5.84 (d, 1 H, J = 19.2 Hz, C*H*=CH), 5.96 (d, 1 H, J = 19.2 Hz, CH=C*H*), 6.51 (d, 1 H, J = 2.0 Hz, C*H*=C).

(±)-Jatrophone (1). With the same procedure as that given for *epi*-jatrophone (**22**), 0.020 g (0.027 mmol) of the vinyl triflate **4** afforded 0.002 g (23.7%) of jatrophone as a white crystalline solid. All spectral data matched that reported in the literature:[4] IR (neat) ν 3000–2800, 1696 (CO), 1659 (CO), 1621 (C=C), 1450, 1398, 1371, 1231, 1160, 1107, 1063 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 1.06 (d, 3 H, J = 7.1 Hz, C*H*$_3$CH), 1.21 (s, 3 H, (C*H*$_3$)$_2$C), 1.33 (s, 3 H, (C*H*$_3$)$_2$C), 1.72 (d, 3 H, J = 0.7 Hz, C*H*$_3$C=C), 1.84 (dd, 1 H, J = 5.7, 13.5 Hz, CH$_2$), 1.85 (d, 3 H, J = 1.6 Hz, C*H*$_3$C=C), 2.12 (dd, 1 H, J = 5.8, 13.6 Hz, CH$_2$), 2.37 (dd, 1 H, J = 0.7, 14.8 Hz, CH$_2$), 2.83 (d, 1 H, J = 14.7 Hz, CH$_2$), 2.92–2.96 (m, 1 H, C*H*CH$_3$), 5.77–5.80 (m, 2 H, C*H*=C, C*H*=CCH*3*), 5.97 (d, 1 H, J = 16.3 Hz, C*H*=CH), 6.42 (d, 1 H, J = 16.3 Hz, CH=C*H*); ^{13}C NMR ($CDCl_3$) δ 6.13, 18.98, 20.78, 26.92, 30.42, 36.64, 38.35, 41.24, 42.47, (CH, CH$_2$, CH$_3$), 99.78 (CO), 112.42, 123.76, 128.73, 137.09, 141.77, 147.13, 159.04, 183.25 (C=C), 202.03 (C=O), 203.93 (C=O); HRMS for C $_{20}$H$_{24}$O$_3$, calcd 312.1726, found 312.1725.

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Supplementary Material Available: Experimental details for the reactions reported in Scheme IV (5 pages). Ordering information is given on any current masthead page.

Effect of Allylic Substituents on the Face Selectivity of Diels–Alder Reactions of Semicyclic Dienes

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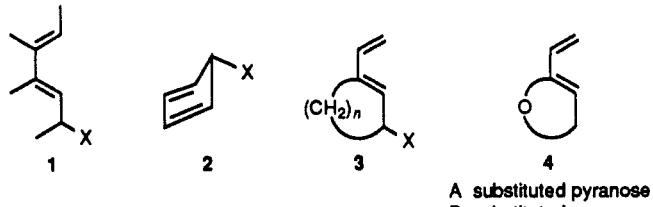
Abstract: Vinylcyclohexenes substituted allylically on the cyclohexene ring were examined as substrates in the Diels–Alder cycloaddition. In the octalin cycloaddition products, the relative stereochemistry of the one angular hydrogen relative to that of the allylic substituent was examined as a measure of the control of face selectivity by the substituent. In the 17 examples reported where the competition for control was between OH–H, MeO–H, (TMS)O–H, OH–CH$_3$, OMe–CH$_3$, and (TMS)O–CH$_3$, the simplest rationale was that size alone controlled the face selectivity of the Diels–Alder cycloaddition.

Introduction

High regiospecificity and stereoselectivity along with the simultaneous creation of multiple chiral centers make the Diels–Alder reaction an important process in organic synthesis.[2] Heteroatom substitution at the allylic position of a diene has a pronounced effect on diastereofacial selection. Attempts have been made to rationalize the observed diastereoselectivity.[3-8] Experiments involving the use of dienes with a stereogenic allylic carbon can be divided into three categories. Acyclic dienes of type **1**[5-11] (X = O, N, Si) have essentially free rotation of the allylic



1 **2** **3** **4**

A substituted pyranose
B substituted pyranose

center, while in cyclic dienes **2**,[12] **3**,[13] and **4**[14] the allylic substituents are restricted in their degree of conformational flexibility. Recent work at Hunter documented a series of Diels–Alder reactions using

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Table I. Relative Topicities of the Diels–Alder Reaction of Different Dienophiles with Semicyclic Dienes Bearing a Stereogenic Allylic Carbon

entry	diene	dienophile	solvent	temp, °C	product syn (%)	product anti (%)	yield, %
1	**6a**	**8**	benzene	25	**11a** (63)	**12a** (37)	73.5
2	**6a**	**8**	methanol	25	(36)	(64)	*a*
3	**6a**	**8**	DMF	25	(17)	(83)	*a*
4	**6b**	**8**	benzene	25	**11b** (11)	**12b** (89)	82.4
5	**6b**	**8**	DMF	25	(10)	(90)	*a*
6	**6c**	**8**	benzene	25	**11c** (9)	**12c** (91)	70.5
7	**6a**	**9**	benzene	reflux	**14a** (20)	**15a** (80)	82.7
8	**6a**	**9**	CH_2Cl_2[b]	25	(19)	(81)	*a*
9	**6c**	**9**	benzene	reflux	**14b** (8)	**15b** (92)	56
10	**6c**	**9**	CH_2Cl_2[b]	25	(9)	(91)	*a*
11	**6a**	**10**	CH_2Cl_2:THF	−78 to room temp	**16** (100)	(0)	81
12	**7a**	**8**	benzene	25	**17a**[c] (92)	**18a** (8)	72.2
13	**7a**	**8**	DMF	25	(45)	(55)	*a*
14	**7b**	**8**	CH_2Cl_2	25	**17b** (26)	**18b** (74)	65.5
15	**7b**	**8**	benzene	50	**17b** (25)	**18b** (75)	*a*
16	**7c**	**8**	benzene	25	**17c** (23)	**18c** (77)	50.4
17	**7c**	**8**	DMF	25	(17)	(83)	*a*

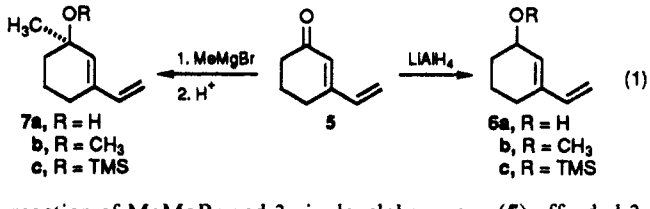
[a] In these cases, the ratios were determined from distinct peaks in the 300-MHz NMR of the reaction mixture, and isolated yields of pure adducts were not determined. [b] Under 6-kbar pressure. [c] Unstable, isolated as the lactone **19**.

acyclic dienes of type **1**, and we have shown that a simple theoretical argument limited to the diene alone cannot explain the observed diastereoselectivity. Only a complete evaluation of the transition state shows promise in prediction of face selectivity in acyclic cases.[15] For example, Hehre put forward a theory[4] based on the electrostatic attraction of the hetero atom (X = O, N) and the dienophile. This theory predicts a syn facial attack (syn to heteroatom) on the face of all classes of dienes. This rationalization failed to account for the experimental results with diene classes **1–4**. In an interesting paper,[13] Overman and Hehre evaluated the face selectivity of dienes of type **3** (n = 2) and obtained largely anti selectivity.

Thus, they modified the original electrostatic theory and put forward an argument where the electrostatic effect between the carbonyl of the dienophile and the allylic heteroatom was repulsive. Fallis, with cyclopentadienes, and le Noble, with an adamantanethione dienophile, have independently interpreted their results according to a version of Cieplak's theory, namely that face selectivity is determined by a transition-state bonding interaction between a developing σ^* orbital and the most electron-donating allylic substituent.[12] Our group has been studying dienes of type **3** (n = 3), and we now describe our results, which are complementary to those of Hehre and Overman, but we present a rationalization based solely on steric arguments.

Results

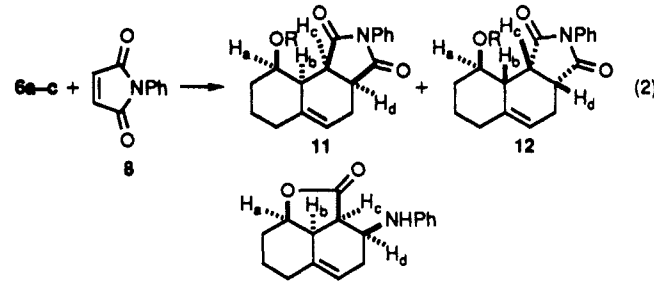
The semicyclic diene 3-vinyl-2-cyclohexen-1-ol (**6a**)[16] was prepared from 3-vinylcyclohexenone (**5**)[17] by reduction with $LiAlH_4$. Protection of the resulting hydroxy group by standard methods furnished 3-methoxy-1-vinylcyclohexene (**6b**) and 3-[(trimethylsilyl)oxy]-1-vinylcyclohexene (**6c**) (eq 1). Grignard



7a, R = H; **b**, R = CH_3; **c**, R = TMS — **5** — **6a**, R = H; **b**, R = CH_3; **c**, R = TMS (1)

reaction of MeMgBr and 3-vinylcyclohexenone (**5**) afforded 3-vinyl-1-methylcyclohexenol (**7a**) (eq 1). Methyl- as well as silyl-protected dienes **7b** and **7c** were prepared from **7a** by standard methods.

A series of Diels–Alder reactions was then carried out in our laboratory by using dienophiles *N*-phenylmaleimide (NPM) (**8**), dimethyl acetylenedicarboxylate (**9**), and *N*-phenyltriazolinedione (**10**) with the dienes **6a–c** and **7a–c** with different solvents and reaction conditions (see Table I). The first entry records the reaction of 3-vinyl-2-cyclohexen-1-ol (**6a**) with *N*-phenylmaleimide (**8**) at room temperature. ^1H NMR of the crude reaction mixture showed the formation of three products. The major product was the adduct **11a** (eq 2), which slowly converts into the tricyclic



a, R = H; **b**, R = CH_3; **c**, R = TMS

lactone **13**. Similar spontaneous lactonization has also been observed earlier by us and other workers[5c,8,11,13] when free hydroxy dienes are subjected to Diels–Alder reaction with NPM (**8**). The crude reaction mixture was refluxed in benzene for complete lactonization of the adduct **11a**, and the syn to anti ratio of 1.7:1 was determined from the ^1H NMR of the mixture of lactone (syn) and alcohol (anti). The two products **12a** and **13** were separated by chromatography. However, adduct **11a** can be isolated by freezing the concentrated reaction mixture where upon **11a** crystallized out as a white solid. When the adduct **11a** was treated with $MeOH/H^+$, it underwent rapid cyclization to the tricyclic lactone **13**. This cyclization strongly suggests that the adduct **11a** was formed by the attack of the dienophile on the face of the diene that is syn to the hydroxy group. The ^1H NMR data also are consistent with syn stereochemistry for the adduct **11a** where proton H_a, resonating at δ 4.34, appears as a broad singlet, indicating a very small (cis) coupling constant between H_a and H_b. On the other hand, the same proton in the minor adduct **12a** appears as a broad multiplet, indicating a trans coupling between H_a and H_b. Thus, minor adduct **12a** is formed by the attack of the dienophile from the face anti to the hydroxy group. Adduct **12a** did not cyclize on treatment with $MeOH/H^+$ at room temperature or under reflux. We assign both adduct **11a** and **12a** as endo products because of the facile cyclization of one of the adducts (**11a**) and because both have comparable coupling constants between H_b and H_c (J = 9.2 Hz for **11a** and 8.2 Hz for **12a**). There was a dramatic reversal in the diastereomeric ratio

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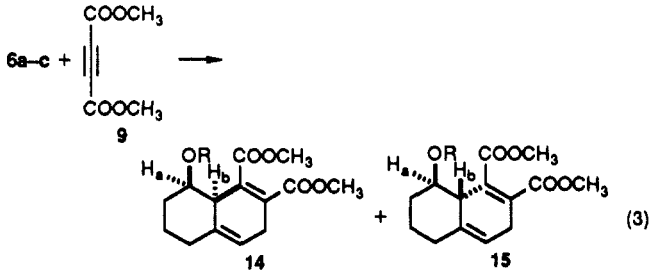
of syn (**11a**) to anti (**12a**) product by changing the reaction solvent from benzene to MeOH and DMF (entries 2 and 3). Entry 4 records the reaction of 3-methoxy-1-vinylcyclohexene (**6b**) with NPM at room temperature in benzene, which showed facial selectivity opposite to that of free diene alcohol **6a**. In this case, the anti adduct **12b** clearly predominates and the facial selectivity is not affected significantly by changing the solvent from benzene to DMF (entry 5). The stereochemistries of **11b** and **12b** were proved by the similarity of their ^{1}H NMR data to that of **11a** and **12a**. Each stereochemical series exhibited a common coupling pattern for the methine proton H_a. For the anti adduct **12b**, the methine proton H_a showed the characteristic broad ddd (J = 4.58, 9.84, 11.0 Hz), whereas for the syn compound the methine proton H_a appeared as a broad singlet. Moreover, methylation of the anti adduct alcohol **12a** with $MeI/Ag_2O/K_2CO_3$ gave methyl ether **12b**.

Silyl-protected diene **6c** also undergoes cycloaddition with NPM slowly, and the facial selectivity is identical with that of methyl ether diene **6b** (entry 6). In this case, the two diastereomeric products appeared as a homogeneous material when chromatographed and were not separable. ^{1}H NMR of the crude sample showed a coupling pattern for the methine proton H_a (ddd, J = 4.7, 9.4, 11.2 Hz) that clearly indicated that the major diastereoisomer **12c** is an anti adduct. The corresponding proton for minor adduct **11c** appeared as a broad singlet. The adduct mixture was easily hydrolyzed by $MeOH/H^+$ to give the anti alcohol **12a** as the major product with a detectable amount of tricyclic lactone **13**.

Entry 7 records the reaction of the alcohol diene **6a** with dimethyl acetylenedicarboxylate (**9**) at reflux temperature in benzene. The reactions are slow at room temperature in the case of acetylenic dienophiles. At reflux, some aromatic products were observed in the ^{1}H NMR. When the reaction was carried out in CH_2Cl_2 under high pressure (6 kbar), the adducts were clean and free from aromatic product (entry 8) and there was no significant change in the diastereomeric ratio. Two major products (eq 3) were separated by chromatography. The stereochemistry



(3)

a, R = H; **b**, R = TMS

for both of the adducts was determined from their ^{1}H NMR spectra. The resonance for the methine proton H_a for the major adduct **15a** appears at δ 3.51 as a broad multiplet, whereas the same proton resonates at δ 4.11 (as a broad singlet) in the minor compound **14a**.

The silyl protection of the diene **6c** further increased the amount of anti adduct **15b** (entry 9). The stereochemistries for both the minor and major adducts **14b** and **15b** were secured by ^{1}H NMR correlation with the alcoholic adducts **14a** and **15a**. The resonance for the methine proton H_a appears as a doublet of a triplet (J = 10.4, 4 Hz) for the major adduct **15b**, whereas in the minor isomer **14b** the same proton appears as a broad singlet. Our results are also consistent with the observations of Roush et al. for acetylenic adducts.[18] Moreover, the major adduct **15b** was hydrolyzed by $MeOH/H^+$ to adduct **15a**, which shows the major product **15b** resulted from an anti attack. Reaction of the diene **6a** with 4-phenyl-1,2,4-triazoline-3,5-dione (**10**) in CH_2Cl_2/THF at low temperature gave a single adduct **16** as a white solid (entry 11). The allylic proton H_b resonates as a doublet (J_{ab} = 8.8 Hz), thus indicating the adduct resulting from an anti attack (eq 4). The

(18) Hall, S. E.; Roush, R. *J. Org. Chem.* **1982**, *47*, 4611.

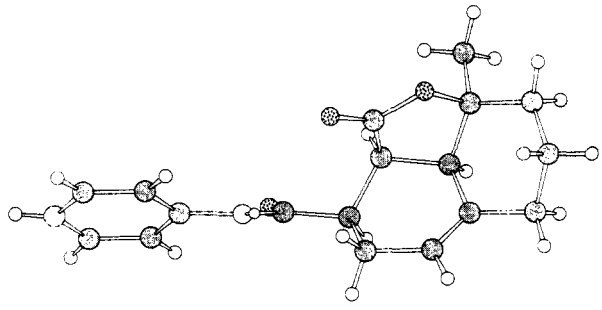
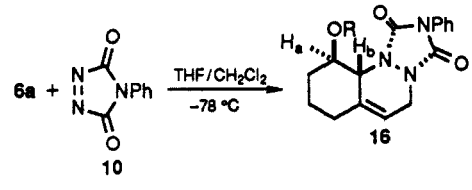


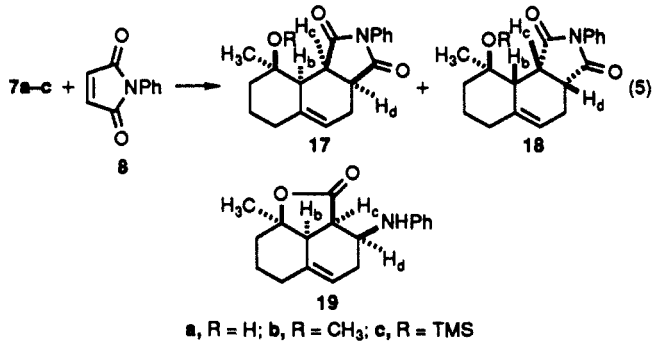
Figure 1. Perspective view of the tricyclic lactone **19**.

methine proton H_a also appears as a broad multiplet, which is also another characteristic of the anti adducts.



(4)

The dienes (**7a–c**) bearing both methyl and hydroxy or alkoxy groups at the allylic position also gave interesting results. The reaction of the diene **7a** with NPM at room temperature in benzene resulted in the formation of a crystalline solid that separated out after stirring overnight. The compound was identified as the tricyclic lactone **19** (eq 5) on the basis of NMR evidence and X-ray crystallography (Figure 1).



(5)

a, R = H; **b**, R = CH_3; **c**, R = TMS

Along with the tricyclic lactone **19**, a minor product was isolated from the mother liquor that was shown to be the anti alcohol **18a** (attack anti to the hydroxy group) (entry 12). This minor product was assumed to be endo and anti to the OH group because of its comparable ^{1}H NMR data with the adduct **12a**. Surprisingly, when the adduct **18a** was treated with $MeOH/H^+$ and refluxed for a prolonged period of time (48 h), tricyclic lactone **19** was obtained. This result is explained by the loss of stereochemistry at the tertiary alcohol center by acid-catalyzed carbonium ion formation followed by regeneration of a more stable product. This experiment ruled out the possibility of **18a** being an exo product, which could not have lactonized. When the solvent was changed from benzene to DMF (entry 13), the diastereomeric ratio changed dramatically from 92:8 to 45:55. Thus, the more polar solvent favors the attack of the dienophile anti to the hydroxyl group.

The reaction of the diene **7b** with NPM was extremely slow in benzene at room temperature. The same reaction was carried out in CH_2Cl_2 under high pressure (6 kbar), which gave a mixture of two products in a ratio of 3:1 (entries 14 and 15). The cycloadducts were separated by chromatography, and the stereochemistry of both the adducts was assigned from the correspondence of their ^{1}H NMR spectra with other members of the series. An X-ray crystallographic analysis (Figure 2) of major, anti to OMe, adduct **18b** confirmed our assignment.

Entry 16 shows the reaction of the silylated diene **7c** with NPM, and two adducts were obtained in a ratio of 3.3:1. The products **17c** and **18c** were not separable by chromatography, and the stereochemistry was elucidated on the basis of their ready con-

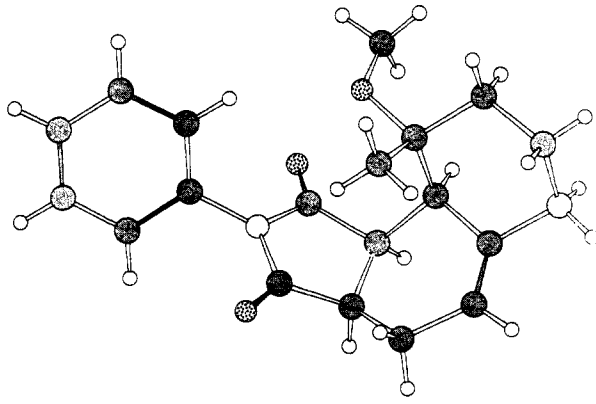


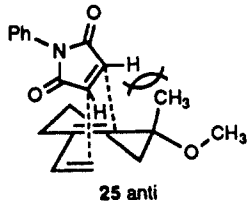
Figure 2. Perspective view of the cycloadduct **18b**.

version to tricyclic lactone **19** and alcohol **18a** by treatment with MeOH and a trace of acid. The isolation of syn to oxygen isomer **17c**, which then lactonizes very easily, excludes the possibility that **18a** and **18c** are syn isomers. When the reaction was run in DMF, there was a slight increase of the anti product **18c** (entry 17).

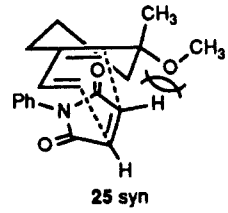
More recently, Kawamata et al. have demonstrated that the reaction of the diene **6d** with methyl vinyl ketone (MVK) (**20**) gave different regio- and stereoisomeric products **21–24** at different temperatures[19] as shown in Scheme I. At 150 °C, the predominant product was the exo-anti adduct **21**, whereas at 110 °C, the endo-anti adduct **24** was formed as the major product. In both of the experiments, the regioisomeric exo adduct **22**, where the acetyl group of the dienophile is distal to the allylic substituent, was formed as the minor adduct and exhibited anti stereochemistry.

Discussion

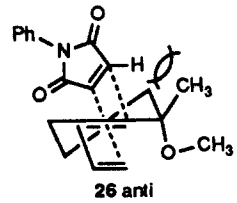
In acyclic dienes, experimentation[5-12] and molecular orbital theory[15] suggested that the face selectivity induced by allylic substituents was due to a balance of forces. Thus, in the transition state, the allylic substituent was rotated so that the heteroatom was essentially coplanar with the diene, with the anti-coplanar form preferred to the syn-coplanar rotamer. Then, the preferred face approached by the dienophile was that where minimum steric repulsions between diene and dienophile existed. In the cases where the allylic substituent is constrained as part of a ring system, the syn-coplanar orientation of the heteroatom is not accessible. Thus, in our experiments, we postulate that there are four principal transition states, **25** syn and anti, where the oxygen is pseudoe-



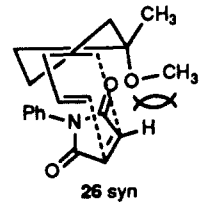
25 anti



25 syn



26 anti



26 syn

quatorial to the cyclohexene, and **26** syn and anti, where the oxygen is pseudoaxial. We suggest that the determining effect is the rather weak interaction of the substituent with the vinyl hydrogen of *N*-phenylmaleimide.

Applying molecular orbital results obtained for acyclic dienes,[15] we postulate that the transition states **26** syn and anti will have higher energies of activation because of unfavorable interactions of the C–O function parallel to the developing bonds in the transition state. We therefore focus on **25** syn and anti using steric effects alone as the basis for selectivity. Thus, for dienes with

Scheme I

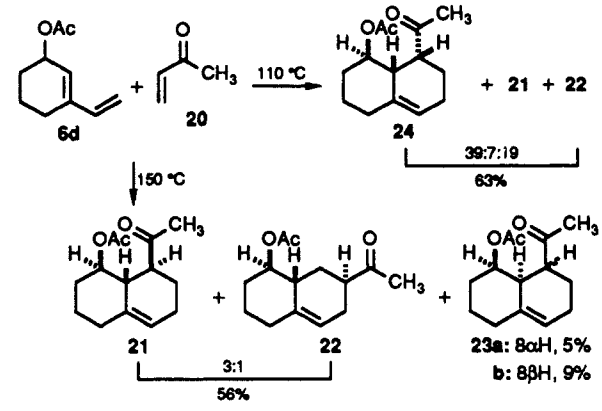


Table II. Comparison of *A* with *n* Values

entry	gp	*A*	*n*
1	H	0	<3
2	OH	0.5	6.3
3	OMe	0.6	9.5
4	Me	1.7	8.5

the methyl carbon shown replaced by H, the face selectivity will be determined by the size of the oxygen substituent. When the groups are H vs OH in a non-hydrogen-bonding solvent, the syn face is slightly favored (1:7:1). When a hydrogen-bonding solvent is used, we postulate that the OH becomes a bulkier group and the anti face is preferred (4:1). If electrostatic repulsions[13] were the force that favored anti product, then the use of polar solvents should reduce, not increase, the yield of anti material, just opposite to our observation. A further argument against the importance of electrostatic effects can be developed from the results of Kawamata et al.[19] Thus, both adducts endo **24** and exo **22** have the same stereochemistry, carbonyl of the dienophile anti to the allylic acetate; yet, the ends of the MVK dienophile have opposite polarities. If an electrostatic effect of the allylic group were important, then one would expect **24** and **22** to have opposite face selectivities. Also, if the forces postulated in the Cieplak–Fallis rationale[12c] were controlling, then syn adducts should have prevailed without exception. A caveat here, as a reviewer notes, is that the geometry of our system may not be ideal for a dominant Cieplak effect. Hence, the observed decrease in syn product where steric effects increase is understandable. When the heterofunction is OMe, we suggest that the face syn to the OMe becomes less reactive because the OMe is a large group toward external approach. We argue that the currently popular use of *A* values[13,20] which are a measure of the intramolecular size of a group interacting with a hydrogen across a cyclohexane ring,[21] is inappropriate for evaluating the volume occupied by the OMe in blocking the approach of a dienophile. We believe a parameter such as the Vogtle–Forster *n* value[22] (see Table II) is a better qualitative descriptor of the volume of a group in electroneutral intermolecular reactions. Fallis also favors this system of size estimation.[12c] When the allylic functions are Me vs OH, hydrogen bonding in DMF increases the size of the OH group so that the syn and anti reactivity are about equal; e.g., the solvated OH group is approximately the size of a Me. When the groups are Me and OMe, the reaction is quite slow and must be run at 6 kbar to obtain good yields.

We interpret this result by arguing that both methyl and methoxyl block diene reactivity, reducing the overall reactivity, but

(19) Kawamata, T.; Harimaya, K.; Iitaka, Y.; Inayama, S. *Chem. Pharm. Bull.* **1989**, *37*, 2307.
(20) Paquette, L. A.; Lin, H.-S.; Gunn, B. P.; Coghlan, M. J. *J. Am. Chem. Soc.* **1988**, *110*, 5818.
(21) Hirsch, J. A. *Top. Stereochem.* **1967**, *1*, 199.
(22) Forster, H.; Vogtle, F. *Angew. Chem., Int. Ed. Engl.* **1977**, 429. It is unfortunate that there is no *n* value for the (TMS)O group.

that methoxy is larger than methyl, consistent with the Forster–Vogtle descriptors. Interestingly, in the key Diels–Alder reaction in the total synthesis of a nogalamycin antibiotic, the face selectivity was controlled by a trimethylsilyloxy group being larger than a methyl group.[23] However Paquette's result in the sterpuric acid series cannot be easily rationalized by considering carbomethoxyl larger than methyl.[20]

In summary, there is a balance of electronic and steric forces that control face selectivity in Diels–Alder transition states of semicyclic dienes, where steric effects seem to be dominant. The reactions lead to stereoselective syntheses of substituted octalins, hexalins, and masked aminocyclohexanols.

Experimental Section

NMR spectra were recorded on GE QE (300-MHz) instruments with tetramethylsilane as the internal standard and $CDCl_3$ as the solvent. Infrared spectra were recorded on a Perkin-Elmer 1310 spectrophotometer. Elemental analyses were performed by Spang Microanalytical Laboratory, Eagle Harbor, MI. The high-resolution mass spectra were obtained by the mass spectral facility at Rockefeller University, New York. Melting points were uncorrected and were determined on a Fisher-John melting point aparatus. Thin-layer chromatograms were done on precoated TLC sheets of silica gel 60 F_{254} (E. Merck) with potassium permanganate spray and/or short- and long-wave ultraviolet light to visualize the spots. PLC plates were prepared by using Kieselgel 60 PF254 (E. Merck), and chromatotron (radial chromatography) plates were prepared by using Kieselgel 60 PF254 gipshaltig (E. Merck). Flash chromatography was performed with silica gel (230–400 mesh) purchased from Aldrich Chemical Co.

3-Vinyl-2-cyclohexen-1-ol (6a).[17] To a suspension of $LiAlH_4$ (1.82, 48 mmol) in anhydrous ether (50 mL) at 0 °C was added dropwise a solution of 3-vinylcyclohexenone[16] (3.5 g, 28.68 mmol) in anhydrous ether (50 mL). After the addition, the cooling bath was removed and the misture was stirred at room temperature for 5 h. The mixture was treated sequentially with ethyl acetate (3.7 mL) and 10% aqueous KOH (11 mL) and then stirred for 30 min. Then, the mixture was filtered, and the insoluble aluminum salt was repeatedly washed with ether. The combined filtrate was dried with anhydrous $MgSO_4$, and evaporation of the solvent furnished a colorless oil. The crude product was purified by distillation (bp 47–48 °C (0.01 mmHg) to give 3.1 g (87.5%) of 3-vinyl-2-cyclohexen-1-ol (**6a**): ^1H NMR (300 MHz, $CDCl_3$) δ 6.39 (dd, J = 10.74, 17.54 Hz, =CHC=), 5.8 (br s, C=CH), 5.24 (d, J = 17.48 Hz, C=C*H*H), 5.09 (d, J = 10.83 Hz, =CH*H*), 4.3 (br s, C*H*OH), 2.3–1.4 (m, OH, 3 CH_2); IR ($CHCl_3$) 3595, 3410, 2925, 1650, 1610, 1440, 1050, 855 cm^{-1}.

3-Methoxy-1-vinylcyclohexene (6b). To a mixture of NaH (50% dispersion in mineral oil, 720 mg, 15 mmol) and DMSO (5 mL) was added dropwise a solution of **6a** (1.22 g, 9.83 mmol) in DMSO (3 mL). The mixture was stirred for a period of 1 h, after which CH_3I (3.0 mL, 45 mmol) was added dropwise and the resulting mixture was stirred overnight. The mixture was poured into water (50 mL) and extracted from EtOAc (3 × 20 mL). The combined extract was washed with brine (20 mL) and dried over anhydrous $MgSO_4$. After the removal of solvent, the crude product was subjected to flash chromatography (petroleum ether/EtOAc, 8:2) to give 883 mg (65%) of 3-methoxy-1-vinylcyclohexene (**6b**) as a colorless oil that was further purified by short-path distillation (bath temperature 70–75 °C (20 mmHg)): ^1H NMR (300 MHz, $CDCl_3$) δ 6.4 (dd, J = 10.76, 17.53 Hz, =CHC=), 5.84 (br s, C=CH), 5.23 (d, J = 17.31 Hz, C=C*H*H), 5.07 (d, J = 10.76 Hz, =CH*H*), 3.90 (br s, CHOMe), 3.42 (s, OMe) 2.2 (m, 2 H), 1.88 (m, 2 H), 1.65 (m, 2 H); IR ($CHCl_3$) 2940, 2880, 1670, 1610, 1375, 1090 cm^{-1}; high-resolution mass calcd for $C_9H_{14}O$ (M^+) 138.1044, found 138.1016.

3-[(Trimethylsilyl)oxy]-1-vinylcyclohexene (6c). BSA (1.8 mL, 7.28 mmol) was added dropwise to neat ice-cooled alcohol **6a** (400 mg, 3.22 mmol), and after addition, the cooling bath was removed. The mixture was stirred overnight. The silylated product was purified by flash chromatography (petroleum ether/EtOAc, 9:1). 3-[(Trimethylsilyl)oxy]-1-vinylcyclohexene (**6c**) was isolated as a colorless oil 454 mg, 71.9% ^1H NMR (300 MHz, $CDCl_3$) δ 6.37 (dd, J = 10.75. 17.5 Hz, =CHC=), 5.67 (br s, C=CH), 5.19 (d, J = 17.71 Hz, C=C*H*H), 5.04 (d, J = 10.71 Hz, =CH*H*), 4.36 (m, CHOSiMe_3), 2.15 (m, 2 H), 1.91 (m, 2 H), 1.63 (m, 2 H), .18 (s, 9 H); IR ($CHCl_3$) 2945, 2880, 1610, 1450, 1070, 1010 cm^{-1}; high-resolution mass calcd for $C_{11}H_{20}OSi$ (M^+) 196.1284, found 196.1278.

(23) Kawasaki, M.; Matsuda, F.; Terashima, S. *Tetrahedron* **1988**, *44*, 5727.

3-Vinyl-1-methyl-2-cyclohexen-1-ol (7a). To a solution of methylmagnesium bromide (5 mL of a 3 M solution in ether, 15 mmol) in dry THF (30 mL) was added dropwise at 0 °C a solution of 3-vinylcyclohexenone (1.51 g, 12.37 mmol in 15 mL of dry THF). After 1 h, 50% NH_4Cl solution (50 mL) was added slowly. The mixture was brought to room temperature and extracted with ether (3 × 50 mL). Combined organic extracts were washed with brine (30 mL) and dried over anhydrous $MgSO_4$. Evaporation of solvent gave an oil that was distilled under vacuum to furnish 3-vinyl-1-methyl-2-cyclohexen-1-ol (**7a**) as a colorless liquid: 1.3 g, 76.5%; bp 49 °C (0.2 mmHg); ^1H NMR (300 MHz, $CDCl_3$) δ 6.35 (dd, J = 10.74, 17.55 Hz; =CHC=), 5.65 (br s, C=CH), 5.24 (d, J = 17.56 Hz, C=C*H*H), 5.07 (d, J = 10.76 Hz, =CH*H*), 2.2–2.07 and 1.8–1.6 (m, OH, 3 CH_2); IR ($CHCl_3$) 3600, 3450, 1610, 1450, 1380, 1060 cm^{-1}; high-resolution mass calcd for $C_9H_{14}O$ (M^+ − 15) 123.0809, found 123.0806.

3-Methoxy-3-methyl-1-vinylcyclohexene (7b). To a mixture of KH (35% dispersion in mineral oil, 457 mg, 4 mmol) and dry THF (10 mL) was added dropwise a solution of **7a** (442 mg, 3.2 mmol) in dry THF (3 mL). The resulting mixture was stirred for 1 h, and CH_3I (1 mL, 15 mmol) was added dropwise. After 1 h, the reaction mixture was poured into water (10 mL) with caution and extracted from EtOAc (3 × 15 mL). The combined extract was washed with brine (15 mL) and dried over anhydrous $MgSO_4$. After solvent evaporation, the crude product was purified by flash chromatography (petroleum ether/EtOAc, 9:1) to give 3-methoxy-3-methyl-1-vinylcyclohexene (**7b**) as a colorless oil: 298 mg, 67.6%; ^1H NMR (300 MHz, $CDCl_3$) δ 6.39 (dd, J = 10.66, 17.65 Hz, =CHC=), 5.63 (br, s, C=CH), 5.23 (d, J = 17.55 Hz, C=C*H*H), 5.07 (d, J = 10.78 Hz, =CH*H*), 3.24 (s, OCH_3) 2.2–2.1 and 1.97–1.44 (m, 6 H), 1.30 (s, CH_3); IR ($CHCl_3$) 2950, 1610, 1455, 1375, 1110, 1070 cm^{-1}.

3-[(Trimethylsilyl)oxy]-3-methyl-1-vinylcyclohexene (7c). BSA (0.5 mL, 2 mmol) was added dropwise to neat ice-cooled alcohol **7a** (130 mg, 0.94 mmol) at 0 °C. Workup as described for the preparation of **6c** gave 3-[(trimethylsilyl)oxy]-3-methyl-1-vinylcyclohexene (**7c**) as a colorless oil: 123 mg, 66.7%; ^1H NMR (300 MHz, $CDCl_3$) δ 6.36 (dd, J = 10.7, 17.48 Hz, =CHC=), 5.68 (br s, C=CH), 5.22 (d, J = 17.21 Hz, C=C*H*H), 5.06 (d, J = 10.74 Hz, =CH*H*), 2.4–2.0 (m, 2 H), 1.88–1.79 (m, 2 H), 1.7–1.5 (m, 2 H), 1.35 (s, Me), 0.13 (s, 9 H); IR ($CHCl_3$) 2950, 1610, 1450, 1030, 910 cm^{-1}.

Reaction of 3-Vinyl-2-cyclohexen-1-ol (6a) with *N*-Phenylmaleimide. A solution of alcohol **6a** (256 mg, 2.06 mmol) and *N*-phenylmaleimide (357 mg, 2.06 mmol) in dry benzene (4 mL) was stirred at room temperature for 3 days. ^1H NMR and TLC of the crude product showed the formation of three products. The reaction mixture was refluxed for 3 h, and the NMR of the crude product showed only two products, which were separated by radial chromatography (CH_2Cl_2/acetone, 19:1). The first fraction was a tricyclic lactone **13** (242 mg, 39.5%) that was crystallized from acetone/water to give colorless needles, mp 240 °C. The second fraction was the anti alcohol **12a** obtained as a foamy solid (207 mg, 33.8%). When the reaction product was concentrated without reflux, the syn alcohol **11a** was crystallized in the freezer. Crystals were filtered and washed with benzene to give pure **11a**, mp 163–64 °C.

11a: ^1H NMR (300 MHz, $CDCl_3$) δ 7.55–7.3 (m, PhH), 5.84 (br s, C=CH), 4.34 (br d, C*H*OH), 3.43 (app t, J = 9.19 Hz, COCH), 3.24 (dt, J = 9.9 and 3.23 Hz, COC*H*CH_2), 2.83 (m, 2 H), 2.6–2.4 (m, 2 H), 2.2–1.5 (m, 4 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 178.90, 177.99, 134.66, 132.39, 129.04, 128.39, 126.69, 119.97, 69.17, 41.02, 40.13, 36.69, 36.11, 33.25, 23.33, 20.99; IR ($CHCl_3$) 3300, 1710, 1600, 1560, 1390 cm^{-1}. Anal. Calcd for $C_{18}H_{19}NO_3$: C, 72.72; H, 6.39; N, 4.71. Found: C, 72.52; H, 6.53; N, 4.74.

12a: ^1H NMR (300 MHz, $CDCl_3$) δ 7.6–7.2 (m, PhH), 5.65 (br s, C=CH), 4.16 (m, C*H*OH), 3.71 (m, COC*H*, O*H*), 3.20 (overlapping ddd, COC*H*CH_2), 2.51 (m, 2 H), 2.3–2.1 (m, 2 H), 1.85–1.5 (m, 4 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 178.66, 178.37, 139.08, 131.75, 129.12, 128.65, 126.69, 126.52, 118.32, 69.70, 44.55, 40.66, 39.54, 32.89, 31.61, 24.72, 22.11; IR ($CHCl_3$) 3450, 1700, 1390, 1140 cm^{-1}; high-resolution mass calcd for $C_{18}H_{18}NO_3$ (M^+ − H) 296.1286, found 296.1274.

13: ^1H NMR (300 MHz, $CDCl_3$) δ 10.1 (br s, NH), 7.7–7.1 (m, PhH), 5.76 (br s, C=CH), 4.78 (app d, J = 3.04 Hz, CHOCO), 3.43 (dd, J = 5.7, 2.8 Hz, CHCO), 3.04 (m, 1 H), 2.96 (dt, J = 8.5, 2.8 Hz, NHCOC*H*CH_2), 2.7–1.5 (series of m, 8 H); IR ($CHCl_3$) 3300, 1745, 1675, 1600, 1550, 1440 cm^{-1}. Anal. Calcd for $C_{18}H_{19}NO_3$: C, 72.72; H, 6.39; N, 4.71. Found: C, 72.66, H, 6.49; N, 4.63.

Reaction of 3-Methoxy-1-vinylcyclohexene (6b) with *N*-Phenylmaleimide. A solution of methyl ether **6b** (181 mg, 1.31 mmol) and *N*-phenylmaleimide (266 mg, 1.53 mmol) in dry benzene (3 mL) was stirred at room temperature for 3 days. The reaction mixture was concentrated, and the ^1H NMR showed the formation of two adducts. The products were separated by radial chromatography (petroleum ether/$CHCl_3$/acetone, 50:48:2). The major adduct (**12b**) was obtained as a solid (309

mg, 75.86%) that was crystallized from petroleum ether/EtOAc to give colorless crystals of **12b**: mp 96 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.6–7.2 (m, PhH), 5.64 (br s, =CH), 4.33 (ddd, J = 11.0, 9.84, 4.58 Hz, C*H*OCH$_3$), 3.65 (dd, J = 8.52, 5.9 Hz, COCH), 3.51 (s, OCH_3), 3.26 (overlapping dt, CH_2CHCO), 2.71 (m, =CHC*H*H), 2.6–1.2 (m, 8 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 179.13, 177.54, 140.62, 129.06, 128.48, 126.52, 119.01, 76.38, 56.4, 43.36, 40.60, 29.13, 27.64, 25.18, 20.19; IR ($CHCl_3$) 1700, 1490, 1380, 1320 cm^{-1}. Anal. Calcd for $C_{19}H_{21}NO_3$: C, 73.71; H, 6.75; N, 4.50. Found: C, 73.32; H, 6.69; N, 4.55.

The minor adduct (**11b**) which was crystallized from petroleum ether/EtOAc as colorless crystals, was isolated along with a trace of *N*-phenylmaleimide: 28.2 mg, 6.9%; mp 120 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.5–7.2 (m, PhH), 5.64 (br s, =CH), 3.90 (d, J = 2.33 Hz, C*H*OCH$_3$), 3.32 (app t, J = 9.7 Hz, COCH), 3.14 (dt, J = 4.4, 9.9 Hz, CH_2CHCO), 3.03 (s, OCH_3), 2.75 (d, J = 9.59 Hz, allylic CH), 2.66 (br d, J = 18.03 Hz, =CHC*H*H), 2.49–1.2 (m, 7 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 135.18, 134.21, 129.14, 128.88, 127.95, 126.04, 118.22, 76.61, 55.36, 40.72, 39.34, 36.96, 36.69, 27.26, 23.42, 21.24; IR ($CHCl_3$) 1700, 1490, 1440, 1380 cm^{-1}; high-resolution mass calcd for $C_{19}H_{21}NO_3$ (M^+ + H) 312.1599, found 311.1527.

Conversion of 12a to 12b. A mixture of alcohol adduct **12a** (50 mg, 0.16 mmol), Ag_2O (42 mg, 0.18 mmol), K_2CO_3 (23 mg, 0.16 mmol), MeI (0.4 mL, 22.8 mmol), and dry $CHCl_3$ (2 mL) was stirred at room temperature for 4 days. After filtration and solvent evaporation, the crude mass was subjected to PLC separation (petroleum ether/EtOAc, 1:1) to give **12b** (19 mg, 36.4%) and 9.3 mg of recovered alcohol **12a**.

Reaction of 3-[(Trimethylsilyl)oxy]-1-vinylcyclohexene (6c) with *N*-Phenylmaleimide (5). A solution of silyl ether **6c** (355 mg, 1.81 mmol) and *N*-phenylmaleimide (365.5 mg, 2.11 mmol) in dry benzene (6 mL) was stirred at room temperature for 4 days. Solvent was removed, and the ^{1}H NMR spectrum of the reaction mixture showed the formation of two adducts. The crude reaction mixture was purified by radial chromatography ($CHCl_3$/acetone, 95:5). The inseparable mixture of diastereomers **11c** and **12c** was obtained as a colorless oil (471 mg, 70.5%). Major adduct **12c**: ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.5–7.2 (m, PhH), 5.63 (br s, =CH), 4.89 (ddd, J = 11.2, 9.4, 4.7 Hz, C*H*OSiCH$_3$), 3.54 (dd, J = 8.58, 5.25 Hz, COCH), 3.26 (m, CH_2CHCO), 2.71 (m, =CHC*H*H), 2.4–1.3 (m, 8 H), 0.22 (s, $SiMe_3$).

Hydrolysis of Silyl Adduct Mixture of 11c and 12c. To a methanolic solution (10 mL) of the silylated adduct mixture of **11c** and **12c** (450 mg, 1.21 mmol) were added few drops of saturated oxalic acid solution. After 2 h of being stirred at room temperature, solvent was removed and the resulting product was dried. The crude mass was passed through a short column of Florisil and eluted with EtOAc. Removal of solvent gave a pasty mass (281 mg, 78%). The ^{1}H NMR of the product was identical with anti alcoholic adduct **12a**. A trace amount of tricyclic lactone **13** was also detected in the ^{1}H NMR spectrum.

Reaction of 3-Vinyl-2-cyclohexen-1-ol (6a) with Dimethyl Acetylenedicarboxylate (DMAD). A solution of alcohol **6a** (136.4 mg, 1.1 mmol) and dimethyl acetylenedicarboxylate (213 mg, 1.5 mmol) in dry benzene (4 mL) was kept under reflux for 40 h. ^{1}H NMR of the concentrated product showed the formation of two adducts along with some aromatic products. The mixture was separated by radial chromatography ($CHCl_3$) to furnish major adduct **15a** (189.37 mg, 64.37%) and minor adduct **14a** (52.6 mg, 18%).

Major adduct **15a**: ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.50 (br s, C=CH), 3.79 (s, OCH_3), 3.82 (s, OCH_3), 3.51 (overlapping ddd, C*H*OH), 3.16 (m, =CHC*H*H and allylic CH), 2.9 (m, =CHCH*H*), 2.44–1.22 (m, 7 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 172.23, 168.57, 137.81, 135.95, 131.20, 117.05, 76.33, 53.23, 53.03, 49.48, 37.19, 35.39, 28.47, 25.95; high-resolution mass calcd for $C_{14}H_{17}O_5$ (M^+ - H) 265.1075, found 265.1071.

Minor adduct **14a**: ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.65 (br s, C=CH), 4.11 (br s, C*H*OH), 3.9 (s, OCH_3), 3.86 (s, OCH_3), 3.3–2.9 (m, =CHC*H*$_2$ and allylic CH), 2.6–1.57 (m, 7 H); high-resolution mass calcd for $C_{14}H_{17}O_5$ (M^+ + H) 267.1232, found 267.1239.

Reaction of 3-[(Trimethylsilyl)oxy]-1-vinylcyclohexene (6c) with DMAD (9). A solution of silyl ether **6c** (202 mg, 1.03 mmol) and dimethyl acetylenedicarboxylate (257 mg, 1.81 mmol) in dry benzene (4 mL) was kept under reflux for 3 days. ^{1}H NMR of the concentrated crude product showed the formation of two adducts. The products were separated by flash chromatography ($CHCl_3$) to give minor adduct **14b** (7.25 mg, 2%), major adduct **15b** (172.52 mg, 49.5%), and a mixture of **14b** and **15b** (15.15 mg, 4.35%).

Major adduct **15b**: ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.46 (br s, =CH), 3.78 (s, OCH_3), 3.77 (s, OCH_3), 3.43 (dt, J = 10.4, 3.99 Hz, C*H*OSiMe$_3$), 3.20 (m, =CHC*H*H and allylic C*H*), 2.83 (m, =CHCH*H*), 2.28–1.25 (series of m, 6 H), 0.11 (s, $SiMe_3$); IR ($CHCl_3$) 1725, 1440, 1270, 1105 cm^{-1}.

Minor adduct **14b**: ^{1}H NMR (300 MHz, $CDCl_3$) 5.53 (br s, =CH), 4.2 (br s, C*H*OSiMe$_3$), 3.8 (s, 2 OCH_3), 3.12 (m, =CHC*H*H and allylic C*H*), 2.9 (m, =CHCH*H*), 2.35–1.57 (series of m, 6 H), 0.063 (s, $SiMe_3$); high-resolution mass calcd for $C_{17}H_{27}O_5Si$ (M^+ + H) 339.1627, found 339.1577.

Hydrolysis of Silyl Adduct 15b. A methanolic solution (1 mL) of the silylated adduct **15b** (30 mg, 0.08 mmol) with few drops of saturated oxalic acid solution was stirred at room temperature for 0.5 h. Similar workup as described for the hydrolysis of **11c** and **12c** gave adduct alcohol **15a** (19.7 mg, 83.5%).

Reaction of 3-Vinyl-2-cyclohexen-1-ol (6a) with 4-Phenyl-1,2,4-triazoline-3,5-dione (10). A solution of alcohol **6a** (92.7 mg, 0.74 mmol) in 2 mL of dry THF/CH_2Cl_2 (1:1) was added dropwise to a solution (2 mL) of 4-phenyl-1,2,4-triazoline-3,5-dione (130 mg, 0.74 mmol) in dry THF/CH_2Cl_2 (1:1) at −78 °C. The resulting solution was stirred for 15 min, the cooling bath was removed, and the solution was stirred for an additional 15 min. The solvent was removed, and ^{1}H NMR showed the formation of a single adduct. The concentrated product was dissolved in CH_2Cl_2 (1 mL) and passed through a short column of silica gel. The column was eluted with CH_2Cl_2, and on solvent removal the cycloadduct **16** was obtained as a solid (179 mg, 80.9%). The adduct was crystallized from water/acetone to give white crystalline solid (mp 205–206 °C). Adduct **16**: ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.58–7.3 (m, PhH), 5.76 (br s, =CH), 5.34 (d, J = 3.21 Hz, OH), 4.32 (d, J = 8.79, allylic CH), 4.18 (overlapping qd, =CHC*H*$_2$N), 3.81 (m, C*H*OH), 2.46 (m, 1 H), 2.25 (m, 1 H), 1.9 (m, 1 H), 1.64 (m, 1 H), 1.39 (m, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 134.07, 129.28, 129.24, 128.48, 125.79, 125.72, 125.67, 114.46, 74.26, 64.2, 43.0, 34.07, 33.94, 24.15; IR ($CHCl_3$) 3350, 1700, 1499, 1460 cm^{-1}. Anal. Calcd for $C_{16}H_{17}N_3O_3$: C, 64.2; H, 5.68; N, 14.04. Found: C, 63.96; H, 5.80; N, 13.87.

Reactions of 3-Vinyl-1-methyl-2-cyclohexen-1-ol (7a) with *N*-Phenylmaleimide. A solution of alcohol **7a** (226 mg, 1.63 mmol) and *N*-phenylmaleimide (283 mg, 1.63 mmol) in dry benzene (3 mL) was stirred at room temperature. After a few hours, the tricyclic lactone **19** started to separate out as a white solid. The reaction was continued for 3 days. The crude mixture was concentrated, and ^{1}H NMR of the mixture showed the formation of two products. To the concentrated product was added benzene (5 mL), and the insoluble lactone **19** was filtered, washed with benzene, and crystallized from acetone/water as colorless needles, mp 213 °C. ^{1}H NMR of the mother liquor showed a mixture of two adducts, which were separated by PLC (petroleum ether/EtOAc, 3:1) to give the tricyclic lactone **19** (19 mg, combined yield 66.9%) and the minor adduct alcohol **18a** (27 mg, 5.3%).

Lactone **19**: ^{1}H NMR (300 MHz, $CDCl_3$) δ 10.1 (br s, NH), 7.7–7.1 (m, PhH), 5.75 (br s, C=CH), 3.73 (dd, J = 5.75, 2.8 Hz, COCH), 2.92 (dt, J = 8.5, 2.75 Hz, NHCOC*H*CH$_2$), 2.82 (br s, OCCHC*H*), 2.8–1.5 (series of m, 8 H), 1.54 (s, CH_3); IR ($CHCl_3$) 3305, 1740, 1670, 1600, 1555, 1445 cm^{-1}. Anal. Calcd for $C_{19}H_{21}NO_3$: C, 73.31; H, 6.75; N, 4.50. Found: C, 73.54; H, 6.70; N, 4.52.

Minor adduct **18a**: ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.6–7.3 (m, PhH), 5.74 (br s, C=CH), 4.76 (s, OH), 3.68 (app t, J = 8.9 Hz, COCH), 3.12 (ddd, J = 15.8, 8.9, 6.9 Hz, COC*H*CH$_2$), 2.95 (d, J = 9.41 Hz, allylic CH), 2.59 (m, COCHC*H*H), 2.41–1.39 (m, 6 H), 1.24 (s, CH_3); IR ($CHCl_3$) 3420, 1700, 1600, 1490, 1395 cm^{-1}; high-resolution mass calcd for $C_{19}H_{20}NO_3$ (M^+ - H) 310.1443, found 310.1481.

X-ray Data for 19. The crystals are monoclinic, space group P_2 $1/c$ (No. 14), with dimensions A = 5.393 (2) Å, b = 14.504 (2) Å, c = 19.776 (2) Å, and ρ = 1.35 g/cm^3 for Z = 4 $C_{19}H_{21}NO_3$, M = 311.38. The intensity data were measured with a sealed-tube diffractometer (Mo Kα resolution). The crystal dimensions were 0.70 × 0.30 × 0.20 cm^3. There were 2703 unique reflections measured for θ < 25°, of which the 1973 with $I > 3.0sI$ were used for refinement. The data was reduced and the structure solved and refined with use of the SDP package. The solution was obtained by direct methods procedures with MULTAN followed by full-matrix least-squares refinement. Hydrogen atoms were included in the final cycles. The final discrepancy indices are R = 0.040 and R_w = 0.039.

Reaction of 3-Methoxy-3-methyl-1-vinylcyclohexene (7b) with *N*-Phenylmaleimide. A solution of methyl ether **7b** (290 mg, 1.9 mmol) and *N*-phenylmaleimide (330 mg, 1.9 mmol) in dry CH_2Cl_2 (2.5 mL) was kept under high-pressure apparatus for 5 days. The reaction mixture was concentrated, and the ^{1}H NMR of the mixture showed the formation of two products. The concentrated mixture was dissolved in a minimum amount of EtOAc and was cooled overnight in the freezer. The major adduct **18b** crystallized out as a solid, which was filtered (234 mg) and was recrystallized from petroleum ether/EtOAc to furnish colorless crystals (mp 122 °C). The mother liquor was concentrated and subjected to separation by radial chromatography (petroleum ether/$CHCl_3$/acetone, 50:48:2) to give an additional amount of **18b** (56.1 mg, combined yield 46.9%).

Major product **18b**: ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.6-7.24 (m, PhH), 5.7 (br s, C=CH), 3.49 (dd, J = 8.39, 5.49 Hz, COCH), 3.32 (dt, J = 8.7, 2.16 Hz, $COCHCH_2$), 3.23 (s, OCH_3), 2.79 (ddd, J = 16.17, 6.08, 1.98 Hz, =CHCHH), 2.63 (app d, J = 5.35 Hz, allylic CH), 2.46-1.39 (m, 7 H), 1.59 (s, CH_3); ^{13}C NMR (75 MHz, $CDCl_3$) δ 179.09, 177.56, 140.27, 132.14, 129.16, 128.52, 126.42, 119.81, 76.78, 48.5, 45.65, 42.14, 40.95, 31.81, 31.15, 24.02, 21.39, 20.31; IR ($CHCl_3$) 1710, 1500, 1450, 1390 cm^{-1}; high-resolution mass calcd for $C_{20}H_{24}NO_3$ (M^+ + H) 326.1756, found 326.1785.

X-ray Data. The crystals are triclinic, space group $P\bar{1}$, with a = 7.62 (4) Å, b = 9.37 (6) Å, c = 12.33 (3) Å, and ρ_{calc} = 1.28 g cm^{-3} for Z = 2 $C_{20}H_{23}NO_3$, M = 325.41. The intensity data were measured on a rotation anode diffractometer (Cu Kα radiation). The size of the crystal used for data collection was approximately 0.2 × 0.3 × 0.5 mm. A total of 2760 independent reflections were measured for $\theta < 60°$, of which 2333 were used for structure refinement ($I > 3.0\sigma I$). The structure was solved by a multisolution procedure (SDP software) and was refined by full-matrix least squares. In the final refinement, the hydrogen atoms were added and included in the structure factors but their parameters were not refined. The final discrepancy indices are R = 0.109 and R_w = 0.109 and 0.112 for 2333 observed reflections.

The other fraction was the minor adduct **17b** (115 mg, 18.6%), which was isolated along with a trace of NPM. Minor adduct **17b**: ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.6-7.3 (m, PhH), 5.7 (br s, C=CH), 3.46 (dd, J = 8.97, 7.59 Hz, COCH), 3.32 (dt, J = 8.3, 3.44 Hz, $COCHCH_2$), 3.13 (s, OCH_3), 2.8 (m, 1 H), 2.56 (app d, J = 7.69 Hz, allylic CH), 2.5-1.4 (m, 7 H), 1.38 (s, CH_3); IR ($CHCl_3$) 1710, 1495, 1450, 1385 cm^{-1}; high-resolution mass calcd for $C_{20}H_{24}NO_3$ (M^+ + H) 326.1756, found 326.1686.

Reaction of 3-[(Trimethylsilyl)oxy]-3-methyl-1-vinylcyclohexene (7c) with *N*-Phenylmaleimide. A solution of silyl ether **7c** (123 mg, 0.59 mmol) and *N*-phenylmaleimide (102 mg, 0.59 mmol) in dry benzene (2 mL) was stirred for 5 days. The reaction mixture was concentrated, and the ^{1}H NMR showed the formation of two products. PLC separation (petroleum ether/EtOAc, 8:2) furnished two fractions. The major fraction was a mixture of adducts **17c** and **18c** (113 mg, 50%), which could not be further separated. The second fraction was the unreacted NPM (37 mg).

Hydrolysis of Silyl Adduct Mixture of 17c and 18c. To a methanolic solution (2 mL) of a silyl adduct mixture of **17c** and **18c** (113 mg, 0.29 mmol) was added a few drops of saturated oxalic acid solution, and the solution was stirred for 0.5 h. Solvent was removed, and the resulting mass was dried under vacuum. The crude mixture was separated by PLC (CH_2Cl_2/EtOAc, 9:1) to give lactone **19** (16.1 mg, 17.5%) and anti alcohol **18a** (68 mg, 74.1%).

Lactonization of 18a. A methanolic solution (1 mL) of the anti alcohol **18a** (27 mg, 0.08 mmol) with a few drops of saturated oxalic acid solution was kept under reflux for 72 h. Solvent was removed, and the crude mixture was purified by passing through a short column of Florisil and by eluting with EtOAc. Evaporation of solvent furnished a pasty mass, and ^{1}H NMR showed a mixture of products. The major product was identical with the tricyclic lactone **19**. The mixture was not further separated.

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Tandem Anionic [3,3] Sigmatropy and S_N' Displacement. New Synthetic Technology for the Construction of Hydroazulenone and Related Frameworks

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Abstract: Transmetalation of the 3-(trimethylstannyl)-2-norcarenes **9** and **28b** provides for the acquisition of optically pure bicyclic vinyllithium derivatives. These have been added to (±)-2-chlorocyclohexanone and the resultant *cis*-chlorohydrins have been exposed to excess vinylmagnesium bromide under conditions which promote pinacol rearrangement and allow for subsequent 1,2-addition to the newly liberated carbonyl group. Following analysis of the response of divinyl carbinols **12** and **13** to anionic oxy-Cope rearrangement, the title process has been examined for **31-34**. The precise conformational demands have been analyzed for each example. To some extent these are a function of the usual energetic advantages that accrue to chairlike conformations. However, other factors clearly contravene. These capabilities allow in turn for both syn and anti S_N' displacement of methoxide ion. The sequential operation of a [3,3] sigmatropic step and S_N' displacement is shown to be a powerful tool for rapid hydroazulenone construction.

Hydroazulenoid ring systems are structural units frequently encountered in naturally occurring substances such as the guaianolides and pseudoguaianolides.[2] Due to the high level of interest in these bioactive molecules[3] and the well-recognized problems associated with medium-ring construction, elaboration of these often richly functionalized target molecules has come to be regarded as a challenging and attractive synthetic undertaking. Achievements in the last 15 years have been truly impressive, culminating inter alia in total syntheses of bulnesol,[4] carpesiolin,[5] confertin,[6] cyclocolorenone,[7] damsin,[8] damsinic acid,[9] estafiatin,[10]

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