.

Experimental Section

General. All NMR spectra were recorded at 200 or 300 MHz. Proton and carbon chemical shifts are reported in ppm relative to chloroform-d_1 or toluene-d_8. All gas-liquid chromatography (GLC) yields reported were calculated, after sample analysis, using a 25 m × 0.2 mm × 0.33 μm film thickness HP-5 (crosslinked 5% Ph Me silicone) capillary column, by comparing the peak areas of products/substrates to undecane (internal standard). The relative response factors, determined by analysis of standard solutions, were 1.00 for undecane, 1.02 for **13**, 1.09 for **14**, 0.89 for **16**, 1.15 for **17**, 1.16 for **18**, 1.07 for **19**, 1.14 for **20**, 1.02 for **21**, 1.00 for **22**, 1.03 for **23**, 1.10 for **24**, 0.98 for **25**, 1.06 for **26**, 1.08 for **27** + **28**, 1.08 for **27**, 1.08 for **28**, 1.00 for **29**, 0.99 for **30**, 0.96 for **31**, 1.07 for **32**, 1.24 for **33**, 1.29 for **34**, 0.94 for **35**, and 0.92 for **36**. Preparative GLC separations were performed at 160 °C using a 10 ft. × 1/4 in. column packed with 10% SE-30 on Chromosorb W. Preparative high performance liquid chromatography (HPLC) separations were performed by normal phase chromatography using a 250 mm × 10 mm Alltech LiChrosorb Si-60 5 μm column with hexanes as eluent or by reverse phase chromatography using a 250 mm × 10 mm Alltech LiChrosorb RP-18 5 μm column with 90% acetonitrile (CH_3CN) in H_2O as eluent. Additional preparative chromatography was performed by medium pressure liquid chromatography (MPLC) using a 29 cm × 2 cm LiChroprep Si 60, 40–63 μm silica gel column with hexanes as eluent and by gravity chromatography using a 0.5 cm × 7 cm silica gel column with pentane as eluent. Variations of these chromatography conditions are noted for individual experiments. All chromatography solvents were distilled prior to use. Dichlo-

romethane (CH_2Cl_2) was freshly distilled from phosphorus pentoxide. Solutions of 0.1 M trifluoromethanesulfonic acid (CF_3SO_3H) and methanesulfonic acid (CH_3SO_3H) were used immediately after preparation by adding 5 mL of dry 1,1,2-trichlorotrifluoroethane or CH_2Cl_2 to a previously sealed ampule containing 0.5 mmol of CF_3SO_3H or CH_3SO_3H under argon. *p*-Toluenesulfonic acid monohydrate (*p*-TsOH·H_2O) was added as a solid or as a 0.005 M solution in CH_2Cl_2. Experiments using *p*-TsOH·H_2O were stirred for 15 min before adding the substrate last. Aliquots (1 mL) and reaction mixtures were quenched with excess triethylamine. Reaction mixtures were evaporated to dryness using a rotary evaporator. All glassware was oven-dried and all reactions were carried out under an inert (nitrogen or argon) atmosphere with rapid stirring. All final products were isolated as clear oils.

Acid Reprotonation/Isomerization Studies of 4, 5, 13, 14, 18, 19, 21–31, and 35 (Standard Procedure). To 0.005 M solutions of substrate in methylene chloride containing undecane as an internal standard was added acid according to the conditions in Table 1. Aliquots were analyzed by GLC according to the general procedure. Complete experimental information is available as supplementary material.

Optimized GLC Yields of 16–36. To 0.005 M solutions of substrate in methylene chloride containing undecane as an internal standard was added acid according to the conditions in Table 1. Aliquots were analyzed by GLC according to the general procedure. Complete experimental information is available as supplementary material.

Ratio of (22 + 23)/24 from 6 under Various Conditions (Standard Procedure). To 0.005 M solutions of **6** in methylene chloride containing undecane as an internal standard was added 10–100 mol % of CF_3SO_3H, CH_3SO_3H, or *p*-TsOH·H_2O at −78 °C to 40 °C. Aliquots were analyzed by GLC according to the general procedure. Complete experimental information is available as supplementary material.

Isolation of [3a*R,7*R**,7a*R**]-7-(1-Methylethenyl)-2,3,-3a,6,7,7a-hexahydro-1*H*-indene (16).** To a solution containing 81 mg (0.5 mmol) of (3*E*,8*E*)-2-methyl-1,3,8,10-undecatetraene (**1**) in 100 mL of CH_2Cl_2 was added 0.25 mL (0.025 mmol, 5%) of a 0.1 M solution of CF_3SO_3H. After stirring for 2 min, the yellow solution was quenched and evaporated to dryness. The residue was purified by gravity chromatography (2 cm × 12 cm), followed by preparative GLC to give 45 mg (56%) of **16**: ^{1}H NMR ($CDCl_3$) δ 5.81 (1 H, d), 5.59 (1 H, m), 4.72 (1 H, s), 4.68 (1 H, s), 2.26 (1 H, t of d, *J* = 10.8, 6 Hz), 2.14–2.00 (2 H, m), 1.81–1.61 (5 H, m), 1.68 (3 H, s), 1.39 (1 H, t of d, *J* = 10.9, 6 Hz), 1.25–1.04 (2 H, m); ^{13}C NMR ($CDCl_3$) δ 148.71 (s), 129.88 (d), 127.04 (d), 110.19 (t), 48.24 (d), 46.75 (d), 45.01 (d), 32.66 (t), 29.60 (t), 28.08 (t), 21.92 (t), 18.72 (q); exact mass *m/e* 162.1407 (calcd for $C_{12}H_{18}$, 162.1408). Anal. Calcd for $C_{12}H_{18}$: C, 88.82; H, 11.18. Found: C, 88.96; H, 11.22.

Isolation of [3a*R,7*R**,7a*R**]-4-Methyl-7-(1-methylethenyl)-2,3,3a,6,7,7a-hexahydro-1*H*-indene (17).** To a solution containing 88 mg (0.5 mmol) of (3*E*,8*E*)-2,9-dimethyl-1,3,8,-10-undecatetraene (**2**) in 100 mL of CH_2Cl_2 at room temperature was added 0.10 mL (0.010 mmol, 2%) of 0.1 M CF_3SO_3H. After 15 s, the red solution was quenched and evaporated to dryness. The residue was purified by gravity chromatography, followed by reverse phase chromatography, followed by normal phase chromatography to give, after a difficult separation, 24.1 mg (27%) of **17**: ^{1}H NMR ($CDCl_3$) δ 5.26 (1 H, s), 4.71 (1 H, s), 4.67 (1 H, s), 2.19 (1 H, t of d, *J* = 10.7, 6.1 Hz), 1.89 (2 H, m), 1.74–1.61 (5 H, m), 1.67 (6 H, s), 1.41 (1 H, q of d, *J* = 10.7, 6.1 Hz), 1.27–1.06 (2 H, m); ^{13}C NMR ($CDCl_3$) δ 148.93 (s), 136.76 (s), 120.79 (d), 110.07 (t), 48.32 (d), 48.12 (d), 46.78 (d), 33.06 (t), 28.33 (t), 28.27 (t), 21.78 (t), 20.81 (q), 18.78 (q); exact mass *m/e* 176.1573 (calcd for $C_{13}H_{20}$, 176.1565). Anal. Calcd for $C_{13}H_{20}$: C, 88.56; H, 11.44. Found: C, 88.61; H, 11.42.

Isolation of (1*E*)-1-(3-Methyl-2-butenylidene)-2-(2-methyl-1-propenyl)cyclopentane (18) and (1*Z*)-1-(3-Methyl-2-butenylidene)-2-(2-methyl-1-propenyl)cyclopentane (19). To a solution containing 95 mg (0.5 mmol) of (3*E*,8*E*)-2,11-dimethyl-1,3,8,10-dodecatetraene (**3**) in 100 mL of CH_2Cl_2 was added 0.10 mL (0.010 mmol, 2%) of 0.1 M CF_3SO_3H. After stirring for 10 s, the orange solution was quenched and evaporated to dryness. The residue was purified by gravity chromatography, followed by medium pressure chromatography to give 83 mg (87%) of a 86:14 mixture of **18** and **19**, respectively. Analytical samples of **18** and **19** were separated, with **19** eluting first, by reverse phase chromatography (95% CH_3CN in H_2O). Data for **18**: ^{1}H NMR ($CDCl_3$) δ 5.88 (2 H, s), 4.98 (1 H, d, *J* = 8.9 Hz), 3.20 (1 H, distorted d), 2.48 (1 H, distorted q), 2.32 (1 H, distorted pentet), 1.90–1.21 (4 H, m), 1.78 (3 H, s), 1.74 (3 H, s), 1.72 (3 H, s), 1.67 (3 H, s); ^{13}C NMR ($CDCl_3$) δ 147.27 (s), 132.33 (s), 131.86 (s), 127.80 (d), 122.67 (d), 116.97 (d), 44.76 (d), 34.31 (t), 29.28 (t), 26.17 (q), 25.82 (q), 24.68 (t), 18.13 (q), 18.05 (q); exact mass *m/e* 190.1736 (calcd for $C_{14}H_{22}$, 190.1722). Anal. Calcd for $C_{14}H_{22}$: C, 88.35; H, 11.65. Found: C, 88.35; H, 11.68. Data for **19**: ^{1}H NMR ($CDCl_3$) δ 6.13 (1 H, d, *J* = 11.5 Hz), 5.86 (1 H, d, *J* = 11.5 Hz), 5.05 (1 H, d, *J* = 10 Hz), 3.44 (1 H, distorted q), 2.37 (2 H, m), 1.93 (1 H, m), 1.74 (3 H, s), 1.73 (3 H, s), 1.72 (1 H, m), 1.71 (3 H, s), 1.69 (3 H, s), 1.46 (2 H, m); ^{13}C NMR ($CDCl_3$) δ 147.31 (s), 131.91 (s), 128.98 (d), 128.69 (s), 122.19 (d), 117.87 (d), 40.40 (d), 34.97 (t), 34.93 (t), 26.43 (q), 25.75 (q), 24.99 (t), 17.92 (q), 17.81 (q); exact mass *m/e* 190.1705 (calcd for $C_{14}H_{22}$, 190.1721). Anal. Calcd for $C_{14}H_{22}$: C, 88.35; H, 11.65. Found: C, 88.20; H, 11.70.

Isolation of [3a*R,6*S**,7*S**,7a*R**]-6-Methyl-7-(1-methylethenyl)-2,3,3a,6,7,7a-hexahydro-1*H*-indene (20) and (1*E*)-1-((2*E*)-2-butenylidene)-2-(2-methyl-1-propenyl)cyclopentane (21).** To a solution containing 88 mg (0.5 mmol) of a 24:76 mixture of (3*E*,8*E*,10*E*)-2-methyl-1,3,8,10-dodecatetraene (**4**) and (3*E*,8*E*,10*Z*)-2-methyl-1,3,8,10-dodecatetraene (**5**), respectively, in 100 mL of CH_2Cl_2 at 0 °C was added 0.10 mL (0.010 mmol, 2%) of 0.1 M CF_3SO_3H. After 5 min, the pink solution was quenched and evaporated to dryness. The residue was purified by gravity chromatography, followed by reverse phase chromatography to give 18 mg (21%) of **21** and 34 mg of impure **20**. Normal phase chromatography gave 25 mg (28%) of pure **20**. Data for **20**: ^{1}H NMR ($CDCl_3$) δ 5.77 (1 H, d), 5.57 (1 H, m), 4.86 (1 H, s), 4.67 (1 H, s), 2.45 (1 H, m), 2.27 (1 H, d of d, *J* = 11.2, 6.1 Hz), 1.92–1.60 (5 H, m), 1.71 (3 H, s), 1.48 (1 H, q of d, *J* = 11.1, 6.2 Hz), 1.27–0.99 (2 H, m), 0.79 (3 H, d); ^{13}C NMR ($CDCl_3$) δ 146.02 (s), 133.74 (d), 128.28 (d), 110.99 (t), 50.75 (d), 46.50 (d), 41.34 (d), 33.59 (d), 29.45 (t), 28.45 (t), 23.10 (q), 22.37 (t), 17.29 (q); exact mass *m/e* 176.1555 (calcd for $C_{13}H_{20}$, 176.1565). Anal. Calcd for $C_{13}H_{20}$: C, 88.56; H, 11.44. Found: C, 88.50; H, 11.35. Data for **21**: ^{1}H NMR ($CDCl_3$) δ 6.12 (1 H, distorted t, *J* = 13 Hz), 5.67 (1 H, d, *J* = 11 Hz), 5.53 (1 H, d of q, *J* = 15, 7 Hz), 4.95 (1 H, d, *J* = 8.9 Hz), 3.19 (1 H, distorted q), 2.47 (1 H, distorted q), 2.32 (1 H, distorted pentet), 1.94–1.53 (3 H, m), 1.74 (3 H, d, *J* = 7 Hz), 1.73 (3 H, s), 1.65 (3 H, s), 1.24 (1 H, m); ^{13}C NMR ($CDCl_3$) δ 147.41 (s), 131.85 (s), 129.40 (d), 127.60 (d), 126.27 (d), 120.57 (d), 44.55 (d), 34.24 (t), 29.30 (t), 25.77 (q), 24.67 (t), 18.26 (q), 18.00 (q); exact mass *m/e* 176.1566 (calcd for $C_{13}H_{20}$, 176.1565). Anal. Calcd for $C_{13}H_{20}$: C, 88.56; H, 11.44. Found: C, 88.61; H, 11.48.

Isolation of [4a*S,9a*R**]-2,4a,5,6,7,8,9,9a-Octahydro-1,1-dimethyl-9-methylene-1*H*-benzocycloheptene (22) and [4a*S**,8*S**,8a*R**]-1,2,3,4,4a,7,8,8a-Octahydro-8a-methyl-8-(1-methylethenyl)naphthalene (24).** To a solution containing 76.0 mg (0.40 mmol) of (3*E*,8*E*)-9,11-dimethyl-1,3,8,10-dodecatetraene (**6**) in 80 mL of CH_2Cl_2 at −23 °C was added 0.40 mL (0.040 mmol, 10%) of 0.1 M CF_3SO_3H. After 20 min, the yellow-orange solution was quenched and evaporated to dryness. The residue was purified by gravity chromatography, followed by normal phase chromatography, to give 40.5 mg (53%) and 16.7 mg (22%) of **22** and **24**, respectively. Data for **22**: ^{1}H NMR ($CDCl_3$) δ 5.64 (1 H, m), 5.54 (1 H, d, *J* = 10.3 Hz), 4.82 (1 H, s), 4.60 (1 H, s), 2.69 (1 H, br s), 2.10 (1 H, d, *J* = 7.4 Hz), 2.06 (1 H, m), 1.94–1.46 (8 H, m), 1.20 (1 H, m), 1.00 (3 H, s), 0.89 (3 H, s); ^{13}C NMR ($CDCl_3$) δ 152.51 (s), 130.84 (d), 125.05 (d), 114.63 (t), 54.84 (d), 36.04 (t), 35.07 (br t), 34.53 (d), 33.27 (t), 32.74 (s), 31.16 (t), 30.24 (q), 29.44 (q), 25.01 (t); exact mass *m/e* 190.1724 (calcd for $C_{14}H_{22}$, 190.1722). Anal. Calcd for $C_{14}H_{22}$: C, 88.35; H, 11.65. Found: C, 88.41; H, 11.73. Data for **24**: ^{1}H NMR ($CDCl_3$) δ 5.57 (1 H, m), 5.27 (1 H, d, *J* = 9.9 Hz), 4.85 (1 H, s), 4.72 (1 H, s), 2.27–1.84 (4 H, m), 1.76 (3 H, s), 1.70–1.01 (8 H, m), 0.80 (3 H, s); ^{13}C NMR ($CDCl_3$) δ 146.92 (s), 131.47 (d), 125.99 (d), 112.19 (t), 53.04

(d), 47.04 (d), 37.59 (t), 35.85 (s), 30.06 (t), 27.32 (t), 26.73 (t), 24.46 (q), 21.88 (t), 10.87 (q); exact mass *m/e* 190.1723 (calcd for $C_{14}H_{22}$, 190.1722). Anal. Calcd for $C_{14}H_{22}$: C, 88.35; H, 11.65. Found: C, 88.54; H, 11.65.

Isolation of [4a*S,9a*S**]-2,4a,5,6,7,9a-Hexahydro-1,1,9-trimethyl-1*H*-benzocycloheptene (23).** To a solution containing 75.9 mg (0.4 mmol) of **6** in 80 mL of CH_2Cl_2 at −78 °C was added 0.20 mL (0.02 mmol, 5%) of 0.1 M CF_3SO_3H. After 11 min, the faint orange solution was quenched and evaporated to dryness. The residue was purified by normal phase chromatography to give 26.9 mg (35%) of **22**, 18.1 mg (24%) of **23**, and 7.1 mg (9%) of **24**. Data for **23**: ^{1}H NMR ($CDCl_3$) δ 5.62 (1 H, t, J = 6.5 Hz), 5.54 (2 H, s), 2.27 (2 H, s), 2.13−1.99 (3 H, m), 1.81 (3 H, s), 1.77−1.22 (5 H, m), 1.03 (3 H, s), 1.02 (3 H, s); ^{13}C NMR ($CDCl_3$) δ 138.40 (s), 132.26 (d), 126.14 (d), 124.63 (d), 50.93 (d), 39.25 (t), 35.59 (d), 34.07 (s), 31.75 (2 C, q and t), 28.21 (q), 27.78 (br q), 25.54 (t), 24.13 (t); exact mass *m/e* 190.1720 (calcd for $C_{14}H_{22}$, 190.1722). Anal. Calcd for $C_{14}H_{22}$: C, 88.35; H, 11.65. Found: C, 88.39; H, 11.64.

Isolation of [4a*S,9a*R**]-2,4a,5,6,7,8,9,9a-Octahydro-1,1,3-trimethyl-9-methylene-1*H*-benzocycloheptene (25).** To a solution containing 102.0 mg (0.50 mmol) of (3*E*,8*E*)-2,9,-11-trimethyl-1,3,8,10-dodecatetraene (**7**) in 100 mL of CH_2Cl_2 at −23 °C was added 0.50 mL (0.050 mmol, 10%) of 0.1 M CF_3SO_3H. After 2 min, the solution was quenched and evaporated to dryness. The residue was purified by gravity chromatography, followed by reverse phase chromatography, to give 20.1 mg (20%) of **25** as a clear, colorless oil. Additional purification by normal phase chromatography gave 15.4 mg (15%) of **27** and 8.6 mg (8%) of **28**. Data for **25**: ^{1}H NMR ($CDCl_3$) δ 5.21 (1 H, s), 4.80 (1 H, s), 4.58 (1 H, s), 2.67 (1 H, br s), 2.06 (1 H, m), 2.06 (1 H, d, J = 6.5 Hz), 1.83−1.67 (4 H, m), 1.66 (3 H, s), 1.63−1.44 (4 H, m), 1.21 (1 H, m), 0.96 (3 H, s), 0.89 (3 H, s); ^{13}C NMR ($CDCl_3$) δ 152.57 (s), 131.60 (s), 124.53 (d), 114.45 (t), 54.37 (d), 41.17 (t), 35.16 (br t), 34.61 (d), 33.36 (t), 33.24 (s), 31.47 (t), 30.10 (q), 29.51 (q), 24.91 (t), 23.92 (q); exact mass *m/e* 204.1890 (calcd for $C_{15}H_{24}$, 204.1878). Anal. Calcd for $C_{15}H_{24}$: C, 88.16; H, 11.84. Found: C, 88.10; H, 11.79.

Isolation of [4a*S,9a*S**]-2,4a,5,6,7,9a-Hexahydro-1,1,3,9-tetramethyl-1*H*-benzocycloheptene (26).** To a solution containing 202.3 mg (1.00 mmol) of **7** in 200 mL of CH_2Cl_2 at −78 °C was added 0.50 mL (0.050 mmol, 5%) of 0.1 M CF_3SO_3H. After 1 h, 20 min, an additional 0.5 mL (0.050 mmol, 5%) of 0.1 M CF_3SO_3H was added. After 1.5 h, the faint orange solution was quenched and evaporated to dryness. The residue was purified by reverse phase chromatography (95% CH_3CN in H_2O) to give 33 mg (16%) of **25** and 42.6 mg (21%) of a 1:1 mixture of **27** + **28**. Final purification by normal phase chromatography gave 14.2 mg (7%) of **26**. Data for **26**: ^{1}H NMR ($CDCl_3$) δ 5.57 (1 H, t), 5.22 (1 H, s), 2.18 (2 H, m), 2.03 (2 H, m), 1.93−1.25 (6 H, m), 1.77 (3 H, s), 1.62 (3 H, s), 1.01 (3 H, s), 0.99 (3 H, s); ^{13}C NMR ($CDCl_3$) δ 138.38 (s), 131.42 (s), 126.20 (d), 125.99 (d), 50.62 (d), 44.11 (t), 35.58 (d), 34.47 (s), 31.86 (t), 31.75 (q), 28.26 (q), 27.62 (br q), 25.42 (t), 23.96 (t), 23.81 (q); exact mass *m/e* 204.1879 (calcd for $C_{15}H_{24}$, 204.1878). Anal. Calcd for $C_{15}H_{24}$: C, 88.16; H, 11.84. Found: C, 88.18; H, 11.84.

Isolation of [3a*R,7*R**,7a*S**]-4,6,6-Trimethyl-7-(1-methylethenyl)-2,3,3a,6,7,7a-hexahydro-1*H*-indene (27), [3a*S**,7*R**,7a*S**]-4,6,6-Trimethyl-7-(1-methylethenyl)-2,3,-3a,6,7,7a-hexahydro-1*H*-indene (28), and [7*R**,7a*S**]-4,6,6-Trimethyl-7-(1-methylethenyl)-2,3,5,6,7,7a-hexahydro-1*H*-indene (29).** To a solution containing 40 mg (0.20 mmol, 40%) of *p*-TsOH·H_2O in 100 mL of CH_2Cl_2 at 23 °C was added 102.4 mg (0.50 mmol) of **7**. After 1 h, the faint pink solution was quenched and evaporated to dryness. Following gravity chromatography to give 94 mg of a yellow oil, purification by reverse phase chromatography gave 23.3 mg (23%) of **27** + **28** as a 1:1 mixture by ^{1}H NMR. Final purification by normal phase chromatography gave 16.2 mg (16%) of **29**. Although **27** + **28** were not completely resolvable, pure analytical samples of each isomer were obtained by normal phase chromatography by careful peak clipping, with **28** eluting first. Data for **27**: ^{1}H NMR ($CDCl_3$) δ 4.94 (1 H, s), 4.88 (1 H, s), 4.65 (1 H, s), 1.98 (1 H, d, J = 11.4 Hz), 1.90−1.79 (2 H, m), 1.75 (3 H, s), 1.74−1.65 (3 H, m), 1.64 (3 H, s), 1.59 (1 H, m), 1.24 (1 H, m), 1.10 (1 H, m), 0.99 (3 H, s), 0.86 (3 H, s); ^{13}C NMR ($CDCl_3$) δ 145.40 (s), 133.75 (d), 133.19 (s), 114.27 (t), 57.92 (d), 49.33 (d), 44.06 (d), 38.63 (s), 30.03 (q), 28.61 (t), 28.20 (t), 26.32 (q), 22.59 (br q), 22.16 (t), 20.64 (q); exact mass *m/e* 204.1875 (calcd for $C_{15}H_{24}$, 204.1878). Anal. Calcd for $C_{15}H_{24}$: C, 88.16; H, 11.84. Found: C, 88.37; H, 11.78. Data for **28**: ^{1}H NMR ($CDCl_3$) δ 5.10 (1 H, s), 4.95 (1 H, s), 4.66 (1 H, s), 2.31−2.14 (2 H, m), 1.95 (1 H, m), 1.82−1.72 (2 H, m), 1.72 (3 H, s), 1.66 (3 H, s), 1.63−1.31 (3 H, m), 1.20 (1 H, m), 0.93 (3 H, s), 0.85 (3 H, s); ^{13}C NMR (C_7D_8, 105 °C) δ 145.81 (s), 134.07 (d), 133.44 (s), 115.22 (t), 55.28 (d), 45.74 (d), 38.07 (d), 36.48 (s), 32.14 (t), 31.45 (t), 30.74 (q), 24.72 (t), 24.54 (q), 23.17 (br q), 22.52 (q); exact mass *m/e* 204.1873 (calcd for $C_{15}H_{24}$, 204.1878). Anal. Calcd for $C_{15}H_{24}$: C, 88.16; H, 11.84. Found: C, 88.15; H, 11.90. Data for **29**: ^{1}H NMR ($CDCl_3$) δ 4.84 (1 H, s), 4.69 (1 H, s), 2.25 (3 H, br s), 1.93 (1 H, d), 1.75 (3 H, s), 1.74−1.55 (6 H, m), 1.54 (3 H, s), 0.90 (3 H, s), 0.89 (3 H, s); ^{13}C NMR ($CDCl_3$) δ 146.46 (s), 135.56 (s), 121.86 (s), 112.18 (br t), 57.18 (d), 49.75 (t), 42.97 (d), 33.74 (s), 32.56 (t), 29.76 (q), 28.20 (t), 23.70 (br q), 23.58 (t), 22.13 (q), 19.02 (q); exact mass *m/e* 204.1882 (calcd for $C_{15}H_{24}$, 204.1878). Anal. Calcd for $C_{15}H_{24}$: C, 88.16; H, 11.84. Found: C, 88.43; H, 11.88.

Isolation of (1*E*)-1-(1,3-Dimethyl-2-butenylidene)-2-(2-methyl-1-propenyl)cyclopentane (30) and (1*Z*)-1-(1,3-Dimethyl-2-butenylidene)-2-(2-methyl-1-propenyl)cyclopentane (31). To a solution containing 9.8 mg (0.049 mmol, 10%) of *p*-TsOH·H_2O in 100 mL of CH_2Cl_2 at 23 °C was added 101 mg (0.50 mmol) of **7**. After 30 min, the solution was quenched and evaporated to dryness. The residue was purified by normal phase chromatography to give 21.5 mg (21%) and 52 mg (51%) of 1:1 mixtures, by ^{1}H NMR, of **27** + **28** and **30** + **31**, respectively. Using normal phase chromatography, the sample of **30** + **31** was recycled two times, clipping product peaks each time, to obtain separate, pure samples of **30** and **31**. Data for **30**: ^{1}H NMR ($CDCl_3$) δ 5.69 (1 H, s), 4.93 (1 H, d, J = 9.6 Hz), 3.22 (1 H, distorted q), 2.30 (2 H, distorted t), 1.89−1.30 (4 H, m), 1.72 (3 H, s), 1.67 (3 H, s), 1.65 (3 H, s), 1.62 (3 H, s), 1.61 (3 H, s); ^{13}C NMR ($CDCl_3$) δ 142.71 (s), 130.82 (s), 128.19 (d), 128.03 (s), 127.17 (d), 125.06 (s), 41.91 (d), 34.86 (t), 31.05 (t), 26.10 (q), 25.77 (q), 24.61 (t), 20.19 (q), 19.38 (q), 17.67 (q); exact mass *m/e* 204.1877 (calcd for $C_{15}H_{24}$, 204.1878). Anal. Calcd for $C_{15}H_{24}$: C, 88.16; H, 11.84. Found: C, 88.01; H, 11.83. Data for **31**: ^{1}H NMR ($CDCl_3$) δ 5.66 (1 H, s), 5.00 (1 H, d, J = 9.6 Hz), 3.34 (1 H, distorted q), 2.13 (2 H, br s), 1.74 (3 H, s), 1.68 (3 H, s), 1.67 (3 H, s), 1.60 (6 H, s), 1.93−1.36 (4 H, m); ^{13}C NMR ($CDCl_3$) δ 142.79 (s), 131.63 (s), 128.98 (d), 128.32 (s), 127.83 (d), 125.28 (s), 41.31 (d), 34.82 (t), 32.38 (t), 25.85 (q), 25.66 (q), 25.22 (t), 19.67 (q), 18.93 (q), 17.77 (q); exact mass *m/e* 204.1883 (calcd for $C_{15}H_{24}$, 204.1878). Anal. Calcd for $C_{15}H_{24}$: C, 88.16; H, 11.84. Found: C, 88.23; H, 11.92.

Isolation of (1*E*)-1-(3-Methyl-2-butenylidene)-2-((1*E*)-1-propenyl)cyclopentane (32). To a solution containing 176 mg (1.0 mmol) of (3*E*,8*E*)-11-methyl-1,3,8,10-dodecatetraene (**8**) in 200 mL of CH_2Cl_2 at 23 °C was added 0.50 mL (0.050 mmol, 5%) of 0.1 M CF_3SO_3H. After 1 h, the red solution was quenched and evaporated to dryness. The residue was initially purified by gravity chromatography (2 cm × 12 cm silica gel) to give 171 mg of a yellow oil. Purification by reverse phase chromatography gave 16.5 mg (9%) of **32**: ^{1}H NMR ($CDCl_3$) δ 5.96 (1 H, d, J = 11.3 Hz), 5.86 (1 H, d, J = 11.3 Hz), 5.45 (1 H, d of q, J = 15.2, 6.3 Hz), 5.27 (1 H, d of d, J = 15.1, 6.5 Hz), 2.95 (1 H, distorted q), 2.43 (1 H, distorted q), 2.28 (1 H, distorted pentet), 1.86−1.30 (4 H, m), 1.79 (3 H, s), 1.74 (3 H, s), 1.69 (3 H, d, J = 6.3 Hz); ^{13}C NMR ($CDCl_3$) δ 146.98 (s), 134.18 (d), 132.63 (s), 125.41 (d), 122.82 (d), 117.85 (d), 49.24 (d), 34.34 (t), 29.47 (t), 26.32 (q), 24.67 (t), 18.28 (q), 18.05 (q); exact mass *m/e* 176.1566 (calcd for $C_{13}H_{20}$, 176.1565). Anal. Calcd for $C_{13}H_{20}$: C, 88.56; H, 11.44. Found: C, 88.58; H, 11.54.

Isolation of (1*E*)-(3-Methyl-2-butenylidene)-2-(2-methyl-1-propenyl)cyclohexane (33). To a solution containing 102 mg (0.5 mmol) of (4*E*,9*E*)-2,12-dimethyl-2,4,9,11-tridecatetraene (**9**) in 100 mL of CH_2Cl_2 at 0 °C was added 0.25

mL (0.025 mmol, 5%) of 0.1 M CF_3SO_3H. After stirring for 10 min, the faint orange solution was quenched and evaporated to dryness. The residue was purified by gravity chromatography, followed by medium pressure chromatography, followed by reverse phase chromatography (95% CH_3CN in H_2O), to give 20.0 mg (20%) of **33**: ^1H NMR ($CDCl_3$) δ 6.66 (1 H, d, J = 11.3 Hz), 5.94 (1 H, d, J = 11.3 Hz), 5.19 (1 H, d, J = 9 Hz), 2.90 (1 H, t of d, J = 9, 4 Hz), 2.64 (1 H, d of t, J = 9, 4 Hz), 2.00 (1 H, m), 1.77 (3 H, s), 1.75 (3 H, s), 1.72 (3 H, s), 1.70–1.63 (1 H, m), 1.58 (3 H, s), 1.54–1.21 (5 H, m); ^{13}C NMR ($CDCl_3$) δ 142.11 (s), 133.11 (s), 131.70 (s), 126.88 (d), 120.56 (d), 117.07 (d), 43.73 (d), 35.30 (t), 28.29 (t), 27.69 (t), 26.35 (q), 25.88 (q), 25.32 (t), 18.08 (q), 18.01 (q); exact mass *m/e* 204.1862 (calcd for $C_{15}H_{24}$, 204.1878). Anal. Calcd for $C_{15}H_{24}$: C, 88.16; H, 11.84. Found: C, 88.12; H, 11.96.

Isolation of (1*E*)-(3-Methyl-2-butenylidene)-2-methyl-2-(2-methyl-1-propenyl)cyclohexane (34). To a solution containing 54 mg (0.25 mmol) of (4*E*,9*E*)-2,4,12-trimethyl-2,4,9,11-tridecatetraene (**10**) in 50 mL of CH_2Cl_2 at 0 °C was added 0.25 mL (0.025 mmol, 10%) of 0.1 M CF_3SO_3H. After 30 s, the light brown solution was quenched and evaporated to dryness. The residue was purified by gravity chromatography, followed by reverse phase chromatography (95% CH_3CN in H_2O), to give 12.5 mg (23%) of **34**: ^1H NMR ($CDCl_3$) δ 6.10 (2 H, s), 5.14 (1 H, s), 2.61 (1 H, m), 1.81 (3 H, s), 1.78 (3 H, s), 1.71–1.20 (7 H, m), 1.67 (3 H, s), 1.51 (3 H, s), 1.17 (3 H, s); ^{13}C NMR ($CDCl_3$) δ 146.55 (s), 132.81 (s), 132.51 (d), 132.27 (s), 121.07 (d), 116.43 (d), 45.06 (t), 43.04 (s), 28.53 (t), 27.51 (q), 26.49 (t), 26.39 (2 C, q), 23.11 (t), 18.15 (q), 17.82 (q); exact mass *m/e* 218.2031 (calcd for $C_{16}H_{26}$, 218.2034). Anal. Calcd for $C_{16}H_{26}$: C, 88.00; H, 12.00. Found: C, 87.81; H, 12.03.

Isolation of [4a*R,8*R**,8a*S**]-1,2,3,4,4a,7,8,8a-Octahydro-6-methyl-8-(1-methylethenyl)naphthalene (35).** To a solution containing 47.0 mg (0.25 mmol) of (3*E*,9*E*)-2,11-dimethyl-1,3,9,11-dodecatetraene (**15**) in 50 mL of CH_2Cl_2 at −23 °C was added 0.12 mL (0.012 mmol, 5%) of 0.1 M CF_3SO_3H. After 3 min, the colorless solution changed to orange and was immediately quenched and evaporated to dryness. The residue was purified by gravity chromatography, followed by normal phase chromatography, to give 24.3 mg (52%) of **35**: ^1H NMR ($CDCl_3$) δ 5.12 (1 H, s), 4.72 (2 H, s), 2.14 (1 H, t of d, J = 11.0, 6.0 Hz), 2.03 (1 H, br d), 1.72–1.59 (6 H, m), 1.63 (6 H, s), 1.42–1.12 (2 H, m), 1.07–0.96 (2 H, m), 0.80 (1 H, m); ^{13}C NMR ($CDCl_3$) δ 147.91 (s), 132.78 (s), 126.65 (d), 111.48 (t), 48.72 (d), 42.57 (d), 42.48 (d), 36.36 (t), 33.74 (t), 30.15 (t), 26.95 (t), 26.80 (t), 23.22 (q), 18.09 (q); exact mass *m/e* 190.1725 (calcd for $C_{14}H_{22}$, 190.1722). Anal. Calcd for $C_{14}H_{22}$: C, 88.35; H, 11.65. Found: C, 88.49; H, 11.66.

Isolation of [4a*S,8*R**,8a*R**]-1,2,3,4,4a,5,8,8a-Octahydro-6-methyl-8-(1-methylethenyl)naphthalene (36).** To a solution containing 35.3 mg (0.19 mmol) of **35** in 40 mL of CH_2Cl_2 at −23 °C was added 0.10 mL (0.010 mmol, 5%) of 0.1 M CF_3SO_3H. After 10 min, the light yellow solution was quenched and evaporated to dryness. The residue was purified by gravity chromatography, followed by normal phase chromatography, to give 7.5 mg (21%) of **35** and 16.4 mg (46%) of **36**. Data for **36**: ^1H NMR ($CDCl_3$) δ 5.08 (1 H, s), 4.73 (1 H, s), 4.70 (1 H, s), 2.43 (1 H, d, J = 9.7 Hz), 1.89–1.66 (6 H, m), 1.63 (3 H, s), 1.57 (3 H, s), 1.48–1.07 (3 H, m), 1.05–0.95 (2 H, m), 0.78 (1 H, m); ^{13}C NMR ($CDCl_3$) δ 148.19 (s), 133.95 (s), 124.86 (d), 111.59 (t), 52.66 (d), 40.31 (d), 38.22 (t), 38.16 (d), 34.23 (t), 31.14 (t), 26.58 (t), 26.41 (t), 23.48 (q), 18.65 (q); exact mass *m/e* 190.1711 (calcd for $C_{14}H_{22}$, 190.1722). Anal. Calcd for $C_{14}H_{22}$: C, 88.35; H, 11.65. Found: C, 88.43; H, 11.66.

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Supplementary Material Available: Complete syntheses of **1**–**15**, along with experimental and characterization data for all intermediates, complete spectral data for **16**–**36**, including NMR peak correlation charts, additional experimental information encompassing acid reprotonation/isomerization studies of **4**, **5**, **13**, **14**, **18**, **19**, **21**–**31**, and **35**, optimized GLC yields of **16**–**36**, and the ratio of (**22** + **23**)/**24** from **6** under various conditions (73 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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