Reactivity of (3-Chloro-2-methylenecycloalkyl)palladium Chloride Dimers: Addition of Stabilized Carbon Nucleophiles and Application to Cyclopentannulation and Cyclohexannulation

William A. Donaldson,* Jinkang Wang, Valerie G. Cepa, and John D. Suson†

Department of Chemistry, Marquette University, Milwaukee, Wisconsin 53233

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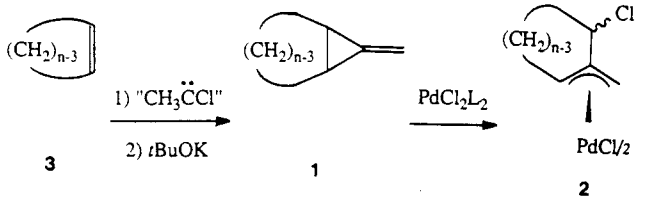
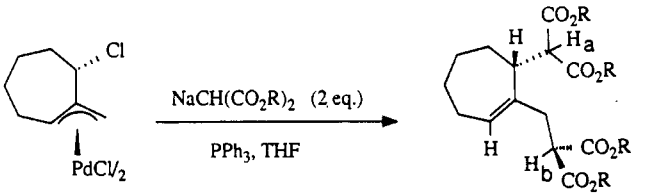
The title compounds react as either "trimethylenemethane dication" synthons or "isoprenyl monocation" synthons with stabilized carbon nucleophiles in the presence of phosphine ligands. This reactivity is dependent on size of the carbocyclic ring, substituents on the ring, the amount and nature of the nucleophile, and the nature of the phosphine ligand. The product (**4a**) from alkylation of 2 equiv of malonate anion with (3-chloro-2-methylenecycloheptyl)palladium chloride dimer (**2a**) was cyclized via oxidative coupling to afford the octahydroazulene skeleton. The cyclodialkylation of 1 equiv of the dianion of dimethyl 3-ketoglutarate with **2a**, followed by saponification and decarboxylation, afforded 9-ketobicyclo[5.4.0]undec-1-ene.

The application of (π-allyl)palladium complexes to organic synthesis is well documented. These complexes may react as organometallic electrophiles with carbon and heteroatom nucleophiles in a highly chemo-, regio-, and stereoselective fashion.[1] In addition, the reactivity of (π-allyl)palladium complexes as organometallic nucleophiles has recently been described.[2] These versatile complexes may be generated stoichiometrically from olefins[3] or dienes[4] or catalytically from allylic acetates,[5] carbonates,[6] or sulfones.[7] We[8] and others[9] have reported on the ring opening of ω-methylenebicyclo[n.1.0]alkanes **1** with palladium chloride to afford (3-chloro-2-methylenecycloalkyl)palladium chloride dimers (**2**) in excellent yields. Since compounds **1** may be prepared from the corresponding cyclic olefins **3**, these steps represent an overall ring homologation methodology. We have investigated the cleavage of complexes **2** in methanolic potassium hydroxide.[10] The results from the cleavage reactions indicate that the (3-chloro-2-methylenecycloalkyl)palladium chloride dimers may react as "1,3-diactivated" complexes. The reactivity of 1,1-, 1,2-, 1,3- and 1,4-diactivated palladium allyl complexes with carbon nucleophiles has been reported.[11] We herein report on the reactivity of complexes **2** with stabilized carbon nucleophiles and dinucleophiles.[12]



Results and Discussion[13]

The reaction of (3-chloro-2-methylenecycloheptyl)palladium chloride dimer (**2a**) with 2 equiv of sodium dimethyl or diethyl malonate in the presence of triphenylphosphine afforded the tetraesters **4a** and **4b** in excellent isolated yield. The structural assignment for **4a** is based upon its ^{1}H NMR spectral data. The signals for H_a and H_b appear as a doublet (δ 4.05, J = 11.7) and a doublet of doublets (δ 3.55, J = 5.6, 11.2), respectively. This clearly indicates that the malonate functional groups are attached to a methine and a methylene carbon. A single olefinic signal (δ 5.67, dd, J = 6.1, 7.8) and the appearance of the methyl esters as four distinct signals (δ 3.72, 3.71, 3.69, 3.68) suggests the presence of a cyclic olefin containing an asymmetric center. The spectral data for **4b** are similar.



4a, R = Me (93%)
b, R = Et (75%)

The two new C–C bonds of **4** are likely formed in a sequential fashion, either via initial attack at the Pd-allyl or initial displacement of the C3 chloride. There is ample evidence for the former reaction[1] as well as the latter reaction. Notably, Kemmitt has previously reported car-

† In part.

(1) Trost, B. M.; Verhoeven, T. R. *Comprehensive* Organometallic *Chemistry*; Pergamon Press: New York, 1982; Chapter 57, Vol. 8, pp 799–938.
(2) Masuyama, Y.; Hayashi, R.; Otake, K.; Kurusu, Y. *J. Chem. Soc., Chem. Commun.* **1988**, 44–5. Tabuchi, T.; Inanaga, J.; Yamaguchi, M. *Tetrahedron Lett.* **1987**, 215–6.
(3) Trost, B. M.; Strege, P. E.; Weber, L.; Fullerton, T. J.; Dietsche, T. J. *J. Am. Chem. Soc.* **1978**, *100*, 3407–15.
(4) Backvall, J. E. *Acc. Chem. Res.* **1983**, *16*, 335–42. Larock, R. C.; Takagi, K.; Hershberger, S. S.; Mitchell, M. A. *Tetrahedron Lett.* **1981**, 5231–4. Larock, R. C.; Mitchell, M. A. *J. Am. Chem. Soc.* **1978**, *100*, 180–8.
(5) Trost, B. M.; Verhoeven, T. R. *J. Am. Chem. Soc.* **1978**, *100*, 3407–15.
(6) Minami, I.; Takahashi, K.; Shimizu, I.; Kimura, T.; Tsuji, J. *Tetrahedron* **1986**, *42*, 2971–7. Tsuji, J. *Pure Appl. Chem.* **1986**, *58*, 869–78.
(7) Trost, B. M. *Bull. Chem. Soc. Jpn.* **1988**, *61*, 107–24. Trost, B. M.; Schmuff, N. R. *J. Am. Chem. Soc.* **1985**, *107*, 396–405.
(8) Donaldson, W. A. *Organometallics* **1986**, *5*, 223–30.
(9) Albright, T. A.; Clemens, P. R.; Hughes, R. P.; Hunton, D. E.; Margerum, L. D. *J. Am. Chem. Soc.* **1982**, *104*, 5369–79. Clemens, P. R.; Hughes, R. P.; Margerum, L. D. *J. Am. Chem. Soc.* **1981**, *103*, 2428–30. Hughes, R. P.; Hunton, D. E.; Schumann, K. *J. Organomet. Chem.* **1980**, *184*, C67–C69.
(10) Donaldson, W. A. *Tetrahedron* **1987**, *43*, 2901–8. Donaldson, W. A.; Taylor, B. S. *Tetrahedron Lett.* **1985**, 4163–6.
(11) (a) Lu, X.; Haung, Y. *J. Organomet. Chem.* **1984**, *298*, 185–90. (b) Trost, B. M.; Vercauteren, J. *Tetrahedron Lett.* **1985**, 113–4. (c) Backvall, J. E.; Nordberg, R. E.; Nystrom, J. E. *Tetrahedron Lett.* **1982**, 1617–20. (d) Backvall, J. E.; Nystrom, J. E.; Nordberg, R. E. *Tetrahedron* **1985**, *41*, 5761–4. (e) Lu, X.; Haung, Y. *Tetrahedron Lett.* **1986**, 1615–6. (f) Haung, Y.; Lu, X. *Tetrahedron Lett.* **1987**, 6219–20. (g) Haung, Y.; Lu, X. *Tetrahedron Lett.* **1988**, 5663–4.
(12) Preliminary communication: Donaldson, W. A.; Grief, V. J. *Tetrahedron Lett.* **1986**, 2345–8.
(13) All compounds described in this paper are racemic mixtures of enantiomers unless otherwise indicated. For simplicity only one enantiomer is diagrammed.

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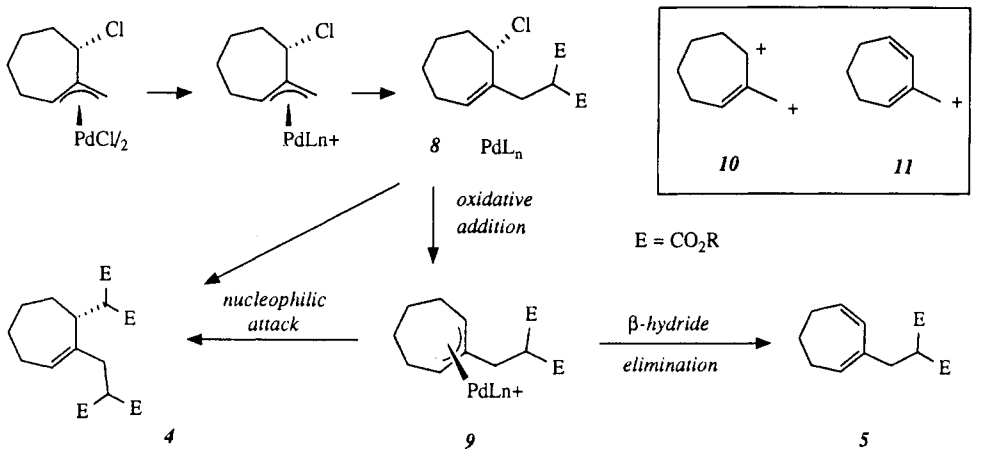
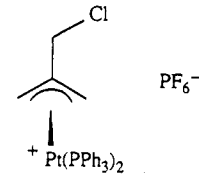
Scheme I



bon–chloride bond activation in similar (2-(chloromethyl)allyl)platinum complexes **6**.[14] In addition, the π-allyl complex **7** reacts with malonate anion via displacement of the allylic halide.[15]



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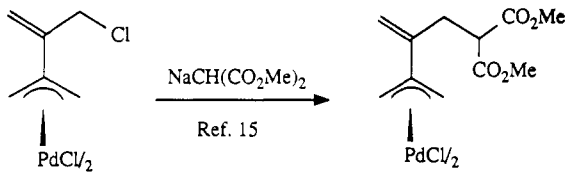
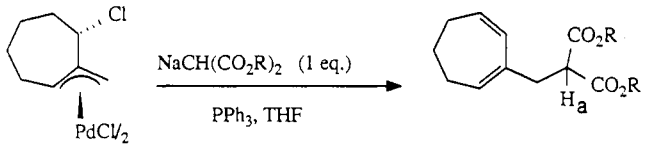


7

The reaction of **2a** with 1 equiv of malonate anion in the presence of triphenylphosphine yielded the diene diesters **5a** and **5b**. The structural assignment for **5a** is based upon its ^{1}H and ^{13}C NMR spectral data. In particular, the ^{13}C NMR spectrum of **5a** (Table II) contains four olefinic resonances and the olefinic region of the ^{1}H NMR spectrum integrates to three protons. These spectral features indicate a 2-substituted-1,3-cycloheptadiene fragment. The appearance of the methyl esters as a single singlet (δ 3.64) and the appearance of H_a as a triplet (δ 3.40, J = 8) are consistent with a structure without any asymmetric center. The spectral data for **5b** are similar.



2a

5a, R = Me (81%)
b, R = Et (78%)

The reaction of **2a** with 1 equiv of sodium diethyl malonate in the absence of any phosphine ligand gave only recovered **2a** (>95%) as indicated by ^{1}H NMR spectroscopy. The latter two results clearly indicate the *initial* nucleophilic attack occurs on the coordinated allylic functionality.

The following mechanism is proposed to rationalize the formation of **4** and **5** (Scheme I). Initial nucleophilic attack occurs at the unsubstituted allylic terminus to afford the allylic chloride **8**. Oxidative addition of Pd(0) to the allylic halide **8**, with inversion at C3 gives the new π-allyl **9**. In the absence of an additional equivalent of nucleophile **9** undergoes β-hydride elimination to afford the cycloheptadiene product **5**.[16] Nucleophilic attack on **9** gives the product **4** in which two new carbon–carbon bonds have been formed. Alternatively, product **4** might arise via displacement of the allylic chloride of **8** by malonate nucleophile. Notably, the displacement of an allylic chloride by malonate usually requires more vigorous reaction conditions (CH_3CN, reflux, 12 h)[17] than was used in this work. *Thus under the appropriate reaction conditions, complex* ***2a*** *may react as either a "trimethylenemethane dication"*[18] *synthon (**10**) or an "isoprenyl monocation" synthon (**11**).*

The new π-allyl **9** is a symmetrical intermediate. The use of chiral phosphine ligands in place of triphenylphosphine would destroy this symmetry and could result in asymmetric induction in the attack of the second nucleophile.[19] Surprisingly, the reaction of racemic π-allyl **2a** with 2 equiv of malonate anion in the presence of chiral phosphine ligands gave only the product from β-hydride elimination (**5a**). Notably, the nature of the phosphine ligand has an effect on the relative rates of malonate attack on intermediate **9** compared to β-hydride elimination. Thus the reaction of **2a** with malonate in the presence of DIPHOS, $(Ph_2PCp)_2Fe$, polymer supported triphenylphosphine or TOT gave increasing ratios of products **5**:**4**.

In sharp contrast, reaction of the six-membered cyclic π-allyl **2b** with 2 equiv of sodium dimethyl malonate in the presence of *S*,*S*-DIOP gave a mixture of **4c**, **12a**, and **12b** (5:1:1). The structure of product **4c** is assigned by com-

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(15) Hegedus, L. S.; Kambe, N.; Tamura, R.; Woodgate, P. D. *Organometallics* **1983**, *2*, 1658–61.
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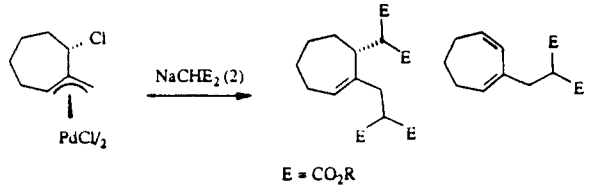
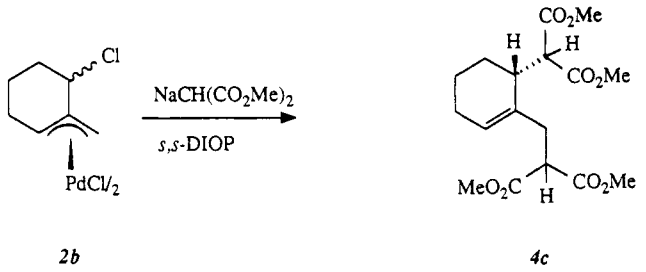
(17) Backvall, J. E.; Vagberg, J. O.; Granberg, K. L. *Tetrahedron Lett.* **1989**, 617–20.
(18) "Zwitterionic trimethylenemethane" synthons and "trimethylenemethane dianion" synthons have been reported. (a) Trost, B. M.; Chan, D. M. T. *J. Am. Chem. Soc.* **1983**, *105*, 2326–35. (b) Molander, G.; Shubert, D. C. *J. Am. Chem. Soc.* **1987**, *109*, 576–8. In addition, methylenecyclopropane has been ring opened with Pd(0) to act as a "trimethylenemethane diradical" synthon: Binger, P.; Lu, Q. H.; Wedemann, P. *Angew. Chem., Int. Ed. Engl.* **1985**, *24*, 316–7.
(19) Asymmetric alkylation of symmetrical π-allyls has been affected by the use of chiral chelating bisphosphine ligands: (a) Trost, B. M.; Dietsche, T. J. *J. Am. Chem. Soc.* **1973**, *95*, 8200–1. (b) Trost, B. M.; Murphy, D. J. *Organometallics* **1985**, *4*, 1143–5.

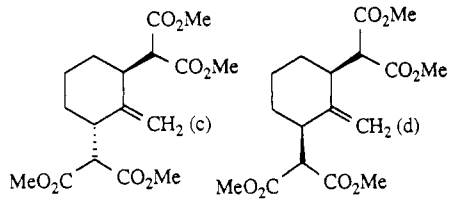


Ligand	4a	5a
DIPHOS	73%	19%
[(Ph$_2$P)Cp]$_2$Fe	48%	30%
PS-PPh$_3$	35%	21%
(o-CH$_3$C$_6$H$_4$)$_3$P	0%	25%
NMPP	0%	75%
S,S-DIOP	0%	53%
R-PROPHOS	0%	13%

parison of its ^{1}H NMR spectral data to that obtained for **4a**. The ^{1}H NMR spectra of the mixture of **4c**, **12a**, and **12b** in the presence of varying amounts of the chiral LSR Eu(facam)$_3$ show no splitting of the signals for H_a or H_b. This may be due either to the presence of only a single enantiomer or, more likely, due to failure to separate the enantiomeric signals. The structural assignments for **12a** and **12b** are based upon their NMR spectral behavior in the presence of Eu(facam)$_3$. The signals for H_c of **12a** separate into two signals (3:2 ratio) while the signals for H_d of meso **12b** do not separate in the presence of the chiral LSR.

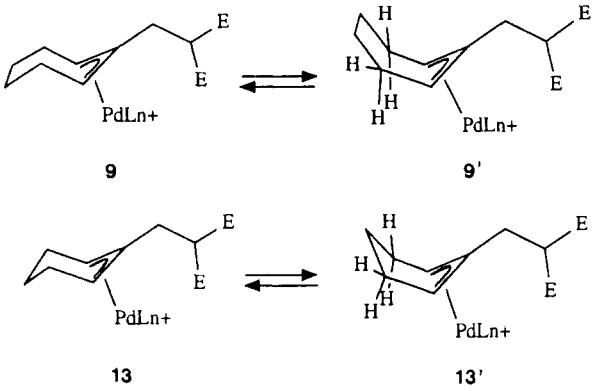


2b *4c*



12a *12b*

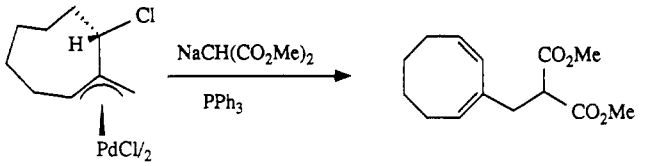
The formation of **12a** and **12b** requires initial attack of malonate on **2b** at the *endocyclic* allylic terminus. Attack at the endocyclic terminus has previously been observed for (methylenecyclohexyl)palladium complexes.[20] The optical enrichment of **12a** may be due to a number of possibilities; one is that the initial reactant **2b** is an inseparable mixture of diastereomers.[8] While the results concerning the optical enrichment of **4c** are inconclusive, the above results indicate a profound difference in reactivity between the (cycloheptyl)- and the (cyclohexyl)-palladium allyl intermediates, **9** and **13**, under identical reaction conditions. Only in the boat conformer of each is the proper orientation for β-hydride elimination achieved. The axial β-hydrogens of **9′** are closer to the Pd metal than the axial β-hydrogens of **13′**. Thus, the relative rates of β-hydride elimination vs nucleophilic attack should be greater for **9** than for **13**.



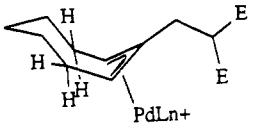
9 **9′**

13 **13′**

The reaction of **3c** with 1 or 2 equiv of sodium dimethyl malonate, in the presence of triphenylphosphine, gave only the 1,3-cyclooctadiene product **5c**. The structural assignment for **5c** is based upon comparison of its ^{1}H and ^{13}C NMR spectral data with that obtained for **5a**. Thus, only the product from β-hydride elimination is obtained from intermediate **14** under the *ideal reaction conditions* for attack of a second nucleophile upon the intermediate **9**. This difference in reactivity reflects the fact that the β-hydrogens in **14** are even closer to the Pd metal then in the seven-membered π-allyl intermediate **9**.

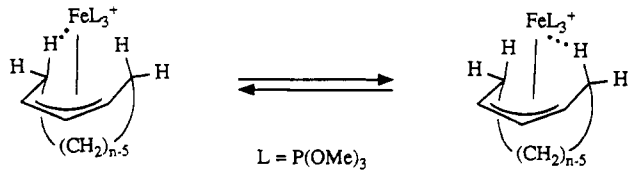


2c **5c**



14

It has previously been noted from the fluxional behavior of cationic cyclic π-allyl-μ-hydride iron complexes **15** that the β-hydrogens become considerably closer to the metal center with an increase in the carbocyclic ring size.[21] Thus the barrier for the exchange of agostic[22] hydrogens in **15** decreases from E_a = 10.4 kcal/mol for the cyclohexenyl complex (n = 6) to E_a < 5 kcal/mol for the cyclooctenyl complex (n = 8).



15 **15′**

endo-2-Methyl-7-methylenebicyclo[4.1.0]heptane (**16**) was prepared from 3-methylcyclohexene in the following manner: (i) addition of dichlorocarbene,[23] (ii) lithium–halogen exchange with *t*-BuLi followed by quench with

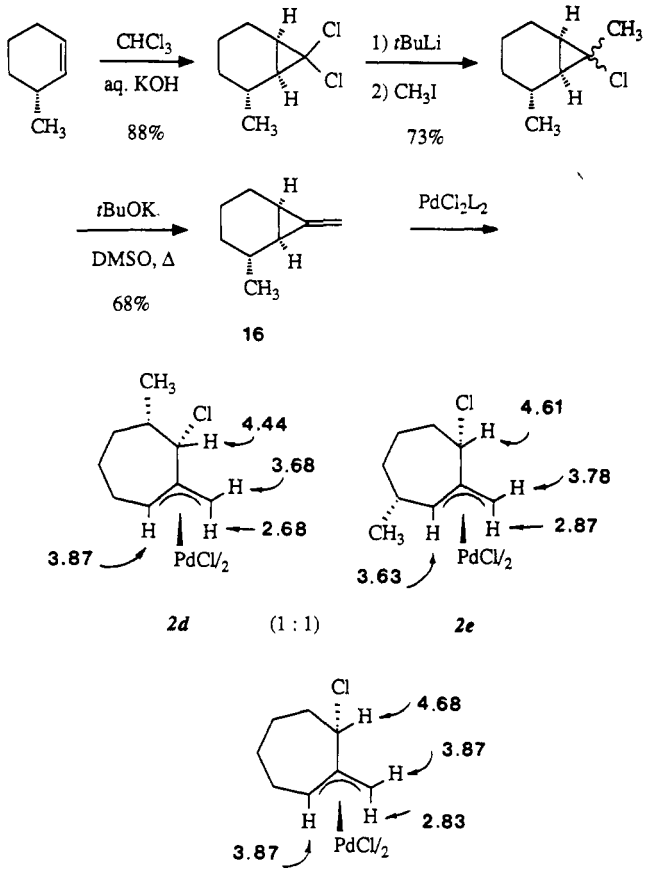
(20) Trost, B. M.; Weber, L.; Strege, P. E.; Fullerton, T. J.; Dietsche, T. J. *J. Am. Chem. Soc.* **1978**, *100*, 3416–26.

(21) Ittel, S. D.; Van Catledge, F. A.; Jensen, J. P. *J. Am. Chem. Soc.* **1979**, *101*, 6905–11.

(22) The term agostic is used to define a hydrogen that is covalently bonded simultaneously to both a carbon atom and a transition-metal atom: Brookhart, M.; Green, M. L. H. *J. Organomet. Chem.* **1983**, *250*, 395–408.

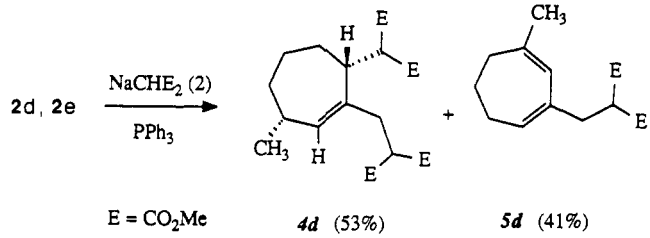
(23) Julia, S.; Ginebreda, A. *Synthesis* **1977**, 682–3.

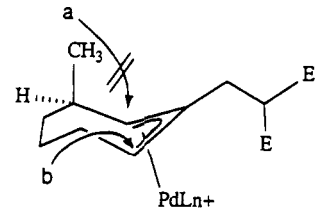
Scheme II



methyl iodide,[24] and (iii) dehydrohalogenation[25] (Scheme II). The stereochemical assignment for **16** is based upon analogy to the addition of dibromocarbene to 3-methylcyclohexene.[26] Chloropalladation of **16** gave a mixture of two isomeric π-allyl complexes **2d** and **2e** (1:1 ratio). The structural assignment for **2d** is based upon comparison of its ^{1}H NMR spectral data with that of **2a**.[8,9] Notably the signals for H_1, H_{syn}, and H_{anti} of **2d** are all within ±0.1 ppm of those for **2a**. The signal for H_3 of **2d** appears as a doublet (δ 4.44, J = 4.5), indicating that the methyl substituent must be present on C4. It has previously been shown that the chloropalladation of compounds **2** occurs with transfer of Cl to the less hindered face of the methylenecyclopropane ring.[8] Thus the C3 chlorine and the C4 methyl group must be mutually cis. The structural assignment for isomer **2e** (i.e., C7 methyl) is made in order that the two structures are not the same. Separation of the mixture of isomers was not attempted, since reaction of each isomer would proceed via the same intermediate π-allyl (vide supra).

Reaction of the mixture of **2d** and **2e** with 2 equiv of sodium dimethyl malonate gave a separable mixture of tetraester **4d** and diene diester **5d**. The structural assignment for **4d** is based upon comparison of its ^{1}H and ^{13}C NMR spectral data with those obtained for **4a**. In particular, the vinylic proton of **4d** (H_a) appears as a doublet (δ 5.23, J = 4), indicating that the methyl group is on the adjacent carbon. The structural assignment for **5d** is based upon comparison of its ^{1}H and ^{13}C NMR spectral data with those obtained for **5a**. The position of the methyl substituent (i.e., C4 vs C7) is based upon integration of the vinyl proton signals and upon the predicted[27] chemical shifts for the olefinic carbons.



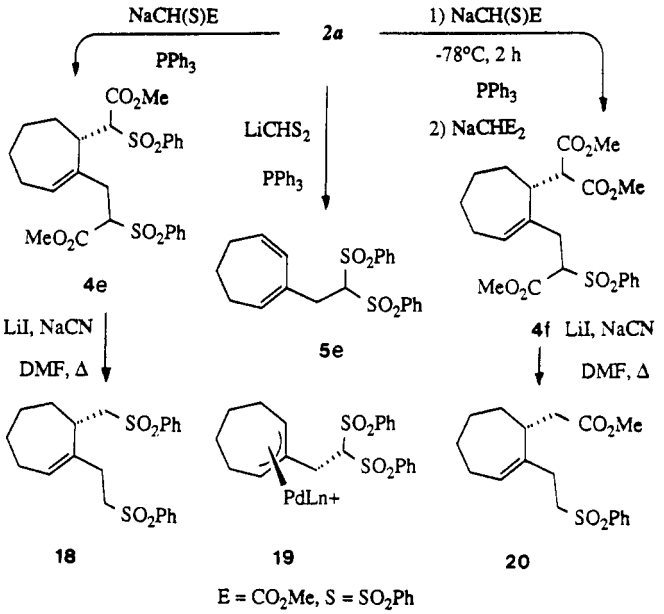


The regioselectivity observed for attack of the second equivalent of malonate anion may be rationalized by inspection of the intermediate Pd–allyl species **17**. Attack of malonate anion on the intermediate **17**, on the face opposite the palladium metal, is hindered along approach a by the axial methyl substituent. For this reason, only attack along the alternative approach b is observed. A similar rationale has been proposed for the regioselectivity of nucleophilic attack upon (*exo*-4-methylcyclohexadiene)Mo(CO)$_2$Cp.[28]

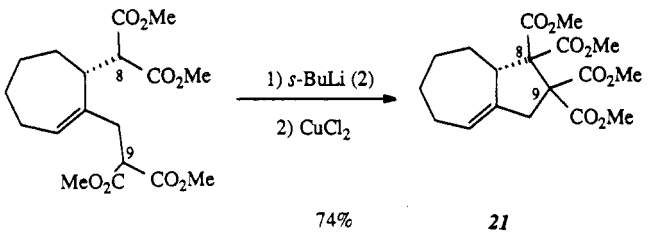
The reaction of **2a** with 2 equiv of sodium methyl (phenylsulfonyl) acetate in the presence of triphenylphosphine yielded **4e** as a mixture of diastereomers. The mixture was decarbomethoxylated under Krapcho conditions[29] to afford a single disulfone (**18**) in good yield. The structural assignment for **18** is based upon comparison of its ^{1}H and ^{13}C NMR spectral data with that obtained for **4a**. In contrast, the reaction of **2a** with 2 equiv of lithiobis(phenylsulfonyl)methane in the presence of triphenylphosphine gave only the cycloheptadiene **5e**. The structural assignment for **5e** is based upon comparison of its ^{1}H and ^{13}C NMR spectral data with those obtained for **5a**. The formation of only **5e** is presumably due to the difference in the rates of β-hydride elimination compared to the attack of the second equivalent of the bulky bis(phenylsulfonyl)methane anion on the sterically crowded π-allyl intermediate **19**.

The reaction of **2a**, in the presence of triphenylphosphine, with 1 equiv of sodium methyl (phenylsulfonyl)acetate followed by 1 equiv of sodium dimethyl malonate gave the triester **4f** as a mixture of diastereomers. The yield of **4f** is dependent upon the time delay between the addition of the two different nucleophiles; shorter time intervals gave poorer yields of **4f** along with **4a** and **5a**. The diastereomeric mixture **4f** was decarbomethoxylated to afford a single sulfone (**20**). These results indicate that the sequential generation of the two electrophilic sites may be exploited to produce a differentially functionalized cycloheptene.

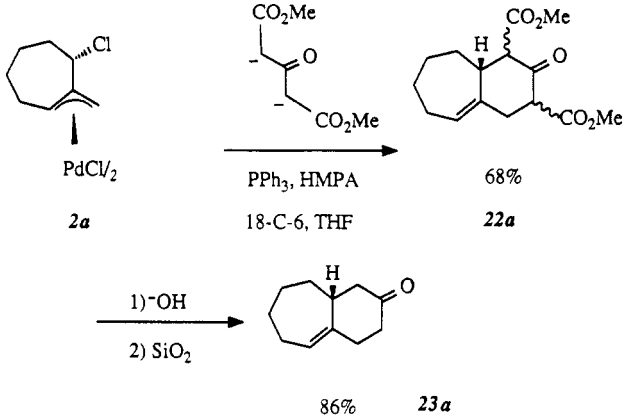
(24) Kitatani, K.; Hiyama, T.; Nozak, H. *Bull. Chem. Soc. Jpn.* **1977**, *50*, 3288–94.
(25) Arora, S.; Binger, P. *Synthesis* **1974**, 801–3.
(26) Reinarz, R. B.; Fonken, G. J. *Tetrahedron Lett.* **1973**, 4013–6.
(27) For ^{13}C NMR chemical shift data for 1,3-dienes, see: Hasegawa, K.; Asami, R.; Takahashi, K. *Bull. Chem. Soc. Jpn.* **1978**, *51*, 916–20.
(28) Pearson, A. J.; Khan, M. D. I.; Clardy, J. C.; Cun-heng, H. *J. Am. Chem. Soc.* **1985**, *107*, 2748–57. Faller, J. W.; Murray, H. H.; White, D. L.; Chao, K. H. *Organometallics* **1983**, *2*, 400–9.
(29) McMurray, J. *Org. React.* **1976**, *24*, 187–224.



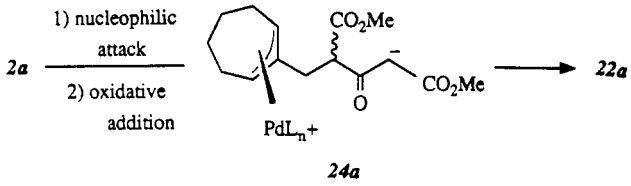
Oxidative coupling[30] of the dianion of **2a** with $CuCl_2$ gave the octahydroazulene tetraester **21**. The structural assignment for **21** is based upon comparison of its ^1H and ^{13}C NMR spectral data with those of **2a**. Notably, the signals for H_a and H_b of **2a** are not present in the ^1H NMR spectrum of **21**. In addition, the resonance signals for C8 and C9 of **21** (δ 70.0, 65.1) shift to lower field and decrease in intensity compared to those of **2a** (δ 52.6, 52.2). *Thus the methodology presented in this paper in* conjunction *with the chloropalladation reaction*[8] *represents a short, novel, efficient route for transformation of cyclohexene into the octahydroazulene skeleton.* This skeleton is present in a wide variety of naturally occuring guianolides and pseudoguianolides.[31]



The reaction of **2a** with the dianion of dimethyl 3-ketoglutarate[32] in the presence of triphenylphosphine gave the cyclohexanone diester **22a** as a mixture of diastereomers. Saponification and decarboxylation afforded a single product (**23a**). The structural assignment for **23a** is based upon its ^1H and ^{13}C NMR spectral data. The ^{13}C NMR signal at δ 210.1 and the C=O stretch at 1725 cm^{-1} are consistent with a six-membered cyclic ketone. In addition, the ^{13}C NMR chemical shifts of the signals for the cycloheptene fragment of **23a** and **21** are similar and the vinylic proton of **23a** appears as a triplet (δ 5.80, J = 7). The cyclization probably occurs via initial nucleophilic attack at the exocyclic terminus followed by oxidative addition of Pd(0) into the resultant allylic halide to afford the



zwitterionic π-allyl intermediate **24**. Subsequent rapid intramolecular attack at either allylic terminus, on the face opposite to the palladium metal, affords the product **22a** via a formal *6-Exo-Tet* or a *6-Endo-Trig* ring closure.[33] As might be anticipated, product yields for the intramolecular closure are dependent on concentration of the reaction, with the best results obtained for dilutions of less than 20 mM. A similar stepwise [3 + 3] cycloannulation has recently been reported.[11g]



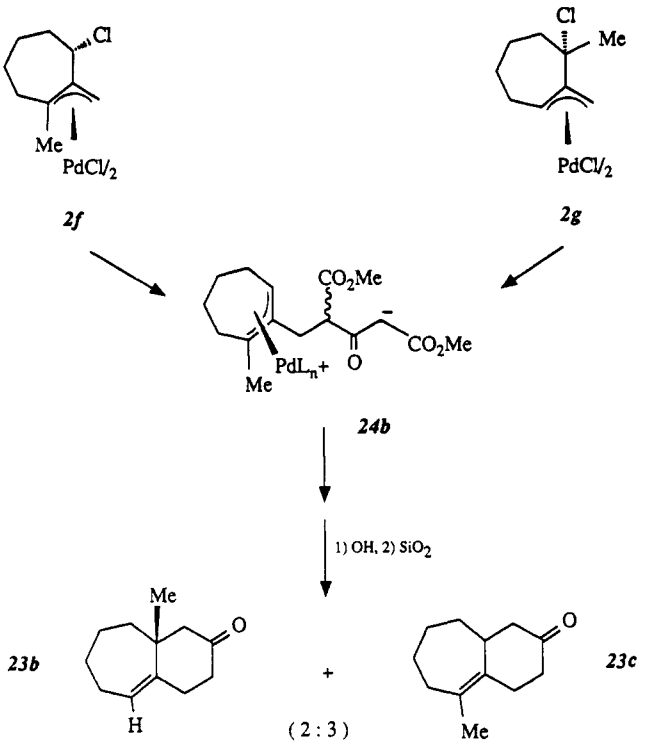
Reaction of the isomeric methyl-substituted π-allyls **2f** and/or **2g** with dimethyl 3-ketoglutarate dianion, followed by saponification–decarboxylation, afforded a mixture of 7-methyl- and 2-methylbicyclo[5.4.0]undec-1-en-9-ones (**23b** and **23c**, respectively, 2:3 ratio). The structural assignments for **23b** and **23c** are based upon comparison of their ^1H and ^{13}C NMR spectral data with those obtained for **23a**. The signal for the vinylic proton of **23b** appears at δ 5.70 (t, J = 7), the signal for the methyl substituent appears at δ 1.17, and the olefinic carbons appear at δ 144.0 and 126.7, respectively. The signal for the methyl substituent of **23c** appears as a singlet at δ 1.75.

Formation of the same product mixture from either **2f** or **2g** may be rationalized on the basis of a common intermediate. Nucleophilic attack at the exocyclic allylic terminus of either **2f** or **2g**, followed by oxidative addition of Pd(0), generates a single π-allyl intermediate (**24b**). Subsequent intramolecular attack at the more substituted terminus eventually affords the product **23b**, while attack at the less hindered terminus gives the product **23c**.

Conclusion

Chloropalladation of ω-methylenebicyclo[n.1.0]alkanes affords (3-chloro-2-methylenecycloalkyl)palladium chloride dimers in excellent yield. These complexes will react as "trimethylenemethane dication" synthons or "isoprenyl monocation" synthons with carbon nucleophiles. The two electrophilic sites of the trimethylenemethane dication synthon are sequentially generated.

(30) Chung, S. K.; Dunn, L. B. *J. Org. Chem.* **1983**, *48*, 1125–7.
(31) Heathcock, C. H.; Graham, S. L.; Pirrung, M. C.; Pavac, F.; White, C. T. *The Total Synthesis of Natural Products*; Wiley-Interscience: New York, 1983; Vol. 5, pp 333–77.
(32) Dimethyl 3-ketoglutarate has previously been condensed with 1,2-diketones for the formation of the bicyclo[3.3.0]octane ring system: Weber, R. W.; Cook, J. M. *Can. J. Chem.* **1978**, *56*, 189–92. Bertz, S. H.; Cook, J. M.; Gawish, A.; Weiss, U. *Org. Synth.* **1985**, *64*, 27–38.
(33) X-ray crystallographic data for (π-allyl)palladium complexes indicate that the hybridization at the allyl carbons is in between sp^3 and sp^2; thus an absolute designation of tet or trig is not possible. Both the *6-Exo-Tet* and the *6-Endo-Trig* ring closures are "favored": Baldwin, J. E. *J. Chem. Soc., Chem. Commun.* **1976**, 734–6.



Experimental Section[34]

The (π-allyl)palladium complexes **2a–c,f,g** were prepared by literature procedures.[8]

Dimethyl [[7-[2-Methoxy-1-(methoxycarbonyl)-2-oxoethyl]-1-cyclohepten-1-yl]methyl]propanedioate (4a). To a solution of (3-chloro-2-methylenecycloheptyl)palladium chloride dimer (**2a**, 0.20 g, 0.70 mmol) and triphenylphosphine (0.73 g, 2.8 mmol) in dry THF (10 mL) was added a solution of sodium dimethyl malonate (1.61 mmol, freshly prepared from excess NaH and dimethyl malonate) in THF (10 mL). The clear yellow reaction mixture became opaque upon addition of the anion solution. The reaction mixture was stirred for 20 h at room temperature. The solvent was evaporated and the residue was extracted with ether (4 × 25 mL) via a cannula under N_2. The resulting organic layer was washed with water (20 mL), dried ($MgSO_4$), and evaporated. The crude product was purified by flash chromatography using hexane/ethyl acetate (28:1) as eluant. The product fractions were combined and concentrated under reduced pressure to yield a light yellow oil. Distillation (Kugelrohr) afforded the product as a colorless oil: 0.24 g (93%); bp 140–150 °C/0.21 mmHg; IR (neat, cm^{-1}) 1720 s; 250-MHz ^1H NMR ($CDCl_3$) δ 5.67 (dd, J = 6.1, 7.8, 1 H), 4.05 (d, J = 11.7, 1 H), 3.72, 3.71, 3.69, 3.68 (four s, 12 H), 3.55 (dd, J = 5.6, 10.2, 1 H), 2.93 (br d, 1 H), 2.5 (m, 2 H), 2.1 (m, 2 H), 1.7 (m, 4 H), 1.5 (m, 1 H), 1.1 (m, 1 H); $^{13}C\{^1H\}$ NMR ($CDCl_3$) δ 169.4, 168.6, 139.6, 131.9, 52.6, 52.2, 51.9, 51.1, 42.2, 39.4, 28.7, 27.4, 27.0, 26.2; GC/MS 370 (M^+, 1.1), 307 (16), 238 (36), 206 (13), 187 (14), 178 (35), 147 (31), 133 (67), 106 (100), 91 (69). Anal. Calcd for $C_{18}H_{26}O_8$: C, 58.37; H, 7.08. Found: C, 58.53; H, 7.26.

Diethyl [[7-[2-ethoxy-1-(ethoxycarbonyl)-2-oxoethyl]-1-cyclohepten-1-yl]methyl]propanedioate (4b) was prepared from the reaction of sodium diethyl malonate (2 equiv) with **2a** in a fashion similar to the preparation of **4a**: 0.28 g (75%); bp 115–120 °C/0.07 mmHg; IR (neat, cm^{-1}) 1750 s; 60-MHz ^1H NMR ($CDCl_3$) δ 5.75 (t, J = 6.8, 1 H), 4.15 (two q and m, J = 7.0, 9 H), 3.50 (dd, J = 9.0, 12.9, 1 H), 3.2–1.0 (m, 12 H), 1.25 (t, J = 7, 12 H); $^{13}C\{^1H\}$ NMR ($CDCl_3$) δ 168.7, 168.1, 139.6, 131.5, 61.2, 60.9, 51.9, 51.2, 41.8, 39.2, 28.5, 27.2, 26.8, 26.1, 14.0, 13.9. Anal. Calcd for $C_{20}H_{30}O_8$: C, 60.29; H, 7.60. Found: C, 61.09; H, 7.74.

Dimethyl (1,6-Cycloheptadien-1-ylmethyl)propanedioate (5a). To a solution of **2a** (1.18 g, 4.16 mmol) and triphenylphosphine (3.27 g, 12.5 mmol) in dry THF (15 mL) was added a solution of sodium dimethyl malonate (4.16 mmol) in THF (15 mL). The clear yellow reaction mixture became opaque upon addition of the anion. The reaction mixture was heated to reflux for 24 h, during which time the mixture became dark red in color. The reaction mixture was cooled to room temperature and filtered through a bed of Celite. The resulting yellow solution was concentrated under reduced pressure and purified by flash chromatography using hexane/ethyl acetate (28:1) as eluant. The product fractions were combined and the solvent was removed under reduced pressure. The residue was distilled (Kugelrohr) under high vacuum to afford the product as a colorless oil: 0.80 g (81%); bp 85–90 °C/0.07 mmHg; IR (neat, cm^{-1}) 1725 s; 60-MHz ^1H NMR ($CDCl_3$) δ 5.8–5.4 (m, 3 H), 3.64 (s, 6 H), 3.40 (t, J = 8, 1 H), 2.52 (d, J = 8, 2 H), 2.3–1.4 (m, 6 H); $^{13}C\{^1H\}$ NMR ($CDCl_3$) δ 169.3, 139.4, 134.8, 131.6, 127.5, 52.3, 51.4, 38.4, 31.3, 29.7, 27.8. Anal. Calcd for $C_{13}H_{18}O_4$: C, 65.53; H, 7.61. Found: C, 65.72; H, 7.43.

Diethyl (1,6-cycloheptadien-1-ylmethyl)propanedioate (5b) was prepared from the reaction of sodium diethyl malonate (1 equiv) with **2a** in a fashion similar to the preparation of **5a**: 0.86 g (78%); bp 90–95 °C/0.07 mmHg; IR (neat, cm^{-1}) 1750 s; 60-MHz ^1H NMR ($CDCl_3$) δ 5.8–5.4 (m, 3 H), 4.15 (q, J = 7.0, 4 H), 3.44 (t, J = 8.0, 1 H), 2.7–1.0 (m, 8 H), 1.25 (t, J = 7, 6 H); $^{13}C\{^1H\}$ NMR ($CDCl_3$) δ 169.1, 134.1, 133.1, 131.5, 127.8, 61.3, 52.3, 38.3, 31.3, 30.9, 29.8, 14.1. Anal. Calcd for $C_{15}H_{22}O_4$: C, 67.64; H, 8.33. Found: C, 67.74; H, 8.35.

Effect of Phosphine Ligand: DIPHOS. The reaction of sodium diethyl malonate (2 equiv) with **2a** was carried out as previously described except that 1,2-bis(diphenylphosphino)ethane (2 equiv) was used instead of triphenylphosphine. Purification of the crude product by flash chromatography with hexanes/ethyl acetate (28:1) gave **5b** (19%) followed by **4b** (73%).

Effect of Phosphine Ligand: $[(Ph_2P)Cp]_2Fe$. The reaction of sodium diethyl malonate (2 equiv) with **2a** was carried out as previously described except that 1,1′-bis(diphenylphosphino)-ferrocene (2 equiv) was used instead of triphenylphosphine. Purification of the crude product by flash chromatography with hexanes/ethyl acetate (28:1) gave **5b** (30%) followed by **4b** (48%).

Effect of Phosphine Ligand: Polymer Supported. The reaction of sodium diethyl malonate (2 equiv) with **2a** was carried out as previously described except that polystyrene-supported triphenylphosphine (2 equiv of P/Pd, 2% DVB crosslink, 9.5% P, Aldrich) was used instead of triphenylphosphine. Purification of the crude product by flash chromatography with hexanes/ethyl acetate (28:1) gave **5b** (21%) followed by **4b** (35%).

Effect of Phosphine Ligand: Tri-*o*-tolylphosphine. The reaction of sodium dimethyl malonate (2 equiv) with **2a** was carried out as previously described except that tri-*o*-tolylphosphine (4 equiv) was used instead of triphenylphosphine. Purification of the crude product by flash chromatography with hexanes/ethyl acetate (28:1) gave **5a** (25%).

Effect of Chiral Phosphine Ligands. The reaction of sodium dimethyl malonate (2 equiv) with **2a** was carried out as previously described except that either neomenthyldiphenylphosphine (2 equiv), (+)-2,3-*O*-isopropylidene-2,3-dihydroxy-1,4-bis(diphenylphosphino)butane (*S,S*-DIOP, 1 equiv), or (*R*)-(+)-1,2-bis(diphenylphosphino)propane (*R*-PROPHOS, 1 equiv) was used instead of triphenylphosphine. Purification of the crude product by flash chromatography with hexanes/ethyl acetate (28:1) gave only **5a** in 75%, 53%, and 13% yield, respectively.

Dimethyl [[6-[2-Methoxy-1-(methoxycarbonyl)-2-oxoethyl]-1-cyclohexen-1-yl]methyl]propanedioate (4c) and Dimethyl α,α'-Bis(methoxycarbonyl)-2-methylene-1,3-cyclohexanediacetate (12). To a solution of (3-chloro-2-methylenecyclohexyl)palladium chloride dimer (**2b**, 0.173 g, 0.639 mmol) and *S,S*-DIOP (0.32 g, 0.64 mmol) in dry THF (10 mL)

(34) **General Data.** Melting points were obtained on a Mel-Temp melting point apparatus and are uncorrected. All organometallic reactions were run in flame-dried glassware under an atmosphere of nitrogen. Spectrograde solvents were used without further purification with the exception of diethyl ether and tetrahydrofuran (THF), which were distilled from sodium- and potassium–benzophenone ketyl, respectively, dimethyl sulfoxide (DMSO), which was refluxed over CaH_2 before distillation, and methylene chloride, which was distilled from phosphorus pentoxide. The term "flash chromatography" refers to the procedure of Still, Kahn, and Mitra.[35] All title compounds were determined to be of ≥95% purity by a combination of two or more of the following: TLC, ^1H NMR, $^{13}C\{^1H\}$ NMR, GC/MS, or elemental analysis. All coupling constants are given in hertz.

(35) Still, W. C.; Khan, M.; Mitra, A. *J. Org. Chem.* **1978**, *43*, 2923–5.

was added a solution of sodium dimethyl malonate (1.28 mmol) in THF (10 mL). The clear yellow reaction mixture became opaque upon addition of the anion solution. The reaction mixture was stirred for 20 h at room temperature. The solvent was evaporated and the residue was extracted with ether (4 × 25 mL) via a cannula under N_2. The resulting organic layer was washed with water (20 mL), dried ($MgSO_4$), and evaporated. The crude product was purified by flash chromatography using hexane/ethyl acetate (28:1) as eluant. The product fractions were combined, concentrated, and distilled (Kugelrohr) under high vacuum to afford a mixture of **4c**, **12a**, and **12b** (ca. 5:1:1) as a colorless oil: 0.18 g (79%); bp 95–100 °C/0.05 mmHg; IR (neat, cm^{-1}) 1725 s, 890 m; 300-MHz ^1H NMR ($CDCl_3$) **4c** δ 5.62 (br t, J = 4.5, 1 H), 3.80 (d, J = 11.0, 1 H), 3.73, 3.72, 3.71, 3.69 (four s, 12 H), 3.63 (t, J = 4.3, 1 H), 2.9 (m, 1 H), 2.55 (m, 2 H), 2.0 (m, 2 H), 1.45 (m, 2 H); **12a** and **12b** (partial) δ 4.76 (s, 1 H), 4.59 (s, 1 H); HRMS, m/z 325.1278 [calcd for $C_{16}H_{21}O_7$ (M – OMe), 325.1287], 224.1047 [calcd for $C_{12}H_{16}O_4$ (M – $CH_2(CO_2Me)_2$), 224.1048].

Dimethyl (1,7-cyclooctadien-1-ylmethyl)propanedioate (5c) was prepared from the reaction of sodium dimethyl malonate (1 or 2 equiv) with **2c** in a fashion similar to the preparation of **5a**: 0.10 g (71%) and 0.06 g (43%), respectively; bp 110–130 °C/0.07 mmHg; IR (neat, cm^{-1}) 1750 s; 60-MHz ^1H NMR ($CDCl_3$) δ 5.8–5.3 (m, 3 H), 3.62 (s, 6 H), 3.40 (t, J = 6, 1 H), 2.60 (d, J = 6, 2 H), 2.3–1.2 (m, 8 H); $^{13}C\{^1H\}$ NMR ($CDCl_3$) δ 169.6, 133.3, 133.2, 129.2, 126.5, 52.3, 51.4, 36.7, 29.7, 28.6, 27.8, 24.1; GC/MS: 252 (M^+, 11), 189 (18), 133 (18), 132 (22), 120 (100), 105 (48), 92 (73), 91 (86); HRMS, m/z 252.1365 [calcd for $C_{14}H_{20}O_4$, m/z 252.1361].

***exo*-2-Methyl-7-methylenebicyclo[4.1.0]heptane (16).** To a solution of 3-methylcyclohexene (3.56 g, 36.6 mmol) in $CHCl_3$ (40 mL) were added aqueous NaOH (50%, 40 mL) and cetyltrimethylammonium bromide (0.15 g). The reaction mixture was vigorously stirred for 24 h. The mixture was diluted with H_2O (500 mL) and separated. The organic layer was dried ($MgSO_4$) and the solvent evaporated. Distillation under aspirator pressure gave 7,7-dichloro-2-methylbicyclo[4.1.0]heptane as a colorless oil: 5.76 g (88%); bp 154–156 °C/19 mmHg; 300-MHz ^1H NMR ($CDCl_3$) δ 2.15 (m, 1 H), 2.0–1.8 (m, 2 H), 1.63 (d, J = 13, 1 H), 1.6–1.2 (m, 5 H), 1.32 (d, J = 4, CH_3); ^{13}C NMR ($CDCl_3$) δ 66.8, 33.6, 29.8, 26.5, 25.6, 23.4, 19.6, 18.7. To a solution of 7,7-dichloro-2-methylbicyclo[4.1.0]heptane (5.17 g, 28.9 mmol) and 18-crown-6 (0.1 g) in THF (80 mL) cooled to −95 °C was added dropwise a solution of *t*-BuLi (26 mL, 1.7 M, 44.2 mmol) over a period of 15 min. The solution was stirred at −95 °C for 30 min and then iodomethane (9.5 mL, 0.15 mol) was added dropwise. The reaction mixture was slowly allowed to warm over a period of 6 h. The mixture was diluted with H_2O (200 mL) and separated. The aqueous layer was extracted twice with petroleum ether (80 mL). The combined organic layers were dried ($MgSO_4$) and evaporated. Distillation of the residue gave 7-chloro-2,7-dimethylbicyclo[4.1.0]heptane as a colorless oil: 3.36 g (73%); bp 61–64 °C/1.8 mmHg; ^1H NMR ($CDCl_3$) δ 2.0–0.7 (m), 1.57 (s), 1.11 (d, J = 7). Gas chromatography indicated this to be a 2:1 mixture of diastereomers, which was used without further characterization. To a solution of *t*-BuOK (2.33 g, 20.8 mmol) in DMSO (30 mL) heated at 95 °C was added dropwise a solution of 7-chloro-2,7-dimethylbicyclo[4.1.0]heptane (3.30 g, 20.8 mmol) over a priod of 30 min. The reaction mixture was heated at 95 °C for 18 h, cooled, and poured over ice (60 g). The solution was extracted with petroleum ether (4 × 50 mL). The combined extracts were dried ($MgSO_4$) and filtered and the solvent was carefully removed under reduced pressure. Distillation under high vacuum gave **16** as a colorless oil: 1.73 g (68%); bp 25–30 °C/3.5 mmHg; IR (cm^{-1}, neat) 890 s; ^1H NMR ($CDCl_3$) δ 5.27 (br d, J = 4, 2 H), 2.1–0.7 (m, 9 H), 1.10 (d, J = 6, CH_3); ^{13}C NMR ($CDCl_3$) δ 142.3, 101.2, 31.5, 29.3, 23.5, 22.6, 19.7, 19.1, 14.2.

Chloropalladation of 16. To a solution of $PdCl_2(CH_3CN)_2$ (0.50 g, 1.93 mmol) in CH_2Cl_2 (25 mL) was added a solution of **16** (0.23 g, 1.93 mmol) in CH_2Cl_2 (10 mL). The red-orange solution rapidly turned pale yellow, and the reaction mixture was stirred for an additional 30 min. The solvent was removed under reduced pressure and the residue was purified by column chromatography (60–200-mesh SiO_2). A golden yellow fraction was eluted with $CHCl_3$. The solvent was removed under reduced pressure and dried under high vacuum to give a pale yellow solid: 0.49 g (85%); mp 135–146 °C dec. Anal. Calcd for $[C_9H_{14}Cl_2Pd]_2$: C, 36.09; H, 4.71. Found: C, 36.32; H, 4.66. The product was identified by NMR spectroscopy as consisting of a mixture of **2d** and **2e** (ca. 1:1). **2d**: 300-MHz ^1H NMR ($CDCl_3$) δ 4.44 (d, J = 4.5, H3), 3.87 (m, H1), 3.68 (s, H_{syn}), 2.76 (s, H_{anti}), 2.4–1.0 (m), 1.70 (d, CH_3); ^{13}C NMR ($CDCl_3$, partial) δ 123.4 (C2), 82.5 (C1), 66.3 (C3), 61.3 (C allyl). **2e**: 300-MHz ^1H NMR ($CDCl_3$) δ 4.61 (br d, J = 4.5, H3), 3.78 (s, H_{syn}), 3.63 (br s, H1), 2.87 (s, H_{anti}), 2.4–1.0 (m), 1.24 (d, CH_3); ^{13}C NMR ($CDCl_3$, partial) δ 123.1 (C2), 91.5 (C1), 62.3 (C3), 61.3 (C allyl).

Reaction of 2d and 2e with Malonate Anion. To a solution of **2d** and **2e** (0.20 g, 0.68 mmol) and triphenylphosphine (0.70 g, 2.7 mmol) in dry THF (15 mL) was added a solution of sodium dimethyl malonate (2.67 mmol, freshly prepared from excess NaH and dimethyl malonate) in THF (15 mL). The clear yellow reaction mixture became opaque upon addition of the anion solution. The reaction mixture was stirred for 20 h at room temperature. The solvent was evaporated and the residue was extracted with ether (4 × 25 mL) via a cannula under N_2. The resulting organic layer was washed with water (20 mL), dried ($MgSO_4$), and evaporated. The crude product was purified by flash chromatography using hexane/ethyl acetate (28:1) as eluant. The diene **5d** (0.07 g, 41%) was eluted first, followed by unreacted dimethyl malonate and then the tetraester **4d** (0.14 g, 53%). **5d**: ^1H NMR ($CDCl_3$) δ 5.66 (br m, 1 H), 5.47 (br s, 1 H), 3.70 (s, 6 H), 3.52 (t, J = 6, 1 H), 2.60 (br d, J = 6, 2 H), 2.3–0.9 (m), 1.85 (s, CH_3); $^{13}C\{^1H\}$ NMR ($CDCl_3$) δ 169.6, 143.7, 133.2, 129.7, 123.4, 52.3, 52.2, 38.8, 35.7, 29.3, 28.3, 26.8. **4d**: IR (cm^{-1}, neat) 1736 s, 1438 m; 300-MHz ^1H NMR ($CDCl_3$) δ 5.27 (d, J = 4, 1 H), 4.02 (d, J = 12, 1 H), 3.72, 3.70, 3.68, 3.67 (four s, 12 H), 3.55 (dd, J = 5, 10, 1 H), 2.89 (m, 1 H), 2.6–1.1 (m, 9 H), 0.94 (d, J = 7, 3 H); $^{13}C\{^1H\}$ NMR ($CDCl_3$) δ 169.1, 168.5, 139.2, 137.4, 52.4, 52.0, 51.0, 42.0, 39.7, 36.0, 33.7, 28.2, 25.0, 24.0; GC/MS 252 (M – 132, 18), 161 (6), 133 (27), 120 (100), 105 (23); HRMS, m/z 353.1588 [calcd for $C_{18}H_{25}O_7$ (M – OMe), 353.1599); 252.1360 [calcd for $C_{14}H_{20}O_4$ (M – $CH_2(CO_2Me)_2$), 252.1361].

Methyl [[7-[2-Methoxy-1-(phenylsulfonyl)-2-oxoethyl]-1-cyclohepten-1-yl]methyl](phenylsulfonyl)acetate (4e). To a solution of **2a** (0.20 g, 0.70 mmol) and triphenylphosphine (0.73 g, 2.8 mmol) in dry THF (5 mL) was added a solution of sodium methyl (phenylsulfonyl)acetate (1.5 mmol, freshly prepared from excess NaH and methyl (phenylsulfonyl)acetate) in THF (5 mL). The reaction mixture was stirred at room temperature overnight. The solvent was removed under reduced pressure and the residue was extracted with ether (3 × 30 mL) via cannula under N_2. The resulting organic layer was washed with water (25 mL) and dried over $MgSO_4$, and the solvent was removed under reduced pressure. The crude product was separated by flash chromatography with benzene/ethyl acetate (18:1) as eluant. One of the fractions contained a single diastereomer: 0.09 g; 60-MHz ^1H NMR ($CDCl_3$) δ 7.9–7.3 (m, 10 H), 5.55 (t, J = 7, 1 H), 4.63 (d, J = 12, 1 H), 3.90 (dd, J = 6, 10, 1 H), 3.50, 3.27 (two s, 6 H), 2.87 (br d, J = 12, 1 H), 2.7–1.0 (m, 10 H). Trailing fractions consisted of **4e** and its diastereomer as identified by ^1H NMR spectroscopy: 0.14 g. The combined diastereomeric fractions (0.24 g, 61%) were used in the next step without further purification.

7-[1-(Phenylsulfonyl)methyl]-1-[2-(phenylsulfonyl)-ethyl]-1-cycloheptene (18). A solution of lithium iodide (0.23 g, 1.7 mmol), **4e** (0.18 g, 0.34 mmol), and sodium cyanide (0.017 g, 0.34 mmol) in DMF (20 mL) was heated to 130 °C for 24 h under N_2. The reaction mixture was cooled and water (75 mL) was added. The solution was adjusted to pH 7 and extracted with ether (3 × 25 mL). The combined organic extracts were washed with water (20 mL) and dried ($MgSO_4$) and the solvent was evaporated to afford a colorless oil: 0.10 g (71%); 60-MHz ^1H NMR ($CDCl_3$) δ 8.0–7.4 (m, 10 H), 5.50 (t, J = 6, 1 H), 3.2 (m, 4 H), 2.7–0.9 (m, 11 H); $^{13}C\{^1H\}$ NMR ($CDCl_3$) δ 140.4, 139.3, 133.7, 129.3, 128.0, 56.5, 54.9, 41.1, 37.1, 31.6, 29.9, 26.8, 25.6.

2-[2′,2′-Bis(phenylsulfonyl)ethyl]-1,3-cycloheptadiene (5e). To a solution of **2a** (0.30 g, 1.05 mmol), triphenylphosphine (1.10 g, 4.20 mmol), and dibenzo-18-crown-6 (0.1 g) in THF (20 mL) was added a solution of lithiobis(phenylsulfonyl)methane (2.31 mmol, prepared from bis(phenylsulfonyl)methane and *n*-BuLi (0.92 mL, 2.5 M) in THF (20 mL). The reaction mixture was stirred at room temperature for 96 h. The solvent was removed under vacuum and the residue was extracted with diethyl ether

(3 × 30 mL) via cannula under N_2. The resulting organic layer was washed with water (2 × 20 mL) and dried over $MgSO_4$, and the solvent was removed under reduced pressure. The crude product was purified by flash chromatography using hexane/ethyl acetate (5:1), (4:1), and (3:1) as eluant. The product fractions were combined and concentrated under reduced pressure to yield a white solid: 0.13 g (31%); mp 123–126 °C; 60-MHz ^1H NMR ($CDCl_3$) δ 8.0–7.1 (m, 10 H), 6.0–5.2 (m, 3 H), 4.42 (t, J = 6, 1 H), 2.83 (d, J = 6, 2 H), 2.2–1.3 (m, 6 H); $^{13}C\{^1H\}$ NMR ($CDCl_3$) δ 138.7, 136.1, 134.2, 133.3, 130.7, 129.5, 129.0, 126.0, 83.0, 38.9, 31.1, 29.9, 27.3. Anal. Calcd for $C_{21}H_{22}O_4S_2$: C, 62.67; H, 5.51. Found: C, 62.37; H, 5.40.

Dimethyl [1-[3-Methoxy-3-(phenylsulfonyl)-3-oxopropyl]-1-cyclohepten-7-yl]propanedioate (4f). To a solution of **2a** (0.19 g, 0.67 mmol) and triphenylphosphine (0.73 g, 2.8 mmol) in dry THF (6 mL) at −78 °C was added a solution of sodium methyl(phenylsulfonyl)acetate (0.87 mmol) in THF (10 mL). The clear yellow reaction mixture became opaque after 2 min. The reaction mixture was stirred for 2 h at −78 °C. To the cold reaction mixture was added a solution of sodium dimethyl malonate (0.67 mmol) in THF (10 mL). The reaction mixture was slowly warmed to room temperature overnight. The solvent was evaporated and the residue was extracted with ether (3 × 35 mL) via cannula under N_2. The resulting organic layer was washed with water (20 mL), dried ($MgSO_4$), and evaporated. The crude product was purified by flash chromatography using benzene/ethyl acetate (18:1) as eluant. The product fractions were combined and concentrated under reduced pressure to yield **4f** as a pale oil: 0.14 g (56%); 60-MHz ^1H NMR ($CDCl_3$) δ 8.1–7.4 (m, 5 H), 5.63 (t, J = 7, 1 H), 4.5–3.9 (m, 2 H), 3.67, 3.59 (two s, 9 H), 3.1–1.0 (m, 11 H); GC/MS 370 (M^+, 1.1), 307 (16), 238 (36), 206 (13), 187 (14), 178 (35), 147 (31), 133 (67), 106 (100), 91 (69).

Methyl 1-[3-(phenylsulfonyl)propyl]-1-cycloheptene-7-acetate (20) was prepared from decarbomethoxylation of **4f** in a fashion similar to the preparation of **18** from **4e**: 0.05 g (52%); IR (CH_2Cl_2, cm^{-1}) 1734 s, 1308 s, 1150 s; 60-MHz ^1H NMR ($CDCl_3$) δ 8.1–7.5 (m, 5 H), 5.47 (t, J = 7, 1 H), 3.50 (s, 3 H), 3.23 (m, 2 H), 2.7–1.2 (m, 11 H); $^{13}C\{^1H\}$ NMR ($CDCl_3$) δ 172.9, 141.4, 139.4, 133.6, 129.3, 128.9, 128.1, 55.5, 51.6, 39.4, 35.6, 31.8, 30.4, 27.4, 27.2, 25.9.

Tetramethyl 1,2,3,4,4a,5,6,7-Octahydro-2,2,3,3-azulenetetracarboxylate (21). To a solution of *sec*-butyllithium (3.0 mL, 1.4 M, 4.2 mmol) in THF (60 mL) cooled to 0 °C was added via syringe a solution of **4a** (0.22 g, 0.59 mmol) in THF (15 mL). The mixture was stirred for 40 min during which time it turned a light milky white color. A suspension of copper(II) chloride (0.65 g, 4.8 mmol) in THF (20 mL) was transferred into the reaction mixture via syringe and the mixture became green and later changed to brown in color. After 20 h the reaction mixture was washed with water (2 × 40 mL). The aqueous layers were extracted with ether (3 × 30 mL), the combined organic phases were dried ($MgSO_4$), and the solvent was evaporated to yield a yellow liquid. Distillation under high vacuum (Kugelrohr) gave a colorless oil: 0.16 g (74%); bp 120–125 °C/0.25 mmHg; 60-MHz ^1H NMR ($CDCl_3$) δ 5.8–5.4 (br m, 1 H), 3.73, 3.66 (two s + m, 7 H), 2.83 (d, J = 16, 1 H), 2.4–1.1 (m, 9 H); $^{13}C\{^1H\}$ NMR ($CDCl_3$) δ 171.2, 170.4, 170.0, 169.5, 142.8, 123.6, 70.0, 65.1, 52.9, 52.6, 52.3, 51.5, 43.2, 42.6, 30.4, 29.4, 28.6, 26.9. Anal. Calcd for $C_{18}H_{24}O_8 \cdot H_2O$: C, 55.95; H, 6.78. Found: C, 56.47; H, 6.64.

2,4-Dicarbomethoxy-2,3,4,4a,5,6,7,8-octahydro-3-oxo-1*H*-benzocycloheptene (22a). To a solution of dimethyl 3-ketoglutarate (0.16 mL, 1.05 mmol), dibenzo-18-crown-6 (0.05 g), HMPA (0.38 g, 1.9 mmol) in THF (5 mL) cooled to −78 °C was slowly added, via syringe, a solution of *tert*-butyllithium (1.7 M, 2.05 mL, 3.5 mmol). The reaction mixture was stirred at −78 °C for 30 min. To the cold solution was added a solution of **2a** (0.30 g, 1.05 mmol) and triphenylphosphine (1.10 g, 4.2 mmol) in THF (25 mL). A yellow precipitate formed within 10 min and the reaction was maintained at −78 °C for 30 min. The reaction mixture was allowed to warm to room temperature. The solvent was removed under reduced pressure to afford a yellow solid, which was extracted with ether (3 × 30 mL) via cannula under N_2. The resulting organic layer was washed with water (30 mL) and dried ($MgSO_4$), and the solvent was evaporated. The crude product was purified by flash chromatography using hexane/ethyl acetate (16:1) as eluant. The product fractions were concentrated to yield a yellow liquid, which was distilled (Kugelrohr) under vaccum to give a clear oil: 0.20 g (68%); bp 90–120 °C/0.50 mmHg; IR (neat, cm^{-1}) 1725 s, 1650 m; ^1H NMR ($CDCl_3$) δ 5.67 (t, J = 6, 1 H), 3.66–3.77 (4 s, 6 H), 3.6–1.0 (m, 13 H). The diastereomeric mixture was used in the next step without further purification.

2,3,4,4a,5,6,7,8-Octahydro-3-oxo-1*H*-benzocycloheptene (23a). The mixture of diastereomers **21** (0.11 g, 0.39 mmol) was suspended in 1 N aqueous potassium hydroxide (10 mL) and the emulsion was stirred for 24 h. The reaction mixture was extracted with ether (15 mL) and the aqueous layer was slowly acidified to pH 2 with dilute HCl. The acidic aqueous solution was extracted with $CHCl_3$ (2 × 25 mL) and the combined $CHCl_3$ extracts were stirred with silica gel (3 g) for 24 h. The silica gel was removed by filtration and washed with $CHCl_3$ (25 mL). The combined $CHCl_3$ layers were dried ($MgSO_4$), and the solvent was evaporated to afford an oily residue. Distillation (Kugelrohr) under vacuum gave a clear oil: 0.094 g (86%); bp 48–60 °C/0.10 mmHg; IR (neat, cm^{-1}) 1720 s, 1590 w, 760 m; 60-MHz ^1H NMR ($CDCl_3$) δ 5.80 (br t, J = 7, 1 H), 2.8–1.0 (m, 15 H); $^{13}C\{^1H\}$ NMR ($CDCl_3$) δ 210.1, 141.8, 126.8, 46.7, 39.2, 37.7, 34.5, 31.6, 31.4, 27.8, 26.5; GC/MS 164 (M^+, 41), 149 (5), 122 (22), 107 (39), 93 (61), 79 (100).

2,3,4,4a,5,6,7,8-Octahydro-4a-methyl-3-oxo-1*H*-benzocycloheptene and 2,3,4,4a,5,6,7,8-octahydro-7-methyl-3-oxo-1*H*-benzocycloheptene (23b, 23c) were prepared from **2f** or **2g** in a manner similar to the preparation of **23a**. Purification of the crude product by flash chromatography with hexanes/ethyl acetate (10:1) as eluant gave a clear oil (28%). This was determined to be a mixture of **23b** and **23c** (ca. 2:3) by ^1H NMR integration and GC/MS. **23b**: 60-MHz ^1H NMR ($CDCl_3$, partial) δ 5.70 (t, J = 7), 1.17 (s); $^{13}C\{^1H\}$ NMR ($CDCl_3$) δ 213.8, 144.0, 126.7, 55.8, 40.3, 39.7, 33.4, 29.8, 27.4, 27.0, 24.0, 21.4; GC/MS: 178 (M^+, 30), 163 (26), 150 (29), 136 (28), 135 (28), 121 (41), 107 (52), 93 (86), 91 (62), 79 (100), 67 (54). **23c**: ^1H NMR ($CDCl_3$, partial) δ 1.75 (s); $^{13}C\{^1H\}$ NMR ($CDCl_3$) δ 213.8, 133.0, 47.2, 38.5, 37.7, 35.5, 34.7, 31.6, 25.5, 25.0; GC/MS 178 (M^+, 75), 163 (20), 136 (21), 135 (16), 121 (43), 107 (65), 79 (100), 77 (54), 67 (47).

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Supplementary Material Available: ^1H or ^{13}C NMR spectra of compounds **4c**, **12a**, **12b**, **4d**, **16**, **20**, **23a**, **23b**, and **23c** (8 pages). Ordering information is given on any current masthead page.