Conjugatively Stabilized Bridgehead Olefins: Formation and Reaction of Remarkably Stable Homoadamant-3-enes Substituted with Phenyl and Methoxycarbonyl Groups

Masatomi Ohno, Motohiro Itoh, Masami Umeda, Ryoji Furuta, Kazumoto Kondo, and Shoji Eguchi*

Contribution from the Institute of Applied Organic Chemistry, Faculty of Engineering, Nagoya University, Chikusa, Nagoya 464-01, Japan

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Abstract: Conjugatively stabilized double bonds were formed at the bridgehead of homoadamantane by way of the 1,2-carbon shift of adamantylcarbene (-carbenoid) intermediates generated from decomposition of the diazo precursors (1-adamantyl)diazophenylmethane (**7**) and methyl (1-adamantyl)diazoacetate (**10**). Decomposition to 4-phenyl- and 4-methoxycarbonyl-substituted homoadamant-3-enes **1** and **2** was much more efficient *via* catalysis with $Rh_2(OAc)_4$ in dichloromethane than by photolysis or thermolysis (FVP; in the case of **7**, indane-fused homoadamantane was produced by a phenylcarbene rearrangement followed by insertion to a bridged methylene). In the Rh catalysis, reactions of **7** and **10** in hexane and with $Rh_2(NHCOCH_3)_4$ did not promote the formation of **1** and **2**, suggesting that the polarized structure of the Rh−carbene complex participated in the 1,2-carbon shift. The substituted bridgehead olefins were considerably stable even at 0 °C to room temperature (more than half of **1** and **2** survived in solution at room temperature after 12 and 1 h, respectively), while parent homoadamant-3-ene was recorded to be unstable at −20 °C. Therefore, after decomposition of the diazo precursors was complete, reagents (electrophies for **1** and nucleophiles for **2**) were allowed to react at these temperatures to give 3,4-disubstituted homoadamantane derivatives, including some cycloadducts. With atmospheric oxygen, addition and subsequent bond cleavage occurred smoothly to give bicyclo[3.3.1]nonanones. The remarkable stability of **1** and **2** was considered to be the result of conjugation with the substituents, along with some steric protection, which allowed the polarized structure to have a greater effect in reducing the strain energy. This notion was verified by examining longer carbon−carbon double bonds using spectroscopy and PM3 calculations.

Bridgehead olefins have attracted continuous attention since Bredt first reported the prohibition of a double bond at a bridgehead. Various studies have been performed to understand the nature of such bonds, and the experimental and theoretical results have been reviewed several times.[1] The current understanding of the relative stability of bridgehead olefins can be expressed by the rules suggested by Wiseman[2] (who evaluated the system as a *trans*-cycloalkene) and Schleyer[3] (who considered olefin strain energy). In recent studies,[4] noradamantene[5] and adamantene[6] have been shown to be highly unstable. Homoadamant-3-ene (**3**)[7] is a bridged cycloheptene with an olefin strain energy of 20 kcal/mol.[3] This value suggests that it can be observed only at very low temperature, which is in fact the case.[7e]

The introduction of a substituent to such bridgehead olefins is believed to alter their stability and reactivity. Schleyer suggested that replacement of the vinyl hydrogen by bulky groups or substituents which provide electronic stabilization might result in observable species.[3] In this regard, Jones reported that 4-(1-adamantyl)homoadamant-3-ene (**4**) was amazingly stable and was unaffected by heating up to 185 °C.[7g] The unusual stability of **4** has been attributed to steric protection.

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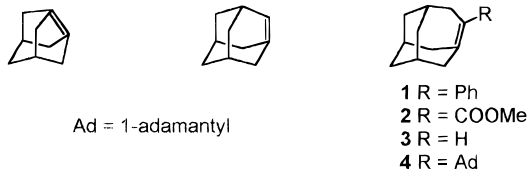
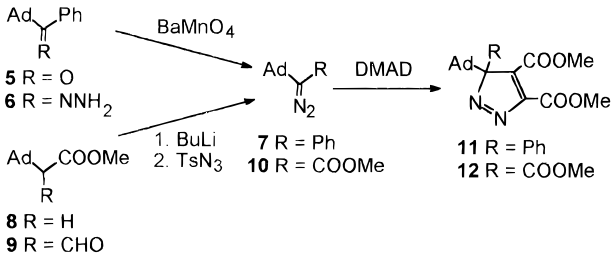


Figure 1.

Scheme 1

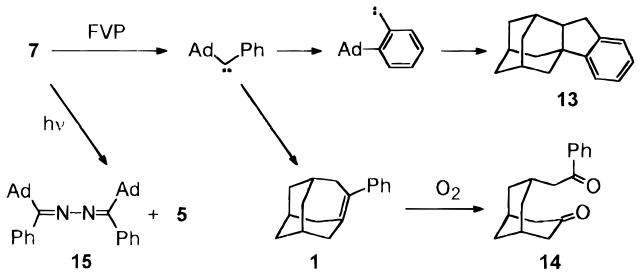


We report here phenyl- and methoxycarbonyl-substituted homoadamant-3-enes **1** and **2**, which are remarkably stable mainly due to a conjugative effect.

The conjugative bridgehead olefins **1** and **2** were formed using the carbene method: *i.e.*, 1,2-carbon shift of the carbene intermediate. The corresponding diazo precursors were prepared by oxidation of 1-adamantyl phenyl ketone hydrazone (**6**) with $BaMnO_4$[7g,8] and by formylation of methyl (1-adamantyl)acetate (**8**) followed by diazo transfer with tosyl azide and butyllithium[9] (Scheme 1). (1-Adamantyl)diazophenylmethane (**7**) was a wine-colored solid, which was sufficiently pure for our purposes as estimated from the isolated yield (80%) of the 1,3-dipolar cycloadduct **11** with dimethyl acetylenedicarboxylate, and was used without further purification. Methyl (1-adamantyl)diazoacetate (**10**) was a yellow crystal, which could be purified by silica gel chromatography, and which gave a similar 1,3-dipolar cycloadduct **12** (88%). The obtained phenyl- and methoxycarbonyl-substituted diazo compounds were subjected to thermolytic, photolytic, and catalytic decompositions.

We first examined the case of a phenyl substituent. Thermolysis of **7** was carried out by means of spray flash vacuum pyrolysis;[10] a hexane solution of **7** was injected into a quartz tube heated with an electric furnace and the products were collected with a dry ice-cooled trap. After chromatographic separation, two major products were obtained as an oil and a crystal in yields (GLC) of 36% and 13% (400 °C), 37% and 23% (600 °C), and 14% and 24% (800 °C), respectively. Their respective structures were characterized spectroscopically as indano[1,2-1′,2′]adamantane (**13**) and 7-phenacylbicylo[3.3.1]-nonan-3-one (**14**). The MS parent peaks at m/z 224 and 256 showed that they corresponded to **7**-N_2 and **7**-N_2+O_2, respectively. In the ^{13}C-NMR spectra, the indane-fused form of **13** was suggested by a loss of symmetry, as indicated by the presence of 10 signals due to all of the adamantane ring carbons (DEPT analysis), and a C_s-symmetric bicyclic structure for **14** was supported by the presence of only 6 signals due to the 9 ring carbons. The ^{1}H-NMR and IR spectra were compatible with the assigned structures, as indicated by a methylene signal with an ABC coupling pattern due to an indane ring in **13** and by a doublet methylene signal due to a phenacyl group in **14**, together with carbonyl absorption at 1701 and 1688 cm^{-1} for

Scheme 2



14. The formation of these products was explained by competitive interaction of the carbene center with each ring. The indane-fused adamatane **13** was produced as the result of interaction with a phenyl ring *via* tandem phenylcarbene rearrangement[11] and intramolecular C−H insertion. The diketone **14** was produced as the result of interaction with an adamantane ring. The desired route to 4-phenylhomoadamant-3-ene (**1**), *i.e.*, the 1,2-carbon shift of the carbene intermediate was apparently followed by oxidative ring cleavage with atmospheric oxygen. Strained bridgehead olefins are known to undergo fragmentation to dicarbonyl compounds.[12] On the other hand, photolysis did not give a desired result. A hexane solution of **7** was irradiated with a high-pressure Hg lamp through a Pyrex filter, but the decomposition was sluggish (1 h to complete the reaction) and only azine **15** (32%) and ketone **5** (32%) were produced. These results are summarized in Scheme 2.

Catalytic decomposition was the most effective process for generating **1** (Scheme 3). When a dichloromethane solution of **7** was treated with a catalytic amount of $Rh_2(OAc)_4$ under an atmosphere of nitrogen, extrusion of nitrogen was complete within 5 min at room temperature. Interestingly, 4-phenylhomoadamant-4-ene (**16**) was obtained in 72% yield, even when HCl was added to the resulting reaction mixture after decomposition was complete. This result implies that the 1,2-carbon shift took place more selectively under catalytic conditions and the resulting bridgehead olefin could survive at room temperature (if unstable at this temperature, the reaction could be performed in the presence of a trapping reagent). The survivability of **1** was estimated by the decrease in the yield of the product resulting from delayed addition of a reagent. When $Rh_2(OAc)_4$-catalyzed decomposition at ambient temperature was followed by addition of HCl after an appropriate interval, the yield of **16** dropped from 71% (0 h) to 45% (after 12 h) and 0% (after 24 h).[13] This suggests that more than half of the bridgehead olefin **1** remained in solution[14] at ambient temperature after 12 h. The action of a weak acid such as acetic acid, instead of HCl, also gave **16** in 53% yield. A catalyst/solvent effect was observed in this rearrangement. Decomposition in hexane proceeded more slowly to give the non-rearranged coupling product, azine **15**, in 40% yield. Furthermore, $Rh_2(NHCOCH_3)_4$ did not promote the smooth decomposition of **7**, and only gave **15** as a separable product. On the other hand, $Rh_2(OCOCF_3)_4$ induced the 1,2-carbon shift more effectively and increased the yield of **16** (73% yield after addition of acetic acid).

(8) Oxidation was also attempted using MnO_2. However, the yield of **7** was low, as estimated from the cycloadduct **11** (34% yield), and the long reaction time (2 h) resulted in the formation of byproducts [*e.g.*, α-(1-adamantyl)benzyl alcohol].

(9) Regitz, M.; Maas, G. *Diazo Compounds*; Academic Press: Orlando, 1981; Chapter 13.

(10) Rubin, Y.; Lin, S. S.; Knobler, C. B.; Anthony, J.; Boldi, A. M.; Diederich, F. *J. Am. Chem. Soc.* **1991**, *113*, 6943.

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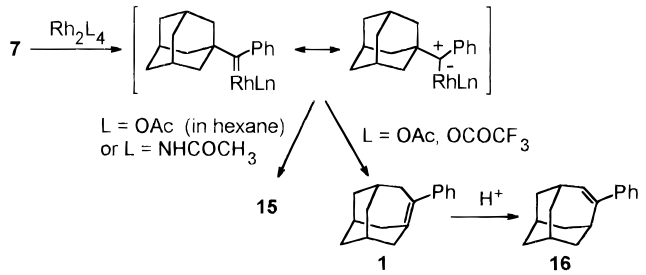
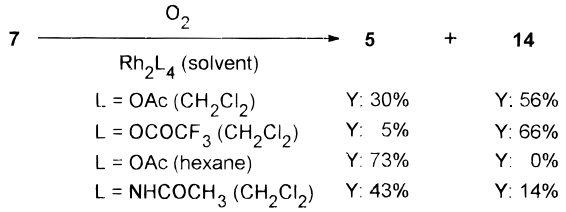
(13) These yields were based on the relative intensity of ^{1}H NMR signals of the products (**16**: δ 6.21, **35**: δ 3.49) to those of an internal standard (benzyl ether: δ 4.56).

(14) Concentration of the solution: ca. 0.035 M.

Scheme 3



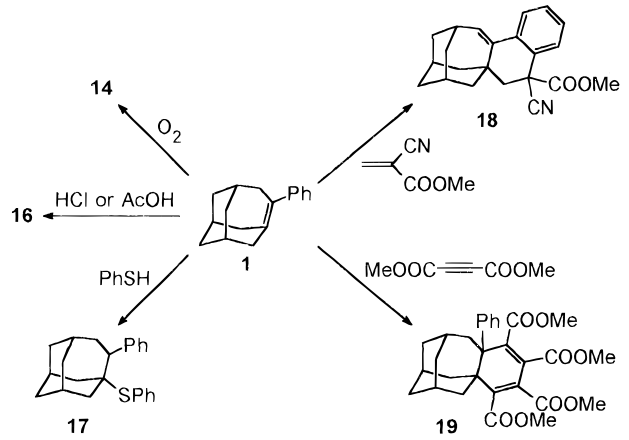
Scheme 4



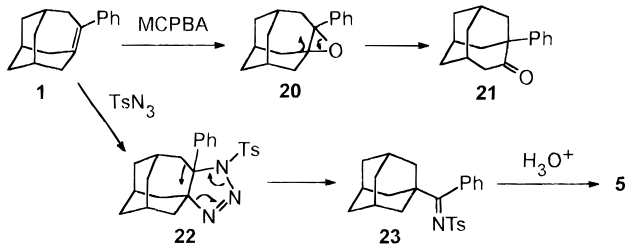
More evidently, the rearrangement aptitude of the Rh−carbene complex intermediate was demonstrated under an atmosphere of oxygen (Scheme 4). In this case, the Rh-carbene complex reacts with oxygen before and after the 1,2-carbon shift. Diketone **14** may be formed if facilitated by a ligand on Rh and if not inhibited by the solvent. Otherwise, **5** is formed without skeletal rearrangement. As a result, decomposition of **7** with $Rh_2(OAc)_4$ or $Rh_2(OCOCF_3)_4$ in dichloromethane saturated with oxygen gave **14** as the major product. In contrast, **5** was the major product under similar conditions in hexane with $Rh_2(NHCOCH_3)_4$. Thus, it is apparent that the more polar solvent and electron-accepting ligand favored the 1,2-carbon shift. Padwa recently demonstrated that ligands affected switching between competitive carbenoid transformations.[15] When the ligand is more electron accepting, the rhodium−carbene complex becomes more polarized, and a reactive cation center may therefore be involved in the carbenoid reaction. Davies also reported a polarizing solvent effect in this polarization.[16] A nonpolar solvent such as hexane disfavors the polarized structure of the complex, leading to the formation of a product different from that in dichloromethane. The above adamantylcarbene → homoadamant-3-ene rearrangement seems to be closely related to the cationic adamantylmethyl → homoadamantyl rearrangement,[17] and the polarized intermediate may therefore participate prominently in the present reaction. This is consistent with the observed solvent and ligand effects. A similar result was obtained in the catalytic decomposition of diazo ester **10** (*vide infra*).

Although the stability of the bridgehead double bond was enhanced with a phenyl group, it was still highly reactive. The decomposition products found after allowing a solution of **1** to stand under an atmosphere of nitrogen were not characterized, since no low molecular weight products (*e.g.*, a dimeric product) could be separated on chromatography. Nevertheless, **1** reacted with various reagents to give fragmentation, addition, and rearrangement products. Diketone **14** was formed rapidly (59%)

Scheme 5



Scheme 6



when a solution of **1** was exposed to air after Rh-catalyzed decomposition. In this case, about half of **1** was destroyed within 60 min (GLC measurement). While this result suggests that this bond has a radical nature, a polar nature was indicated in reactions with electrophiles. Reactions with proton acids were as delineated above. The proton attacked the bridgehead carbon, and subsequent deprotonation gave the isomeric homoadamant-4-ene **16**.[7g] The appreciable reactivity with acetic acid reflects the nature of this strained olefin.[18] In contrast, nucleophilic addition of ethanol or aniline did not occur (*vide infra*). In this sense, while thiophenol was expected to be unreactive, adduct **17** was obtained, albeit in a low yield. Presumably, it was produced *via* a radical pathway.[19] Some cycloaddition reactions were also successful, and the cycloadduct structures were characterized by ^{13}C NMR spectra coupled with DEPT analysis and other spectral methods. Methyl α-cyanoacrylate underwent formal [4 + 2] cycloaddition with **1** to give **18** after oxidative rearomatization. Compound **18** might be formed *via* either a diradical or a zwitterionic intermediate.[12a,20] The reaction with dimethyl acetylenedicarboxylate was unusual, and gave the [2 + 2 + 2] cycloadduct **19**. These results are summarized in Scheme 5. Scheme 6 illustrates two other cycloaddition reactions involving a skeletal rearrangement. Epoxidation with *m*-chloroperbenzoic acid gave rise to 3-phenylhomoadamantan-4-one (**21**) as a result of homoadamantyl → homoadamantyl rearrangement of the oxirane-fused homoadamantane **20**.[2] 1,3-Dipolar cycloaddition with tosyl azide produced imine **23**, which could be hydrolyzed to **5**, *via* ring contraction of the triazoline-fused homoadamantane **22**.[21]

In a related study on a cage compound, Eaton reported the Bamford−Stevens reaction of tosylhydrazone **24** of cubyl phenyl

(15) (a) Padwa, A.; Austin, D. J.; Price, A. T.; Semonnes, M. A.; Doyle, M. P.; Protopopova, M. N.; Winchester, W. R.; Tran, A. *J. Am. Chem. Soc.* **1993**, *115*, 8669. (b) Brown, D. S.; Eliott, M. C.; Moody, C. J.; Mowlem, T. J.; Marino, J. P., Jr.; Padwa, A. *J. Org. Chem.* **1994**, *59*, 2447. (c) Padwa, A.; Austin, D. J. *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 1797. See also: (d) Cox, G. G.; Haigh, D.; Hindley, R. M.; Miller D. J.; Moody, C. J. *Tetrahedron Lett.* **1994**, *35*, 3139. (e) Pirrung, M. C.; Morehead, A. T., Jr. *J. Am. Chem. Soc.* **1994**, *116*, 8991.

(16) (a) Davies, H. M. *Tetrahedron* **1993**, *49*, 5203. (b) Davies, H. M.; Hu, B.; Saikali, E.; Bruzinski, P. R. *J. Org. Chem.* **1994**, *59*, 4535.

(17) Fort, R. C., Jr. *Adamantane, The Chemistry of Diamond Molecules*; Marcel Dekker: New York, 1976: p 193.

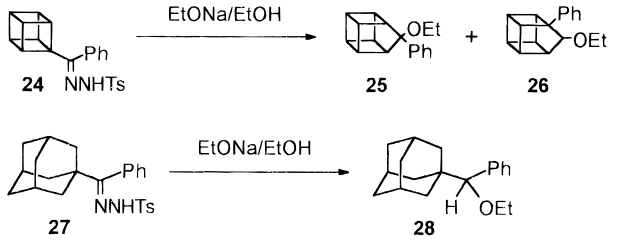
(18) Similarly, the reaction with bromine gave a bromo-substituted product which was reduced to **16** with $Bu_3SnH/AlBN$. An analogous electrophilic addition and elimination mechanism and formation of the reduction product **16** may allow assignment of a tentative structure as 3-bromo-4-phenylhomoadamant-4-ene. The conclusive assignment awaits further elaboration because 11 lines due to homoadamantene ring carbons appeared in the ^{13}C NMR spectrum despite C_s symmetry.

(19) Mlinaric-Majerski, K.; Kaselj, M. *J. Org. Chem.* **1994**, *59*, 4362.

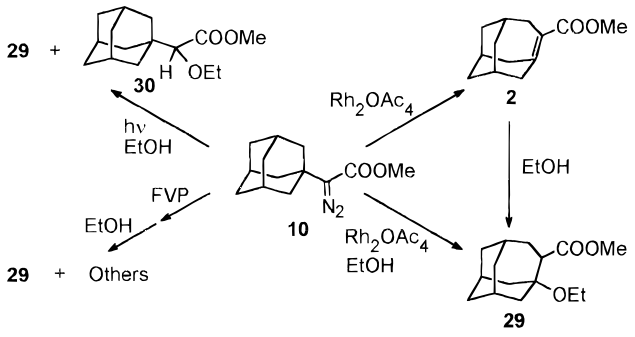
(20) Rasoul, H. A. A.; Hall, H. K., Jr. *J. Org. Chem.* **1982**, *47*, 2080.

(21) Lwowski, W. *1,3-Dipolar Cycloaddition Chemistry*; Padwa A., Ed.; J. Wiley & Sons: New York, 1984; Vol. 1, Chapter 5.

Scheme 7



Scheme 8

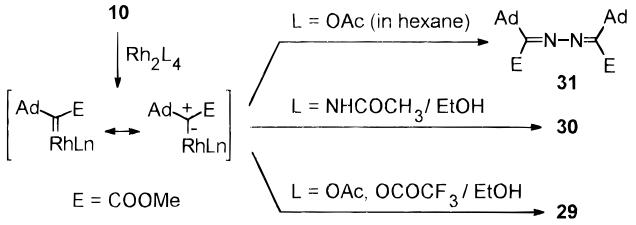


ketone, which was accomplished with sodium ethoxide in ethanol at reflux temperature to give the rearranged products **25** and **26** which had a homocubane structure.[22] In contrast, no such product was obtained from tosylhydrazone **27** or adamantyl phenyl ketone (**5**) under identical conditions. Only the insertion product **28**, which retained an adamantane structure, was obtained in good yield. This result can be explained by the difference in the strain of each polycycle; unlike a cubyl system, a strain-free adamantyl system need not rearrange to the homolog in the absence of a catalyst or more energetic conditions.

We next turn to the decomposition of diazo ester **10**. Thermolytic, photolytic, and catalytic decompositions were carried out as for **7** (Scheme 8). In this case, the resulting bridgehead olefin is an α,β-unsaturated ester, which is expected to be trapped with an alcohol. Therefore, it was first characterized as the ethanol adduct. Spray flash vacuum pyrolysis (550 °C) gave a complex mixture after the pyrolysates were treated with ethanol, from which only methyl 3-ethoxyhomoadamantane-4-carboxylate (**29**) was isolated in 8% yield. Photolysis (hexane solution including ethanol, room temperature, 7 h) produced the rearranged product **29** and the direct insertion product **30** in 28% and 31% yields, respectively. Alternatively, catalytic decomposition with $Rh_2(OAc)_4$ was again most effective for the formation of the bridgehead olefin. When **10** was treated in the presence of a catalytic amount of $Rh_2(OAc)_4$ in dichloromethane including ethanol at room temperature, adduct **29** was obtained in 52% yield. Interestingly, even the successive addition of ethanol after decomposition of **10** at 0 °C furnished a comparable yield of **29** (56%). This result indicates that the bridgehead α,β-unsaturated ester **2** is considerably stable around 0 °C. The survivability of **2** was estimated by the method that was used for **1**. In this case, aniline was used as a trapping reagent and the yield of the product **35** (see below) after an appropriate interval dropped from 80% (0 h) to 48% (after 1 h) and 0% (after 2 h),[13] indicating that more than half of **2** still survived at ambient temperature after 1 h. The present case and the aforementioned phenyl-substituted case confirm that the bridgehead olefin is stabilized with a conjugative substituent.

In the above catalytic reaction including ethanol, a catalyst/solvent effect controlled the mode of rearrangement of **10**, as it had for **7** (Scheme 9). Decomposition occurred more slowly in hexane (1 h at room temperature) to give azine **31**.[23] While a slight increase in the yield of **29** was observed with $Rh_2(OCOCF_3)_4$, non-rearranged insertion product **30** was obtained with $Rh_2(NHCOCH_3)_4$. Consequently, the dipolar nature of the Rh−carbene complex plays a significant role in promoting the 1,2-carbon shift.

Scheme 9



The α,β-unsaturated ester at the bridgehead survived at 0 °C. Therefore, the addition of **2** was successfully attempted after completion of Rh-catalyzed decomposition. However, as with **1**, identifiable decomposition products could not be obtained after **2** was left without a reagent. After **10** was decomposed with $Rh_2(OAc)_4$ in dichloromethane at 0 °C for 10 min, oxygen was bubbled into the resulting solution to give the ring-cleaved tricarbonyl compound **32** in 41% yield. This is similar to **1** → **14**.[12] While **1** did not react with a nucleophile, **2** underwent a smooth addition reaction with an alcohol to give 3-alkoxyhomoadamantane-4-carboxylates; as shown above, ethanol was used to examine the efficiency of "lysis". Likewise, adducts **33** and **34** were obtained with methanol and benzyl alcohol in comparable yields, respectively. The formation of these adducts indicates that the bridgehead unsaturated ester is highly reactive, since unstrained methyl crotonate underwent no such addition reaction under the same conditions. Other nucleophiles such as aniline, benzylamine, and thiophenol gave adducts **35**−**37** in 42−80% yields. As shown above, the effective reaction with aniline was employed as a survival test. Crowded nucleophiles such as 2-propanol and diethylamine did not react because of steric congestion at the bridgehead. The reaction with proton acids such as hydrogen chloride and trifluoroacetic acid led to the formation of 1,4-addition products **38** and **39** (78 and 53% yields, respectively). The same product **38** was obtained with the Lewis acid titanium tetrachloride. Reduction was achieved with triethylsilane in the presence of trifluoromethanesulfonic acid to yield methyl homoadamantane-4-carboxylate (**40**). These addition products were characterized by spectroscopy and/or independent synthesis. The rearranged structures were based on 11 signals due to skeletal carbons in the ^{13}C NMR spectra coupled with DEPT analysis. In the ^1H NMR spectra, however, the coupling pattern of C_4−H was not clearly resolved.[24] Compound **40** was synthesized as a representative compound; 4-homoadamantanone (**41**) was converted into homoadamantane-4-carboxaldehyde (**43**) ($Ph_3P{=}COMe$ and then $HClO_4$[25]), which was further oxidized to **44** ($KMnO_4$) and esterified (CH_2N_2) to authentic methyl homoadamantane-4-carboxylate. This ester was consistent with the reduction product derived from **2**. The cycloaddition of **2** was performed by a simple Diels−Alder reaction with butadiene to give **45** in 19% yield.[6c,d,g,h] These results are summarized in Scheme 10.

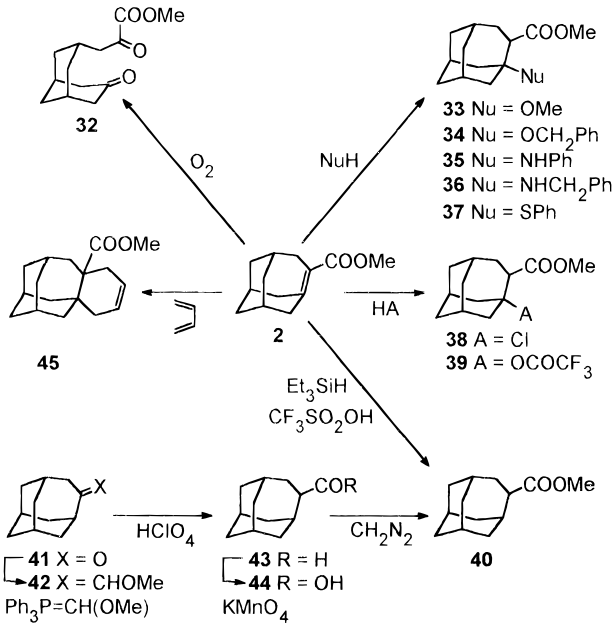
(22) Eaton, P. E.; White, A. J. *J. Org. Chem.* **1990**, *55*, 1321.

(23) Glaser, R.; Chen, G. S.; Barnes, C. L. *J. Org. Chem.* **1993**, *58*, 7446.

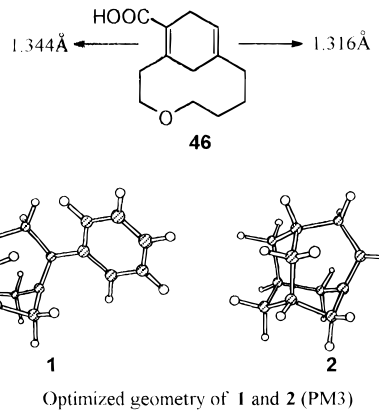
(24) Russian chemists previously reported compounds **38** and **40**. In their ^1H NMR, the C_4−H signal was described simply as a triplet. However, it is split in a more complicated fashion and structures cannot be assigned simply by referring to the data given therein: Krasutskii, P. A.; Semenova, I. G.; Safronova, E. E.; Novikova, M. I.; Yurchenko, A. G. *Zh. Org. Khim.* **1989**, *25*, 2336.

(25) Danishefsky, S.; Nagasawa, K.; Wang, N. *J. Org. Chem.* **1975**, *40*, 1989.

Scheme 10



Finally, the enhanced stability of bridgehead olefins should be addressed. As is well-known, parent homoadamant-3-ene **3** is unstable at ambient temperature and can be observed only at much lower temperature. Indeed, Jones first characterized **1** spectroscopically at −196 °C.[7e] In contrast, 4-phenyl- and 4-methoxycarbonyl-substituted homoadamant-3-enes **1** and **2** are considerably more stable at ambient temperature (*vide supra*). The stabilization by phenyl and methoxycarbonyl substituents seems to be due essentially to their conjugative ability,[26] while kinetic stability due to steric protection, as in **4**, may also play a role. Resonance of the bridgehead olefin with these groups promotes polarization of this bond to cause its single-bond character to increase while the strain energy is reduced. An informative X-ray analysis was recently reported by Shea,[4a] who found that the carboxyl group-substituted bridgehead double bond in bicyclic diene **46** was longer than the unsubstituted bridgehead double bond. The optimized geometry according to PM3 calculations[27] suggests that the double bonds in **1** (1.363 Å) and **2** (1.362 Å) are longer than that in **3** (1.345 Å).[28] In comparison, 4-*tert*-butylhomoadamant-3-ene, which can be considered a model kinetically stabilized compound, was estimated to have a bond length of 1.356 Å. Thus, the bridgehead double bonds with phenyl and methoxycarbonyl groups were further lengthened as a result of conjugation. The optimized geometry illustrated below showed some steric effect compared with the parent homoadamant-3-ene **1**, but a conjugative effect should be considered to play a significant role in the observed stabilization.



Optimized geometry of **1** and **2** (PM3)

Figure 2.

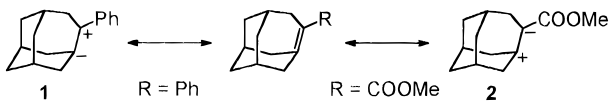


Figure 3.

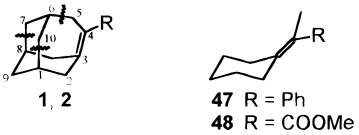


Figure 4.

Here, the polarizability of **1** and **2** is essentially different. As was seen in the reactions with HCl and nucleophiles, protonation occurred at the bridgehead carbon of **1**, leading to **16**, and chlorination ocurred at that of **2**, leading to **38**, and nucleophiles such as ethanol and aniline reacted with **2** but not with **1**. Thus, these compounds show an opposite polarization of the C_3-C_4 bond (negative at C_3 for **1** and positive at C_3 for **2**).

The spectroscopic features[29] of the strained double bonds in **1** and **2** were compared with those of normal double bonds in (1-cyclohexylidene)ethylbenzene (**47**) and methyl 2-cyclohexylidenepropanoate (**48**)[30] (which are formed by disconnections at the C_5-C_6, C_7-C_8 and C_1-C_{10} bonds of homoadamant-3-ene).

In the IR spectra, weak absorption bands were observed at 1574 cm^{-1} for **1** and at 1570 cm^{-1} for **2**, which are 69−79 cm^{-1} lower than those at 1653 cm^{-1} for **47** and at 1639 cm^{-1} for **48**. Deviation from the standard is due to distortion[6i] and is closely related to the 62-cm^{-1} shift from **3** (1610 cm^{-1}) to ethylidenecyclohexane (1672 cm^{-1}). In the ^{13}C NMR spectra, olefinic signals were seen at δ 148.3 and 143.1 for **1** (olefinic signals of **47** at δ 129.4 and 147.8) and at δ 170.5 and 128.8 for **2**, together with a carbonyl signal at δ 171.9 (olefinic signals for **48** at δ 148.2 and 119.7 with a carbonyl signal at δ 171.0).[31] The lower shifts observed in **1** and **2** were compatible with a more cationic nature at C_4 and C_3, respectively.

(26) A phenyl substituent (at C_2) was previously reported to stabilize the bicyclo[3.3.1]non-1-en-3-one system: see ref 12a.

(27) MOPAC Ver 5.00 (QCPE No. 445): Stewart J. J. P. *QCPE Bull.* **1989**, *9*, 10. Hirano, T. *JCPE Newsletter* **1989**, *9*(2), 36. Revised as Ver 5.01 by J. Toyoda for Apple Macintosh. HyperChem. 4.0 (Hypercube Inc.) on an IBM compatible computer.

(28) The relative stability can be predicted by the "olefin strain" energy (OS) defined by Schleyer. He noted that the OS-generalization for trisubstituted olefins [the difference between the heat of formation ($\Delta H_f°$) of an olefin and that of its parent alkane represents the heat of hydrogenation ($\Delta H_H°$); for most trisubstituted bridgehead olefins, OS and $\Delta H_H°$ are related by a constant difference, 26.1 kcal/mol] was not directly applicable to tetrasubstituted analogs. Nevertheless, our PM3 calculations indicated that the difference between the $\Delta H_f°$ of **1**, **2** and **3** and the $\Delta H_f°$ of their parent alkanes were 44.1, 46.2, and 49.0 kcal/mol, respectively. If changes in $\Delta H_H°$ caused by substituting phenyl and methoxycarbonyl groups for a hydrogen are assumed to be about −1 to −4 kcal/mol (cf. Jesen, J. L. *Prog. Phys. Org. Chem.* **1976**, *12*, 189), the OS's of **1** and **2** can be estimated to be slightly lower than that of **3**.

(29) These spectra were recorded at ambient temperature for IR and at −80 °C for ^{13}C NMR as soon as Rh-catalyzed decomposition was complete. Although the sample used was a crude product, olefinic signals could be distinguished from noisy signals due to contaminants.

(30) Compounds **47** and **48** were prepared from cyclohexanone and the corresponding phosphonate reagents according to previously reported procedures—for **47**: Shakak, I.; Almong, J.; Bergman, E. D. *Isr. J. Chem.* **1969**, *9*, 585. For **48**: Courout, P.; Ghribi, A. *Synthesis* **1991**, 790.

(31) The other ^{13}C NMR signals were observed with DEPT analysis at δ 27.5 (CH_2), 27.7 (CH), 36.2 (CH_2), 36.9 (CH), 42.9 (CH_2), 48.8 (CH_2), 124.9 (CH_2), 126.5 (CH_2), 127.7 (CH_2), and 139.6 (quarternary C) for **1**, and at δ 27.8 (CH), 28.3 (CH_2), 35.7 (CH), 35.8 (CH_2), 41.3 (CH_2), 41.7 (CH_2), and 51.0 (CH_3) for **2**. The ^1H NMR signals were observed at δ 1.41−2.52 (15 H, m) and 7.12−7.37 (5 H, m) for **1** and at δ 1.45−2.20 (15 H, m) and 3.70 (3 H, s) for **2**.

In summary, bridgehead olefins substituted with phenyl and methoxycarbonyl groups were formed in a homoadamantane system using the 1,2-carbon shift of the carbene (carbenoid) intermediate. Among the methods used to decompose the diazo precursors, catalysis with $Rh_2(OAc)_4$ was the most effective for producing the desired 4-substituted homoadamant-3-enes, which were more stable than unsubstituted homoadamant-3-ene. This finding was explained by strain relief of the double bond as a result of conjugation with the 4-substituent and to some extent by steric protection. The survivability of this bond at 0 °C to room temperature allowed the subsequent addition reaction with nucleophiles or electrophiles after Rh-catalyzed decomposition was complete, and a variety of 3,4-disubstituted homoadamantane derivatives could be obtained. The 1,2-carbon shift of the Rh−carbene complex was significantly affected by its polarized structure.

Experimental Section

General. IR spectra were recorded on a JASCO FT/IR 5300 spectrophotometer. ^{1}H and ^{13}C NMR were obtained with a Varian GEMINI-200 spectrometer at 200 and 50 MHz, respectively, for samples in $CDCl_3$ solution with $SiMe_4$ as an internal standard. *J* values are given in hertz. Mass spectra were recorded on a JEOL JMS-AX505H spectrometer (EI at 70 eV). Microanalyses were performed with a Perkin-Elmer 2400 elemental analyzer. Melting points were determined on a Yanaco MP apparatus and are uncorrected. Unless a melting point is given, the compound was obtained as an oil. Flash chromatography was performed with a silica gel column (Fuji-Davison BW-300) eluted with mixed solvents [hexane (H), ethyl acetate (A)]. THF was dried with Na−benzophenone and used after distillation. Dichloromethane was dried and distilled over calcium chloride, kept over molecular sieves, and bubbled with a nitrogen gas in an ultrasonic bath before use. $Rh_2(OAc)_4$ was purchased from Aldrich, and $Rh_2(OCOCF_3)_4$ and $Rh_2(NHCOCH_3)_4$ were prepared by previously reported methods.[32,33]

1-Adamantyl Phenyl Ketone Hydrazone (6). The starting ketone **5** was prepared in 84% yield from PhLi and 1-adamantanecarboxylic acid, instead of the reported method using $PhMgBr/CdCl_2$/1-adamantanecarbonyl chloride (53%).[34] A solution of **5** (4.8 g, 20 mM) and hydrazine monohydrate (10 mL, 200 mM) in methanol (80 mL) was refluxed for 8 h. The product was extracted with ether and recrystallized from hexane to give **6** as a white crystal (3.36 g, 66%). Mp 143−145 °C. IR (KBr) 3377, 2901, 1628, 1577, 711 cm^{-1}; ^{1}H NMR δ 1.50−2.05 (m, 15 H), 3.75 (br s, 2 H), 7.00−7.50 (m, 5 H); ^{13}C NMR δ 28.55, 36.70, 36.86, 40.05, 128.49, 128.78, 129.22, 133.78, 161.27. Anal. Calcd for $C_{17}H_{22}N_2$: C, 80.27; H, 8.72; N, 11.01. Found: C, 80.00; H, 8.80; N, 10.87.

(1-Adamantyl)diazophenylmethane (7). To a suspension of $BaMnO_4$ (512 mg, 2 mM) and CaO (776 mg, 13.8 mM) in ether (6 mL) was added a solution of **6** (127 mg, 0.5 mM) in ether (8 mL) under an atmosphere of nitrogen, and the mixture was stirred at room temperature for 15 min. Filtration of solids and evaporation of the solvent left a wine-colored solid **7**, which was characterized by IR absorption at 2033 cm^{-1} and MS signals at *m*/*z* (%) 252 (M, 5), 224 (66), 223 (100), 135 (61), and by the cycloadduct; **7** was dissolved in hexane (2 mL)/benzene (1 mL), and the solution was mixed with dimethyl acetylenedicarboxylate (71 mg, 0.5 mM) and stirred at room temperature for 2 h. After evaporation of the solvent, the product was chromatographed (H/A 10/1) to give **11** (158 mg, 80%). Mp 155−156 °C. IR (KBr) 2925, 1750, 1730 cm^{-1}; ^{1}H NMR δ 1.50−2.15 (m, 15 H), 3.58 and 3.95 (s, each 3 H), 7.30−7.50 (m, 5 H). MS (EI) *m*/*z* (%) 394 (M, 29); 380 (32), 363 (100). Anal. Calcd for $C_{22}H_{26}N_2O_4$: C, 70.03; H, 6.64; N, 7.10. Found: C, 70.03; H, 6.77; N, 7.03.

Although attempts to purify **7** failed (for example, recrystallization at −78 °C), the compound was sufficiently pure and was therefore used without further purification for subsequent reactions. The sample was dried over P_2O_5 under vacuum before use.

Methyl 2-(1-Adamantyl)-3-oxopropanoate (9). To a solution of LDA in THF (1 mL) prepared from BuLi (0.7 mL of 1.6 M hexane solution, 1.1 mM) and diisopropylamine (114 mg, 1.1 mM) was added a solution of **8** (208 mg, 1 mM) in THF (1 mL) at −78 °C under an atmosphere of nitrogen, and stirring was continued for 35 min. A solution of ethyl formate (88 mg, 1.2 mM) in THF (1 mL) was added and the mixture was stirred for an additional 2.5 h at the same temperature. The reaction mixture was poured into ice−water, extracted with ether, washed with water, and dried over Na_2SO_4. Evaporation to dryness left a residue, which was chromatographed (H/A 25/1) to give **9** (153 mg, 65%). Mp 52−54 °C. IR (KBr) 2920, 2860, 1745, 1720 cm^{-1}; ^{1}H NMR δ 1.60−2.10 (m, 15 H), 2.81 (d, J = 4.8 Hz, 1 H) 3.76 (s, 3 H), 9.85 (d, J = 4.8 Hz, 1 H); ^{13}C NMR δ 28.58, 36.56, 38.09, 40.58, 51.91, 68.96, 169.66, 200.70; MS (EI) *m*/*z* (%) 236 (M, 3), 222 (6), 208 (100). Anal. Calcd for $C_{14}H_{20}O_3$: C, 71.16; H, 8.53. Found: C, 71.10; H, 8.66.

Methyl (1-Adamantyl)diazoacetate (10). To a solution of **9** (236 mg, 1 mM) in THF (2 mL) was added BuLi (0.62 mL of 1.6 M hexane solution, 1 mM) at 0 °C under an atmosphere of nitrogen, and stirring was continued for 30 min. A solution of tosyl azide (215 mg, 1.1 mM) and hexamethylphosphoramide (179 mg, 1 mM) in THF (1 mL) was then added and stirring was continued for 1 h at 0 °C and for 4 h at room temperature. Hexane (20 mL), 1 *N* aqueous NaOH (2 mL), and water (20 mL) were added in succession, and the mixture was shaken well. The organic layer was separated, washed with water, and dried over Na_2SO_4. After evaporation of the solvent, the residue was chromatographed (H/A 20/1) to give **10** (117 mg, 50%). Mp 85−87 °C. IR (KBr) 2912, 2065, 1701 cm^{-1}; ^{1}H NMR δ 1.60−2.10 (m, 15 H), 3.73 (s, 3 H). ^{13}C NMR δ 28.76, 31.04, 31.43, 36.53, 40.43, 51.37, 167.46; MS (EI) *m*/*z* (%) 234 (M, 12), 206 (100). Anal. Calcd for $C_{13}H_{18}N_2O_2$: C, 66.64; H, 7.74; N, 11.96. Found: C, 66.56; H, 7.66; N, 12.03.

In the above experiment, the yield of **10** dropped to 19% in the absence of hexamethylphosphoramide. As with **7**, **10** was treated with 1.5 equiv of dimethyl acetylenedicarboxylate at room temperature for 10 days to give **12** in 88% yield. Mp 125−128 °C. IR (KBr) 2912, 1745, 1720 cm^{-1}; ^{1}H NMR δ 1.74−2.32 (m, 15 H), 3.86, 3.93 and 3.94 (s, each 3 H); MS (EI) *m*/*z* (%) 376 (M, 6), 361 (15), 345 (54), 330 (51), 135 (100). Anal. Calcd for $C_{19}H_{24}N_2O_6$: C, 60.63; H, 6.43; N, 7.44. Found: C, 60.89; H, 6.60; N, 7.20

Thermolysis of 7. A solution of **7** in hexane (2 mL), starting from 127 mg (0.5 mM) of **6**, was injected into an 8 mm × 50 cm quartz tube fitted with a rubber septum at the top and a dry ice-cooled trap at the bottom under vacuum (0.2 mmHg), while the center (30 cm) was heated with an electric furnace at 400−800 °C. The collected products were subjected to chromatography (hexane and then H/A 10/1) to give **13** as the first fraction and **14** as the second fraction. The yields of **7** and **13** based on **6** were determined by GLC: 13% and 37% at 400 °C, 23% and 36% at 600 °C, and 24% and 14% at 800 °C, respectively.

13: IR (neat) 2906, 1467, 752 cm^{-1}; ^{1}H NMR δ 1.25−2.32 (m, 14 H), 2.66 (dd, 1 H, J = 4.8, 14.8 Hz), 2.91 (dd, 1 H, J = 12.2, 14.8 Hz), 7.04−7.29 (m, 4 H); ^{13}C NMR δ 28.42, 29.59, 30.66, 31.27, 33.48, 37.97, 39.68, 39.74, 40.84, 44.39, 53.72, 121.11, 125.83, 126.37, 126.47, 143.57, 153.71; MS (EI) *m*/*z* (%) 224 (M, 55), 167 (100), 130 (24). Anal. Calcd for $C_{17}H_{20}$: C, 91.01; H, 8.99. Found: C, 91.10; H, 8.90.

14: mp 50.0−51.5 °C; IR ($CHCl_3$) 2930, 1701, 1688, 1597 cm^{-1}; ^{1}H NMR δ 0.85−2.60 (m, 13 H), 2.77 (d, 1 H, J = 6.6 Hz) 7.40−8.00 (m, 5 H); ^{13}C NMR δ 24.99, 28.70, 28.89, 34.64, 45.44, 50.37, 128.44, 129.00, 133.46, 137.61, 200.19, 213.66; MS (EI) *m*/*z* (%) 256 (M, 3), 238 (10), 152 (100), 120 (90). Anal. Calcd for $C_{17}H_{20}O_2$: C, 79.65; H, 7.86. Found: C, 79.71; H, 7.89.

Photolysis of 7. A solution of **7** in hexane (4 mL), starting from 64 mg (0.25 mM) of **6**, was irradiated with a high-pressure Hg lamp through a Pyrex filter for 1 h under an atmosphere of nitrogen. White precipitates were separated by filtration to give azine **15** (19 mg, 32% based on **6**). From the mother liquor, 19 mg (32%) of **5** was separated by chromatography (H/A 50/1).

15: mp 231−234 °C; IR ($CHCl_3$) 2925, 1605, 1495 cm^{-1}; ^{1}H NMR δ 1.25−2.00 (m, 30 H), 6.94−7.40 (m, 10 H); ^{13}C NMR δ 28.35, 36.70, 39.78, 40.48, 127.40, 127.74, 127.84, 136.79, 166.23; MS (EI) *m*/*z* (%)

(32) Johnson, S. A.; Hunt, H. R.; Newmann H. M. *Inorg. Chem.* **1963**, *2*, 960.
(33) Doyle, M. P.; Bagheri, V.; Wandless, T. J.; Harn, N. K.; Brinker D. A.; Eagle, C. T.; Loh, K.-L. *J. Am. Chem. Soc.* **1990**, *112*, 1906.
(34) Stetter, H.; Rauscher, E. *Chem. Ber* **1960**, *93*, 1161.

476 (M, 83), 372 (100), 299 (60). Anal. Calcd for $C_{34}H_{40}N_2$: C, 85.67; H, 8.46; N, 5.88. Found: C, 85.82; H, 8.63; N, 5.75.

Catalysis of 7. A solution of **7** in dichloromethane (2 mL), starting from 64 mg (0.25 mM) of **6**, was mixed with a catalytic amount of $Rh_2(OAc)_4$ in dichloromethane (1 mL) at room temperature under an atmosphere of nitrogen, and nitrogen was evolved instantly. The reaction mixture was stirred for 5 min and hydrogen chloride (0.75 mL of a 2 M dichloromethane solution, 1.5 mM) was added. After being stirred overnight, the reaction mixture was poured into water and extracted with dichloromethane. The extracts were washed with water, dried over Na_2SO_4, and evaporated to dryness. The residue was chromatographed (hexane) to give **16** (40 mg, 71% base on **6**): IR (neat) 2925, 1645, 1600, 1495 cm^{-1}; ^1H NMR δ 1.80−2.45 (m, 14 H), 6.21 (dd, 1 H, J = 8.8, 1.8 Hz), 7.15−7.40 (m, 5 H); ^{13}C NMR δ 29.58, 32.25, 34.09, 34.19, 36.75, 37.40, 125.86, 126.59, 128.46, 135.62, 145.19, 150.67; MS (EI) *m*/*z* (%) 224 (M, 100), 167 (21), 155 (45). Anal. Calcd for $C_{17}H_{20}$: C, 91.01; H, 8.99. Found: C, 90.91; H, 9.09.

When the above catalysis was followed by the addition of acetic acid (0.15 mL, 2.5 mM), **16** was obtained in 53% yield. **16** was obtained at a yield of 73% when $Rh_2(OCOCF_3)_4$ was used as a catalyst. A similar procedure using $Rh_2(NHCOCH_3)_4$ gave only 8 mg (13%) of **15** as a separable product. When a hexane solution of **7** was stirred in the presence of $Rh_2(OAc)_4$ for 2 h to complete the reaction, 24 mg (40%) of **15** was obtained.

Catalysis of 7 under an Atmosphere of Oxygen. Starting from 64 mg (0.25 mM) of **6**, catalytic decomposition of **7** with $Rh_2(OAc)_4$ was carried out as described above under a stream of oxygen, and the reaction mixture was stirred overnight while exposed to air. After evaporation of the solvent, the residue was chromatographed (H/A 20/1 and then H/A 3/1) to give 18 mg (30% based on **6**) of **5** as the first fraction and 36 mg (56% based on **6**) of **14** as the second fraction. Likewise, reactions using $Rh_2(OCOCF_3)_4$ and $Rh_2(NHCOCH_3)_4$ as catalysts gave 3 mg (5%) of **5** and 42 mg (66%) of **14**, and 26 mg (43%) of **5** and 9 mg (14%) of **14**, respectively. When the $Rh_2(OAc)_4$-catalyzed reaction was conducted using hexane as a solvent, 44 mg (73%) of **5** was obtained.

Reaction of 1 after Catalysis of 7. This reaction was carried out by adding an appropriate reagent soon after the catalytic decomposition of **7** with $Rh_2(OAc)_4$ as described above. The reaction mixture of **1** formed *in situ* [starting from 64 mg (0.25 mM) of **6**] and the reagent in dichloromethane (3 mL) was stirred overnight at room temperature under an atmosphere of nitrogen. Workup [(a) evaporation of the solvent, or (b) evaporation after the reaction mixture was poured into water, and the organic layer was extracted with dichloromethane and dried over Na_2SO_4] and chromatography gave the product; the yields given below are based on **6**.

With Oxygen. Exposure to air, workup a, and chromatography (H/A 3/1) gave **14** (38 mg, 59%).

With Thiophenol. Addition of thiophenol (83 mg, 0.75 mM), workup (b; the mixture was also washed with aqueous NaOH) and preparative TLC (H/A 10/1) gave **17** (6 mg, 7%). IR (neat) 2901, 1581, 1491 cm^{-1}; ^1H NMR δ 1.04−2.52 (m, 16 H), 3.26 (t, J = 9.8 Hz, 1 H), 7.20−7.46 (m, 10 H); ^{13}C NMR δ 29.32, 29.51, 31.42, 34.03, 35.99, 38.37 41.10, 45.78, 48.93, 57.11, 77.45, 126.94, 128.00, 128.57, 128.83, 130.16, 134.26, 138.88, 145.97; MS (EI) *m*/*z* (%) 334 (M, 26), 225 (100), 135 (20). Anal. Calcd for $C_{23}H_{26}S$: C, 82.58; H, 7.84. Found: C, 82.42; H, 8.01.

With Methyl α-Cyanoacrylate. Addition of a solution of methyl α-cyanoacrylate (28 mg, 0.25 mM) in dichloromethane (0.2 mL), workup a, and chromatography (H/A 10/1) gave **18** (16 mg, 19%). IR (neat) 2909, 2225, 1745, 1630, 1483 cm^{-1}; ^1H NMR δ 1.54−2.30 (m, 13 H), 2.15 and 2.42 (d, J = 13.4 Hz, each 1 H), 3.87 (s, 3 H), 6.79 (d, J = 9.4 Hz, 1 H), 7.01−7.63 (m, 4 H); ^{13}C NMR δ 29.72, 29.84, 32.15, 33.13, 33.22, 35.85, 36.01, 36.74, 41.90, 42.23, 47.32, 49.46, 53.99, 119.95, 125.89, 127.40, 127.50, 129.58, 130.16, 136.82, 143.42, 169.41; MS (EI) *m*/*z* (%) 333 (M, 100), 292 (61), 274 (98). Anal. Calcd for $C_{22}H_{23}NO_2$: C, 79.25; H, 6.95; N, 4.20. Found: C, 79.10; H, 6.97; N, 4.31.

With Dimethyl Acetylenedicarboxylate. Addition of dimethyl acetylenedicarboxylate (355 mg, 2.5 mM), workup b, and chromatography (H/A 10/1) gave **19** (33 mg, 26%): IR ($CHCl_3$) 2906, 1724, 1595 cm^{-1}; ^1H NMR δ 1.55−2.65 (m, 15 H), 3.29, 3.76, 3.79 and 3.95 (s, each 3 H), 7.18−7.35 (m, 5 H); ^{13}C NMR δ 27.58, 28.04, 28.15, 31.90, 31.96, 33.63, 37.89, 43.52, 44.36, 51.82, 52.47, 52.54, 52.85, 62.66, 106.30, 116.72, 124.63, 127.81, 128.17, 129.01, 133.18, 145.37, 147.75, 161.80, 163.02, 164.86, 169.90; MS (EI) *m*/*z* (%) 508 (M, 1), 493 (3), 444 (31), 149 (47), 135 (39), 105 (100); HRMS calcd for $C_{29}H_{32}O_8$ 508.2097, found 508.2082.

With *m*-Chloroperbenzoic Acid. Addition of a solution of *m*-chloroperbenzoic acid (130 mg, 0.75 mM) including $NaHCO_3$ (63 mg, 0.75 mM) in THF (1 mL) and water (1 mL), workup b, and chromatography (H/A 5/1) gave **21** (17 mg, 28%). Mp 75−79 °C. IR (KBr) 2905, 1693, 1602, 1496 cm^{-1}; ^1H NMR δ 1.56−2.41 (m, 15 H), 2.78 (d, J = 4.0 Hz, 2 H), 7.17−7.36 (m, 5 H); ^{13}C NMR δ 26.07, 28.18, 35.18, 37.06, 39.14, 51.59, 55.02, 126.52, 126.59, 128.23, 148.29, 216.71; MS (EI) *m*/*z* (%) 240 (M, 65), 212 (14), 155 (100), 134 (29). Anal. Calcd for $C_{17}H_{20}O$: C, 84.95; H, 8.39. Found: C, 84.82; H, 8.51.

With *p*-Toluenesulfonyl Azide. Addition of *p*-toluenesulfonyl azide (30 mg, 0.28 mM), workup b, and chromatography (H/A 10/1) gave **23** (57 mg, 58%) as a 3/2 syn and anti mixture. Mp 133−143 °C. IR (KBr) 2903, 1604, 1584, 1331, 1155 cm^{-1}; ^1H NMR δ 1.55−2.55 (m, 14 H), 2.32 and 2.40 (s, 2/3 × 3 H and 1/3 × 3 H), 3.51 (d, J = 4.2 Hz, 1 H), 7.04−7.71 (m, 9 H); ^{13}C NMR δ 21.61, 28.10, 36.29, 39.24, 44.83, 126.68, 127.57, 127.68, 129.12, 129.63, 135.29, 138.91, 143.55, 193.24 and the corresponding peaks due to the minor isomer; MS (EI) *m*/*z* (%) 393 (M, 38), 238 (98), 135 (100). Anal. Calcd for $C_{24}H_{27}NO_2S$: C, 73.24; H, 6.91; N, 3.56. Found: C, 73.20; H, 7.11; N, 3.50.

Imine **23** could be hydrolyzed to **5** by heating in wet ethanol with sulfuric acid.

Bamford−Stevens Reaction of 27. The starting tosylhydrazone **27** was obtained in 76% yield by refluxing a solution of **5** (240 mg, 1 mM) and tosylhydrazide (186 mg, 1 mM) in methanol (2 mL) for 30 h. Sodium (80 mg) was dissolved in dry ethanol (3 mL) and to this solution was added **27** (106 mg, 0.26 mM). The resulting solution was refluxed for 6 h under an atmosphere of nitrogen. The reaction mixture was poured into saturated aqueous $NaHCO_3$ (30 mL) and dichloromethane (30 mL). The organic layer was separated, washed with water, and dried over Na_2SO_4. Evaporation to dryness and chromatographic separation (hexane) of the residue gave **28** (53 mg, 83%).

27: Mp 157−159 °C; IR (KBr) 3500, 2925, 1600, 1340 cm^{-1}; ^1H NMR δ 1.50−2.02 (m, 15 H), 2.47 (s, 3 H), 6.70−8.30 (m, 10 H). Anal. Calcd for $C_{24}H_{28}N_2O_2S$: C, 70.49; H, 6.85; N, 6.85. Found: C, 70.38; H, 6.92; N, 6.80.

28: IR (neat) 2920, 1605, 1090 cm^{-1}; ^1H NMR δ 1.13 (t, J = 7.0 Hz, 3 H), 1.35−2.00 (m, 15 H), 3.19 and 3.36 (dq, J = 9.6, 7.0 Hz, each 1 H) 3.70 (s, 1 H), 7.18−7.35 (m, 5 H); ^{13}C NMR δ 15.28, 28.54, 37.15, 37.30, 38.65, 64.82, 90.65, 127.27, 127.60, 128.93, 139.93; MS (EI) *m*/*z* (%) 270 (M, 9), 135 (100). Anal. Calcd for $C_{19}H_{26}O$: C, 84.39; H, 9.69. Found: C, 84.60; H, 9.65.

Thermolysis of 10. The diazo ester **10** (23 mg, 0.1 mM) dissolved in hexane (1 mL) was thermolyzed at 550 °C as with **7**. The hexane solution collected in a cold trap was stirred with ethanol (1 mL) at room temperature overnight. After evaporation of the solvent, the residue was subjected to chromatography (H/A 20/1), but only 2 mg (8%) of **29** was isolated from the complex mixture. **29**: see below.

Photolysis of 10. A solution of **10** (23 mg, 0.1 mM) in hexane (1 mL) including ethanol (0.025 mL, 0.4 mM) was photolyzed (room temperature, 7 h) as with **7**. After evaporation of the solvent, the products were chromatographed (H/A 20/1) to give **30** (8 mg, 31%) as the first fraction and **29** (7 mg, 28%) as the second fraction.

29: mp 38−40 °C; IR ($CHCl_3$) 2908, 1726, 1159, 1070 cm^{-1}; ^1H NMR δ 1.06 (t, J = 6.9 Hz, 3 H), 1.45−2.50 (m, 15 H), 3.16 (m, 1 H), 3.47 and 3.51 (dq, J = 12.6, 6.9 Hz, each 1 H), 3.68 (s, 3 H); ^{13}C NMR δ 16.10, 27.24, 27.86, 31.29, 34.57, 34.62, 36.01, 37.79, 39.81, 44.95, 51.55, 52.92, 56.39, 77.33, 176.53; MS (EI) *m*/*z* (%) 252 (M, 3), 207 (34), 147 (48), 123 (100). Anal. Calcd for $C_{15}H_{24}O_3$: C, 71.39; H. 9.59. Found: C, 71.41; H, 9.58.

30: IR ($CHCl_3$) 2909, 1736, 1107 cm^{-1}; ^1H NMR δ 1.20 (t, J = 7.0 Hz, 3 H), 1.51−1.98 (m, 15 H), 3.32 and 3.56 (dq, J = 9.4, 7.0 Hz, each 1 H), 3.37 (s, 1 H), 3.75 (s, 3 H); ^{13}C NMR δ 15.01, 28.41, 36.53, 37.08, 38.52, 51.41, 66.68, 88.22, 172.95; MS (EI) *m*/*z* (%) 252 (M, 2), 193 (88), 135 (100). Anal. Calcd for $C_{15}H_{24}O_3$: C, 71.39; H, 9.59 Found: C, 71.41; H, 9.58.

Catalysis of 10 in the Presence of EtOH. A solution of **10** (23 mg, 0.1 mM) in dichloromethane (1 mL) including ethanol (0.025 mL, 0.4 mM) was mixed with a catalytic amount of $Rh_2(OAc)_4$ at room temperature under an atmosphere of nitrogen, and the mixture was stirred overnight. After evaporation of the solvent, the product was chromatographed (H/A 20/1) to give 13 mg (52%) of **29**. The same experiments using $Rh_2(OCOCF_3)_4$ and $Rh_2(NHCOCH_3)_4$ as catalysts gave 14 mg (56%) of **29** and 12 mg (48%) of **30**, respectively. On the other hand, the $Rh_2(OAc)_4$-catalyzed reaction conducted in hexane (2 mL) gave **31** (8 mg, 36%). Mp 55−58 °C. IR ($CHCl_3$) 2901, 1736, 1628, 1153 cm^{-1}; ^1H NMR δ 1.59−2.02 (m, 30 H), 3.84 (s, 6 H); ^{13}C NMR δ 28.06, 36.56, 38.18, 39.45, 51.12, 166.27, 171.96; MS (EI) *m*/*z* (%) 440 (M, 6), 381 (100), 135 (76). Anal. Calcd for $C_{26}H_{36}N_2O_4$: C, 70.88; H, 8.24; N, 6.36. Found C, 70.98; H, 8.25; N, 6.42.

Reaction of 2 after Catalysis of 10. An appropriate reagent was added to **2** formed *in situ*, as soon as a mixture of **10** (23 mg, 0.1 mM) and a catalytic amount of $Rh_2(OAc)_4$ in dichloromethane (2 mL) was stirred at 0 °C for 10 min under an atmosphere of nitrogen. The reaction mixture was then stirred overnight at room temperature. After evaporation of the solvent, the residue was subjected to chromatography to give the product.

With Oxygen. Treatment with oxygen (bubbling for 15 min) and exposure to air overnight followed by chromatography (H/A 2/1) gave **32** (10 mg, 42%): IR ($CHCl_3$) 2932, 1730, 1703, 1057 cm^{-1}; ^1H NMR δ 1.56−2.53 (m, 13 H), 2.65 (d, J = 7.0 Hz, 2 H), 3.87 (s, 3 H); ^{13}C NMR δ 24.44, 28.20, 28.71, 46.15, 50.49, 53.18, 161.91, 194.10, 213.16; MS (EI) *m*/*z* (%) 238 (M, 1) 206 (3), 179 (91), 151 (100). Anal. Calcd for $C_{13}H_{18}O_4$: C, 65.53, H, 7.61. Found: C, 65.41; H, 7.79.

With Methanol. Addition of methanol (1 mL) and chromatography (H/A 20/1) gave **33** (14 mg, 59%): IR ($CHCl_3$) 2908, 1726, 1197, 1076 cm^{-1}; ^1H NMR δ 1.46−2.47 (m, 15 H), 3.13 (m, 1 H), 3.23 and 3.69 (s, each 3 H); ^{13}C NMR δ 27.14, 27.77, 31.27, 34.58, 34.74, 35.93, 36.98, 39.56, 43.82, 49.17, 51.62, 52.70, 79.34, 176.55; MS (EI) *m*/*z* (%) 238 (M, 3), 207 (74), 146 (32), 135 (100). Anal. Calcd for $C_{14}H_{22}O_3$: C, 70.56; H, 9.31. Found: C, 70.55, H, 9.31.

With Ethanol. Addition of ethanol (1 mL) and chromatography (H/A 20/1) gave **29** (14 mg, 56%).

With Benzyl Alcohol. Addition of benzyl alcohol (52 mg, 0.5 mM) and chromatography (H/A 20/1) gave **34** (13 mg, 41%): IR ($CHCl_3$) 2909, 1725, 1603, 1159 cm^{-1}; ^1H NMR δ 1.53−2.56 (m, 15 H), 3.24 (m, 1 H), 3.57 (s, each 3 H), 4.52 and 4.58 (dq, J = 12.0 Hz, each 1 H), 7.18−7.72 (m, 5 H); ^{13}C NMR δ 27.31, 27.85, 31.25, 34.63, 34.68, 35.96, 36.95, 39.74, 44.87, 51.57, 53.71, 63.23, 78.83, 127.25, 128.49, 128.77, 140.33, 176.49; MS (CI) *m*/*z* (%) 315 (M + H, 48), 207 (100). Anal. Calcd for $C_{20}H_{26}O_3$: C, 76.39; H, 8.33. Found: C, 76.27; H, 8.45.

With Aniline. Addition of aniline (93 mg, 1 mM) and chromatography (H/A 10/1) gave **35** (24 mg, 80%). Mp 95−98 °C. IR ($CHCl_3$) 3526, 2908, 1723, 1601, 1161 cm^{-1}; ^1H NMR δ 1.54−2.56 (m, 16 H), 3.25 (m, 1 H), 3.49 (s, 3 H), 6.72−7.71 (m, 5 H); ^{13}C NMR δ 27.28, 27.89, 31.42, 35.48, 35.77, 35.90, 39.23, 40.08, 47.07, 51.42, 53.41, 58.82, 118.82, 119.23, 129.07, 146.30, 177.02; MS (EI) *m*/*z* (%) 299 (M, 100), 242 (37), 207 (60), 170 (94). Anal. Calcd for $C_{19}H_{25}NO_2$: C, 76.21; H, 8.42; N, 4.68. Found: C, 76.23; H, 8.45; N, 4.50.

With Benzylamine. Addition of benzylamine (54 mg, 0.5 mM) and chromatography (H/A 10/1) gave **36** (13 mg, 42%): IR ($CHCl_3$) 3549, 2909, 1723, 1604, 1152 cm^{-1}; ^1H NMR δ 1.46−2.42 (m, 16 H), 3.11 (m, 1 H), 3.66 (s, 3 H), 3.78 (s, 2 H), 7.19−7.30 (m, 5 H); ^{13}C NMR δ 27.36, 27.89, 31.59, 35.27, 36.06, 36.21, 39.41, 39.54, 46.02, 46.68, 51.49, 52.88, 57.19, 127.02, 128.49, 128.65, 144.86, 177.37; MS (EI) *m*/*z* (%) 313 (M, 10), 256 (9), 207 (13), 184 (100). Anal. Calcd for $C_{20}H_{27}NO_2$: C, 76.64; H, 8.68; N, 4.47. Found: C, 76.62; H, 8.72; N, 4.32.

With Thiophenol. Addition of thiophenol (55 mg, 0.5 mM), removal of the excess reagent under vacuum (3 mmHg at 100 °C), and chromatography (H/A 5/1) gave **37** (19 mg, 60%): IR ($CHCl_3$) 2907, 1725, 1157 cm^{-1}; ^1H NMR δ 1.36−2.84 (m, 15 H), 3.01 (m, 1 H), 3.77 (s, 3 H), 7.35−7.64 (m, 5 H); ^{13}C NMR δ 28.54, 28.79, 31.94, 35.51, 35.79, 38.02, 38.38, 38.60, 48.38, 51.50, 53.55, 54.85, 128.82, 129.20, 132.24, 138.04, 176.73; MS (EI) *m*/*z* (%) 316 (M, 10), 207 (100), 147 (44). Anal. Calcd for $C_{19}H_{24}O_2S$: C, 72.21; H, 7.64. Found: C, 72.05; H, 7.68.

With Hydrogen Chloride. Addition of hydrogen chloride (2 mL of a 0.5 M dichloromethane solution, 1 mM) and chromatography (H/A 10/1) gave **38** (19 mg, 78%). Mp 47−49 °C (lit. mp 50−51 °C).[24] IR ($CHCl_3$) 2911, 1730, 1163 cm^{-1}; ^1H NMR δ 1.50−2.52 (m, 14 H), 3.09 (m, 1 H), 3.21 (m, 1 H), 3.71 (s, 3 H); ^{13}C NMR δ 29.13, 29.42, 31.33, 34.13, 35.65, 36.77, 39.25, 42.59, 51.76, 53.10, 57.80, 73.76, 175.74; MS (EI) *m*/*z* (%) 242/244 (M, 1), 206 (100), 174 (48), 135 (93). Anal. Calcd for $C_{13}H_{19}O_2Cl$: C, 64.33; H, 7.89. Found: C, 64.38, H, 7.83.

This compound was also obtained with $TiCl_4$; addition of $TiCl_4$ (0.2 mL of a 0.5 M dichloromethane solution, 0.1 mM) was followed by stirring at 0 °C for 30 min. The rection mixture was poured into ice−water, extracted with dichloromethane, washed with water, and dried over Na_2SO_4. Evaporation to dryness left a residue, which was chromatographed as above to give **38** (6 mg, 25%).

With Trifluoroacetic Acid. Addition of trifluoroacetic acid (12 mg, 0.11 mM) and chromatography (H/A 5/1) gave **39** (17 mg, 53%): IR ($CHCl_3$) 2913, 1776, 1732, 1170 cm^{-1}; ^1H NMR δ 1.51−2.54 (m, 15 H), 2.70 (m, 1 H), 3.65 (s, 3 H), 3.82 (m, 1 H); ^{13}C NMR δ 27.42, 31.11, 33.77, 35.05, 35.74, 37.80, 37.99, 44.11, 50.39, 52.04, 91.71, 114.72 (q, J = 286 Hz), 156.16 (q, J = 41 Hz), 175.05; MS (EI) *m*/*z* (%) no molecular ion, 207 (100). Anal. Calcd for $C_{15}H_{18}F_3O_4$: C, 56.42; H, 5.68. Found: C, 56.23; H, 5.88.

With Triethylsilane and Trifluoromethanesulfonic Acid. Addition of a solution of triethylsilane (116 mg, 1 mM) and trifluoromethanesulfonic acid (15 mg, 0.1 mM) in dichloromethane (1 mL) and chromatography (H/A 20/1) gave **40** (9 mg, 43%). IR (neat) 2903, 1734, 1165 cm^{-1}; ^1H NMR δ 1.47−2.40 (m, 15 H), 2.75 (m 1 H), 3.66 (s, 3 H); ^{13}C NMR δ 27.13, 27.42, 31.10, 32.24, 34.50, 35.53, 36.34, 36.42, 40.15, 40.41, 49.91, 51.76, 178.13; MS (EI) *m*/*z* (%) 208 (M, 94), 176 (62), 148 (100). An authentic sample was obtained as follows: Homoadamantanone (164 mg, 1 mM) was added to a Wittig reagent prepared from (methoxymethyl)triphenylphosphonium chloride (343 mg, 1.1 mM) and lithium diisopropylamide [diisopropylamine (0.14 mL, 1 mM) + butyllithium (0.7 mL of 1.6 M hexane solution, 1 mM), 1 mM in THF (2 mL)] at −78 °C, and the mixture was stirred for 4 h at this temperature and then for 4 h at room temperature. The usual workup and chromatographic separation (hexane) gave **42** (40 mg, 22%) as a 1:5 stereoisomeric mixture: IR (neat) 1662 cm^{-1}; ^1H NMR δ 1.45−2.44 (m, 15 H), 3.18 (m, 1 H), 3.53 and 3.56 (s, 3 H × 5/6 and 3 H × 1/6), 5.66 and 5.85 (m, 1 H × 5/6 and 1 H × 1/6); ^{13}C NMR (major isomer) δ 27.69, 30.21, 30.53, 36.43, 36.95, 37.72, 37.89, 38.58, 38.90, 59.44, 125.31, 140.61; MS (EI) *m*/*z* (%) 192 (M, 100), 135 (53). A solution of **42** (50 mg, 0.3 mM) in ether (6 mL) was refluxed with 70% hydroperchloric acid (0.21 mL) for 15 min. The usual workup and chromatographic separation (H/A 20/1) gave aldehyde **43** (40 mg, 75%): IR (neat) 1722 cm^{-1}; ^1H NMR δ 1.27−2.62 (m, 18 H), 9.68 (s, 1H); ^{13}C NMR δ 26.93, 27.18, 30.73, 31.68, 32.42, 32.80, 35.93(2C), 39.78, 39.97, 57.28, 205.51: MS (EI) *m*/*z* (%) 178 (M, 18), 148 (100). Oxidation of **43** (18 mg, 0.1 mM) was performed by stirring with $KMnO_4$ (11 mg, 0.07 mM) in water (1 mL) and dichloromethane (1 mL) including 0.1 mL of H_2SO_4 at 10 °C for 4 h to give acid **44** (15 mg, 69%): IR (KBr) 3500−2500, 1697 cm^{-1}; ^1H NMR δ 1.48−2.80 (m, 18 H), 13.02 (br s, 1H); ^{13}C NMR δ 27.09, 27.38, 31.08, 32.28, 34.33, 35.51, 36.14, 36.34, 40.15, 40.36, 49.75, 183.60; MS (EI) *m*/*z* (%) 194 (M, 100), 148 (40). Finally, esterification of **44** with diazomethane gave the authentic sample (62% yield), which was identical with the reduced product from **2**.

With Butadiene. Addition of butadiene by bubbling (15 min) and chromatography (H/A 10/1) gave **45** (5 mg, 19%): IR (neat) 2905, 1728, 1660 cm^{-1}; ^1H NMR δ 1.23−2.69 (m, 19 H), 3.63 (s, 3 H), 5.67 (m, 2 H); ^{13}C NMR δ 28.33, 28.51, 32.89, 36.43, 37.68, 38.10, 38.23, 38.85, 41.17, 42.21, 44.40, 48.67, 51.62, 52.48, 126.14, 126.56, 179.11; MS (EI) *m*/*z* (%) 260 (M, 18), 200 (100), 135 (54). Anal. Calcd for $C_{17}H_{24}O_2$: C, 78.42; H, 9.29. Found: C, 78.47; H, 9.22.

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