Chiral Oxabicyclic Systems from Ribonolactone

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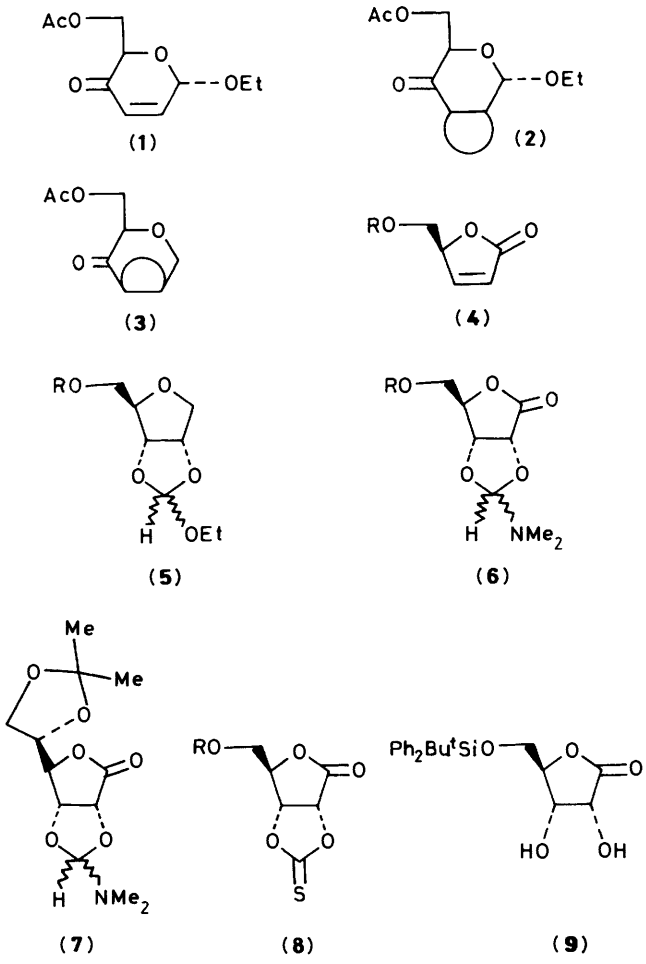
We describe the synthesis of (−)-5-*O*-diphenyl-t-butylsiloxymethyl-5*H*-furan-2-one (**4**) from D-ribonolactone; conversion of this chiral butenolide into (+)-(1*R*,6*S*,7*S*)-7-diphenyl-t-butylsiloxymethyl-8-oxabicyclo[4.3.0]non-3-en-9-one (**10**) (by means of a Diels-Alder reaction with butadiene); and thence *via* an efficient six-step sequence into (+)-(1*R*,2*S*,5*S*)-2-diphenyl-t-butylsiloxymethyl-3-oxabicyclo[3.3.0]octan-7-one (**15**). A structure proof for this final product was provided by *X*-ray structural analysis. The crystals are triclinic, space group *P*1 with $Z = 2$, $a = 8.351(9)$, $b = 17.400(8)$, $c = 8.591(8)$ Å; $\alpha = 77.8(1)$, $\beta = 71.1(1)$, $\gamma = 93.8(1)°$. 3 423 Independent reflections were measured on a diffractometer and the structure has been refined to *R* 0.069. In the two independent molecules, the 3-oxabicyclo[3.3.0]octan-7-one fragments have strikingly different conformations.

During the last 10 years there has been a resurgence in interest in carbohydrates, primarily because organic chemists have discovered their merits as cheap and stereochemically defined starting materials for synthesis. Several excellent reviews have appeared extolling the virtues of various carbohydrates, and describing their use in synthesis, most notably those by Fraser-Reid and Anderson,[1] Hanessian,[2] Inch,[3] and Joulié.[4] We were particularly attracted by the annulation reactions reported by Fraser-Reid and his co-workers, whereby the glucoside derivative (**1**) participated in cycloadditions to produce new fused three, four, five, and six-membered rings of general structure (**2**) and (**3**). These bicyclic compounds were then converted into a variety of natural products and analogues, for example actinobolin,[5] grandisol,[6] and chrysanthemic acids.[7]

We reasoned that a chiral butenolide such as compound (**4**) could serve in place of compound (**1**) for annulations, and that the desired oxabicyclic systems could also serve as key intermediates for elaboration into natural products and analogues. The first requirement was an efficient route to the butenolide (**4**) which would allow obtention of multigram quantities of this compound. We excluded the known route from (*S*)-glutamic acid[8] since this would involve the use of relatively large amounts of selenium reagents for introduction of the double bond. Other methods for the introduction of unsaturation include deoxygenation of vicinal diols as their cyclic orthoformates,[9] cyclic dimethylaminomethylene acetals,[10] and cyclic thioxocarbonates.[11] We obtained a quantitative yield of the requisite orthoformate (**5**; R = H) from ribonolactone and triethylorthoformate (THF, 12 h at reflux), and thence the 5-*O*-benzoyl derivative (**5**; R = PhCO) (PhCOCl–pyridine-CH_2Cl_2). However, thermal and acid-catalysed deoxygenation proved to be inefficient even on a small scale.†

Camps reported[9b] that deoxygenation *via* dimethylaminomethylene acetals (**6**) (from ribonolactone) using the method of Hanessian[10] (reaction with excess MeI then pyrolysis) resulted in a complex mixture of products. In consequence we did not examine this method. Very recently (and after the present work was completed) Godefroi reported[12] a method whereby the acetal (**7**) (derived from ascorbic acid) could be converted in excellent yield, and on a multi-gram scale, into the corresponding butenolide. This may well represent the method of choice for the production of chiral butenolides.



Our efforts were then concentrated upon deoxygenation *via* the thioxocarbonate (**8**; R=$SiPh_2Bu^t$). These reactions have been accomplished most often using the Corey-Winter method,[11a] but Camps reported[9b] that the thioxocarbonate (**8**; R = Me) did not yield the expected product using this method. We thus attempted a modified method[11b] which involved reaction of compound (**8**; R = $SiPh_2Bu^t$), formed from (**9**) and thiocarbonyl-

† Professor J. Font, and Drs. G. W. J. Fleet and A. Davidson have since informed us that the deoxygenation of (**5**; R = H) can be carried out on the 10 g scale using a Kugelröhr apparatus, but there is some concern that racemisation can occur at C-4 during subsequent protection of the primary hydroxy group. In addition, thermal deoxygenation of the 5-*O*-protected orthoesters is, unfortunately, much less efficient.

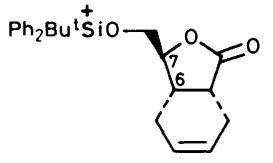
di-imidazole (refluxing acetone), with neat 1,3-dimethyl-2-phenyl-1,3-diazaphospholidine. A multitude of products was obtained and the reaction was not further investigated.

Finally, the method of Ireland[11c] was employed (Raney nickel in refluxing THF), and in this way we were able to obtain the desired butenolide (**4**) routinely and efficiently on a 10 g scale: three steps from ribonolactone *via* compounds (**9**) and (**8**; R = $SiPh_2Bu^t$) in an overall yield of 60%.

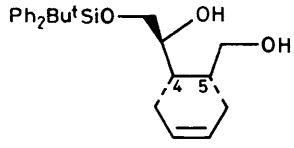
An attempt was made to remove the silyl ether grouping, in order to assess the optical purity of the resultant alcohol. However, extensive decomposition (and presumably racemisation) occurred using fluoride or acid, and these attempts were then abandoned. The $[\alpha]_D$ values obtained for our samples of compound (**4**) did, however, compare very favourably (within 2°) with a sample supplied by Professor S. V. Ley, which had been prepared from L-glutamic acid.[8]

The annulation attempts commenced with reactions of the butenolide (**4**) and butadiene under a variety of conditions. In toluene or xylene as solvent, and at temperatures of 180—210 °C, yields of the desired Diels-Alder cycloadduct (**10**) ranged from 0 to 71%. No reaction occurred when butadiene sulphone[13] was used as a source of butadiene (6 h, 110 °C); nor was any reaction observed when 1.5 mol equiv. of $AlCl_3$ were employed (CH_2Cl_2, −78 to −40 °C). This latter method was employed successfully by Fraser-Reid.[1] Yields of 92% have been claimed[14] for the Diels-Alder reaction between methyl acrylate and butadiene using 0.45 mol equiv. of $AlCl_3$ in benzene at 50—60 °C, but in our case only resinous material resulted.

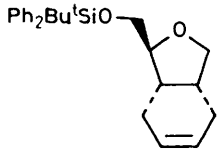
Finally, reproducible conditions were found, and the reaction can be carried out routinely on a multigram scale using 0.33 mol equiv. of $AlCl_3$ in CH_2Cl_2 (55 °C, 1 week) with yields of cycloadduct (**10**) ranging from 75—80%. Under these conditions there was little, if any, loss of the silyl group; and more important, the stereochemical integrity of the the butenolide was not compromised. A control experiment in which the butenolide was subjected to the same conditions as employed in the reaction, but without the butadiene, resulted in a slight fall in the optical rotation (*ca.* 15%; $[\alpha]_D^{20}$ −83.1 to −70.1°), suggesting that a slow racemisation was occurring. However, in the cycloaddition reaction mixture, only one product was discernible on t.l.c. using a number of solvent systems, and this product was isolated, after chromatography, in high yield (75—80%). Furthermore, only one set of ^1H n.m.r. signals was visible, even in the presence of the chiral shift reagent tris[trifluoroacetyl-(+)-camphorato]europium(III), and it seems reasonable to conclude that only one stereoisomer had been produced. We had anticipated that the bulky silyl group would ensure that cyclo-addition had occurred on the opposite face of the molecule, and the value for $J_{6,7}$ of 3.9 Hz would be consistent with the structure assigned to compound (**10**). Similar directing effects were noted by Fraser-Reid.[1]



(**10**)



(**11**)



(**12**)

Reduction of this lactone to the diol (**11**) was achieved in quantitative yield using $LiBH_4$ in THF, and this was converted

Table 1. Atomic co-ordinates (× 10^{-4}) with estimated standard deviations in parentheses

Atom	*x*	*y*	*z*	Atom	*x*	*y*	*z*
Si(A)	5 572[a]	7 123[a]	6 180[a]	Si(B)	4 413(4)	2 888(2)	3 771(4)
C(41A)	6 898(9)	7 641(4)	6 783(8)	C(11B)	2 984(15)	3 575(7)	4 773(18)
C(42A)	8 365(13)	8 184(6)	5 612(13)	C(12B)	2 486(36)	4 138(15)	3 419(35)
C(43A)	8 832(14)	8 809(6)	6 442(13)	C(13B)	3 900(27)	4 075(11)	5 564(31)
O(44A)	7 494(9)	9 227(4)	7 006(9)	C(14B)	1 327(19)	3 095(8)	6 128(27)
C(45A)	6 735(16)	9 012(8)	8 785(17)	C(21B)	5 030(13)	2 221(6)	5 392(15)
C(46A)	7 659(15)	8 388(7)	9 474(14)	C(22B)	6 170(15)	2 471(9)	6 169(17)
C(47A)	9 298(15)	8 461(7)	7 984(15)	C(23B)	6 520(17)	1 935(11)	7 456(17)
C(48A)	8 208(18)	8 541(10)	10 939(16)	C(24B)	5 769(21)	1 198(10)	7 891(21)
C(49A)	9 944(17)	9 021(8)	10 160(19)	C(25B)	4 587(21)	921(10)	7 288(21)
C(50A)	10 582(16)	9 071(8)	8 258(15)	C(26B)	4 284(16)	1 444(7)	6 009(17)
O(51A)	10 693(14)	9 315(8)	10 927(15)	C(31B)	6 320(16)	3 441(6)	1 912(16)
C(11A)	3 883(16)	6 509(6)	8 241(14)	C(32B)	6 028(19)	3 765(8)	368(20)
C(13A)	2 507(29)	6 062(11)	7 763(24)	C(33B)	7 386(25)	4 233(10)	−1 004(21)
C(12A)	4 697(29)	5 984(11)	9 243(26)	C(34B)	9 225(21)	4 312(8)	−994(24)
C(14A)	3 013(20)	7 065(8)	9 226(18)	C(35B)	9 283(18)	3 955(9)	491(21)
C(21A)	4 562(12)	7 815(6)	4 957(13)	C(36B)	7 996(14)	3 532(7)	1 887(17)
C(22A)	3 660(15)	7 581(8)	3 884(17)	O(41B)	3 200(8)	2 363(3)	3 076(9)
C(23A)	2 949(15)	8 155(11)	3 049(17)	C(42B)	3 723(15)	1 808(8)	2 043(15)
C(24A)	3 113(14)	8 917(9)	3 159(17)	C(43B)	2 170(16)	1 258(7)	2 252(17)
C(25A)	3 918(15)	9 145(7)	4 183(17)	O(44B)	1 508(11)	760(4)	3 964(11)
C(26A)	4 660(11)	8 609(6)	5 060(12)	C(45B)	15(18)	993(7)	4 812(17)
C(31A)	6 871(15)	6 487(6)	4 889(15)	C(46B)	−893(15)	1 286(7)	3 551(17)
C(32A)	8 269(19)	6 247(8)	5 296(19)	C(47B)	614(15)	1 657(6)	2 033(15)
C(33A)	9 284(21)	5 778(8)	4 420(21)	C(48B)	−1 761(20)	611(9)	3 115(24)
C(34A)	8 984(22)	5 544(8)	3 050(21)	C(49B)	−1 335(26)	864(9)	1 223(26)
C(35A)	7 682(20)	5 803(10)	2 621(22)	C(50B)	119(32)	1 528(12)	446(24)
C(36A)	6 680(19)	6 265(8)	3 484(18)	O(51B)	−2 092(26)	598(8)	404(25)

[a] Fixed co-ordinates

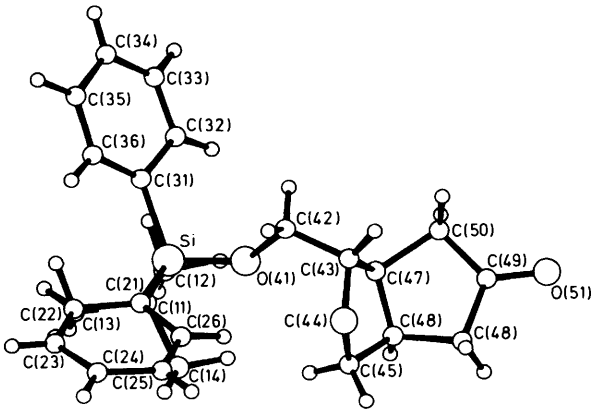


Figure 1. The structure of molecule A projected onto the plane of atoms Si(A), O(41A), C(31A)

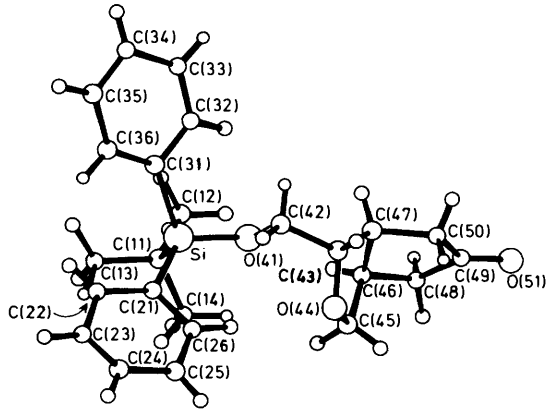


Figure 2. The structure of molecule B projected onto the plane of atoms Si(B), O(41B), C(31B)

Table 2. Molecular dimensions in A and B.

(*a*) Distances (Å)

	Molecule A	Molecule B		Molecule A	Molecule B
Si–O(41)	1.657(8)	1.648(8)	C(11)–C(13)	1.553(29)	1.518(31)
Si–C(11)	1.912(9)	1.886(13)	C(11)–C(12)	1.471(27)	1.540(33)
Si–C(21)	1.855(11)	1.847(13)	C(11)–C(14)	1.492(20)	1.537(17)
Si–C(31)	1.878(11)	1.875(10)	C(21)–C(22)	1.467(20)	1.421(21)
O(41)–C(42)	1.433(11)	1.441(16)	C(21)–C(26)	1.402(14)	1.368(14)
C(42)–C(43)	1.514(17)	1.498(18)	C(22)–C(23)	1.383(22)	1.409(22)
C(43)–O(44)	1.385(13)	1.447(14)	C(23)–C(24)	1.351(25)	1.311(25)
C(43)–C(47)	1.516(18)	1.558(19)	C(24)–C(25)	1.370(22)	1.359(28)
O(44)–C(45)	1.407(15)	1.362(16)	C(25)–C(26)	1.380(17)	1.376(22)
C(45)–C(46)	1.504(19)	1.535(22)	C(31)–C(32)	1.388(22)	1.431(23)
C(46)–C(47)	1.517(15)	1.476(14)	C(31)–C(36)	1.395(22)	1.391(19)
C(46)–C(48)	1.537(21)	1.515(24)	C(32)–C(33)	1.374(22)	1.389(19)
C(47)–C(50)	1.565(20)	1.601(29)	C(33)–C(34)	1.412(28)	1.370(29)
C(48)–C(49)	1.491(18)	1.506(29)	C(34)–C(35)	1.333(27)	1.386(27)
C(49)–C(50)	1.527(20)	1.489(27)	C(35)–C(36)	1.355(23)	1.351(16)
C(49)–O(51)	1.205(23)	1.224(34)			

(*b*) Angles (°)

O(41)–Si–C(11)	105.2(5)	104.1(5)	C(47)–C(50)–C(49)	105.8(9)	103.3(14)
O(41)–Si–C(21)	109.3(4)	109.6(5)	Si–C(11)–C(13)	107.7(9)	110.5(11)
C(11)–Si–C(21)	110.1(5)	109.9(6)	Si–C(11)–C(12)	110.0(13)	110.0(13)
O(41)–Si–C(31)	106.7(5)	108.4(5)	C(13)–C(11)–C(12)	114.0(13)	108.3(12)
C(11)–Si–C(31)	112.5(4)	112.3(5)	Si–C(11)–C(14)	108.3(7)	110.3(9)
C(21)–Si–C(31)	112.5(5)	112.2(5)	C(13)–C(11)–C(14)	106.8(13)	109.9(15)
Si–O(41)–C(42)	123.3(7)	127.0(7)	C(12)–C(11)–C(14)	109.7(14)	107.8(14)
O(41)–C(42)–C(43)	110.0(8)	108.5(9)	Si–C(21)–C(22)	123.8(8)	124.3(8)
C(42)–C(43)–O(44)	112.0(10)	109.4(12)	Si–C(21)–C(26)	118.5(9)	119.9(11)
C(42)–C(43)–C(47)	113.0(9)	116.3(10)	C(22)–C(21)–C(26)	117.7(10)	115.6(12)
O(44)–C(43)–C(47)	105.8(9)	103.9(9)	C(21)–C(22)–C(23)	118.1(13)	121.1(13)
C(43)–O(44)–C(45)	111.8(9)	108.4(9)	C(22)–C(23)–C(24)	121.8(15)	117.4(16)
O(44)–C(45)–C(46)	108.2(10)	108.6(11)	C(23)–C(24)–C(25)	121.1(13)	125.3(17)
C(45)–C(46)–C(47)	102.7(9)	99.4(10)	C(24)–C(25)–C(26)	120.7(12)	116.6(14)
C(45)–C(46)–C(48)	115.0(12)	112.7(11)	C(21)–C(26)–C(25)	120.5(11)	123.8(13)
C(47)–C(46)–C(48)	106.1(11)	106.4(12)	Si–C(31)–C(32)	116.8(11)	116.9(10)
C(43)–C(47)–C(46)	104.2(10)	107.4(10)	Si–C(31)–C(36)	128.0(11)	125.6(10)
C(43)–C(47)–C(50)	111.2(9)	114.7(13)	C(32)–C(31)–C(36)	115.0(12)	117.5(10)
C(46)–C(47)–C(50)	104.1(10)	105.8(12)	C(31)–C(32)–C(33)	120.6(17)	118.5(16)
C(46)–C(48)–C(49)	107.0(10)	104.9(12)	C(32)–C(33)–C(34)	121.8(17)	122.7(17)
C(48)–C(49)–C(50)	108.4(13)	110.6(19)	C(33)–C(34)–C(35)	117.3(15)	117.2(13)
C(48)–C(49)–O(51)	124.8(13)	126.2(16)	C(34)–C(35)–C(36)	121.0(19)	122.5(15)
C(50)–C(49)–O(51)	126.8(11)	123.0(20)	C(31)–C(36)–C(35)	124.2(16)	121.2(14)

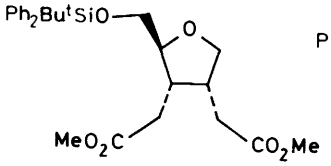
directly into the oxabicycle (**12**) (83% yield) upon treatment with one equivalent of tosyl chloride in pyridine at 0—5 °C.

Oxidative cleavage of the cyclohexene ring at first proved difficult. Reaction with excess $NaIO_4$ and a catalytic amount of RuO_2[15] produced the desired diester (**13**) (after esterification of the diacid with diazomethane), but with concomitant formation of several other products. These included lactones (reintroduction of a carbonyl into the tetrahydrofuran ring) and products

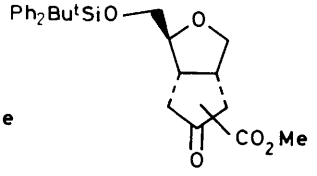
Table 3. Selected torsion angles in A and B

	Molecule A	Molecule B
C(21)–Si–O(41)–C(42)	−61.8	−69.7
C(31)–Si–O(41)–C(42)	60.2	53.0
C(11)–Si–O(41)–C(42)	180.0	−172.7
O(41)–Si–C(21)–C(26)	−15.7	−9.4
O(41)–Si–C(31)–C(32)	30.0	39.0
Si–O(41)–C(42)–C(43)	154.9	159.0
O(41)–C(42)–C(43)–O(44)	−58.1	−67.6
C(42)–C(43)–O(44)–C(45)	107.0	108.9
C(43)–C(44)–O(45)–C(46)	−0.0	33.0
O(44)–C(43)–C(47)–C(46)	26.2	−7.1
O(44)–C(45)–C(46)–C(47)	16.4	−35.4
C(45)–C(46)–C(47)–C(43)	−25.3	23.9
C(48)–C(46)–C(47)–C(50)	−29.7	29.7
C(45)–C(46)–C(48)–C(49)	−89.0	−136.5
C(47)–C(46)–C(48)–C(49)	23.8	−28.6
C(46)–C(48)–C(49)–C(50)	−7.7	16.2
C(48)–C(46)–C(47)–C(50)	−29.7	29.7
C(46)–C(47)–C(50)–C(49)	24.9	−19.2
C(48)–C(49)–C(50)–C(47)	−10.7	1.5

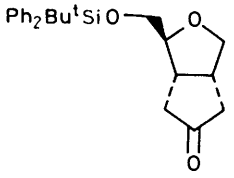
of oxidation of the phenyl groups. Reaction with $KMnO_4$ in the presence of $Bu_4N^+HSO_4^-$—the method[16] employed by Baldwin in his synthesis of tabtoxin[17]—also provided a complex mixture of products. Finally, success was attained using excess $NaIO_4$ and a catalytic amount of $KMnO_4$,[18] and the diester (**13**) was obtained in 80% yield after esterification.



(**13**)



(**14**)



(**15**)

The last two steps of the sequence were executed without problem by means of a Dieckmann cyclisation ($K^+Bu^tO^-$ in benzene at room temperature) to yield compound (**14**), and thence formation of the desired oxabicyclo[3.3.0]octanone (**15**) by demethoxycarbonylation (NaCl in Me_2SO). This crystalline compound was examined by *X*-ray crystallography, and these results are discussed below.

The overall sequence from (**4**) to (**15**) can be carried out reproducibly, and in good yield (32—41% for the six steps) on a multigram scale (at least 3 g for each step). This useful chiral intermediate is thus available for the synthesis of natural products *etc.*, and in the accompanying paper we describe its use in the preparation of a biologically active prostacyclin analogue.

Discussion of X-*Ray Data.*—There are two independent molecules in the unit cell which are shown in Figures 1 and 2 together with the atomic numbering scheme. Both figures are projections onto the plane of atoms C(31), Si, and O(41) and clearly show the different conformations of the two molecules, particularly for the two five-membered rings. These differences are also apparent in the torsion angles given in Table 3.

Essentially the difference is located in the five-membered ring containing atoms C(43), O(44), C(45), C(46), and C(47). In molecule A, the ring is an envelope with C(47A) 0.41 Å from the plane of the remaining four atoms (maximum deviation 0.01 Å). In molecule B, the ring is also an envelope but this time C(45B) is 0.47 Å from the plane of the remaining four atoms (maximum deviation 0.04 Å).

The conformations of the lactone ring are also different. In molecule A, C(46A) is 0.20 and C(47A) is −0.28 Å from the plane of atoms C(48A)–C(49A)–C(50A) while in molecule B the ring has more of an envelope shape with C(46B) 0.42 and C(47B) only −0.04 Å from the plane of atoms C(48B)–C(49B)–C(50B).

The remaining features of the molecules have much in common. The Si–C(11) bonds are longer [1.912(9), 1.886(13) Å] than the Si–C(benzene) bonds [Si–C(21) 1.855(11), 1.847(13) Å; Si–C(31) 1.878(11), 1.875(10) Å]. As is apparent from the torsion angles, the two phenyl rings have similar orientations in the two molecules. It is interesting that in both molecules Si–C(21)–C(22) is larger than Si–C(21)–C(26) [123.8(8), 124.3(8) *versus* 118.5(9), 119.9(11)°] and Si–C(31)–C(36) is much larger than Si–C(31)–C(32) [128.0(11), 125.6(10) versus 116.8(11), 116.9(10)°]. No doubt this is a consequence of the crowding around the silicon atom.

There are no intramolecular distances of note in the unit cell.

Experimental

I.r. spectra were recorded on a Perkin-Elmer 157 double-beam grating spectrophotometer or a Perkin-Elmer 1420 ratio recording spectrophotometer (liquid films for oils, Nujol mulls for solids). ^1H N.m.r. spectra were recorded with a Varian T-60 (60 MHz), a varian HA100 (100 MHz) or a Perkin-Elmer R34 (220 MHz) instrument. 250 MHz ^1H n.m.r. spectra were recorded at Tate and Lyle Research Centre, Reading, on a Bruker WH250 instrument and 400 MHz ^1H n.m.r. spectra were recorded at the Chemistry Department at Warwick University on a Bruker WH400 instrument. Tetramethylsilane was used as the internal standard. ^{13}C N.m.r. spectra were recorded at the City of London Polytechnic on a Jeol FX90Q (90 MHz) instrument.

Accurate mass spectra were obtained from P.C.M.U. (Harwell) using a VG Analytical ZAB-IF Spectrometer and associated data system. Elemental analyses were performed at Butterworth Laboratories Ltd., or at the Chemistry Department, City University.

Analytical t.l.c. was performed on plastic sheets precoated with 0.25 mm of silica gel containing a fluorescent indicator UV_{254} ('Polygram', supplied by Camlab, Cambridge). The t.l.c. strips were viewed under ultraviolet light and then sprayed with dilute $H_3PO_4 \cdot 12MoO_3 \cdot 24H_2O$ solution (alcoholic) or dilute $KMnO_4$ solution (aqueous). Flash chromatography was performed on silica gel at 32—63 μm particle size ('Woelm' silica gel, supplied by Park Scientific Ltd.).

Purification of solvents and reagents was generally carried out according to Perrin. Solvents were usually dried by refluxing over a drying agent for 2 h followed by distillation; for example, THF was distilled from CaH_2, DME from $LiAlH_4$, and pyridine from BaO. The solvents were then stored in the dark over 4A sieves, in a tightly stoppered bottle, under an atmosphere of nitrogen. Acetone and DMF were dried over 3A sieves.

(+)-5-O-(*Diphenyl-t-butylsilyl*)-D-*ribono*-1,4-*lactone* (**9**).—Imidazole (20.23 g, 0.297 mol), followed by diphenyl-t-butylsilyl

chloride (83.5 ml, 40.69 g, 0.148 mol) were added to a solution of D-ribonolactone (20 g, 0.135 mol) in dry DMF (200 ml) and the colourless solution so formed was allowed to stand at room temperature overnight. The reaction mixture was then poured into iced water (200 ml) and was then extracted with ether (2 × 200 ml). The combined organic extracts were washed with water (3 × 100 ml), dried ($MgSO_4$) and concentrated under reduced pressure to a colourless oil. The product was precipitated by trituration with light petroleum to remove diphenyl-t-butylsilanol, and recrystallised by dissolution in ether followed by addition of light petrol to turbulence to yield a white amorphous solid (38.1 g, 84%) which displayed the following characteristics: m.p. 72—74 °C (softened), 83—84 °C (melted); R_F 0.49 (ether); $[\alpha]_D^{24}$ + 45.4° (*c* 5 in ether); $\nu_{max.}$(Nujol) 3 300, 1 785, 1 180, 1 110, 1 080, 975, 935, 725, and 700 cm^{-1}; δ (220 MHz; $CDCl_3$) 1.03 (9 H, s, Bu^t), 3.76 (1 H, dd, 5-H, J_{gem} 12, $J_{4,5}$ = 2 Hz), 3.88 (1 H, dd, 5′-H, $J_{4,5'}$ 2.5 Hz), 3.5—3.9 (2 H, br s, D_2O exch.), 4.44—4.55 (2 H, m, 3-, 4-H), 4.80 (1 H, d, $J_{2,3}$ 5 Hz, 2-H), and 7.30—7.50 and 7.54—7.70 (6 H + 4 H, 2 × m, 2 × Ph) (Found: C, 65.34; H, 6.86. $C_{21}H_{26}O_5Si$ requires C, 65.26; H, 6.78%).

(−)-5-O-(*Diphenyl-t-butylsilyl*)-2,3-O-(*thiocarbonyl*)-D-*ribono*-1,4-*lactone* (**8**; R=$SiPh_2Bu^t$).—To a stirred solution of the diol (**9**), (15 g, 0.039 mol) in dry acetone (500 ml), 1,1′-thiocarbonyldi-imidazole (8.34 g, 0.047 mol) was added. The resulting yellow solution was heated at reflux for 1 h when t.l.c. (ether) indicated the reaction to be complete. The cooled reaction mixture was concentrated under reduced pressure to *ca.* 100 ml and then poured into water (200 ml). The resulting aqueous mixture was extracted with dichloromethane (3 × 100 ml) and the combined organic extracts were washed with saturated aqueous sodium hydrogen carbonate (2 × 100 ml) and water (2 × 100 ml), then dried ($MgSO_4$) and concentrated under reduced pressure to a red oil. Purification by flash chromatography [light petroleum–ether 2:1)] gave the product as a white solid which was recrystallised by dissolution in ether followed by addition of light petroleum to turbulence. The white micro crystalline product (14.1 g, 85%) displayed the following characteristics: m.p. 116.5—117 °C; R_F 0.31 [EtOAc–light petroleum (1:4)]; $[\alpha]_D^{24}$ −2.1° (*c* 10.9, in ether); $\nu_{max.}$(Nujol) 1 800, 1 330, 1 170, 1 115, 1 100, 1 030, 980, 940, and 725 cm^{-1}; δ (100 MHz; $CDCl_3$) 1.03 (9 H, s, Bu^t), 3.77—4.08 (2 H, ABX, $J_{4,5}$ 1.9, $J_{4,5'}$ 1.5, J_{gem} 11.9 Hz, 5-, 5′-H), 4.88—4.96 (1 H, distorted t, 4-H), 5.51 (2 H, dd, $J_{2,3}$ 7.5 Hz, 2-, 3-H), and 7.30—7.52 and 7.52—7.70 (6 H + 4 H, 2 × m, 2 × Ph) (Found: C, 61.68; H, 5.92. $C_{22}H_{24}O_5SiS$ requires C, 61.56; H, 5.71%).

(−)-5-O-*Diphenyl-t-butylsiloxymethylfuran*-2(5H)-*one* (**4**).—The thioxocarbonate (**8**) (13.78 g, 0.032 mol) was added to a suspension of Raney nickel (*ca.* 41 g) which had been pretreated by refluxing in acetone (150 ml; AR) for 6 h. The vigorously stirred reaction mixture was then heated to reflux until t.l.c. [EtOAc–light petroleum (1:3)] indicated the reaction to be complete (1.5 h). The cooled reaction mixture was then filtered, and the solid residue washed with ether. The filtrate was concentrated to a pale yellow oil which was crystallised by dissolution in hot petrol followed by cooling. The product was recrystallised from light petroleum to give white crystals (9.3 g, 82%) which displayed the following characteristics: m.p. 79—80 °C; R_F 0.23 [ether–light petroleum, (2:1)]; $[\alpha]_D^{24}$ −81.8° (*c* 10.5, in $CHCl_3$); $\nu_{max.}$(Nujol) 1 770, 1 750, 1 616, 1 430, 1 330, 1 160, 1 130, 1 110, 1 020, 750, and 710 cm^{-1}; δ (60 MHz; $CDCl_3$) 1.05 (9 H, s, Bu^t), 3.86 (2 H, d, $J_{4,5}$ 5 Hz, 5-, 5′-H), 5.0 (1 H, m, 4-H), 6.1 (1 H, dd, $J_{2,4}$ 2, $J_{2,3}$ 6 Hz, 2-H), 7.2—7.8 (11 H, m, 2 × Ph + 3-H) (Found: C, 71.33; H, 7.00. $C_{21}H_{24}O_3Si$ requires C, 71.56; H, 6.87%).

(+)-(1R,6S,7S)-7-*Diphenyl-t-butylsiloxymethyl*-8-*oxabicyclo*-[4.3.0]*non*-3-*en*-9-*one* (**10**).—The butenolide (**4**) (7.234 g, 0.021 mol) in dry dichloromethane (50 ml) was added to a stirred suspension of aluminium chloride (0.926 g, 7 mmol) in dry dichloromethane (25 ml). The yellow solution was then transferred to a tube prepared for sealing and butadiene (40 ml; dried by passage through 4A sieves) was bubbled in at −5 °C. The tube was then sealed and heated in an oil bath at 55—60 °C for 1 week. The reaction mixture was then poured into a cold (0 °C) saturated aqueous sodium hydrogen carbonate solution (150 ml) and the solution extracted with dichloromethane (2 × 150 ml). The combined organic extracts were washed with water (2 × 100 ml), dried ($MgSO_4$) and concentrated under reduced pressure to a pale yellow oil. Purification by flash chromatography [ether–light petroleum (1:3)] gave the product as a white solid which was recrystallised from light petroleum (6.4 g, 76%), m.p. 73—74 °C; R_F 0.34 [ether–light petroleum (1:3)]; $[\alpha]_D^{24}$ +19.6° (*c* 10, in $CHCl_3$); $\nu_{max.}$(Nujol) 1 780br, 1 590, 1 430, 1 360, 1 170, 1 110, 820, 740, and 700 cm^{-1}; δ_H (400 MHz; $CDCl_3$) 1.07 (9 H, s, Bu^t) 1.88—1.94 (1 H, m, 2-H), 2.20—2.45 (3 H, m, 2′-, 5, 5-H), 2.67—2.73 (1 H, m, $J_{6,7}$ 3.9 Hz, 6-H), 3.00 (td, 1 H, $J_{1,6}$ 4.4, $J_{1,2}$ 8.6 Hz, 1-H), 3.76 and 3.87 (2 × dd, 10-, 10′-H, J_{gem} 11.4, $J_{7,10}$ 3.9, $J_{7,10'}$ 3.9 Hz), 4.15 (1 H, q, 7-H), 5.76—5.86 (2 H, m, CH=CH), and 7.40—7.47 and 7.65—7.68 (6 H + 4 H, 2 × m, 2 × Ph); δ_C (90 MHz; $CDCl_3$) 19.18 (Bu^{t}C), 22.54 (C-5), 25.52 (C-2), 26.76 (Me_3C), 34.08 (C-6), 37.41 (C-1), 64.28 (C-10), 84.84 (C-7), 135.52 (C-4), 135.60 (C-3), and 179.45 (C-9) (Found: C, 73.77; H, 7.49. $C_{25}H_{30}O_3Si$ requires C, 73.86; H, 7.44%).

(4S,5R)-4-[(S)-2-*Diphenyl-t-butylsiloxy*-1-*hydroxyethyl*]-5-*hydroxymethylcyclohexene* (**11**).—Lithium borohydride (11.5 ml, 0.023 mol; 2M solution in THF) was added to a solution of the lactone (**10**), (9.4 g, 0.023 mol) in dry THF (100 ml) at room temperature under nitrogen. The colourless reaction mixture was left to stir at room temperature for 1.5 days. Water (150 ml) was then added and the product extracted with dichloromethane (3 × 100 ml). The combined organic extracts were washed with water (2 × 50 ml), dried ($MgSO_4$) and concentrated under reduced pressure to a colourless oil (9 g, quantitative), R_F 0.29 [ether–light petroleum (1:1)]; $\nu_{max.}$ (thin film) 3 560, 3 300br, 1 590, 1 470, 1 430, 1 115, 830, 740, and 705 cm^{-1}; δ (220 MHz; $CDCl_3$) 1.05 (9 H, s, Bu^t), 1.74—2.30 (6 H, complex, 3-, 4-, 5-, 6-H), 3.44—4.00 (7 H, m, all -CHO- and 2 × OH), 5.52 (m, 2 H, HC=CH), and 7.30—7.40 and 7.60—7.70 (6 H, 4 H, 2 × m, 2 × Ph); (Found: M^+, 410.2286. Calc. for $C_{25}H_{34}O_3Si$: M^+, 410.2277) (Found: M^+ − Bu^t 353.1578. Calc. for $C_{21}H_{25}O_3Si$: M − Bu^t, 353.1573).

(1R,6S,7S)-7-*Diphenyl-t-butylsiloxymethyl*-8-*oxabicyclo*-[4.3.0]*non*-3-*ene* (**12**).—Toluene-*p*-sulphonyl chloride (4.5 g, 0.024 mol) was added to a solution of the crude diol (**11**), (9.83 g, 0.023 mol) in dry dichloromethane (50 ml) and dry pyridine (15 ml) at 0 °C and the reaction mixture was stored in the fridge (4—5 °C) overnight. T.l.c. [ether–light petroleum (1:2)] then indicated that some starting material was still present. A further aliquot of toluene-*p*-sulphonyl chloride (1 g, 5 mmol, *i.e.* 0.029 mol in total) was, therefore, added at 0 °C and the reaction mixture placed in the fridge overnight. The reaction mixture was then poured into water (100 ml), dichloromethane (50 ml) was added and the layers were separated. The aqueous layer was further extracted with dichloromethane (50 ml) and the combined organic phases were washed with water (2 × 50 ml), stirred over $NaHSO_4$, dried ($MgSO_4$) and concentrated under reduced pressure to a pale yellow oil. Purification by flash chromatography gave the product as a colourless oil (7.5 g, 83%), R_F 0.49 [ether–light petroleum (1:3)]; $\nu_{max.}$ (thin film):

2 940, 2 860, 1 590, 1 475, 1 430, 1 120, 830, 745, and 705 cm^{-1}; δ (400 MHz; $CDCl_3$) 1.09 (9 H, s, Bu^t), 1.80—2.03 (2 H, complex, 1-, 6-H), 2.15—2.38 (4 H, complex, 2-, 5-H), 3.63 (1 H, dd, J_{gem} 7.84, $J_{1,9}$ 3.5 Hz, 9-H), 3.69—3.79 (3 H, complex, 7-, 10-H); 3.92 (1 H, dd, $J_{1,9'}$ 5.0 Hz, 9'-H,), 5.63—5.68 and 5.70—5.75 (2 × 1 H, 2 × m, CH=CH), and 7.25—7.46 and 7.67—7.74 (6 H + 4 H, 2 × m, 2 × Ph) (Found: $M^+ - Bu^t$ 335.1467. Calc. for $C_{21}H_{23}O_2$2i: $M - Bu^t$, 335.1461).

(2S,3R,4S)-2-*Diphenyl-t-butylsiloxymethyl*-3,4-*bis*(*methoxycarbonylmethyl*)*tetrahydrofuran* (**13**).—The alkene (**12**) (3.724 g, 9.5 mmol) was dissolved in a 2:1 acetone–water mixture (375 ml), and sodium periodate (22.35 g, 0.105 mol) was added followed by potassium permanganate (0.105 g, 0.95 mmol). The purple suspension was stirred vigorously at room temperature overnight. Water (200 ml), followed by dilute HCl (10 ml; 2M) was then added and the mixture extracted with ether (2 × 200 ml). The combined organic extracts were washed with saturated aqueous sodium chloride (40 ml), dried ($MgSO_4$) and concentrated under reduced pressure to a white solid foam (4.6 g, 100% crude yield).

The diacid was not characterised but was dissolved in ether (20 ml) and a solution of diazomethane in ether added until nitrogen evolution ceased and the characteristic yellow colour of diazomethane persisted. The solution was concentrated under reduced pressure and the resulting yellow oil purified by flash chromatography [light petroleum–ether (1:1)] to give the product as a colourless oil (3.7 g, 80% over the two steps), R_F 0.25 [light petroleum–ether (2:1)]; $\nu_{max.}$ (thin film) 1 740, 1 590, 1 430, 1 365, 915, 830, 740, and 710 cm^{-1}; δ (250 MHz; $CDCl_3$) 1.08 (9 H, s, Bu^t), 2.24—2.48 (4 H, complex, CH_2CO_2), 2.70—2.91 (2 H, complex, 3-, 4-H), 3.66 and 3.68 (2 × 3 H, 2 × s, 2 × CO_2Me), 3.6—4.00 (m, 5 H, all CHO), and 7.34—7.45 and 7.64—7.72 (6 H + 4 H, 2 × m, 2 × Ph) (Found: $M^+ - Bu^t$, 427.1576. Calc. for $C_{23}H_{27}O_6Si$: $M - Bu^t$, 427.1577).

2-*Diphenyl-t-butylsiloxymethyl*-6-*methoxycarbonyl*-3-*oxabicyclo*[3.3.0]*octan*-7-*one* (*and the* 8-*Methoxycarbonyl Isomer*) (**14**).—Potassium t-butoxide (1.152 g, 0.01 mol) was added to a solution of the diester (**13**) (3.312 g, 6.84 mmol) in dry benzene (200 ml) at room temperature under nitrogen. The yellow solution so formed was stirred at room temperature for 4 h. Aqueous HCl (30 ml; 5%) was added and the mixture shaken until the aqueous layer remained acidic. The organic layer was then concentrated to *ca.* one quarter of the original volume, dried ($MgSO_4$) and concentrated further to an amber oil which was not purified further (3.20 g, 100% crude yield), R_F 0.39 [ether–light petroleum (1:2)]; $\nu_{max.}$ (thin film) 2 960, 2 940, 2 860, 1 760, 1 730, 1 660, 1 620, 1 450, 1 430, 1 365, and 1 115 cm^{-1}; δ (60 MHz; $CDCl_3$) 1.08 (9 H, s, Bu^t), 2.0—4.5 (10 H, complex), 3.40 (3 H, s, CO_2Me), and 7.3—7.8 (10 H, m, 2 × Ph).

(+)-(1R,2S,5S)-2-*Diphenyl-t-butylsiloxymethyl*-3-*oxabicyclo*[3.3.0]*octan*-7-*one* (**15**).—The crude β-keto ester (**14**) (3.2 g, 6.84 mmol) was dissolved in distilled Me_2SO (10 ml). Sodium chloride (0.40 g, 6.84 mmol) was added followed by water (*ca.* 0.01 ml, 0.093 mol). The yellow reaction mixture was heated at 100 °C for 5.5 h. Water (20 ml) was then added and the product extracted into dichloromethane (3 × 20 ml). The combined organic extracts were dried ($MgSO_4$) and concentrated under reduced pressume to an orange oil which was purified by flash chromatography [light petroleum–ether (1:1)]. The product, obtained as a colourless oil (2.25 g, 83% over the two steps) was crystallised from aqueous ethanol to give white crystals, m.p. 40—42 °C, R_F 0.38 [ether–light petroleum (1:1)]; $[\alpha]_D^{24}$ +3.3° (*c* 3.6, in $CHCl_3$); $\nu_{max.}$(Nujol): 1 745, 1 590, 1 115, 825, 745, and 705 cm^{-1}; δ (400 MHz; $CDCl_3$) 1.05 (9 H, s, Bu^t), 2.12—2.23 (2 H, m, 6-, 8-H), 2.46—2.53 (2 H, m, 6'-, 8'-H), 2.84 (1 H, m, 1-H), 2.97 (1 H, m, 5-H), 3.61 (1 H, dd, J_{gem} 8.9, $J_{4,5}$ 4.9 Hz, 4-H), 3.66—3.78 (3 H, m, 2-, and 9-H), 4.15 (1 H, dd, $J_{4',5}$ 6.7 Hz, 4'-H), and 7.36—7.44 and 7.64—7.68 (6 H + 4 H, 2 × m, 2 × Ph); (Found: C, 72.98; H, 7.62. $C_{24}H_{30}O_3Si$ requires: C, 73.06, H, 7.65%).

X-*Ray Structure Elucidation*.—Crystals of $C_{24}H_{30}O_3Si$, M = 394.3, triclinic, space group $P\bar{1}$, Z = 2, a = 8.351(9), b = 17.400(8), c = 8.591(8) Å, α = 77.8(1), β = 71.1(1), γ = 93.8(1)°, U = 1 142.3 Å^3, D_c = 1.12 g cm^{-3}, $F(000)$ = 424, λ = 0.7107 Å, μ = 1.23 cm^{-1}.

Precession photographs established the preliminary cell constants and space group. A crystal was mounted to rotate around the *a* axis on a Stoe STAD12 diffractometer and data was collected *via* variable width ω scan. Background counts were 20 s and a scan rate of 0.0333° s^{-1} was applied to a width of (2.0 + 0.5 tan μ/sin θ). 6 436 Independent reflections with 2θ < 50° were measured of which 3 423 having $I > 3\sigma(I)$ were used in subsequent refinements. The structure could not be solved by direct methods. The positions of the silicon atoms were obtained from the Patterson function. We were not able to disentangle the structure in $P1$ so we worked in $P\bar{1}$. Most of the atoms of one complete molecule were located in $P\bar{1}$ by Fourier methods. We then reverted to $P1$ to obtain the positions of the other molecule by Fourier methods. Eventually all non-hydrogen atoms were located and refined anisotropically. Hydrogen atoms were fixed in trigonal positions and those in the same ring were given a common thermal parameter which was refined. The structure was refined using full-matrix least squares. The weighting scheme used was $w = 1/(\sigma^2(F) + 0.003F^2)$ where $\sigma(F)$ was taken from counting statistics. This gave equivalent values of $w\Delta^2$, over ranges of F_o and sin θ/λ. Calculations were performed using SHELX 76[19] and local programs on the Amdahl V7/A computer at the University of Reading. The final R factor was 0.069 (R_w = 0.076). (The opposite and rejected enantiomorph gave R 0.070). Final co-ordinates are given in Table 1 and molecular dimensions in Table 2. Selected torsion angles are given in Table 3.

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