Asymmetric Induction in the Intramolecular 1,3-Diyl Trapping Reaction. Use of a Stereogenic Atom Located on the Chain Linking the Diyl and Diylophile

Keith J. Stone[†] and R. Daniel Little*[‡]

Contribution from the Department of Chemistry, University of California—Santa Barbara, Santa Barbara, California 93106. *Received July 30, 1984*

Abstract: The primary objective in this investigation was to develop a general method to achieve significant amounts of asymmetric induction in the intramolecular 1,3-diyl trapping reaction. This goal has been achieved by generating a diyl containing one stereogenic atom located on the chain linking the diyl and diylophile. Thus, extrusion of nitrogen from the chiral diazenes **2a** or **2b** afforded **4** (CA) as the major product at temperatures ranging from −31 to 81 °C. The broad range of temperatures examined was accessible due to the possibility of deazetizing **2a** or **2b** either thermally or photochemically. The reaction became more selective as the temperature was lowered, and at −31 °C, a 96% de (98% ds) of CA was obtained. When these diastereomeric diazenes were individually subjected to the same reaction conditions, the same products and in the same ratios were formed. This result provides the first experimental evidence that the intramolecular 1,3-diyl reaction proceeds through a time averaged-planar diyl intermediate. Thermal and photochemical deazetation of **2b** at the same temperature (50 °C) provided the same products in the same ratios even though the reaction times were 40 and 2.5 h, respectively. In addition, Arrhenius plots [ln (product ratio) vs. $1/T$] of each pair of products CA–ca, CA–CS, and ca–CS over a 110 °C range were found to be linear when data from both thermally and photochemically initiated reactions were utilized. These two results imply a common 1,3-diyl intermediate for both modes of deazetation. The relative contributions of enthalpy and entropy of activation in determining the product distribution were also obtained from the Arrhenius plots. For the CA–ca pair, the difference in enthalpy of activation is relatively large (2.14 kcal/mol in favor of CA) and is responsible for the large temperature effect upon the product ratio while entropic factors (1.3 eu in favor of ca) do not play a large role. For the CA–CS pair, the difference of entropy of activation (3.9 eu) contributes more to the product ratio than does the difference in enthalpy of activation (0.5 kcal/mol) within the temperature range examined, although both favor CA. With regard to the third pair of products, ca–CS, the differences of enthalpy and entropy of activation are relatively large (1.65 kcal/mol and 5.2 eu) and oppose each other, i.e., CS is favored enthalpically while ca is favored entropically.

In a recent review,[1a] Mosher and Morrison wrote "... the science of asymmetric synthesis has come of age. Asymmetric synthesis must be systematically considered in any synthetic strategy aimed at the formation of chiral compounds." This interesting comment was undoubtedly made in view of the interest and major advances that have been recorded in the field of asymmetric synthesis during the past decade.[1] While major advances in asymmetric induction have been reported, comparatively little progress has been made in regard to the enantioselective construction of the linearly fused tricyclopentanoid ring system.[2] Since the intramolecular 1,3-diyl trapping reaction has proven to be an excellent method for the preparation of this skeleton while at the same time generating four new stereocenters, we sought to broaden the scope of the reaction by inducing asymmetry in the trapping step.[3]

In addition, and probably more important in regard to laying a solid foundation for future efforts, we focused our attention upon two "secondary" objectives. In particular, if asymmetric induction can be achieved, then we wish to utilize the results to assist in refining our view of the factors that are responsible for the control of selectivity and to learn more about the energy surface of trimethylenemethane derivatives in intramolecular 1,3-diyl trapping reactions.

Background. We view the intramolecular 1,3-diyl trapping reaction as a kinetically controlled process. Thus, the product distribution is determined by the activation barriers leading to each of the products, with the major product being formed from the lowest energy pathway. Therefore, the requirement to induce asymmetry is to generate diastereomeric transition states with different energies. To date, there have been two approaches to achieve this goal.

Use of a Chiral Ester.[3b,4] We reasoned that the use of a chiral ester appended to the terminal carbon of the diylophile π bond might constitute the simplest way to induce asymmetry in the diyl trapping reaction. To this end, we reported the synthesis and deazetation of the diastereomeric pair of chiral diazenes **1a,b**. The major products were predicted to be cis,anti ring fused tricyclopentanoids in analogy with previous results using a methyl ester.[3d,e] This was found to be the case, although the cis,anti to cis,syn product ratio decreased from 6.7:1 with the methyl ester[3d] to 5.6:1 with the (−)-menthyl ester **1a** (R* = menthyl) and 3.3:1 with the (−)-8-phenylmenthyl ester **1b** (R* = 8-phenylmenthyl). More important, however, was the small amount of diastereoselectivity that was observed in the reactions. In *both* instances, only ca. 5% de (52.5% ds) was observed.[5] Clearly, a much more satis-

[†] This article was taken in part from: Stone, K. J. Ph.D. Thesis, University of California, Santa Barbara, submitted May 1984.

[‡] Alfred P. Sloan Foundation Fellow, 1980–1984.

(1) (a) Mosher, H. S.; Morrison, J. D. *Science (Washington, D.C.)* **1983**, *221*, 1013–1019. (b) ApSimon, J. W.; Sequin, R. P. *Tetrahedron* **1979**, *35*, 2797–2842. (c) "Asymmetric Reactions and Processes in Chemistry"; Eliel, E. L., Otsuka, S., Eds.; American Chemical Society: Washington, DC, 1982; ACS Symp. Ser. No. 185. (d) Hanessian, S. "Total Synthesis of Natural Products: The 'Chiron' Approach"; Pergamon Press: Elmsford, NY, 1983. (e) Dagani, R. *Chem. Eng. News* **1984**, 21. (f) Mislow, K.; Siegel, J. *J. Am. Chem. Soc.* **1984**, *106*, 3319.

(2) See, for example: (a) Trost, B. M.; Curran, D. P. *J. Am. Chem. Soc.* **1981**, *103*, 7380–7381. (b) Demuth, M.; Schnaffner, K. *Angew. Chem., Int. Ed. Engl.* **1982**, *21*, 820–836.

(3) For a preliminary account of this work refer to: Little, R. D.; Stone, K. J. *J. Am. Chem. Soc.* **1983**, *105*, 6976. Additional examples of the intramolecular 1,3-diyl trapping reaction can be found in: (a) Little, R. D.; Muller, G. W.; Venegas, M. G.; Carrol, G. L.; Bukhari, A.; Patton, L.; Stone, K. *Tetrahedron* **1981**, *37*, 4371–4383. (b) Little, R. D.; Moeller, K. D. *J. Org. Chem.* **1983**, *48*, 4487–4492. (c) Little, R. D.; Higby, R. G.; Moeller, K. D. *J. Org. Chem.* **1983**, *48*, 3139–3140. (d) Little, R. D.; Muller, G. W. *J. Am. Chem. Soc.* **1981**, *103*, 2744–2749. Capillary column GC analysis consistently indicates a 6.7:1 ratio, rather than the 9:1 ratio previously indicated. (e) Little, R. D.; Muller, G. *J. Am. Chem. Soc.* **1979**, *101*, 7129–7130. (f) Little, R. D.; Carroll, G. L. *Tetrahedron Lett.* **1981**, *22*, 4389–4392. (g) Little, R. D.; Carroll, G. L.; Petersen, J. L. *J. Am. Chem. Soc.* **1983**, *105*, 928–932. For reviews on TMM, see: (a) Weiss, F. *Q. Rev., Chem. Soc.* **1970**, 278–309, (b) Dowd, P. *Acc. Chem. Res.* **1972**, *5*, 242–248. (c) Berson, J. A. *Acc. Chem. Res.* **1978**, *11*, 446–453. (d) Berson, J. A. In "Diradicals"; Borden, W. T., Ed.; Wiley: New York, 1982; pp 151–194.

(4) See, for example: (a) Roush, W. R.; Gillis, H. R.; Ko, A. I. *J. Am. Chem. Soc.* **1982**, *104*, 2269–2283. (b) Oppolzer, W.; Kurth, M.; Reichlin, D.; Moffatt, F. *Tetrahedron Lett.* **1981**, *22*, 2545–2548.

(5) For an interesting and informative discussion of the meaning and use of the indicators percent de and percent ds, refer to ref 13 of: Thaisrivongs, S.; Seebach, D. *J. Am. Chem. Soc.* **1983**, *105*, 7407.

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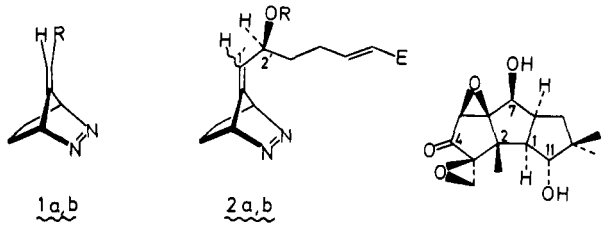
factory alternative was required.

Use of a Stereogenic Atom.[1e,f] The second approach to inducing asymmetry was to incorporate a stereogenic atom on the chain linking the diyl and diylophile. The nature and location of this atom was chosen to allow access to the naturally occurring, biologically active coriolins. Of the several functional groups and stereogenic atoms found in the coriolins, the C-ring hydroxyl-

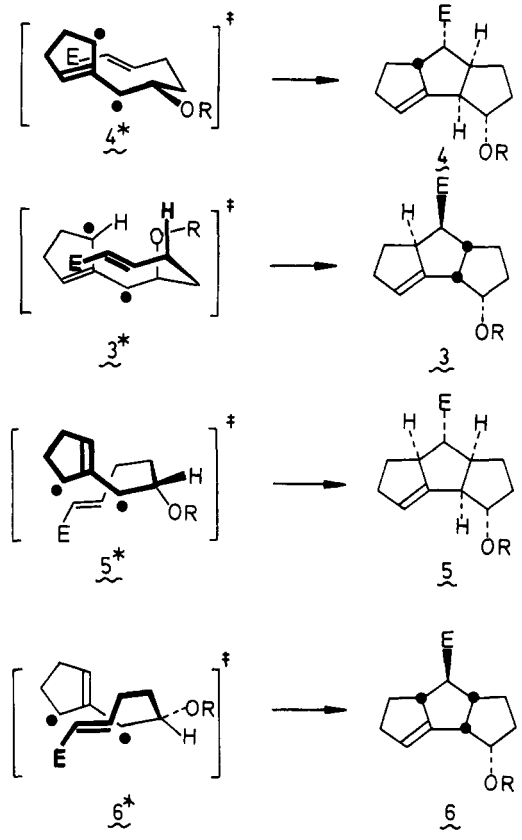


1a,b 2a,b

R = $CH_2C(CH_3)_2CH_2CH{=}CHCO_2R^*$ (+)-CORIOLIN

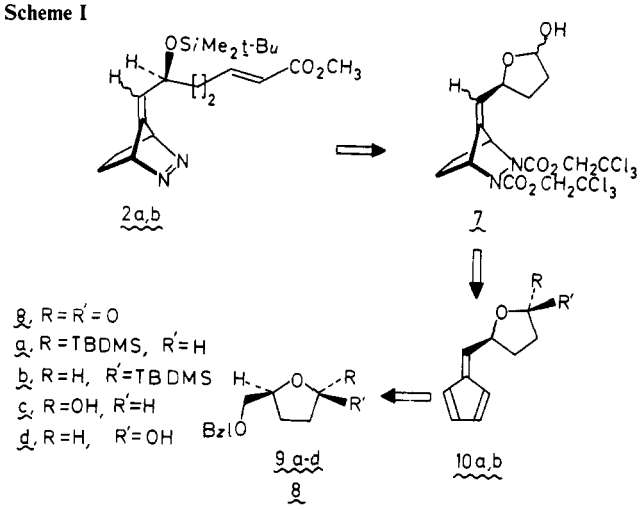
bearing carbon appeared particularly well suited to build into a 1,3-diyl precursor. Thus, our initial target became the diastereomeric diazenes **2a,b** (E = CO_2CH_3, R = $SiMe_2$-*t*-Bu).

Previous reports from these laboratories allow one to conclude that conformational, stereoelectronic, and steric factors influence the stereo- and regiochemical outcome of the intramolecular diyl trapping reaction.[3] With these factors in mind, focus attention upon the transition-state representations **3*–6***. Experience has taught us that transition states leading to the cis,anti ring fused products are of lower energy than those leading to the cis,syn. Thus, we would expect that transition-state representations **3*** and **4*** would be of lower energy than **5*** and **6***. Of the first pair, **4*** would be expected to be of lower energy due to the existence of the energy-raising nonbonded interactions which are present in **3*** but not in **4***. To the extent that these expectations represent accurate descriptions of fact, one can reasonably anticipate the achievement of asymmetric induction to an extent that is related to the energy difference between **3*** and **4***.



Synthesis of the Chiral Diazenes 2a,b. Our approach to **2a,b**, shown retrosynthetically in Scheme I, differs from previous syntheses of diazenes used for intramolecular 1,3-diyl trapping reactions in that the diylophile is introduced *after* the formation

Scheme I



2a,b 7

8, R = R' = O
a, R = TBDMS, R' = H
b, R = H, R' = TBDMS
c, R = OH, R' = H
d, R = H, R' = OH

9a-d 10a,b

8

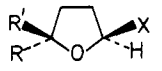
of the 7-alkylidene bicyclo[2.2.1]heptane framework. Conceivably, by adopting this approach, a variety of different diylophiles could be obtained from the lactols **7**. In addition, since the R group in **2** is incorporated at a late stage in the synthesis, a variety of groups could be employed here as well. The main concern was to obtain the diazenes in optically pure form; thus our strategy was designed to be able to easily discern if any epimerization occurred at the stereogenic atom of the aldehyde or fulvene. If some of the chirality was lost, we also wanted to be able to separate and isolate the desired material without having to carry out a time-consuming resolution. It appeared that the simplest way to achieve these goals was to incorporate a second stereogenic atom into the aldehyde precursor(s). Then, in the event of epimerization, diastereomers would result that, at least in theory, would be distinguishable and separable.

The synthesis began with (*S*)-glutamic acid which was transformed into the known benzylated lactone **8** (Bzl = benzyl) by using the procedure of Taniguchi and co-workers.[6,7] The second stereogenic atom was introduced by reducing **8** with DIBAL-H in ether–hexane at −78 °C to the diastereomeric lactols **9c,d** in 91% yield in a ratio of approximately 1:1 by proton NMR. These lactols were not separable by distillation or chromatography so the pair was silylated with *tert*-butyldimethylsilyl (*t*-$BuMe_2Si$) chloride and imidazole in DMF to afford the easily separable substituted tetrahydrofurans **9a,b**. Although the yield varied from run to run (64–91%), the two diastereomers were consistently formed in a 1.9:1 ratio thereby implying that some epimerization at C_5 had occurred during silylation.

Since the starting materials were present in roughly equal proportions, it is tempting to speculate that the major product is the trans isomer **9a** and that it may be the thermodynamically preferred product. Proton NMR data also suggest that this is true. In particular, the C_2H and C_5H signals appear further downfield in the major isomer than in the minor. This implies a trans relationship of the substituents since, in this geometry, C_2H and C_5H are expected to be sterically deshielded by the silyloxy and (benzyloxy)methyl groups, respectively. In addition, the CH_2OBzl resonances were further downfield in the minor isomer than in the major diastereomer. The methylene signals furthest downfield are expected to correspond to the cis isomer due to steric deshielding by the silyloxy group. Similar relative chemical shifts of the corresponding protons in compounds **11a,b**, **12a,b**, and **10a,b** are also observed. The carbon-13 NMR spectra

(6) (a) For a review of synthetic applications of (*S*)-glutamic acid, see: Smith, L. R.; Williams, H. J. *J. Chem. Educ.* **1979**, *56*, 696–698. (b) Austin, A. T.; Howard, J. *J. Chem. Soc.* **1961**, 3593–3603. (c) Gringore, O. H.; Rouessac, F. P. "Organic Syntheses"; Wiley: New York, in press. We are grateful to Professor Rouessac (Laboratory of Organic Synthesis, University of Main, F-72017, LeMans, France) for sending us a preprint of this manuscript.

(7) Taniguchi, M.; Koga, K.; Yamada, S. *Tetrahedron* **1974**, *30*, 3547–3552.



9 - **12**

a, R = DMTBS, R'=H
b, R = H, R'=DMTBS
9, X = CH_2OBzl
11, X = CH_2OH
12, X = CHO
10, X = CH= 

shed no more light on the assignments since the corresponding chemical shifts in each diastereomeric pair **9a,b** and **11a,b** were essentially the same. (Refer to the Experimental Section for details.)

In an attempt to confirm the assignments, nuclear Overhauser enhancement difference spectroscopy (NOEDS) experiments were carried out on the two alcohols **11a,b**. We hoped to observe signal enhancements of C_2H and C_5H in the cis isomer. Unfortunately, sequential presaturation of C_2H and C_5H in each compound resulted in no observable enhancement of any signal.

It is important to note that, even though the cis–trans assignments may be reversed, the new stereogenic atom (C_5) becomes an sp^2 hybridized carbon later in the synthesis. Therefore, the actual configuration of C_5 is in fact irrelevant with respect to the ultimate objective of this investigation.

As stated earlier, the diastereomeric silyl ethers **9a,b** were separated from each other. Both of these compounds were independently carried on in the remainder of the synthesis in the same manner. For the sake of simplicity, the following discussion of the preparation of the chiral diazenes **2a,b** will focus mainly upon the trans isomers. Complete experimental details and spectral data of both series of compounds, **a** and **b**, are given in the Experimental Section.

The benzyl group of **9a** was most efficiently removed by hydrogenolysis over a palladium on carbon catalyst in THF to afford the alcohol **11a**. Typical yields for this transformation were about 80% although they varied greatly on occasion.

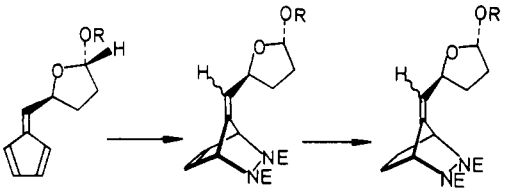
Oxidation of **11a** to aldehyde **12a** was carried out using a Swern oxidation.[8] Thus, treatment of **11a** with Me_2SO and oxalyl chloride in CH_2Cl_2 at −50 to −60 °C followed by treatment with triethylamine afforded **12a** in 70–81% yield. Both this aldehyde and its diastereomer **12b** change from a fluid oil to a sticky, viscous material upon storage. Apparently, the aldehydes oligomerize. This made characterization of the aldehydes quite difficult at first since the monomers were always accompanied by some oligomer. Fortunately, however, the monomer and oligomer form of both **12a** and **12b** readily interconvert: when standing neat, the aldehydes exist almost completely as the oligomers, whereas when in a solvent such as methylene chloride or chloroform, the mixtures equilibrate to give monomer predominantly.

Oxidation of **11a** proceeded without any epimerization at C_2 regardless of the degree of oligomerization. This fact was firmly established since a sample of **12b** (derived from **9b**) was available for comparison. Since **12b** would be the enantiomer of aldehyde **12a** which had epimerized at C_2, both compounds would possess the same physical and spectral properties. The diastereomers **12a,b** can be easily distinguished by capillary GC and 300-MHz proton NMR. In practice, none of the enantiomer of **12b** was detected in the product derived from the oxidation of **11a**.

In the next step of the synthesis, however, epimerization at C_2 did occur. That is, when the *trans*-fulvene **10a** was prepared from aldehyde **12a**, approximately 11% of the *cis*-fulvene (enantiomer of **10b**) was also formed. Again, thanks to the second stereogenic atom, these diastereomers could be easily distinguished by GC, TLC, and proton NMR. In addition, they were readily separable by liquid chromatography on silica gel, thus allowing isolation of the optically pure fulvene **10a**.

In an effort to optimize the yield and minimize epimerization of the chiral fulvenes **10a,b**, a variety of experiments were carried out. Although the investigation led to the development of an efficient procedure for the preparation of fulvenes,[9] the highest yields of fulvenes **10a,b** were about 45%. These were attained when either aldehyde **12a** or **12b** was treated with 2.5 equiv of cyclopentadiene and 5.0 equiv of pyrrolidine in methanol at room temperature for 40–48 h.

With the configurationally pure stereogenic atom and the five-membered ring destined to become the cyclopenta-1,3-diyl ring in hand, the next stage of the synthesis called for the preparation of the bicyclo[2.2.1] ring system. This was accomplished by carrying out a Diels–Alder reaction between fulvene **10a** and bis(2,2,2-trichloroethyl) azodicarboxylate[10] in ether at 0 °C for 1 h. This reaction generated the diastereomeric compounds **13a** in an approximately 1:1 ratio as determined by proton NMR. The $C_{5,6}$ π bond of each compound was selectively hydrogenated using diimide to afford a mixture of diastereomers **14a**.[11] After chromatography, the bis(carbamates) **14a** were isolated as a

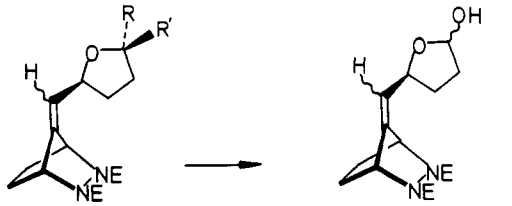


10a **13a** **14a**

R=TBDMS E = $CO_2CH_2CCl_3$

mixture in 86% yield from **10a**. The cis analogue of **14a**, namely, **14b**, was prepared similarly from **10b** in 80% yield.

Following the formation of the bicyclic framework, the diylophile was introduced. Thus, isomers **14a** were desilylated with a 1:1 mixture of hydrofluoric acid (HF) and tetra-*n*-butylammonium fluoride (TBAF) in wet THF (ca. 5% H_2O) at room temperature for 4.5 h. In this way, the four diastereomeric lactols **7** were formed in roughly equal amounts in combined yields



14a,b **7**

a R=OTBDMS, R'=H
b R=H, R'=OTBDMS

ranging from 73% to 84%. All four isomers possessed the *S* configuration at $C_{2'}$, and, although they could be separated into two pairs (stereochemistry undetermined) by liquid chromatography, they were generally carried on together in the next reaction. The *same* four lactols were formed when the cis silylated bis(carbamates) **14b** were subjected to the same reaction conditions.

It is interesting to note that when TBAF alone was utilized as a desilylating agent lactols **7** were formed in only 32% yield. The proton NMR spectrum of the crude product of this reaction revealed that a significant amount of trichloroethanol was present, implying that some saponification had occurred. Apparently, the

(8) (a) Mancuso, A. J.; Huang, S. L.; Swern, D. *J. Org. Chem.* **1978**, *43*, 2480–2482. (b) Mancuso, A. J.; Brownfain, D. S.; Swern, D. *J. Org. Chem.* **1979**, *44*, 4148–4150. (c) For a review on activated Me_2SO as an oxidant, see: Mancuso, A. J.; Swern, D. *Synthesis* **1981**, 165–185.

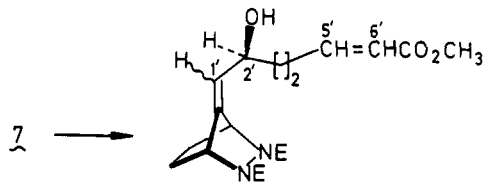
(9) Little, R. D.; Stone, K. J. *J. Org. Chem.* **1984**, *48*, 1849.

(10) Little, R. D.; Venegas, M. "Organic Syntheses"; Stevens, R. V., Ed.; Wiley: New York, 1983; Vol. 61, pp 17–21.

(11) The diimide precursor, dipotassium azodicarboxylate, was made according to the procedure of: Berson, J. A.; Poonian, M. S.; Libbey, W. J. *J. Am. Chem. Soc.* **1969**, *91*, 5567.

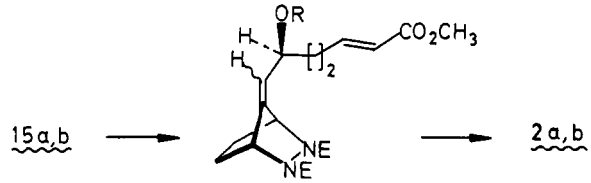
TBAF solution creates a reaction medium that is too basic to allow the desired reaction to proceed efficiently. In addition, when HF was employed as the sole reagent for desilylation, the desired reaction proceeded substantially slower compared with the reactions using the HF–TBAF mixture.

Introduction of the diylophile was efficiently achieved using a Wittig reaction between the lactols **7** and methyl (triphenylphosphoranylidene)acetate and afforded the four isomeric products **15a–d**, which were formed in 88–97% yield in a ratio of 5.2:4.6:1:1,



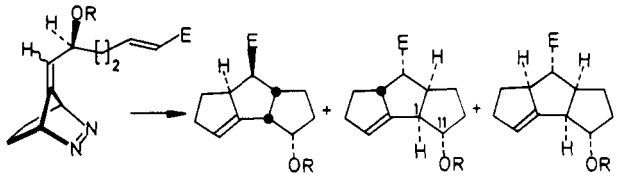
15a,b, $C_{5'}C_{6'}$-E
15c,d, $C_{5'}C_{6'}$-Z

respectively. All four isomers possess the *S* configuration at $C_{2'}$ but differ in the olefin geometry (*E* for **15a,b** and *Z* for **15c,d**) and the asymmetry of the bicyclic ring system (absolute configurations of C_1 and C_4 were not determined). The two *E* isomers **15a,b** were carried on *independently* in the remainder of the synthesis and were eventually transformed into their corresponding diazenes **2a,b** by silylation (*t*-$BuMe_2SiCl$) and conversion of the bis(carbamate) unit into the diazene linkage.[3]



16a,b

Deazetation of the Chiral Diazenes 2a and 2b. Pyrolysis of 2a and Structural Assignment of the Products. When diazene **2a** was heated in refluxing acetonitrile for 2.5 h, the three linearly fused tricyclopentanoids **3–5** were produced in 91% combined yield.



2a **3** **4** **5**

E = CO_2CH_3
R = TBDMS

Since the products are diastereomers and not enantiomers, isolation of each of the three isomers was achieved by liquid chromatography.

Both the 300-MHz proton NMR spectrum and the capillary column gas chromatogram of even the crude product mixture reveal two striking aspects of this reaction. First, *the reaction was very clean and, second, it was highly stereoselective*; the three diastereomers **3–5** were formed in a 1.15:13.6:1 ratio, respectively.[12] More importantly, with respect to the two cis,anti ring fused tricyclopentanoids **3** and **4**, the observed product ratio corresponds to 84.2% de (92.1% ds).[5] Thus, in this first critical experimental test, we attained a synthetically useful amount of diastereoselectivity.

Structural assignment for **4** was based upon analogy with previous trapping experiments and extensive 300-MHz proton NMR experiments. Thus, the unique appearance of a clean doublet for C_7H in both **4** and its desilylated analogue is analogous to that observed in other cis,anti ring fused tricyclopentanoids bearing an ester group at C_7 which we have previously characterized.[3,13] In addition, proton–proton decoupling experiments allowed assignment of nearly every proton in **4**.

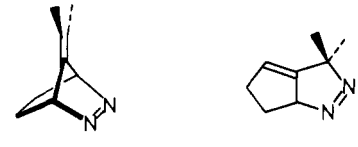
Having assigned the resonance corresponding to C_1H, we next carried out a series of NOEDS experiments to determine the geometric relationship between C_1H and $C_{11}H$.[14] The most significant observation was the virtual absence of signal enhancement of $C_{11}H$ upon presaturation of C_1H and the small enhancement (2%) of C_1H upon presaturation of $C_{11}H$. These results imply that C_1H and $C_{11}H$ possess a trans relationship, in agreement with our prediction that **4** would be the major product from deazetation of **2**.

Being aware of the fact that the absence of NOE cannot prove a geometrical relationship, we carried out the same experiments on the minor cis,anti ring fused product **3**.[14] Unlike the major product **4**, tricyclopentanoid **3** showed relatively large enhancements of both C_1H and $C_{11}H$. Specifically, presaturation of C_1H resulted in a 22% NOE of the signal corresponding to $C_{11}H$ while presaturation of $C_{11}H$ afforded a 19% NOE of the C_1 resonance. These results firmly establish that C_1H and $C_{11}H$ have a cis relationship in **3**. Furthermore, since C_{11} possesses an *S* configuration, assignment of the absolute configuration of the four newly formed stereogenic atoms in **3** follow as 1*S*,6*S*,7*S*,8*R*, as depicted.

Since C_1H and $C_{11}H$ are cis to each other in the minor cis,anti product, it follows that C_1H and $C_{11}H$ are trans to each other in the major cis,anti isomer. Consequently, the four new stereogenic atoms in **4** possess the following configurations: 1*R*,6*R*,7*R*,8*S*. That is, *not only does the major trapping product possess the same relative stereochemistry as the naturally occurring tricyclopentanoids but the same absolute stereochemistry as well.* Obviously, this result bodes well for the possible application of the reaction to a total synthesis of optically pure coriolin.

Assignment of structure **5** to the third isolated product from the trapping reaction is tentative. From our predictions based upon an examination of molecular models, the similarities of its IR, NMR, and mass spectra with **3** and **4** and, by analogy, with previous intramolecular 1,3-diyl trapping reactions, the product is assumed to be the cis,syn ring fused tricyclopentanoid shown. The other cis,syn ring fused product that might have been formed, namely, **6**, appears by Dreiding molecular models to be much more sterically congested than **5**. Presumably, these steric interactions would manifest themselves by raising the energy of transition state **6*** leading to **6**.

Experimental Evidence for a Time-Averaged Planar 1,3-Diyl. Each of the 1,3-diyl precursors **2a** and **2b** could conceivably give rise to a different product distribution if, for example, some bond formation between the diylophile and the incipient 1,3-diyl began prior to complete loss of nitrogen. In this event, one diastereomeric diazene would induce asymmetry of a different nature than the other. Another intriguing possibility would be to find that, in analogy with the intermolecular trapping of the 1,3-diyls derived from the bridged and fused diazenes **19** and **20**,[15] even intramo-



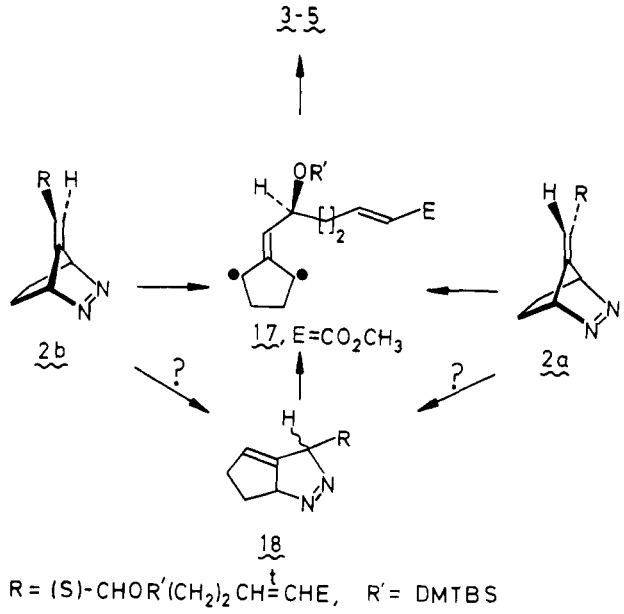
19 **20**

(12) The product ratios were obtained from the observed GC integrations and thus assume equal response factors for the diastereomers. Isolated ratios were somewhat lower, but, because of the small scale of the reactions, only a few milligrams of the minor products were formed making accurate isolated ratios difficult to determine.

(13) In comparison to the doublet arising from C_7H of the cis,anti ring fused products the corresponding proton in the isomeric cis,syn tricyclopentanoids appears as a more complicated (i.e., coupled) signal. For details, refer to the Experimental Section.

(14) We also assigned product **3** as being cis,anti ring fused on the basis of analogy with previous results and the appearance of a doublet for C_7H (2.685 ppm, J = 9.9 Hz).

Scheme II



lecular trapping is too slow to preserve any differences between the geometry of the diyl precursors. With these factors in mind, we initiated the study described below.

When diazene **2b** was heated in refluxing acetonitrile, we observed not only the same products **3–5** but also *the same product ratios* as were found in the case of diazene **2a**. These results strongly suggest that in both cases, complete cleavage of the C–N bonds occurs prior to any C–C bond formation between the 1,3-diyl and the diylophile. That is, both **2a** and **2b** lead to the same cyclopenta-1,3-diyl **17** and it behaves as a time-averaged planar intermediate. Furthermore, if some rearrangement from the bridged diazenes **2** to the fused diazenes **18** does occur, then the fused diazenes also extrude nitrogen to generate the same time-averaged planar diyl intermediate **17** (Scheme II).

Low-Temperature Photolysis of 2b. Implication of a Temperature-Dependent Product Distribution. In an attempt to determine what effect the mode of deazetation and temperature have upon the trapping reaction, **2b** was photolyzed in acetonitrile at 7 °C (450-W Hanovia, Pyrex filter). We were exceptionally pleased to note that the reaction was even more diastereoselective than the pyrolysis conducted at 81 °C. Analysis of the product mixture by capillary GC revealed that tricyclopentanoids **3–5** were formed in a 1:26:1.5 ratio, respectively. This meant that a 92.6% de (96.3% ds) of cis,anti products had been achieved. In addition, it is interesting to note that although **4** was again formed in preference to both **3** and **5**, the ratio of **3**:**5** changed from one where **3** was formed in preference to **5** at 81 °C (1.15:1) to one where **5** was formed in preference to **3** at 7 °C (1:1.50). The significance of this finding will be discussed later.

Considering that these preliminary results were obtained at different temperatures and from different modes of deazetation, we wondered whether the observed results were due simply to the temperature difference or if a different mechanism was operating under each set of reaction conditions. Since the reactions proceed through a 1,3-diyl intermediate (vide supra) and the products are formed in a kinetically controlled fashion, eq 1, where A and B

$$\ln([A]/[B]) = -\Delta\Delta H^{\ddagger}_{A-B}/RT + \Delta\Delta S^{\ddagger}_{A-B}/R \qquad (1)$$

refer to two different products formed in a kinetically controlled process, is applicable.

If linearity is obtained in a plot of ln ([A]/[B]) vs. $1/T$, then the relative enthalpic and entropic contributions to the transition states leading to the observed products can be obtained. In addition, if the data from the thermally initiated reactions fall on the same straight line as those from the photochemically initiated reactions, we can conclude that both reactions proceed via the same 1,3-diyl.

(15) (a) Cichra, D.; Platz, M. S.; Berson, J. A. *J. Am. Chem. Soc.* **1977**, *99*, 8507–8509. (b) Cichra, D. A.; Duncan, C. A.; Berson, J. A. *J. Am. Chem. Soc.* **1980**, *102*, 6527–6533.

Table I. Product Ratios of the Linearly Fused Tricyclopentanoids **3–5** Obtained from Pyrolysis and Photolysis of Diazenes **2a,b** in Acetonitrile at Various Temperatures

temp, °C	**4**/**3** (% ds)[b] (CA/ca)	**4**/**5** (CA/CS)	**3**/**5** (ca/CS)
−31[c]	48.5 ± 1.7 (98)	20.0 ± 0.7	0.41 ± 0.02
−2[c]	24.2 ± 0.7 (96)	16.7 ± 0.2	0.69 ± 0.01
7[c]	26.2 ± 0.9 (96.3)	17.7 ± 0.2	0.68 ± 0.02
50[c]	14.1 ± 0.3 (93.4)	14.7 ± 0.7	1.05 ± 0.06
50[d]	14.7 ± 0.1 (93.6)	15.1 ± 0.2	1.03 ± 0.01
66[d]	12.8 ± 0.6 (92.8)	15.0 ± 0.9	1.18 ± 0.12
81[d]	11.7 ± 0.2 (92.1)	14.2 ± 0.9	1.22 ± 0.08

[a] Average ± standard deviation of at least three capillary column GC injections (see ref 12). [b] See ref 5. [c] Photochemical deazetation ($\lambda \geq 300$ nm). [d] Thermal deazetation.

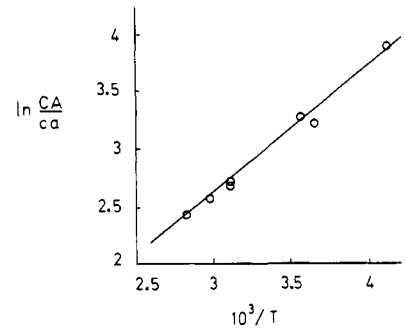


Figure 1. Arrhenius plot for the pair of products **4** (CA) and **3** (ca) formed from deazetation of **2a** and **2b** (r = 0.989).

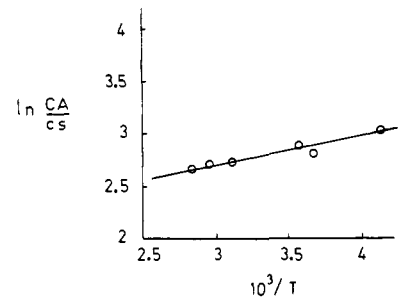


Figure 2. Arrhenius plot for the pair of products **4** (CA) and **5** (CS) formed from deazetation of **2a,b** (r = 0.965).

Experimental Evidence for the Formation of a Common Intermediate from the Photochemical and Thermochemical Reactions. Determination of Differences in Activation Parameters. Thermally initiated reactions were carried out at 81, 66, and 50 °C. Photochemically initiated reactions were run at 50, 7, −2, and −31 °C. All reactions were carried out in acetonitrile and were continued until no starting material could be detected by TLC; the product distribution was determined by capillary column GC analysis. The three diastereomeric tricyclopentanoids **3–5** designated as minor cis,anti (ca), major cis,anti (CA), and cis,syn (CS), respectively, were formed in each case. The results are summarized in Table I and the Arrhenius plots of eq 1 (least-squares line fitting) are illustrated in Figures 1 and 2. In each case, linearity was observed throughout the entire temperature range. Significantly, the results from both thermal and photochemically initiated runs fall on the same line. For the reactions that were conducted both photochemically and thermally at the same temperature, namely, 50 °C, the thermal run required 40 h for completion whereas the photochemical run was complete in only 2.5 h. Thus, we were assured that there was essentially no thermal contribution to the results obtained photochemically. It is important to note that both of these reactions provided the same products and in the same ratio. These results indicate that *the same 1,3-diyl intermediate is involved in both the thermal*

Table II. Differences of Enthalpy, Entropy, and Free Energy[a] of Activation for the Formation of Tricyclopentanoids **3–5** from the 1,3-Diyl **2**

A	B	$\Delta\Delta H^{\ddagger}_{A-B}$[b]	$\Delta\Delta S^{\ddagger}_{A-B}$[c]	$\Delta\Delta G^{\ddagger}_{A-B}$[a,b] (A/B)[d] 81 °C	25 °C	−31 °C
4 (CA)	**3** (ca)	−2.14	−1.3	−1.69 (11.0)	−1.76 (19.5)	−1.83 (44.9)
4 (CA)	**5** (cs)	−0.50	+3.9	−1.87 (14.3)	−1.65 (16.2)	−1.43 (19.6)
3 (ca)	**5** (CS)	+1.65	+5.2	−0.12 (1.2)	+0.11 (0.83)	+0.40 (0.44)

[a] Calculated values. [b] In kcal/mol. [c] In cal/(mol deg) (eu). [d] Calculated product ratio at the indicated temperatures.

and photochemically initiated reactions.

The results summarized in Figure 1 illustrate the case of greatest interest from the viewpoint of potential application to a total synthesis of optically pure coriolin. It is apparent from the figure that there is a large temperature effect upon the CA/ca product ratio. This can be attributed to the relatively large magnitude of $\Delta\Delta H^{\ddagger}$ (−2.14 kcal/mol). Even though the ca product is favored entropically, the enthalpy term dominates at any temperature below the extrapolated isokinetic temperature of about 1300 °C;[16] therefore, *the desired product CA is formed selectively over the entire temperature range* that was examined. Finally, it should be noted that *at −31 °C, the ratio of products is 48.5:1, corresponding to a gratifying 96% de (98% ds).*

From an examination of the data for the CA/CS temperature dependence (Figure 2), one observes that both the enthalpy and entropy of activation favor the formation of the CA diastereomer. In this case, however, the magnitude of $\Delta\Delta H^{\ddagger}$ (−0.5 kcal/mol) is significantly smaller than that observed for the cis,anti pairs. This factor manifests itself in the form of a slower rate of change in the product ratios as the temperature is changed. For example, CA/CS only increases from 14.2 (93.4% ds) at 81 °C to 20.0 (95.2% ds) at −31 °C, whereas a change from 11.7 (84% ds) to 48.5 (98% ds) is observed for CA/ca. Notice that, because of the relative magnitudes of $\Delta\Delta H^{\dagger}$ and $\Delta\Delta S^{\dagger}$, the entropic term in eq 1 is larger than the enthalpic term until the temperature is below about 140 K (−133 °C). This implies that, *within the temperature range examined, entropy differences contribute more to the observed product ratios than do enthalpy differences.*

Although the combined yield of the ca and CS tricyclopentanoids is never a large percentage of the total (a maximum of 13.6% at 81 °C and a minimum of 6.6% at −31 °C), it is still of interest to examine their activation parameters. A plot of ln (ca/CS) vs $1/T$ is again linear.[17] However, unlike the previous two cases, the slope of the line is negative, thereby indicating an enthalpic preference (1.65 kcal/mol) in the transition state leading to the CS product. The intercept is positive and indicates an entropic preference of 5.2 eu in the transition state leading to the ca tricyclopentanoid. In addition, the isokinetic temperature (47 °C) happens to fall within the temperature range that was examined. In particular, when the temperature is above 47 °C, the ca product is formed in excess of the CS, whereas when the temperature is below the isokinetic temperature the CS tricyclopentanoid is formed as the major product.

Having determined the relative enthalpies and entropies of activation for each pair of products, we can calculate the relative free energies of activation at any temperature. Table II summarizes the results obtained at 81, 25, and −31 °C.

Discussion

Our original plan for inducing asymmetry in the intramolecular 1,3-diyl trapping reaction was designed to take advantage of the favorable pseudochair conformation, secondary orbital interactions, and the existence of steric interactions in one of the two diastereomeric transition states leading to cis,anti ring fused tricyclopentanoids. These effects are depicted collectively in transition-state representations **3*** and **4***. We hoped that, as a result of these effects, the activation energy associated with **4*** would be significantly less than that associated with **3*** and, consequently, we would see the formation of predominately one product, namely, CA. The preceding results indicate that this objective has been achieved.

At the outset of this investigation, we assumed that in an intramolecular cyclization, the entropy of activation associated with transition states leading to diastereomeric products would be similar and thus not play a significant role in distinguishing between competitive pathways. We did find this to be the case with respect to the two cis,anti ring fused products ca and CA, where the observed selectivity is primarily due to enthalpic differences in the transition states leading to each product. This result is in accord with our prediction that the sterically demanding OR functional group, when strategically located on the chain linking the 1,3-diyl and diylophile, would introduce an energy-raising steric interaction in only one (i.e., **3***) of the two transition states leading to the diastereomeric cis,anti tricyclopentanoids. The entropic difference between these two transition states is quite small relative to the enthalpic difference and thus does not contribute much in determining the ratio of these two products. Even at the highest temperature examined (81 °C), the enthalpic contribution is roughly 5 times larger than the entropic contribution.

In regard to the other two pairs of products, however, the *differences in entropy of activation are large enough to make significant contributions to the energy differences between the respective transition-state pairs.* For example, the CA:CS ratio is determined primarily by the differences in entropy of activation. Within the temperature range examined, the entropic contribution to the difference in transition-state energies is roughly twice that of the enthalpic contribution. Evidently, it is the more ordered conformation of the transition state leading to the CS product that makes it less energetically favorable than that leading to the CA tricyclopentanoid. Although this is not obvious from the drawing (**5***), a possible rationale is found in an examination of molecular models. This reveals that for the carbon α to the ester to reach one of the radical centers of the cyclopentyl ring en route to the CS product the diylophile π bond (and the chain connecting it to the 1,3-diyl) must coil to a conformation that is "tighter" than in the transition state leading to the CA product. In addition, this "tighter" conformation is accompanied by eclipsing interactions between the hydrogen atoms and the OR group of the connecting chain. These interactions may be partially responsible for the observed enthalpic preference for formation of the CA product.

In the third pair of products, namely, the ca and the CS tricyclopentanoids, the difference in entropies of activation is quite large (ca. 5 eu, corresponding to about 1.5 kcal/mol at room temperature). This again implies that the transition state leading to the CS product is very ordered relative to the alternate pathways. *In the absence of this large entropic difference, the CS product would have been formed in great preference to the ca product.* That is, if enthalpy alone was responsible for determining the ratio of this pair of products, at 25 °C the ratio would have been about 16:1 (compared to the observed 1.2:1) in favor of the CS product! *A similar calculation with respect to the CA–CS pair reveals that the CA product would have been formed in only a 2.3:1 (compared to 19:1) preference!* These two calculations point out that entropy, in at least this intramolecular cyclization,

(16) See, for example: Bunnett, J. F. In "Techniques in Organic Chemistry"; Weissberger, A., Ed.; Interscience: New York, 1961; Vol. VIII, pp 204–210. See also: Giese, B. *Acc. Chem. Res.* **1984**, *17*, 438–442.

(17) We are grateful to a referee who has correctly pointed out that it is unnecessary to illustrate a linear plot of ln (ca/CS) vs. $1/T$, since if ln (CA/ca) and ln (CA/CS) vs. $1/T$ are linear, then ln (ca/CS) vs. $1/T$ is also linear. In fact, ln (ca/CS) = ln (CA/CS) − ln (CA/ca). As a result, any conclusions drawn from a plot of ln (ca/CS) vs. $1/T$ are redundant. This point is clearly illustrated from an examination of line 3 of Table II where every entry is the arithmetic difference of the first two entries. We do, however, feel that it is worthwhile to provide the brief discussion presented in the text, especially since the isokinetic temperature actually occurred within the operating temperature range. Furthermore, the fact that a plot of ln (ca/CS) vs. $1/T$ *is* linear highlights the internal consistency of the data.

plays a significant role in determining the product distribution.

The results of the present work emphasize the value of running kinetically controlled reactions at least two temperatures to determine which factors are actually at work; we encourage others to do the same when conditions permit. We have been fortunate to be able to take advantage of a broad range of temperatures in this investigation due to the possibility of generating the 1,3-diyls both thermally and photochemically.

These results have expanded the scope of the intramolecular 1,3-diyl trapping reaction as a synthetic tool and have helped refine our views of the energy surface as well as the factors responsible for determining the outcome of the reaction.

Experimental Section

Proton nuclear magnetic resonance (^{1}H NMR) spectra were measured on a Nicolet NT 300 (300 MHz), Varian XL 100 (100 MHz), Varian CFT 20/FT 80 (80 MHz), or Varian EM 360 or T60 (60 MHz) spectrometer in $CDCl_3$ containing ca. 0.05% tetramethylsilane (Me_4Si) internal reference. Carbon-13 nuclear magnetic resonance (^{13}C NMR) spectra were measured on a Nicolet NT 300 (75 MHz) or a Varian CFT 20/FT 80 (20 MHz) spectrometer in $CDCl_3$ solution. All spectra were recorded fully decoupled from protons and, in some cases, off resonance partially decoupled. When off-resonance decoupling was done, the multiplicity is also included for each signal. Chemical shifts are reported in ppm relative to the central line of $CDCl_3$ being 77.000 ppm.

Infrared (IR) spectra were recorded on a Perkin-Elmer 283 spectrometer. Samples were as a thin film on sodium chloride plates. Absorbing frequencies are reported in wavenumbers (cm^{-1}) with the most intense absorbances underlined. Broad absorbances are indicated as "br".

Mass spectra (MS) were recorded by Dr. H. M. Webb of UCSB on a ZAB 2-F mass spectrometer. Ionization was initiated by either electron impact (EI) with 70 eV of energy, positive chemical ionization (PCI) utilizing methane (CH_4), ionized with 100–150 eV of energy, or negative chemical ionization (NCI) utilizing methane, ionized with 100–500 eV of energy. Data are reported as the mass to charge ratio of the observed ion, where "M" refers to the molecular ion. HRMS refers to high-resolution mass spectroscopy.

Elemental analyses were determined by Galbraith Laboratories, Inc., Knoxville, TN.

Optical rotations were measured on either a Rudolph Research Autopol III or a Perkin-Elmer 141 Polarimeter utilizing a 589-nm wavelength (sodium D line) polarized beam. Solvents used to prepare the samples were spectral grade.

Thin-layer chromatography (TLC) was done on silica gel precoated glass plates (J. T. Baker Si250F or E. Merck Silica Gel 60 F-254) with 254-nm fluorescent indicator. Data are reported as follows: R_f (eluting solvent; method of observation (where UV, anis, and PMA refer to ultraviolet hand-held lamp, *p*-anisaldehyde stain, and phosphomolybdic acid stain, respectively)). Gravity-flow liquid chromatography (LC) was done on E. Merck silica gel 60 (70–230 or 230–400 mesh, ASTM). Medium-pressure liquid chromatography (MPLC) was performed on a variety of Altex columns packed with E. Merck silica gel 60 (230–400 mesh, ASTM). Solvents used for elution were passed through the system with an FMI Model RSP4 lab pump at 60–100 psi. The eluent was continuously monitored at 280 nm with an Altex Model 150 monitoring system. Ether, pentane, and Skelly Solve F (SSF, 30–60 °C boiling range) were distilled prior to use; reagent grade methylene chloride, ethyl acetate, and ethanol were used without purification. Solvent mixtures were prepared by volume.

Analytical gas chromatography (GC) was carried out on a Hewlett-Packard 5830A gas chromatograph equipped with a Hewlett-Packard 18850 terminal and a flame ionization detector. The carrier gas was helium for columns A–C and nitrogen for column D. For the capillary columns A–C a split injection port (split ratio 100–200:1) was used and nitrogen was employed as a make-up gas in the FID. The columns are abbreviated as follows: A, 60 m × 0.21 mm i.d. DB-5 (J and W Scientific); B, 60 m × 0.259 mm i.d. Carbowax (J and W Scientific); C, 25 m × 0.200 mm i.d. Ultra II (5% phenylmethylsilicone, Hewlett-Packard).

Gas chromatography–mass spectra (GC–MS) were obtained by Dr. R. Petty of UCSB (Marine Science Institute) on a Hewlett-Packard 5992A system fitted with a 15 m × 0.3 mm i.d. DB-1 column.

(*S*)-Tetrahydro-5-oxo-2-furancarboxylic Acid.[6] This lactone–acid was prepared from (*S*)-glutamic acid (Aldrich, 0.50-mol scale) according to the procedure of Gringore and Rouessac[6c] in 72% yield after distillation (150–165 °C, 0.05–0.5 torr). Material obtained in this way was found to be suitable for use in the next reaction without recrystallization.

(*S*)-Tetrahydro-5-oxo-2-(hydroxymethyl)furan. This alcohol was prepared by selective reduction of lactone–acid (0.32 mol) with borane–methyl sulfide (Aldrich) according to the procedure of Silverstein et al.,[18a] in 95% yield after distillation (106–122 °C, 0.1–0.4 torr): R_f 0.37 (7% EtOH/93% CH_2Cl_2; anis); $[\alpha]^{22}$ +31.3 (*c* 3.83, EtOH) [lit.[18a] $[\alpha]^{20}$ +29.6 (*c* 0.4, EtOH)].

(*S*)-Tetrahydro-5-oxo-2-[(benzyloxy)methyl]furan (8). This benzyl ether was prepared from the lactone–alcohol (0.215 mol) according to the procedure of Taniguchi et al.,[7] utilizing benzyl bromide and silver oxide in DMF in 77% after distillation (114–125 °C, 0.004 torr): R_f = 0.29 (70% ether/30% pentane; UV, anis, PMA); R_f 0.62 (20% ether/80% CH_2Cl_2); ^{1}H NMR (300 MHz) δ 7.35–7.25 (m, 5 H, Ph); 4.69–4.62 (m, 1 H, C_2H), 4.60–4.50 (AB, A = 4.56 and B = 4.54, CH_2Ph, J_{AB} = 12.3 Hz), 3.70–3.54 (AB of ABX, 2 H, J_{AB} = 10.5 Hz, CH_2OBzl), 2.68–2.41, 2.34–2.21, and 2.18–2.05 (3 m, 2 H, 1 H, and 1 H, CH_2CH_2); ^{13}C NMR (75 MHz) 177.10 (s, C=O), 137.46 (s, C_1 of Ph), 128.17 and 127.32 (2 d, C_2 + C_6 and C_3 + C_5 of Ph), 127.50 (d, C_4 of Ph), 78.77 (d, C_2), 73.22 (t, *C*H_2Ph), 71.34 (t, *C*H_2O), 28.15 and 23.81 (2 t, C_3 and C_4) ppm; IR 3030, 2940, 2860, *1775*, 1495, *1455*, 1420, 1360, *1185*, *1120*, *942*, 915, *740*, *700* cm^{-1}.

(2*S*)-Tetrahydro-5-hydroxy-2-[(benzyloxy)methyl]furan (9c,d). To a solution of benzylated lactone **8c** (33.69 g, 163 mmol) in 540 mL of ether, cooled in a dry ice–acetone bath, was added dropwise 163 mL of DIBAL-H (Alfa, 20% in hexane, 148 mmol) over 30 min. After 20 min methanol (85 mL) was added, the cold bath was removed, and the reaction mixture was allowed to warm to room temperature. Rochelle's salt solution (410 mL of 30% aqueous sodium potassium tartrate) was added and the mixture was stirred until two clear layers were visible (ca., 45 min). The organic layer was separated and extracted with 30% Rochelle's salt solution (4 × 200 mL). The aqueous portions were combined and extracted with CH_2Cl_2 (4 × 200 mL). The organic portions were combined, dried over $MgSO_4$, and concentrated in vacuo. The crude product (34.12 g) was vacuum distilled (100–112 °C, 8 mtorr) to afford 28.21 g (91% or 83% from lactone) of a diastereomeric mix (about 1:1 by ^{1}H NMR) of lactols **9c,d**: R_f 0.20 (20% ether/80% CH_2Cl_2; UV, anis, PMA); ^{1}H NMR (300 MHz) δ 7.42–7.26 (m, 10 H, 2 Ph), 5.62–5.57 and 5.47–5.42 (2 m, 1 H each, C_5H of each isomer), 4.65–4.52 (m, 4 H, 2CH_2Ph), 4.50–4.40 and 4.35–4.27 (2 m, 1 H each, C_2H of each isomer), 3.67–3.59 and 3.52–3.44 (2 m, 2 H each, CH_2OBzl of each isomer), 2.20–1.83 and 1.73–1.62 (2 m, 8 H, CH_2CH_2 of each isomer), 1.95 (br s, 2 H, OH of each isomer); ^{13}C NMR (75 MHz) 138.07 and 137.60 (C_1 of Ph of each isomer), 128.19 and 127.56 (C_2–C_6 of Ph), 98.50 (COH of each isomer), 78.55 and 76.88 (C_2 of each isomer), 73.07 and 72.31 (*C*H_2Ph and *C*H_2OBzl of each isomer), 34.09 and 32.58 (C_4 of each isomer), 25.58 and 24.94 (C_3 of each isomer) ppm; IR *3400* (br), 3030, *2950–2910* (br), *2865*, 1500, *1455*, 1365, 1200, *1110–1065*, *1020* (br), *730*, *695* cm^{-1}; MS (PCI, CH_4), *m/z* 191 (M − OH), 173, 155, 143, 129, 119 [M − (C_7H_7) + 2 H], 101 [M − ($HOCH_2$Ph) + H], 99, 91 (C_7H_7), 87, 85, 29 (CHO); HRMS (PCI, CH_4), *m/z* 191.1092 (calcd for $C_{12}H_{15}O_2$, M − OH, 191.1071).

(2*S*,5*R*)- and (2*S*,5*S*)-Tetrahydro-5-[(*tert*-butyldimethylsilyl)oxy]-2-[(benzyloxy)methyl]furan [9a (trans) and 9b (cis)]. Preparation of these two compounds was accomplished by silylation of an approximate 1:1 (by 300-MHz ^{1}H NMR) mix of lactols **9c,d**. Generally, the products were formed in a 2:1 ratio in favor of the trans (see discussion in text for basis of assignment) and in yields ranging from 64% to 91%. Following the standardized procedure for silylation, 3.94 g (18.9 mmol) of lactols **9c,d** were converted into 7.91 g of a crude oil which was chromatographed by MPLC (15 mL/min, 15 × 250 and 15 × 1000 and 25 × 1000 mm columns connected in series) on SiO_2. Elution with 5% ether/95% SSF afforded 3.20 g (52.4%) of the trans isomer **9a** and 1.65 g (27.0%) of the cis isomer **9b**. R_f 0.41 (trans) and 0.28 (cis) (10% ether/90% SSF; UV, anis).

Spectral data for the trans isomer **9a**: $[\alpha]^{23}$ +43.9° (*c* 1.53, EtOH); ^{1}H NMR (300 MHz) δ 7.40–7.25 (m, 5 H, Ph), 5.53 (apparent d, 1 H, C_5H, *J* = 4.5 Hz), 4.56 (s, 2 H, CH_2Ph), 4.39–4.30 (m, 1 H, C_2H), 3.45 (apparent d, 2 H, CH_2OBzl, *J* = 4.8 Hz), 2.17–2.05, 1.99–1.87, 1.83–1.75, and 1.73–1.63 (4 m, 1 H each, CH_2CH_2), 0.879 (s, 9 H, *t*-Bu), 0.100 and 0.098 (2 s, 3 H each, $(CH_3)_2$ Si); ^{13}C NMR (75 MHz) 138.31 (C_1 of Ph), 128.18, 127.61 and 127.43 (C_2–C_6 of Ph), 99.05 (C_5), 76.71 (C_2), 73.16 (*C*H_2Ph), 72.44 (*C*H_2OBzl), 34.42 (C_4), 25.72 ((*C*H_3)$_3$C), 17.86 ((*C*H_3)$_3$C), −4.32 and −5.15 ((*C*H_3)$_2$Si) ppm; IR *2960*, *2930*, *2860*, 1460, 1360, *1255*, 1120, *1030*, *835*, *777*, 735, 695 cm^{-1}; MS (EI), *m/z* 265 (M − *t*-Bu), 201 (M − CH_2OCH_2Ph), 91 (C_7H_7); HRMS $C_{14}H_{21}O_3Si$, (M − *t*-Bu) *m/z* 265.1272 (calcd 265.1260), $C_{10}H_{21}O_2Si$ (M − CH_2OCH_2Ph) 201.1309 (calcd 201.1311).

Spectral data for the cis isomer **9b**: $[\alpha]^{23}$ −44.1° (*c* 1.51, EtOH); ^{1}H NMR (300 MHz) δ 7.35–7.25 (m, 5 H, Ph), 5.46 (apparent t, 1 H, C_5H,

(18) (a) Ravid, U.; Silverstein, R. M.; Smith, L. R. *Tetrahedron* **1978**, *34*, 1449–1452. (b) Krishnamurthy, S.; Thompson, K. L. *J. Chem. Educ.* **1977**, *54*, 778–779.

J = 2.1 Hz), 4.64–4.50 (AB, A = 4.61, B = 4.53, CH_2Ph, J_{AB} = 12.0 Hz), 4.25–4.15 (m, 1 H, C_2H), 3.60–3.46 (AB or ABX, CH_2OBzl, J_{AB} = 9.6 Hz), 2.00–1.68 (m, 4 H, CH_2CH_2), 0.862 (s, 9 H, *t*-Bu), 0.082 and 0.073 (2 s, 3 H each, $(CH_3)_2Si$); ^{13}C NMR (20 MHz) 138.50 (s, C_1 of Ph) 129.22, 127.47, and 127.44 (3 d, C_2–C_6 of Ph), 99.11 (d, C_5), 76.85 (d, C_2), 73.25 (t, CH_2Ph), 72.62 (t, CH_2OBzl), 34.47 (t, C_4), 25.73 (q, $(CH_3)_3C$), 25.73 (t, C_3), 17.86 (s, $(CH_3)_3C$), −4.34 and −5.14 (2q, $(CH_3)_2Si$) ppm; IR *2950*, *2930*, *2860*, 1460, 1370, *1255*, 1110, 1090 (br), *995*, 835, 777, 735, 695 cm^{-1}; MS (EI), m/z 265 (M − *t*-Bu), 201 (M − CH_2OCH_2Ph), 91 (C_7H_7); MS (PCI, CH_4) m/z 321 (M − 1), 191 [M − 131 (*t*-$BuMe_2SiOH$)], 91 (C_7H_7); HRMS $C_{14}H_{21}O_3Si$, (M − *t*-Bu) m/z 265.1268 (calcd 265.1260), $C_{10}H_{21}O_2Si$ (M − CH_2OCH_2Ph) 201.1315 (calcd 201.1311).

(2*S*,5*R*)- and (2*S*,5*S*)-Tetrahydro-5-[(*tert*-butyldimethylsilyl)oxy]-2-(hydroxymethyl)furan [11a (trans) and 11b (cis)]. Debenzylation of **9a,b** to prepare these two compounds was carried out under a variety of different conditions (H_2 gas, Pd/C, EtOAc, EtOH, MeOH, or THF; Na/NH_3; Li/NH_3; Li/Et_2NH-THF; NH_4HCO_2, Pd/C, MeOH) with varying results [0–94% yield, reaction times from 3 h to several weeks (for hydrogenolyses), and 10–90% conversion to product]. The most consistent results were obtained under the conditions given below; in any case, it is imperative that the starting material be exceptionally pure.

For the trans diastereomer **11a**: In a 500-mL Erlenmeyer flask containing the trans benzyl ether **9a** (2.85 g, 8.84 mmol) and 45 mL of THF was added 10% Pd/C (Aldrich, 0.97 g). The flask was fitted with a large rubber septum and purged with H_2 by using a H_2-filled balloon. A positive pressure of H_2 was maintained over the reaction mixture via a H_2-filled balloon while it was stirred vigorously with a magnetic stirring bar. After 3 h, no starting material could be detected by TLC [R_f trans benzyl ether **9a** 0.75; R_f trans alcohol **11a** 0.30 (10% ether/90% CH_2Cl_2; anis, PMA)], so the reaction mixture was vacuum filtered through 2 in. of Celite in a 100-mL coarse sintered glass funnel. The filter cake was washed with ether (100 mL) and the filtrate was concentrated in vacuo to afford 2.3 g of crude product. This material was chromatographed on 100 g of SiO_2 in a 40-mm-diameter column. Elution with 7% ether/93% CH_2Cl_2 afforded 1.67 g of a slightly yellow oil. To remove the color, the material was distilled (Kugelrohr, 85–90 °C, 0.5 torr) to give 1.66 g (81%) of pure trans alcohol **11a**: $[\alpha]^{25}$ +66.3° (*c* 1.03, EtOH); ^1H NMR (300 MHz) δ 5.55–5.52 (X of ABX, apparent dd, 1 H, C_5H, J = 4.2, 0.9 Hz), 4.32–4.23 (m, 1 H, C_2H), 3.71–3.63 and 3.52–3.43 (2 m, 1 H each, CH_2OH coupled to C_2H and OH; simplify to dds, J = 6.0, 5.1 Hz, upon irradiation of C_2H at 4.27 ppm), 2.16–2.05 (m, 1 H, C_3H; simplifies upon irradiation of C_2H at 4.27 ppm), 2.02–1.96 (X of ABX, apparent t, OH, J = 6.3 Hz; simplifies upon irradiation of CH_2OH (either 3.65 or 3.47 ppm)), 1.95–1.80 (m, 2 H, C_4H_2; simplifies upon irradiation of C_5 at 5.33 ppm), 1.76–1.61 (m, 1 H, C_3H; simplifies upon irradiation of C_2H (4.27 ppm)), 0.884 (s, 9 H, $(CH_3)_3C$), 0.100 (s, 6 H, $(CH_3)_2Si$); ^{13}C NMR (20 MHz) 98.93 (d, C_5), 78.22 (d, C_2), 64.52 (t, CH_2OH), 34.64 (t, C_4), 25.51 (q, $(CH_3)_3C$), 24.66 (t, C_3), 17.63 (s, $(CH_3)_3C$), −4.53 and −5.38 (2 q, $(CH_3)_2Si$) ppm; IR *3500–3300*, *2950*, *2930*, 2890, *2860*, 1460, 1360, *1250*, 1195, 1170, *1110*, 1080, *1020* (br), 915, *835*, *780* cm^{-1}. Anal. Calcd for $C_{11}H_{24}O_3Si$: C, 56.85; H, 10.41; Si, 12.09. Found: C, 56.62; H, 10.50; Si, 12.30.

A similar procedure was utilized to prepare the cis diastereomer **11b** from the cis benzyl ether **9b** (126 mg, 0.391 mmol). After 4 days, TLC analysis revealed that reaction was complete [R_f cis benzyl ether **9b** 0.65; R_f cis alcohol **11b** 0.29 (50% ether/50% SSF; anis, PMA)], so the reaction mixture was vacuum filtered through 1 in. of Celite. The filter cake was washed with ether (10 mL), the filtrate concentrated in vacuo, and the crude product purified by LC on 10 g of SiO_2 in a 10-mm-diameter column. Elution with 50% ether/50% SSF afforded 84 mg (93%) of pure cis alcohol **11b**: R_f 0.35 (10% ether/90% CH_2Cl_2; anis, PMA); $[\alpha]^{25}$ −62.7° (*c* 1.2, EtOH); ^1H NMR (300 MHz) δ 5.47 (apparent d, 1 H, C_5H, J = 3.2 Hz), 4.33–4.25 (m, 1 H, C_2H), 3.81–3.75 and 3.53–3.44 (2 m, 1 H each, CH_2OH coupled to C_2H and OH; simplifies to an apparent d, J = 11.4 Hz, and an apparent t (br), J = 7.0 Hz, upon irradiation of C_2H at 4.3 ppm; simplifies to dds, J = 11.6, 2.5 Hz, and J = 11.9, 3.1 Hz, upon irradiation of OH at 2.75 ppm), 2.80–2.70 (m, 1 H, OH), 2.14–2.04 (m, 1 H, C_3H; simplifies upon irradiation of C_2H at 4.3 ppm), 2.0–1.8 (m, 3 H, C_3H and C_4H_2; simplifies upon irradiation of either C_5H at 5.47 ppm or C_2H at 4.3 ppm), 0.900 (s, 9 H, $(CH_3)_3C$), 0.132 and 0.120 (2 s, 3 H each, $(CH_3)_2Si$); ^{13}C NMR (20 MHz) 99.19 (d, C_5), 78.22 (d, C_2), 65.02 (t, CH_2OH), 34.99 (t, C_4), 25.73 (q, $(CH_3)_3C$), 24.87 (t, C_3), 17.91 (s, $(CH_3)_3C$), −4.31 and −5.12 (2 q, $(CH_3)_2Si$) ppm; IR 3500–3300, *2960*, *2930*, 2890, *2860*, 1463, 1360, *1255*, 1198, 1170, 1112, 1081, *1045*, *1025*, *1000* (br), 915, *838*, *778* cm^{-1}. Anal. Calcd for $C_{11}H_{24}O_3Si$: C, 56.85; H, 10.41; Si, 12.09. Found: C, 56.89; H, 10.60; Si, 12.12.

(2*S*,5*R*)- and (2*S*,5*S*)-Tetrahydro-5-[(*tert*-butyldimethylsilyl)oxy]-2-furancarboxaldehyde [12a (*trans*) and 12b (*cis*)]. The best procedure found to transform either alcohol to its corresponding aldehyde was the Swern oxidation.[8] Yields for the preparation of the cis aldehyde **12b** were generally higher (90–100%) than the trans aldehyde **12a** (70–81%). In this way, for example, 1.76 g (7.59 mmol) of the trans alcohol **11a** was converted into material which was chromatographed on 150 g of SiO_2 in a 40-mm-diameter column. Elution with 80% CH_2Cl_2/20% SSF afforded 1.22 g (70%) of pure trans aldehyde **12a**: R_f 0.2–0.3 (CH_2Cl_2; anis); $[\alpha]^{25}$ +46.4° (*c* 1.0, $CHCl_3$); ^1H NMR (300 MHz) δ 9.65 (d, 1 H, CHO, J = 1.2 Hz), 5.67 (app d, 1 H, C_5H, J = 4.1 Hz), 4.50–4.45 (apparent ddd, 1 H, C_2H, J = 9.5, 4.1, 1.2 Hz), 2.40–2.25, 2.05–1.95, and 1.93–1.72 (3 m, 1 H, 1 H, and 2 H, CH_2CH_2), 0.887 (s, 9 H, $(CH_3)_3C$), 0.123 and 0.113 (2 s, 3 H each, $(CH_3)_2Si$); ^{13}C NMR (20 MHz) 201.87 (d, CHO), 99.70 (d, C_5), 81.91 (d, C_2), 34.14 (t, C_4), 25.58 (q, $(CH_3)_3C$), 25.03 (t, C_3), 17.73 (s, $(CH_3)_3C$), −4.47 and −5.30 (2 q, $(CH_3)_2Si$) ppm; IR 3460 (br, weak), *2950*, *2930*, 2890, *2860*, *1740*, 1460, 1360, *1255*, 1110, *1030* (br), 1000, 980, 915, *835*, *775* cm^{-1}; MS (PCI, CH_4), m/z 231 (M + H), 215 (M − CH_3), 201 (M − CHO), 173 (M − *t*-Bu), 171, 99 (M − *t*-$BuMe_2SiO$); HRMS, m/z 231.1429 (M + H, calcd for $C_{11}H_{23}O_3Si$ 231.1416), 215.1122 (M − 15, calcd for $C_{10}H_{19}O_3Si$ 215.1104).

Upon standing neat, this aldehyde oligomerizes into a very viscous oil which is insoluble in MeOH (the solvent for the next reaction in the sequence), but soluble in most other less polar organic solvents (e.g., ether, $CHCl_3$, CH_2Cl_2). Dissolving the oligomer in CH_2Cl_2 or $CHCl_3$ allows it to equilibrate back into predominantly its monomeric state. Alternately, the aldehyde can be stored as a solution in, for example, CH_2Cl_2, to maintain its monomeric state. Since there is always some oligomer present with monomer, the optical rotations reported for both **12a** and **12b** should be regarded with caution.

^1H NMR of the oligomer from **12a** (300 MHz) δ 5.60–5.40 (br m, 1 H), 5.25–4.50 (v br m, 1 H) 4.25–4.05 (br m, 1 H), 2.20–1.70 (m, 4 H), 0.872 (br s, 9 H), 0.086 (br s, 6 H).

For the cis aldehyde: R_f 0.25–0.35 (CH_2Cl_2; anis); $[\alpha]^{25}$ −82.5° (*c* 1.8, $CHCl_3$); ^1H NMR (300 MHz) δ 9.68 (d, 1 H, CHO, J = 2.2 Hz), 5.59 (apparent dd, 1 H, C_5H, J = 2.4, 2.2 Hz), 4.29–4.23 (apparent dt, 1 H, C_2H, J = 8.0, 2.2 Hz), 2.18–2.09 and 1.92–1.85 (2 m, 2 H each, CH_2CH_2), 0.878 (s, 9 H, $(CH_3)_3C$), 0.123 (s, 6 H, $(CH_3)_2Si$); IR 3460 (br, weak), *2960*, *2940*, 2910, 2890, *2860*, *1740*, 1465, 1375, *1258*, 1100 (br), 1025, *995*, *840*, *780* cm^{-1}; MS (PCI, CH_4), m/z 230 (M + 1), 215 (M − CH_3), 201 (M − CHO), 173 (M − *t*-Bu), 171, 129 (*t*-$BuMe_2SiOH_2$), 99 (M − *t*-$BuMe_2SiOH$), HRMS, m/z 231.1407 (M + H, calcd for $C_{11}H_{23}O_3Si$ 231.1416), 173.0646 (M − *t*-Bu, calcd for $C_7H_{13}O_3Si$ 173.0634).

6-[(2′*S*,5′*R*)- and 6-[(2′*S*,5′*S*)-Tetrahydro-5′-[(*tert*-butyldimethylsilyl)oxy]-2′-furanyl]fulvene [10a (trans) and 10b (cis)]. Both of these compounds were prepared in the same fashion from their corresponding aldehyde precursors **12a** and **12b**, and in each case the desired product was accompanied by about 11% of its $C_{2'}$ epimerized diastereomer which was separated by LC. Alternately, the configurationally pure 2′*S* diastereomeric pairs of biscarbamates (**13a,b**) could be separated following the next reaction. Preliminary experiments indicated that the latter process would afford slightly higher (ca. 5%) yields for the two-step sequence, although the chromatographic separation after the Diels–Alder reaction is somewhat more difficult. The following is a representative example of the preparation of the cis fulvene **10b**.

To a solution of cis aldehyde **12b** (370 mg, 1.61 mmol) in MeOH (AR grade, 1.6 mL) were added cyclopentadiene (0.33 mL, 4.0 mmol) and pyrrolidine (freshly distilled under nitrogen, 0.67 mL, 8.0 mmol) via syringe. The solution turned yellow within a few minutes and then brown within an hour. After 42 h of stirring, acetic acid (0.48 mL, 8.4 mmol) was added and the reaction mixture was diluted with ether and water (10 mL each). The aqueous portion was washed with ether (2 × 5 mL), and the combined organic portions were then washed with water (2 × 10 mL) and brine (10 mL), dried over $MgSO_4$, and concentrated in vacuo. The dark brown oil (434 mg) was chromatographed on 40 g of SiO_2 in a 20-mm-diameter column. Elution with 5% ether/95% SSF afforded 192 mg (43%) of pure cis fulvene **10b** as a bright yellow oil: R_f 0.19 (5% ether/95% SSF; UV, anis); $[\alpha]^{26}$ −19.5° (*c* 0.92, $CHCl_3$); ^1H NMR (300 MHz) δ 6.54–6.52, 6.48–6.45, and 6.22–6.20 (3 m, 1 H, 2 H, and 1 H, C_1H–C_4H), 6.385 (d, 1 H, C_6H, J = 9.0 Hz), 5.526 (apparent d, 1 H, C_5H, J = 3.0 Hz), 5.05–4.95 (m, 1 H, $C_{2'}H$), 2.19–1.90 (m, 4 H, CH_2CH_2), 0.904 (s, 9 H, $(CH_3)_3C$), 0.123 and 0.111 (2 s, 3 H each, $(CH_3)_2Si$); IR 3080, *2955*, *2935*, *2860*, 1659, 1653, 1475, 1463, *1255*, 1190, 1150, 1100, 1020, *955*, 940, 895, *835*, *778*, *765*, *615* cm^{-1}; MS (PCI, CH_4), m/z 279 (M + H), 263 (M − CH_3), 221 (M − *t*-Bu), 201 (M − C_6H_6), 199, 171 (M − C_6H_6CHO), 147, 145, 129, 119, 103, 91, 75, 73; HRMS, m/z 279.1781 ((M + H), calcd for $C_{16}H_{27}O_2Si$ 279.1780).

Trans fulvene **10a**: R_f 0.25 (5% ether/95% SSF; UV, anis); $[\alpha]^{25}$ +68.4° (*c* 1.5, $CHCl_3$); ^1H NMR (300 MHz) δ 6.55–6.47, 6.48–6.45,

and 6.191 (2 m and dt, 2 H, 1 H, and 1 H, J = 5.4, 1.5 Hz (for dt), C_1–C_4), 6.281 (apparent d, 1 H, C_6H, J = 8.1 Hz), 5.615 (apparent dd, 1 H, C_5·H, J = 4.5, 1.5 Hz), 5.168 (apparent td, 1 H, C_2·H, J = 8.1, 6.3 Hz), 2.42–2.30, 2.15–2.03, 1.96–1.86, and 1.79–1.68 (4 m, 1 H each, CH_2CH_2), 0.900 (s, 9 H, $(CH_3)_3C$), 0.119 (s, 6 H, $(CH_3)_2Si$); IR 3080, *2960*, *2935*, *2860*, 1660, 1654, 1483, 1475, 1465, 1345, 1260, 1255, 1193, 1150, 1090, *1022*, 995, 980, 898, *840*, 780, *765*, 615 cm^{-1}; MS (PCI, CH_4), m/z 279 (M + H), 263 (M – CH_3), 221 (M – *t*-Bu), 201 (M – C_6H_6), 199, 171 (M – C_6H_6CHO), 147, 145, 129, 119, 103, 91, 75, 73; HRMS, m/z 279.1808 (M + H, calcd for $C_{16}H_{27}O_2Si$ 279.1780).

(2′*S*,5′*R*)- and (2′*S*,5′*S*)-*N*,*N*′-(Bis[(2,2,2-trichloroethoxy)carbonyl])-2,3-diaza-7-(tetrahydro-5′-[(*tert*-butyldimethylsilyl)oxy]-2′-furanylidene)bicyclo[2.2.1]hept-5-enes (13a and 13b). Both of these diastereomeric pairs of biscarbamates were prepared in the same fashion from their corresponding trans and cis fulvene precursors (**10a,b**, respectively). The following is a representative example starting from the cis fulvene.

To a solution of **10b** (186.5 mg, 0.670 mmol) in ether (1.2 mL) cooled in a 0 °C ice bath was added bis(2,2,2-trichloroethyl) azodicarboxylate[10] (255 mg, 0.670 mmol) via a powder funnel under a stream of N_2. The funnel was rinsed with 1 mL of ether. The reaction became homogeneous after about 5 min. After 1 h at 0 °C, the reaction mixture was concentrated in vacuo to afford 426.5 mg of a viscous yellow oil which may foam under reduced pressure. This material was used directly in the next step of the reaction sequence (hydrogenation) but can be purified by LC. The diastereomeric cis products **13b** are formed in about a 1:1 ratio as determined by ^1H NMR: R_f 0.26 (30% ether/70% SSF; anis); ^1H NMR (300 MHz) δ 6.90–6.70 (m, 2 H, C_5HC_6H), 5.45–5.40 (m, 1 H, C_5·H, simplifies to apparent d upon irradiation of m at 1.95 or 1.86 ppm), 5.12–5.07 (2 d, overlapping, 1 H, C_7=CH of each diastereomer, J = 8.1, 7.8 Hz; simplifies to 2 s (5.10 and 5.83 ppm) upon irradiation of C_2·H at 4.5 ppm), 4.95–4.70 (m, 6 H, C_1H, C_4H, and $2CH_2CCl_3$), 4.55–4.45 (m, 1 H, C_2·H; simplifies upon irradiation of C_7=CH at 5.1 ppm or m at 1.86 ppm), 2.03–1.90 (m, 1 H, C_4·H), 1.90–1.70 (m, 3 H, C_4·H and C_3·H_2), 0.869 and 0.865 (2 s, 9H, $(CH_3)_3C$ of each diastereomer), 0.070 and 0.053 (2 s, 6 H, $(CH_3)_2Si$ of each diastereomer); IR *2950* (br), 2890, *2860*, *1800–1720*, 1440, *1380*, *1330–1180*, *1130–1100*, *1050–990*, 935, 900, *850–750*, *720* (br) cm^{-1}.

For the trans isomers **13a**: R_f 0.31 (30% ether/70% SSF; anis); ^1H NMR (300 MHz) δ 6.90–6.70 (m, 2 H, C_5HC_6H), 5.54 and 5.50 (2 apparent d, 1 H, C_5·H of each diastereomer, J = 4.5 Hz for both), 5.01 and 4.99 (br s and apparent d, 1 H, C_7=CH of each diastereomer, J = 3.9 Hz), 4.95–4.65 (m, 7 H, C_1H, C_4H, C_2·H, and $2CH_2CCl_3$), 2.25–2.13, 2.05–1.87, 1.86–1.75, and 1.55–1.40 (4 m, 1 H each, CH_2CH_2), 0.884 (s, 9 H, $(CH_3)_3C$), 0.102 (s, 6 H, $(CH_3)_2Si$ of one diastereomer), 0.094 and 0.091 (2 s, 3 H each, $(CH_3)_2Si$ of other diastereomer); IR *2960*, *2930*, 2910, 2890, *2860*, *1780–1720*, 1465, 1440, *1380* (br), *1340–1260*, 1185, *1120* (br), 1050–1020, 990, 900, 840, 780, 715 cm^{-1}.

(2′*S*,5′*R*)- and (2′*S*,5′*S*)-*N*,*N*′-(Bis[(2,2,2-trichloroethoxy)carbonyl])-2,3-diaza-7-[tetrahydro-5′-(*tert*-butyldimethylsilyloxy)-2′-furanylidene] bicyclo[2.2.1]heptanes (14a and 14b). To a solution of the crude cis Diels–Alder adducts **13b** (426.5 mg, 0.647 mmol) dissolved in 2.6 mL of CH_2Cl_2 was added dipotassium azodicarboxylate[11] (650 mg, 3.85 mmol). The solution was cooled in an ice-water bath (6–10 °C), and a solution of acetic acid (0.42 mL, 7.4 mmol) in 0.69 mL of CH_2Cl_2 was added dropwise over 12 min. After it was stirred an additional hour, the reaction mixture was vacuum filtered through a medium glass frit. The filter cake was rinsed with ether (3 × 10 mL) and the filtrate was concentrated in vacuo to afford 400 mg of a slightly yellow foam. Pure **14b** (354 mg, 80% from fulvene **10b**) was obtained by LC on 40 g of SiO_2 in a 20-mm-diameter column, eluting with 40% ether/60% SSF: R_f 0.32 (40% ether/60% SSF; anis); ^1H NMR (300 MHz) δ 5.54–5.47 (2 d, overlapping, 1 H, C_2·HC*H* of each diastereomer, J = 9.0, 9.6 Hz), 5.47–5.40 (m, 1 H, C_5·H), 5.1–4.6 (m, 6 H, C_1H, C_4H, and $2CH_2CCl_3$), 4.60–4.50 (m, 1H, C_7=CH), 2.20–1.70 (m, 8 H, $C_5H_2C_6H_2$ and C_3·H_2C_4·H_2), 0.879 and 0.877 (2 s, 9 H, $(CH_3)_3C$ of each diastereomer), 0.079 (s, 6 H, $(CH_3)_2Si$); IR *2955*, *2930*, *2860*, *1770–1720*, 1470–1440, *1390* (br), *1315* (br), *1250* (br), *1190* (br), *1120* (br), *1050* (br), *990*, 940, 840, 775, 715 cm^{-1}, *MS* (NCI, CH_4) m/z 664, 663, *662*, 661, *660*, 658 (M, 1.3:1:2.6:1.3:3.7:1.6, Cl isotopes), *529*, *527* (M – CH_2CCl_3), *379*, *381*, *383* [(=$NCO_2CH_2CCl_3)_2$], 265 [M – (=$NCO_2CH_2CCl_3)_2$ and CH_3], 231, 206, 204, 173; HRMS, m/z 658.0157 (calcd for $C_{22}H_{32}O_6N_2Si^{35}Cl_6$ 658.0161).

In a separate reaction, a sample of purified trans Diels–Alder adducts **13a** (1.08 g, 1.64 mmol) was hydrogenated in the same manner to afford 930 mg (86%) of the diastereomers **14a** after LC (50 g of SiO_2, 20-mm-diameter column, 20% ether/80% SSF): R_f 0.20 (20% ether/80% SSF; anis); ^1H NMR (300 MHz) δ 5.56–5.54 (2 apparent dd, 1 H, C_5·H of each diastereomer, J = 4.2, 0.6 Hz; J = 4.5, 1.2 Hz), 5.44 and 5.40 (2 d, 1 H, C_7=CH of each diastereomer, J = 6.3 and 8.4 Hz), 5.20–4.60 (m, 7 H, C_1H, C_4H, C_2·H, and $2CH_2CCl_3$), 2.28–1.95, 1.95–1.77, and 1.58–1.47 (3 m, 1 H, 6 H, and 1 H, $C_5H_2C_6H_2$ and C_3·H_2C_4·H_2), 0.885 (s, 9 H, $(CH_3)_3C$), 0.098 (s, 6 H, $(CH_3)_2Si$); IR *2960*, *2935*, 2890, *2865*, *1770–1725*, 1465, 1455, 1440, *1385* (br), *1340–1280*, *1250* (br), 1180, *1150–1120*, 1050, 1020, 940, 900, 840, 780, 720 cm^{-1}. Anal. Calcd for $C_{22}H_{32}N_2O_6SiCl_6$: C, 39.95; H, 4.88; N, 4.24; Si, 4.25; Cl, 32.16. Found: C, 39.80; H, 4.97; N, 4.67; Cl, 32.37.

(2′*S*)-*N*,*N*′-(Bis[(2,2,2-trichloroethoxy)carbonyl])-2,3-diaza-7-(tetrahydro-5′-hydroxy-2′-furanylidene)bicyclo[2.2.1]heptanes (7). Four diastereomeric lactols, each possessing the *S* configuration at $C_{2'}$, were formed in about a 1:1:1:1 ratio starting from either the cis (**14b**) or trans (**14a**) silylated precursor, in yields ranging from 73% to 84%. By LC on SiO_2, these diastereomers could be separated into two pairs giving similar ^1H NMR, IR, and MS. In general, these pairs were not separated but carried on together in the next reaction. The following is a representative example, starting from the trans silylated precursor **14a**.

To a solution of **14a** (1.05 g, 1.59 mmol) in 12 mL of THF was added 1.5 mol equiv of fluoride as a 1:1 mixture of hydrofluoric acid (HF) and tetra-*n*-butylammonium fluoride (TBAF) [2 mL, 2.4 mmol of a 1.2 M solution of F^-, prepared from 0.35 mL of 1.0 M TBAF in THF (Aldrich) and 0.25 mL of 1.4 M HF in THF (prepared from 0.5 mL of 47% HF and 9.5 mL of THF)]. The reaction mixture was stirred at room temperature for 4.5 h, diluted with ether (25 mL), and extracted with half-saturated brine (2 × 25 mL). The organic portion was dried over $MgSO_4$ and concentrated in vacuo to afford 957 mg of a brown foam. This was chromatographed on 60 g of SiO_2 in a 20-mm-diameter column. Elution with 80% ether/20% SSF afforded 706 mg (81%) of the desired lactols **7**.

Spectral data for the pair of lactols with R_f 0.28 (80% ether/20% SSF, anis): ^1H NMR (300 MHz) δ 5.61–5.59 and 5.53–5.47 (2 m, 1 H, C_5·H of each diastereomer), 5.56 and 5.44 (2 d, 1 H, C_7=CH of each diastereomer, J = 6.9, 7.2 Hz), 5.20–4.50 (m, 7 H, C_1H, C_4H, C_2·H, and $2CH_2CCl_3$), 2.50 (br s, 1 H, OH, chemical shift concentration dependent), 2.30–1.50 (m, 8 H, $C_5H_2C_6H_2$ and C_3·H_2C_4·H_2); IR 3500–3400, *2960* (br), 2860 (br), *1770–1720*, 1440, *1390*, *1320* (br), *1248*, 1188, 1150, *1130* (br), *1050* (br), 1015, 980, 935, 842, 815, *790*, *760*, *720* cm^{-1}; MS (NCI, CH_4), m/z 585, 583, 581 (M + Cl), 550, 549, 548, 547, 546, 545, 544 (M), 454, 452, 415, 413 (M – CH_2CCl_3), 398, 396 (M – $HOCH_2CCl_3$), 382, 380, 378 [(=$NCO_2CH_2CCl_3)_2$], 371, 369, 349, 347, 345, 266, 265 [M – (CH_2CCl_3 + $HOCH_2CCl_3$)] 233, 231, 197, 193 [M – ($CO_2CH_2CCl_3)_2$].

Spectral data for the pair of lactols with R_f 0.22 (80% ether/20% SSF, anis): ^1H NMR (300 MHz) δ 5.61–5.59 and 5.53–5.47 (2 m, 1 H, C_5·H of each diastereomer), 5.52–5.50 and 5.41 (m and d, 1 H, C_7=CH of each diastereomer, J = 8.1 Hz), 5.20–4.50 (m, 7 H, C_1H, C_4H, C_2·H, and $2CH_2CCl_3$), 2.50 (m, 1 H, OH, chemical shift concentration dependent), 2.30–1.50 (m, 8 H, $C_5H_2C_6H_2$ and C_3·H_2C_4·H_2); IR 3500–3400, *2960* (br), 2930, 2860, *1770–1720*, 1440, *1390*, *1320* (br), *1248*, 1188, 1150, *1130* (br), *1050* (br), 980, 940, 842, 818, *792*, *787*, 768, 760, *720* cm^{-1}; MS (NCI, CH_4), m/z 585, 583, 581 (M + Cl), 550, 549, 548, 547, 546, 545, *544* (M, M – 1), 454, 452, 415, 413 (M – CH_2CCl_3), 398, 396 (M – $HOCH_2CCl_3$), 382, 380, 378 [(=NCO_2C-$H_2CCl_3)_2$], 371, 369, 349, 347, 345, 266, 265 [M – (CH_2CCl_3 + $HOCH_2CCl_3$)], 233, 231, 197, 193 [M – ($CO_2CH_2CCl_3)_2$].

(1*S*,4*R*,2′*S*)- and (1*R*,4*S*,2′*S*)-*N*,*N*′-(Bis[(2,2,2-trichloroethoxy)carbonyl])-2,3-diaza-7-[(*Z* and *E*)-6′-carbomethoxy-2′-hydroxyhex-5-enylidene]bicyclo[2.2.1]heptanes (15a–d). A solution of lactols **7** (419 mg, 0.766 mmol) and methyl (triphenylphosphoranylidene)acetate (384 mg, 1.15 mmol) in a 5 mL of CH_3CN was heated to reflux for 20 h. Concentration in vacuo afforded a yellow oil and a white precipitate which was diluted with 70% ether/30% SSF (10 mL) and stirred several minutes, and then the solution was separated from the precipitate by pipet. This was repeated 4 times and then the combined liquid portions were concentrated in vacuo. The four diastereomeric products were obtained by LC on 60 g of SiO_2 in a 20-mm-diameter column. Elution with 70% ether/30% SSF afforded two *Z* olefins (**15c**, R_f 0.32, 34.0 mg, and **15d**, R_f 0.22, 34.5 mg) and two *E* olefins (**15a**, R_f 0.28, 178 mg, and **15b**, R_f 0.18, 157.5 mg) in a total yield of 87.5% (TLC: 80% ether/20% SSF; UV, anis).

Spectral data for **15c**: ^1H NMR (300 MHz) δ 6.28–6.18 (m, 1 H, C_5·H), 5.86 (d, 1 H, C_6·H, J = 11.4 Hz), 5.64 (d, 1 H, C_1·H, J = 6.9 Hz), 5.25–4.40 (m, 6 H, C_1H, C_4H, and $2CH_2CCl_3$), 4.30–4.20 (m, 1 H, C_2·H), 3.72 (s, 3 H, CO_2CH_3), 2.40–1.50 (m, 8 H, $C_5H_2C_6H_2$ and C_3·H_2C_4·H_2).

Spectral data for **15d**: ^1H NMR (300 MHz) δ 6.29–6.19 (m, 1 H, C_5·H), 5.90 (d, 1 H, C_6·H, J = 11.4 Hz), 5.45 (d, 1 H, C_1·H, J = 5.7 Hz), 5.30–4.50 (m, 6 H, C_1H, C_4H, and $2CH_2CCl_3$), 4.40–4.20 (m, 1 H, C_2·H), 3.74 (s, 3 H, CO_2CH_3), 2.40–1.50 (m, 8 H, $C_5H_2C_6H_2$ and C_3·H_2C_4·H_2).

Spectral data for **15a**: ^{1}H NMR (300 MHz) δ 6.94 (dt, 1 H, $C_{5'}H$, J = 15.6, 6.9 Hz), 5.84 (d, 1 H, $C_{6'}H$, J = 15.6 Hz), 5.45 (d, 1 H, $C_{1'}H$, J = 7.5 Hz), 5.20–4.50 (m, 6 H, C_1H, C_4H, and $2CH_2CCl_3$), 4.35–4.23 (m, 1 H, $C_{2'}H$), 3.73 (s, 3 H, CO_2CH_3), 2.40–1.50 (m, 8 H, $C_5H_2C_6H_2$ and $C_{3'}H_2C_{4'}H_2$); IR *3520–3450*, *2960*, 2920, 2875, 2840, *1770–1705*, 1665, 1640, *1440*, *1385* (br), *1340–1260*, *1240* (br), 1180, *1125* (br), *1045* (br), 835, 805, 785, 750, *710* (br) cm^{-1}; MS (NCI, CH_4), m/z 641, 639, 637, 635 (M + Cl), 605, 604, 603, 602 (M, M − 1), 474, 473, 472, *471*, 470, *469* (M − CH_2CCl_3), 384, *382*, *380*, *378* [(=$NCO_2CH_2CCl_3)_2$], *321* [M − (CH_2CCl_3 + $HOCH_2CCl_3$)], 277, 275, 273, 262, *249*, 235, *233*, *231*, 199, *197*; HRMS (NCI, CH_4), m/z 598.9480 (calcd for $C_{19}H_{21}O_7N_2Cl_6$ (M − 1) 598.9479).

Spectral data for **15b**: ^{1}H NMR (300 MHz) δ 6.93 (dt, 1 H, $C_{5'}H$, J = 15.6, 6.9 Hz), 5.85 (d, 1 H, $C_{6'}H$, J = 15.6 Hz), 5.43 (br d, 1 H, $C_{1'}H$, J_{app} = 5.7 Hz), 5.30–4.50 (m, 6 H, C_1H, C_4H, and $2CH_2CCl_3$), 4.36–4.20 (m, 1 H, $C_{2'}H$), 3.73 (s, 3 H, CO_2CH_3), 2.40–1.50 (m, 8 H, $C_5H_2C_6H_2$ and $C_{3'}H_2C_{4'}H_2$); IR 3540–3400, *2960*, 2935, 2860, *1770–1715*, 1660, *1441*, *1438*, *1390* (br), *1320* (br), *1285*, *1245*, 1185, 1150, *1130* (br), *1050* (br), 845 (br), 815 (br), *790*, *760*, *720*; *MS* (NCI, CH_4), m/z 643, 641, *639*, 637, 635 (M + Cl), 605, 604, 603, 602, 601, 600 (M, M − 1), 474, 473, 472, *471*, 470, *469* (M − CH_2CCl_3), 427, 425, 384, *382*, *380*, 378 [(=$NCO_2CH_2CCl_3)_2$], 349, 347, 345, 322, *321* [M − (CH_2CCl_3 + $HOCH_2CCl_3$)], 298, 277, *275*, *273*, 262, *249*, 248, 235, *233*, *231*, 218, *199*, *197*; *HRMS* (NCI, CH_4), m/z 599.9534 (calcd for $C_{19}H_{22}N_2O_7Cl_6$ 599.9558).

(1*S*,4*R*,2′*S*)- and (1*R*,4*S*,2′*S*)-*N*,*N*′-(Bis[(2,2,2-trichloroethoxy)-carbonyl])-2,3-diaza-7-((*E*)-6′-carbomethoxy-2′-[(*tert*-butyldimethylsilyl)oxy]hex-5′-enylidene)bicyclo[2.2.1]heptanes (16a,b). Both of these silylated *E* olefins possess the 2′*S* configuration, although the absolute configuration of C_1 and C_4 relative to **15a**,**b** is uncertain. The alcohols and corresponding silylated compounds are distinguishable by their TLC and spectroscopic properties. With regard to compound numbering, alcohol **15a** gives silylated compound **16a**, and, likewise, **15b** gives **16b**. Both silyl ethers were made under the same conditions; the following is a representative example for the preparation of **16b**.

To a flask containing alcohol **15b** (119 mg, 0.197 mmol) was added tert-butyldimethylsilyl chloride (44.6 mg, 0.296 mmol) in a N_2 glovebox. The flask was removed from the glovebox, and under a stream of N_2 were added imidazole (40.3 mg, 0.592 mmol) and dry DMF (0.5 mL). The reaction mixture, which became homogeneous after a few minutes, was stirred for a total of 1.5 h, diluted with ether (5 mL), and poured into water (10 mL). The aqueous portion was washed with ether (5 mL), and then the combined organic portions were washed with 0.5 M HCl, saturated $NaHCO_3$, water, and brine. Drying over $MgSO_4$ and concentration in vacuo afforded 161 mg of a colorless oil which was subjected to LC on 10 g of SiO_2 in a 10-mm-diameter column. Elution with 35% ether/65% SSF afforded 115 mg (82%) of pure **16b**: R_f 0.30 (35% ether/65% SSF; UV, anis); $[\alpha]^{25}$ +15.1° (*c* 2.7, $CHCl_3$); ^{1}H NMR (300 MHz) δ 6.93 (dt, 1 H, $C_{5'}H$, J = 15.6, 7.0 Hz), 5.83 (dt, 1 H, $C_{6'}H$, J = 15.6, 1.5 Hz), 5.41 (d, 1 H, $C_{1'}H$, J = 7.8 Hz), 5.20–4.45 (m, 6 H, C_1H, C_4H, $2CH_2CCl_3$), 4.30–4.20 (m, 1 H, $C_{2'}H$), 3.72 (s, 3 H, CO_2CH_3), 2.28–1.50 (m, 8 H, $C_5H_2C_6H_2$ and $C_{3'}H_2C_{4'}H_2$), 0.878 (s, 9 H, $(CH_3)_3C$), 0.042 and 0.007 (2s, 3 H each, $(CH_3)_2Si$); IR *2960* (br), *2940*, 2895, *2860*, *1780–1715*, 1660, 1465, 1440, *1390* (br), *1340–1300*, *1280–1240*, 1185, *1150–1120* (br), *1090*, *1055* (br), 1010, 980, 940, *840* (br), 815, *780* (br), *720* (br), 665 cm^{-1}; MS (NCI, CH_4), m/z 718 (M), 588, *587*, 586, *585*, 584, *583* (M − CH_2CCl_3), 543, 542, *541*, 540, *539* (M − $CO_2CH_2CCl_3$), 443, 436, *435* [M − (CH_2CCl_3 + $HOCH_2CCl_3$)], 384, *382*, *380*, 378 [(=$NCO_2CH_2CCl_3)_2$], 303, 233, 231; HRMS (NCI, CH_4), m/z 583.1190 (calcd for $C_{23}H_{34}N_2O_7SiCl_3$ (M − CH_2CCl_3) 583.1200).

Spectral data for **16a**: R_f 0.20 (35% ether/65% SSF; UV, anis); ^{1}H NMR (300 MHz) δ 6.92 (dt, 1 H, $C_{5'}H$, J = 15.6, 6.9 Hz), 5.80 (d, 1 H, $C_{6'}H$, J = 15.6 Hz), 5.42 (br d, 1 H, $C_{1'}H$, J_{app} = 6.6 Hz), 5.25–4.45 (m, 6 H, C_1H, C_4H and $2CH_2CCl_3$), 4.40–4.25 (m, 1 H, $C_{2'}H$), 3.72 (s, 3 H, CO_2CH_3), 2.30–1.50 (m, 8 H, $C_5H_2C_6H_2$ and $C_{3'}H_2C_{4'}H_2$), 0.875 (s, 9 H, $(CH_3)_3C$), 0.051 and −0.014 (2 s, 3 H each, $(CH_3)_2Si$); IR *2960*, *2940*, 2895, *2860*, *1780–1710*, 1660, 1475, 1465, 1455, *1390* (br), *1340–1300*, *1285–1240*, 1185, *1155–1120*, *1090* (br), *1060* (br), 1010, 980 (br), 940, 885, *840* (br), 815, *790–760*, *720* (br), 680 cm^{-1}; MS (NCI, CH_4), m/z 587, 586, *585*, 584, *583* (M − CH_2CCl_3), 541, 539 (M − $CO_2CH_2CCl_3$), 505, *436*, *435* [M − (CH_2CCl_3 + $HOCH_2CCl_3$)], 410, *409* [M − ($CO_2CH_2CCl_3$, *t*-$BuMe_2Si$, CH_3)] 384, 382, 380, 378 [(=N-$CO_2CH_2CCl_3)_2$], 303, 233, 231; HRMS (NCI, CH_4), m/z 583.1217 (calcd for $C_{23}H_{34}N_2O_7SiCl_3$ (M − CH_2CCl_3) 583.1200), 435.1953 [calcd for $C_{21}H_{31}N_2O_6Si$ (M − (CH_2Cl_3 + $HOCH_2CCl_3$)) 435.1951].

(1*R*,4*S*,2′*S*)- and (1*S*,4*R*,2′*S*)-2,3-Diaza-7-((*E*)-6-carbomethoxy-2′-[(*tert*-butyldimethylsilyl)oxy]hex-5-enylidene)bicyclo[2.2.1]hept-2-enes (2a,b). Both diazenes were prepared in the same fashion from their corresponding bis(carbamate) precursors **16a**,**b**. Combined yields for the two reactions [Zn(Cu) reduction and Fe(III) oxidation] varied from 56% to 69% after chromatography. It should be noted that although the crude product from these reactions was usually a colorless oil formed in an apparent quantitative yield, LC was necessary to obtain pure azo. Evidently, there are some inorganic byproducts in the crude product, since the ^{1}H NMR (300 MHz) of the crude material is essentially indistinguishable from that of the purified material. Analysis by TLC, however, does reveal that something in the crude product remains on the base line after elution. This is not a decomposition product of the azo since it is not seen following LC.

Reduction. To a solution of the bis(carbamate) **16a** (96 mg, 0.134 mmol) in methanol (0.3 mL) was added Zn (Cu) (103 mg, 1.6 mmol). The heterogeneous mixture was heated to reflux in a 70 °C oil bath for 1.5 h and then vacuum filtered through a Buchner funnel. The solid was rinsed with methanol (3 × 0.5 mL) and ether (2 × 0.5 mL).

Oxidation. The filtrate was cooled in a 0 °C ice bath, and to it was added an aqueous solution of potassium ferricyanide (132 mg, 0.40 mmol, in 0.35 mL of water) via pipet. The bright yellow suspension, which formed immediately, was stirred vigorously at 0 °C for 15 min and then diluted with water (15 mL) and ether (25 mL). The organic portion was washed with water (4 × 15 mL) and brine (1 × 15 mL). The large amount of yellow-white foam that was present between the two layers was allowed to settle 10 min before draining off the aqueous portion after each extraction. The combined aqueous portions were washed with ether (1 × 15 mL). This organic extract, combined with the previous organic material, and dried over $MgSO_4$. Concentration in vacuo afforded 48 mg of a colorless oil which was purified by LC on 7 g of SiO_2 in a 10-mm-diameter column. Elution with 50% ether/50% SSF afforded 33.5 mg (69%) of diazene **2a**: R_f 0.25 [50% ether/50% SSF; UV, anis (distinctive green-brown color after staining with anis)]; ^{1}H NMR (300 MHz) δ 6.92 (dt, 1 H, $C_{5'}H$, J = 15.6, 6.9 Hz), 5.80 (d, 1 H, $C_{6'}H$, J = 15.6 Hz), 5.40 (br s, 1 H, C_1H), 5.13–5.10 (m, 2 H, C_4H and $C_{1'}H$), 4.15 (app q, 1 H, $C_{2'}H$, J = 6.5 Hz), 3.72 (s, 3 H, CO_2CH_3), 2.28–2.08 (m, 2 H, $C_{4'}H_2$), 1.72–1.44 (m, 4 H, $C_{3'}H_2$ and $C_5H_{exo}C_6H_{exo}$), 1.20–1.10 (m, 2 H, $C_5H_{endo}C_6H_{endo}$; app d at 1.14, J = 8.1 Hz), 0.848 (s, 9 H, $(CH_3)_3C$), 0.009 and −0.067 (2 s, 3 H each, $(CH_3)_2Si$); IR 3020, *2965–2930*, *2860*, *1730*, *1660*, 1465, *1440*, 1390, 1360, 1320 (br), *1285–1250*, 1208, 1170, *1100–1075*, 1010, 980 (br), 940, 900, *840* (br), 780, 710, 680 cm^{-1}.

Spectral data for **2b**: R_f 0.30 [50% ether/50% SSF; UV, anis (distinctive green-brown color after staining with anis)]; ^{1}H NMR (300 MHz) δ 6.93 (dt, 1 H, $C_{5'}H$, J = 15.6, 6.9 Hz), 5.81 (dt, 1 H, $C_{6'}H$, J = 15.6, 1.5 Hz), 5.42 (br s, 1 H, C_1H), 5.14 (d, 1 H, $C_{1'}H$, J = 7.5 Hz), 5.13 (br s, 1 H, C_4H), 4.14 (app q, 1 H, $C_{2'}H$, J = 6.5 Hz), 3.73 (s, 3 H, CO_2CH_3), 2.20–2.10 (m, 2 H, $C_{4'}H_2$), 1.75–1.45 (m, 4 H, $C_{3'}H_2$ and $C_5H_{exo}C_6H_{exo}$), 1.20–1.10 (m, 2 H, $C_5H_{endo}C_6H_{endo}$; app d at 1.15, J = 8.5 Hz), 0.877 (s, 9 H, $(CH_3)_3C$), 0.033 and −0.009 (2 s, 3 H each, $(CH_3)_2Si$); IR 3020, *2960–2930*, *2860*, *1725*, *1660*, 1472, 1465, *1440*, 1390, *1280–1250*, 1205, 1107, 1135, *1090* (br), 1050, 1005, 978, 970, 940, 895, *840* (br), *775*, 710, 672 cm^{-1}.

(1*R*,6*R*,7*R*,8*S*,11*S*)-, (1*R*,6*S*,7*R*,8*S*,11*S*)-, and (1*S*,6*S*,7*S*,8*R*,11*S*)-11-[(*tert*-Butyldimethylsilyl)oxy]-7-carbomethoxytricyclo[6.3.0.0^{2,6}]undec-2-ene (4, 5, and 3). The linearly fused tricyclopentanoids **3–5** are formed as the major products (>80%) upon either thermally or photochemically initiated extrusion of nitrogen from either diazene **2a** or **2b** as discussed in the text. Since the diazenes are slowly converted into the tricyclopentanoids over time, even when stored at −6 °C (e.g., a sample of pure **2b**, after 14 days in a freezer, contained ca. 15% of **3–5**), it is imperative to carry out each reaction with a sample of pure diazene in order to obtain an accurate product distribution. The diazenes can be easily separated from the tricyclopentanoids by LC (see preparation of diazenes **2a**,**b** for conditions). All reactions were allowed to proceed at the indicated temperature until the diazene could no longer be detected by TLC. Product ratios were determined by taking the statistical average of at least three GC injections. Good separation of the peaks was achieved by using either column A or C at 200 °C (isothermal runs). The injection temperature was 200 °C and the detector temperature 240 °C. Retention times were 48.8, 49.8, and 51.1 min on column A and 21.3, 22.0, and 22.6 min on column B for the tricyclopentanoids **3–5**, respectively. For the thermally initiated reactions, reagent grade acetonitrile was used without purification. For the photochemically initiated reactions, N_2 was bubbled through spectral grade acetonitrile for at least 5 min prior to addition of the diazene and photolysis. For the reactions carried out at 81 °C, a 0.01 M solution of diazene was submersed in an oil bath preheated to 85 °C and stirred at reflux for 2.5 h. For the reactions run at 66 and 50 °C, the temperature was controlled (±0.1 °C) by utilizing a B. Braun Melsungen AG Frigomix/Thermomix 148 constant-temperature bath.

The 66 °C reaction required 7 h while the 50 °C thermally initiated reaction required 40 h. All of the photochemically initiated reactions

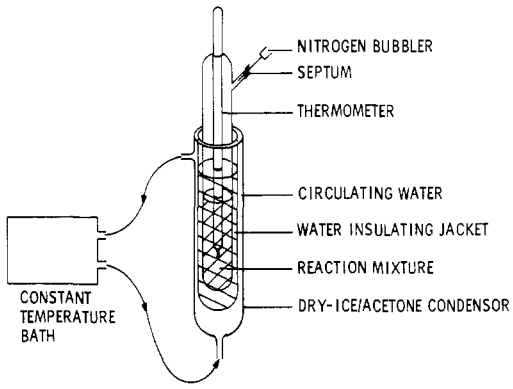


Figure 3. Reaction apparatus for pyrolysis at 66 and 50 °C, as well as for the photolysis at 50 °C. For the photolysis, the 450-W Hanovia lamp was placed in an immersion well.

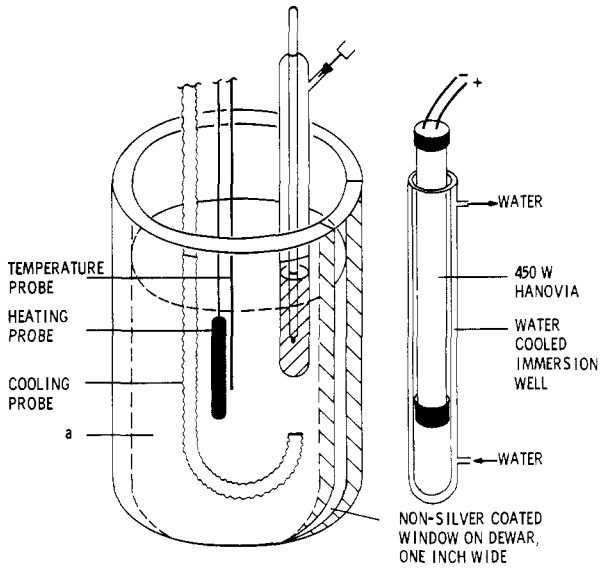


Figure 4. Reaction apparatus for photolysis at 7, −2, and −31 °C. The Dewar was filled with either an ice slurry (7 and −2 °C reactions) or acetonitrile (−31 °C reaction).

required 2.5 h of irradiation in the apparatus shown in Figure 3 (for 50 °C reaction) or Figure 4 (for 7, −2, and −31 °C reactions). In each case, the lamp was approximately 3 in. from the diazene solution. For the reactions run at 7 and −2 °C, the temperature was maintained (±1 °C) by filling the Dewar flask with an ice–water slurry and a brine–ice slurry, respectively. For the reaction run at −31 °C (±1 °C), the temperature was controlled utilizing a Neslab Exatrol and Cryocool immersion cooler CC-100 with the heating and cooling probes submersed in the acetonitrile filled Dewar (Figure 4).

In a preparative reaction, a solution of diazene **2a** (33.5 mg, 0.919 mmol) in acetonitrile (9.2 mL) was refluxed for 2.5 h. The solvent was removed in vacuo to afford 29.5 mg of an oil. Analysis by GC (column A) revealed that the tricyclopentanoids **3–5** had formed in a ratio of 1.15:13.6:1, respectively. The crude product was subjected to LC on 8 g of SiO_2 in a 7-mm-diameter column. Elution with 3% ether/97% SSF afforded 1.5 mg of a mixture of **3** and **5** [1:14.6, respectively, R_f for **5** 0.22 (5% ether/95% SSF; anis), 2.0 mg of a mixture of **3**, **4**, and **5** [2.16:2.76:1, respectively, R_f 0.20 (**3**) and 0.19 (**4**)], and 23.0 mg of a mixture of **3** and **4** (1:14.7), for a combined yield of 86% of tricyclopentanoids.

Spectral data for the major cis, anti tricyclopentanoid **4**: ^{1}H NMR (300 MHz) δ 5.39 (br s, 1 H, C_3H), 3.96 (app q, 1 H, $C_{11}H$, J = 4.5 Hz; simplifies upon irradiation of C_1H at 2.9 ppm), 3.62 (s, 3 H, CO_2CH_3), 3.35–3.25 (m, 1 H, C_6H; simplifies upon irradiation of C_3H at 5.4 ppm and C_7H at 2.65), 3.25–3.15 (m, 1 H, C_8H; simplifies upon irradiation of C_1H at 2.9 ppm, C_9H at 2.1 ppm and C_9H at 1.3 ppm), 2.95–2.90 (m, 1 H, C_1H; simplifies upon irradiation of $C_{11}H$ at 3.95 ppm and C_8H at 3.2 ppm), 2.65 (apparent d, 1 H, C_7H, J = 8.7 Hz; simplifies to a br s upon irradiation of C_6H at 3.3 ppm), 2.60–2.45 (m, 2 H, C_4H_2; simplifies upon irradiation of C_3H at 5.4 ppm, C_1H at 2.9 ppm and C_5H at 2.0 ppm), 2.18–2.06 (m, 1 H, C_9H; simplifies upon irradiation of C_8H at 3.2 ppm, $C_{10}H_2$ at 1.6 ppm and C_9H at 1.3 ppm), 2.06–1.94 (m, 1 H, C_5H; simplifies upon irradiation of C_6H at 3.3 ppm, C_4H_2 at 2.5 ppm and C_5H at 1.3 ppm), 1.72–1.50 (m, 2 H, $C_{10}H_2$; simplifies upon irradiation of $C_{11}H$ at 3.96, C_9H at 2.1 ppm and C_9H at 1.3 ppm), 1.37–1.18 (m, 2 H, C_5H and C_9H; simplifies upon irradiation of C_6H at 3.3 ppm, C_8H at 3.2 ppm, C_9H at 2.1 ppm, C_5H at 2.0 ppm and $C_{10}H_2$ at 1.6 ppm), 0.877 (s, 9 H, $(CH_3)_3C$), 0.055 and 0.034 (2 s, 3 H each, $(CH_3)_2Si$).

Nuclear Overhauser enhancement difference spectroscopy (NOEDS) on tricyclopentanoid **4** gave the following results: presaturation of C_1H at 2.92 ppm resulted in no NOE on $C_{11}H$; presaturation of C_8H at 3.2 ppm resulted in no NOE on $C_{11}H$; presaturation of $C_{11}H$ at 3.96 ppm resulted in 2% NOE on C_1H and no NOE on C_8H.

^{13}C NMR (75 MHz) 175.2 (s, CO_2), 152.71 (s, C_2), 120.08 (d, C_3), 80.18 (d, C_{11}), 77 (CO_2CH_3, under $CDCl_3$ resonance), 53.34, 52.24, 51.01 and 50.57 (4 d, C_1, C_6, C_7, and C_8), 37.37, 36.36, 30.57, and 27.93 (4 t, C_4, C_5, C_9, and C_{10}), 25.87 (q, $(CH_3)_3C$), 18.5 (s, $(CH_3)_3C$), −4.61 (q, $(CH_3)_2Si$); IR *2960–2940*, *2865*, *1740–1735*, 1465, 1440, 1375, 1260 (br), 1195, *1170* (br), 1120, 1090, 1060, 1030, 1005 (br), 910, 900, 875 (br), 840, 778. *MS* (PCI, CH_4) 337 (M + H), 321 (M − CH_3), 305 (M − OCH_3), 279 [M − $(CH_3)_3C$], 247, 205 (M − *t*-$BuMe_2Si$), 203, 173, 149, 145 cm^{-1}; HRMS (PCI, CH_4) m/z 337.2203 (calcd for $C_{19}H_{33}SiO_3$ (M + H) 337.2199).

Spectral data for the cis,syn tricyclopentanoid **5**: ^{1}H NMR (300 MHz) δ 5.27 (br s, 1 H, C_3H), 4.10 (br s, 1 H, $C_{11}H$), 3.69 (s, 3 H, CO_2CH_3), 3.28–3.12 (m, 2 H), 2.83–2.75 (m, 1 H), 2.70–2.45 (m, 3 H), 2.15–2.03 (m, 1 H), 2.03–1.92 (m, 1 H), 1.79 (dd, 1 H, J = 10.5, 9.3 Hz), 1.65–1.20 (m, 6 H), 0.876 (s, 9 H, $(CH_3)_3C$), 0.068 and 0.056 (2 s, 3 H each, $(CH_3)_2Si$); IR *2960* (br), *2865*, *1745–1735*, 1465, 1445, 1438, 1385–1365, *1290–1260*, 1180–1160, 1140–1125, 1052 (br), 900, 835 (br), 775 cm^{-1}; MS (EI), m/z 321 (M − CH_3), 305 (M − OCH_3), 279 (M − *t*-Bu), 247, 219, 203, 173, 167, 149, 145, 75; (PCI, CH_4) 337 (M + H), 321 (M − CH_3), 305 (M − OCH_3), 279 (M − *t*-Bu), 247, 219, 205 (M − *t*-$BuMe_2Si$), 203; HRMS (PCI, CH_4), m/z 337.2218 (calcd for $C_{19}H_{33}SiO_3$ (M + H) 337.2199); 279.1412 (calcd for $C_{15}H_{23}SiO_3$ (M − CH_3) 279.1416).

The minor cis,anti tricyclopentanoid **3** has not been isolated in pure form, but from the 2.0-mg fraction containing a known ratio of **3**, **4**, and **5** (2.16:2.76:1, respectively), several of the ^{1}H NMR signals due to **3** can be observed by accounting for the signals known to be attributable to **4** and **5**. The following new signals are present in the ^{1}H NMR (300 MHz): 5.31 (br s, 1 H, C_3H), 4.23 (br s, 1 H, $C_{11}H$), 3.42–3.35 (m, 1 H), 3.01 (br s, 2 H), 2.685 (d, 1 H, C_7H, J = 9.9 Hz), 0.847 (s, 9 H, $(CH_3)_3C$), 0.026 (s, CH_3Si).

An NOEDS experiment on this sample gave the following results: presaturation of the two-proton signal (presumably C_1H and C_8H) at 3.0 ppm resulted in a 22% NOE on $C_{11}H$. In addition, presaturation of $C_{11}H$ at 4.23 ppm resulted in a 19% NOE on the two proton signal at 3.0, thus establishing that not only is that signal due in part to C_1H, but also that it possesses a cis relationship with $C_{11}H$. Since C_{11} has an *S* configuration, it follows that C_1 also has an *S* configuration.

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