vinyl ketone, 78-94-4; ethyl 1-acetonyl-2-oxocyclopentanecarboxylate, 61771-77-5; methallyl chloride, 563-47-3.

References and Notes

(1) D. Becker and J. Kalo, *Tetrahedron Lett.*, 3725 (1971).
(2) E. Fernholz and H. E. Stavely, Abstracts, 102nd Meeting of the American Chemical Society, Atlantic City, N.J., Sept. 1941, p 39 M.
(3) J. A. Marshall and M. T. Pike, *Tetrahedron Lett.*, 3107 (1965).
(4) R. H. Lenhard and S. Bernstein, *J. Am. Chem. Soc.*, **78**, 989 (1956).
(5) G. I. Poos, G. E. Arth, R. E. Beyler, and L. H. Sarett, *J. Am. Chem. Soc.*, **75**, 422 (1953).
(6) C. Djerassi, M. Shamma, and T. Y. Kan, *J. Am. Chem. Soc.*, **80**, 4723 (1958).
(7) (a) J. W. de Leeuw, E. R. de Waard, T. Beetz, and H. O. Huisman, *Recl. Trav. Chem. Pays-Bas*, **92**, 1047 (1973); (b) R. A. Moss and D. J. Smudin, *J. Org. Chem.*, **41**, 611 (1976); (c) M. Santelli, *C. R. Hebd. Seances Acad. Sci.*, **261**, 3150 (1965).
(8) A. J. Hubert and H. Reimlinger, *Synthesis*, 97 (1969).
(9) A. J. Hubert and H. Reimlinger, *Synthesis*, 405 (1970).
(10) (a) J. A. Hirsch and L. Y. Lin, *J. Chem. Soc., Perkin Trans. 1*, 1366 (1973); (b) K. H. Schulte-Elte, H. Strickler, F. Gautschi, W. Pickenhagen, M. Gadola, J. Limacher, B. L. Muller, F. Wuffli, and G. Ohloff, *Justus Liebigs Ann. Chem.*, 484 (1975); (c) J. C. Aumiller and J. A. Whittle, *J. Org. Chem.*, **41**, 2959 (1976).
(11) J. J. Brown, R. H. Lenhard, and S. Bernstein, *J. Am. Chem. Soc.*, **86**, 2183 (1964).
(12) J. A. Marshall and D. J. Schaeffer, *J. Org. Chem.*, **30**, 3642 (1965).
(13) A. S. Dreiding and A. J. Tomasewski, *J. Am. Chem. Soc.*, **77**, 411 (1955).
(14) W. G. Dauben, G. W. Shaffer, and N. D. Vietmeyer, *J. Org. Chem.*, **33**, 4060 (1968).
(15) W. G. Dauben, J. W. McFarland, and J. B. Rogan, *J. Org. Chem.*, **26**, 297 (1961).
(16) D. Becker, J. Kalo, and N. C. Brodsky, *J. Org. Chem.*, following paper in this issue.
(17) G. Bauduin, Y. Pietrasanta, and B. Pucci, *Tetrahedron Lett.*, 2889 (1975).
(18) S. D. Levine and P. A. Diassi, *J. Org. Chem.*, **30**, 1325 (1965).
(19) C. R. Engel and S. Rakhit, *Can. J. Chem.*, **40**, 2153 (1962).
(20) D. Caine and F. N. Tuller, *J. Org. Chem.*, **34**, 222 (1969).
(21) K. A. Parker and W. S. Johnson, *J. Am. Chem. Soc.*, **96**, 2556 (1974).
(22) S. Swaminathan and M. S. Newman, *Tetrahedron*, **2**, 88 (1958).
(23) Z. Harel, D.Sc. Thesis, Technion, Israel Institute of Technology, Haifa, Israel (1977).
(24) H. J. Reich, J. M. Renga, and I. L. Reich, *J. Am. Chem. Soc.*, **97**, 5434 (1975).
(25) For example, in CCl_4 the vinylic protons of cyclohexene appear at δ 5.57, while those of 3,3-dimethyl-1-cyclohexene appear at δ 5.1–5.35: R. M. Delaney, S. Middleton, and W. F. Norfolk, *Aust. J. Chem.*, **23**, 1015 (1970).
(26) K. Wiesner, R. Vlahov, and K. Muzika, *Tetrahedron Lett.*, 2309 (1973).
(27) F. J. McQuillin, *J. Chem. Soc.*, 528 (1955).
(28) D. Caine and G. Hasenhuettl, *Tetrahedron Lett.*, 743 (1975).
(29) Y. Fukuyama and T. Tokoroyama, *Tetrahedron Lett.*, 4869 (1973).
(30) J. M. Bessiere and H. Christol, *Bull. Soc. Chim. Fr.*, 2147 (1968).
(31) E. Piers, W. de Waal and R. W. Britton, *Can. J. Chem.*, **47**, 4299 (1969).
(32) J. Karliner, H. Budzikiewicz and C. Djerassi, *J. Am. Chem. Soc.*, **87**, 580 (1965).
(33) W. Herz, *J. Am. Chem. Soc.*, **78**, 1485 (1956).

New Approach to the Synthesis of 4,4-Disubstituted Cycloalkenones

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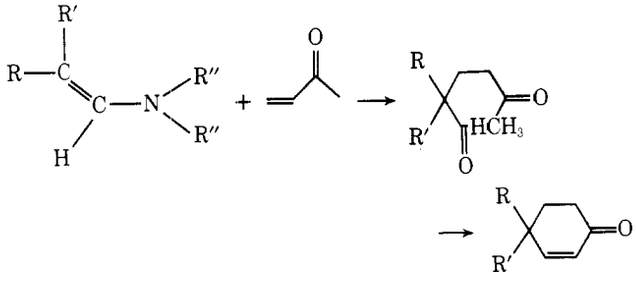
4,4-Disubstituted cycloalkenones were synthesized from appropriate bicyclic systems. The ozonide of each bicyclic system was treated by either the oxidative or the reductive route, giving products which were easily transformed to monocyclic enones. The advantages and limitations of the two routes are described.

Introduction

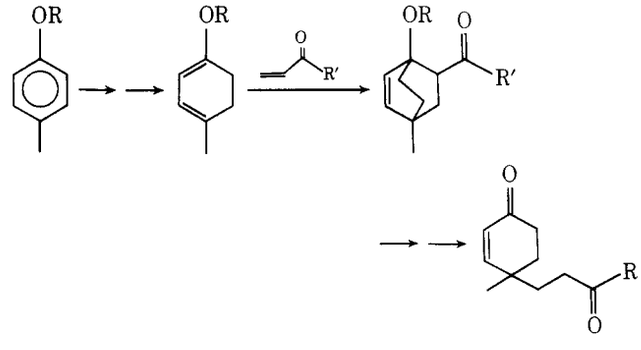
Conjugated cycloalkenone systems are very useful intermediates in synthesis, and therefore, much effort has been invested in developing methods for their preparation. The most common method is annelation, which has been improved and adapted to a wide variety of syntheses.[1] Conjugated 4,4-disubstituted cyclohexenones may be synthesized by many routes, but most of those were tailored to specific problems. Stork[2] has developed a general method consisting of condensation of the enamine with methyl vinyl ketone to produce the desired compound.



This method was applied by Yamada[3] to the synthesis of optically active 4,4-disubstituted cyclohexenones using optically active enamines.

Recently Martin[4] has described a new route to a suitable enamine for this type of annelation, starting with the appropriate ketone and diethyl lithiomorpholinomethyl phosphonate.

Another approach to conjugated cyclohexenones is based on the cleavage of bicyclic systems. For example, the starting material for the synthesis of (±)-Trichodermin was prepared by cleavage of an appropriate bicyclo[4.1.0]heptane by Raphael.[5] Birch[6] suggested a more general method based on the cleavage of bicyclo[2.2.2]octenes which were prepared by Diels–Alder addition to cyclic dienes.



In this report we summarize work in which conjugated 4,4-disubstituted cycloalkenones were prepared from conjugated bicyclic enones. The method consists basically of three steps, the first of which is the shift of the double bond induced by ketalization. The next step is cleavage of the double bond

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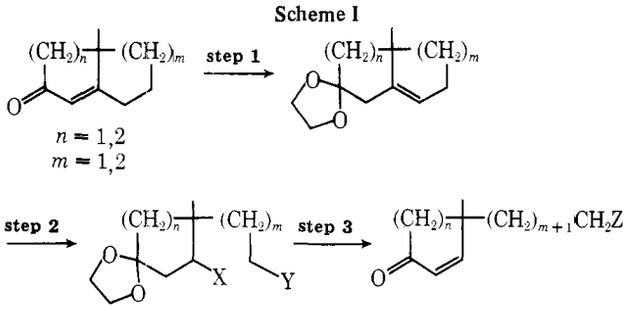
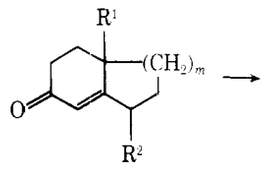
Scheme I

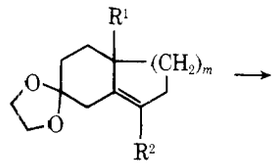


in its new position by ozonolysis to an intermediate which is easily transformed in the third step by mild acid catalysis to the desired 4,4-disubstituted cycloalkenone as described in Scheme I.

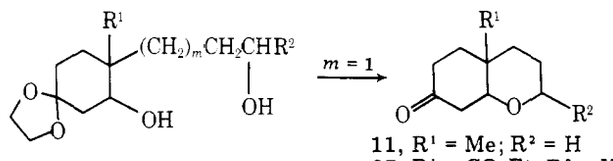
Scheme II. Reductive Route



1, R^1 = Me; R^2 = H; m = 2
17, R^1 = CO_2Et; R^2 = H; m = 2
8, R^1 = Me; R^2 = H; m = 1
24, R^1 = CO_2Et; R^2 = H; m = 1
29, R^1 = Me; R^2 = Me; m = 2
37, R^1 = Me; R^2 = Me; m = 1

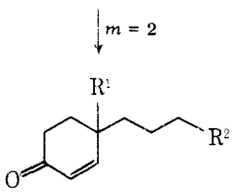


2, R^1 = Me; R^2 = H; m = 2
18, R^1 = CO_2Et; R^2 = H; m = 2
9, R^1 = Me; R^2 = H; m = 1
25, R^1 = CO_2Et; R^2 = H; m = 1
30, R^1 = Me; R^2 = Me; m = 2
38, R^1 = Me; R^2 = Me; m = 1



3, R^1 = Me; R^2 = H; m = 2
19, R^1 = CO_2Et; R^2 = H; m = 2
10, R^1 = Me; R^2 = H; m = 1
26, R^1 = CO_2Et; R^2 = H; m = 1
31, R^1 = Me; R^2 = Me; m = 2
39, R^1 = Me; R^2 = Me; m = 1

11, R^1 = Me; R^2 = H
27, R^1 = CO_2Et; R^2 = H
40, R^1 = Me; R^2 = Me



4, R^1 = Me; R^2 = CH_2OH
5, R^1 = Me; R^2 = CH_2OAc
20, R^1 = CO_2Et; R^2 = CH_2OH
21, R^1 = CO_2Et; R^2 = CH_2OAc
6, R^1 = Me; R^2 = CO_2H
7, R^1 = Me; R^2 = CO_2Me
22, R^1 = CO_2Et; R^2 = CO_2H
23, R^1 = CO_2Et; R^2 = CO_2Me
32, R^1 = Me; R^2 = CH(Me)OH
33, R^1 = Me; R^2 = CH(Me)OAc
34, R^1 = Me; R^2 = C(=O)Me

Results and Discussion

The fact that a double bond conjugated to a ketone may shift during ketalization has been known for some time.[7,8] For this work we synthesized a series of appropriate bicyclic enone systems which were ketalized in the usual manner. However, results described in the literature did not enable us to predict the position of the double bond in every case. In the accompanying paper[9] we have summarized some of the factors determining the position of the double bond in these bicyclic systems.

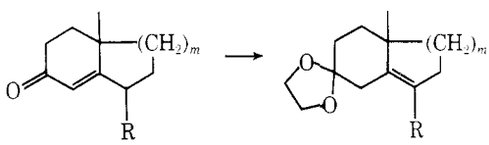
The first compound studied was **1**, since it was known that the double bond shifts to the β,γ position.[10] Ketalization was carried out with ethylene glycol using *p*-toluenesulfonic acid as catalyst in refluxing benzene with continuous removal of water. The ketal **2** was ozonized in methylene chloride at −78 °C followed by reduction with excess sodium borohydride (reductive method, Scheme II). The resulting crude ketal diol **3** was isolated in 90% yield and treated with oxalic acid solution to give hydroxycyclohexenone, which was then oxidized with Jones' reagent to the corresponding acid **6** in good yield. The fact that compound **6** was obtained in a few simple steps and in good yield encouraged us to study the scope and limitation.

We wished to determine whether the above pathway could be used to synthesize the known acid **14**.[6] The appropriate starting material was **8**,[11] which was ketalized in good yield with full shift of the double bond.[9] However, upon completing the above sequence of reactions, we found that the sole product was the ketone ether (perhydrochromanone) **11**. All our efforts to prevent formation of the ether ring by methods such as use of milder acidic or basic conditions or protection of the primary alcohol failed. Attempts to cleave **11** to **14** were also unsuccessful.

The tendency of 1,5-diols to form cyclic ethers is well known,[12] and this sequence is recommended as a simple and high-yield route to 7-perhydrochromanones.

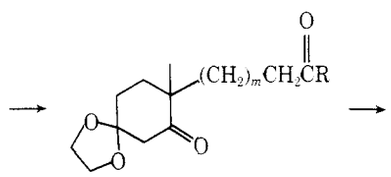
Since the corresponding acid **14** had been prepared and isolated under strongly acidic conditions from its ester without lactone formation,[13] we based our solution on early oxidation of the terminal carbon atom to a carboxylic acid (oxidative route, Scheme III) in order to prevent cyclization, in the following manner.

Scheme III. Oxidative Route

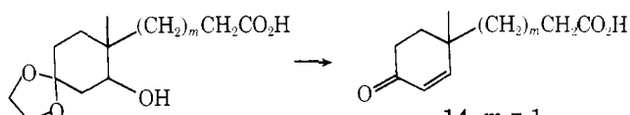


8, R = H; m = 1
1, R = H; m = 2
37, R = Me; m = 1

9, R = H; m = 1
2, R = H; m = 2
38, R = Me; m = 1



12, R = OH; m = 1
15, R = OH; m = 2
41, R = Me; m = 1



13, m = 1
16, m = 2

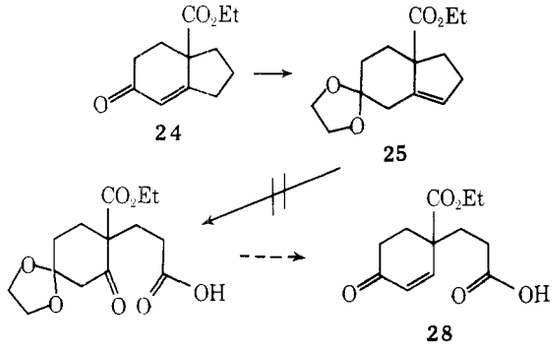
14, m = 1
6, m = 2

The ketal **9** was ozonized at −78 °C and oxidized[14] at 0 °C with Jones' reagent to the ketal acid **12**, which was isolated by a special technique (see Experimental Section) to prevent hydrolysis of the ketal function. This sequence provides a versatile intermediate **12** containing three functional groups which may be utilized selectively. In order to achieve our goal keto acid **12** was converted by sodium borohydride to alcohol **13**, which was transformed easily under mildly acidic conditions to **14** in moderate yield. Isolation of keto acid **14** prepared by the oxidative route met with some difficulty from accompanying byproducts. In order to determine whether the difficulty may be attributed to the oxidative route itself or to the particular starting material, ketal **2** was treated similarly yielding keto acid **6** via the ketal acid **15**. Since byproducts lowered the yield in this case also, the reductive approach is recommended, as will be shown later.

Another group of compounds which we studied were bicyclic compounds containing a carboethoxy group in the angular position. Treatment of ketal ester **18**, prepared from **17**[15] by the reductive route, enabled isolation of **22** in high yield.

Attempts to decarboxylate keto acid ester **22** by methods described in the literature[16,17] for 4-carboethoxycyclohexenone to form a cyclohexenone monosubstituted with a hydrocarbon chain at the 4 position failed.

In order to study the generality of the synthesis of perhydrochromanones, ketal ester **25** was prepared from **24**[18] and

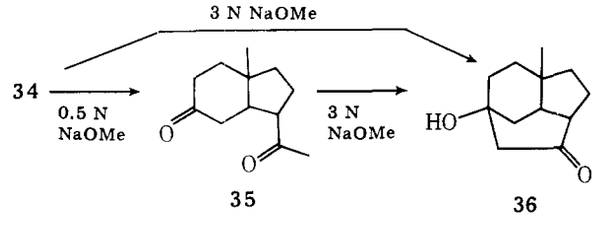


its subjection to the reductive route led to **27** as expected. The alternative preparation of **28** by the oxidative route led to a mixture of products from which the desired keto acid ester **28** could not be isolated.

Replacement in the starting material of a hydrogen atom in the γ position by an alkyl group enables preparation of side chains containing a keto function. For example, the 4-oxopentyl chain was prepared from compound **29**.[19]

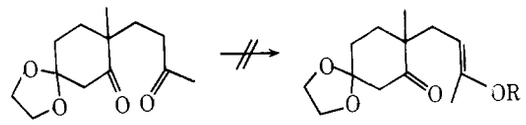
Ketal **30** was synthesized and cleaved as described, giving keto alcohol **32** in good yield; from this, ketocyclohexenone **34** was prepared. In this case the reductive method was found to be efficient, whereas using the oxidative route the same difficulties as mentioned above were encountered.

Ketocyclohexenone **34**, which is readily available by this method, may serve as a useful intermediate to certain polycyclic systems. Thus treating **34** with 3 N sodium methoxide



resulted in transformation to the tricyclic compound **36** in high yield. Double cyclizations of this type are known[20] in similar systems and have been used by Yamada[21] for the total synthesis of (±)-derbrobine. We then found that on treating **34** under milder conditions, such as 0.5 N sodium methoxide, intermediate bicyclic system **35** could be obtained. The high tendency of the 4-oxopentyl chain to cyclize and form a five-membered ring, in preference to a seven-membered ring, is known in the literature.[22,23]

Attempts to apply the reductive route to the synthesis of the corresponding 3-oxobutyl side chain from **37**[9] failed and led to formation of the keto ether **40** in high yield. Applying the oxidative route to the synthesis of the 3-oxobutyl chain is conditional on selective protection of one carbonyl group. For this ketal, dione **41** was prepared in good yield and found to be acid sensitive. However attempts at selective protection,



41

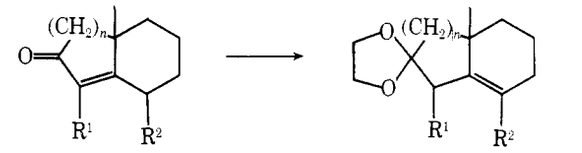
for example, by enol acetate formation, were unsuccessful.

In the accompanying paper it was shown that the shift of the double bond upon ketalization is affected by ring size and the degree of substitution at the α and γ positions. Although certain systems gave mixtures of isomeric ketals, these mixtures were investigated without separation, hoping they would serve per se as starting materials. Ketalization of compound **42**[24] gave two ketals **43** and **44** in a 1:1 ratio (Scheme IV) due to the presence of the α-methyl substituent, in contrast to the unsubstituted compound **1** in whose ketal the double bond had shifted completely.

The reductive method was applied to the mixture of **43** and **44** and the desired acid, **48**, was separated in good yield based on ketal **43**. In the course of the preparation of **46**, the products from ketal **44** did not interfere, since they probably dissolved in the aqueous phase during workup. Furthermore, ketal **43** could be isolated from the mixture by selective deketalization of ketal **44**.

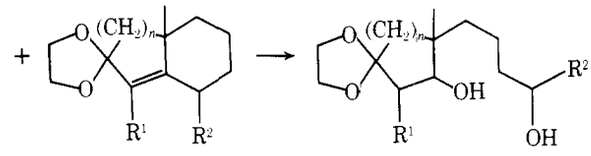
Upon ketalization of **50**[25] we found that the effect of the γ substituent was not sufficient to cause complete migration of

Scheme IV



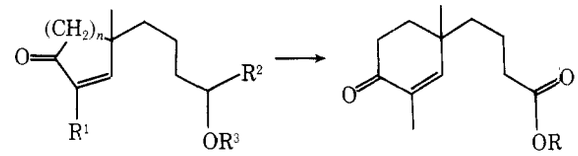
42, R^1 = Me; R^2 = H; n = 2
50, R^1 = H; R^2 = Me; n = 1

43, R^1 = Me; R^2 = H; n = 2
51, R^1 = H; R^2 = Me; n = 1



44, R^1 = Me; R^2 = H; n = 2
52, R^1 = H; R^2 = Me; n = 1

45, R^1 = Me; R^2 = H; n = 2
53, R^1 = H; R^2 = Me; n = 1



46, R^1 = Me; R^2 = R^3 = H; n = 2
47, R^1 = Me; R^2 = H; R^3 = Ac; n = 2
54, R^1 = H; R^2 = Me; R^3 = H; n = 1
55, R^1 = H; R^2 = Me; R^3 = Ac; n = 1

48, R = H
49, R = Me

the double bond, and the ratio of **51** to **52** was 7:3. The mixture was cleaved as usual by the reductive method and cyclopentenone alcohol **54** could be separated in moderate yield.

In summary, it may be concluded that in cases in which the double bond shifts into a six-membered ring, cycloalkenones substituted in the 4 position with long chains may be synthesized in high yield by the reductive method. When the double bond is located in a five-membered ring, the reductive method leads to keto ethers in very high yields, and only the oxidative method enables preparation of the desired substituted cycloalkenones.

Experimental Section

Infrared spectra were recorded on Perkin-Elmer 237 in chloroform. The ultraviolet spectra were measured on Cary 15. The NMR spectra were recorded on Varian A60 and Varian T60 using tetramethylsilane as internal standard. Mass spectra were determined on an Atlas CH_4. The gas–liquid chromatography was carried out using Varian Aerograph Model 90-P, carrier gas was helium, column 15% Xe-60 on Chromosorb Q, 9 ft.

4-(4-Hydroxybutyl)-4-methyl-2-cyclohexen-1-one (4). Ozonolysis of 0.6 g (2.88 mmol) of **2** dissolved in 50 mL of 3:1 methylene chloride/methanol at −78 °C under nitrogen was carried out with ozone until a light blue color was stable for 5 min. The ozonide was reduced with 300 mg of sodium borohydride at −78 °C for 3 h. The reaction mixture was warmed to room temperature and quenched with 30 mL of water. The organic layer was separated and the water was extracted with three 30-mL portions of ether and dried over anhydrous magnesium sulfate. The ether was removed under reduced pressure and 0.66 g (90%) of **3** was isolated as a crude oil: IR 3500 (OH), 1100 cm^{-1} (ketal); NMR ($CDCl_3$) δ 3.96 [s, 4 H, $(-OCH_2)_2$], 3.66 (m, 3 H), 3.55 (br, 2 H, OH), 0.95 (s, 3 H, CH_3).

To a solution of 1.38 g (5.65 mmol) of **3** in 180 mL of 1:1 tetrahydrofuran/water was added 20 g of oxalic acid and the solution was refluxed for 3 h. To the cooled solution sodium chloride was added to saturation and the tetrahydrofuran was removed under reduced pressure. The solution was extracted by three 60-mL portions of methylene chloride, washed with 5% sodium bicarbonate and brine, and dried over magnesium sulfate. The solvent was removed by reduced pressure to give 0.80 g (80%) of oil **4**: IR 3450 (OH) 1675 cm^{-1} (>C=O); NMR ($CDCl_3$) δ 6.64, 5.77 (AB, 2 H, J_{AB} = 10 Hz, vinylic), 4.73 (br s, 1 H, OH), 3.56 (m, 2 H, $-CH_2OH$), 1.13 (s, 3 H, CH_3).

It was found that **4** was unstable in GC. The acetate was prepared according to Bayless[26] and **5** was purified for analysis: IR 1720 ($-C(=O)CH_3$), 1680 cm^{-1} [c-C(=O)CH=CH$(C_2)_3$]; UV λ_{max} (MeOH) 227 nm (ϵ 9.5 × 10^3); NMR ($CDCl_3$) δ 6.72, 5.83 (AB, 2 H, J = 10 Hz, vinylic), 4.10 (t, 2 H, J = 6 Hz, $-CH_2OAc$) 2.05 (s, 3 H $-CCH_3$), 1.13 (s, 3 H, CH_3); MS M^+ 224, calcd 224.

Anal. Calcd for $C_{13}H_{20}O_3$: C, 69.61; H, 8.99. Found: C, 69.46; H, 8.99.

4-(1-Methyl-4-oxo-2-cyclohexenyl)butanoic Acid (6). (a) **4** (3.0 g, 0.16 mmol) dissolved in 150 mL of acetone was oxidized with Jones' reagent at 0 °C. The excess of reagent was quenched by 2-propanol and the acetone was removed under reduced pressure. The product was extracted with three 40-mL portions of chloroform and dried over anhydrous magnesium sulfate. The solvent was removed and 1.9 g (60%) of **6** was obtained: IR 3500–3200 (–COOH), 1720 (–COOH), 1680 cm^{-1} [c-C(=O)CH=CH$(CH_2)_3$]; NMR ($CDCl_3$) δ 8.4 (br, s, 1 H, $-CO_2H$) 6.72, 5.83 (AB, 2 H, J = 10 Hz, vinylic), 1.13 (s, 3 H, CH_3).

The methyl ester **7** was prepared by treatment with excess diazomethane in order to enable purification by GC for analysis: MS M^+ 210, calcd 210; UV λ_{max} (MeOH) 227 nm (ϵ 8.5 × 10^3).

Anal. Calcd for $C_{12}H_{18}O_3$: C, 68.54; H, 8.63. Found: C, 68.29; H, 8.23.

(b) Ozonolysis of 1.1 g (5.3 mmol) of ketal **2** was carried out in 50 mL of 3:1 methylene chloride/methanol at −78 °C with excess ozone. The solvents were removed at 0 °C under reduced pressure and the ozonide was dissolved in 40 mL of acetone and added via an addition funnel to 20 mL of Jones' reagent at 0 °C. Excess oxidizing reagent was destroyed with 2-propanol and the reaction mixture was filtered over Celite and sodium carbonate. The acetone was removed, the water layer was acidified to pH 5, extracted by three 50-mL portions of chloroform, and dried over anhydrous magnesium sulfate. The solvents were removed and 0.94 g of crude **15** was obtained: IR 3500–3300 (–COOH), 1715 cm^{-1} (–COOH).

Reduction of 0.94 g (3.6 mmol) of **15** in 100 mL of tetrahydrofuran was carried out with 0.35 g of sodium borohydride at 0 °C for 2 h. To the cooled stirred solution 100 mL of 10% hydrochloric acid was added and the solution refluxed for 18 h. The reaction mixture was saturated with sodium chloride and the solvent was removed under reduced pressure. The water layer was extracted with three 60-mL portions of chloroform. The organic layer was dried over anhydrous magnesium sulfate and the solvent was removed under reduced pressure to give 0.7 g of crude acid **6** (50% pure by GC).

Octahydro-4a-methyl-7*H*-1-benzopyran-7-one (11). Ketal **9** was prepared from 3 g of **8** as usual[9] and 3.3 g (85%) were obtained: IR 1100 cm^{-1}; NMR ($CDCl_3$) δ 5.30 (m, 1 H, vinylic), 3.95 (s, 4 H, ketal), 1.07 (s, 3 H, CH_3).

Ozonolysis was carried out on 1.0 g (5.1 mmol) as described for **3** and 1.0 g (84%) of **10** was obtained: IR 3500 cm^{-1} (OH); NMR ($CDCl_3$) δ 3.95 (s, 4 H, $-OCH_2CH_2O-$), 3.65 (m, 3 H, $-CH_2OH$, >CHOH), 2.6 (m, 2 H, –OH), 0.93 (s, 3 H, CH_3).

To a solution of 0.9 g (3.9 mmol) of **10** in 180 mL of 1:1 tetrahydrofuran/water was added 20 g of oxalic acid. The solution was refluxed for 3 h, cooled to room temperature, and saturated with sodium chloride. The tetrahydrofuran was removed under reduced pressure and the water layer was extracted with three 80-mL portions of methylene chloride. The combined organic layers were dried over anhydrous magnesium sulfate. The solvent was removed under reduced pressure to give 0.54 g (77%) of crude **11** (95% according to GC).

11 was purified for analysis by GC to yield crystals: mp 42.5–44 °C; IR 1715 cm^{-1} (>C=O); NMR ($CDCl_3$) δ 4.0 (m, 1 H, HCO–), 3.53 (m, 2 H, $-H_2CO-$), 1.15 (s, 3 H, CH_3); MS M^+ 168, calcd 168.

Anal. Calcd for $C_{10}H_{16}O_2$: C, 71.39; H, 9.59. Found: C, 71.39; H, 9.64.

3-(1-Methyl-4-oxo-2-cyclohexene)propionic Acid (14). On ozonolysis of 0.36 g (1.8 mmol) of ketal **9** cleaved as described for **15**, 0.45 g (80%) of **12** was isolated as a crude oil: IR 3500–3200 (–COOH), 1720 cm^{-1} (–COOH); NMR ($CDCl_3$) δ 6.20 (m, 1 H, OH), 3.95 (s, 4 H, $-OCH_2CH_2O-$), 1.1 (s, 3 H, CH_3).

A solution of 0.32 g (1.3 mmol) of **12** in 15 mL of tetrahydrofuran was treated with 0.4 g of sodium borohydride as described for **16** to give 0.26 g (80%) of **13** as a crude oil: IR 3500 (–COOH), 1730 cm^{-1} (–COOH).

13 (0.26 g, 1.3 mmol) was dissolved in 8 mL of tetrahydrofuran and 8 mL of 5% hydrochloric acid in water and refluxed overnight. The solution was cooled to room temperature and neutralized with sodium carbonate. The tetrahydrofuran was removed under reduced pressure and the water layer washed with methylene chloride. The aqueous solution was acidified with concentrated hydrochloric acid and extracted four times with 20-mL portions of methylene chloride. The solvent was dried over magnesium sulfate and removed under reduced pressure to give 0.12 g (40%) of crude acid **14**.

4-(4-Hydroxybutyl)-4-carboethoxy-2-cyclohexen-1-one (20). Ketalization of 0.48 g (2.1 mmol) of **17** was carried out as usual. **18** (0.6 g) was obtained as a crude oil: IR 1725 cm^{-1} [$-C(=O)OC_2H_5$]; NMR ($CDCl_3$) δ 5.65 (m, 1 H, vinylic), 4.2 (q, 2 H, OCH_2CH_3), 3.97 (s, 4 H, $-OCH_2CH_2O-$), 1.27 (t, 3 H, CH_3CH_2-).

Ozonolysis of 2.66 g (10 mmol) of **18** dissolved in 130 mL of methylene chloride and 20 mL of methanol with an excess of ozone was carried out as described for **3**. **19** (2.34 g; 77%) was obtained: IR 3500 (OH), 1720 cm^{-1} (–COOEt).

Deketalization and dehydration of 0.45 g (1.47 mmol) of **19** in 100 mL of 1:1 tetrahydrofuran/water and 10 g of oxalic acid was carried out as described for **4**. After removal of the solvent 0.28 g (85%) of the keto alcohol ester **20** was obtained: IR 3600–3400 (OH), 1730 (–COOEt), 1680 cm^{-1} [$-C(=O)C=Cl$]; NMR ($CDCl_3$) δ 6.97, 6.02 (AB, 2 H, J = 10 Hz, vinylic), 4.28 (q, 2 H, $-\mathbf{CH}_2CH_3$), 3.70 (m, 3 H, $-\mathbf{CH}_2OH$), 1.30 (t, 3 H, CH_3CH_2-).

In order to obtain an analytical sample the acetate **21** was prepared in pyridine with acetyl chloride as usual: IR 1730 [–COOEt, $-OC(=O)CH_3$], 1680 cm^{-1}; NMR ($CDCl_3$) δ 6.97, 6.02 (AB, 2 H, J = 10 Hz, vinylic), 4.30 (q, 2 H, $O\mathbf{CH}_2CH_3$) 2.07 (s, 3 H, $CH_3C(=O)-$), 1.03 (t, 3 H, $\mathbf{CH}_3CH_2-$).

Anal. Calcd for $C_{15}H_{22}O_5$: C, 63.81; H, 7.85. Found: C, 63.82; H, 7.81.

4-[1-Carboethoxy-4-oxo-2-cyclohexene]butaonic Acid (22). Oxidation of 1 g (4.45 mmol) of hydroxyketo acid **20** with 20 mL of Jones' reagent in 30 mL of acetone was carried out at 0 °C and quenched with 5 mL of 2-propanol. The solvents were removed under reduced pressure and the water layer was extracted with five 40-mL portions of chloroform. From the organic phase the acid was extracted with five 10-mL portions of 5% sodium bicarbonate. The combined aqueous layers were acidified with concentrated hydrochloric acid to pH 2 and extracted with five 50-mL portions of chloroform. The organic layers were combined and dried over magnesium sulfate. The solvent was removed under reduced pressure to give 0.70 g (60%) of

the keto acid **22**: IR 3500-3000 (-COOH) 1730 (-COOH, -COOEt), 1680 cm^{-1} [c-C(=O)CH=CH$(CH_2)_3$]; NMR ($CDCl_3$) δ 6.97, 6.02 (AB, 2 H, J = 10 Hz, vinylic), 4.25 (q, 2 H, OCH_2CH_3) 1.30 (t, 3 H, CH_3CH_2-).

In order to purify this compound the methyl ester **23** was prepared with excess diazomethane: IR 1735 (-COOR), 1685 cm^{-1} [c-C(=O)-CH=CH$(CH_2)_3$]; NMR ($CDCl_3$) δ 6.97, 6.02 (AB, 2 H, J = 10 Hz, vinylic), 4.23 (q, 2 H, OCH_2CH_3), 3.7 (s, 3 H, CH_3O-), 1.3 (t, 3 H, CH_3CH_2-); UV λ_{max} (MeOH) 223 (ϵ 7.2 × 10^3).

Anal. Calcd for $C_{14}H_{20}O_5$: C, 62.67, H, 7.51. Found: C, 62.15, H, 8.08.

Octahydro-4a-carboethoxy-7*H*-1-benzopyran-7-one (27). Ketalization of 4.0 g (1.9 mmol) of **24** was carried out as usual to give in quantitative yield the ketal **25**: IR 1716 (-COOEt) 1090 cm^{-1} (ketal); NMR ($CDCl_3$) δ 5.58 (m, 1 H, vinylic), 4.17 (q, 2 H, $-CH_2O$), 3.13 (s, 4 H, $-OCH_2CH_2O$-), 1.23 (t, 3 H, CH_3CH_2-).

Ozonolysis of 2.0 g (7.9 mmol) of **25** dissolved in 50 mL of methylene chloride and 10 mL of methanol was carried out as usual to yield 1.4 g of crude diol **26**: IR 3480 (-OH), 1720 cm^{-1} (-COOEt).

Hydrolysis of 0.2 g (0.69 mmol) of **26** was carried out in 60 mL of 1:1 tetrahydrofuran/water and 7 g of oxalic acid. The reaction mixture was refluxed for 3 h. At room temperature the solution was saturated with sodium chloride and the tetrahydrofuran was removed under reduced pressure. The water was extracted with three 40-mL portions of methylene chloride. The organic layer was washed with 5% sodium carbonate and dried over anhydrous magnesium sulfate. The solvent was removed and 0.13 g of **27** in 50% overall yield was obtained: IR 1725 cm^{-1} (-COOR); NMR ($CDCl_3$) δ 4.25 (q, 2 H, CH_3CH_2O-), 3.50 (m, 3 H, >$CHOCH_2$-), 1.30 (t, 3 H, CH_3CH_2-); MS M^+ 226, calcd 226.

Anal. Calcd for $C_{12}H_{18}O_4$: C, 63.70; H, 8.02. Found: C, 63.88; N, 8.17.

4-Methyl-4-(4-pentanol)-2-cyclohexenone (32). Ketalization was carried out on 3.7 g (19.6 mmol) of **29** dissolved in 150 mL of dry benzene as usual. The yield was 4.15 g (95%) of **30**: IR 1100 cm^{-1} (ketal); NMR ($CDCl_3$) δ 3.97 (s, 4 H, $-OCH_2CH_2O$-), 1.63 (s, 3 H, CH_3C=C-), 1.1 (s, 3 H, CH_3-).

Ozonolysis of 2.03 g (9.15 mmol) of **30** dissolved in 100 mL of methylene chloride and 20 mL of methanol at −78 °C was carried out as described for **2**.

After removal of the solvents 2.35 g (93%) of crude diol **31** was isolated: IR 3500 (-OH), 1100 cm^{-1} (ketal); NMR ($CDCl_3$) δ 3.97 (s, 4 H, $-O(CH_2)_2O$-), 2.47 (m, 2 H, HCOH), 1.17 (d, 3 H, J = 6 Hz, CH_3CH-) 0.93 (s, 3 H, CH_3-).

Crude diol **31** (0.9 g, 3.49 mmol) was dissolved in 140 mL of 1:1 tetrahydrofuran/water, 15 g of oxalic acid was added and the solution was refluxed for 3 h. Workup as usual yielded 0.625 g (85%) of **32**: IR 3600 (OH), 1660 cm^{-1} [c-C(=O)CH=CH$(CH_2)_3$]; NMR ($CDCl_3$) δ 6.7, 5.96 (AB, 2 H, J = 10 Hz, vinylic), 3.80 (m, 1 H, >CHOH) 1.08 (s, 3 H, CH_3); MS M^+ 196, calcd 196.

The acetate **33** was prepared in the usual way with acetyl chloride in pyridine: IR 1720 [OC(=O)CH_3], 1665 cm^{-1} [c-C(=O)-CH=CH$(CH_2)_3$]; NMR ($CDCl_3$) δ 6.70, 5.96 (AB, 2 H, J = 10 Hz, vinylic), 2.05 (s, 3 H, $-OCOCH_3$), 1.23 (d, 1 H, J = 6 Hz, HCOH), 1.08 (s, 3 H, CH_3); UV λ_{max} (MeOH) 227 mm (ϵ 1.2 × 10^4).

Anal. Calcd for $C_{14}H_{22}O_3$: C, 70.55; H, 9.31. Found: C, 70.60; H, 8.91.

4-Methyl-4-(4-oxopentyl)-2-cyclohexenone (34). Oxidation of 0.18 g (9.18 mmol) of hydroxy ketone **32** was carried out in a solution of 0.3 g of chromium trioxide, 0.2 mL of water, and 3 mL of pyridine. The mixture was stirred overnight at room temperature. To the reaction mixture was added 10 mL of water and the solids were removed by filtration with Celite. The water layer was extracted with four 30-mL portions of ether. The organic layers were combined and washed with 5% hydrochloric acid and brine. The solution was dried over anhydrous magnesium sulfate and the solvents were removed under reduced pressure to give 0.163 g (91%) of diketone **34**: IR 1715 (>C=O), 1675 cm^{-1} [c-C(=O)CH=CH$(CH_2)_3$]; NMR ($CDCl_3$) δ 6.70, 5.96 (AB, 2 H, J = 10 Hz, vinylic), 2.17 (s, 3 H, CH_3CO) 1.17 (s, 3 H, CH_3); UV λ_{max} (MeOH) 226 nm (ϵ 6.9 × 10^3); MS M^+ 194, calcd 194.

Anal. Calcd for $C_{12}H_{18}O_2$: C, 74.14; H, 9.34. Found: C, 73.84; H, 9.20.

3-Acetyl-7a-methyl-3a,6,7,7a-tetrahydro-5-(4*H*)-indanone (35). Sodium methoxide (0.5 N) in methanol was prepared from 0.17 g of sodium and 15 mL of anhydrous methanol. Diketone **34** (0.1 g, 0.51 mmol) dissolved in 1 mL of methanol was added at 0 °C and stirred for 2 h. Brine was added and the methanol was removed under reduced pressure. The water layer was extracted with three 25-mL portions of methylene chloride. The organic layers were washed with water and dried over anhydrous magnesium sulfate and the solvent was removed to give 0.095 g (90%) of **35**: IR 1715 cm^{-1} (>C=O); NMR ($CDCl_3$) δ 2.20 (s, 3 H, CH_3C-); MS M^+ 194, calcd 194.

Anal. Calcd for $C_{12}H_{18}O_2$: C, 74.19; H, 9.34. Found: C, 74.22; H, 9.27.

1-Hydroxy-7-methyltricyclo[5.2.2.$0^{4,8}$]undecan-3-one (36). Sodium methoxide (2.5 N) in methanol was prepared from 5 g of sodium and 100 mL of methanol. Diketone **34** (1.05 g, 5.4 mmol) dissolved in 2 mL of methanol was added dropwise at 0 °C and stirred overnight under nitrogen at room temperature. To the reaction mixture was added 25 mL of brine and the solvent was removed under reduced pressure. The water layer was extracted with three 40-mL portions of methylene chloride. The organic layers were combined, washed with brine, and dried over anhydrous magnesium sulfate. The solvent was removed and 0.9 g (86%) of crude oil was isolated. The crude oil was crystallized from hexane to give **36** in high yield: mp 116–118 °C; IR 3580 (OH), 1700 cm^{-1} (>C=O); NMR ($CDCl_3$) δ 1.08 (s, 3 H, CH_3); MS M^+ 194, calcd 194.

Anal. Calcd for $C_{12}H_{18}O_2$: C, 74.19; H, 9.34. Found: C, 73.76; H, 9.29.

Octahydro-2,4a-dimethyl-(7*H*)-1-benzopyran-7-one (40). Ketal **38** was prepared from 1 g (6.1 mmol) of **37** as usual. **38** (1.25 g) was obtained as a crude oil: IR 1090 cm^{-1} (ketal); NMR ($CDCl_3$) δ 3.98 (s, 4 H, $-OCH_2CH_2O$-), 1.62 (s, 3 H, CH_3C=C), 1.03 (s, 3 H, CH_3).

Ozonolysis of 0.18 g (0.86 mmol) of **33** was carried out as described for **2**, followed by sodium borohydride treatment. The crude diol **39** (0.17 g) was dissolved in 90 mL of 1:1 tetrahydrofuran/water and 10 g of oxalic acid was added and refluxed for 3 h. The reaction mixture was worked up as usual to give 0.14 g (89%) of **40**: IR 1715 (>C=O), 1100 cm^{-1} (-O-); NMR ($CDCl_3$) δ 3.60 (m, 2 H, >CHO-), 1.25 (d, 3 H, CH_3CO), 1.17 (s, 3 H, CH_3); MS M^+ 182, calcd 182.

Anal. Calcd for $C_{11}H_{18}O_2$: C, 72.49; H, 9.96. Found: C, 72.81; H, 9.79.

Ketalization of 4,4a,5,6,7,8-Hexahydro-1,4a-dimethyl-2(3*H*)-naphthalenone (42). Ketone **42** (2.09 g, 11.2 mmol) was ketalized in 60 mL of dry benzene, 1.5 g of ethylene glycol, and 60 mg of *p*-toluenesulfonic acid and the solution was refluxed for 4 days with constant removal of water. Hexane (100 mL) was added and the acid was quenched with sodium carbonate. The organic layer was washed three times with 30 mL of 5% sodium bicarbonate and dried over anhydrous sodium carbonate. The solvent was removed. A 2.1-g (84%) mixture of two ketals **43** and **44** in a 1:1 ratio was obtained: IR 1090 cm^{-1} (ketal); MS M^+ 222, calcd 222.

In order to isolate isomer **43** 50 mg of a mixture of 1:1 **43/44** was dissolved in 2 mL of benzene and 1 mL of tetrahydrofuran. A solution of 0.5 g of magnesium sulfate in 5 mL of water was added and the mixture was stirred overnight at room temperature. The solvents were removed under reduced pressure and the water extracted with three 10-mL portions of methylene chloride. The organic layers were combined and dried over anhydrous magnesium sulfate. Crude oil (50 mg) was isolated. The crude oil was chromatographed over basic alumina plate eluting with 1:12 acetone/hexane to yield 20 mg (80%) of clean **43**: NMR ($CDCl_3$) δ 5.46 (m, 1 H, vinylic), 4.0 (d, 4 H, $-OCH_2CH_2O$-), 1.13 (s, 3 H, CH_3), 1.0 (d, 3 H, J = 7 Hz, CH_3CH<).

2,4-Dimethyl-4-(4-butanol)-2-cyclohexenone (46). A mixture of 1 g (4.5 mmol) of **43/44** in a 1:1 ratio was dissolved in 50 mL of methylene chloride and ozonized at −78 °C as usual. Crude oil (0.82 g) was isolated and was used in the next step without further purification: NMR ($CDCl_3$) δ 4.0 (m, 4 H, $-OCH_2CH_2O$-), 3.70 (m, 3 H, -OCH-), 1.1 (d, 3 H, CH_3CH), 0.91 (s, 3 H, CH_3).

Crude diol **45** was dissolved in 50 mL of 1:1 tetrahydrofuran/water and 5 g of oxalic acid was added and refluxed overnight. The reaction was worked up as usual and 0.45 g of crude oil was obtained (84% yield based on one isomer): IR 3450 (-OH), 1670 cm^{-1} [c-C(=O)-CH=CH$(CH_2)_3$]; NMR ($CDCl_3$) δ 6.5 (br s, 1 H, vinylic), 3.60 (m, 2 H, $-CH_2O$-), 1.77 (d, 3 H, J = 2 Hz, CH_3C=CH), 1.13 (s, 3 H, CH_3).

Acetate **47** was prepared as usual with pyridine–acetyl chloride: IR 1730 (acetate), 1670 cm^{-1} [c-C(=O)CH=CH$(CH_2)_3$]; NMR ($CDCl_3$) δ 6.47 (br s, 1 H, vinylic), 4.10 (t, 2 H, $-CH_2OH$), 2.07 [s, 3 H, CH_3C(=O)-] 1.77 (d, 3 H, J = 2 Hz, CH_3CH=C), 1.13 (s, 3 H, CH_3); MS M^+ 238, calcd 238; UV λ_{max} (MeOH) 236 mm (ϵ 8.8 × 10^3).

Anal. Calcd for $C_{14}H_{22}O_3$: C, 70.55; H, 9.31. Found: C, 70.66; H, 9.18.

4-(1,3-Dimethyl-4-oxo-2-cyclohexene)butanoic Acid (48). Oxidation of 0.44 g (2.2 mmol) of crude keto alcohol **46** was carried out with 6 mL of Jones' reagent at 0 °C in 30 mL of acetone. 2-Propanol was added to quench the excess reagent and the acetone was removed under reduced pressure. The water layer was extracted with three 30-mL portions of chloroform. The solvent was dried over an-

hydrous magnesium sulfate and removed to give 0.30 g (65%) acid **48**, and the corresponding methyl ester **49** was prepared with excess diazomethane: IR 1735 (-COOR), 1675 cm^{-1} [c-C(=O)-CH=CH$(CH_2)_3$]; NMR ($CDCl_3$) δ 6.49 (br s, 1 H, vinylic), 3.72 (s, 3 H, -OMe) 1.73 (d, 3 H, J = 2 Hz, CH_3CH=C), 1.13 (s, 3 H, CH_3); UV λ_{max} (MeOH) 236 mm (ϵ 5.5 × 10^3); MS M^+ 224, calcd 224.

Ketalization of 5,6,7,7a-tetrahydro-4,7a-dimethylindan-2(4*H*)-one (50). Ketalization of 0.31 g (1.9 mmol) of **50** was carried out in 70 mL of dry benzene, 2.4 mL of ethylene glycol, and 31 mg of *p*-toluenesulfonic acid for 5 days and worked up as usual. Oil (0.43 g) was obtained in quantitative yield. According to the NMR the ratio **51**/**52** was 7:3. **51**: NMR ($CDCl_3$) δ 3.93 (br, 4 H, J = 3 Hz, -OCH_2CH_2O-), 2.63 (bs, 2 H, O_2CCH_2C=), 1.87 (s, 2 H, O_2CCH_2-), 1.55 (bs, 3 H, CH_3C=C), 1.13 (s, 3 H, CH_3). **52** NMR ($CDCl_3$) δ 5.25 (bd, 1 H, J = 2 Hz, CH=C), 3.95 (s, 4 H, -OCH_2CH_2O-), 2.00 (s, 2 H, CCH_2-), 1.18 (s, 3 H, CH_3C=C), 1.08 (d, 3 H, J = 6 Hz, CH_3C-).

Isomer **51** was isolated from the mixture following the procedure described for **43**.

4-(4-Hydroxypentyl)-4-methyl-2-cyclopenten-1-one (54). Ozonolysis of 1.08 g (5.2 mmol) of a mixture of **51** and **52** in 100 mL of methylene chloride and 20 mL of methanol at −78 °C was performed as described before. The crude diol (0.81 g; 64%) was isolated: IR 3400 (-OH), 1070 cm^{-1} (ketal); NMR ($CDCl_3$) δ 3.9 (s, 4 H, -OCH_2CH_2O-), 1.18 (d, 3 H, J = 6 Hz, CH_3CH 1.03 (s, 3 H, CH_3).

Crude diol **53** (0.18 g) was dissolved in 140 mL of 1:1 tetrahydrofuran/water and 15 g of oxalic acid and refluxed for 3 h. The reaction mixture was worked up as usual and 0.44 g (74%) of **54** as crude oil was isolated: IR 3460 (OH), 1710 cm^{-1} [c-C(=O)CH=CH$(CH_2)_2$]; NMR ($CDCl_3$) δ 7.52, 6.10 (AB, 2 H, J = 6 Hz, vinylic), 1.25 (s, 3 H, CH_3), 1.08 (d, 3 H, CH_3CH).

The corresponding acetate **55** was prepared from 0.33 g of **54** in 5 mL of pyridine and 0.25 mL of acetyl chloride. The keto acetate **54** was purified on basic alumina plates and elated with 3:7 acetone/hexane in 61% yield: IR 1725 ($OCCH_3$), 1700 cm^{-1} [c-C(=O)-CH=CH$(CH_2)_2$]; NMR ($CDCl_3$) δ 7.45, 6.05 (AB, 2 H, J = 6 Hz, vinylic), 2.03 (s, 3 H, CH_3C-); MS M^+ 224, calcd 224.

Registry No.—**2**, 3287-60-3; **3**, 65969-91-7; **4**, 33948-33-3; **5**, 65969-92-8; **6**, 33919-22-1; **7**, 33919-23-2; **8**, 17299-55-7; **9**, 59586-82-2; **10**, 65969-94-0; **11**, 33948-34-4; **12**, 65969-95-1; **13**, 65969-96-2; **14**, 33948-32-2; **15**, 65969-93-9; **17**, 7478-39-9; **18**, 65898-58-0; **19**, 65969-97-3; **20**, 65969-68-8; **21**, 65969-69-9; **22**, 33919-24-3; **23**, 65969-70-2; **24**, 65969-71-3; **25**, 65898-59-1; **26**, 65969-72-4; **27**, 65969-73-5; **29**, 4071-63-0; **30**, 65898-63-7; **31**, 65969-74-6; **32**, 65969-75-7; **33**, 65969-76-8; **34**, 65969-77-9; **35**, 65969-78-0; **36**, 65969-79-1; **37**, 65898-67-1; **38**, 65898-64-8; **39**, 65969-80-4; **40**, 65969-81-5; **42**, 878-55-7; **43**, 65898-65-9; **44**, 65898-56-8; **45**, 65969-82-6; **46**, 65969-83-7; **47**, 65969-84-8; **48**, 65969-85-9; **49**, 65969-86-0; **50**, 65969-87-1; **51**, 65898-60-4; **52**, 65898-52-4; **53**, 65969-88-2; **54**, 65969-89-3; **55**, 65969-90-6.

References and Notes

(1) M. E. Jung, *Tetrahedron*, **32**, 3 (1976).
(2) G. Stork, A. Brizzolara, H. Landesman, J. Szmuszkovicz, and R. Terrell, *J. Am. Chem. Soc.*, **85**, 207 (1963).
(3) S. Yamada and G. Otani, *Tetrahedron Lett.*, 4237 (1969); K. Hiroi and S. Yamada, *Chem. Pharm. Bull.*, **21**, 47 (1973).
(4) (a) S. F. Martin, *J. Org. Chem.*, **41**, 3337 (1976); (b) S. F. Martin, T. S. Chou, and C. W. Payne, *ibid.*, **42**, 2520 (1977).
(5) E. W. Colvin, S. Malchenko, R. A. Raphael, and J. S. Roberts, *J. Chem. Soc., Perkin Trans. 1*, 1989 (1973).
(6) A. J. Birch and J. S. Hill, *J. Chem. Soc. C*, 419 (1966); 125 (1967).
(7) E. Fernholz and H. E. Stavely, Abstracts, 102nd Meeting of the American Chemical Society, Atlantic City, N.J., Sept. 1941, p 39 M.
(8) J. W. De Leeuw, E. R. De Waard, T. Beetz, and H. O. Huisman, *Recl. Trav. Chim. Pays Bas*, **92**, 1047 (1973).
(9) D. Becker, N. C. Brodsky, and J. Kalo, *J. Org. Chem.*, preceding paper in this issue.
(10) J. A. Marshall and M. T. Pike, *Tetrahedron Lett.*, 3107 (1965).
(11) W. G. Dauben, G. W. Shaffer, and N. D. Vietmeyer, *J. Org. Chem.*, **33**, 4060 (1968).
(12) A. J. Birch, P. L. Macdonald, and V. H. Powell, *J. Chem. Soc. C*, 1469 (1970).
(13) D. Becker, D.Sc. Thesis, Haifa (1968).
(14) A. S. Narula and S. Dev, *Tetrahedron Lett.*, 1733 (1969).
(15) A. S. Dreiding and A. J. Tomasewski, *J. Am. Chem. Soc.*, **77**, 411 (1955).
(16) W. S. Johnson, P. J. Neustaedter, and K. K. Schmiegel, *J. Am. Chem. Soc.*, **87**, 5148 (1965).
(17) G. Habermehl and A. Haaf, *Chem. Ber.*, **102**, 186 (1969).
(18) W. G. Dauben, J. W. McFarland, and J. B. Rogan, *J. Org. Chem.*, **26**, 297 (1961).
(19) D. Caine and F. N. Tuller, *J. Org. Chem.*, **34**, 222 (1969).
(20) W. S. Johnson, S. Shulman, K. L. Williamson, and R. Pappo, *J. Org. Chem.*, **27**, 2015 (1962).
(21) Y. Hayakawa, H. Nakamura, K. Aoki, M. Suzuki, K. Yamada, and Y. Hirata, *Tetrahedron*, **27**, 5157 (1971).
(22) D. H. R. Barton, A. D. S. Campos-Neves, and A. I. Scott, *J. Chem. Soc.*, 2698 (1957).
(23) J. C. Aumiller and J. A. Whittle, *J. Org. Chem.*, **41**, 2955 (1976).
(24) F. J. McQuillin, *J. Chem. Soc.*, 528 (1955).
(25) Y. Fukuyama and T. Tokoroyama, *Tetrahedron Lett.*, 4869 (1973).
(26) A. Bayless and H. Zimmer, *J. Org. Chem.*, **34**, 3696 (1969).

Selective Reduction of Alkenes and Alkynes by the Reagent Lithium Aluminum Hydride–Transition-Metal Halide

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The reactions of alkenes and alkynes with $LiAlH_4$ in admixture with first-row transition-metal halides have been studied in detail. When $LiAlH_4$ and $TiCl_3$, VCl_3, $CrCl_3$, $FeCl_2$, $FeCl_3$, $CoCl_2$, or $NiCl_2$ were mixed in equimolar quantities, alkenes were reduced in quantitative yield to the corresponding alkanes. However, when the transition-metal halide was used in catalytic amount, only $CoCl_2$, $NiCl_2$, and $TiCl_3$ were effective in reducing olefins to alkanes in high yield. 1-Methylcyclohexene (a trisubstituted olefin), which is reduced only poorly by hydrozirconation or $LiAlH_4$–$TiCl_3$, was reduced in quantitative yield by $LiAlH_4$–$CoCl_2$ and $LiAlH_4$–$NiCl_2$. The following olefins were reduced to the corresponding alkanes in quantitative yield by one or more transition-metal halides in admixture with $LiAlH_4$: 1-octene, 1-hexene, *cis*-2-hexene, *trans*-2-hexene, styrene, cyclohexene, and 2-ethylhexene. Phenylacetylene was reduced quantitatively to styrene using $LiAlH_4$–$FeCl_2$ or to ethylbenzene when $LiAlH_4$–$NiCl_2$ was used. Diphenylacetylene could be reduced to *cis*-stilbene in the absence of *trans*-stilbene by $LiAlH_4$–$NiCl_2$. 1-Octyne could be reduced to octane in quantitative yield by $LiAlH_4$–$FeCl_2$ or to 1-octene by $LiAlH_4$–$NiCl_2$. Deuterium incorporation studies indicate that the intermediate transition-metal alkyls formed in these reactions are not stable, as only 12–47% deuterium incorporation is observed except when $TiCl_3$ is used as the catalyst.

Application of transition-metal hydrides in organic synthesis has been an area of considerable interest in recent years. Although the ability of transition-metal hydrides to add to olefins to form C–M bonds has been known for some years,[1] the synthetic utility of this reaction is still under development.

Recently, hydrozirconation of alkenes and alkynes has been shown to yield a versatile intermediate for useful synthetic

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