Electrophilic and Radical Transannular Cyclizations of 5-Cyclodecenone To Give either Hydronaphthalene or Hydroazulene Products

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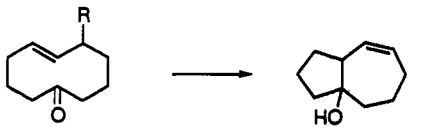
The transannular cyclizations of the *E* and *Z* double-bond isomers of 5-cyclodecenone were investigated in order to determine the regio- and stereochemical preferences of the unsubstituted ring system. Electrophilic cyclization of the *E* isomer under either protic or Lewis acid conditions led to hydronaphthalenols with a preference for the trans ring fusion, while the *Z* led to only cis-fused hydronaphthalenols. Cyclization of the ketyl radical generated from the ketone led exclusively to a cis-fused hydroazulenol, regardless of double-bond geometry, although the *E* isomer was considerably more reactive than the *Z* isomer. The stereochemistry of the ring fusion in the products from (*E*)-5-cyclodecenone can be rationalized by cyclization through its lowest energy conformations in which the carbonyl oxygen is anti to the alkene hydrogen at C6, leading to the trans-fused hydronaphthalenol, and syn to the alkene hydrogen at C5, leading to the cis-fused hydroazulenol. For (*Z*)-5-cyclodecenone, molecular mechanics calculations found two low energy conformations, only one of which brings the alkene and the carbonyl groups close enough for their reaction with each other. In this conformation, the alkene hydrogens at C5 and C6 are syn to the oxygen of the ketone, leading to a cis ring fusion regardless of whether 1,5- or 1,6-cyclization is observed. The difference in regiochemistry in radical versus electrophilic cyclizations is explicable on the basis of the differences in mechanism for the two reaction pathways. The radical cyclizations are kinetic in nature with the ketyl radical adding to the proximate C5 alkene carbon in a very exothermic step, akin to the cyclization of 1-hexenyl radicals. The stereochemistry of the acid-induced cyclizations can be explained through the intermedicacy of either nonclassical or contact ion pairs, the regiochemistry reflecting the greater stability of the hydronaphthalene ring system over the hydroazulene. A system of nomenclature for unambiguously labeling each of the low energy conformations of (*E*)-5-cyclodecenones is also proposed.

Introduction

Given our interest in developing and promoting the use of transannular cyclizations of 5-cyclodecenones,[2] we are interested in determining the factors that control the outcomes of these cyclizations. For each cyclization there is the possibility of regioisomers, i.e., bicyclo[5.3.0]- and bicyclo[4.4.0]decan-1-ols could conceivably be obtained, and of stereoisomers, either cis or trans fused at the ring fusion of the product(s). Furthermore, when a chiral center on the ten-membered ring is preserved through the cyclization, the number of potential stereoisomers is doubled, since there will be two possible cis-fused isomers and two possible trans-fused isomers for each regioisomer. In practice, the regiochemistry can usually be anticipated on the basis of the substituents on the ten-membered ring and the conditions used to induce cyclization, e.g., fluoride-induced cyclization of both allyl silane **1a** and allyl stannane **1b** lead exclusively to the cis-fused hydroazulenol **3a**,[2a,b] which is consistent with the expected regiochemistry of such reactions. The a priori prediction of the stereochemistry of these cyclizations is a more subtle matter, however, since for **1b** the stereochemistry of the product can be altered to give only the trans-fused isomer **3b** by simply changing the reaction conditions.[2b]



1a: R=$SiMe_3$; **1b**: R=$SnBu_3$
2: R=H

3a: cis
3b: trans

All possible combinations of regioisomers and stereoisomers have been observed as products in transannular cyclization of 5-cyclodecenones.[3] It would be useful to know the regio- and stereochemistry from transannular cyclization of the unsubstituted skeleton, (*E*)-5-cyclodecenone (**2**), whose cyclizations have not previously been studied, so that comparisons could be drawn between the

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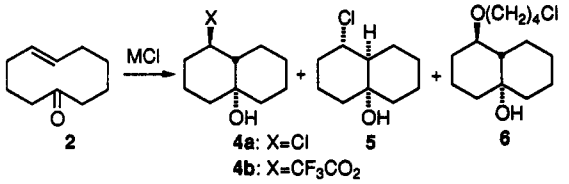
(1) Author to whom correspondence should be sent concerning the calculations.
(2) (a) Jisheng, L.; Gallardo, T.; White, J. B. *J. Org. Chem.* **1990**, *55*, 5426–5428. (b) Fan, W.; White, J. B. *Tetrahedron Lett.* **1993**, *34*, 957–960. (c) Synthesis of (±)-Africanol and (±)-Isoafricanol. Fan, W.; White, J. B. *J. Org. Chem.* **1993**, *58*, 3557–3562. (d) A Molecular Modelling and NMR Spectroscopic Examination of (*E*)-5-Cyclodecenone and Its 2-Methyl and 10-Methyl Analogs. Chu, Y.; Colclough, D.; White, J. B.; Smith, W. B. *Magn. Reson. Chem.* In Press.
(3) For examples leading to *trans*-hydroazulenes, see refs 2b and (a) Akhbar, M.; Marsh, S. *J. Chem. Soc. C* **1966**, 937–942. (b) Shiobara, Y.; Iwata, T.; Kodama, M.; Asakawa, Y.; Takemoto, T.; Fukazawa, Y. *Tetrahedron Lett.* **1985**, *26*, 913–916. (c) Harimaya, K.; Gao, J.-F.; Ohkura, T.; Kawamata, T.; Itaka, Y.; Guo, Y.-T.; Inayama, S. *Chem. Pharm. Bull.* **1991**, *39*, 843–853. (d) Lorenc, L.; Rajkovic, Ml; Milovanovic, A.; Mihailovic, M. Lj. *J. Chem. Soc., Perkin Trans. 1* **1988**, 1495–1499. For examples leading to *cis*-hydroazulenes, see refs 2a–c and (e) González, A.; Galindo, A.; Palenzuela, J. A.; Mansilla, H. *Tetrahedron Lett.* **1986**, *27*, 2771–2774. For an example leading to a *trans*-hydronaphthalene, see: (f) Niwa, M.; Iguchi, M.; Yamamura, S. *Bull. Chem. Soc. Jpn.* **1976**, *49*, 3148–3154. For examples leading to both *cis*- and *trans*-hydronaphthalenes, see: (g) Paquett, L. A.; Shi, Y.-J. *J. Am. Chem. Soc.* **1990**, *112*, 8478–8489.

0022-3263/93/1958-6303$04.00/0

Table I. Acid-Induced Transannular Cyclizations of (*E*)-5-Cyclodecenone (2)



2 4a: X=Cl 5 6
4b: X=CF_3CO_2

entry	acid[a]	solvent	X	4	yield, % 5	6
1	Me_2AlCl	CH_2Cl_2	Cl	64	4.5	
2	$SnCl_4$	CH_2Cl_2	Cl	66	8	
3	aqueous HCl[b]	CH_2Cl_2	Cl	55	12	
4	HCl (gas)	CH_2Cl_2	Cl	52	22	
5	aqueous HCl[b]	THF	Cl	33	31	3.5
6	HCl (gas)	THF	Cl	28	26	5
7	CF_3CO_2H	CH_2Cl_2	O_2CCF_3	64		

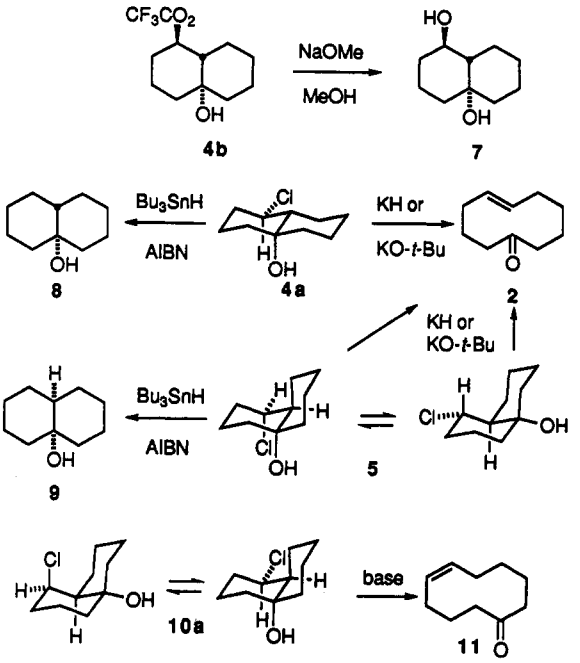
[a] All reactions were started at 0 °C and warmed to room temperature, except for entry 2, which was started at −35 °C and allowed to warm to 0 °C. [b] The same reaction using aqueous HBr gave essentially the same product ratios of the corresponding bromohydrins in combined yields of 85–95%.

"normal" selectivity of the unsubstituted cyclodecenone with those of substituted 5-cyclodecenones under the same reaction conditions. Such a study is reported herein, with the *Z* isomer of **2** also included so that the effect of the alkene geometry can also be taken into account. From ours and other's work, there are four general categories in which the mechanistic pathways for cyclization of 5-cyclodecenones can be grouped: nucleophilic addition of an allyl anion or its equivalent to the ketone (e.g., fluoride-induced cyclizations of **1a,b**), concerted ene cyclization, electrophilic addition of the ketone to the alkene, and radical cyclization of a ketyl radical to the alkene. This study is limited to the latter two mechanistic pathways, involving activation of the keto group by acids or by one-electron reducing agents, since the first two mechanistic pathways normally require an additional substituent at an allylic position or on the alkene, respectively. During the study, it became clear that the systems previously used for designating the conformations of (*E*)-5-cyclodecenones were inadequate, and a new system was developed on the basis of the three stereochemical relationships that uniquely define each low energy conformation.

Results

Acid-Induced Transannular Cyclizations of (*E*)-5-Cyclodecenone (2). (*E*)-5-Cyclodecenone (**2**) was prepared via the anionic oxy-Cope rearrangement of *trans*-1,2-diethenylcyclohexanol,[4] and its acid-induced cyclizations are given in Table I. 1,6-Cyclization was observed in all cases, and even though under certain conditions a mixture of diastereomers was obtained, for each ring fusion only one of the two possible stereoisomers was produced. Treatment of **2** with Lewis acids (Me_2AlCl or $SnCl_4$ in CH_2Cl_2) led predominantly to the chlorine-containing, trans-fused hydronaphthalenol **4a** (>60%) and a small amount (<10%) of the corresponding cis-fused product **5**. A slightly less selective reaction was observed using either gaseous or aqueous HCl in CH_2Cl_2, but the same reaction in THF gave essentially a 1:1 mixture of **4a** and **5**, along with a product (**6**) derived from participation of the solvent in the reaction. The stereochemistry of **6** was not rigorously proved as was done for **4a** and **5** (vide infra), but it appears to have the same trans ring fusion as demonstrated for **4a** on the basis of the similarities of their ^1H NMR and ^{13}C NMR spectra. Chlorohydrins **4a** and **5** were independently resubjected to treatment with either HCl or $SnCl_4$, and no interconversion between them was observed by TLC, although there was some decomposition under more vigorous conditions than those used in the cyclizations. A more selective cyclization was observed using CF_3CO_2H in CH_2Cl_2, leading exclusively to the trans monoester **4b**.

Scheme I



The regiochemistry and the relative stereochemistry of the acid-catalyzed cyclizations of (*E*)-5-cyclodecenone (**2**) were demonstrated through chemical correlations of the products to known compounds (Scheme I). The structure and stereochemistry of the trifluoroacetate derivative **4b** was assigned on the basis of its saponification to the known diol **7**.[5] The hydronaphthalene structure and the relative stereochemistry of the ring fusions for **4a** and **5** were established by radical dechlorination to the known[6] *trans*- and *cis*-bicyclo[4.4.0]decan-1-ols **8** and **9**, respectively. The coupling pattern and coupling constants for the hydrogen α to the chlorine atom of **4a** (td, J = 10.8, 4.2 Hz) are essentially the same as those for the hydrogen α to the trifluoroacetoxy group of **4b** (td, J = 10.8, 4.4 Hz) and are consistent with that hydrogen being axial and vicinal to two axial and one equatorial hydrogen. The facile Grob fragmentation of **4a**, which led cleanly to (*E*)-5-cyclodecenone (**2**), is also consistent with trans,trans stereochemistry for this molecule.[5] Grob fragmentation of the cis isomer **5** also regenerated **2**, which led to it be assigned the cis,cis stereochemistry. The alternative stereochemical assignment for **5**, the cis,trans isomer **10a**, would be expected to give rise to (*Z*)-5-cyclodecenone (**11**).[5]

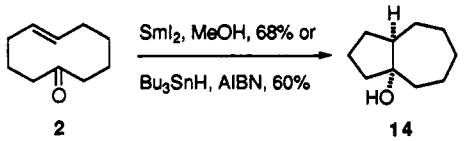
Synthesis and Transannular Acid-Induced Cyclizations of (*Z*)-5-Cyclodecenone (11). A practical synthesis of (*Z*)-5-cyclodecenone (**11**) was needed in order to ascertain the effect of the alkene geometry on the regio-

(4) (a) Kato, T.; Kondo, H.; Nishino, M.; Tanaka, M.; Hata, G.; Miyake, A. *Bull. Chem. Soc. Jpn.* **1980**, *53*, 2958–2961. (b) Holt, D. A. *Tetrahedron Lett.* **1981**, *22*, 2243–2246.

(5) Wharton, P. S.; Hiegel, G. A. *J. Org. Chem.* **1965**, *30*, 3254–3257.
(6) Molander, G.; Etter, J. B. *J. Org. Chem.* **1986**, *51*, 1778–1786.

and stereochemistry of the cyclization.[7] 6-Hydroxycyclodecenone (**12a**), which can be prepared in gram quantities by treatment of decalin with singlet oxygen,[8] was converted in five steps into **11** (Scheme II). The results from treatment of **11** with either protic or Lewis acids were similar to those of its *E* isomer in that only 1,6-cyclization was observed. The notable differences are that the ring fusion is exclusively cis, and the stereochemistry at the chiral secondary center of **10a,b** is inverted with respect to the cis-fused product **5** obtained from (*E*)-5-cyclodecenone (**2**). The stereochemistry of the chloride **10a** is consistent with its Grob fragmentation to regenerate (*Z*)-5-cyclodecenone (**11**), and its dechlorination to give the cis hydronaphthalenol **9**. The stereochemistry of the trifluoroacetate **10b** was confirmed by its saponification to the known diol **10c**.[5] It was observed that the (*Z*)-cyclodecenone **11** was qualitatively less reactive in these acid-induced cyclizations than the corresponding reactions of its *E* isomer **2**, which is consistent with the reports in the literature where such comparisons can be made.[3a,d,g]

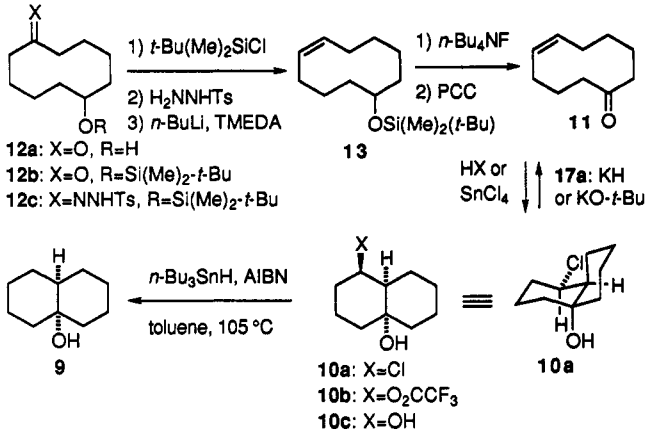
Radical Transannular Cyclizations of (*E*)- and (*Z*)-5-Cyclodecenones (2 and 11). A ketyl radical intermediate can be generated through formally two different types of reductive processes. One is the covalent addition of another radical species such as $Bu_3Sn^•$ to the carbonyl oxygen, and the other is through the agency of one-electron reducing agents. For cyclodecenone **2**, two sets of reaction conditions, Bu_3SnH/AIBN[9a] and SmI_2/MeOH,[9b] were found to induce clean cyclization, and both conditions gave exclusively the bicyclo[5.3.0]decan-1-ol **14**[2a] with the cis ring fusion. It should be noted that under these conditions the cyclizations were clean but somewhat sluggish and led to the recovery of a small amount of starting material. In neither reaction was the product from simple reduction of the ketone, 5-cyclodecen-1-ol, observed. Deletion of the MeOH in the SmI_2 reaction led to a low yield (23%) of a 1:1 mixture of **14** and its didehydro derivative *cis*-bicyclo[5.3.0]dec-5-en-1-ol (**3a**)[2a,10] and numerous unidentified products.



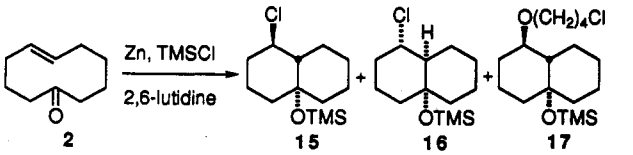
2 **14**

Several other reaction conditions with the potential for generating either a radical or ketyl radical anion intermediate from ketone **2** were investigated. Treatment of cyclodecenone **2** with sodium naphthalenide led to an instantaneous reaction and a plethora of unidentified products.[11] Treatment of **2** with Mg/Me_3SiCl in THF[12]

Scheme II

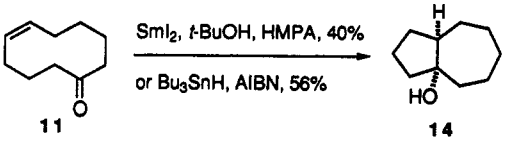


for prolonged periods of time (up to 2 weeks) led, as determined by TLC, to recovery of starting material, along with traces of the hydronaphthalenols **4a** and **5**. Zn/Me_3-SiCl/2,6-lutidine in THF has previously been used to induce radical cyclizations with δ,ϵ-unsaturated ketones[13] and proved to be a more reactive set of conditions toward cyclodecenone **2** than those involving Mg. However, the products from this reaction, an approximately 1:1 mixture of the trimethylsilyl ethers **15** and **16** along with a substantial amount of the trimethylsilyl ether **17**, showed the same regiochemistry as observed in acid-induced cyclizations, as demonstrated by their conversion to **4a**, **5**, and **6**, respectively, upon treatment with fluoride.[14] These results may reflect a lower energy barrier for sequential acid complexation and cyclization of cyclodecenone **2** compared to its reduction to give the ketyl radical intermediate.



2 **15** **16** **17**

cis-Alkene **11** was far less reactive than its trans isomer **2**, but its radical cyclizations resulted in the same regio- and stereochemistry. Whereas most of **2** was consumed after 1 day of reflux in benzene with *n*-Bu_3SnH/AIBN, the corresponding reaction with **11** in refluxing toluene after 3 days left appreciably more of the starting material. Unlike **2**, **11** was unreactive toward only SmI_2/ROH and required the addition of HMPA in order to induce reaction to give a mixture of products, of which the major compound by weight was the cis hydroazulenol **14**.



11 **14**

Conformational Analysis of (*E*)- and (*Z*)-5-Cyclodecenone (2 and 11). It can be determined from molecular models that (*E*)-5-cyclodecenone (**2**) is like an (*E,E*)-1,6-

(7) (*Z*)-5-Cyclodecenone (**11**) has previously been prepared by a multistep procedure that leads to a mixture of cis and trans isomers; see: Goering, H. L.; Closson, W. D.; Olsen, A. C. *J. Am. Chem. Soc.* **1961**, *83*, 3507–3511.

(8) McMurry, J. E.; Lectka, T.; Hodge, C. N. *J. Am. Chem. Soc.* **1989**, *111*, 8867–8872.

(9) (a) For an example of the intramolecular cyclization of an aldehyde with an unactivated alkene mediated by Bu_3SnH/AIBN, see: Beckwith, A. L. J. *J. Am. Chem. Soc.* **1986**, *108*, 5893–5901. (b) For an example of the intramolecular cyclization of an acyclic ketone with an unactivated alkene mediated by SmI_2/ROH, see: Molander, G. *Tetrahedron Lett.* **1987**, *28*, 4867–4870.

(10) The mixture of **14** and **3a** could arise from disproportionation of an intermediate secondary radical. Such a disproportionation has been seen for a tertiary radical and presumably reflects slow reduction of the carbon-centered radical to the corresponding anion; see: Curran, D. P.; Totleben, M. J. *J. Am. Chem. Soc.* **1992**, *114*, 6050–6058.

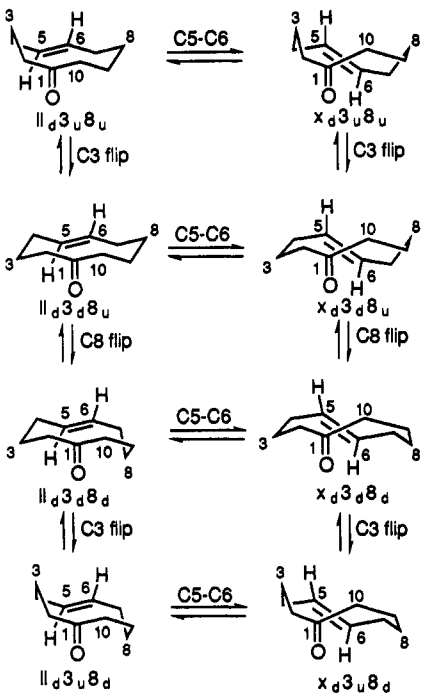
(11) In more highly substituted 5-cyclodecenones, these reaction conditions have proven useful for inducing cyclization; see refs 2b,c.

(12) For examples of the successful use of these reactions conditions to induce cyclization of γ,δ-unsaturated aldehydes, see: Hutchinson, C. R. *J. Org. Chem.* **1985**, *50*, 5193–5199.

(13) Corey, E. J.; Pyne, S. G. *Tetrahedron Lett.* **1983**, *24*, 2821–2824.

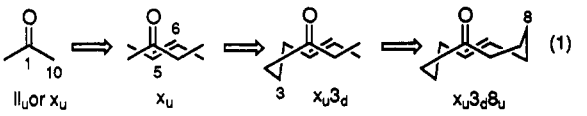
(14) See Jasperse et al. (Jasperse, C. P.; Curran, D. P.; Fevig, T. L. *Chem. Rev.* **1991**, *91*, 1237–1286) 1272, for a discussion on the advantages and disadvantages of Mg- and Zn-induced ketyl/alkene cyclizations.

Scheme III



cyclodecadiene in that the C1(O)–C10 unit clearly prefers a transoid geometry. (*E*)-5-Cyclodecenones can be thought of as being constructed of two parallel four-carbon fragments (C2–C1–C10–C9 and C4–C5–C6–C7) joined by two one-carbon fragments (C3 and C8). There are four independent operations that interconvert the low energy conformations of this molecule: rotation of either the C1–C10 or C5–C6 unit 180° through the ring and flipping either the C3 or C8 methylene units "up" and "down" (Scheme III). A system of nomenclature based on the three independent relationships that uniquely define each of these conformations has been developed in our group for the purpose of designating the low energy conformers of (*E*)-5-cyclodecenones: the relative orientation of the C1–C10 and C5–C6 units, the position of the C3 methylene unit (either "up" or "down"), and the position of the C8 methylene unit (also either "up" or "down"). For (*E*)-5-cyclodecenone (**2**), there are two unique orientations of the C1–C10 and C5–C6 bonds: they can be either "parallel" or "crossed", which we symbolize with a double "l" (i.e., ll) and an "x", respectively. Furthermore, in order to designate unambiguously all of the low energy conformations of substituted (*E*)-5-cyclodecenones, the two possible parallel and two possible crossed orientations are distinguished by the subscript "u" (for "up") or subscript "d" (for "down"), which indicate the relative position of the oxygen atom of the ketone at C1 with respect to the plane of the ring. The relative positions of the C3 and C8 methylenes are similarly designated with subscripts u or d, which leads to the descriptors attached to each of the conformations in Scheme III. The ring-flipped conformation for all of these is degenerate and not shown but would be named by inverting all subscripts.[15] This analysis of the (*E*)-5-cyclodecenone ring system was supported by a molecular mechanics study.[2d,16] The two major conformations, $ll_d3_d8_u$ and $ll_d3_d8_d$, are both parallel conformers differing only in the position of the C8 methylene. They comprise over 90% of the total population and are 2–3 kcal/mol lower in energy than the other six conformers of Scheme III.

This system makes it easy to draw a conformation given its descriptor and easy to derive the descriptor given a conformation. For example, the $x_u3_d8_u$ conformer would be drawn, as illustrated in eq 1, by first drawing the C2–C1–C10–C9 fragment with the carbonyl oxygen up, drawing the C4–C5–C6–C7 fragment so that the C1–C10 and C5–C6 bonds cross, and then sketching the C3 and C8 methylenes down and up, respectively. Another advantage of this system of nomenclature is that it divides the conformations into four subgroups (x_u, x_d, ll_u, and ll_d) that each correspond to one of the four ring fusions (two cis and two trans) possible for 1,5- and 1,6-cyclization of substituted (*E*)-5-cyclodecenones.



There have been several other systems of nomenclature used to designate the different conformations of (*E*)-5-cyclodecenones, the most useful being the B/C nomenclature in which the ten-membered ring is described as the envelope of three cyclohexane rings and the letters "B" and "C" are used to designate "boat" and "chair" subunits within the cyclodecane ring.[17–20] Using this system, the $ll_d3_d8_u$ conformer of Scheme III would be called the CCC conformer, the $ll_d3_d8_d$ would be the CCB, etc. The B/C nomenclature works well for parallel conformers and does have the advantage of striking a cord of familiarity by relating the conformations of cyclodecanes to the well-known chair and boat forms of cyclohexanes, but this is also a weakness because the general presumption of chair conformations being lower in energy than boat conformations is misleading in cyclodecane rings. There are also several practical problems with the use of this system of nomenclature. One is that it is internally inconsistent. For example, as illustrated in eq 2, the CCC would be better named CC′C, where C′ represents the ring-flipped

(15) For a substituted (*E*)-5-cyclodecenone there would be a total of 16 low energy conformations to be considered, since the ring-flipped conformations obtained by carrying out all four of these independent operations on any one of the eight conformations described for (*E*)-5-cyclodecenone (**2**) would not be degenerate.

(16) These calculations were carried out using PCMODEL in conjunction with the global minimization program GMMX. These programs were written by K. E. Gilbert and J. J. Gajewski and are available from Serena Software, Bloomington, IN. A detailed description of PCMODEL has recently appeared; Gajewski, J. J.; Gilbert, K. E.; McKelvey, J. In *Advances in Molecular Modeling*, Liotta, D., Ed.; JAI Press: Greenwich, CT, 1990; Vol. 2, pp 65–92.

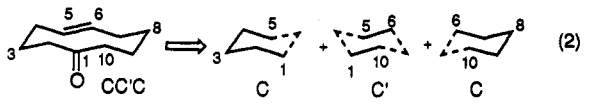
(17) For examples of the use of the B/C nomenclature, see: (a) Still, W. C.; Galynker, I. *Tetrahedron* **1981**, *37*, 3981–3996. (b) Schreiber, S. L.; Hulin, B.; Liew, W.-F. *Tetrahedron* **1986**, *42*, 2945–2950.

(18) The conformations of an (*E*)-5-cyclodecenone[19a] have also been labeled using the C/T system (C = chair, T = twist boat) of Wharton[19b] as modified by Sutherland[19c] in which the cyclodecane ring is described as the envelope of two cyclohexane rings. For example, the $ll_d3_d8_u$ conformation in Scheme III would be described as the CC conformer. This system was actually developed to describe the conformations of (*E*,*E*)-1,5-cyclodecadienes and not the (*E*,*E*)-1,6-cyclodecadienes that (*E*)-5-cyclodecenones resemble, and it suffers from the same limitations described in the text for the B/C system of nomenclature.

(19) (a) Terada, Y.; Yamamura, S. *Tetrahedron Lett.* **1979**, 1623–1626. (b) Wharton, P. S.; Poon, Y.-C.; Kluender, H. C. *J. Org. Chem.* **1973**, *38*, 735–740. (c) Sutherland, J. K. *Tetrahedron* **1974**, *30*, 1651–1660.

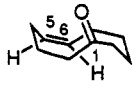
(20) While this manuscript was in preparation, Goto published a modified version of the Dale nomenclature for medium and large cycloalkanes; see: Goto, H. *Tetrahedron* **1992**, *48*, 7131–7144. This system of nomenclature is more generally applicable than the ll/x nomenclature we have proposed, as ours is limited to rings whose conformational analysis resembles that of (*E*,*E*)-1,6-cyclodecadiene. However, our proposed system is more readily understood and applied for (*E*)-5-cyclodecenones and is more useful in relating the stereochemical outcome of the cyclizations to the conformational isomers of (*E*)-5-cyclodecenones.

chair conformer of C. Another problem arises in attempting to name all 16 of the low energy conformations of substituted (*E*)-5-cyclodecenones. Even if one uses primes, e.g., C and C′, to extend the number of conformations that can be named, there is still a problem in adequately naming the crossed conformations, since the "center ring" in the cyclodecenone is neither a chair nor a boat.

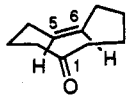


(2)

Molecular mechanics calculations with global minimum searching[16] were also carried out on (*Z*)-5-cyclodecenone (**11**), leading to six different conformations. The two lowest energy conformations are depicted below and account for over 90% of the Boltzmann distribution. The lowest energy conformation (MMX energy = 12.1 kcal/mol) has an anti relationship between the C=O bond and both of the alkene C—H bonds, which would lead to a trans ring fusion for both 1,5- and 1,6-cyclization. Next lowest in energy by about 0.3 kcal/mol is a conformation with a syn orientation between these three bonds, which would lead to a cis ring fusion in either a hydronaphthalene or a hydroazulene product. Given that only products with cis ring fusions were observed from 5-cyclodecenone **11** irrespective of the reaction conditions, it is useful to note that there is a significant difference in the distances between the carbonyl carbon and both alkene carbons in these two conformations. For the anti conformation, these distances are on the order of 3.5–3.6 Å, while for the syn conformer they are both a little less than 3.1 Å. It has recently been observed in the ene reactions of a set of (*E*)-5-cycloalkenones that cyclization took place in those substrates with a calculated distance between C1 and C5 of less than 3.0 Å and failed in one substrate with a calculated distance of 3.3 Å.[21] This rationale would also explain why the reactions of (*Z*)-5-cyclodecenone (**11**) are more sluggish than those of its *E* isomer **2**, given the shorter distances between C1 and C5 or C6 in the latter compound.



11 anti

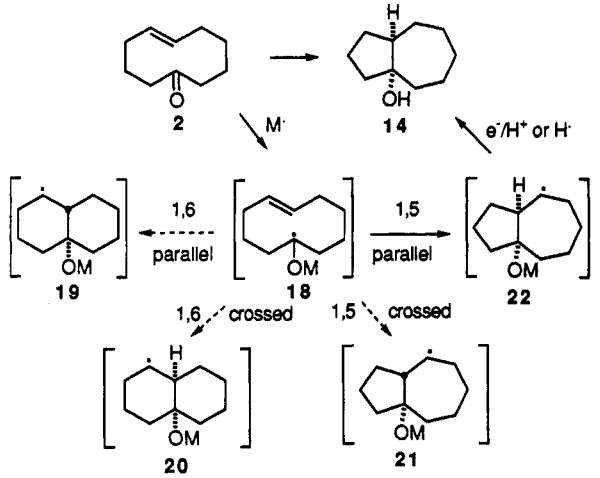


11 syn

Discussion

Regio- and Stereochemistry of the Radical Cyclizations. When this study was begun, the addition of a ketyl radical to an alkene within a 10-membered ring was unprecedented.[2b,22] The potential routes for the radical cyclization of cyclodecenone **2** are laid out in Scheme IV. In principle, cyclization of the first intermediate, ketyl radical **18**, could have proceeded by any one of four reaction pathways to give any one or a mixture of the cis- and trans-fused hydronaphthalene and hydroazulene radicals **19–22**. The "normal" regiochemistry in the 5-cyclodecenone ring system would lead to a hydroazulene in analogy to the radical cyclizations of acyclic 1-hexenyl radicals, which usually lead to 1,5-

Scheme IV



cyclization.[23] However, it was also possible that the ten-membered ring could affect the regiochemistry to give, in analogy to the acid-induced cyclizations, a hydronaphthalene. It was also conceivable for the radical addition to be reversible, leading to the thermodynamically more stable hydronaphthalene ring system (vide infra).[24] Given that the only observed product is the cis-fused hydroazulene **14**, the simplest scenario is that the ketyl radical **18** undergoes exclusive and irreversible 1,5-cyclization from a parallel conformation to give the intermediate cis-fused hydroazulene radical **22**, which does not undergo interconversion with any of the other radical species but is irreversibly trapped to give **14**.

An irreversible kinetic cyclization is supported by several lines of evidence. In the radical dechlorinations of **4a**, **5**, and **10a** to give hydronaphthalenols **8** and **9**, there is indirect experimental evidence that, once formed, the hydroazulene radical **22** does not interconvert with the hydronaphthalene radicals **19** and **20**. These radical dechlorinations generate the hydronaphthalene radical intermediates **19** and **20** (M = H) under similar conditions (Bu_3SnH/AIBN) to one of the sets of conditions used in the radical cyclization of cyclodecenone **2**. The absence of any hydroazulene products in these dechlorinations does not by itself prove that the hydronaphthalene radicals **19** and **20** cannot interconvert with hydroazulene radicals **21** and **22**, since it could be argued that their absence simply reflects greater thermodynamic stability of the hydronaphthalene radicals (vide infra). But coupled with the observation that no hydronaphthalene products are isolated in the radical cyclization of cyclodecenone **2**, it can

(21) Janardhana, S.; Rajagopalan, K. *J. Chem. Soc., Perkin Trans. 1* **1992**, 2727–2728.

(22) (a) Radical cyclization of 6-bromocyclodecanone, using Bu_3SnH, gave bicyclo[4.4.0]decan-1-ol, presumably through addition of the radical generated at C6 to the ketone; see: Beckwith *J. Org. Chem.* **1983**, *48*, 4718–4722. (b) Dissolving metal reduction (Li/NH_3) of 5-cyclodecynone is reported to give a 25:1 mixture of bicyclo[4.4.0]dec-5-en-1-ol and bicyclo-[5.3.0]dec-6-en-1-ol. This cyclization could proceed through initial reduction of either the alkyne or ketone, followed by addition of a radical anion, radical, or anion intermediate to the other functional group; see: Balf, R. J.; Rao, B.; Weiler, L. *Can. J. Chem.* **1971**, *49*, 3135–3142. (c) Addition of Bu_3Sn·(Bu_3SnH/AIBN) to 5-cyclodecynone is proposed to proceed through addition of the tin radical to C6 of the alkyne and addition of that radical to the ketone to give an intermediate hydroazulenol, which further fragments, leading ultimately to the same product as that from aldol condensation/dehydration of cyclopentanone with itself. See: Baldwin, J. E.; Adlington, R. M.; Robertson, J. *Tetrahedron* **1991**, *47*, 6795–6812.

(23) For a recent review on intramolecular free-radical cyclizations, see: RajanBabu, T. V. *Acc. Chem. Res.* **1991**, *24*, 139–145.

(24) The isomerization of a hydroazulene radical into a hydronaphthalene radical through reversible ring opening to give an acyl-stabilized 5-cyclodecyl radical has been proposed. See: Dowd, P.; Zhang, W. *J. Org. Chem.* **1992**, *57*, 7163–7171.

Table II. Calculated (MMX) Heats of Formation (H_f) for Radicals 18–22 and Their Hypothetical Transition Structures[a]

radical	H_f for radical intermediate (kcal/mol)	H_f of transition structure (kcal/mol)
18	-21	
19	-85.1	-10.9
20	-83.0	-7.49
21	-71.8	-6.63
22	-72.4	-11.4

[a] See text for explanation.

be inferred that at no time are hydronaphthalene radicals formed either directly from cyclodecyl radical 18 or indirectly from hydroazulene radical 22, because if they were formed they would have been trapped as hydronaphthalene products 8 and 9 under these conditions.

The results from molecular mechanics calculations (PCMODEL), using the parameters of Spellmeyer and Houk,[25] on the radical 18 (M = H),[26] on radicals 19–22, and on hypothetical transition structures[27] connecting them along their reaction pathways are also consistent with the scenario presented in Scheme IV. The radical 18 (M = H) exhibited a similar set of low energy conformers as found for the cyclodecenone 2 (Scheme III), and global minimum searching predicted that the equivalent $ll_d3_d8_u$ and $ll_d3_d8_d$ conformers are the low energy conformers with heats of formation of approximately -21 kcal/mol. The lowest energy crossed conformations were approximately 1.5 kcal/mol less stable. The heats of formation for the four radical intermediates 19–22 and for their hypothetical transition structures that connect them with ketyl radical 18 are given in Table II. It should be noted from the heats of formation of radical intermediates 18–22 that even though the hydronaphthalene radicals 19 and 20 are lower in energy than the hydroazulene radicals 21 and 22, the cyclization of ketyl radical 18 to any of the radicals 19–22 is sufficiently exothermic to make it effectively irreversible so that the product(s) from this step will reflect the relative energies of the transitions structures and not the ground states of the radicals 19–22. The calculated energies for the transition structures of 19–22 are consistent with the pathway leading from ketyl radical 18 to the cis-fused hydroazulene radical 22 being lowest in energy, albeit not by a large enough margin to explain the exclusive formation of hydroazulene radical 22 in preference to the hydronaphthalene radical 19. However, they are consistent with a lower energy reaction pathway for cyclization from a parallel conformation relative to the alternative reaction pathway through a crossed conformation that would have given radical intermediates 20 or 21. The observed preference for 1,5-cyclization to give 22 over 1,6-cyclization to give 19 is akin to the observed preference for *5-exo-trig* cyclization over *6-endo-trig* cyclization in acyclic 1-hexenyl radicals.[23,28a] This is a notable correlation because the low energy conformations $ll_d3_d8_u$ and $ll_d3_d8_d$ of cyclodecyl radical 18 are preorganized to adopt the chairlike transition state that has been put forward as a model for explaining the regio- and stereochemistry in acyclic 1-hexenyl radicals.[28b] This preference reflects a better angle for addition of the ketyl radical at C1 to C5 of the alkene and, given the exothermicity of the radical cyclization, may also be related to the shorter distance between C1 and C5 (2.8–2.9 Å) in the lowest energy parallel $ll_d3_d8_u$ and $ll_d3_d8_d$ conformations compared to the distance between C1 and C6 (2.9–3.1 Å).

There is one caveat that should be mentioned concerning these molecular mechanics calculations, which concerns whether interconversion among cyclodecene conformations can take place after the generation of the cyclodecyl radical 18. By fixing various bonds and reminimizing, the energy barrier for the flipping of the C3 and C8 methylene units in the cyclodecyl radical 18 is calculated to be a few kilocalories per mole. In comparison, the energy of activation for 180° rotation of the alkene unit through the ten-membered ring in cyclodecene itself is estimated to be about 11 kcal/mol,[29] which is approximately the same as the calculated energy barrier for cyclization of cyclodecyl radical 18 to give radical 22. Thus the cyclodecyl radical 18 can undergo flipping of the C3 and C8 methylene units prior to cyclization, which has no effect on the stereochemistry of the cyclization, but may not be able to equilibrate among parallel and crossed conformations prior to cyclization, which does affect the stereochemistry of the cyclization. The implication is that the stereochemistry of the cyclization may actually be determined by the relative energies and the relative reduction potentials of the different conformations of cyclodecenone 2. This admonition does not necessarily alter the analysis, however, since the relative stabilities of parallel and crossed conformations for cyclodecenone 2 and cyclodecyl radical 18 are approximately the same.

For (*Z*)-cyclodecenone 11, no modeling of radical intermediates was done, but its cyclization to give the cis ring fusion and hydroazulene skeleton of 14 can be understood in much the same way as the corresponding cyclization of (*E*)-cyclodecenone 2. It can be argued that cyclization to give the cis ring fusion reflects a greater reactivity in the syn conformer relative to the anti conformer due to closer proximity of the carbonyl carbon to the alkene in the former. With respect to the regiochemistry in the cyclization, the ketyl radical in the syn conformation is similar to that of the low energy parallel conformations of the (*E*)-cyclodecyl radical 18 in that it is also preorganized to adopt a chairlike transition state that mimics the proposed transition state of acyclic 1-hexenyl radicals.[28b]

Regio- and Stereochemistry of the Acid-Induced Cyclizations. Conceptually, as many as eight different products, taking into account both regio- and stereoisomers, could have arisen from the electrophilic cyclization of either (*Z*)- or (*E*)-5-cyclodecenones (11 or 2). The eight chlorohydrins from net addition of HCl are illustrated in Table III, along with their calculated MMX heats of formation. It should be clear that even though only the thermodynamically more stable hydronaphthalene prod-

(25) Recent ab initio calculations on the 5-hexenyl radical (Spellmeyer, D. C.; Houk, K. N. *J. Org. Chem.* **1987**, *52*, 959–974) were consistent with the experimental observation of kinetic formation of the cyclopentylcarbinyl radical over the thermodynamically more stable cyclohexyl radical. These results were used to provide a set of MM2 parameters for molecular modeling purposes, whose calculated energies closely matched those of the ab initio calculations for the 5-hexenyl radical as well as those for addition of methyl radical to either alkene carbon of propene. These parameters have been ported into the PCMODEL program (ref 16).

(26) Calculations for the radical 18 (M = Me_3Sn) paralleled the more facile calculations of 18 (M = H). A similar set of calculations were also attempted on 18 (M = *n*-Bu_3Sn), but free rotation within the three butyl groups made their interpretation difficult, since slight variations of the butyl groups altered the energy significantly.

(27) The difference between a transition state and a transition structure has recently been nicely clarified. See: Houk, K. N.; Li, Y.; Evenseck, J. D. *Angew. Chem., Int. Ed. Engl.* **1992**, *31*, 682–708 (pages 684–685).

(28) (a) Beckwith, A. L. J.; Easton, C. J.; Serelis, A. K. *J. Chem. Soc., Chem. Commun.* **1980**, 482–483. (b) Beckwith, A. L. J.; Lawrence, T.; Serelis, A. K. *J. Chem. Soc., Chem. Commun.* **1980**, 484–485.

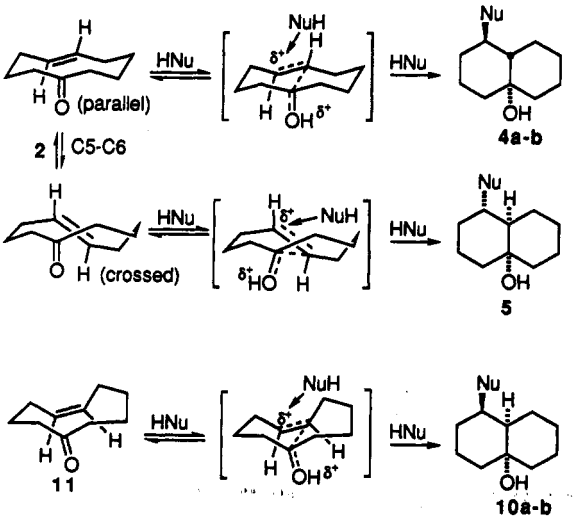
(29) Binsch, G.; Roberts, J. D. *J. Am. Chem. Soc.* **1965**, *87*, 5157–5162.

Table III. Heats of Formation (H_f) of the Possible Chlorohydrin Products from 5-Cyclodecenone

chlorohydrin	H_f
1-hydroxy-5-chlorobicyclo[4.4.0]decane	
trans, anti (**4a**)[a]	-94.8
trans, syn	-92.9
cis, anti (**10a**)	-91.9
cis, syn (**5**)	-91.2
1-hydroxy-6-chlorobicyclo[5.3.0]decane	
trans, anti	-82.1
trans, syn	-79.2
cis, anti	-79.3
cis, syn	-78.3

[a] Trans and cis refer to the relative stereochemistry of the ring fusion and anti and syn to the relationship between the hydroxyl and chloro substituents.

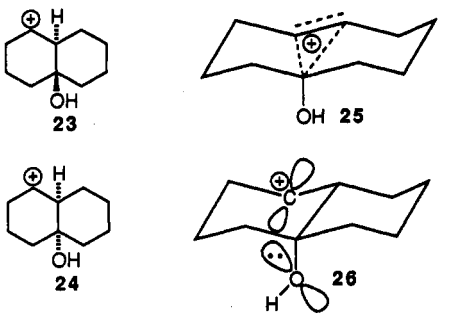
Scheme V



ucts were isolated from the acid-induced cyclizations, the experimental results are inconsistent with a reaction mechanism in which each step is under thermodynamic control. The observation that **4a**, **5**, and **10a** could be recovered unchanged when resubjected to treatment with either protic or Lewis acids indicates that at least the last step of the reaction, which presumably involves carbon–chlorine bond formation, is irreversible.

Although an explanation for the range in selectivities (cf. entries 5 and 6 with entry 7) is beyond the scope of this study, there are several interrelated experimental observations that can be related to the mechanism of these cyclizations. One is that for each cyclization, even those that gave a mixture of products, only one of the two possible stereoisomers was isolated for a given ring fusion. Another is that the cis-fused hydronaphthalenol **5**, obtained as a minor product from cyclodecenone **2**, differs in its relative stereochemistry from that of the cis-fused hydronaphthalenol **10a**, obtained as the sole product from cyclodecenone **11**. It is useful to note that each product can be thought of as arising from net anti addition of the carbonyl carbon and the nucleophile (Cl^- or $CF_3CO_2^-$) to the alkene. For **4a,b**, this represents anti addition to a parallel conformation of cyclodecenone **2**; for the minor product **5**, the same addition from a higher energy crossed conformation; and for **10a,b** anti addition to the syn conformation of cyclodecenone **11** (Scheme V). Formation of hydronaphthalene **6** arises from interception by the solvent of the cation intermediate.

The actual structure of the intermediate cation in these cyclizations is debatable. Similar anti additions to a cyclodecene were observed by Goering and Closson in the solvolyses of the *p*-nitrobenzoates of (*Z*)- and (*E*)-5-cyclodecen-1-ol, with the *Z* isomer leading to a cis ring fusion and the *E* isomer leading to a trans.[30] They could explain the stereochemistry of their products using either classical or nonclassical carbocations as intermediates, but discrete classical ions, e.g. **23** and **24**, are problematic in



this work because it would appear to require that there be a common intermediate, i.e. **24**, in the formation of the cis-fused products **5** and **10a**. However, bridging, nonclassical carbocation intermediates, e.g. **25**, by exposing only one face of the alkene to nucleophilic attack, would account for translation of the stereochemistry latent in both the original alkene geometry and the conformation from which it cyclizes into each product. Another possibility is the intermediacy of contact ion pairs like **26**, wherein interaction of a lone pair of electrons on the oxygen with a classical carbocation would also account for net anti addition to the alkene.[31] Such contact ion pairs have been proposed to explain the stereochemistry in intermolecular Prins reactions[32a,b] and have been supported by both a theoretical and experimental study on protonated oxetane intermediates, which resemble such ion pairs.[32c] However, the stereochemistry and product distribution from such ene reactions has also been explained by a three-membered intermediate from electrophilic addition of an oxonium to an alkene, akin to the nonclassical ion **25**.[32d,e]

The difference in regiochemistry between the electrophilic and radical cyclizations is explicable from the differences in their mechanisms. For the ketyl radical cyclization of **18**, there is a highly exothermic and irreversible cyclization step in which the relative stabilities of the radical intermediates **19–22** are not reflected in the competing transition states. For the electrophilic cyclizations there are cation intermediates, which more closely resemble the hydroazulene and hydronaphthalene products than does the cyclodecyl radical **18** and are therefore more likely to reflect in the competing transitions states the greater stability of the hydronaphthalene ring system over the hydroazulene. This greater stability is evidenced in the relative energies of the chlorohydrins found in Table III and also by the heats of formation, calculated using the PM3 modification of the MNDO

(30) Goering, H. L.; Closson, W. D. *J. Am. Chem. Soc.* **1961**, *83*, 3511–3517.

(31) We thank one of the referees for bringing this type of intermediate to our attention.

(32) (a) Blomquist, A. T.; Wolinsky, J. *J. Am. Chem. Soc.* **1957**, *79*, 6025–6030. (b) Schowen, K. B.; Smissman, E. E.; Schowen, R. L. *J. Org. Chem.* **1968**, *33*, 1873–1876. (c) Meresz, O.; Leung, K. P.; Denes, A. S. *Tetrahedron Lett.* **1972**, 2797–2800. (d) Dolby, L. J. *J. Org. Chem.* **1962**, *27*, 2971–2975. (e) Dolby, L. J.; Lieske, C. N.; Rosencrantz, D. R.; Schwarz, M. J. *J. Am. Chem. Soc.* **1963**, *85*, 47–52.

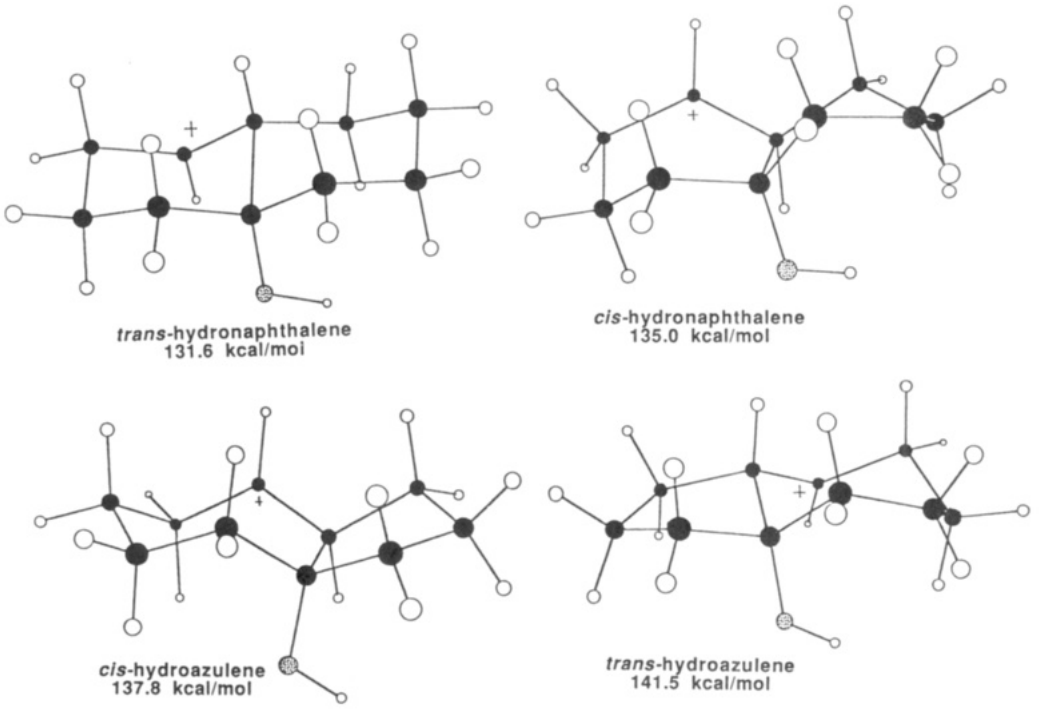


Figure 1. Structures and heats of formation from PM3 (MNDO) calculations of carbocation structures.

semiempirical method,[33] of the cis- and trans-fused hydronaphthalene and hydroazulene carbocations (Figure 1). In relating the energetics for 1,6- versus 1,5-cyclization to the energies of the carbocations, there are two comparisons to be made. One is between the trans-fused hydronaphthalene cation and the cis-fused hydroazulene (the intermediates from cyclization from a parallel conformer), and the other is between the cis-fused hydronaphthalene cation and the trans-fused hydroazulene (the intermediates from cyclization from a crossed conformer). In both comparisons, the hydronaphthalene carbocations are lower in energy, which is consistent with the observed regiochemical preference for 1,6-cyclization. It should be added that electrophilic cyclizations that lead to hydroazulene products via 1,5-cyclization, such as the acid-induced cyclization of cyclodecenone **1b**,[2b] are not problematic since it can be argued that the tributylstannyl group at C7 of **1b** alters the "normal" regiochemistry by stabilizing the pathway that leads to the hydroazulene product and by intercepting this pathway by loss of the stannyl group.

Conclusion

In comparing the reactivity of the substituted cyclodecenones **1a,b** to that of the unsubstituted cyclodecenones **2** and **11**, it is clear that the $SiMe_3$ and $SnBu_3$ groups of cyclodecenones **1a,b** alter the regiochemistry of their electrophilic transannular cyclization, since the unsubstituted cyclodecenones **2** and **11** lead to the hydronaphthalene ring system instead of the hydroazulene. With respect to the radical cyclizations, the stannyl group of **1b** is not necessarily controlling the regio- and stereochemistry of the cyclization given that unsubstituted **2** and **11** also lead to a cis-fused hydroazulene, but the stannyl substituent still has several advantages. The tin moiety makes for a more reactive substrate, provides a handle for controlling the stereochemistry to give either possible ring fusion,[2b] and also leaves behind an alkene that can be used in further transformations.[2c] The most obvious advantage of the unsubstituted cyclodecenones comes from the observation that the alkene geometry can be used to control the stereochemistry of the ring fusion of their hydronaphthalene products. It is particularly noteworthy for **4b** and **10b** that three contiguous chiral centers can be generated in one step with complete and predictable control over their relative stereochemistry. To further understand the stereoselectivity of the cyclizations of the allylsilane and allylstannane derivatives requires an understanding of the conformational selectivity of these cyclizations under different reaction conditions. Such studies are in progress and will be reported in due course.

Experimental Studies

General. Unless otherwise noted, all starting materials were obtained from commercial suppliers and used without further purification. Ether and tetrahydrofuran (THF) were distilled under nitrogen from sodium/benzophenone. Dichloromethane was distilled from P_2O_5. Triethylamine, *N,N,N′,N′*-tetramethylethylenediamine (TMEDA) and 2,6-lutidine were distilled from CaH_2 and stored over KOH. Chlorotrimethylsilane was distilled from *N,N*-dimethylaniline onto CaH_2. Samarium powder was purchased from Rhône-Poulenc, Phoenix, Az. Reactions involving organometallic reagents were carried out under argon (balloon) in oven-dried glassware. Reactions were monitored by thin-layer chromatography using Whatman precoated glass plates of 250-μm-thickness silica gel with a fluorescent indicator. Flash chromatography was carried out using American Matrex silica gel (35–70 μm, 60-Å pore). IR spectra were recorded on a Perkin-Elmer 1310 IR spectrophotometer. ^1H NMR spectra were recorded on a Nicolet NT-200 WB instrument in $CDCl_3$ unless otherwise indicated. Chemical shifts are expressed in parts per million (δ) relative to internal tetramethylsilane (δ = 0.0) or $CHCl_3$ (δ = 7.26). Data are reported as follows: chemical shift, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, br = broad), coupling constant(s), and integration. ^{13}C NMR spectra were determined on a Nicolet NT-200 WB

(33) (a) Dewar, M. J. S.; Healy, E. F.; Stewart, J. J. P. *J. Chem. Soc., Faraday Trans. 2* **1984**, *80*, 227–233. (b) MOPAC, version 6, Quantum Chemistry Program Exchange no. 504, University of Indiana, Bloomington, IN. The PM3 modification has been described. See: Stewart, J. J. P. *J. comput.-Aided Mol. Design* **1990**, *4*, 1-105.

instrument (50.3 MHz, $CDCl_3$) and the chemical shifts are reported in parts per million (δ) relative to the center peak of $CDCl_3$ (δ = 77.0). Low-resolution mass spectra were obtained on a GC-Finnegan TSQ 70 quadrapole mass spectrometer. The temperatures given for Kugelrohr distillations refer to oven temperatures.

***trans*-1,2-Diethenylcyclohexanol.** 1,2-Diethenylcyclohexanol was prepared as described in the literature[4] from 2-chlorocyclohexanone and vinylmagnesium bromide. Purification by flash chromatography (hexanes/EtOAc 25:1) gave *trans*-1,2-diethenylcyclohexanol in 38% yield as a colorless oil: IR (film 3400, 3080, 1640, 1440, 990, 960, 910 cm^{-1}; ^1H NMR δ 5.79–5.96 (m, 2H), 4.98–5.29 (m, 4H), 2.00–2.17 (m, 1H), 1.20–1.85 (m, 8H); ^{13}C NMR δ 145.9, 138.9, 116.1, 111.8, 73.1, 48.1, 37.8, 25.8, 25.8, 21.2.

(*E*)-5-Cyclodecenone (2). To potassium hydride (35% dispersion in mineral oil, 6 g, 52 mmol) washed with hexanes (3 × 5 mL) and suspended in THF (70 mL) at room temperature was added *trans*-1,2-diethenylcyclohexanol (2.0 g, 13.2 mmol) in THF (15 mL) dropwise by syringe. The reaction mixture was refluxed for 6 h, cooled in an ice bath, and then carefully quenched with 10% NH_4Cl (100 mL). The reaction mixture was extracted with Et_2O (3 × 100 mL), washed with saturated NaCl (100 mL), dried with $MgSO_4$, filtered, and concentrated. [Note: By TLC (hexanes/EtOAc 6:1; l_f approximately 0.67) *trans*-1,2-divinylcyclohexanol and **2** are indistinguishable.] Purification by flash chromatography (hexanes/EtOAc 25:1) gave **2**[34] (1.37 g, 9.0 mmol, 68%) as a colorless oil: ^1H NMR δ 5.1–5.4 (m, 2H), 1.2–2.6 (m, 14H); ^{13}C NMR δ 213.0, 134.4, 131.2, 45.6, 43.1, 34.1, 33.2, 28.7, 28.0, 22.1.

(1*R,5*R**,6*R**)- and (1*R**,5*S**,6*S**)-5-Chlorobicyclo[4.4.0]decan-1-ols (4a and 5). (a) Dry HCl in Dichloromethane.** HCl gas was bubbled through a solution of **2** (96 mg, 0.63 mmol) in dichloromethane (5 mL) at 0 °C. After 10 min, the cooling bath was removed and the bubbling continued for another 10 min. The pale yellow solution was diluted with dichloromethane (10 mL), washed with H_2O (15 mL) and saturated NaCl (10 mL), dried with $MgSO_4$, filtered, and evaporated to give a purplish oil. Purification by flash chromatography (hexanes/EtOAc 20:1) gave, in order of elution, the trans ring fusion product **4a** (62 mg, 0.33 mmol, 52%) as a colorless oil and the cis ring fusion product **5** (26 mg, 0.13 mmol, 22%) as a colorless oil that solidified upon standing, mp 68–70 °C. An analytical sample of **4a** was obtained by Kugelrohr distillation (0.3 mmHg, 60 °C): IR (film) 3450 (br), 1440, 940 cm^{-1}; ^1H NMR δ 3.92 (td, J = 10.8, 4.2 Hz, 1H), 2.22–2.31 (m, 1H), 2.06–2.11 (m, 1H), 1.07–1.87 (m, 13H); ^{13}C NMR δ 72.0, 63.4, 51.8, 39.9, 39.2, 37.9, 25.7, 25.0, 21.3, 21.2; LRMS *m/e* (rel intensity EI (M^+ not observed), 153 (90), 111 (100), 98 (15), 58 (25), 55 (80). Anal. Calcd for $C_{10}H_{17}ClO$: C, 63.63; H, 9.08. Found: C, 63.53; H, 9.35. **For 5**: IR (CCl_4) 3600 (br), 1445, 980 cm^{-1}; ^1H NMR δ 4.1 (m, 1H), 2.1–2.3 (m, 1H), 1.25–1.82 (m, 14H); ^{13}C NMR δ 72.2 (br), 60.6 (br), 50.7 (br), 39.5 (br), 35.8 (br), 33.9, 24.3 (br), 21.8, 21.0 (br); LRMS *m/e* (rel intensity EI 189.5, 187.7 (M^+, 0.3), 153 (100), 111 (20), 97 (15), 77 (8), 55 (13). Anal. Calcd for $C_{10}H_{17}ClO$: C, 63.63; H, 9.08. Found: C, 63.45; H, 9.32.

Aqueous HCl in Dichloromethane. To a solution of **2** (100 mg, 0.66 mmol) in dichloromethane (5 mL) at room temperature was added concentrated HCl (0.2 mL of a 37% solution, ca. 3 equiv). The reaction mixture was stirred at room temperature for 2 h, during which time the solution turned pink-purple. The reaction mixture was worked up as described above and gave a mixture of **4a** (68 mg, 0.36 mmol, 55%) and **5** (15 mg, 0.08 mmol, 12%) ring fusion isomers.

Dry HCl Gas in THF. Dry HCl gas was bubbled through a solution at room temperature of **2** (100 mg, 0.66 mmol) in THF (5 mL). After 20 min, the reaction mixture was diluted with Et_2O (10 mL), washed with H_2O (10 mL) and saturated NaCl (10 mL), dried with $MgSO_4$, filtered, and evaporated. The crude product gave, in order of elution upon flash chromatography (hexanes/EtOAc 20:1), **4a** (34.5 mg, 0.184 mmol, 28%), **6** (9 mg, 0.035 mmol, 5%), and **5** (32 mg, 0.17 mmol, 26%). **For 6**: IR (CCl_4) 3470 (br), 1450, 1100, 945 cm^{-1}; ^1H NMR δ 3.53–3.64 (m, 3H), 3.24–3.34 (dt, J = 9.4, 6.2 Hz, 1H), 3.05–3.18 (td, J = 10.2, 4.2 Hz, 1H), 2.0–2.2 (m, 1H), 1.0–2.0 (m, 18H); ^{13}C NMR δ 78.6, 71.7, 68.2, 49.9, 45.0, 40.0, 39.5, 31.9, 29.7, 27.7, 25.8, 23.5, 21.4, 19.5. Anal. Calcd for $C_{14}H_{25}ClO_2$: C, 64.48; H, 9.66. Found: C, 64.46; H, 9.68.

Aqueous HCl in THF. To a solution of **2** (100 mg, 0.66 mmol) in THF (5 mL) at room temperature was added concentrated HCl (0.2 mL of a 37% solution, approximately 3 equiv). The reaction mixture was stirred for 2 h and then worked up as described above to give **4a** (41 mg, 0.22 mmol, 33%), **6** (6 mg, 0.023 mmol, 3.5%), and **5** (38 mg, 0.20 mmol, 31%).

Me_2AlCl. To a solution of **2** (108 mg, 0.71 mmol) in dichloromethane (5 mL) at 0 °C was added Me_2AlCl (1 M solution in hexanes, 0.8 mL, 0.8 mmol). The ice bath was removed, and the reaction was stirred at room temperature for 2 h. Another portion of Me_2AlCl (0.7 mL) was added, and after an additional 3 h, the reaction mixture was poured into 10% NH_4Cl solution (30 mL) and extracted with Et_2O (3 × 30 mL). The combined organic extracts were washed with saturated NaCl (30 mL), dried with $MgSO_4$, filtered, evaporated, and purified as described above to give **4a** (86 mg, 0.46 mmol, 64%) and **5** (6 mg, 0.03 mmol, 4.5%).

$SnCl_4$. To a solution of −2 (200 mg, 1.32 mmol) in dichloromethane (10 mL) at −35 °C was added $SnCl_4$ (1 M solution in dichloromethane, 1.5 mL, 1.5 mmol). The reaction mixture was allowed to warm to 0 °C over 20 min and was then quenched with 10% NH_4Cl (20 mL) and extracted with dichloromethane (2 × 20 mL). The combined organic layers were washed with saturated NaCl (20 mL), dried with $MgSO_4$, filtered, evaporated, and purified as described above to give **4a** (163 mg, 0.87 mmol, 66%) and **5** (20 mg, 0.11 mmol, 8%).

Grob Fragmentations of 4a and 5. Potassium Hydride. To a suspension of potassium hydride (35% dispersion in mineral oil, 120 mg, 1.05 mmol) washed with hexanes (3 × 5 mL) and suspended in THF (2 mL) were added **4a** (83 mg, 0.44 mmol) in THF (3 mL). The reaction mixture was warmed to 60 °C over 15 min, allowed to cool to room temperature, and then carefully quenched with 10% NH_4Cl (10 mL), extracted with Et_2O, washed with H_2O (20 mL) and saturated NaCl (20 mL), dried with $MgSO_4$, filtered, and evaporated. Purification by flash chromatography (hexanes/EtOAc 30:1) gave **2** (46 mg, 0.33 mmol, 69%). This procedure was repeated with **5** (100 mg, 0.53 mmol) in THF (2 mL). The reaction mixture was stirred at room temperature for 1 h and then heated at 50 °C for 10 min to consume the last traces of **5**. The reaction mixture was worked up as described above to give **2** (44 mg, 0.29 mmol, 55%).

Potassium *tert*-Butoxide. To a solution of **4a** (62 mg, 0.33 mmol) in *tert*-butyl alcohol (4 mL) was added potassium *tert*-butoxide (111 mg, 0.99 mmol). The reaction mixture was warmed to 45 °C and stirred for 2 h. The mixture was diluted with Et_2O (20 mL) and H_2O (20 mL). The layers were separated and the aqueous layer was extracted with Et_2O (3 × 20 mL). The combined organic layers were washed with 2 M NaOH (2 × 20 mL) and saturated NaCl (20 mL), dried with $MgSO_4$, filtered, and evaporated. Purification as described above gave **2** (39 mg, 0.26 mmol, 78%).

The above procedure was repeated using **5** (62 mg, 0.33 mmol) and potassium *tert*-butoxide (111 mg, 0.99 mmol) at 45 °C for 1 h. Workup as described above gave **2** (29 mg, 0.19 mmol, 58%).

Bicyclo[4.4.0]decan-1-ols 8 and 9. A solution of **4a** (56 mg, 0.30 mmol) in benzene (2 mL) was degassed with a stream of argon. To this solution were added *n*-Bu_3SnH (0.15 mL, 0.56 mmol) and AIBN (10 mg, 0.06 mmol), and the reaction mixture was refluxed for 18 h. Upon cooling, Et_2O (5 mL) and KF (60% solution, 5 mL) were added, and the reaction mixture was filtered. The filtrate was extracted Et_2O (3 × 20 mL), and the combined organic layers were washed with saturated NaCl (20 mL), dried with $MgSO_4$, filtered, and evaporated. Purification by flash chromatography (hexanes/EtOAc 30:1) gave **8** (29 mg, 0.19 mmol, 63%) as a white, waxy solid: ^{13}C NMR (50.3 MHz, C_6D_6)[6] δ 70.2, 44.1, 39.7, 28.6, 26.2, 21.6. The above procedure was repeated with **5** (47 mg, 0.25 mmol) in benzene (2 mL). After the solution was refluxed for 1.5 h, the reaction mixture was worked up and purified as described above to give **9** (28 mg, 0.18 mmol, 73%) as a white solid: ^{13}C NMR (50.3 MHz, C_6D_6)[6] δ 43.2, 28.3, 23.3. (The literature also reported chemical shifts of 71.1 and 37 (br), which we did not observe.)

(34) Wharton, P. S.; Hiegel, G. A.; Coombs, R. V. *J. Org. Chem.* **1963**, *28*, 3217–3219.

(1R*,5R*,6S*)-1-Hydroxybicyclo[4.4.0]dec-5-yl Trifluoroacetate (4b). To a solution of **2** (100 mg, 0.66 mmol) in dichloromethane (5 mL) at 0 °C was added trifluoroacetic acid (0.15 mL, 220 mg, 1.94 mmol, 3 equiv). The reaction mixture was allowed to warm to room temperature and was stirred for 4 h. The reaction mixture was diluted with dichloromethane (10 mL), washed with H_2O (10 mL containing 1 mL of saturated $NaHCO_3$) and saturated NaCl (10 mL), dried with $MgSO_4$, filtered and evaporated. Purification by flash chromatography (hexanes/EtOAc 20:1) afforded **4b** (112 mg, 0.42 mmol, 64%) as a colorless oil. An analytical sample was obtained by Kugelrohr distillation (65 °C, 0.1 mmHg): IR (film) 3500 (br), 1770, 1445, 1220, 1170, 1160, 1140 cm^{-1}; ^1H NMR δ 5.00 (td, J = 10.8, 4.4 Hz, 1H), 2.04–2.15 (m, 1H), 1.00–1.98 (m; 14H); ^{13}C NMR δ 158.4, 157.6, 156.8, 156.0, 123.2, 117.5, 111.8, 106.1, 79.5, 71.5, 48.0, 39.6, 38.9, 31.4, 25.2, 23.1, 21.0, 19.2; LRMS m/e (rel intensity EI 266 (M^+, 1), 221 (5), 152 (100), 135 (42), 123 (21), 97 (34), 69 (73), 55 (40). Anal. Calcd for $C_{12}H_{17}F_3O_3$: C, 54.13; H, 6.44. Found: C, 54.62; H, 6.61.

(1R*,5R*,6S*)-Bicyclo[4.4.0]decane-1,5-diol (7). To a solution of **4b** (60 mg, 0.225 mmol) in methanol (1 mL) at room temperature was added sodium methoxide (14 mg, 0.26 mmol, 1.2 equiv). After 15 min, the reaction mixture was diluted with Et_2O (15 mL), washed with H_2O (5 mL) and saturated NaCl (5 mL), dried with $MgSO_4$, filtered, and evaporated. Purification by flash chromatography (hexanes/EtOAc 1:1.5) afforded a colorless oil. Residual EtOAc was removed under vacuum (room temperature, 0.1 mmHg) to yield the diol **7** (27 mg, 0.158 mmol, 70%) as a white solid, mp 73–75 °C (lit[5] mp 76 °C): ^1H NMR δ 3.54 (td, J = 10.6, 4.6 Hz, 1H), 1.0–2.1 (m, 15H); ^{13}C NMR δ 71.5, 70.9, 51.2, 39.8, 39.4, 35.8, 25.7, 23.2, 21.4, 19.6.

6-[(*tert*-Butyldimethylsilyl)oxy]cyclodecanone (12b). To a solution of 6-hydroxycyclodecenone (**12a**)[8] (4.98 g, 29.3 mmol) in dry DMF (40 mL) at room temperature were added imidazole (2.3 g, 33.8 mmol) and *tert*-butyldimethylsilyl chloride (5.1 g, 33.8 mmol). After 2 h, H_2O (200 mL) was added and the mixture extracted with Et_2O (3 × 75 mL). The combined extracts were washed with H_2O (2 × 100 mL) and brine (50 mL), dried with $MgSO_4$, filtered, and evaporated. Purification by flash chromatography (hexanes/EtOAc 25:1) gave **12b**[35] (4.78 g, 16.8 mmol, 62%) as a colorless oil, which freezes to give a white solid if stored at −20 °C: IR (film) 1695, 1245, 825, 765 cm^{-1}; ^1H NMR 3.75 (m, 1H), 2.32–2.64 (m, 4H), 1.65–2.0 (m, 4H), 1.4–1.6 (m, 4H), 1.2–1.3 (m, 4H), 0.85 (s, 9H), 0.05 (s, 6H); ^{13}C NMR 214.8, 70.0, 42.0, 33.5, 25.8, 23.5, 22.5, 18.0, −4.47.

6-[(*tert*-Butyldimethylsilyl)oxy]cyclodecanone Tosylhydrazone (12c). To a solution of −12b (2.98 g, 10.5 mmol) in ethanol (35 mL) was added *p*-toluenesulfono hydrazide (2.25 g, 12.1 mmol). The suspension was gently refluxed for 3 h. All solids dissolved upon heating to reflux to give a clear, colorless solution, which yellowed slightly on heating. The volume of the solution was then reduced by two-thirds on a rotary evaporator. After standing at room temperature for 1 h, a small amount of a crystallization was observed. The mixture was then left in the freezer overnight before filtering off the product. A yellow impurity was washed out using a *minimum* amount of ethanol prechilled to −60 °C. The white solid was dried in a desiccator for 24 h to afford **12c** (2.85 g, 60% yield), mp 96–98 °C: ^{13}C NMR 143.8, 135.6, 129.4, 128.2, 71.0, 42.0, 34.8, 33.5, 32.2, 31.4, 30.4, 25.8, 23.6, 23.4, 23.0, 22.5, 21.6, 21.1, 19.6, 18.1, −4.71, −4.82. Anal. Calcd for $C_{23}H_{40}N_2O_3SSi$: C, 61.02; H, 8.91 N, 6.19. Found: C, 61.31; H, 9.17; N, 6.17.

(Z)-5-Cyclodecenone (11). To the hydrazone **12c** (1.16 g, 2.56 mmol) dissolved in hexane/TMEDA (1:1, 20 mL) cooled to −60 °C was added *n*-BuLi (14 mL, 1 M in hexanes, 14 mmol). The resultant red-brown solution was allowed to warm to 0 °C and then kept there for 1 h. The pale yellow solution was quenched with methanol (2 mL), allowed to stir a couple of minutes before adding water (100 mL), and extracted with hexane (4 × 50 mL). The combined organic extracts were washed with 10% NH_4Cl (100 mL) and saturated NaCl (100 mL), dried with $MgSO_4$, filtered, and evaporated. Purification by flash chromatography (100% pentane) gave **13** as a colorless oil (0.462 g, 68%): ^1H NMR 5.30–5.44 (m, 2H), 3.78–3.86 (m, 1H), 1.1–2.3 (m, 14 H), 0.879 (s, 9H), 0.038 (s, 6H); ^{13}C NMR 130.3, 129.5, 71.5, 34.0, 29.8, 26.2, 25.9, 25.3, 24.4, 22.7, 20.0, 18.2, −4.55, −4.67.

To silyl ether **13** (0.642 g, 2.4 mmol) in THF (20 mL) was added *n*-Bu_4NF (1 M in THF, 4.8 mL, 4.8 mmol). The reaction mixture was stirred at room temperature for 2 days, during which time two more equivalents of fluoride were added. The reaction mixture was quenched with 10% NH_4Cl (25 mL), extracted with Et_2O (3 × 50 mL), washed with saturated NaCl (50 mL), dried with $MgSO_4$, filtered, and evaporated. Purification by flash chromatography (hexanes/EtOAc 4:1) gave (*Z*)-5-cyclodecanol[7] (0.327 g, 88%) as an oil, which solidified on standing in a refrigerator: IR (film) 3350 (br), 1460, 1435, 705 cm^{-1}; ^{H} NMR 5.28–5.45 (m, 2H), 3.82–3.93 (m, 1H), 1.0–2.5 (m, 15H); ^{13}C NMR 129.8, 129.7, 70.9, 33.8, 29.7, 26.1, 24.9, 24.4, 22.7, 19.6.

To pyridinium chlorochromate (1.5 g, 6.95 mmol), NaOAc (0.35 g) and a small amount of crushed molecular sieves in CH_2Cl_2 (30 mL) cooled to 0 °C was added (*Z*)-5-cyclodecenol (0.355 g, 2.31 mmol) in CH_2Cl_2 (5 mL). After 15 min, the reaction was diluted with Et_2O, filtered through silica, and evaporated. Purification by flash chromatography (hexanes/EtOAc 20:1) gave (*Z*)-5-cyclodecenone (**11**)[7] (0.32 g, 91%) as a colorless oil: IR 1695, 700 cm^{-1}; ^1H NMR 5.31-5.44 (m, 2H), 1.56–2.49 (m, 14H); ^{13}C NMR 214.5, 132.0, 128.8, 45.8, 34.9, 28.4, 24.5, 23.4, 23.2, 21.1.

(1R*,5R*,6S)-5-Chlorobicyclo[4.4.0]decan-1-ol (10a). To a solution of **11** (48 mg, 0.32 mmol) in CH_2Cl_2 (3 mL) at room temperature was added concentrated HCl (0.1 mL), and the reaction was stirred overnight. More concentrated HCl (0.1 mL) was added, and after 2 h, the reaction was diluted with CH_2Cl_2 (10 mL), washed with H_2O and saturated NaCl (10 mL), dried with $MgSO_4$, filtered, and evaporated. Purification by flash chromatography (hexanes/EtOAc 15:1) gave **10a** as a white solid (0.051 g, 85%), mp 90–91 °C; ^1H NMR 4.62–4.73 (m, 1H), 1.0–2.2 (m, 16H); ^{13}C NMR 74.4, 61.2, 50.1, 42.4, 30.6, 29.6, 25.6, 23.9, 22.5, 21.4 (note: the lines in the ^{13}C NMR spectrum are all sharp; there is no broadening for this cis-fused compound). Anal. Calcd for $C_{10}H_{17}ClO$: C, 63.63; H, 9.08. Found: C, 64.03; H, 9.52.

$SnCl_4$. To **11** (47 mg, 0.31 mmol) in CH_2Cl_2 (2 mL) cooled to −40 °C was added $SnCl_4$ (1 M in CH_2Cl_2, 0.62 mL, 2 equiv). The reaction mixture was allowed to warm and at −5 °C another equivalent of $SnCl_4$ was added to complete the reaction. After a total time of 1 h the reaction mixture warmed to 0 °C and was quenched with 10% NH_4Cl (10 mL), extracted with CH_2Cl_2 (2 × 10 mL), washed with saturated NaCl (10 mL), dried with $MgSO_4$, filtered, and evaporated. Purification by flash chromatography (hexanes/EtOAc 15:1) gave a white solid (35 mg, 60%) identical to that isolated from the HCl reaction.

Radical Dechlorination of 10a. A solution of **10a** (30 mg, 0.16 mmol) in toluene (2.5 mL) was degassed with a stream of argon. To this solution were added *n*-Bu_3SnH (0.16 mL, 0.6 mmol) and AIBN (10 mg, 0.06 mmol), and the reaction mixture was refluxed for 16 h in an oil bath maintained at 100–105 °C. Upon cooling, the reaction mixture was worked up as described above for the corresponding reactions for **4a** and **5** to give **9** (26 mg).

Grob Fragmentation of 10a. The procedures used for the conversion of **4a** and **5** into **2** were repeated on **10a** using KH to give (*Z*)-5-cyclodecenone (**11**) in 41% yield.

(1R*,5R*,6R*)-1-Hydroxybicyclo[4.4.0]dec-5-yl Trifluoroacetate (10b). To **11** (48 mg, 0.316 mmol) in CH_2Cl_2 (3 mL) cooled to 0 °C was added trifluoroacetic acid (0.122 mL, 5 equiv). The solution was allowed to warm to room temperature and then stirred overnight. The reaction mixture was diluted with CH_2Cl_2 (10 mL), washed with water (10 mL) and saturated NaCl (10 mL), dried with $MgSO_4$, filtered, and evaporated. Purification by flash chromatography (hexanes/EtOAc 15:1) yielded **10b** as a gum (55 mg, 65%): ^1H NMR 5.49–5.59 (m, 1H), 1.2–2.0 (m, H); ^{13}C NMR 77.9, 73.4, 46.3, 42.0, 29.9, 25.2, 24.9, 23.6, 22.2, 19.2 (all lines were sharp).

(1R*,5R*,6R*)-Bicyclo[4.4.0]decane-1,5-diol (10c). To **10b** (54 mg, 0.203 mmol) in methanol (2 mL) was added NaOMe (~12 mg, 1 equiv). After 15 min, the reaction mixture was quenched with 10% NH_4Cl (3 mL), extracted with Et_2O (2 × 10 mL), washed with saturated NaCl (10 mL), dried with $MgSO_4$, filtered, and evaporated. Purification by flash chromatography (hexanes/EtOAc 2.5:1) gave **10c** (29 mg, 84%) as a white solid: mp 131–133 °C (lit.[5] mp 133 °C); ^1H NMR 4.19–4.29 (m, 1H), 1.0–1.9 (m, 15H); ^{13}C NMR 73.7, 68.9, 49.3, 42.1, 30.2, 28.9, 25.6,

(35) Hamon, D. P. G.; Krippner, G. Y. *J. Org. Chem.* **1992**, *57*, 7109–7114.

23.9, 21.4, 19.6; mass spectrum, *m/e* 152 (M^+, 100), 134 (18), 127 (40), 113 (29), 55 (36).

***cis*-Bicyclo[5.3.0]decan-1-ol (14). SmI_2.** To a stirred suspension of powdered samarium (752 mg, 5.0 mmol) in THF (25 mL) was added diiodomethane (670 mg, 2.5 mmol), and the suspension was stirred at room temperature for 12 h to give a deep blue-green solution. **2** (152 mg, 1.0 mmol) and methanol (0.085 mL, 2.1 mmol) in THF (6 mL) were added rapidly. After the solution was stirred for 2 h, saturated $NaHCO_3$ (50 mL) was added and the white precipitate was filtered off. The filtrate was extracted with Et_2O (3 × 50 mL), washed with saturated NaCl (50 mL), dried with $MgSO_4$, filtered, and evaporated to give a yellow oil. Purification by flash chromatography (hexanes/EtOAc 15:1) gave *cis*-bicyclo[5.3.0]decan-1-ol (**14**)[2a] (105 mg, 0.68 mmol, 68%). A small amount of starting material was also recovered (20 mg, 0.13 mmol, 13%). **For 14:** ^1H NMR δ 1.0–2.2 (m); ^{13}C NMR δ 84.4, 53.2, 43.8, 40.1, 35.3, 34.3, 31.4, 29.9, 24.1, 23.6. The same reaction was performed without methanol, using samarium (1.2 g, 7.7 mmol), diiodomethane (1.07 g, 4.0 mmol), and **2** (281 mg, 1.87 mmol) in THF (80 mL). Purification gave a 1:1 mixture of **14** and **3a**[2a,b] (65 mg, 23%). **For 3a:** ^{13}C NMR δ 133.2, 129.0, 82.4, 50.3, 42.3, 37.3, 33.3, 28.1, 22.5, 19.6.

***n*-Bu_3SnH.** To a solution of **2** (100 mg, 0.66 mmol) in degassed and refluxing benzene (2 mL) was added via syringe pump over 6 h a solution of *n*-Bu_3SnH (580 mg, 2.0 mmol) and AIBN (10 mg, 0.06 mmol) in benzene (1 mL). Some starting material remained, so more *n*-Bu_3SnH (190 mg, 0.65 mmol) and AIBN (10 mg, 0.06 mmol) in benzene (1 mL) were added in one portion. After a total of 1 day, the reaction mixture was added to 10% NH_4Cl (20 mL) and extracted with Et_2O (3 × 20 mL). The combined organic layers were washed with saturated NaCl (30 mL), dried with $MgSO_4$, filtered, and evaporated. Purification as described above gave a small amount of starting material (8 mg, 8%) as well as **14** (61 mg, 0.40 mmol, 60%) as a thick, colorless oil, which solidified upon standing.

15–17. Zinc/Me_3SiCl/2,6-Lutidine. To a solution of **2** (153 mg, 1 mmol) in THF (10 mL) were added Zn powder (1.3 g, 20 mmol), 2,6-lutidine (0.35 mL, 3 mmol), and Me_3SiCl (0.76 mL, 6 mmol). (A small amount of a whitish precipitate was observed.) Upon refluxing for 18 h and cooling to room temperature, the unreacted Zn was removed by filtration. To the filtrate was added 10% NH_4Cl (50 mL), followed by extraction with Et_2O (3 × 30 mL). The organic layers were combined, washed with saturated NaCl (50 mL), dried with $MgSO_4$, filtered, and evaporated to give a colorless oil. Purification by flash chromatography (100% hexanes) gave a 1:1 mixture of **15** and **16** that was partially separated (147 mg, 0.56 mmol, 56%). **For 15 and 16:** ^{13}C NMR δ 63.9, 60.2, 53.9, 51.8, 40.8, 39.4, 39.0, 38.1, 37.4, 32.9, 26.1, 26.0, 24.9, 22.4, 23.0, 21.8, 21.6, 19.8, 2.68, 2.50. **For 15:** ^1H NMR δ 3.8–4.0 (m, 1H), 2.15–2.3 (m, 1H), 1.9–2.0 (m, 1H), 1.0–1.8 (m, 13H), 0.125 (s, 9H). **For 16:** ^1H NMR δ 3.98–4.14 (td, J = 11.2, 4.2 Hz, 1H), 2.15–2.30 (m, 1H), 1.15–2.0 (m, 14H), 0.122 (s, 9H). Further elution (20:1 hexanes/EtOAc 20:1) gave **17** as a colorless oil (81 mg, 0.24 mmol, 24%): ^1H NMR δ 3.5–3.65 (m, 3H), 3.22–3.36 (dt, J = 8.9, 6.4 Hz, 1H), 2.97–3.13 (td, J = 10.3, 4.1 Hz, 1H), 1.0–2.17 (m, 19H); ^{13}C NMR δ 78.8, 68.0, 51.9, 45.0, 39.4, 39.2, 31.9, 29.7, 27.7, 26.1, 23.2, 21.8, 18.9, 2.55. Treatment of **15** (24 mg, 0.092 mmol), **16** (64 mg, 0.25 mmol), and **17** (160 mg, 0.48 mmol) with *n*-Bu_4NF (1M in THF) in THF at room temperature (10 min, 10 min, and 4 h, respectively) followed by addition of 10% NH_4Cl, extraction with Et_2O, and purification by flash chromatography (15–20:1 hexanes/EtOAc) led to **4a** (13 mg, 0.07 mmol, 75%), **5** (39 mg, 0.21 mmol, 83%), and **6** (89 mg, 0.34 mmol, 71%), respectively.

***cis*-Bicyclo[5.3.0]decan-1-ol (14). SmI_2.** To a stirred suspension of powdered samarium (150 mg, 1.0 mmol) in THF (7 mL) was added diiodomethane (246 mg, 0.92 mmol), and the suspension was stirred at room temperature for 3 h to give a deep blue-green solution. **11** (32 mg, 0.21 mmol) and *tert*-butyl alcohol (0.58 mL, 0.63 mmol) in THF (1 mL) were added rapidly. After the solution was stirred for 1.5 h, there was no reaction as indicated by TLC, and the reaction had maintained its color. HMPA (1 mL) was added, resulting in an immediate color change and consumption of starting material by TLC. The reaction mixture was diluted with saturated $NaHCO_3$ (10 mL), extracted with Et_2O (3 × 10 mL), washed with water (10 mL), dried with $MgSO_4$, filtered, and evaporated. Purification by flash chromatography (hexanes/EtOAc 3:1) gave *cis*-bicyclo[5.3.0]decan-1-ol (**14**)[2a,b] (13 mg, 0.084 mmol, 40%). Further elution provided two additional fractions of 7 mg, containing two unidentified products, and 2 mg of an unidentified substance.

***n*-Bu_3SnH.** To a solution of (*Z*)-5-cyclodecenone (**11**) (35 mg, 0.23 mmol) in degassed and toluene (2.5 mL) were added *n*-Bu_3SnH (0.16 mL, 0.6 mmol) and AIBN (10 mg, 0.06 mmol). The mixture was heated (oil bath temperature 105–110 °C) for 18 h, at which time by TLC a significant amount of starting material remained unreacted. The same portions of *n*-Bu_3SnH and AIBN were added at this time and again after an additional 24 h of heating. After 66 h, the reaction mixture was allowed to cool to room temperature, diluted with Et_2O (5 mL) and stirred with 60% KF solution (5 mL). The layers were separated and the aqueous phase was extracted with Et_2O (2 × 10 mL). The combined organic layers were washed with 10% NH_4Cl (20 mL) and saturated NaCl (20 mL), dried with $MgSO_4$, filtered, and evaporated. Purification by flash chromatography (hexanes/EtOAc 15:1) gave recovered **11** (9 mg, 0.06 mmol, 26%) and hydroazulenol **14**[2a,b] (20 mg, 0.13 mmol, 56%) as a white solid.

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