Synthesis and Mechanistic Study of Fused 2-Pyrrolines via Thermolysis of 6-Substituted-3,5-hexadienyl Azidoformates

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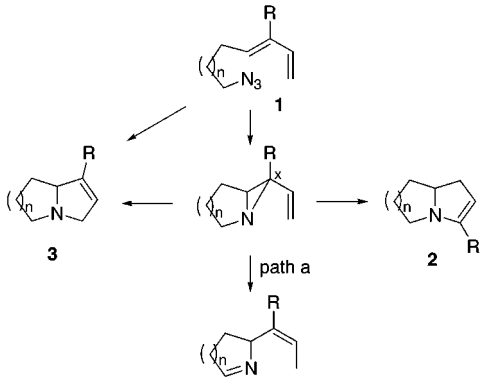
Thermolysis of 3,5-hexadienyl azidoformates at 300 °C, 0.05 Torr, led to a fused 2-pyrroline regiospecifically, regardless of the configuration *E* or *Z* between the C-3 and C-4 double bond. Thermolysis of 6-substituted-3,5(*E*)-hexadienyl azidoformates yielded a kinetically controlled 2-pyrroline with cis configuration between H-1 and H-8a whereas 6-substituted-3,5(*Z*)-hexadienyl azidoformates produced a cis and trans mixture. The mechanism was proposed as the loss of nitrogen to form an acyl nitrene, then addition to a double bond to produce an aziridine. Finally the cleavage of the C−C bond generated a vinylazomethine ylide followed by recyclization to a fused 2-pyrroline.

Introduction

Hudlicky[1] and Pearson[2] extensively applied formal [4 + 1] cycloaddition of azides **1** across a conjugated diene to form indolizidines and pyrrolizidines (Scheme 1). Dienyl azide, the nitrene precursor, was found thermally to undergo intramolecular cycloaddition and loss of nitrogen to give vinylaziridine before rearrangement to pyrroline. Aziridine reactions involving C−N bond cleavage[1b,2a,3] occasionally competed with those involving C−C bond cleavage.[4] Therefore, the regiochemistry of the resulting pyrroline, either 2-pyrroline **2** or 3-pyrroline **3**, was determined mainly by the substitution of the starting dienes and on the experimental conditions of the reaction. For example, the absence of substituent on the diene (**1**, R = H) resulted in a complicated reaction mixture. The presence of a carbethoxyl group on the diene (**1**, R = CO_2-Et) gave C-2 functionalized 2-pyrroline **2** due to C−C bond cleavage.[1b] However, the presence of a thioether group on the diene (**1**, R = SPh) led to C-3 functionalized 3-pyrroline **3** through C−N bond cleavage as a result of the ketal-like center at C_x.[2a] A homodienyl [1,5]-hydrogen shift behaved as another intensely competing reaction (path a).

Scheme 1



A structural change in the reactant was investigated to promote the thermal intramolecular cycloaddition of dienyl azide. We chose *N*-acyl function that could prevent the homodienyl hydrogen shift. The developing amide functionality might stabilize the product, as well as the reactant. However, the thermolysis of acyl azides caused Curtius rearrangement, exclusively yielding isocyanates. Accordingly, dienyl azidoformate **4** was the candidate molecule for exploring the intramolecular cycloaddition. Even though Lwowski et al. has shown that no pyrroline product was observed when carbethoxynitrene reacted with 1,3 dienes,[5] a technique of flash vacuum thermolysis[6] (FVT) would still be a means of producing nitrene and inducing the subsequent thermal cycloaddition. The intramolecular cycloaddition of the azidoformate is an interesting and a potentially valuable transformation in heterocyclic organic chemistry. This is the first time that the thermal cyclization of the dienyl azidoformate has been studied.

The dienyl azidoformate **4** should be obtainable from the corresponding dienyl alcohol by azidoformylation with trichloromethyl chloroformate (diphosgen, $ClCO_2CCl_3$)

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(3) (a) Lindstrom, U. M.; Somfai, P. *J. Am. Chem. Soc.* **1997**, *119*, 8385. (b) Wipf, P.; Fritch, P. C. *J. Org. Chem.* **1994**, *59*, 4875. (c) Stamm, H.; Falkenstein, R. *Chem. Ber.* **1990**, *123*, 2227. (d) Stamm, H.; Sommer, A.; Woderer, A.; Wiesert, W.; Mall, T.; Assithianakis, P. *J. Org. Chem.* **1985**, *50*, 4946. (e) Mente, P. G.; Heine, H. W. *J. Org. Chem.* **1971**, *36*, 3076. (f) Heine, H. W.; Kaplan, M. S. *J. Org. Chem.* **1967**, *32*, 3069. (g) Pepito, A. S.; Dittmer, D. C. *J. Org. Chem.* **1997**, *62*, 7920. (h) Bergmeier, S. C.; Stanchina, D. M. *J. Org. Chem.* **1999**, *64*, 2852.

(4) (a) Anastassiou, A. G.; Hammer, R. B. *J. Am. Chem. Soc.* **1972**, *94*, 303. (b) Nozaki, H.; Fujita, S.; Noyori, R. *Tetrahedron* **1968**, *24*, 2193.

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(6) (a) Wu, P. L.; Wang, W. S. *J. Org. Chem.* **1994**, *59*, 622. (b) Wu, P. L.; Chen, H. C.; Line, M. L. *J. Org. Chem.* **1997**, *62*, 1532. (c) Wu, P. L.; Chu, M.; Fowler, F. W. *J. Org. Chem.* **1988**, *53*, 963. (d) Wu, P. L.; Fowler, F. W. *J. Org. Chem.* **1988**, *53*, 5998.

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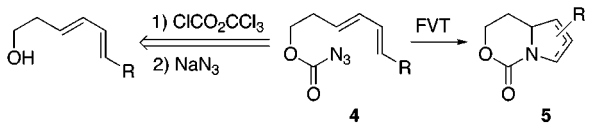
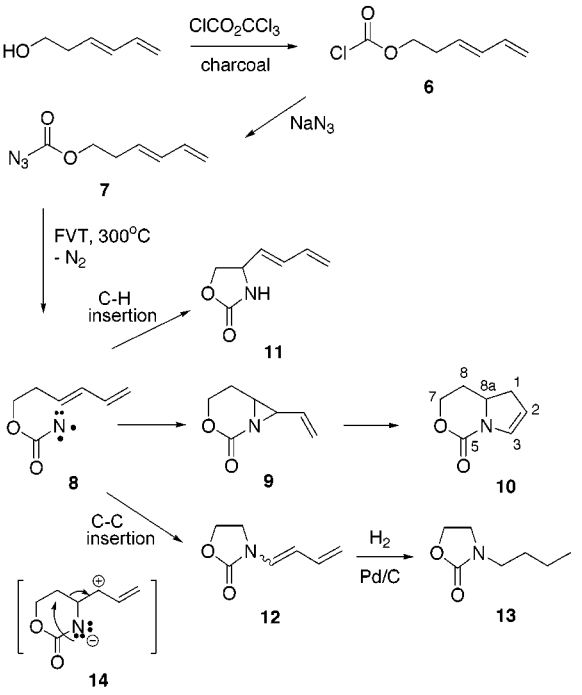
Scheme 2



Scheme 3



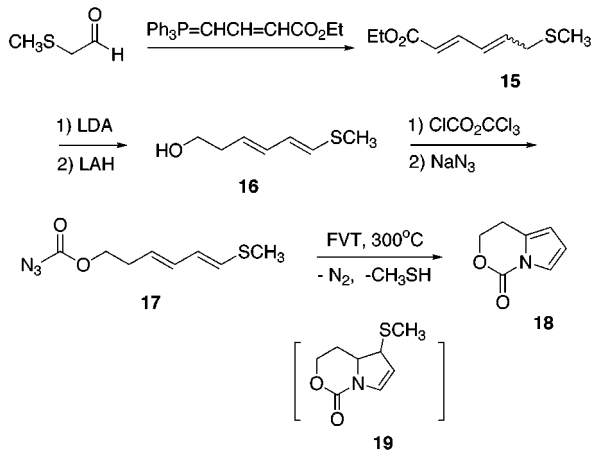
and sodium azide (NaN_3) (Scheme 2). The dienyl alcohol could in turn be produced by the general Wittig reaction. An oxaindolizidinone ring **5** was produced by the cycloaddition of this dienyl azidoformate **4** through FVT.

Results and Discussion

Initial model involved the research in unsubstituted dienyl azidoformate **7** (Scheme 3). Chloroformate **6** could be synthesized by slowly adding (*E*)-3,5-hexadien-1-ol into a suspension of diphosgen along with activated charcoal. The subsequent reaction between **6** and NaN_3 in dry acetone produced the desired azidoformate **7** in high yield.[7]

The azidoformate **7** was quite thermally stable and was almost quantitatively recovered after evaporation through a FVT tube at 250 °C and 0.05 Torr. The starting material was completely consumed at 300 °C and generated a fused 2-pyrroline **10** at a 33% isolated yield. 2-Pyrroline **10** was verified by the ^{1}H NMR spectrum that showed a more downfield shifted signal at δ 6.61 and a more upfield shifted signal at δ 5.17, typical for two protons in an enamine. In addition, the C−H insertion product, isoxazolone **11**, was purified in a 10% yield, and the apparent C−C insertion product, isoxazolone **12**, was isolated as a cis and trans isomeric mixture in a 20% combined yield. The compound **12** might have been obtained by the Wagner-Meerwein rearrangement of the betaine **14** that came from the stepwise addition of nitrene to the double bond.[8] Hydrogenation of the mixture **12** resulted in a single isoxazolone **13**. On the basis of

Scheme 4



the above analysis, the production of 2-pyrroline **10**, rather than 3-pyrroline, and the formation of isoxazolones **11** and **12** showed that the initial step probably involved a loss of nitrogen, forming the active nitrene intermediate **8** at such a high temperature.[9] Subsequently, nitrene **8** underwent a cyclization to form 2-vinylaziridine **9**[10] followed by the rearrangement through C−C bond cleavage to yield pyrroline **10**. Thus, a carbonyl substituent on nitrogen made the cyclization compete more effectively with insertion and inhibited homodienyl hydrogen shift reactions. Attempts to influence the ratio of 2-pyrroline to isoxazolone by varying the FVT temperature caused little change. At high temperature, the product became complex.

The addition of nitrene to the double bond and the rearrangement of vinylaziridine both depended on substitution. With this initial result, we examined the FVT of a series of dienyl azidoformates that possessed substituents on the end of the double bond.

The methylthio group was first selected for this purpose (Scheme 4). The Wittig reaction between methylthioacetaldehyde and (3-carbethoxyallyl)triphenylphosphorane ylide generated a geometric mixture of 6-methylthio-2,4-dienyl ester **15**. Since these isomers produced the same product in the next step, it was not necessary to separate them. Kinetic deconjugation of **15** with LDA and reduction with $LiAlH_4$ yielded the 3(*E*),5(*E*)-dienyl alcohol **16** as the major product. The desired 3(*E*),5(*E*)-dienyl azidoformate **17** was synthesized by chloroformylation with trichloromethyl chloroformate followed by azidonation with NaN_3. This methylthiodienyl azidoformate **17** was subjected to FVT and gave fused pyrrole **18** as the only product at a 40% yield. Apparently the elimination of methanethiol to **18** occurred once the 2-pyrroline **19** was formed.[2a,11] According to the crude ^{1}H NMR analysis, the cyclization of azidoformate **17** hap-

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(8) (a) Goldsmith, D. J.; Soria, J. *Tetrahedron Lett.* **1986**, *27*, 4701. (b) Dauben, W. G.; Bunce, R. A. *J. Org. Chem.* **1982**, *47*, 5042. (c) Wohl. R. A. *Tetrahedron Lett.* **1973**, 3111.

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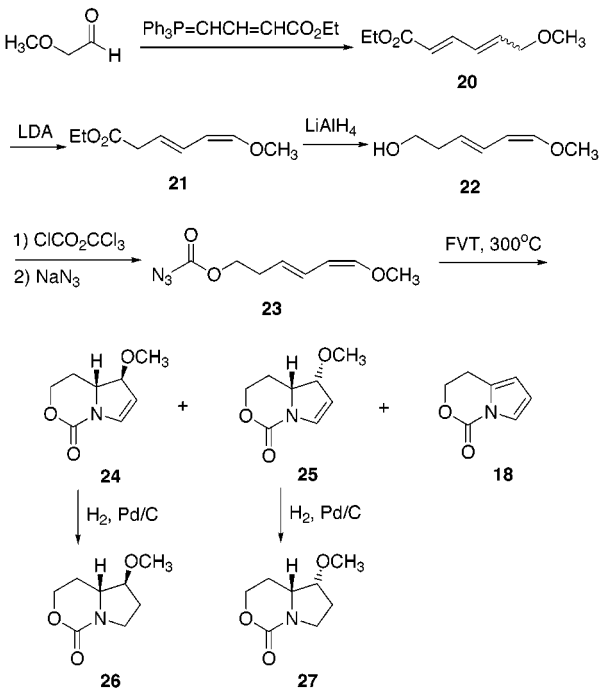
(10) The 2-vinylaziridine was not detected in gas phase thermolysis even at lower temperature. Actually, using a sealed tube, thermolysis of a solution of 6-phenyl-3(*E*),5(*E*)-hexadienyl azidoformate (**34**) in $CHCl_3$ at 150 °C does produce the 2-vinylaziridine which could be recognized from the ^{1}H NMR spectrum of the crude material. The purification of vinylaziridine failed.

(11) Kheruze, Y. J.; Galishev, V. A.; Petrov, A. A.; *J. Org. Chem. USSR* **1988**, *24*, 852.

Scheme 5



pened more cleanly than that of unsubstituted azidoformate **8**. All attempts to observe the isoxazolone product by insertion and 3-pyrroline product by 1,4-addition failed.

An azidoformate **23** bearing a methoxyl substituent on the terminal double bond was synthesized as depicted in Scheme 5. In contrast to **15**, deconjugation of a 2.5:1 mixture of 2(*E*),4(*E*)- and 2(*E*),4(*Z*)-conjugated ester **20** led to a 1:1 mixture of 3(*E*),5(*E*)- and 3(*E*),5(*Z*)-dienyl ester **21**.[12] The separation of the 3(*E*),5(*Z*) and 3(*E*),5(*E*) ester was unsuccessful due to the instability of the enol ether structure in **21**. The hydrolysis of **21** to aldehyde during prolonged chromatography over silica gel was seen. Therefore, a low yield of pure 3(*E*),5(*Z*)-hexadienyl ester **21** was obtained for the following reaction. Reduction of **21** with $LiAlH_4$ yielded alcohol **22** which was subjected to chloroformylation and azidonation to produce the 3(*E*),5(*Z*)-dienyl azidoformate **23**. When pure **23** was thermolyzed, 2-pyrrolines **24** and **25** with a 2:1 ratio were isolated in a 44% combined yield. In addition, the fused pyrrole **18** was obtained in a 11% yield.[13] Neither the 1,4-addition product nor the insertion product was observed. Owing to the lability of 2-pyrroline during column chromatography, only the major **24** was separated for spectral analysis. The compound **25** was also isolated. However, we observed that, after 1 day, compound **25** in $CDCl_3$ decomposed to **18** cleanly. Fortunately, two pyrrolidines **26** and **27** from the hydrogenation of the mixture of **24** and **25** were readily separated for spectral and stereochemical examination. Comparing the total FVT yield of azidoformates **17** and **23** with that of unsubstituted **8**, placing an electron-donating group at terminal double bond might increase the reactivity of azidoformate toward cyclization.

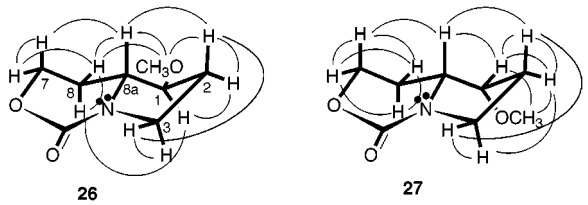
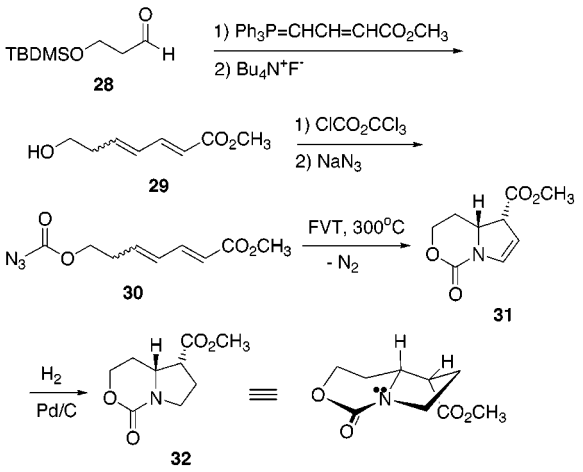


Figure 1. The NOE correlations of compounds **26** and **27**.

Scheme 6



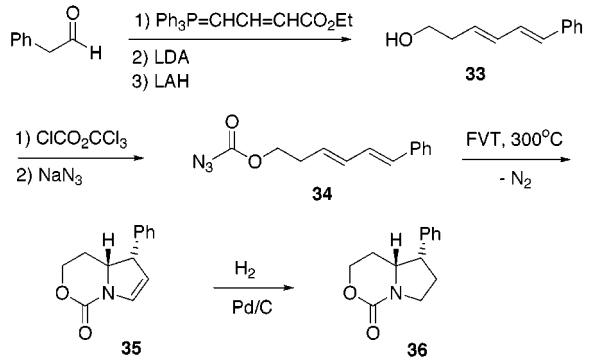
The stereochemical features of the annulation were investigated after the regiochemistry of 2-pyrroline, instead of 3-pyrroline, was solved by the chemical shifts of two vinyl protons (δ 5.37 and 6.73 for **24**; 5.57 and 6.89 for **25**). The stereochemistry of the newly formed chiral center (C-1) relative to the bridgehead chiral carbon (C-8a) and the full assignment of ^1H and ^{13}C NMR signals were obtained from 2D-COSY, HMQC, and NOESY spectra. For simplicity, we use α and β terminology for substituents, α substituents being below the ring. In 2-pyrroline **24**, the presence of NOE between H-1 (δ 4.69) and H-8α (δ 1.95) and the absence of NOE between H-1 and H-8a (δ 3.93) suggested a trans relationship between the protons H-1 and the ring junction methine H-8a, requiring that the methoxyl substituent orientated toward β direction. Moreover, the separable hydrogenated products **26** and **27** also offered stereochemical information because the hydrogenation did not affect the stereogenic center. The absence of NOE between H-8a and H-3β in **26** and **27** led us to tentatively assign the cis conformation (Figure 1). In **26**, the NOEs of H-1 (δ 3.50) with H-8α and/or H-2α (δ 1.71) as well as OCH_3 (δ 3.39) with H-8a (δ 3.36), H-8β and/or H$-$2β (δ 2.28) further confirmed the β-methoxyl orientation (Figure 1). In contrast, the presence of NOEs between H-1 (δ 3.82) and H-8a (δ 3.60), H-2α (δ 2.17), H-2β (δ 1.75) as well as the NOEs between OCH_3 (δ 3.33) and H-2α (δ 2.17) showed an α-methoxyl orientation in **27**.

Subsequently, we prepared an accessible dienyl azidoformate **30** consisting of an electron-withdrawing group CO_2CH_3 at the terminal double bond (Scheme 6). The Wittig reaction between a protected hydroxyaldehyde **28** and (3-carbomethoxypropenyl)triphenylphosphorane followed by deprotection directly yielded the desired alcohol **29** in a 3(*E*),5(*E*) and 3(*Z*),5(*E*) mixture. Chloroformylation and azidonation of **29** afforded a mixture of 3(*E*),5(*E*)- and 3(*Z*),5(*E*)-dienyl azidoformate **30**. Although we did not intend to separate mixture **30**, a single cyclization

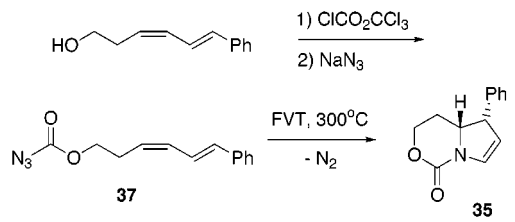
(12) (a) Gutierrez, A. J.; Shea, K. J.; Svoboda, J. J. *J. Org. Chem.* **1989**, *54*, 4335. (b) Grieco, P. A.; Yoshida, K.; He, Z. M. *Tetrahedron Lett.* **1984**, *25*, 5715.

(13) We left the compound **25** in $CDCl_3$ for 1 d and then recorded the ^1H NMR spectrum again. Compound **18**, instead of **25**, was found cleanly by the loss of methanol.

Scheme 7



Scheme 8

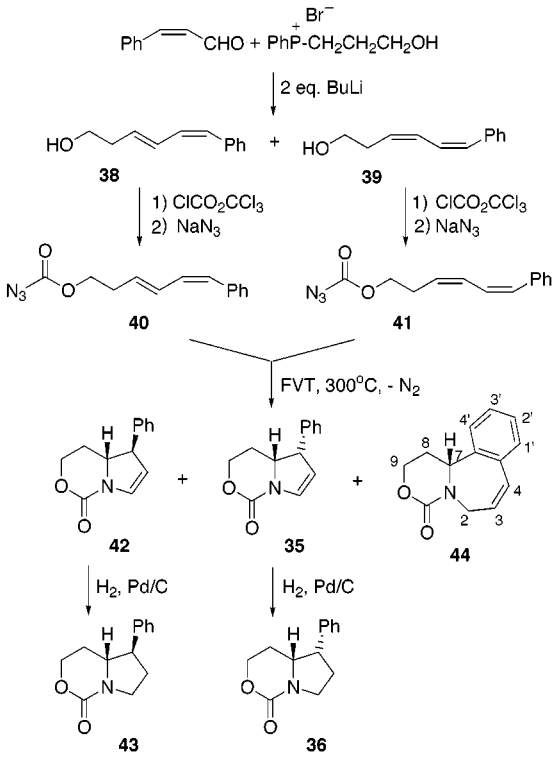


product **31** was obtained stereospecifically at a 71% yield when it was sent through the FVT tube, implying that the thermal rearrangement of **30** with 3(*E*)- and 3(*Z*)-geometry proceeded through the same intermediate at a certain stage. The complete assignments and the α-carbomethoxyl stereochemistry of **31** and its hydrogenated product **32** were clarified by COSY, HMQC, and NOESY 2D-NMR spectra. The structure of **31** was also specified by a single-crystal X-ray analysis on the pyrrolidine **32**. The crystal structure data confirmed that the carbomethoxyl group of **32** occupied an α position. The lone pair electrons on nitrogen were cis to the bridgehead proton. Furthermore, the cis-fused oxaindolizidinone skeleton showed that the six-membered ring was present as a boatlike conformation and the pyrrolidine ring adopted an envelop conformation.

A phenyl substituent as part of the conjugation of the double bond in the azidoformate **34** was synthesized from phenylacetaldehyde (Scheme 7). Evaporating compound **34** through the FVT tube at 300 °C resulted in a stereospecific fused 2-pyrroline **35** at a 51% yield. The NOE between H-1 (*δ* 4.15) and H-8a (*δ* 4.39) demonstrated that the phenyl substituent placed in the α direction. The NOEs of hydrogenated pyrrolidine **36** between H-1 (*δ* 3.47) and H-8a (*δ* 3.92), H-2*β* (*δ* 2.33); H-2′, H-6′ of phenyl (*δ* 7.02) and H-2α (*δ* 2.14), H-3α (*δ* 4.03), H-8α (*δ* 1.22) further clarified the α phenyl stereochemistry.

The opposite stereoisomers must be considered to examine the nature of this stereoselection in detail. We selected the azidoformate with a phenyl substituent as an example. Using the same procedure as described above for the preparation of azidoformate, 6-phenyl-3(*Z*),5(*E*)-hexadien-1-ol yielded 3(*Z*),5(*E*)-dienyl azidoformate **37** (Scheme 8). FVT of **37** at 300 °C gave 2-pyrroline **35** at ca. 50% yield. Surprisingly, both 3(*E*),5(*E*)-azidoformate **34** and 3(*Z*),5(*E*)-azidoformate **37** afforded the same cyclized product **35** in the same yield. This phenomenon let us to make a conclusion that an identical FVT product was obtained regardless of the *E* or *Z* geometry of the C-3 and C-4 double bond in the 3,5-hexadienyl azidoformates.

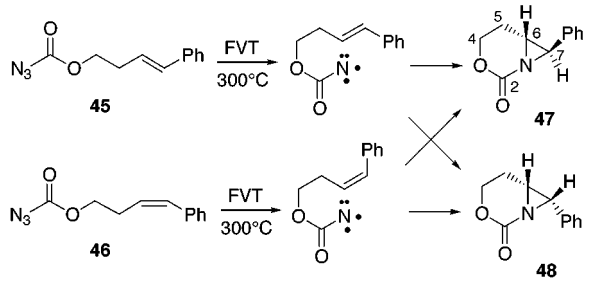
Scheme 9



Cyclizing the isomers with *Z* configuration at the C-5 and C-6 double bond would reveal whether the same product as **35** or an epimer was produced, providing some insight into the cyclization mechanism. The Wittig reaction between (*Z*)-3-phenylpropenal and (3-hydroxypropyl)triphenylphosphonium bromide in the presence of two equivalents of *n*-BuLi produced a mixture of 3(*E*),5(*Z*)-alcohol **38** and 3(*Z*),5(*Z*)-alcohol **39** in a 1:2 ratio (Scheme 9). A pure **39** and a material **38** contaminated with a little **39** was carefully separated by column chromatography. Azidoformylation of **38** and **39** yielded azidoformates **40** and **41**, respectively. FVT of 3(*Z*),5(*Z*)-azidoformate **41** yielded 30% of a tricyclic compound **44** and two 2-pyrroline products with about a 1:2 ratio in a ca. 39% combined yield. The two 2-pyrrolines showed a very similar but not identical NMR spectra. The major 2-pyrroline exhibited spectral data identical with those of **35** having an α orientated phenyl group. The minor one was assigned for the epimer **42** owing to the presence of NOE between phenyl group (*δ* 7.30) and H-8a (*δ* 3.93). The mixture of **35** and **42** was hydrogenated to give the separable pyrrolidines **36** and **43**, respectively. The relative configuration of **43** at junction carbon C-8a and phenyl substituted carbon C-1 was addressed by the 2D-NMR experiments. The existence of NOEs of H-1 (*δ* 2.82) with H-2α (*δ* 2.30) and H-8α (*δ* 1.68); phenyl (*δ* 7.24) with H-8a (*δ* 3.51), H-2*β* (*δ* 2.12), and H-8*β* (*δ* 2.01) led to a *β*-phenyl in **43**. FVT of 3(*E*),5(*Z*)-azidoformate **40** gave almost identical product ratio as **41**. Therefore, the isomeric ratio of **35** and **42** would be independent of the geometry of the C-3 and C-4 double bond again. The production of two stereoisomeric 2-pyrrolines from 3,5(*Z*)-azidoformates **40** and **41** was similar to that observed in the case of FVT of azidoformate **23** involving 5(*Z*)-6-OCH_3 structure.

Resubjection of pyrrolines **35** or **42** through a hot tube under the same FVT condition resulted in recovery of starting material quantitatively. At higher FVT temperature, the starting material recovered was contaminated

Scheme 10



with some unknown compounds, none of which were its epimer or **44**. No equilibrium was established between **35** and **42**.

Mechanistic Study. Since the reaction temperature of 300 °C was above that normally required for the formation of nitrene from azides, the cyclization reaction of 3,5-hexadienyl azidoformate unambiguously proceeded by the loss of nitrogen followed by double bond addition to form vinylaziridine. We postulated that the initial aziridine formation might have been nonstereospecific from the fact that 3(*E*),5(*E*)-phenylazidoformates **34** and 3(*Z*),5(*E*)-phenylazidoformate **37** or the mixture of 3(*Z*),5-(*E*)- and 3(*E*),5(*E*)-carbomethoxyazidoformates **30** always cyclized to give 2-pyrroline derivatives **35** or **31** as the exclusive product. It was reported that alkenes isomerized considerably more slowly than the rate of cyclization.[14] To prove it, 1-phenyl-1(*Z*),3(*Z*)-heptadiene which lacked an azidoformate group was synthesized and did not isomerize into any of the *E* isomer under the same FVT conditions. Hence, the formation of vinylaziridine from its corresponding nitrene should be not stereospecific. The suggestion was confirmed by the FVT of (*E*)- and (*Z*)-4-phenyl-3-butenyl azidoformates **45** and **46** under identical conditions. Both **45** and **46** generated a mixture of aziridines **47** and **48** in 6:1 and 2.5:1 ratios, respectively, without retaining the configuration (Scheme 10).[15] The identity of **47** and **48** was determined by the ^{1}H NMR spectral characteristics of two methine protons on an aziridine ring. The trans methine protons in **47** appeared at δ 2.83 (ddd, J = 8.7, 6.2, 3.0 Hz, H-6β) and 3.30 (d, J = 3.0 Hz, H-7α) with an expected smaller coupling constant (3.0 Hz), whereas the cis methine protons in **48** at δ 3.14 (ddd J = 11.3, 6.3, 5.0 Hz, H-6β) and 3.91 (d, J = 5.0 Hz, H-7β) with a larger coupling constant (5.0 Hz).[16] Accordingly, at such a high temperature and a short reaction time, the formation of the adducts **47** and **48** was readily interpreted by assuming that **45** and **46** initially lose nitrogen to leave active triplet nitrenes which subsequently cyclized with a neighboring double bond to form nonstereospecifically the primary cycloadducts.[17]

The above facts could be accommodated by Scheme 11. The double bond isomerization did not occur and nonstereospecific cyclization from dienyl acylnitrene to vinylaziridines **49** and **50**, or **54** and **55** happened during the FVT process. Because *cis*- and *trans*-vinylaziridines **49** and **50**, or **54** and **55** produced the same intramolecular cycloadducts **53** or **58**, the azomethine ylides **51**, **52**, **56**, and **57**, a fully conjugated 1,3-dienyl anion, was proposed as the intermediate in this process.[18] In fact, cleavage of the allylic C−N bond was preferred when the substituent on nitrogen was an anion-stabilizing group, for example, a carbethoxyl group. The energetic cost of making the cleavage of C−C bond was partially compensated by the resonance of the vinylazomethine ylide.

In the case of 5(*E*)-azidoformates, the formation of azomethine ylides **51** and **52** from aziridines **49** and **50** ($\Delta G^{\ddagger}$ ca. 122 kJ/mol) was usually controlled by the 4-electron conrotatory ring opening. A rotation about one of the ylide C−N bonds ($\Delta G^{\ddagger}$ ca. 92 kJ/mol) led to the loss of original stereochemistry.[19] The conformation given in **52** was required for successful closure to form the 2-pyrroline **53**. An equilibrium should present between **51** and **52**. In addition to possess the same intermediate **52**, the reclosure of the vinylazomethine ylide underwent a 6-electron electrocyclic reaction with disrotatory process, producing the thermodynamically less stable product **53**.[18e,f,20] Complete control of the stereochemistry of C-1 was thus observed.

Similarly, 5(*Z*)-azidoformates lost nitrogen and cyclized nonstereospecifically to vinylaziridines **54** and **55**. The three-membered ring was opened to form azomethine ylides **56** and **57**. The vinylazomethine ylide **57** proceeded through a disrotatory recyclization and gave the expected 2-pyrroline **58** with β-orientated substituent. The terminal substituent in **57** which was cis to the diene chain was forced to assume a more crowded position than in **52**. Furthermore, the double bond character was reduced by resonance among the dienyl anion system and rotation from **57** to **52** was made possible.[21] Therefore, the cyclization of **57** to **58** obtained from 5(*Z*)-azidoformates was slow enough to allow competition from isomerization via rotation about the C−C double bond to form **52** which then cyclized to **53**. Comparing the FVT product ratio for the phenyl substituent (β-Ph-**42**:α-Ph-**35** = 1:2) to that for methoxyl substituent (β-OCH$_3$-**24**:α-OCH$_3$-**25** = 2:1), the larger phenyl group was seriously hindered in the azomethine ylide stage and gave more α-phenyl product **35** (R = Ph).

The isolation of **44** provided a sufficient evidence for the formation of vinylazomethine ylide **57**. Electrocyclic reaction of **57** (R = Ph) through 8-electron conrotatory

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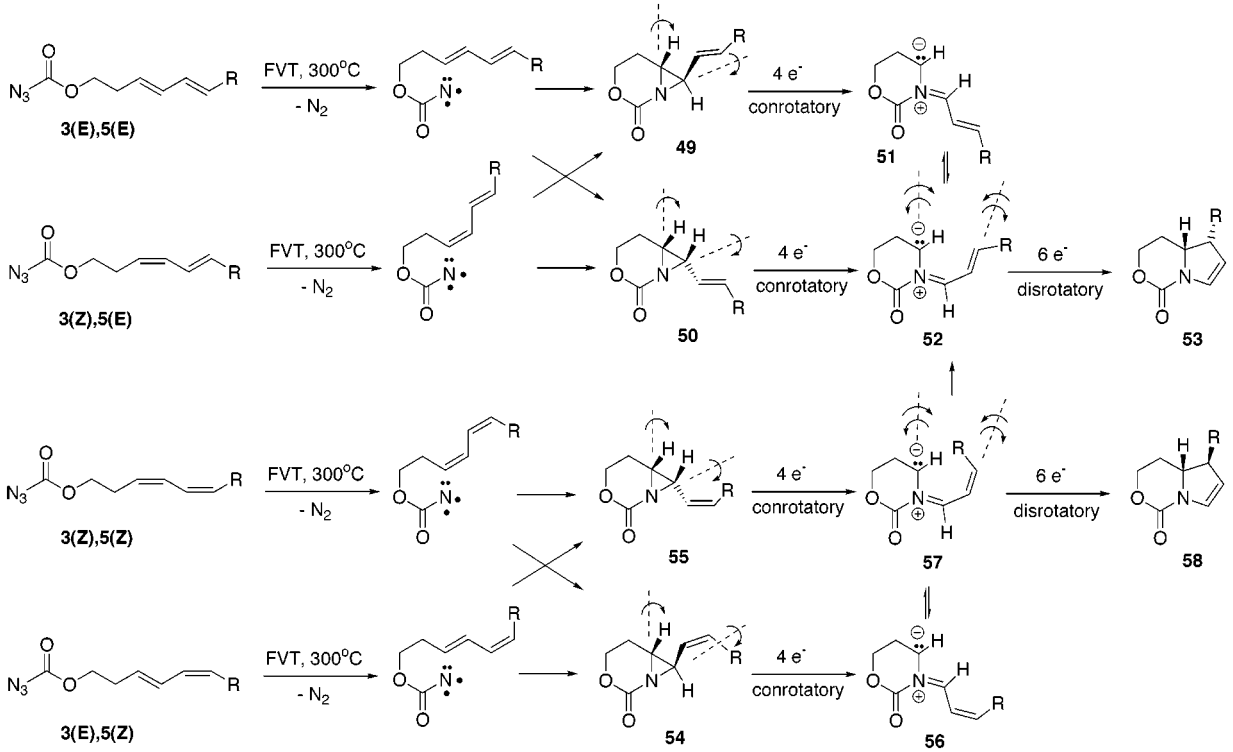
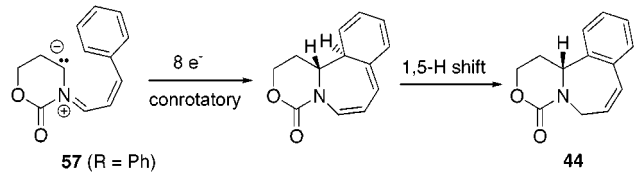
Scheme 11



Scheme 12



process followed by a 1,5-hydrogen shift to form **44** (Scheme 12) competed with the direct cyclization to form **53** and **58**.

The actual yield of 2-pyrrolines reflected the reactivity of azidoformates. The electron-withdrawing substituent CO_2CH_3 (71% yield) and the conjugating group Ph (50% yield) attached to the terminal double bond of the diene could stabilize the vinylazomethine ylides and accelerate the disrotatory rotation to 2-pyrrolines. The electron-donating substituent OCH_3 retarded the cyclization.[22] However, the combined yield of two isomeric 2-pyrrolines **24** and **25**, and one demethanol product **18** was 55%. This value was attributed to the fact that an oxygen-containing substituent could still stabilize the positive charge on nitrogen by inductive effect. Furthermore, an electron-donating group could facilitate the primary cycloaddition for the electron-deficient nitrene to the electron-rich double bond, enhancing the reaction.[23]

In summary, the FVT of 3,5-hexadienyl azidoformates gave a regiospecific and stereospecific fused 2-pyrroline. This azide-diene annulation occurred by nitrogen extrusion to form a triplet acylnitrene then intramolecular cycloaddition to yield a mixture of aziridines. The cleavage of C−C bond produced vinylazomethine ylide followed by recyclization to give 2-pyrroline through a 6-electron disrotatory mode. Regardless of *E* or *Z* configuration between the C-3 and C-4 double bond, the 3,5-hexadienyl azidoformates gave the same products. The *E* configuration on the C-5 and C-6 double bond yielded a kinetically controlled product with the substituent in the α-position, whereas the *Z* configuration produced a mixture of the substituent toward α- and *β*-direction. The reactivity of the cycloaddition of azidoformates increased by the presence of substituents at the terminal double bond, such as methoxycarbonyl, methylthio, methoxyl, and phenyl.

Experimental Section

General. Melting points were taken on a Buchi 535 melting-point apparatus and were not corrected. Infrared spectra were measured on a Nicolet Magna FT-IR spectrometer as either thin films or solid dispersions in KBr. Nuclear magnetic resonance spectra were recorded on Bruker AC-200 and AMX-400 FT-NMR spectrometers; all chemical shifts are reported in ppm from tetramethylsilane as an internal standard. Low- and high-resolution mass spectra were obtained on a VG 70−250S spectrometer. Elemental analyses were performed on a Heraeus CHN−RAPID elemental analyzer. Column chromatography was carried out using 70−230 mesh silica gel (E. Merck). The alkenyl azidoformates, for example 6-phenyl-3,5-hexadienyl azidoformate (**34**), could decompose at ∼150 °C from DTA (differential thermal analysis) data.[9a,24]

(*E*)-3,5-Hexadienyl Azidoformate (7). A suspension of trichloromethyl chloroformate (0.59 g, 3 mmol) in THF (25 mL) along with catalytic amount of activated charcoal (5 mg, 0.4 mmol) was stirred at room temperature for 10 min. A solution of (*E*)-3,5-hexadien-1-ol[25] (0.39 g, 4 mmol) in THF (10 mL) was added dropwise for 2 h. The reaction mixture was stirred for an additional hour at room temperature. The resulting mixture

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was filtered and concentrated under reduced pressure to produce chloroformates **6** quantitatively. This chloroformate could be used in the following reaction without further purification. Therefore the chloroformate **6** added immediately into a suspension of NaN_3 (0.52 g, 8 mmol) in dry acetone (20 mL) and stirred for 3 h at room temperature.[7] The reaction mixture was filtered, concentrated in vacuo, and chromatographed over silica gel eluting with hexane−EtOAc (30:1) to yield azidoformate **7** (0.55 g, 83% yield) as colorless oil: IR (film) ν_{max} 2184, 2136, 1728, 1238 cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 2.47 (2H, q, J = 6.8 Hz), 4.24 (2H, t, J = 6.8 Hz), 5.04 (1H, dd, J = 10.3, 1.9 Hz), 5.14 (1H, dd, J = 16.7, 1.9 Hz), 5.62 (1H, dt J = 14.8, 6.8 Hz), 6.13 (1H, dd, J = 14.8, 10.3 Hz), 6.30 (1H, dt, J = 16.7, 10.3 Hz); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 31.6, 67.5, 116.5, 128.3, 134.0, 136.5, 157.4; MS *m*/*z* (rel int) 167 (2, M^+), 80 (100), 67 (26), 55 (15), 53 (14); HRMS *m*/*z* 167.0659 (Calcd for $C_7H_9N_3O_2$ 167.0695).

General Method for FVT. A modified FVT technique was applied. A hollow tube (10 mm i.d. × 200 mm length) wraped with a heating tape was attached by two flasks. One long flask as a receiver had a sidearm for appling vacuum. The reactant (10∼300 mg) was frozen in the other small flask under liquid nitrogen bath, and a vacuum was applied. Once the vacuum (0.1−0.01 Torr) had been established, the heater was turned on. The temperature of the hot tube was regulated by a temperature controller. When the set temperature was reached, the receiver was placed in a liquid nitrogen bath and the reactant was heated to thaw and evaporate through the hot tube. The product was condensed in the receiver and washed out with acetone. After removal of the solvent, the crude product was purified by column chromatography over silica gel eluting with hexane−EtOAc (1:1).

By the general method for FVT, azidoformate **7** (167 mg, 1 mmol) gave **10** (46 mg, 33% yield), **11** (14 mg, 10% yield), and a cis and trans mixture of **12** (28 mg, 20% yield).

6-Oxa-1,7,8,8a-tetrahydroindolizin-5-one (10). White powder (EtOAc−hexane), mp 50−51 °C; IR (KBr) ν_{max} 1694 (C═O) cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 2.00 (1H, m), 2.23 (1H, m), 2.49 (1H, m), 2.72 (1H, m), 4.13 (2H, m), 4.37 (1H, m), 5.17 (1H, m), 6.61 (1H, m); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 28.1, 36.7, 56.7, 66.8, 109.7, 129.8, 150.0; MS *m*/*z* (rel int) 139 (64, M^+), 94 (77), 80 (56), 67 (100), 53 (28). Anal. Calcd for $C_7H_9NO_2$: C, 60.42; H, 6.52; N, 10.07. Found: C, 60.38; H, 6.65; N, 10.08.

4-(1,3-Butadienyl)-2-oxazolidinone (11). Colorless oil; IR (film) ν_{max} 3268 (br, NH), 1737 (C═O) cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 4.04 (1H, dd, J = 7.8, 6.5 Hz), 4.48 (2H, m), 5.18 (1H, d, J = 9.3 Hz), 5.27 (1H, d, J = 16.4 Hz), 5.62 (1H, dd, J = 14.5, 7.4 Hz), 6.2 (1H, br s, NH), 6.25 (2H, m); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 54.8, 70.2, 118.8, 132.9, 133.8, 136.8, 159.7; MS *m*/*z* (rel int) 139 (40, M^+), 94 (20), 80 (100), 68 (27), 53 (26); HRMS *m*/*z* 139.0636 (Calcd for $C_7H_9NO_2$ 139.0633).

***N*-Butyl-2-oxazolidinone (13).** The inseparable geometric mixture **12** was subjected to hydrogenation using 5% Pd/C as catalyst in EtOAc at room temperature for 12 h. The reaction mixture was filtered, concentrated in vacuo, and chromatographed over silica gel eluting with hexane−EtOAc (1:1) to yield **13** quantitatively as colorless oil: IR (film) ν_{max} 1743 (C═O) cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 0.92 (3H, t, J = 7.4 Hz), 1.33 (2H, sextet, J = 7.4 Hz), 1.52 (2H, quintet, J = 7.4 Hz), 3.24 (2H, t, J = 7.4 Hz), 3.53 (2H, t, J = 8.0 Hz), 4.30 (2H, t, J = 8.0 Hz); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 13.6, 19.8, 29.4, 43.9, 44.5, 61.6, 158.5; MS *m*/*z* (rel int) 143 (3, M^+), 128 (24), 100 (60), 56 (100); HRMS *m*/*z* 143.0947(Calcd for $C_7H_{13}NO_2$ 143.0946).

Ethyl 6-Methylthio-2,4-hexadienoate (15). The Wittig reaction used by Mallory et al. was slightly modified to reduce the decomposition of phosphorane.[26] A solution of (3-carbethoxyallyl)phosphoniun bromide[27] (3.19 g, 7 mmol) in CH_2Cl_2 (30 mL) was stirred at 0 °C while a solution of 6% aqueous NaOH (5 mL) was added dropwise. The fresh prepared methylthioacetaldehyde[28] (0.54 g, 6 mmol) was added. The resulting solution was stirred at 0 °C for 3 h and concentrated in vacuo. The aqueous solution was extracted with EtOAc (25 mL × 3). The combined organic extract was dried with anhydrous $MgSO_4$, filtered, and concentrated in vacuo. The crude product was chromatographed over silica gel eluting with hexane−EtOAc (80:1) to give an inseparable geometric mixture of ethyl 6-methylthio-2,4-hexadienoate (**15**) (0.71 g, 64%) as colorless oil.

6-Methylthio-3(*E*),5(*E*)-hexadien-1-ol (16). Deconjugation of the mixture 15 was proceeded with LDA. A solution of LDA in THF was prepared by the slow addition of n-BuLi (2.5 M in hexane, 2.4 mL, 6 mmol) to a solution of diisopropylamine (0.61 g, 6 mmol) in anhydrous THF (15 mL) under N_2 at −78 °C.[29] Dry hexamethylphosphoramide (1.08 g, 6 mmol) was added dropwise and the mixture allowed to stir 30 min. Ester **15** (0.93 g, 5 mmol) was added to the cold solution dropwise. Stirring was continued an additional hour at −78 °C, then the dark-red mixture was poured into a rapidly stirred solution of acetic acid (0.90 g, 15 mmol) in H_2O (30 mL). The resulting solution was extracted with EtOAc (20 mL × 3), and the combined extract was dried with anhydrous $MgSO_4$, filtered, and concentrated in vacuo. The crude product was chromatographed over silica gel eluting with hexane−EtOAc (80:1) to give pure ethyl 6-methylthio-3(*E*),5(*E*)-hexadienoate (0.66 g, 71% yield) as colorless oil: IR (film) ν_{max} 1728 (C═O) cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 1.26 (3H, t, J = 7.2 Hz), 2.27 (3H, s), 3.09 (2H, d, J = 7.2 Hz), 4.14 (2H, q, J = 7.2 Hz), 5.62 (1H, dt, J = 14.4, 7.2 Hz), 6.00 (1H, dd, J = 14.4, 9.9 Hz), 6.15 (1H, dd, J = 14.4, 9.9 Hz), 6.24 (1H, d, J = 14.4 Hz); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 14.1, 14.6, 38.0, 60.0, 121.5, 124.6, 128.4, 132.7, 171.6; MS *m*/*z* (rel int) 186 (23, M^+), 155 (27), 115 (51), 103 (51), 97 (100), 87 (60), 81 (59), 61 (63), 55 (49); HRMS *m*/*z* 186.0713 (Calcd for $C_9H_{14}O_2S$ 186.0715).

Subsequently, the 6-methylthio-3(*E*),5(*E*)-hexadienoate (0.93 g, 5 mmol) in anhydrous Et_2O (5 mL) was added dropwise to a suspension of $LiAlH_4$ (0.29 g, 7.5 mmol) in anhydrous Et_2O (15 mL). After the addition had completed, the reaction mixture was stirred at room temperature for 2 h. With cooling in an ice bath, a solution of 5% NaOH was added carefully to destroy the excess hydride until the hydrogen evolution ceased. The resulting solution was extract with Et_2O (20 mL × 3). The combined extract was dried with anhydrous $MgSO_4$, filtered, and concentrated in vacuo. The crude product was chromatographed over silica gel eluting with hexane−EtOAc (1:3) to give **16** (0.66 g, 91% yield) as colorless oil: IR (film) ν_{max} 3370 (br, OH) cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 2.12 (1H, br s, OH), 2.27 (3H, s), 2.33 (2H, dt, J = 7.1, 6.4 Hz), 3.65 (2H, t, J = 6.4 Hz), 5.52 (1H, dt, J = 15.0, 7.1 Hz), 5.99 (1H, dd, J = 14.7, 10.1 Hz), 6.15 (1H, dd, J = 15.0, 10.1 Hz), 6.20 (1H, d, J = 14.7 Hz); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 14.7, 35.9, 62.0, 125.3, 126.4, 127.5, 132.3; MS *m*/*z* (rel int) 144 (64, M^+), 113 (74), 111 (70), 97 (47), 67 (100), 65 (96), 57 (55), 55 (40); HRMS *m*/*z* 144.0610 (Calcd for $C_7H_{12}OS$ 144.0609).

6-Methylthio-3(*E*),5(*E*)-hexadienyl Azidoformate (17). The analogous procedure for the preparation of azidoformate **8** was used. Alcohol **16** (0.58 g, 4 mmol) gave **17** (0.68 g, 80% yield) as colorless oil: IR (film) ν_{max} 2186 and 2134 (N_3), 1725 (C═O) cm^{-1}; ^1H NMR ($CDCl_3$, 200 MHz) δ 2.28 (3H, s), 2.45 (2H, dt, J = 7.2, 6.7 Hz), 4.23 (2H, t, J = 6.7 Hz), 5.46 (1H, dt, J = 14.5, 7.2 Hz), 5.97 (1H, dd, J = 14.5, 9.7 Hz), 6.14 (1H, ddt, J = 14.5, 9.7, 1.1 Hz), 6.21 (1H, d, J = 14.5 Hz); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 14.7, 31.7, 67.7, 124.2, 124.9, 128.1, 132.5, 157.4; MS *m*/*z* (rel int) 213 (22, M^+), 126 (61), 97 (48), 79 (100), 65 (56). Anal. Calcd for $C_8H_{11}N_3O_2S$: C, 45.06; H, 5.20; N, 19.70. Found: C, 45.07; H, 5.36; N, 19.68.

6-Oxa-7,8-dihydroindolizin-5-one (18). By the general method for FVT, azidoformate **17** (213 mg, 1 mmol) gave **18** (55 mg, 40% yield) as colorless oil: IR (film) ν_{max} 1746 (C═O) cm^{-1}; ^1H NMR (acetone-d_6, 200 MHz) δ 3.08 (2H, td, J = 6.0,

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1.2 Hz), 4.57 (2H, t, J = 6.0 Hz), 6.04 (1H, m), 6.23 (1H, t, J = 3.2, 2.0 Hz), 7.20 (1H, dd, J = 3.2, 1.5 Hz); ^{13}C NMR (acetone-d_6, 50 MHz) δ 22.6, 69.0, 108.7, 113.0, 119.2, 130.1, 148.3; MS m/z (rel int) 137 (100, M^+), 92 (77), 66 (60), 52 (24); HRMS m/z 137.0479 (Calcd for $C_7H_7NO_2$ 137.0477).

6-Methoxy-3(*E*),5(*Z*)-hexadien-1-ol (22). The analogous procedure for the preparation of ester **15** and alcohol **16** was used. The methoxyacetaldehyde[30] (0.44 g, 6 mmol) gave a geometric mixture of conjugated ester **20** (0.71 g, 70% yield). Deconjugation of ester **20** (0.85 g, 5 mmol) gave a 1:1 mixture of 3(*E*),5(*E*)- and 3(*E*),5(*Z*)-hexadienoates (0.64 g, 75% yield). By careful separation of the mixture, we got 200 mg of pure ethyl 6-methoxy-3(*E*),5(*Z*)-hexadienoate (**21**) as colorless oil: IR (film) ν_{max} 1731 (C=O) cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 1.23 (3H, t, J = 7.0 Hz), 3.07 (2H, dd, J = 7.2, 1.2 Hz), 3.62 (3H, s), 4.11 (2H, q, J = 7.0 Hz), 5.04 (1H, dd J = 10.9, 6.3 Hz), 5.60 (1H, dt, J = 15.7, 7.2 Hz), 5.85 (1H, d, J = 6.3 Hz), 6.43 (1H, ddq, J = 15.7, 10.9, 1.2 Hz); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 14.1, 38.3, 59.9, 60.5, 106.0, 121.3, 126.2, 147.0, 171.8; MS m/z (rel int) 170 (34, M^+), 155 (22), 141 (28), 125 (27), 113 (66), 97 (100), 87 (45), 83 (68), 55 (80); HRMS m/z 170.0945 (Calcd for $C_9H_{14}O_3$ 170.0943).

Reduction of **21** (0.85 g, 5 mmol) gave **22** (0.60 g, 94% yield) as colorless oil: IR (film) ν_{max} 3382 (br, OH) cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 1.84 (1H, br s, OH), 2.33 (2H, qd, J = 6.3, 1.1 Hz), 3 0.63 (3H, s), 3.64 (2H, t, J = 6.3 Hz), 5.04 (1H, dd J = 10.8, 6.2 Hz), 5.51 (1H, dt, J = 15.6, 6.3 Hz), 5.83 (1H, d, J = 6.2 Hz), 6.44 (1H, ddq, J = 15.6, 10.8, 1.1 Hz); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 36.2, 60.0, 62.1, 106.4, 125.7, 126.2, 146.4; MS m/z (rel int) 128 (66, M^+), 111 (35), 97 (100), 81 (45), 68 (46), 55 (45); HRMS m/z 128.0837 (Calcd for $C_7H_{12}O_2$ 128.0837).

6-Methoxy-3(*E*),5(*Z*)-hexadienyl Azidoformate (23). The analogous procedure for the preparation of azidoformate **8** was used. Alcohol **22** (0.51 g, 4 mmol) gave **23** (0.41 g, 70% yield) as colorless oil: IR (film) ν_{max} 2186 and 2134 (N_3), 1728 (C=O) cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 2.45 (2H, qd, J = 7.0, 1.2 Hz), 3.65 (3H, s), 4.22 (2H, t, J = 7.0 Hz), 5.03 (1H, dd, J = 10.9, 6.3 Hz), 5.46 (1H, dt, J = 15.6, 7.0 Hz), 5.85 (1H, d, J = 6.3 Hz), 6.44 (1H, ddq, J = 15.6, 10.9, 1.2 Hz); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 32.0, 60.0, 67.9, 106.1, 124.0, 125.9, 146.8, 157.4; MS m/z (rel int) 197 (1, M^+), 110 (100), 97 (39), 79 (22), 67 (34), 53 (17). Anal. Calcd for $C_8H_{11}N_3O_3$: C, 48.73; H, 5.59; N, 21.32. Found: C, 48.73; H, 5.58; N, 21.27.

By the general method for FVT, azidoformate **23** (197 mg, 1 mmol) gave a 2:1 mixture of 1β-methoxyindolizinone **24** and 1α-methoxyindolizinone **25** (74 mg, 44% yield), accompanied with **18** (15 mg, 11% yield). Due to the instability of 2-pyrroline, only the major **24** was separated by column chromatography for spectral analysis. The compound **25** was isolated but tended to decompose spontaneously.

1β-Methoxy-6-oxa-1,7,8,8aβ-tetrahydroindolizin-5-one (24). Colorless oil; IR (film) ν_{max} 1689 (C=O) cm^{-1}; ^{1}H NMR (acetone-d_6, 400 MHz) δ 1.95 (1H, m, H-8α), 2.30 (1H, m, H-8β), 3.34 (3H, s, OCH_3), 3.93 (1H, ddd, J = 12.0, 6.6, 3.8 Hz, H-8a), 4.30 (1H, td, J = 11.2, 2.9 Hz, H-7β), 4.37 (1H, ddd, J = 11.2, 5.2, 1.6 Hz, H-7α), 4.69 (1H, ddd, J = 6.6, 2.1, 1.1 Hz, H-1), 5.37 (1H, dd, J = 4.4, 2.1 Hz, H-2), 6.73 (1H, dd, J = 4.4, 1.1 Hz, H-3); ^{13}C NMR (acetone-d_6, 100 MHz) δ 27.7 (C-8), 56.3 (OCH_3), 62.9 (C-8a), 67.9 (C-7), 89.3 (C-1), 110.2 (C-2), 132.9 (C-3), 149.7 (C-5); MS m/z (rel int) 169 (5, M^+), 129 (21), 101 (100), 87 (54), 75 (24), 56 (78). Anal. Calcd for $C_8H_{11}NO_3$: C, 56.80; H, 6.51; N, 8.28. Found: C, 56.77; H, 6.58; N, 8.20.

1α-Methoxy-6-oxa-1,7,8,8aβ-tetrahydroindolizin-5-one (25). The partial ^{1}H NMR data for **25**: (acetone-d_6, 400 MHz) δ 3.29 (3H, s, OCH_3), 5.57 (1H, dd J = 4.2, 2.6 Hz, H-2), 6.89 (1H, d, J = 4.2 Hz, H-3); the ^{13}C NMR data: (acetone-d_6, 100 MHz) δ 22.1, 56.2, 60.7, 67.7, 82.0, 110.4, 134.4, 150.5.

Hydrogenation of the 2:1 mixture of **24** and **25** (68 mg, 0.4 mmol) with Pd/C in EtOAc also gave a 2:1 mixture of 1β and 1α-methoxyindolizidinones quantitatively. After separation by column chromatography eluting with EtOAc−hexane (1:1) yielded pure **26** (45 mg) and **27** (22 mg).

1β-Methoxy-6-oxa-8aβ-indolizidin-5-one (26). Colorless oil; IR (film) ν_{max} 1686 (C=O) cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.71 (2H, m, H-2α and H-8α), 2.28 (2H, m, H-2β and H-8β), 3.36 (1H, m, H-8a), 3.39 (3H, s, OCH_3), 3.50 (1H, m, H-1), 3.54 (1H, m, H-3α), 3.62 (1H, dt, J = 10.0, 2.0 Hz, H-3β), 4.14 (1H, td, J = 11.2, 2.4 Hz, H-7β), 4.36 (1H, ddd, J = 11.2, 4.4, 1.6 Hz, H-7α); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 26.9 (C-8), 28.3 (C-2), 44.1 (C-3), 57.6 (OCH_3), 60.0 (C-8a), 66.2 (C-7), 84.6 (C-1), 152.6 (C-5); MS m/z (rel int) 171 (79, M^+), 149 (30), 139 (22), 113 (33), 100 (61), 72 (74), 71 (50), 68 (100), 56 (36). Anal. Calcd for $C_8H_{13}NO_3$: C, 56.14; H, 7.60; N, 8.19. Found: C, 56.08; H, 7.63; N, 8.26.

1α-Methoxy-6-oxa-8aβ-indolizidin-5-one (27). Colorless oil; IR (film) ν_{max} 1683 (C=O) cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.75 (1H, m, H-2β), 1.99 (1H, m, H-8α), 2.11 (1H, m, H-8β), 2.17 (1H, m, H-2α), 3.33 (3H, s, OCH_3), 3.49 (1H, td, J = 10.8, 1.1 Hz, H-3β), 3.60 (1H, m, H-8a), 3.63 (1H, m, H-3α), 3.82 (1H, t, J = 3.2 Hz, H-1), 4.16 (1H, ddd, J = 13.1, 10.9, 2.2 Hz, H-7β), 4.38 (1H, ddd, J = 10.9, 4.3, 1.8 Hz, H-7α); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 21.8 (C-8), 27.2 (C-2), 44.8 (C-3), 56.6 (OCH_3), 60.6 (C-8a), 66.1 (C-7), 80.3 (C-1), 153.4 (C-5); MS m/z (rel int) 171 (55, M^+), 149 (59), 139 (18), 113 (25), 100 (46), 72 (59), 71 (52), 68 (100), 56 (39); HRMS m/z 171.0893 (Calcd for $C_8H_{13}NO_3$ 171.0895).

Methyl 7-Hydroxy-2(*E*),4(*E*)-heptadienoate and Methyl 7-Hydroxy-2(*E*),4(*Z*)-heptadienoate (29). The Wittig reaction procedure for the preparation of **15** was used. 3-(*tert*-Butyldimethylsiloxy)propanal[31] (1.13 g, 6 mmol) gave a 1:1 mixture of a protected hydroxyl ester (0.75 g, 46% yield). A solution of tetrabutylammonium fluoride in THF (1.0 M, 4 mL) was added to a stirred solution of the above ester (1.08 g, 4 mmol) in THF (20 mL).[32] The mixture was stirred for 2 h at room temperature. The resulting solution was extracted with EtOAc (20 mL × 3). The combined extract was dried with anhydrous $MgSO_4$, filtered, and concentrated in vacuo. The crude product was chromatographed over silica gel eluting with hexane−EtOAc (10:1) to give a 1:1 mixture of **29** (0.51 g, 82% yield). The mixture was not necessary to separate and use directly in the next step.

6-Carbomethoxy-3(*E*),5(*E*)-hexadienyl Azidoformate and 6-Carbomethoxy-3(*Z*),5(*E*)-hexadienyl Azidoformate (30). The analogous procedure for the preparation of azidoformate **8** was used. Alcohol **29** (0.62 g, 4 mmol) gave a 4:5 mixture of 3(*E*),5(*E*) and 3(*Z*), 5(*E*) azidoformates **30** (0.81 g, 90% yield) by ^{1}H NMR spectrum. The mixture was rechromatographed with 1% EtOAc/hexane to give a little of pure 3(*Z*),5(*E*) isomer as colorless oil and material enriched in 3(*E*),5(*E*) isomer for spectral analysis: IR (film) ν_{max} 2184 and 2136 (N_3), 1724 (C=O) cm^{-1}; ^{1}H NMR for 3(*E*),5(*E*) isomer ($CDCl_3$, 200 MHz) δ 2.56 (2H, q, J = 6.6 Hz), 3.74 (3H, s), 4.29 (2H, t, J = 6.6 Hz), 5.85 (1H, d, J = 15.5 Hz), 6.04 (1H, dt, J = 15.0, 6.6 Hz), 6.27 (1H, dd, J = 15.0, 10.6 Hz), 7.25 (1H, dd, J = 15.5, 10.6 Hz); for 3(*Z*),5(*E*) isomer δ 2.71 (2H, dtd, J = 7.5, 6.7, 1.0 Hz), 3.76 (3H, s), 4.28 (2H, t, J = 6.7 Hz), 5.81 (1H, dt, J = 10.6, 7.6 Hz), 5.93 (1H, d, J = 15.2 Hz), 6.27 (1H, br t, J = 11.2 Hz), 7.54 (1H, ddt, J = 15.2, 11.6, 1.0 Hz); ^{13}C NMR for 3(*E*),5(*E*) isomer ($CDCl_3$, 50 MHz) δ 32.0, 51.5, 66.8, 120.5, 131.2, 137.3, 144.1, 157.4, 167.3; for 3(*Z*),5(*E*) isomer δ 27.5, 51.6, 67.0, 122.5, 129.4, 134.2, 138.4, 157.4, 167.3; MS m/z (rel int) 225 (2, M^+), 138 (21), 107 (30), 79 (100), 59 (34).Anal. Calcd for $C_9H_{11}N_3O_4$: C, 48.00; H, 4.93; N, 18.56. Found: C, 48.02; H, 4.94; N, 18.55.

1α-Carbomethoxy-6-oxa-1,7,8,8aβ-tetrahydroindolizin-5-one (31). By the general method for FVT, azidoformate mixture **30** (113 mg, 0.5 mmol) gave **31** (70 mg, 71% yield) as single product: White crystal (EtOAc−hexane), mp 140−141 °C; IR (film) ν_{max} 1728 (C=O), 1695 (C=O) cm^{-1}; ^{1}H NMR (acetone-d_6, 400 MHz) δ 1.90 (1H, qd, J = 13.4, 4.4 Hz, H-8α), 2.24 (1H, m, H-8β), 3.66 (3H, s, OCH_3), 3.80 (1H, ddd, J =

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10.0, 2.9, 1.2 Hz, H-1), 4.27 (1H, ddd, J = 13.4, 10.8, 2.0 Hz, H-7β), 4.38 (1H, ddd, J = 10.8, 4.4, 2.0 Hz, H-7α), 4.42 (1H, ddd, J = 13.4, 10.0, 4.0 Hz, H-8a), 5.23 (1H, dd, J = 4.0, 2.9 Hz, H-2), 6.78 (1H, dd, J = 4.0, 1.2 Hz, H-3); ^{13}C NMR (acetone-d_6, 100 MHz) δ 25.4 (C-8), 51.8 (C-1), 52.0 (OCH_3), 58.8 (C-8a), 67.4 (C-7), 108.6 (C-2), 133.3 (C-3), 149.9 (C-5), 171.4 (OC=O); MS m/z (rel int) 197 (31, M^+), 167 (15), 138 (100), 94 (88), 67 (34), 59 (18), 57 (47). Anal. Calcd for $C_9H_{11}NO_4$: C, 54.82; H, 5.63; N, 7.10. Found: C, 54.83; H, 5.65; N, 7.15.

1α-Carbomethoxy-6-oxa-8aβ-indolizidin-5-one (32). Hydrogenation of **31** (59 mg, 0.3 mmol) with Pd/C in EtOAc also gave pure **32** quantitatively: White crystal (EtOAc−hexane), mp 79−80 °C; IR (film) ν_{max} 1730 (C=O), 1690 (C=O) cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.61 (1H, qd, J = 12.8, 4.3 Hz, H-8α), 1.99 (1H, m, H-2β), 2.09 (1H, dq, J = 12.8, 1.8 Hz, H-8β), 2.20 (1H, m, H-2β), 3.15 (1H, t, J = 6.6 Hz, H-1), 3.48 (1H, td, J = 11.0, 2.0 Hz, H-3β), 3.69 (3H, s, OCH_3), 3.84 (1H, m, H-8a), 3.88 (1H, m, H-3α), 4.15 (1H, td, J = 12.8, 1.8 Hz, H-7β), 4.35 (1H, ddd, J = 12.8, 4.3, 1.8 Hz, H-7α); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 25.0 (C-8), 26.0 (C-2), 46.1 (C-3), 47.2 (C-1), 51.9 (OCH_3), 57.9 (C-8a), 65.9 (C-7), 152.5 (C-5), 172.0 (OC=O); MS m/z (rel int) 199 (35, M^+), 168 (20), 140 (51), 68 (100), 59 (23) 55 (29). Anal. Calcd for $C_9H_{13}NO_4$: C, 54.27; H, 6.58; N, 7.03. Found: C, 53.94; H, 6.72; N, 7.10.

6-Phenyl-3(*E*),5(*E*)-hexadien-1-ol (33). The analogous procedure for the preparation of ester **15** and alcohol **16** was used. The phenylacetaldehyde (0.72 g, 6 mmol) gave the conjugated ethyl 6-phenyl-2,4-hexadienoate (0.86 g, 66% yield). Deconjugation of the ester (1.08 g, 5 mmol) gave ethyl 6-phenyl-3(*E*),5(*E*)-hexadienoate (0.81 g, 75% yield) as colorless oil: IR (film) ν_{max} 1731 (C=O) cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 1.27 (3H, t, J = 7.2 Hz), 3.15 (2H, dd, J = 7.2, 0.9 Hz), 4.14 (2H, q, J = 7.2 Hz), 5.88 (1H, dt, J = 15.2, 7.2 Hz), 6.27 (1H, ddd, J = 15.2, 10.2, 0.9 Hz), 6.48 (1H, d, J = 15.7 Hz), 6.77 (1H, dd, J = 15.7, 10.2 Hz), 7.30 (5H, m); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 14.2, 38.2, 60.7, 125.7, 126.3, 127.5, 128.3, 128.6, 132.0, 133.9, 137.2, 171.4; MS m/z (rel int) 216 (24, M^+), 143 (46), 128 (100), 115 (17), 91 (12), 77 (9); HRMS m/z 216.1150 (Calcd for $C_{14}H_{16}O_2$ 216.1150).

Reduction of this ester (1.08 g, 5 mmol) gave **33** (0.81 g, 93% yield): White plates ν_{max} 3281 (br, OH) cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 1.68 (1H, br s, OH), 2.43 (2H, br q, J = 6.3 Hz), 3.72 (2H, t, J = 6.3 Hz), 5.80 (1H, dt, J = 15.1, 7.2 Hz), 6.32 (1H, dd, J = 15.1, 10.2 Hz), 6.49 (1H, d, J = 15.6 Hz), 6.77 (1H, dd, J = 15.6, 10.2 Hz), 7.30 (5H, m); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 36.1, 61.9, 126.2, 127.3, 128.5, 128.7, 130.7, 131.1, 133.2, 137.3; MS m/z (rel int) 174 (47, M^+), 143 (100), 128 (91), 115 (30), 91 (28), 77 (7). Anal. Calcd for $C_{12}H_{14}O$: C, 82.72; H, 8.10. Found: C, 82.73; H, 8.12.

6-Phenyl-3(*E*),5(*E*)-hexadienyl Azidoformate (34). The analogous procedure for the preparation of azidoformate **8** was used. Alcohol **33** (0.70 g, 4 mmol) gave **34** (0.83 g, 85% yield) as colorless oil: IR (film) ν_{max} 2186 and 2138 (N_3), 1733 (C=O) cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 2.53 (2H, br q, J = 6.8 Hz), 4.27 (2H, t, J = 6.8 Hz), 5.73 (1H, dt, J = 15.1, 6.8 Hz), 6.29 (1H, dd, J = 15.1, 10.2 Hz), 6.48 (1H, d, J = 15.6 Hz), 6.74 (1H, dd, J = 15.6, 10.2 Hz), 7.30 (5H, m); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 31.9, 67.6, 126.2, 127.4, 128.4, 128.5, 131.7 (two carbons), 133.6, 137.1, 157.5; MS m/z (rel int) 243 (11, M^+), 156 (100), 128 (51), 115 (39), 91 (47), 77 (7). Anal. Calcd for $C_{13}H_{13}N_3O_2$: C, 64.19; H, 5.39; N, 17.27. Found: C, 64.01; H, 5.46; N, 17.14.

1α-Phenyl-6-oxa-1,7,8,8aβ-tetrahydroindolizin-5-one (35). By the general method for FVT, azidoformate **34** (121 mg, 0.5 mmol) gave **35** (55 mg, 51% yield): White crystal (EtOAc−hexane), mp 130−131 °C; IR (film) ν_{max} 1692 (C=O) cm^{-1}; ^{1}H NMR (acetone-d_6, 400 MHz) δ 1.04 (1H, m, H-8α), 1.80 (1H, m, H-8β), 4.15 (1H, dd, J = 9.3, 3.6 Hz, H-1), 4.22 (2H, m, H-7), 4.39 (1H, ddd, J = 13.5, 9.3, 4.1 Hz, H-8a), 5.37 (1H, dd, J = 4.1, 3.6 Hz, H-2), 6.91 (1H, d, J = 4.1 Hz, H-3), 7.09 (2H, d, J = 7.3 Hz, H-2′ and −6′ of Ph), 7.27 (1H, t, J = 7.3 Hz, H-4′ of Ph), 7.34 (2H, t, J = 7.3 Hz, H-3′ and −5′ of Ph); ^{13}C NMR (acetone-d_6, 100 MHz) δ 25.0 (C-8), 52.1 (C-1), 60.9 (C-8a), 67.3 (C-7), 113.7 (C-2), 128.1 (C-4′), 129.3 (C-2′ and −6′), 129.4 (C-3′ and −5′), 131.8 (C-3), 139.3 (C-1′), 150.7 (C-5); MS m/z (rel int) 215 (77, M^+), 170 (84), 143 (90), 128 (67), 115 (100), 91 (28), 77 (20). Anal. Calcd for $C_{13}H_{13}NO_2$: C, 72.56; H, 6.05; N, 6.51. Found: C, 72.47; H, 6.10; N, 6.50.

1α-Phenyl-6-oxa-8aβ-indolizidin-5-one (36). Hydrogenation of **35** (65 mg, 0.3 mmol) with Pd/C in EtOAc also gave pure **36** quantitatively: White crystal (EtOAc−hexane), mp 141−142 °C; IR (film) ν_{max} 1673 (C=O) cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.22 (1H, qd, J = 11.7, 5.1 Hz, H-8α), 1.70 (1H, m, H-8β), 2.14 (1H, m, H-2α), 2.33 (1H, m, H-2β), 3.47 (1H, t, J = 6.0 Hz, H-1), 3.61 (1H, td, J = 11.7, 2.9 Hz, H-3β), 3.92 (1H, dt, J = 11.7, 6.0 Hz, H-8a), 4.03 (1H, dt, J = 11.7, 8.8 Hz, H-3α), 4.18 (2H, m, H-7), 7.02 (2H, d, J = 7.2 Hz, H-2′ and −6′ of Ph), 7.26 (1H, t, J = 7.2 Hz, H-4′ of Ph), 7.32 (2H, t, J = 7.2 Hz, H-3′ and −5′ of Ph); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 24.9 (C-8), 29.7 (C-2), 46.2 (C-3), 47.9 (C-1), 59.6 (C-8a), 66.0 (C-7), 127.1 (C-4′), 127.9 (C-2′ and −6′), 128.8 (C-3′ and −5′), 140.4 (C-1′), 153.0 (C-5); MS m/z (rel int) 217 (100, M^+), 118 (60), 113 (81), 91 (17), 77 (7), 68 (63). Anal. Calcd for $C_{13}H_{15}NO_2$: C, 71.89; H, 6.91; N, 6.45. Found: C, 71.86; H, 7.02; N, 6.43.

6-Phenyl-3(*Z*),5(*E*)-hexadienyl Azidoformate (37). The analogous procedure for the preparation of azidoformate **8** was used. 6-Phenyl-3(*Z*),5(*E*)-hexadien-1-ol[21] (0.70 g, 4 mmol) gave **37** (0.86 g, 88% yield) as colorless oil: IR (film) ν_{max} 2186 and 2137 (N_3), 1729 (C=O) cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 2.69 (2H, dt, J = 7.7, 6.9 Hz), 4.28 (2H, t, J = 6.9 Hz), 5.46 (1H, dt, J = 10.8, 7.7 Hz), 6.30 (1H, td, J = 10.8 Hz), 6.58 (1H, d, J = 15.5 Hz), 7.01 (1H, dd, J = 15.5, 10.8 Hz), 7.30 (5H, m); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 27.3, 67.5, 123.3, 125.5, 126.4, 127.7, 128.6, 131.9, 133.8, 137.1, 157.4; MS m/z (rel int) 243 (11, M^+), 156 (100), 141 (24), 128 (21), 115 (45), 91 (56), 77 (8); HRMS m/z 243.1010 (Calcd for $C_{13}H_{13}N_3O_2$ 243.1008).

6-Phenyl-3(*E*),5(*Z*)-hexadien-1-ol (38) and 6-Phenyl-3(*Z*),5(*Z*)-hexadien-1-ol (39). The solution of n-BuLi (2.5 M in hexane, 5.6 mL, 14 mmol) was added dropwise to a suspension of (3-hydroxypropyl)triphenylphosphonium bromide[33] (2.81 g, 7 mmol) in THF (30 mL) at −78 °C. The resulting mixture was stirred for 1 h at room temperature and cooled to −35 °C. A fresh distilled chlorotrimethylsilane (0.76 g, 7 mmol) was added and stirred for 30 min. Then, (*Z*)-3-phenylpropenal[34] (0.79 g, 6 mmol) was added and stirred for 2.5 h. The mixture was warmed to room temperature and stirred for another 3 h. The resulting solution was quenched with 5% aqueous HCl and extracted with EtOAc (20 mL × 3). The combined extract was dried with anhydrous $MgSO_4$, filtered, and concentrated in vacuo. The crude product was chromatographed over silica gel eluting with hexane−EtOAc (10:1) to give a 1:4 mixture of 6-phenyl-3(*E*),5(*Z*)-hexadien-1-ol and 6-phenyl-3(*Z*),5(*Z*)-hexadien-1-ol (0.84 g, 80% yield). The mixture was rechromatographed with 10% EtOAc/hexane to give pure **39** (0.65 g, 62% yield) as colorless oil: IR (film) ν_{max} 3384 (br, OH), 1671 (C=O) cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 2.58 (2H, dtd, J = 7.6, 6.6, 1.4 Hz), 3.73 (2H, t, J = 6.6 Hz), 5.62 (1H, dt, J = 10.6, 7.6 Hz), 6.65 (3H, m), 7.30 (5H, m); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 31.1, 61.9, 124.8, 126.9, 127.2, 128.1, 129.0, 129.8, 130.4, 137.2; MS m/z (rel int) 174 (37, M^+), 143 (90), 128 (100), 115 (42), 91 (30), 77 (21), 65 (12); HRMS m/z 174. (Calcd for $C_{13}H_{13}N_3O_2$ 174.). In addition, a material enriched in **38** isomer was also isolated for spectral analysis: ^{1}H NMR ($CDCl_3$, 200 MHz) δ 2.38 (2H, dt, J = 7.2, 6.4 Hz), 3.70 (2H, t, J = 6.4 Hz), 5.85 (1H, dt, J = 15.0, 7.2 Hz), 6.23 (1H, dd, J = 11.5, 10.7 Hz), 6.38 (1H, d, J = 11.5 Hz), 6.71 (1H, dd, J = 15.0, 10.7 Hz), 7.30 (5H, m).

6-Phenyl-3(*E*),5(*Z*)-hexadienyl Azidoformate (40) and 6-Phenyl-3(*Z*),5(*Z*)-hexadienyl Azidoformate (41). The analogous procedure for the preparation of azidoformate **8** was used. Alcohol **39** (0.70 g, 4 mmol) gave **41** (0.86 g, 88% yield) as colorless oil: IR (film) ν_{max} 2184 and 2137 (N_3), 1729 (C=O) cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 2.71 (2H, qd, J = 7.0,

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1.5 Hz), 4.30 (2H, t, J = 7.0 Hz), 5.55 (1H, dt, J = 10.7, 7.0 Hz), 6.52 (1H, t, J = 10.7 Hz), 6.56 (1H, d, J = 10.7 Hz), 6.66 (1H, tt, J = 10.7, 1.5 Hz), 7.32 (5H, m); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 27.0, 67.5, 124.3, 127.1, 127.3, 127.9, 128.2, 129.1, 131.3, 137.1, 157.4; MS m/z (rel int) 243 (15, M^+), 156 (100), 141 (42), 128 (82), 115 (66), 91 (85), 77 (17), 65 (17); HRMS m/z 217.0853 (Calcd for $C_{11}H_{11}N_3O_2$ 217.0851). In addition, a material enriched in **40** was also isolated for spectral analysis: ^{1}H NMR ($CDCl_3$, 200 MHz) δ 2.51 (2H, dt, J = 7.2, 6.6 Hz), 4.26 (2H, t, J = 6.6 Hz), 5.79 (1H, dt, J = 15.1, 7.2 Hz), 6.21 (1H, t, J = 11.2 Hz), 6.32 (1H, d, J = 11.2 Hz), 6.68 (1H, dd, J = 15.1, 11.2 Hz), 7.33 (5H, m).

By the general method for FVT, azidoformate **40** or **41** (121 mg, 0.5 mmol) gave **35** (28 mg, 26% yield), **42** (14 mg, 13%yield), and **44** (32 mg, 30% yield).

1β-Phenyl-6-oxa-1,7,8,8aβ-tetrahydroindolizin-5-one (42). White powder; IR (film) ν_{max} 1695 (C═O) cm^{-1}; ^{1}H NMR (acetone-d_6, 400 MHz) δ 2.10 (1H, m, H-8α), 2.25 (1H, m, H-8β), 3.93 (1H, td, J = 11.0, 4.0 Hz, H-8a), 4.16 (1H, m, H-1), 4.20 (1H, m, H-7β), 4.35 (1H, ddd, J = 11.1, 4.5, 1.6 Hz), H-7α) 5.27 (1H, dd, J = 4.3, 1.9 Hz, H-2), 6.77 (1H, dd, J = 4.3, 2.2 Hz, H-3), 7.30 (5H, m, C_6H_5); ^{13}C NMR (acetone-d_6, 100 MHz) δ 28.0 (C-8), 56.8 (C-1), 66.4 (C-8a), 67.6 (C-7), 113.8 (C-2), 128.0 (C-4′), 128.5 (C-2′ and −6′), 129.6 (C-3′ and −5′), 131.6 (C-3), 142.7 (C-1′), 149.8 (C-5); MS m/z (rel int) 215 (100, M^+), 187 (28), 170 (84), 156 (18), 143 (58), 128 (32), 115 (78), 77 (11); HRMS m/z 215.0949 (Calcd for $C_{13}H_{13}NO_2$ 215.0946).

5,6-Benzo-1-aza-10-oxabicyclo[5.4.0]undeca-3,5-dien-11-one (44). White powder (EtOAc−hexane), mp 156−158 °C; IR (film) ν_{max} 1684 (C═O) cm^{-1}; ^{1}H NMR (acetone-d_6, 400 MHz) δ 2.38 (1H, dddd, J = 14.7, 9.5, 5.5, 4.5 Hz, H-8β), 2.70 (1H, dtd, J = 14.7, 5.5, 3.6 Hz, H-8α), 4.10 (1H, ddd, J = 17.2, 5.0, 1.3 Hz, H-2α), 4.25 (1H, ddd, J = 17.2, 5.0, 1.5 Hz, H-2β), 4.35 (1H, ddd, J = 12.6, 5.5, 4.5 Hz, H-9β), 4.47 (1H, ddd, J = 12.6, 9.5, 3.6 Hz, H-9α),4.74 (1H, t, J = 5.5 Hz, H-7), 6.06 (1H, dt, J = 11.5, 5.0 Hz, H-3), 6.65 (1H, d, J = 11.5 Hz, H-4), 7.29 (3H, m, H-1′, 2′, 3′), 7.46 (1H, d, J = 7.7 Hz, H-4′); ^{13}C NMR (acetone-d_6, 100 MHz) δ 26.1 (C-8), 48.4 (C-2), 56.5 (C-7), 65.4 (C-9), 126.2 (C-4′), 128.2 (C-3′), 128.5 (C-2′), 129.4 (C-3), 131.9 (C-1′), 132.0 (C-4), 138.0 (C-5), 139.0 (C-6), 152.8 (C-11); MS m/z (rel int) 215 (100, M^+), 187 (22), 170 (24), 154 (70), 143 (90), 128 (60), 115 (92), 89 (17), 77 (17), 63 (14); HRMS m/z 215.0947 (Calcd for $C_{13}H_{13}NO_2$ 215.0946). Anal. Calcd for $C_{13}H_{13}NO_2$: C, 72.56; H, 6.05; N, 6.51. Found: C, 72.47; H, 6.09; N, 6.39.

1β-Phenyl-6-oxa-8aβ-indolizidin-5-one (43). Hydrogenation of **42** (30 mg, 0.14 mmol) with Pd/C in EtOAc also gave pure **43** quantitatively: White powder (EtOAc−hexane), mp 102−103 °C; IR (film) ν_{max} 1690 (C═O) cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.68 (1H, m, H-8α), 2.01 (1H, m, H-8β), 2.12 (1H, qd, J = 10.7, 2.3 Hz, H-2β), 2.30 (1H, m, H-2α), 2.82 (1H, td, J = 10.7, 6.4 Hz, H-1), 3.51 (1H, td, J = 10.7, 4.0 Hz, H-8a), 3.70 (2H, m, H-3), 4.12 (1H, td, J = 11.2, 2.0 Hz, H-7β), 4.36 (1H, ddd, J = 11.2, 4.4, 1.5 Hz, H-7α), 7.24 (2H, dd, J = 7.4, 3.5 Hz, H-2′ and −6′ of Ph), 7.29 (1H, t, J = 7.4 Hz, H-4′ of Ph), 7.36 (2H, t, J = 7.4 Hz, H-3′ and −5′ of Ph); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 27.0 (C-8), 30.8 (C-2), 46.2 (C-3), 52.2 (C-1), 62.7 (C-8a), 66.4 (C-7), 127.3 (C-2′ and −6′), 127.5 (C-4′), 128.9 (C-3′ and −5′), 138.4 (C-1′), 152.9 (C-5); MS m/z (rel int) 217 (100, M+), 118 (50), 113 (74), 100 (41), 91 (40), 77 (12), 68 (50). Anal. Calcd for C13H15NO2: C, 71.89; H, 6.91; N, 6.45. Found: C, 71.65; H, 6.91; N, 6.33.

(*E*)-4-Phenyl-3-butenyl Azidoformate (45) and (*Z*)-4-Phenyl-3-butenyl Azidoformate (46). The analogous procedure for the preparation of azidoformate **40** and **41** was used. Benzaldehyde (0.64 g, 6 mmol) gave a 1:3 mixture of (*E*)- and (*Z*)-4-phenyl-3-buten-1-ol (0.75 g, 46% yield). The mixture was rechromatographed with 10% EtOAc/hexane to give pure (*E*)- and (*Z*)-4-phenyl-3-buten-1-ol as colorless oil. For (*E*)-4-phenyl-3-buten-1-ol: ^{1}H NMR ($CDCl_3$, 200 MHz) δ 2.45 (2H, qd, J = 6.8, 1.0 Hz), 3.72 (2H, t, J = 6.8 Hz), 6.18 (1H, dt, J = 15.9, 6.8 Hz), 6.47 (1H, dt, J = 15.9, 1.0 Hz), 7.25 (5H, m); For (*Z*)-4-phenyl-3-buten-1-ol: ^{1}H NMR ($CDCl_3$, 200 MHz) δ 2.58 (2H, qd, J = 7.0, 1.7 Hz), 3.69 (2H, t, J = 7.0 Hz), 5.67 (1H, dt, J = 11.7, 7.0 Hz), 6.56 (1H, dt, J = 11.7, 1.7 Hz), 7.25 (5H, m).

The analogous procedure for the preparation of azidoformate **8** was used. The pure (*E*)-4-phenyl-3-buten-1-ol (0.59 g, 4 mmol) gave **45** (0.76 g, 87% yield) as colorless oil: IR (film) λ_{max} 2184 and 2139 (N_3), 1731 (C═O) cm^{-1}; 1H NMR (CDCl3, 200 MHz) δ 2.61 (2H, qd, J = 6.8, 1.3 Hz), 4.33 (2H, t, J = 6.8 Hz), 6.14 (1H, dt, J = 15.9, 6.8 Hz), 6.49 (1H, dt, J = 15.9, 1.3 Hz), 7.30 (5H, m); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 32.2, 67.7, 124.3, 126.1, 127.4, 128.3, 133.1, 137.0, 157.5; MS m/z (rel int) 217 (4, M^+), 130 (100), 117 (82), 115 (94), 91 (82), 77 (21); HRMS m/z 217.0853 (Calcd for $C_{11}H_{11}N_3O_2$ 217.0851). the pure (*Z*)-4-Phenyl-3-buten-1-ol (0.59 g, 4 mmol) gave **46** (0.72 g, 83% yield) as colorless oil: IR (film) ν_{max} 2185 and 2138 (N_3), 1731 (C═O) cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 2.72 (2H, qd, J = 7.0, 1.7 Hz), 4.29 (2H, t, J = 7.0 Hz), 5.63 (1H, dt, J = 11.6, 7.0 Hz), 6.59 (1H, dt, J = 11.6, 1.7 Hz), 7.30 (5H, m); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 27.8, 67.7, 126.0, 126.9, 128.2, 128.5, 132.0, 136.7, 157.4; MS m/z (rel int) 217 (2, M^+), 130 (100), 117 (59), 115 (67), 91 (59), 77 (15); HRMS m/z 217.0852 (Calcd for $C_{11}H_{11}N_3O_2$ 217.0.0851).

***trans*-1-Aza-3-oxa-2-oxo-7β-phenyl-6β-bicyclo[4.1.0]heptane (47) and *cis*-1-Aza-3-oxa-2-oxo-7β-phenyl-6β-bicyclo[4.1.0]heptane (48).** By the general method for FVT, azidoformate **45** (108 mg, 0.5 mmol) gave **47** and **48** as 6:1 mixture quantitatively whereas azidoformate **46** (108 mg, 0.5 mmol) gave **47** and **48** as 2.5:1 mixture determined by crude ^{1}H NMR spectrum. The mixture of **47** and **48** obtained from FVT was not further separated due to the instability of aziridine ring skeleton. For the major isomer **47**: IR (film) ν_{max} 1717 (C═O) cm^{-1}; ^{1}H NMR ($CDCl_3$, 200 MHz) δ 1.58 (1H, dddd, J = 14.6, 12.3, 8.7, 4.4 Hz, H-5α), 2.46 (1H, ddt, J = 14.6, 6.2, 1.9 Hz, H-5β), 2.83 (1H, ddd, J = 8.7, 6.2, 3.0 Hz, H-6β), 3.30 (1H, d, J = 3.0 Hz, H-7α), 4.37 (1H, ddd, J = 10.8, 4.6, 1.9 Hz, H-4α), 4.53 (1H, ddd, J = 12.3, 10.8, 2.0 Hz, H-4β), 7.25 (5H, m, C_6H_5); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 25.0, 43.8, 48.9, 68.1, 126.1, 128.3, 128.5, 135.7, 159.9; MS m/z (rel int) 189 (79, M^+), 144 (39), 130 (81), 117 (100), 91 (75), 77 (32), 56 (38); HRMS m/z 189.0789 (Calcd for $C_{11}H_{11}NO_2$ 189.0790). The partial ^{1}H NMR spectrum for the minor isomer **48**: δ 3.14 (1H, ddd J = 11.3, 6.3, 5.0 Hz, H-6β), 3.91 (1H, d, J = 5.0 Hz, H-7β).

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Supporting Information Available: Copies of ^{1}H and ^{13}C NMR spectra of **7**, **10**, **11**, **13**, **16**−**18**, **22**−**24**, **26**, **27**, **29**−**37**, and **41**−**44**; X-ray data for **32**. This material is avaliable free charge via the Internet at http://pubs.acs.org

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