$C_{10}H_{12}O$ 148.0888, found 148.0884. The spectral data for **15** was consistent with the reported data.[21f]

Acknowledgment. We thank Ms. Mary Uhrig from R. J. Reynolds Tobacco Company for the mass spectral determinations. Financial support of this work by the National Science Foundation (CHE 8517881) and the donors of the Petroleum Research Fund, administered by the American Chemical Society, is gratefully acknowledged.

Registry No. **1a**, 104525-94-2; **1b**, 119987-21-2; **1c**, 126554-34-5; **1d**, 126554-33-4; **1e**, 134418-82-9; **1f**, 126554-43-6; **1g**, 134418-83-0; **1h**, 132524-91-5; **1i**, 126554-35-6; **1j**, 132524-92-6; **2** (isomer 1), 110362-29-3; **2** (isomer 2), 110362-30-6; **4a** (isomer 1), 136175-46-7; **4a** (isomer 2), 136175-47-8; **4b** (isomer 1), 136175-48-9; **4b** (isomer 2), 136175-49-0; **4c** (isomer 1), 136175-50-3; **4c** (isomer 2), 136175-51-4; **4d** (isomer 1), 136175-52-5; **4d** (isomer 2), 136175-53-6; **4e** (isomer 1), 136175-54-7; **4e** (isomer 2), 136175-55-8; **4f** (isomer 1), 136175-56-9; **4f** (isomer 2), 136175-57-0; **4g** (isomer 1), 136175-58-1; **4g** (isomer 2), 136175-59-2; **4h**, 136175-60-5; **4i**, 136175-61-6; **4j**, 136175-62-7; **5a**, 136175-63-8; **5b**, 136175-64-9; **5c**, 136175-65-0; **5d**, 136175-66-1; **5e**, 136175-67-2; **5f**, 136175-63-8; **5g**, 136175-68-3; **5h**, 136175-69-4; **5i**, 108462-35-7; **6** (isomer 1), 136175-70-7; **6** (isomer 2), 136235-12-6; **7**, 136175-71-8; **8**, 136175-72-9; **9**, 136175-73-0; **10a**, 136175-74-1; **10b**, 136175-75-2; **10c**, 136175-76-3; **10e**, 136175-77-4; **10g**, 136175-78-5; **12c**, 136175-79-6; **12j**, 136175-80-9; **15**, 13656-81-0; $Rh_2(OAc)_4$, 15956-28-2; $Rh_2(Piv)_4$, 65545-21-3.

Supplementary Material Available: Copies of the ^1H NMR spectra for compounds **4d**, **4g**, **4i**, **5c**, **5e**, **5h**, **9**, **10b**, **10c**, **10e**, **10g**, and **12b** (12 pages). Ordering information is given on any current masthead page.

New Low-Valent Titanium Reagents for Dicarbonyl Coupling and Their Use in a General Method of Annulation

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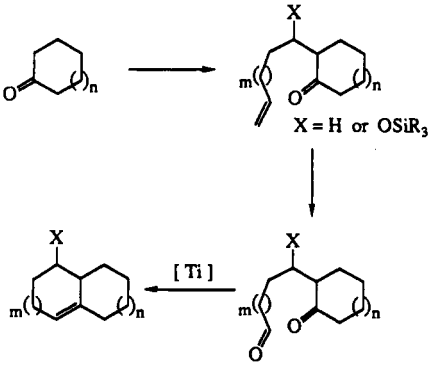
New low-valent titanium reagents have been prepared by reducing $TiCl_3$ (1 mol) with C_8K (2 mol) or by reducing $TiCl_4$ (1 mol) with Na–naphthalene (2.75 mol). Ketones carrying a chain that incorporates a suitably placed oxo function (aldehyde or ketone) undergo intramolecular dicarbonyl coupling to produce a bicyclic compound when treated with an excess (16–17 mol of titanium halide per mol of dicarbonyl compound) of one of these reagents. The procedure works well even for highly oxygenated substrates and constitutes a general method of annulation. Other reducing agents besides C_8K or Na–naphthalene are suitable, and a brief examination of Na(Hg) and Na–K alloy was made. The $C_8K/TiCl_3$ system was also used to convert a *cis*-1,2-diol into the corresponding olefin.

We report here full details of the development of some new low-valent titanium reagents in which the metal has formally a valency of 1. These reagents can be used in a general method of annulation (see Scheme I)[1] and, unlike some other low-valent titanium species that we have tested, also work with highly oxygenated compounds.

Introduction

The McMurry reaction,[2] in which carbonyl compounds—usually ketones or aldehydes—are coupled by use of low-valent titanium to produce olefins, has served for many years as an extremely useful procedure.[3] The reagent is tentatively regarded[4,5] as a titanium(0) species, and the scope of the method has been examined in detail.[3a] The reaction is heterogeneous, and so the mechanism is a difficult one to probe, although considerable progress has been made.[3a,4]

Scheme I

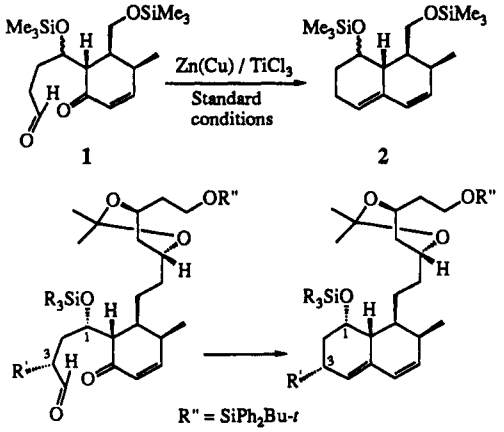


Several years ago, as a model study[6] for the synthesis[7] of compactin and mevinolin, we treated compounds **1** under standard conditions[8] with the titanium reagent

(1) Clive, D. L. J.; Keshava Murthy, K. S.; Zhang, C.; Hayward, W. D.; Daigneault, S. *J. Chem. Soc., Chem. Commun.* **1990**, 509.
(2) (a) McMurry, J. E.; Fleming, M. P. *J. Am. Chem. Soc.* **1974**, *96*, 4708. (b) Mukaiyama, T.; Sato, T.; Hanna, J. *Chem. Lett.* **1973**, 1041. (c) Tyrlik, S.; Wolochowicz, I. *Bull. Soc. Chim. Fr.* **1973**, 2147.
(3) Reviews: (a) McMurry, J. E. *Chem. Rev.* **1989**, *89*, 1513. (b) Pons, J.-M.; Santelli, M. *Tetrahedron* **1988**, *44*, 4295. (c) Betschart, C.; Seebach, D. *Chimia* **1989**, *43*, 39. (d) Lenoir, D. *Synthesis* **1989**, 883.
(4) Dams, R.; Malinowski, M.; Westdorp, I.; Geise, H. Y. *J. Org. Chem.* **1982**, *47*, 248. Dams, R.; Malinowski, M.; Geise, H. J. *Bull. Soc. Chim. Belg.* **1981**, *90*, 1141. Dams, R.; Malinowski, M.; Geise, H. J. *Transition Met. Chem. (London)* **1982**, *7*, 37.
(5) For the valence state of titanium, when $LiAlH_4$ is used, see ref 4.
(6) Anderson, P. C.; Clive, D. L. J.; Evans, C. F. *Tetrahedron Lett.* **1983**, *24*, 1373.
(7) Clive, D. L. J.; Keshava Murthy, K. S.; Wee, A. G. H.; Siva Prasad, J.; da Silva, G. V. J.; Majewski, M.; Anderson, P. C.; Evans, C. F.; Haugen, R. D.; Heerze, L. D.; Barrie, J. *J. Am. Chem. Soc.* **1990**, *112*, 3018.
(8) McMurry, J. E.; Fleming, M. P.; Kees, K. L.; Krepski, L. R. *J. Org. Chem.* **1978**, *43*, 3255.

0022-3263/91/1956-6447$02.50/0

prepared from $TiCl_3$ and Zn(Cu) couple. The desired products **2** were formed in acceptable yield (ca. 72%), and on that basis, we proceeded with our synthetic plan to the stage of compounds **3a** and **3b**. However, when the same conditions were applied to **3a**, we were unable (but, see below[9]) to isolate any of the desired products **4a**. We also checked spectroscopically for the presence of compounds in which one or more of the protecting groups had been lost but, which, nevertheless, had the hexahydronaphthalene substructure of **4a**. We next tried the reagent made in the usual way[2a,10] from $TiCl_3$ and $LiAlH_4$, but again, as far as we could tell, the desired products **4a** were not formed.



3a R = Me; R' = H; both epimers at C-1

3b R = Et; R' = H; both epimers at C-1

3c R = Et; R' = Me; 1-*S* only

3d R = Et; R' = Et; 1-*S* only

4a-d (R, R' have values corresponding to those in **3a-d**

At this stage, a full examination of the literature revealed that among the many examples of the McMurry reaction very few involved highly oxygenated substrates,[11] and the process had been reported not to work if the starting material contained an ethylene ketal group.[8,12]

When the $LiAlH_4/TiCl_3$ procedure was repeated (using **3b**), but in the presence of an excess of triethylamine,[13] compounds **4b** could be obtained in yields of 30–35%.

These observations suggested that, in reactions involving Zn(Cu) couple or $LiAlH_4$, the presence of Lewis acids was damaging, and so we decided to use potassium graphite (C_8K)[14] as the intermediate reducing agent because it would not introduce additional Lewis acid species and would probably react more complete[4,15] than lumps of metallic potassium. The first experiment, in which **3b** was treated with an excess of the reagent prepared by the action of C_8K (3 mol) on $TiCl_3$ (1 mol), afforded the desired products **4b** in 71% yield, but the next few attempts to reproduce this result gave disappointing yields (0–35%).

Table I[a]

entry	substrate	$TiCl_3$:C_8K	substrate:$TiCl_3$	yield (%)
a	**3b**	1.00:4.07	1.00:10.00	0
b	**3b**	1.00:3.00	1.00:10.00	30
c	**3b**	1.00:2.09	1.00:17.14	85
d	**3c**	1.00:2.53	1.00:9.89	22
e	**3c**	1.00:2.14	1.00:9.97	42
f	**3c**	1.00:2.11	1.00:16.40	86
g	**3d**	1.00:1.97	1.00:17.20	89

[a] All reactions were run in 1,2-dimethoxyethane (DME).

Weighings for these experiments had been carried out in a glovebag, and we suspected that unintentional exposure of the very air-sensitive C_8K or $TiCl_3$ to oxygen or to moisture had altered the stoichiometry from the intended level. Therefore, the effect of changing the proportions of all the ingredients in the conversion of **3b** into **4b** was investigated, and we were fortunate in being able to establish quickly, and to confirm with other examples (see Table I) that good yields are obtained by using C_8K (2 mol) and $TiCl_3$ (1 mol) per 0.058–0.062 mol of dicarbonyl substrate. The low-valent titanium reagent was generated by heating the C_8K and $TiCl_3$ in refluxing DME for an arbitrary period of 2 h, followed by slow addition (over ca. 9 h) of the dicarbonyl compound at room temperature, and then a further period (ca. 5 h) at reflux. When the reaction was followed by thin-layer chromatography it became clear that an intermediate is formed during the addition, but most of the final product is generated in the second reflux period. These conditions were routinely used in the compactin,[7] mevinolin,[7] and 3-ethylcompactin[16] series, i.e., with **3b–d** (see Tables I and II). No epimerization takes place α to the aldehyde group in **3c**[7] or **3d**.[16]

Discussion

From the above experiments it was clear that we had available a general method for annulation, as summarized in Scheme I. The process involves attaching a chain carrying a potential, or actual, carbonyl group α to the carbonyl of a cyclic ketone. Then, after unmasking the pendant carbonyl (if necessary), the two carbonyls are coupled to generate a bicyclic olefin. The titanium reagent has been tested in the demanding case represented by the natural products chemistry (**3** → **4**) discussed above.

We have studied a number of examples (see Table II) in which we used several different ways for attaching the carbonyl side chain. This was done by aldol condensation (**3a–d, 5a, 6a, 7a, 10a, 11a, 16a, 17a**), by alkylation (**12a, 13a, 14a**), or by Michael addition (**8a, 9a, 15a, 18a**), and, in appropriate cases, the second carbonyl was introduced by ozonolysis (**3a–d, 5a, 6a, 7a, 10a, 11a, 13a, 14a**), or by Wacker oxidation[17] (**12a, 16a, 17a, 18a**).

In our initial experiments, the $C_8K/TiCl_3$ system was used for the dicarbonyl coupling, and many of our later experiments were also done with this reagent. Usually, the dicarbonyl compound was added at reflux (instead of at room temperature as with **3a–d**) but we have not made a systematic study of the effect of the temperature during the addition period. We have, however, examined modifications of the reagent that avoid, as far as possible, the need to weigh compounds as highly air-sensitive as C_8K and $TiCl_3$. (Such materials are best handled in a drybox.) To this end we evaluated sodium–naphthalene ($Na/C_{10}H_8$), stock solutions of which are easily dispensed by syringe techniques, and $TiCl_4$, which is a distillable liquid. In

(9) As described later in the text our best yield of **4b** (we did not examine **3a** further) with the Zn–Cu based reagent is less then 40%.

(10) Cf. McMurry, J. E.; Fleming, M. P. *J. Org. Chem.* **1976**, *41*, 896.

(11) Cf. Ziegler, F. E.; Lim, H. *J. Org. Chem.* **1982**, *47*, 5229. Posner, G. H.; Switzer, C. *J. Am. Chem. Soc.* **1986**, *108*, 1239. Mikami, K.; Takahashi, K.; Nakai, T. *J. Am. Chem. Soc.* **1990**, *112*, 4035.

(12) Jung, M. E.; Hatfield, G. L. *Tetrahedron Lett.* **1983**, *24*, 3175.

(13) Cf. McMurry, J. E.; Miller, D. D. *J. Am. Chem. Soc.* **1983**, *105*, 1660. We thank Professor J. E. McMurry for drawing our attention to the beneficial effects of triethylamine.

(14) Boldrini, G. P.; Savoia, D.; Tagliavini, E.; Trombini, C.; Umani-Ronchi, A. *J. Organomet. Chem.* **1985**, *280*, 307.

(15) Cf. Reference 8 and Fürstner, A.; Csuk, R.; Rohrer, C.; Weidmann, H. *J. Chem. Soc., Perkin Trans. 1* **1988**, 1729.

(16) Clive, D. L. J.; Keshava Murthy, K. S.; George, R.; Poznansky, M. J. *J. Chem. Soc., Perkin Trans. 1* **1990**, 2099.

(17) Magnus, P. D.; Nobbs, M. S. *Synth. Commun.* **1980**, *10*, 273.

addition, we examined 40% w/w sodium amalgam (Na/Hg)[18] and 17% w/w sodium–potassium alloy (Na–K).[19] These reducing agents are liquids, and they were both used with $TiCl_4$. Again, a particular ratio of reducing agent and $TiCl_4$ was required for optimum results, except in the case of Na(Hg) (see Table III), and the ratio corresponds closely to the formal production of titanium(I). In each case the reagent had to be used in substantial excess, just as we had found with the original formulation. The results of some of these experiments are shown in Table II. We found that with Na(Hg) the choice of solvent is important (as judged by experiments with **12a**); the reactions were cleaner when run in DME than in THF. We also examined a few intermolecular cases (see Table II, **19a–21a**), but, although we did not at the time make an extensive study, the ratios with both $Na–C_{10}H_8/TiCl_4$ and $C_8K/TiCl_3$ seemed to be important, and we later examined the subject in detail with benzophenone (see below and Tables IV and V).

In reactions involving aldehydes, we have gained the impression that care should be taken to use materials that are free of the corresponding acids, and so the starting materials were always protected from air.

In some cases prolonged reaction times (e.g., for **7b**, **10b**, **11b**, **12b**) or use of a higher boiling solvent (dioxane instead of DME) are advantageous (**10b**, **11b**).

One feature of experiments with $Na–C_{10}H_8/TiCl_4$/THF is the need to separate relatively large amounts of naphthalene from the desired product, and this can be difficult in some cases. Therefore, in the hope of simplifying product isolation, we tried 1-(dimethylamino)-naphthalene,[20] which, of course, is extractable into acid; however, significant cleavage of the sp^2-carbon nitrogen bond occurs under the reaction conditions so that the product mixtures still contain substantial amounts of naphthalene. When the amine was used in catalytic quantities, reduction of $TiCl_4$ was incomplete in THF at room temperature, even after sonication[21] for 24 h.[22] An attempt at sonochemical dispersion[21] of potassium metal in DME, with the intention of then adding $TiCl_4$, was unsuccessful, lumps of potassium[23] still being visible after several hours. The use of toluene, in which such dispersion has been reported,[24] was not examined.[25] However, Na(Hg) was tried successfully (see Tables II and III), and here the problem of separating naphthalene does not arise.

The simple examples used to demonstrate the annulation method (Table II) generally worked well, and so we sought a very sensitive substrate that could be used as a test case instead of **3a–d**. We already knew that our $C_8K/TiCl_3$ reagent was superior to the classical species (with **3b** as the substrate), but we wanted a more accessible example. Compound **12a** was chosen for this purpose as it was reported[12] not to undergo intramolecular coupling with the standard Zn(Cu) couple/$TiCl_3$ reagent.

Our $C_8K/TiCl_3$ reagent worked well with **12a** (75%) and so did the material generated from $Na–C_{10}H_8$ and $TiCl_4$ (70%) (Table III). In both cases the yield was sensitive to the ratio of the components of the reaction mixture but, surprisingly, when we used Na(Hg) as the intermediate reducing agent, there was little dependence (within the range we studied) on the ratio of amalgam to $TiCl_4$ (at a constant $TiCl_4$/substrate ratio of 17:1).

At this point in our investigation it was reported[26] that use of a $TiCl_3$–DME complex[27] (instead of $TiCl_3$) with Zn(Cu) couple yielded an improved formulation of the classical reagent, and we decided to compare our low-valent titanium species with the new one. In the event, our experiments showed that **12a** is not a very demanding material in the present context because the intramolecular coupling works well with all the reagents we tried, *including* the standard Zn(Cu) couple/$TiCl_3$. We could detect (see Table III) no substantive advantage with the DME complex, but we did find that with $C_8K/TiCl_3$ and $Na–C_{10}H_8/TiCl_4$, and only with these, the outcome is very sensitive to the ratio of the components. The product **12b** is not sensitive to C_8K or to Zn(Cu) couple in refluxing DME, but an excess of C_8K, over and above the optimum amount, must be avoided during formation of the reagent.

We also made a brief study of the coupling of benzophenone with the $C_8K/TiCl_3$ system and established, with the $C_8K/TiCl_3$ ratio fixed at 2.1:1, that a large excess of reagent is required (see Table IV).

During the course of our work we felt it would be desirable to do an extensive study in which the titanium/reducing agent and the titanium/substrate ratios are systematically varied over a wide range. Carrying out this survey with an intramolecular coupling would have been extremely labor intensive as some 80 experiments were contemplated, and each would involve slow addition of the dicarbonyl compound over about 10 h. We chose, therefore, to study an intermolecular example (in which case the substrate is added in one portion), and we used benzophenone, since its reaction could be monitored easily by gas chromatography. We arbitrarily prepared the reagent by heating the components for 2 h in refluxing THF. Our results are shown in Table V. We appreciate that benzophenone is not particularly sensitive to the ratios, but nevertheless, the table shows clearly that, for highest yields, the ratios that we had found by chance with **3b** are close to those that give a global maximum for benzophenone. Significant amounts of 1,2-diphenylethane are produced if the $Na–C_{10}H_8/TiCl_4$ ratio is greater than 3.2:1.[28] A comparison of the results in Tables IV and V suggests that the active species (and/or its amount) in the $C_8K/TiCl_3$ and $Na/C_{10}H_8$ systems are different, because the sensitivity of yield to ratios is not the same with both reagents.

In view of the successful coupling of **12a** with the classical Zn(Cu) couple/$TiCl_3$ reagent (see Table III), we took our remaining supply of **3b** from the compactin series and tried the classical Zn(Cu) couple method again. This time the desired product was isolated, but in less than 40% yield. We conclude, therefore, that our reagents do have advantages over the conventional (formally titanium(0) species) and are appropriate to try with highly oxygenated substrates.[29] Our reagents, with the possible exception of that made from Na(Hg), are clearly different in behavior from the other titanium species we have examined, and they ($C_8K/TiCl_3$ and $Na/C_{10}H_8/TiCl_4$) are mild enough for application to compounds of type **3**. The Na(Hg)/$TiCl_4$

(18) Fieser, L. F.; Fieser, M. *Reagents for Organic Synthesis*; Wiley: New York, 1967; Vol. 1, p 1033.
(19) Fieser, L. F.; Fieser, M. *Reagents for Organic Synthesis*; Wiley: New York, 1967; Vol. 1, p 1102.
(20) Cohen, T.; Bhupathy, M. *Acc. Chem. Res.* **1989**, *22*, 152.
(21) Branson Sonic Bath, type B-12, 80 W.
(22) We have not tested a naphthalene-containing polymer. Cf. Harvey, S.; Raston, C. L. *J. Chem. Soc., Chem. Commun.* **1988**, 652.
(23) See refs 4 and 8 for information on rates of metal dissolution in THF containing $TiCl_3$ (no sonication).
(24) Luche, J. L.; Petrier, C.; Dupuy, C. *Tetrahedron Lett.* **1984**, *25*, 753.
(25) See also: Nayak, S. K.; Banerji, A. *J. Org. Chem.* **1991**, *56*, 1940.
(26) McMurry, J. E.; Lectka, T.; Rico, J. G. *J. Org. Chem.* **1989**, *54*, 3748.
(27) It is not clear whether the stoichiometry $TiCl_3(DME)_2$ or $TiCl_3(DME)_{1.5}$ should be used for the reagent made by the reported method. See footnote 13 in ref 26.
(28) In these experiments the $TiCl_4$/benzophenone ratio was 6:1–10:1.
(29) Cf. McMurry, J. E.; Dushin, R. G. *J. Am. Chem. Soc.* **1990**, *112*, 6942.

Table II[a]

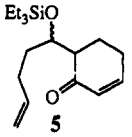
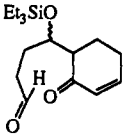
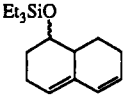
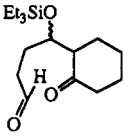
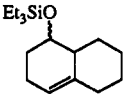
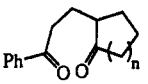
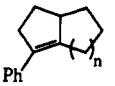
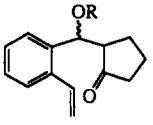
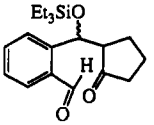
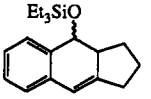
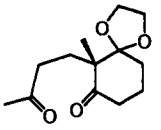
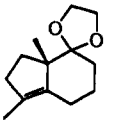
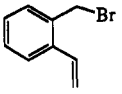
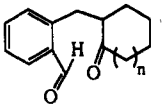
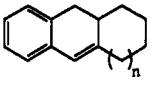
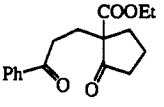
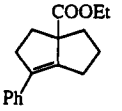
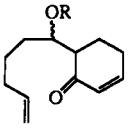
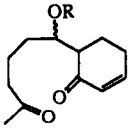
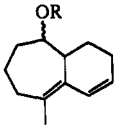
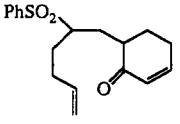
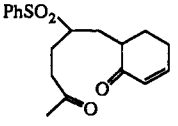
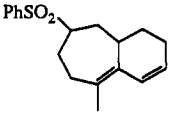
	carbonyl substrate	method[b]	product	yield (%)
	3b	A; rt[c]	**4b**	85
	3a	B; rt	**4a**	71
	3c	A; rt[c]	**4c**	86
	3d	A; rt[d]	**4d**	89
				
5	**5a**[e]	A	**5b**[e]	82
	5a[e]	D	**5b**[e]	65
	6a (*R*,R**)[f]	C	**6b** (*R*,S**)	71–86
				
	7a[e]	A	**7b**[e]	64
				
	8a, *n* = 1	A	**8b**, *n* = 1	86
	9a, *n* = 2	A	**9b**, *n* = 2	87
				
10, R = H	**10a** (*R*,S**)	A	**10b** (*R*,R**)	50
10, R = $SiEt_3$	**10a** (*R*,S**)	A[g]	**10b** (*R*, R**)	64[g]
	11a (*R*,R**)	A	**11b** (*R*,S**)	51
	11a (*R*,R**)	A[g]	**11b** (*R*,S**)	67[g]
				
	12a	A[h]	**12b**	75[h]
	12a	B[h]	**12b**	69[h]
				
13	**13a**, *n* = 1	A	**13b**, *n* = 1	81
	14a, *n* = 2	A	**14b**, *n* = 2	86
				
	15a	A	**15b**	61
	15a	B	**15b**	69
	15a	C	**15b**	66–73
				
16, R = $SiEt_3$	**16a**, R = $SiEt_3$	A	**16b**, R = $SiEt_3$	74[i]
17, R = Ac	**17a**, R = Ac	B	**17b**, R = Ac	58[j]
				
18	**18a**	B	**18b**[j]	39
	benzophenone	C	tetraphenylethylene	
	19a		**19b**	84[k]
	cyclohexanone	C	cyclohexylidenecyclohexane	
	20a		**20b**	56
	20a	A	**20b**	58

Table II[a] (Continued)

carbonyl substrate	method[b]	product	yield (%)
cyclododecanone **21a**	A	cyclododecylidenecyclododecane **21b**	85

[a] Yields refer to isolated compounds. [b] A = $C_8K/TiCl_3$/DME; B = Na-$C_{10}H_8/TiCl_4$/THF; C = Na(Hg)/$TiCl_4$/DME; D = Na-K/$TiCl_4$/THF. [c] See ref 7. [d] See ref 16. [e] Mixture of both isomers. [f] The relative configuration at the two stereogenic centers is specified. Note that (*R**,*R**)-(±)-**6a** gives the (*R**,*S**)-(±)-product (without any epimerization). There is a corresponding change in notation when **10a** and **11a** are converted into their respective products. The stereochemical assignments to **6b**, **10b**, and **11b** (and hence to their precursors) follow from a consideration of the coupling constants for the C*H*OSi signals. [g] Dioxane was used as the solvent, and the dicarbonyl compound was added at reflux. [h] See also Table III. [i] Combined yield of the separated [(*R**,*R**)-(±) and (*R**,*S**)-(±)] isomers. [j] A single isomer of undetermined stereochemistry. [k] See also Tables IV and V.

Table III.[a] **Intramolecular Coupling of 12a to 12b**

	system	$TiCl_n$:reductant	substrate:$TiCl_n$	yield (%)
a	Na/N*/$TiCl_4$/THF/**12a**	1.00:4.20	1.00:17.00	21
b	Na/N*/$TiCl_4$/THF/**12a**	1.00:3.50	1.00:17.00	41
c	Na/N*/$TiCl_4$/THF/**12a**	1.00:2.98	1.00:17.40	61
d	Na/N*/$TiCl_4$/THF/**12a**	1.00:2.78	1.00:15.90	67
e	Na/N*/$TiCl_4$/THF/**12a**	1.00:2.66	1.00:17.40	70
f	Na/N*/$TiCl_4$/THF/**12a**	1.00:2.00	1.00:17.00	23
g	$C_8K/TiCl_3$/DME/**12a**	1.00:2.07	1.00:16.85	75
h	$C_8K/TiCl_3$/DME/**12a**	1.00:3.50	1.00:10.05	28
i	Zu(Cu)/$TiCl_3(DME)_2$/DME/**12a**	1.00:2.00	1.00:17.06	62
j	Zu(Cu)/$TiCl_3(DME)_2$/DME/**12a**	1.00:1.02	1.00:17.00	69
k	Zu(Cu)/$TiCl_3$/DME/**12a**	1.00:2.30	1.00:22.25	67
l	Zu(Cu)/$TiCl_3$/DME/**12a**	1.00:1.00	1.00:16.85	72
m	Zu(Cu)/$TiCl_3(DME)_2$/DME/**12a**	1.00:2.28	1.00:22.45	70
n	Zu(Cu)/$TiCl_3(DME)_2$/DME/**12a**	1.00:3.14	1.00:7.80	70
o	Na(Hg)/$TiCl_3$/DME/**12a**	1.00:2.00	1.00:17.00	67
p	Na(Hg)/$TiCl_3$/DME/**12a**	1.00:2.70	1.00:17.00	69
q	Na(Hg)/$TiCl_3$/DME/**12a**	1.00:3.00	1.00:17.00	63
r	Na(Hg)/$TiCl_3$/DME/**12a**	1.00:3.50	1.00:17.00	56
s	Na(Hg)/$TiCl_3$/DME/**12a**	1.00:4.20	1.00:17.00	63

[a] N* = naphthalene.

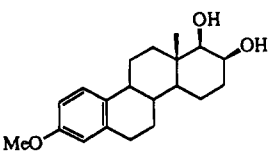
Table IV. Coupling of Benzophenone with $C_8K/TiCl_3$/DME[a]

entry	C_8K:$TiCl_3$	$TiCl_3$: $Ph_2C{=}O$	yield of $Ph_2C{=}CPh_2$ (%)	recovery of $Ph_2C{=}O$ (%)
a	2.23:1.00	1.94:1.00	33	58
b	2.04:1.00	4.11:1.00	79	13
c	2.10:1.00	8.00:1.00	91	0
d	2.99:1.00	8.21:1.00	89	0
e	4.46:1.00	6.00:1.00	>10	*b*

[a] In a typical experiment, benzophenone (54.7 mg, 0.30 mmol) in DME (6 mL) was added in one portion to a refluxing mixture of the titanium reagent (from $TiCl_3$ (370.0 mg, 2.40 mmol) and C_8K (681.7 mg, 5.04 mmol)) in DME (10 mL). Refluxing was continued for 12 h. Yields refer to isolated compounds. [b] Not measured.

reagent has not been tested with **3**, but its performance is adequate with **12a**.

Finally, we were curious to establish whether vicinal diols can be converted into olefins with the present reagents,[30] but we have examined this point only in a cursory manner. The *cis*-1,2-diol **22** gave the corresponding olefin when treated with the $C_8K/TiCl_3$ reagent. The yield was excellent (92%), but the reaction was slow in boiling THF (67 °C), and was best done in diglyme at 85 °C.



22

(30) Cf. ref 8. We have not tried to adjust the temperature or time in any of our coupling reactions, so as to stop the process at the diol stage (Cf. McMurry, J. E.; Rico, J. G. *Tetrahedron Lett.* **1989**, *30*, 1169).

Experimental Section

The same general procedures were followed as described previously,[31] all reactions involving titanium being done under argon.[32] Petroleum ether refers to material with bp 35–60 °C. All aldehydes were checked for the absence of carboxylic acids and were carefully protected from air during use.

6-[1-[(Triethylsilyl)oxy]-4-pentenyl]-2-cyclohexen-1-one (5). (a) 6-(1-Hydroxy-4-pentenyl)-2-cyclohexen-1-one. *n*-BuLi (1.6 M in hexanes, 34.40 mL, 55.0 mmol) was added dropwise to a stirred and cooled (0 °C) solution of *i*-Pr_2NH (8.50 mL, 60.6 mmol) in dry ether (100 mL). Stirring at 0 °C was continued for 10 min, and the mixture was then cooled to −78 °C. 2-Cyclohexen-1-one (4.82 mL, 49.8 mmol) was added over ca. 20 min. The resulting yellow solution was stirred at −78 °C for 60 min, and 4-pentenal[33] (5.90 mL, 59.7 mmol) was then added in one portion, followed, after 10 min, by glacial acetic acid (8.6 mL, 150.2 mmol). The mixture was left to warm to room temperature and was then diluted with water (100 mL). The layers were separated, and the aqueous phase was extracted with ether (3 × 100 mL). The combined organic extracts were dried ($MgSO_4$) and evaporated. Flash chromatography of the residue over silica gel (4 × 15 cm) with 3:7 EtOAc/hexane gave the desired aldols (7.3749 g, 82%) as an apparently homogeneous (TLC, silica, 3:7 EtOAc/hexane) oil: IR ($CHCl_3$ cast) 3450, 1669, cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) (two diastereoisomers in a ratio of ca. 1:4) δ 1.35–1.85 (m, 3 H), 1.85–2.60 (m, 6 H), 2.68 (d, *J* = 6.0 Hz, 0.2 H; exchanges with D_2O), 3.85–3.96 (m, 0.80 H), 4.08 (dd, *J* = 3.0, 1.0 Hz, 0.8 H; exchanges with D_2O), 4.14–4.24 (m, 0.2 H), 4.90–5.10 (m, 2 H), 5.75–5.95 (m, 1 H), 5.95–6.10 (m, 1 H), 6.95–7.10 (m, 1 H) (in the presence of D_2O the signal at δ 3.85–3.96 simplified to a doublet of triplets (*J* = 8.5, 3.0 Hz) and the signal at δ 4.14–4.24 also simplified to a doublet of triplets (*J* = 9.5, 4.5 Hz)); ^{13}C NMR ($CDCl_3$, 75.469 MHz) (major isomer) δ 24.980, 25.764, 29.210, 32.871, 51.565,

(31) Clive, D. L. J.; Boivin, T. L. B.; Angoh, A. G. *J. Org. Chem.* **1987**, *52*, 4943.

(32) Cf. Yamamoto, A.; Ookawa, M.; Ikeda, S. *J. Chem. Soc., Chem. Commun.* **1969**, 841.

(33) Made by PCC oxidation of the parent commercial alcohol.

Table V.[a] Conditions for Benzophenone Coupling

	Na-naph/$TiCl_4$												
$TiCl_4/Ph_2C{=}O$	2.00	2.20	2.40	2.60	2.70	2.80	3.00	3.10	3.20	3.40	3.60	3.80	4.00
2.00	33.3	45.6	38.2	38.7	46.8	53.3	56.9	71.9	65.4	48.9	52.0	53.9	42.5
4.00	54.7	57.4	80.6	70.4	83.3	69.4	81.9	83.1	71.9	79.5	55.1	47.6	40.8
6.00	82.1	80.3	82.9	85.1	86.1	100	100	98.8	69.2[b]	65.1	53.7	43.7	38.9
8.00	84.9	87.3	91.8	94.0	100[c]	100	100[d]	100	59.3	66.8	52.2	52.5	45.8[e]
9.0	82.2	90.0	92.4	95.4	100	100	100	94.2	58.6	70.6	55.9	50.5	46.5
10.0	76.6	94.3	96.7	98.4	100	100	100	91.0	62.4	69.4	58.2	48.5	47.5

[a] Yields determined by GC. [b] In a preparative experiment with Na-naph/$TiCl_4$ (3.19:1); $TiCl_4/Ph_2C{=}O$ (5.0:1); yield = 72%. [c] In a preparative experiment with Na-naph/$TiCl_4$ (2.66:1); $TiCl_4/Ph_2C{=}O$ (8.1:1); yield = 87%. [d] In a preparative experiment with Na-naph/$TiCl_4$ (3.00:1); $TiCl_4/Ph_2C{=}O$ (8.1:1); yield = 82%. [e] In a preparative experiment with Na-naph/$TiCl_4$ (4.13:1); $TiCl_4/Ph_2C{=}O$ (8.1:1); yield <60%.

71.094, 114.628, 129.782, 138.494, 150.909, 203.432; (minor isomer) δ 17.992, 22.474, 30.399, 32.203, 55.204, 69.209, 114.787, 130.077, 138.262, 150.684, 201.759; exact mass m/z calcd for $C_{11}H_{16}O_2$ 180.1150, found 180.1148. Anal. Calcd for $C_{11}H_{16}O_2$: C, 73.30; H, 8.95. Found: C, 73.36; H, 9.10.

(b) 6-[1-[(Triethylsilyl)oxy]-4-pentenyl]-2-cyclohexen-1-one (5). A general procedure[34] for triethylsilylation was used: Et_3SiCl (1.43 mL, 8.48 mmol) was added to a solution of the above aldols (764.3 mg, 4.24 mmol) in dry pyridine (10.0 mL). The solution was heated at 60 °C for 4 h, cooled to room temperature, diluted with ether (60 mL), and extracted with 10% w/v $CuSO_4 \cdot 5H_2O$ (4 × 20 mL). The combined aqueous extracts were back-extracted with ether (30 mL), and the combined ether extracts were washed with water (2 × 50 mL), dried ($MgSO_4$), and evaporated. Flash chromatography of the residue over silica gel (3 × 15 cm) with 1:9 EtOAc/hexane gave **5** (1.1078 g, 88.7%) as an apparently homogeneous (TLC, silica, 1:9 EtOAc/hexane) oil: IR ($CHCl_3$ cast) 2959, 2876, 1677, 1089 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) (two isomers in a ratio of 1:4) δ 0.50–0.70 (m, 6 H), 0.85–1.05 (m, 9 H), 1.45–2.55 (m, 9 H), 4.38–4.48 (dt, J = 8.0, 4.0 Hz, 0.8 H), 4.48–4.54 (dt, J = 6.8, 2.5 Hz, 0.2 H), 4.90–5.10 (m, 2 H), 5.75–6.05 (m, 2 H), 6.90–7.00 (m, 2 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) (major isomer) δ 4.89, 6.69, 21.85, 25.86, 30.53, 32.09, 53.38, 70.14, 114.09, 130.10, 138.42, 149.62, 199.21; (minor isomer) δ 20.95, 25.19, 29.92, 34.58, 50.61, 69.12, 114.39, 130.25, 137.99, 199.30; exact mass m/z calcd for $C_{17}H_{30}O_2Si$ 294.2015, found 294.2011. Anal. Calcd for $C_{17}H_{30}O_2Si$: C, 69.33; H, 10.27. Found: C, 69.37; H, 10.33.

2-Oxo-γ-[(triethylsilyl)oxy]-3-cyclohexene-1-butanal (5a). Ozone was bubbled through a stirred and cooled (−78 °C) solution of triethylsilyl ethers **5** (3.04 g, 10.32 mmol) in dry CH_2Cl_2 (50 mL), until just a trace of starting material remained (TLC, silica, 1:3 EtOAc/hexane). Ph_3P (5.41 g, 20.64 mmol) was added, and the solution was left at −78 °C for 10 min. The cold bath was removed, and the mixture was stirred overnight and then evaporated. Flash chromatography of the residue over silica gel (4 × 15 cm), first with 1:19 EtOAc/hexane (to separate triphenylphosphine) and then with 1:3 EtOAc/hexane, gave **5a** (2.41 g, 78.9%) as an oil. (The two components were chromatographically resolvable (TLC, silica, 1:3 EtOAc/hexane)): IR ($CHCl_3$ cast) 1725, 1675 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) (two diastereoisomers in a ratio of 1:4) δ 0.50–0.70 (m, 6 H), 0.85–1.05 (m, 9 H), 1.60–2.65 (m, 9 H), 4.38–4.45 (dt, J = 8.3, 4.0 Hz, 0.8 H), 4.45–4.55 (dt, J = 6.3, 3.0 Hz, 0.2 H), 5.92–6.08 (m, 1 H), 6.90–7.02 (m, 1 H), 9.76 (t, J = 1.65 Hz, 0.8 H), 9.80 (t, J = 1.5 Hz, 0.2 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) (major isomer) δ 4.977, 6.880, 1.928, 25.343, 26.066, 41.359, 53.304, 69.854, 130.163, 150.281, 199.543, 202.555; (minor isomer) δ 5.067, 6.939, 21.604, 25.286, 27.889, 40.395, 51.255, 68.600, 130.236, 150.210, 199.381, 201.851; exact mass m/z calcd for $C_{16}H_{28}O_3Si$ 296.1808, found 296.1808.

(R*,R*)-(±)-2-Oxo-γ-[(triethylsilyl)oxy]-3-cyclohexene-1-butanal (6a). The above procedure was followed using triethylsilyl ethers **5** (5.8364 g, 19.82 mmol), CH_2Cl_2 (100 mL), and Ph_3P (10.39 g, 39.63 mmol). Flash chromatography of the total reaction product over silica gel (7.5 × 20 cm) with 1:19 EtOAc/hexane (1500 mL), 1:9 EtOAc/hexane (1000 mL), and then with 3:17 EtOAc/hexane gave **6a** (2.7994 g, 60%) as a homogeneous (TLC, silica, 1:3 EtOAc/hexane) oil, and a mixture of **6a** and the corresponding (R*,S*)-(±)-isomer (which was the major (89%) component of the mixture) (1.8717 g, 22%) as an oil. Compound **6a** had: IR ($CHCl_3$ cast) 1725, 1675 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 0.61 (q, J = 8.0 Hz, 6 H), 0.95 (t, J = 8.0 Hz, 9 H), 1.62–1.94 (m, 3 H), 2.18–2.65 (m, 6 H), 4.44 (dt, J = 8.5, 4.0 Hz, 1 H), 5.98 (ddd, J = 10.0, 3.0, 1.0 Hz, 1 H), 6.95–7.04 (m, 1 H), 9.78 (t, J = 1.6 Hz, 1 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) δ 4.99, 6.91, 21.94, 25.30, 26.09, 41.39, 53.32, 69.87, 130.18, 150.30, 199.57, 202.60; exact mass m/z calcd for $C_{16}H_{28}O_3Si$ 296.1808, found 296.1808.

General Procedures for Titanium-Mediated Dicarbonyl Coupling. Procedure A. Freshly prepared potassium graphite (C_8K)[14] and $TiCl_3$ were weighed under argon in a drybox and transferred successively to a 100-mL round bottomed flask containing dry DME. The mixture was refluxed for 2 h under argon, and the carbonyl compound in dry DME was added by syringe pump over 10 h to the stirred and refluxing slurry of titanium reagent. Stirring was continued for an additional 3 h. The mixture was cooled to room temperature and filtered under argon through a pad of Florisil (3.5 × 5 cm) contained in a sintered funnel that was equipped with an argon inlet near the top. The pad was washed with ether (3 × 50 mL). The combined filtrates were evaporated and the crude product was isolated as described in the individual examples.

Procedure B. Na was added to a stirred solution of naphthalene (1 mol per mol Na) in THF (argon atmosphere). Stirring was continued for 2 h, and then $TiCl_4$ (freshly distilled from copper powder) was added over about 10 min while the flask was cooled with a cold-water bath, a small portion of THF being used to rinse all the halide into the reaction vessel. The resulting black mixture was refluxed for 30 min and cooled to room temperature. A solution of the carbonyl compound in THF was injected over 10 h at room temperature. The mixture was then refluxed for 4 h, cooled to room temperature and filtered, under argon, through a pad of Florisil, using ether as the wash solvent. The filtrate was evaporated and the product was isolated as described for the individual examples. In some cases, the carbonyl compound was added at the reflux temperature of THF.

Procedure C. $TiCl_4$ was added dropwise to a stirred suspension of liquid sodium amalgam (39.5% w/w) in DME (or THF) while the flask was cooled with a cold-water bath, a small portion of solvent being used to rinse all the halide into the reaction vessel. The resulting mixture was refluxed with stirring for 5 h and then cooled to room temperature. A solution of the carbonyl compound in DME (or THF) was injected over 10 h at room temperature. The mixture was then refluxed for 4 h, cooled to room temperature and filtered, under argon, through a pad of Florisil, using ether as the wash solvent. The filtrate was evaporated and the product was isolated as described for the individual examples.

Procedure D. $TiCl_4$ was added dropwise to a stirred suspension of liquid sodium–potassium alloy (17% w/w Na) in DME while the flask was cooled with a cold-water bath, a small portion of DME being used to rinse all the halide into the reaction vessel. The resulting mixture was refluxed with stirring for 4 h, and then a solution of the carbonyl compound in DME was injected over 10 h. The mixture was then refluxed for a further 4 h, cooled to room temperature and filtered, under argon, through a pad of Florisil, using ether as the wash solvent. The filtrate was evaporated, and the product was isolated as described for the individual examples.

(34) Hart, T. W.; Metcalfe, D. A.; Scheinmann, F. *J. Chem. Soc., Chem. Commun.* **1979**, 156.

Triethyl[(1,2,3,7,8,8a-hexahydro-1-naphthalenyl)oxy]silane (5b). Procedure A was followed, using $TiCl_3$ (265.3 mg, 1.72 mmol), C_8K (488.3 mg, 3.61 mmol) in DME (25 mL), and **5a** (30.0 mg, 0.101 mmol) in DME (5 mL). Flash chromatography of the crude product over silica gel (1 × 10 cm) with petroleum ether gave **5b** (22.0 mg, 82%) as an apparently homogeneous (TLC, silica, 1:9 ether/petroleum ether) oil: IR ($CHCl_3$ cast) 3020, 2952, 1098 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) (two diastereoisomers in a ratio of 1:4) δ 0.50–0.70 (m, 6 H), 0.90–1.05 (m, 9 H), 1.58–2.48 (m, 9 H), 3.40 (m, 0.2 H), 4.05 (br s, 0.7 H), 5.38 (br s, 0.2 H), 5.50 (br s, 0.8 H), 5.60–5.75 (m, 1 H), 6.04 (d, J = 10.0 Hz, 1 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) (major isomer) δ 5.207, 7.061, 21.194, 25.792, 26.058, 30.218, 40.468, 68.698, 122.890, 126.926, 130.187, 134.018; (minor isomer) δ 5.128, 6.985, 25.287, 26.470, 32.398, 43.645, 73.763, 122.548, 127.818, 128.984, 135.518; exact mass m/z calcd for $C_{16}H_{28}OSi$ 264.1909, found 264.1910. Anal. Calcd for $C_{16}H_{28}OSi$: C, 72.66; H, 10.67. Found: C, 72.94; H, 10.67.

(*R,*S**)-(±)-Triethyl[(1,2,3,7,8,8a-hexahydro-1-naphthalenyl)oxy]silane (6b). (a).** Procedure C was followed, using Na(Hg) (40%, 890.7 mg, 15.50 mmol), $TiCl_4$ (0.62 mL, 5.64 mmol) in DME (25 mL), and **6a** (98.4 mg, 0.33 mmol) in DME (10 mL). Refluxing was continued for a further 5 h after the addition. Flash chromatography of the crude product over silica gel (1 × 15 cm), first with hexane and then with 1:19 EtOAc/hexane, gave **6b** (75.2 mg, 86%) as a homogeneous (TLC, silica, 1:19 EtOAc/hexane) oil: IR ($CHCl_3$ cast) 3010, 2952, 1099 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 0.61 (q, J = 8.5 Hz, 6 H), 0.95 (t, J = 8.5 Hz, 9 H), 1.55–1.85 (m, 4 H), 1.95–2.45 (m, 5 H), 4.02 (br s, 1 H), 5.48 (br s, 1 H), 5.60–5.70 (m, 1 H), 6.04 (d, J = 9.5 Hz, 1 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) δ 5.115, 7.052, 21.173, 25.768, 26.039, 30.201, 40.447, 68.679, 122.891, 126.939, 130.173, 134.012; exact mass m/z calcd for $C_{16}H_{28}OSi$ 264.1909, found 264.1906. Anal. Calcd for $C_{16}H_{28}OSi$: C, 72.66; H, 10.67. Found: C, 72.64; H, 10.63. This experiment was repeated several times (on different scales); the yield varied between 71 and 86%.

(b). Procedure D was followed, using sodium–potassium alloy (17% w/w Na, 990.6 mg, 28.36 mmol), $TiCl_4$ (1.13 mL, 10.31 mmol) in DME (40 mL), and **6a** (179.8 mg, 0.61 mmol) in DME (10 mL). Flash chromatography of the crude product over silica gel (1.5 × 15 cm) with hexane gave **6b** (104.4 mg, 65%) as a homogeneous (TLC, silica, 1:19 EtOAc/hexane) oil.

2-Oxo-γ-[(triethylsilyl)oxy]cyclohexane-1-butanal (7a). Compounds **5a**[35] (157.0 mg, 0.53 mmol) in EtOAc (30 mL), together with 5% Pd–C (52.3 mg), were stirred at room temperature under hydrogen for 2.5 h. The mixture was filtered through a pad of Florisil, and the solvent was then evaporated. Flash chromatography of the residue over silica gel (1.5 × 15 cm) with 1:4 EtOAc/hexane gave **7a** (130.6 mg, 83%) as an oil. (The two components were resolvable by TLC (silica, 4:6 ether/petroleum ether)): IR ($CHCl_3$ cast) 1724, 1711 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 0.52–0.68 (m, 6 H), 0.95 (t, J = 8 Hz, 9 H), 1.50–2.55 (m, 13 H), 4.20–4.30 (two overlapping q, 1 H), 9.74–9.80 (m, 1 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) (major isomer) δ 5.07, 6.90, 24.52, 27.41, 27.86, 28.36, 39.55, 42.38, 55.04, 68.57, 202.05, 211.59; (minor isomer) δ 4.96, 6.82, 24.86, 25.69, 26.85, 27.25, 40.93, 42.18, 56.66, 69.67, 202.53, 211.26; exact mass m/z calcd for $C_{14}H_{25}O_3Si$ $(M - C_2H_5)^+$ 269.1573, found 269.1567. Anal. Calcd for $C_{16}H_{30}O_3Si$: C, 64.38; H, 10.13. Found: C, 64.09; H, 10.15.

Triethyl[(1,2,3,5,6,7,8,8a-octahydro-1-naphthalenyl)oxy]silane (7b). A slight modification of procedure A was followed, using $TiCl_3$ (269.0 mg, 1.74 mmol) and C_8K (480.0 mg, 3.55 mmol) in DME (25 mL) and **7a** (20.0 mg, 0.067 mmol) in DME (5 mL). Refluxing was continued for a further 30 h after the addition. Flash chromatography of the crude product over silica gel (1 × 10 cm) with petroleum ether gave **7b**, which was almost exclusively (^1H NMR (300 MHz)) one isomer, (10.4 mg, 64%): ^1H NMR ($CDCl_3$, 300 MHz) δ 0.55 (q, J = 11.0 Hz, 6 H), 0.96 (t, J = 11.0 Hz, 9 H), 1.10–2.20 (m, 13 H), 3.85–3.95 (m, 1 H), 5.30 (br s, 1 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) δ 5.02, 7.02, 23.52, 26.69, 28.23, 28.74, 28.99, 38.07, 44.53, 70.04, 117.47, 140.82; exact mass m/z calcd for $C_{16}H_{30}OSi$ 266.2065, found 266.2062. In another experiment, using a different batch of **7a**, the product was a mixture of isomers (ca. 1:2) and the minor component had: ^{13}C NMR ($CDCl_3$, 75.469 MHz) δ 5.21, 6.98, 23.88, 26.18, 27.62, 28.74, 31.41, 35.17, 46.41, 75.05, 118.53, 139.30.

2-(3-Oxo-3-phenylpropyl)cyclopentanone (8a). This compound was prepared (79%) from phenyl vinyl ketone and the pyrrolidine enamine of cyclopentanone (see supplementary material).[36]

2,3,3a,4,5,6-Hexahydro-1-phenylpentalene (8b). Procedure A was followed, using C_8K (1.7390 g, 12.86 mmol) and $TiCl_3$ (0.9427 g, 6.11 mmol) in DME (20 mL) and **8a** (79.5 mg, 0.368 mmol) in DME (10 mL). Flash chromatography of the crude product over silica gel (1.5 × 15 cm) with pentane gave **8b** (58.8 mg, 86%) as a colorless oil: IR ($CHCl_3$ cast) 3080–3010, 2948, 2857, 1494, 759, 691 cm^{-1}; ^1H NMR (CD_2Cl_2, 300 MHz) δ 1.00–1.15 (m, 1 H), 1.40–1.55 (m, 1 H), 1.90–2.20 (m, 4 H), 2.40–2.55 (m, 2 H), 2.90–3.15 (m, 3 H), 7.15–7.50 (m, 5 H); ^{13}C NMR (CD_2Cl_2, 75.469 MHz) δ 26.26, 30.18, 30.78, 32.47, 39.60, 55.72, 126.14, 126.83, 128.52, 128.67, 137.80, 151.28; exact mass m/z calcd for $C_{14}H_{16}$ 184.1247, found 184.1247. Anal. Calcd for $C_{14}H_{16}$: C, 91.25; H, 8.75. Found: C, 91.01; H, 8.97.

2-(3-Oxo-3-phenylpropyl)cyclohexanone (9a). This compound was prepared (86%) from phenyl vinyl ketone and the pyrrolidine enamine of cyclohexanone (see supplementary material).[36]

2,4,5,6,7,7a-Hexahydro-3-phenyl-1*H*-indene (9b). Procedure A was followed, using C_8K (2.0544 g, 15.19 mmol) and $TiCl_3$ (1.1193 g, 7.26 mmol) in DME (20 mL) and **9a** (101.6 mg, 0.434 mmol) in dry DME (15 mL). Flash chromatography of the crude product over silica gel (1.5 × 15 cm) with 1:19 EtOAc/hexane, followed by Kugelrohr distillation (160 °C (15 mmHg)), gave **9b** (81.7 mg, 87%) as a homogeneous (TLC, silica, 1:19 EtOAc/hexane) oil: IR ($CHCl_3$ cast) 3080–3020, 2924, 2848, 1598 cm^{-1}; ^1H NMR (CD_2Cl_2, 300 MHz) δ 1.05–1.30 (m, 2 H), 1.30–1.50 (m, 2 H), 1.70–1.85 (m, 2 H), 1.85–2.20 (m, 3 H), 2.55–2.85 (m, 4 H), 7.15–7.40 (m, 5 H); ^{13}C NMR (CD_2Cl_2, 75.469 MHz) δ 26.42, 27.37, 27.68, 29.78, 36.13, 36.32, 48.58, 126.47, 128.25, 128.39, 132.39, 145.45; exact mass m/z calcd for $C_{15}H_{18}$ 198.1409, found 198.1411. Anal. Calcd for $C_{15}H_{18}$: C, 90.85; H, 9.15. Found: C, 90.82; H, 9.34.

(*R,*S**)-(±)- and (*R**,*R**)-(±)-2-[(2-Ethenylphenyl)[(triethylsilyl)oxy]methyl]cyclopentanone (10) (R = $SiEt_3$). (a) 2-[(2-Ethenylphenyl)hydroxymethyl]cyclopentanone.** *n*-BuLi (1.6 M in hexanes, 6.25 mL, 10.0 mmol) was added dropwise to a stirred and cooled (0 °C) solution of *i*-Pr_2NH (1.40 mL, 10.0 mmol) in dry THF (50 mL). The mixture was stirred at 0 °C for 10 min and was then cooled to −78 °C. A solution of cyclopentanone (0.88 mL, 10 mmol) in THF (5.0 mL) was added over ca. 5 min, and the resulting yellow solution was stirred at −78 °C for a further 45 min. Then a solution of 2-ethenylbenzaldehyde[37] (1.94 g, 14.7 mmol) in THF (5 mL) was added in one portion, followed, after 10 min, by saturated aqueous NH_4Cl (20 mL). The mixture was left to warm to room temperature, the layers were separated, and the aqueous phase was extracted with ether (3 × 30 mL). The combined organic extracts were washed with brine (30 mL), dried ($MgSO_4$), and evaporated. Flash chromatography of the residue over silica gel (4 × 15 cm), first with 15:85 ether/petroleum ether (to separate unreacted aldehyde) and then with ether, gave crude alcohols **10** (R = H). This material was used directly in the next step.

(b) (*R,*S**)-(±)- and (*R**,*R**)-(±)-2-[(2-Ethenylphenyl)[(triethylsilyl)oxy]methyl]cyclopentanone (10) (R = $SiEt_3$).** Et_3SiCl (3.35 mL, 20.0 mmol) was added to a stirred and cooled (0 °C) solution of the above crude alcohols, *i*-Pr_2NH (2.8 mL, 20.0 mmol), and DMAP (250 mg, 2.0 mmol) in ether (50 mL). The cooling bath was then removed, and stirring at room temperature was continued for 36 h. The mixture was then filtered, and the filtrate was washed with water (2 × 20 mL) and brine (20 mL), dried ($MgSO_4$), and evaporated. Flash chromatography of the residue over silica gel (5 × 24 cm) with 5:95 ether/petroleum ether gave (*R**,*S**)-(±)-**10** (R = $SiEt_3$) (1.490 g, 46%) as a homogeneous (TLC, silica, 5:95 ether/petroleum ether) oil and (*R**,*R**)-(±)-**10** (R = $SiEt_3$) (996.0 mg, 30%) as a homogeneous (TLC, silica, 5:95 ether/petroleum ether) oil. (*R**,*S**)-(±)-**10** (R = $SiEt_3$) had: IR ($CHCl_3$ cast) 2955, 2876, 1749 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz)

(35) This material was a different batch from that described above for the preparation of **5a**.

(36) Cf. Gill, N. S.; James, K. B.; Lions, F.; Potts, K. T. *J. Am. Chem. Soc.* **1952**, *74*, 4923.

(37) Dale, W. J.; Starr, L.; Strobel, C. W. *J. Org. Chem.* **1961**, *26*, 2225.

δ 0.50 (q, J = 8.0 Hz, 6 H), 0.85 (t, J = 8.0 Hz, 9 H), 1.54–1.70 (m, 2 H), 1.98–2.36 (m, 5 H), 5.35 (dd, J = 11.0, 1.5 Hz, 1 H), 5.62 (dd, J = 17.2, 1.5 Hz, 1 H), 5.68 (s, 1 H), 7.00 (dd, J = 17.2, 11.0 Hz, 1 H), 7.18 (m, 2 H), 7.42 (dd, J = 7.8, 1.5 Hz, 1 H), 7.54 (dd, J = 7.8, 1.5 Hz, 1 H); ^{13}C NMR ($CDCl_3$, 100.614 MHz) δ 4.65, 6.76, 20.62, 21.99, 39.51, 55.36, 66.52, 116.69, 125.68, 126.08, 126.99, 127.44, 133.42, 133.99, 140.98, 219.38; exact mass m/z calcd for $C_{18}H_{25}O_2Si$ (M – C_2H_5)$^+$ 301.1623, found 301.1623. (R*,R*)-(±)-10 (R = $SiEt_3$) had: IR ($CHCl_3$ cast) 2955, 2876, 1742 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 0.45–0.60 (m, 6 H), 0.86 (t, J = 8.0 Hz, 9 H), 1.55–1.75 (m, 2 H), 1.80–2.25 (m, 6 H), 2.50–2.60 (m, 1 H), 5.24 (d, J = 4.5 Hz, 1 H), 5.28 (dd, J = 10.5, 1.5 Hz, 1 H), 5.58 (dd, J = 17.0, 1.5 Hz, 1 H), 7.08 (dd, J = 17.0, 10.5 Hz, 1 H), 7.20–7.30 (m, 2 H), 7.40–7.50 (m, 2 H); ^{13}C NMR ($CDCl_3$, 100.614 MHz) δ 4.74, 6.71, 20.51, 26.66, 38.64, 56.24, 71.30, 116.09, 125.63, 127.32, 127.36, 127.61, 134.76, 135.29, 139.97, 217.72; exact mass m/z calcd for $C_{18}H_{25}O_2Si$ (M – C_2H_5)$^+$ 301.1623, found 301.1623.

(R*,S*)-(±)-2-[(2-Oxocyclopentyl)[(triethylsilyl)oxy]methyl]benzaldehyde (10a). Ozone was bubbled into a stirred and cooled (–78 °C) solution of triethylsilyl ether (R*,S*)-(±)-10 (R = $SiEt_3$) (140.0 mg, 0.424 mmol) in CH_2Cl_2 (30 mL) until a blue color was visible. Ph_3P (330.0 mg, 1.26 mmol) was then added and the solution was left at –78 °C for 10 min. The cooling bath was removed and the mixture was stirred overnight and evaporated. Flash chromatography of the residue over silica gel (1 × 15 cm), first with petroleum ether (to separate Ph_3P) and then with 2:3 ether/petroleum ether, gave **10a** (129.4 mg, 91%) as a homogeneous (TLC, silica, 2:3 ether/petroleum ether) oil: IR ($CHCl_3$ cast) 2956, 2876, 1749, 1696 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.50 (q, J = 8.0 Hz, 6 H), 0.85 (t, J = 8.0 Hz, 9 H), 1.55–1.75 (m, 2 H), 1.95–2.45 (m, 5 H), 6.22 (d, J = 2.5 Hz, 1 H), 7.40–7.50 (m, 1 H), 7.56–7.65 (m, 1 H), 7.80 (d, J = 9.0 Hz, 2 H), 10.22 (s, 1 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) δ 4.66, 6.73, 20.67, 22.68, 39.24, 55.91, 68.29, 127.32, 133.41, 133.53, 146.89, 192.78, 217.75; exact mass m/z calcd for $C_{17}H_{23}O_3Si$ (M – C_2H_5)$^+$ 303.1417, found 303.1417.

(R*,R*)-(±)-Triethyl[(2,3,3a,4-tetrahydro-1H-benz[f]inden-4-yl)oxy]silane (10b). A slight modification of procedure A was followed, using $TiCl_3$ (525.0 mg, 3.40 mmol) and C_8K (959.0 mg, 7.09 mmol) in DME (30 mL) and **10a** (66.5 mg, 0.20 mmol) in DME (5 mL). Refluxing was continued for an additional 30 h after the addition, and flash chromatography of the crude product over silica gel (1 × 16 cm) with 1:9 ether/petroleum ether gave **10b** (30.2 mg, 50%) as a homogeneous (TLC, silica, 1:9 ether/petroleum ether) oil: IR ($CHCl_3$ cast) 2954, 2874 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.45 (q, J = 8.0 Hz, 6 H), 0.85 (t, J = 8.0 Hz, 9 H), 1.50–2.65 (m, 7 H), 4.65 (d, J = 4.2 Hz, 1 H), 6.35 (d, J = 2.5 Hz, 1 H), 7.00–7.25 (m, 4 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) δ 5.284, 6.799, 25.162, 26.735, 31.272, 46.933, 70.186, 117.001, 125.324, 125.925, 128.262, 128.603, 135.303, 135.655, 147.915; exact mass m/z calcd for $C_{19}H_{28}OSi$ 300.1909, found 300.1915.

The yield of **10b** was increased to 64% when dioxane was used instead of DME.

(R*,R*)-(±)-2-[(2-Oxocyclopentyl)[(triethylsilyl)oxy]methyl]benzaldehyde (11a). Triethylsilyl ether (R*,R*)-(±)-10 (R = $SiEt_3$) (395.0 mg, 1.19 mmol) was ozonized in the same way as (R*,S*)-(±)-10 (R = $SiEt_3$), and **11a** (357.0 mg, 98%) was obtained as a homogeneous (TLC, silica, 2:3 ether/petroleum ether) oil: IR ($CHCl_3$ cast) 2956, 2876, 1741, 1694 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.54 (q, J = 8.0 Hz, 6 H), 0.85 (t, J = 8.0 Hz, 9 H), 1.60–2.35 (m, 5 H), 2.42–2.52 (m, 1 H), 5.78 (d, J = 3.0 Hz, 1 H), 7.42–7.50 (m, 1 H), 7.55–7.62 (m, 1 H), 7.70–7.85 (m, 2 H), 10.25 (s, 1 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) δ 4.75, 6.72, 20.68, 27.53, 39.66, 55.24, 71.53, 127.51, 128.63, 132.43, 133.19, 133.28, 145.62, 193.72, 218.01; exact mass m/z calcd for $C_{17}H_{23}OSi$ (M – C_2H_5)$^+$ 303.1417, found 303.1417.

(R*,S*)-(±)-Triethyl[(2,3,3a,4-tetrahydro-1H-benz[f]inden-4-yl)oxy]silane (11b). A slight modification of procedure A was followed, using $TiCl_3$ (514.5 mg, 3.34 mmol), C_8K (943.0 mg, 6.98 mmol) in DME (30 mL), and **11a** (66.5 mg, 0.20 mmol) in DME (5 mL). Refluxing was continued for a further 30 h after addition. Flash chromatography of the crude product over silica gel (1 × 16 cm) with 1:9 ether–petroleum ether gave **11b** (31.0 mg, 51%) as a homogeneous (TLC, silica, 1:9 ether–petroleum ether) oil: IR ($CHCl_3$ cast) 2956, 2875 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.75 (q, J = 8.0 Hz, 6 H), 1.04 (t, J = 8.0 Hz, 9 H), 1.35–1.65 (m, 2 H), 1.86–2.00 (m, 1 H), 2.20–2.68 (m, 4 H), 4.65 (d, J = 13.2 Hz, 1 H), 6.25 (d, J = 3.0 Hz, 1 H), 6.92–7.00 (m, 1 H), 7.10–7.20 (m, 2 H), 7.40–7.50 (m, 1 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) δ 5.33, 7.09, 24.78, 30.73, 32.53, 48.73, 76.66, 118.73, 123.50, 124.91, 126.21, 126.87, 135.37, 138.76, 148.36; exact mass m/z calcd for $C_{19}H_{28}OSi$ 300.1909, found 300.1915.

The yield of **11b** was increased to 67% when dioxane was used instead of DME.

2',3',3'a,5',6',7'-Hexahydro-1',3'a-dimethylspiro[1,3-dioxolane-2,4'-[4H]indene] (12b). Compound **12b** was prepared a number of times (see Table III).

(a). A slight modification of procedure A was followed, using $TiCl_3$ (524.5 mg, 1.72 mmol), C_8K (942.2 mg, 3.61 mmol) in DME (30 mL), and **12a**[12] (48.0 mg, 0.20 mmol) in DME (5 mL). The carbonyl compound was injected at reflux over 10 h, and the mixture was refluxed for an additional 30 h. Flash chromatography of the crude product over silica gel (1.5 × 15 cm) with 1:19 EtOAc/hexane gave **12b** (31.2 mg, 75%) as a homogeneous (TLC, silica, 1:19 EtOAc/hexane) oil: IR ($CHCl_3$ cast) 2936, 2877, 1170, 1120, 1086, 1058, 1035, 929 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.15 (s, 3 H), 1.35–1.50 (m, 2 H), 1.55–1.92 (m, 7 H), 2.05–2.48 (m, 4 H), 3.96 (s, 4 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) δ 14.05, 21.62, 23.09, 29.86, 30.36, 35.44, 55.78, 64.66, 65.26, 112.64, 129.24, 136.31; exact mass m/z calcd for $C_{13}H_{20}O_2$ 208.1463, found 208.1462.

(b). A slight modification of procedure B was followed, using Na (234.6 mg, 10.20 mmol), naphthalene (1.3200 g, 10.20 mmol), and $TiCl_4$ (0.42 mL, 3.83 mmol) in THF (38 mL) and **12a**[12] (53.7 mg, 0.22 mmol) in THF (5 mL). The carbonyl compound was injected at reflux over 10 h, and the mixture was refluxed for an additional 30 h. Flash chromatography of the crude product over silica gel (1.5 × 15 cm) with 1:19 EtOAc/hexane gave **12b** (33.0 mg, 70%) as a homogeneous (TLC, silica, 1:19 EtOAc/hexane) oil.

(c). A slight modification of procedure C was followed, using $TiCl_4$ (0.71 mL, 6.50 mmol), Na(Hg) (39.5%, 1.0210 g, 17.5 mmol) in DME (40 mL), an initial reflux period of 5 h, and **12a**[12] (91.3 mg, 0.38 mmol) in DME (10 mL). The carbonyl compound was injected at reflux over 10 h, and the mixture was refluxed for an additional 30 h. Flash chromatography of the crude product over silica gel (1.5 × 15 cm) with 1:19 EtOAc/hexane gave **12b** (52.7 mg, 69%) as a homogeneous (TLC, silica, 1:19 EtOAc/hexane) oil.

(d). Use of $TiCl_3$–DME Complex. Freshly prepared Zn–Cu[8] (221.0 mg, 3.40 mmol) and $TiCl_3(DME)_2$ (524.5 mg, 3.40 mmol)[27] were weighed under argon in a drybox and transferred successively to a 100-mL round-bottomed flask containing dry DME (30 mL). The mixture was refluxed for 2 h under argon. Diketone **12a**[12] (48.0 mg, 0.20 mmol) in dry DME (5 mL) was added over 10 h to the stirred and refluxing slurry of titanium reagent. Stirring was continued for an additional 28 h. The mixture was cooled to room temperature and filtered under argon through a pad of Florisil (3.5 × 5 cm) contained in a sintered funnel that was equipped with an argon inlet near the top. The pad was washed with ether (3 × 50 mL). Evaporation of the combined filtrates and flash chromatography of the residue over silica gel (1 × 15 cm) with 1:19 EtOAc/hexane gave **12b** (30.2 mg, 72.6%) as a homogeneous (TLC, silica, 1:19 EtOAc/hexane) oil.

2-[(2-Oxocyclohexyl)methyl]benzaldehyde (13a). (a) 2-[(2-Ethenylphenyl)methyl]cyclohexanone. Compound **13**[38] (2.00 g, 10.1 mmol) was added to a stirred solution of the pyrrolidine enamine of cyclohexanone (1.84 g, 12.2 mmol) in dioxane (25 mL). The resulting mixture was refluxed for 23 h under argon and cooled. Water (5 mL) was added, and the mixture was refluxed for an additional 4.5 h and then allowed to cool to room temperature. The solvent was removed under water-pump vacuum, and the residue was extracted with ether (3 × 40 mL). The combined organic extracts were washed with 2 M aqueous HCl (2 × 20 mL) and water (2 × 40 mL), dried ($MgSO_4$), and evaporated. Flash chromatography of the residue over silica gel (4 × 15 cm) with 1:49 EtOAc/petroleum ether gave the product (739.0 mg, 34%) as an oil that was sufficiently pure for the next

(38) Prepared from 2-ethenylbenzaldehyde by reduction ($LiAlH_4$, 83%) and treatment with PBr_3 (88%). Cf. Oppolzer, W.; Roberts, D. A.; Bird, T. G. C. *Helv. Chim. Acta* **1979**, *62*, 2017.

stage. The material had: IR ($CHCl_3$ cast) 1709 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.20–2.70 (m, 10 H), 3.25–3.45 (m, 1 H), 5.28 (dd, J = 11.0, 1.5 Hz, 1 H), 5.64 (dd, J = 17.0, 1.5 Hz, 1 H), 6.92 (dd, J = 18.8, 10.8 Hz, 1 H), 7.05–7.30 (m, 3 H), 7.44–7.54 (m, 1 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) δ 25.14, 28.03, 32.51, 33.39, 42.14, 51.66, 115.61, 125.84, 126.47, 127.55, 130.65, 134.57, 136.73, 137.73, 212.34; exact mass m/z calcd for $C_{15}H_{18}O$ 214.1358, found 214.1358. The crude material was used directly in the next step.

(b) 2-[(2-Oxocyclohexyl)methyl]benzaldehyde (13a). The above crude olefinic ketone (354.5 mg, 1.65 mmol) was ozonized in the same way as (*R**,*S**)-(±)-**10** (R = $SiEt_3$), and **13a** (301.4 mg, 84%) was obtained as a homogeneous (TLC, silica, 1:9 EtOAc/petroleum ether) oil: IR ($CHCl_3$ cast) 1707, 1697 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.35–1.95 (m, 4 H), 1.98–2.15 (m, 2 H), 2.24–2.48 (m, 2 H), 2.52–2.66 (m, 1 H), 2.84 (dd, J = 13.5, 7.5 Hz, 1 H), 3.60 (dd, J = 13.5, 5.5 Hz, 1 H), 7.30–7.55 (m, 3 H), 7.84 (dd, J = 7.5, 1.5 Hz, 1 H), 10.22 (s, 1 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) δ 25.30, 28.19, 32.33, 34.06, 42.30, 52.42, 126.74, 132.42, 132.85, 133.51, 134.09, 143.18, 192.70, 212.02; exact mass m/z calcd for $C_{14}H_{16}O_2$ 216.1150, found 216.1146.

1,2,3,4,4a,10-Hexahydroanthracene (13b).[39] Procedure A was followed, using $TiCl_3$ (769.0 mg, 4.97 mmol) and C_8K (1.3900 g, 10.3 mmol) in DME (30 mL) and **13a** (63.2 mg, 0.292 mmol) in DME (10 mL). Refluxing was continued for a further 11 h after the addition. Flash chromatography of the crude product over silica gel (1.5 × 15 cm) with petroleum ether gave **13b** (43.6 mg, 81%) as a homogeneous (TLC, silica, 1:9 ether/petroleum ether) oil: IR ($CHCl_3$ cast) 2925 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.15–1.50 (m, 3 H), 1.70–1.95 (m, 2 H), 1.95–2.25 (m, 2 H), 2.35–2.64 (m, 3 H), 2.90 (dd, J = 15.5, 7.0 Hz, 1 H), 6.14 (s, 1 H), 6.90–7.15 (m, 4 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) δ 26.00, 27.07, 34.31, 35.23, 36.06, 36.52, 121.14, 125.08, 125.96, 126.32, 127.08, 134.15, 134.69, 143.95; exact mass m/z calcd for $C_{14}H_{16}O$ 184.1252, found 184.1254. Anal. Calcd for $C_{14}H_{16}O$: C, 91.25; H, 8.75. Found: C, 91.20; H, 8.95.

2-[(2-Oxocycloheptyl)methyl]benzaldehyde (14a). (a) 2-[(2-Ethenylphenyl)methyl]cycloheptanone. The procedure for 2-[(2-ethenylphenyl)methyl]cyclohexanone was followed, using **13** (2.00 g, 10.1 mmol) and the pyrrolidine enamine of cycloheptanone (2.01 g, 12.2 mmol) in dioxane (25 mL), to give 2-[(2-ethenylphenyl)methyl]cycloheptanone (2.2150 g, 95%): IR ($CHCl_3$ cast) 2928, 1701 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.20–1.90 (m, 8 H), 2.40–2.90 (m, 4 H), 3.15–3.25 (dd, J = 14.0, 5.5 Hz, 1 H), 5.30 (d, J = 11.3 Hz, 1 H), 5.65 (d, J = 17.5 Hz, 1 H), 6.95 (dd, J = 17.5, 11.3 Hz, 1 H), 7.05–7.30 (m, 3 H), 7.44–7.56 (m, 1 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) δ 24.31, 28.48, 29.33, 30.06, 34.74, 43.03, 52.85, 115.69, 125.92, 126.55, 127.56, 130.50, 134.61, 136.88, 137.39, 215.29; exact mass m/z calcd for $C_{16}H_{20}O_2$ 228.1514, found 228.1511. Anal. Calcd for $C_{16}H_{20}O_2$: C, 84.16; H, 8.83. Found: C, 84.12; H, 8.45.

(b) 2-[(2-Oxocycloheptyl)methyl]benzaldehyde (14a). The above olefinic ketone (1.2200 g, 5.343 mmol) was ozonized in the same way as (*R**,*S**)-(±)-**10** (R = $SiEt_3$), and **14a** (1.1690 g, 95%) was obtained as a homogeneous (TLC, silica, 1:9 EtOAc/petroleum ether) oil: IR ($CHCl_3$ cast) 1697, 1599 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.20–1.95 (m, 8 H), 2.45 (dd, J = 9.5, 5.0 Hz, 2 H), 2.80–2.94 (m, 1 H), 3.00 (dd, J = 13.2, 7.0 Hz, 1 H), 3.45 (dd, J = 13.2, 6.5 Hz, 1 H), 7.44–7.55 (m, 3 H), 7.82 (dd, J = 7.5, 1.5 Hz, 1 H), 10.22 (s, 1 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) δ 23.83, 28.50, 28.82, 30.80, 34.20, 42.89, 53.37, 126.67, 132.01, 132.93, 133.36, 133.88, 142.58, 192.58, 214.59; exact mass m/z calcd for $C_{15}H_{18}O_2$ 230.1307, found 230.1304. Anal. Calcd for $C_{15}H_{18}O_2$: C, 78.23; H, 7.88. Found: C, 78.10; H, 7.87.

5a,6,7,8,9,10-Hexahydro-5*H*-cyclohepta[*b*]naphthalene (14b). Procedure A was followed, using $TiCl_3$ (975.7 mg, 6.33 mmol) and C_8K (1.7668 g, 13.1 mmol) in DME (30 mL) and **14a** (86.1 mg, 0.374 mmol) in DME (10 mL). Refluxing was continued for a further 14 h after the addition to give **14b** (64.4 mg, 86%) as a homogeneous (TLC, silica, 1:9 ether/petroleum ether) oil: IR ($CHCl_3$ cast) 2920, 2848 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.32–1.85 (m, 8 H), 2.32–2.85 (m, 5 H), 6.20 (s, 1 H), 6.90–7.15 (m, 4 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) δ 28.52, 28.89, 29.41, 32.97, 36.52, 36.63, 37.99, 122.93, 125.03, 125.94, 126.32, 127.29, 134.71, 134.89, 147.36; exact mass m/z calcd for $C_{15}H_{18}$ 198.1408, found 198.1418. Anal. Calcd for $C_{15}H_{118}$: C, 90.85; H, 9.15. Found: C, 90.90; H, 9.22.

Ethyl 2-Oxo-1-(3-oxo-3-phenylpropyl)cyclopentanecarboxylate (15a). This compound was prepared (80%) from ethyl 2-cyclopentanonecarboxylate, NaH, and phenyl vinyl ketone. Et_3N can be used (90% yield) instead of NaH (see supplementary material).[40]

Ethyl 2,3,4,5-Tetrahydro-6-phenyl-3a(1*H*)-pentalenecarboxylate (15b). (a). Procedure A was followed, using C_8K (1.8034 g, 13.34 mmol) and $TiCl_3$ (0.9995 g, 6.48 mmol) in DME (20 mL), and **15a** (109.9 mg, 0.38 mmol) in DME (10 mL). Flash chromatography of the crude product over silica gel (1.5 × 15 cm) with 1:9 ether/pentane gave **15b** (59.6 mg, 61%) as a homogeneous (TLC, silica, 1:19 ether/pentane) oil: IR ($CHCl_3$ cast) 3080–3020, 2950, 1720, 1157 cm^{-1}; ^1H NMR (CD_2Cl_2, 300 MHz) δ 1.24 (t, J = 6.6 Hz, 3 H), 1.35–1.48 (m, 1 H), 1.78–1.90 (m, 1 H), 2.00–2.32 (m, 3 H), 2.42–2.64 (m, 3 H), 3.05–3.20 (m, 2 H), 4.10 (q, J = 6.6 Hz, 2 H), 7.16–7.46 (m, 5 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) δ 14.42, 25.78, 28.51, 35.80, 35.94, 38.86, 60.78, 68.44, 127.02, 127.47, 128.56, 132.75, 136.96, 148.11, 176.27; exact mass m/z calcd for $C_{17}H_{20}O_4$ 256.1463, found 256.1462. Anal. Calcd for $C_{17}H_{20}O_2$: C, 79.65; H, 7.86. Found: C, 79.57; H, 7.91.

(b). Procedure B was followed, using Na (0.3635 g, 15.81 mmol), naphthalene (2.0267 g, 15.81 mmol), and $TiCl_4$ (0.64 mL, 5.86 mmol) in THF (50.0 mL) and **15a** (99.3 mg, 0.34 mmol) in THF (10 mL). Flash chromatography of the crude product over silica gel (4 × 15 cm) with hexane (to separate naphthalene) and then with 1:19 ether/petroleum ether followed by Kugelrohr distillation (0.3 mmHg, 135 °C) gave **15b** (60.5 mg, 69%) as a homogeneous (TLC, silica, 1:19 EtOAc/hexane) oil.

(c). Procedure C was followed, using $TiCl_4$ (1.44 mL, 13.13 mmol), sodium amalgam (39.5% w/w, 2.0636 g, 35.46 mmol) in THF (100 mL), and **15a** (222.7 mg, 0.77 mmol) in THF (20 mL). Flash chromatography of the crude product over silica gel (1.5 × 15 cm) with 1:19 EtOAc/hexane gave **15b** (144.9 mg, 73%) as a homogeneous (TLC, silica, 1:19 EtOAc/hexane) oil.

6-[[1-(Triethylsilyl)oxy]-5-hexenyl]-2-cyclohexen-1-one (16). (a) 6-(1-Hydroxy-5-hexenyl)-2-cyclohexen-1-one. *n*-BuLi (1.6 M in hexanes, 1.78 mL, 2.88 mmol) was added dropwise to a stirred and cooled (0 °C) solution of *i*-Pr_2NH (0.48 mL, 3.41 mmol) in dry ether (10 mL). Stirring at 0 °C was continued for 10 min and the mixture was then cooled to −78 °C. A solution of 2-cyclohexen-1-one (251.9 mg, 2.62 mmol) in ether (2.0 mL) was added over ca. 15 min. Stirring at −78 °C was continued for 40 min. Then, a solution of 5-hexenal (257.2 mg, 2.62 mmol) in ether (2 mL plus 2 mL as a rinse) was added in one portion. After 10 min, the reaction was quenched with saturated aqueous NH_4Cl (10 mL). The mixture was left to warm to room temperature, the layers were separated, and the aqueous phase was extracted with ether (3 × 20 mL). The combined organic extracts were dried ($MgSO_4$) and evaporated. Flash chromatography of the residue over silica gel (3 × 15 cm) with 3:7 EtOAc/hexane gave the product (383.3 mg, 75.3%) as an apparently homogeneous (TLC, silica, 3:7 EtOAc/hexane) oil: IR ($CHCl_3$ cast) 3460 (broad), 3070–3020, 2921, 2860, 1660, 1399, 1220, 995 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) (two diastereoisomers in a ratio of ca. 1:3) δ 1.30–1.80 (m, 5 H), 1.85–2.20 (m, 3 H), 2.25–2.60 (m, 3.25 H), 3.82–3.94 (m, 0.77 H), 4.04–4.12 (d, J = 3 Hz, 0.75 H, exchanges with D_2O), 4.14–4.24 (m, 0.23 H), 4.90–5.08 (m, 2 H), 5.72–5.90 (m, 1 H), 5.98–6.08 (m, 1 H), 6.96–7.08 (m, 1 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) (major isomer) δ 24.14, 25.16, 25.89, 33.08, 33.72, 51.59, 71.61, 114.60, 129.92, 138.81, 150.93, 203.78; (minor isomer) δ 22.52, 25.55, 32.48, 33.58, 51.62, 69.78, 114.63, 130.23, 138.69, 150.83; exact mass m/z calcd for $C_{12}H_{16}O$ $(M - H_2O)^+$ 176.1201, found 176.1201. Anal. Calcd for $C_{12}H_{18}O_2$: C, 74.19; H, 9.34. Found: C, 74.37; H, 9.34.

(b) 6-[[1-(Triethylsilyl)oxy]-5-hexenyl]-2-cyclohexen-1-one (16). A general procedure[34] for triethylsilylation was used. Et_3SiCl (0.93 mL, 5.52 mmol) was added to a solution of the above aldols (536.2 mg, 2.76 mmol) in dry pyridine (6.0 mL). The solution was heated at 60 °C for 2 h, cooled to room temperature, diluted with ether (50 mL), and extracted with 10% w/v $CuSO_4 \cdot 5H_2O$ (4 × 20 mL). The combined aqueous extracts were back-extracted

(39) Cf. Cook, J. W.; McGinnis, N. A.; Mitchell, S. *J. Chem. Soc.* **1944**, 286.

(40) Cf. Austin, E. M.; Brown, H. L.; Buchanan, G. L. *Tetrahedron*, **1969**, *25*, 5509.

with ether (50 mL), and the combined ether solutions were washed with water (2 × 50 mL), dried ($MgSO_4$), and evaporated. Flash chromatography of the residue over silica gel (3 × 15 cm) with 1:9 EtOAc/hexane gave **16** (693.3 mg, 81%) as an apparently homogeneous (TLC, silica, 1:9 EtOAc/hexane) oil: IR ($CHCl_3$ cast) 3080–3030, 2952, 2876, 1677, 1385, 1084, 1006, 741 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) (two diastereoisomers in a ratio of ca. 1:3) δ 0.52–0.68 (m, 6 H), 0.86–1.00 (m, 9 H), 1.25–1.90 (m, 5 H), 1.95–2.55 (m, 6 H), 4.39–4.45 (m, 0.78 H), 4.46–4.52 (m, 0.22 H), 4.88–5.06 (m, 2 H), 5.75–5.88 (m, 1 H), 5.94–6.06 (m, 1 H), 6.92–7.00 (m, 1 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) (major isomer) δ 5.07, 6.96, 22.05, 25.95, 26.09, 32.56, 33.82, 53.67, 70.53, 114.35, 130.35, 138.95, 149.99, 199.80; (minor isomer) δ 21.12, 25.18, 25.44, 35.00, 51.01, 69.70, 114.60, 130.53, 138.94, 150.02, 199.79; exact mass m/z calcd for $C_{18}H_{32}O_2Si$ 308.2172, found 308.2170. Anal. Calcd for $C_{18}H_{32}O_2Si$: C, 70.07; H, 10.45. Found: C, 70.23; H, 10.51.

6-[5-Oxo-1-[(triethylsilyl)oxy]hexyl]-2-cyclohexen-1-one (16a).[17] $PdCl_2$ (12.8 mg, 0.072 mmol) and CuCl (35.9 mg, 0.36 mmol) were added to a stirred mixture of **16** (56.0 mg, 0.18 mmol) (both isomers), water (0.28 mL), and DMSO (2.0 mL). Oxygen was then bubbled through the resulting mixture for 6 min, and stirring was continued for an additional 1.5 h. The mixture was diluted with water (10 mL) and extracted with ether (4 × 6 mL). The combined organic extracts were washed with brine (10 mL), dried ($MgSO_4$), and evaporated. Flash chromatography of the residue over silica gel (1.5 × 15 cm) with 1:4 EtOAc/hexane gave **16a** (44.2 mg, 75%) as an apparently homogeneous (TLC, silica, 1:4 EtOAc/hexane) oil: IR ($CHCl_3$ cast) 2959, 2875, 1716, 1679, 1086, 1004, 742, 724 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) (two diastereoisomers in a ratio of 1:3) δ 0.50–0.66 (m, 6 H), 0.88–1.00 (m, 9 H), 1.22–1.42 (m, 2 H), 1.46–1.62 (m, 2 H), 1.68–1.86 (m, 2 H), 2.00–2.15 (m, 3 H), 2.15–2.55 (m, 5 H), 4.36–4.44 (m, 0.78 H), 4.44–4.52 (m, 0.22 H), 5.94–6.06 (m, 1 H), 6.92–7.00 (m, 1 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) (major isomer) δ 4.52, 6.38, 20.42, 21.49, 25.54, 29.23, 31.95, 43.09, 52.97, 69.65, 129.73, 149.59, 199.19, 208.42; (minor isomer) δ 19.50, 20.62, 24.86, 29.24, 34.43, 43.08, 50.14, 68.82, 129.90, 149.60, 199.20, 208.44; exact mass m/z calcd for $C_{18}H_{32}O_3Si$ 324.2121, found 324.2123. Anal. Calcd for $C_{18}H_{32}O_3Si$: C, 66.62; H, 9.94. Found: C, 66.33; H, 9.99.

Triethyl[2,6,7,8,9,9a-hexahydro-5-methyl-1*H*-benzocyclohepten-9-yl)oxy]silane (16b). Procedure A was followed, using C_8K (1.2218 g, 9.04 mmol), $TiCl_3$ (677.1 mg, 4.39 mmol) in DME (25 mL), and **16a** (83.3 mg, 0.258 mmol) in DME (10 mL). Flash chromatography of the crude product over silica gel (1.5 × 15 cm) with hexane gave (*R**,*S**)-(±)-**16b**[41] (44.5 mg, 59%) as a homogeneous (TLC, silica, hexane) oil and (*R**,*R**)-(±)-**16b** (11.4 mg, 15%) as a homogeneous (TLC, silica, hexane) oil. The (*R**,*S**)-(±)-isomer had: IR ($CHCl_3$ cast) 3030, 2920, 1100 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 0.55 (q, J = 8.0 Hz, 6 H), 0.92 (t, J = 8.0 Hz, 9 H), 1.40–2.02 (m, 11 H), 2.20–2.50 (m, 2 H), 2.78 (br t, 1 H), 3.88–3.92 (m, 1 H), 5.64–5.72 (m, 1 H), 6.44 (dt, J = 10, 1.80, 1 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) δ 5.50, 7.04, 20.30, 20.32, 23.22, 29.78, 35.70, 39.48, 41.20, 74.67, 126.21, 126.94, 128.77, 133.36; exact mass, m/z calcd for $C_{16}H_{27}O$ $(M - C_2H_5)^+$ 263.1823, found 263.1826.

The (*R**,*R**)-(±)-isomer had: IR ($CHCl_3$ cast) 3030, 2920, 1100 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 0.60 (q, J = 9.0 Hz, 6 H), 0.94 (t, J = 9.0, 9 H), 1.25–2.26 (m, 12 H), 2.52–2.64 (m, 1 H), 2.82 (br s, 1 H), 3.45–3.55 (m, 1 H), 5.72–5.82 (m, 1 H), 6.48 (dd, J = 10.0, 2.0 Hz, 1 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) δ 5.43, 7.06, 19.85; 21.69, 23.14, 23.32, 33.83, 39.92, 42.50, 69.47, 124.80, 127.01, 129.94, 135.00; exact mass m/z calcd for $C_{18}H_{32}OSi$ 292.2216, found 292.1777.

6-[1-Acetoxy-5-hexenyl]-2-cyclohexen-1-one (17). Ac_2O (1.65 mL, 17.5 mmol) was added to a solution of 6-(1-hydroxy-5-hexenyl)-2-cyclohexen-1-one (200.0 mg, 1.03 mmol) prepared as described above, in dry pyridine (1.74 mL, 21.1 mmol), and the mixture was stirred at room temperature for 10 h. The mixture was then diluted with ether (25 mL) and washed with water (2 × 15 mL) and brine (1 × 15 mL). The organic extract was dried ($MgSO_4$) and evaporated. Flash chromatography of the residue over silica gel (3 × 15 cm) with 1:4 EtOAc/hexane gave **17** (215.0 mg, 88%) as an oily mixture of two isomers (ca. 94:6; ^1H NMR (300 MHz)) that were not separable by chromatography (TLC, silica, 1:4 EtOAc/hexane): IR ($CHCl_3$ cast) 3080–3020, 2930, 1755, 1675, 1242 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.40–1.70 (m, 5 H), 1.82–2.18 (m, 6 H), 2.28–2.56 (m, 2 H), 2.72 (dt, J = 12, 4.5, 1 H), 4.90–5.10 (m, 2 H), 5.40–5.50 (m, 1 H), 5.70–5.86 (m, 1 H), 5.95–6.05 (m, 1 H), 6.90–7.00 (m, 1 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) δ 21.22, 23.09, 23.50, 25.26, 25.37, 29.99, 33.43, 49.82, 72.94, 114.80, 130.11, 138.44, 149.50, 149.88, 170.65, 198.40; exact mass m/z calcd for $C_{12}H_{17}O_2$ $(M - CH_3CO)^+$ 193.1229, found 193.1225. Anal. Calcd for $C_{14}H_{20}O_3$: C, 71.16; H, 8.53. Found: C, 70.96; H, 8.42.

6-[1-Acetoxy-5-oxohexyl]-2-cyclohexen-1-one (17a). Oxygen was bubbled into a mixture of $PdCl_2$ (30.0 mg, 0.17 mmol), CuCl (83.8 mg, 0.85 mmol), water (0.66 mL), and DMSO (4.70 mL) for 15 min at room temperature. Compounds **17** (100.0 mg, 0.42 mmol) were then added. Stirring was continued for an additional 30 min (TLC control, silica, 3:7 EtOAc/hexane), and the mixture was diluted with water (20 mL) and extracted with ether (4 × 15 mL). The combined organic extracts were washed with brine (30 mL), dried ($MgSO_4$), and evaporated. Flash chromatography of the residue over silica gel (2 × 15 cm) with 3:7 EtOAc/hexane gave **17a** (92.2 mg, 87%) as an oily mixture of two isomers (ca. 93:7; ^1H NMR (300 MHz)) that were not separable by chromatography (TLC, silica, 3:7 EtOAc/hexane): IR ($CHCl_3$ cast) 2930, 1735, 1715, 1240 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.40–1.75 (m, 5 H), 1.80–2.20 (m, 7 H), 2.30–2.60 (m, 4 H), 2.75 (dt, J = 13.0, 4.5, 1 H), 5.36–5.48 (m, 1 H), 5.95–6.05 (m, 1 H), 6.90–7.05 (m, 1 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) (two isomers) δ (major) 19.91, 21.20, 23.34, 25.46, 29.66, 29.97, 42.88, 49.68, 72.35, 130.04, 149.72, 170.67, 198.39, 208.68; δ (minor) 23.05, 25.09, 31.47, 49.40, 70.68, 129.91, 150.02; exact mass m/z calcd for $C_{14}H_{20}O_4$ 252.1361, found 252.1359. Anal. Calcd for $C_{14}H_{20}O_4$: C, 66.65; H, 7.99. Found: C, 66.85; H, 8.17.

2,6,7,8,9,9a-Hexahydro-5-methyl-1*H*-benzocyclohepten-9-ol Acetate (17b). (a). Procedure B was followed, using Na (315.2 mg, 13.71 mmol), naphthalene (1.7574 g, 13.71 mmol), and $TiCl_4$ (0.56 mL, 5.08 mmol) in THF (50.0 mL) and **17a** (75.0 mg, 0.297 mmol) in THF (10 mL). Flash chromatography of the crude product over silica gel (4 × 15 cm), first with hexane (to separate naphthalene) and then with 1:19 EtOAc/hexane, gave **17b**[42] (38.4 mg, 58%) as white crystals: IR ($CHCl_3$ cast) 3030, 2920, 2830, 1730, 1245 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.30–1.60 (m, 2 H), 1.65–2.10 (m, 13 H), 2.50 (t, J = 13.0 Hz, 1 H), 2.96 (t, J = 4.5 Hz, 1 H), 5.00 (t, J = 4.0 Hz, 1 H), 5.75 (dt, J = 10.0, 4.0 Hz, 1 H), 6.50 (dt, J = 10.0, 2.0 Hz, 1 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) δ 20.22, 20.67, 21.53, 22.51, 29.04, 35.27, 35.65, 38.44, 75.78, 126.13, 126.48, 127.85, 134.69, 171.12; exact mass m/z calcd for $C_{14}H_{20}O_2$ 220.1463, found 220.1463.

2-[2-(Phenylsulfonyl)-5-hexenyl]cyclohexanone (18). (a) 2-[2-(Phenylsulfonyl)ethyl]cyclohexanone.[43] This compound was prepared from phenyl vinyl sulfone and the pyrrolidine enamine of cyclohexanone (see supplementary material). The material was used without purification.

(b) [2-[1,4-Dioxaspiro[4,5]decan-6-yl]ethyl]sulfonylbenzene. A solution of the above crude product (1.32 g), ethylene glycol (645.0 mg, 10.40 mmol), and $TsOH·H_2O$ (98.9 mg, 0.52 mmol) in dry benzene (30 mL) was refluxed under an addition funnel packed with 3-Å molecular sieves for 3 h and was then cooled to room temperature. Water (20 mL) was added and the resulting mixture was washed with saturated aqueous $NaHCO_3$ (1 × 20 mL) and brine (2 × 40 mL), dried ($MgSO_4$), and evaporated. Flash chromatography of the residue over silica gel (4 × 15 cm) with 9:10 EtOAc/hexane gave the required ketal (1.4163 g, 87% over the two steps) as a homogeneous (TLC, silica, 9:10 EtOAc/hexane) white solid: mp 59–61 °C; IR ($CHCl_3$ cast) 2934 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.10–1.80 (m, 10 H), 1.90–2.08 (m, 1 H), 3.18 (dd, J = 9.0, 7.5 Hz, 2 H), 3.70–3.96 (m, 4 H), 7.50–7.70 (m, 3 H), 7.85–7.95 (m, 2 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) δ 22.12, 23.53, 24.64, 29.69, 34.57, 43.16, 55.19, 64.41, 64.66, 110.38, 128.12, 129.19, 133.54, 139.28; exact mass m/z calcd for

(41) Stereochemical assignment is based on the assumption that the major isomer in the aldol condensation has the same stereochemistry as the major isomer of **5**.

(42) The product, if any, from the minor isomer in **17a** was not isolated.

(43) Cf. Risaliti, A.; Fatutta, S.; Forchiassin, M. *Tetrahedron* **1967**, *23*, 1451.

$C_{16}H_{22}O_4S$ 310.1238, found 310.1242.

(c) 2-[2-(Phenylsulfonyl)-5-hexenyl]cyclohexanone (18). *n*-BuLi (1.47 M in hexanes, 2.45 mL, 3.60 mmol) was added dropwise to a stirred and cooled (−78 °C) solution of the above ketal (931.5 mg, 3.00 mmol) in dry THF (20 mL). The solution was stirred at −78 °C for 20 min, and 4-bromobutene (0.76 mL, 3.60 mmol) was then added, followed by HMPA (5.0 mL). The resulting mixture was warmed to −30 °C and stirred at this temperature for 40 min and then at 0 °C for 2 h. Water (30 mL) was added, and the mixture was extracted with ether (3 × 25 mL). The combined organic extracts were washed with saturated aqueous $NaHCO_3$ (1 × 30 mL) and brine (2 × 40 mL), dried ($MgSO_4$), and evaporated. The crude alkylated product was used directly for deketalization.

A mixture of the crude alkylated product in THF (15 mL) and 5% v/v aqueous HCl (7.5 mL) was stirred overnight at 40 °C under argon and then cooled to room temperature. The layers were separated, and the aqueous phase was extracted with ether (3 × 15 mL). The combined organic extracts were washed with saturated aqueous $NaHCO_3$ (1 × 20 mL) and brine (2 × 30 mL), dried ($MgSO_4$), and evaporated. Flash chromatography of the residue over silica gel (5 × 15 cm), first with 1:4 EtOAc/hexane and then with 3:7 EtOAc/hexane, gave **18** as a mixture of two isomers. The major isomer amounted to 369.7 mg (38% over the two steps). The sample of the minor isomer amounted to 289.9 mg (30% over the two steps; 68% overall for both isomers, from the ketal sulfone), but the material contained a little (ca. 11% (^{1}H NMR)) of the other isomer. The major isomer had: IR ($CHCl_3$ cast) 1707 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.20–1.90 (m, 8 H), 2.00–2.45 (m, 6 H), 2.82–2.95 (m, 1 H), 3.15–3.30 (m, 1 H), 4.95–5.05 (m, 2 H), 5.60–5.75 (m, 1 H), 7.50–7.70 (m, 3 H), 7.80–7.92 (m, 2 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) δ 25.26, 28.28, 29.19, 29.46, 30.23, 35.38, 42.38, 48.56, 61.89, 115.84, 128.85, 129.14, 133.64, 136.99, 137.95, 212.82; exact mass *m/z* calcd for $C_{18}H_{24}O_3S$ 320.1446, found 320.1442. Anal. Calcd for $C_{18}H_{24}O_3S$: C, 67.47; H, 7.55; S, 10.01. Found: C, 67.12; H, 7.39; S, 10.02.

The sample of the minor isomer[44] had: IR ($CHCl_3$ cast) 1706 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.20–2.40 (m, 14 H), 2.60–2.72 (m, 1 H), 3.08–3.26 (m, 1 H), 4.90–5.06 (m, 2 H), 5.56–5.74 (m, 1 H), 7.50–7.70 (m, 3 H), 7.80–7.95 (m, 2 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) δ 25.07, 27.62, 27.94, 28.34, 30.74, 34.42, 42.04, 47.53, 60.56, 116.20, 128.98, 129.12, 133.67, 136.71, 137.68, 219.77; exact mass *m/z* calcd for $C_{18}H_{24}O_3S$ 320.1446, found 320.1438.

2-[5-Oxo-2-(phenylsulfonyl)hexyl]cyclohexanone (18a). The procedure for **17a** was followed using **18** (major isomer) (341.6 mg, 1.07 mmol), and flash chromatography of the crude product over silica gel (3 × 15 cm) with 9:11 EtOAc/hexane gave **18a** (307.5 mg, 85%) as a homogeneous (^{1}H NMR (300 MHz), TLC, silica, 2:3 EtOAc/hexane)) oil: IR ($CHCl_3$ cast) 1709 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.18–1.34 (m, 1 H), 1.50–2.20 (m, 12 H), 2.30–2.40 (m, 2 H), 2.78 (t, *J* = 6.8 Hz, 2 H), 2.82–2.95 (m, 1 H), 3.08–3.18 (m, 1 H), 7.54–7.72 (m, 3 H), 7.82–7.92 (m, 2 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) δ 23.43, 25.25, 28.26, 28.58, 30.01, 35.14; 39.54, 42.40, 48.81, 61.54, 128.92, 129.19, 133.77, 137.57, 207.54, 213.05; exact mass *m/z* calcd for $C_{18}H_{24}O_4S$ 336.1395, found 336.1384. Compound **18a** was a single isomer, but its stereochemistry was not determined.

(2,6,7,8,9,9a-Hexahydro-5-methyl-1*H*-benzocyclohepten-8-yl) Phenyl Sulfone (18b). Procedure B was followed, using Na (216.2 mg, 9.40 mmol), naphthalene (1.2054 g, 9.40 mmol), and $TiCl_4$ (0.38 mL, 3.48 mmol) in THF (40 mL) and **18a** (68.9 mg, 0.205 mmol) in THF (10 mL). Flash chromatography of the crude product over silica gel (3 × 15 cm), first with hexane (to separate naphthalene) and then 3:17 EtOAc/hexane, gave **18b** (24.4 mg, 39%) as a homogeneous (TLC, silica, 15:85 EtOAc/hexane) oil: IR ($CHCl_3$ cast) 2927 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.30–1.70 (m, 11 H), 1.85–2.10 (m, 4 H), 2.20–2.45 (m, 3 H), 3.15–3.30 (m, 1 H), 7.50–7.70 (m, 3 H), 7.82–7.92 (m, 2 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) δ 21.22, 23.32, 24.70, 25.26, 27.82, 30.44, 30.66, 33.06, 41.31, 65.20, 127.13, 129.03, 129.09, 133.52, 135.75, 137.70; exact mass *m/z* calcd for $C_{18}H_{24}O_2S$ 304.1496, found 304.1497. Anal. Calcd for $C_{18}H_{24}O_2S$: C, 71.01; H, 7.95; S, 10.53. Found: C, 71.32; H, 8.05; S, 10.57. Compound **18b** was a single isomer, but its stereochemistry was not determined.

Tetraphenylethene (19b).[45] A modification of procedure C was followed, using Na(Hg) (39.5%, 1.7906 g, 21.6 mmol) and $TiCl_4$ (1.25 mL, 11.39 mmol) in DME (55 mL), and an initial reflux period of 4 h. The benzophenone (258.8 mg, 1.42 mmol) was added in one portion. Refluxing was continued for an additional 12 h. The mixture was cooled to room temperature and filtered through a pad of Florisil. The pad was washed well with ether, and the combined filtrates were evaporated. Flash chromatography of the residue over silica gel (1.5 × 15 cm) with 1:19 EtOAc/hexane gave **19b** (119.3 mg, 84%) as a homogeneous (TLC, silica, 1:19 EtOAc/hexane) white solid: mp 219–220 °C (lit.[45] mp 223–224 °C); ^{1}H NMR ($CDCl_3$, 300 MHz) δ 6.90–7.10 (m, 20 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) δ 126.44, 127.67, 131.35, 141.01, 143.76; exact mass *m/z* calcd for $C_{26}H_{20}$ 332.1565, found 332.1564.

GC Investigation of the Coupling of Benzophenone. A large number of experiments was carried out (see Table V). In a typical example, Na (0.9442 g, 41.07 mmol) was added to a stirred solution of naphthalene (5.2644 g, 41.07 mmol) in THF (38.0 mL) (argon atmosphere). Stirring was continued for 2 h, and then $TiCl_4$ (freshly distilled from copper powder, 1.61 mL, 14.67 mmol) was added through the condenser over ca. 10 min while the flask was cooled with a cold-water bath. Then the condenser was rinsed with THF (5.7 mL), and the resulting black mixture was refluxed for 30 min and cooled to room temperature. The total volume of the solution was 49.0 mL (38.0 + 5.7 + 5.3 mL). (It was found that 5.0 g of naphthalene increases the volume of the solution by 5.0 mL). The concentration the titanium reagent in terms of $TiCl_4$ was 0.3 M, and the $TiCl_4$/Na–naphthalene ratio was 1:2.8. Aliquots (2.0, 4.0, 6.0, 8.0, 9.0, and 10.0 mL) of the above reagent were dispensed into six predried and argon-flushed 25-mL round-bottomed flasks, each equipped with a reflux condenser and a magnetic stirring bar. Then, a solution of benzophenone in THF (0.3 M, 1.0 mL) and a solution of adamantane (as internal standard) in THF (0.15 M, 1.0 mL) were added to each of the six flasks. THF was then added to bring the total volume in each flask to 12.0 mL. The resulting mixtures were refluxed for 6 h under argon, cooled to room temperature, and centrifuged for 10 min. The supernatants were examined by GC (10% OV-1, Chromosorb W-HP, 80/100 mesh, 6 ft × $^1/_4$ in., 130 °C for 8.0 min, then rising at 25 °C/min to 250 °C, 250 °C for 20.0 min). By using a calibration graph, the yield was calculated for each of the 78 reactions. The results are shown in Table V.

Cyclohexylidenecyclohexane (20b).[46] **(a).** A slight modification of procedure C was followed, using Na(Hg) (39.5% w/w, 7.4356 g, 127.76 mmol) and $TiCl_4$ (5.20 mL, 47.32 mmol) in DME (60 mL) and cyclohexanone (580.5 mg, 5.91 mmol). The ketone was added in one portion, and refluxing was continued for an additional 36 h. Flash chromatography of the crude product over silica gel (2 × 15 cm) with 1:19 EtOAc/hexane, followed by sublimation (0.1 mmHg, 45 °C), gave **20b** (273.6 mg, 56%) as a homogeneous (TLC, silica, 1:19 EtOAc/hexane) white solid: mp 51–53 °C (lit.[46] mp 53–54 °C); IR ($CHCl_3$ cast) 2920 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.45–1.65 (m, 12 H), 2.15 (t, *J* = 5.5 Hz, 8 H); ^{13}C NMR ($CDCl_3$, 75.469 MHz) δ 27.34, 28.75, 30.16, 129.47; exact mass *m/z* calcd for $C_{12}H_{20}$ 164.1565, found 164.1565.

(b). A slight modification of procedure A was followed, using $TiCl_3$ (544.8 mg, 3.53 mmol), C_8K (1.0213 g, 7.56 mmol) in DME (20 mL), and cyclohexanone (62 μL, 0.60 mmol) in DME (10 mL). The ketone was added in one portion, and refluxing was continued for an additional 12 h. Flash chromatography of the crude product over silica gel (1.5 × 15 cm) with hexane gave **20b** (29.0 mg, 58%) as a homogeneous (TLC, silica, 1:19 EtOAc/hexane) white solid: mp 51–52 °C.

Cyclododecylidenecyclododecane (20b).[8] A slight modification of procedure A was followed, using $TiCl_3$ (367.7 mg, 2.38 mmol), C_8K (678.3 mg, 5.02 mmol) in DME (10 mL), and cyclododecanone (54.7 mg, 0.30 mmol) in DME (5 mL). The ketone was added in one portion, and refluxing was continued for an additional 12 h. Flash chromatography of the crude product over silica gel (1.5 × 15 cm) with 1:19 EtOAc/hexane gave **21b** (42.6

(44) The material contained a little (ca. 11% (^{1}H NMR)) of the other isomer.

(45) *Organic Syntheses*; Wiley: New York, 1963; Collect. Vol. IV, p 914.

(46) Criegee, R.; Vogel, E.; Höger, H. *Ber.* **1952**, *85*, 144.

mg, 85%) as a homogeneous (TLC, silica, 1:19 EtOAc/hexane; ^{13}C NMR) white solid: mp 152–154 °C (lit.[8] 150–152 °C); ^{13}C NMR ($CDCl_3$, 100.614 MHz), δ 22.13, 23.09, 24.52, 26.03, 26.16; 27.53; 133.72; exact mass m/z calcd for $C_{24}H_{44}$ 332.3443, found 332.3437.

3-Methoxy-D-homoestra-1,3,5(10),17-tetraene. Freshly prepared[14] C_8K (3.98 g, 29.4 mmol) and $TiCl_3$ (2.18 g, 14.19 mmol) were weighed under argon in a glovebox and transferred successively to a 250-mL round-bottomed flask equipped with a condenser and containing dry diglyme (60 mL). The mixture was stirred at 85 °C for 2 h under argon. 3-Methoxy-D-homoestra-1,3,5(10)-triene-17β,17aβ-diol[47] **22** (267 mg, 0.84 mmol) was tipped in via the condenser and rinsed into the reaction vessel with dry diglyme (5 mL). Stirring was continued at 150 °C for an arbitrary period of 36 h. The mixture was cooled to room temperature and filtered under a blanket of argon through a pad of Florisil (11 × 4 cm). The pad, which was contained in a sintered funnel equipped with an argon inlet near the top, was washed with CH_2Cl_2 (400 mL) and ether (200 mL). Evaporation of the filtrate, removal of the diglyme by Kugelrohr distillation (80 °C (3 mmHg)), and flash chromatography of the residue over silica gel (2.5 × 20.0 cm) with 1:19 EtOAc/hexane, gave 3-methoxy-D-homoestra-1,3,5(10),17-tetraene (219 mg, 92%) as a white solid: mp 80–82 °C; FT-IR ($CHCl_3$ cast) 2925, 1600, 1500, 1218, 759 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 0.82–0.98 (m, including a singlet at 0.91, 4 H), 1.20–1.69 (m, 10 H), 1.81–1.95 (m, 1 H), 2.0–2.22 (m, 3 H), 2.22–2.39 (m, 2 H), 2.82–2.93 (m, 2 H), 3.79 (s, 3 H), 5.51 (br s, 2 H), 6.64 (d, J = 2.8 Hz, 1 H), 6.72 (dd, J = 8.4, 2.8 Hz, 1 H), 7.22 (d, J = 8.4 Hz, 1 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 20.04, 20.15, 26.26, 26.38, 29.74, 30.21, 34.77, 38.60, 39.14, 44.13, 47.41, 55.24, 111.54, 113.53, 123.94, 126.21, 133.30, 138.05, 139.54, 157.48' exact mass m/z calcd for $C_{20}H_{26}O$ 282.1984, found 282.1983. Anal. Calcd for $C_{20}H_{26}O$: C, 85.05; H, 9.28. Found: C, 84.99; H, 9.63.

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Supplementary Material Available: ^1H NMR spectra of **5a**, **6a**, **7b** (also ^{13}C NMR), **9a**, **10** (R = $SiEt_3$) (both isomers), **10a**, **10b**, **11a**, **11b**, **12b**, **13a**, **16b** (both isomers), **17b**, [[2-(1,4-dioxaspiro[4,5]decan-6-yl)ethyl]sulfonyl]benzene, and **18a**, together with experimental procedures for **8a**, **9a**, **15a**, and 2-[2-(phenylsulfonyl)ethyl]cyclohexanone (60 pages). Ordering information is given on any current masthead page.

On the Stereoselective Opening of Achiral Dioxane Acetals

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The stereoselectivity of allylation of achiral dioxane acetals *cis*- and *trans*-**3** and *cis*- and *trans*-**5** was found to be highly dependent on the nature of the allylmetal reagent, Lewis acid, and stoichiometry. Using $TiCl_2(O\text{-}i\text{-}Pr)_2$ as the Lewis acid in conjunction with allyltrimethylsilane and allyltri-*n*-butylstannane the selectivity of opening ranged from 1/1 to 18.6/1. In reactions with allyltrimethylsilane, the lack of selectivity for both the cis and trans series (1–2.4/1) was shown to arise from rapid equilibration of ion pairs. Control experiments revealed that the acetals underwent opening faster than isomerization. The reactions with allyltri-*n*-butylstannane were more selective and dependent on reagent stoichiometry. Moreover, the sense of asymmetric induction for the cis and trans series was opposite. Control experiments again established that isomerization of the acetals occurs slower than reaction with the stannane. These experiments unambiguously rule out the possibility that the opening proceeds via equilibrating ion pairs. The meso dioxane acetal *cis*-**9** reacted with significantly reduced selectivity compared to the 2,4,6-trisubstituted analogue *cis*-**7**. On the other hand, the chiral acetal (±)-**13** reacted much more selectively than the 2,4,6-trisubstituted analogue (±)-**11**. These reactions illustrate the sensitivity of stereochemical outcome to structural and experimental variables and demonstrate the ability to intercept reactive ion pairs under conditions of kinetic control.

Introduction and Background

The mechanism and origin of stereoselective opening of chiral dioxane acetals constitute important considerations for the design of new asymmetric transformations.[1] In a recent study, Heathcock, Bartlett, Yamamoto et al.[2] described the use of 2,5-disubstituted 1,3-dioxane acetals to distinguish between S_N1 and S_N2 mechanistic limits, Scheme I. Their observation of stereorandom opening of *trans*-**1** and *cis*-**1** with $TiCl_4$ and the silyl enol ether derived from pinacolone led them to conclude that the reaction proceeds by an S_N1 mechanism via rapidly equilibrating oxocarbenium ion pairs, i and ii.

Our own studies on the mechanism of opening of dioxane acetals[3] have identified a stereochemical continuum arising from the intermediacy of three distinct species (intimate ion pair, external ion pair, and separated ions) each with its own stereochemical profile, Scheme II.[4] The stereoselectivity of a given reaction is a composite of those structural and experimental factors that balance the contribution of the different intermediates. A striking example is the difference in allylation selectivity between the meso and chiral acetals *cis*-**7** (*lk*-**8**/*ul*-**8**, 11.1/1) and (±)-**11** (*lk*-**12**/*ul*-**12**, 57.7/1) with allyltrimethylsilane **15** and the

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