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CHIRAL SYNTHESIS OF ASYMMETRICALLY TETRA-*C*-SUBSTITUTED CYCLOPENTANE DERIVATIVES BY DIELS–ALDER ADDITION OF CYCLOPENTADIENE TO UNSATURATED ACYCLIC-SUGAR DERIVATIVES*

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ABSTRACT

Optically pure, substituted cyclopentane derivatives of interest in synthesis of prostaglandin analogs have been obtained by stereocontrolled addition of cyclopentadiene to *trans* α,β-unsaturated sugar derivatives. Methyl (*E*)-4,5,6,7-tetra-*O*-acetyl-2,3-dideoxy-D-*arabino*-hept-2-enonate (**2**), obtained by Wittig addition of Ph_3PCHCO_2Me to *aldehydo*-D-arabinose tetraacetate, reacted with cyclopentadiene in boiling toluene to give 40% of a crystalline, norbornene adduct (**3**) having the 5*S*-*exo* ester, 6*S*-*endo* sugar-chain configuration, as established by crystallography and by conversions into the known, crystalline (2*S*,3*S*)-bis(*p*-tolylsulfonyloxymethyl)bicyclo[2.2.1]heptane. Likewise, the L enantiomer (**19**) of **2** was converted into the crystalline enantiomer of **3**; chromatographic resolution of the other Diels–Alder adducts from the reaction afforded lesser amounts of the other three possible isomeric adducts, which were characterized by appropriate conversions. The Ph_3PCHCO_2Me Wittig adduct (**9**) from 2,3:4,5-di-*O*-isopropylidene-*aldehydo*-D-arabinose with cyclopentadiene in hot toluene gave a crystalline mixture of the isomeric 5*S*,6*S* adducts (**10** and **11**), separable after deacetonation and acetylation as the already characterized product **3** and its 6*S*-*endo* ester, 5*S*-*exo* sugar-chain isomer. Likewise, the L enantiomer of the D dienophile **9** gave a crystalline mixture of 5*R*,6*R* adducts that were the enantiomers of **10** and **11**. A reversed ratio of adducts resulted when the tetraacetylated L dienophile **19** reacted at 0° with cyclopentadiene under $AlCl_3$ catalysis, and 36% of the crystalline 5*S*-*endo* ester, 6*S*-*exo* sugar-chain adduct (**23**) was obtained. Hydroxylation–glycol cleavage of the double bond in **23**, followed by reduction and acetylation, gave 65% of an optically pure cyclopentane derivative having five chiral centers of the same absolute configuration as in prostaglandin $F_{1\alpha}$.

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INTRODUCTION

This work is part of a sustained theme in this laboratory concerned with synthetic applications of unsaturated sugars[1], and, in particular, of recent studies on the use of carbohydrates as asymmetry-transfer agents in generating chiral, noncarbohydrate molecules of potential biological interest. In this context, evaluation of the Diels–Alder reaction between cyclic dienes and unsaturated-sugar dienophiles had as its goal the possibility of developing practical syntheses of optically pure carbocycles bearing multiple carbon substituents capable of differential, synthetic elaboration[5].

The current study focused specifically on the feasibility of producing cyclopentanes bearing multiple carbon substituents of defined relative stereochemistry and enantiomeric homogeneity by way of Diels–Alder reaction between cyclopentadiene and an unsaturated sugar derived by Wittig chain-extension of a protected *aldehydo* sugar. It was hypothesized that a high degree of asymmetric induction in the cyclo-addition reaction, with a dienophile of defined geometrical isomerism, might permit the isolation, through crystallization, of a single one of the eight possible isomeric reaction-products; modification of the reaction conditions (thermal *vs.* acid-catalyzed conditions) might further influence the reaction toward a different isomer as the favored product.

For the present exploratory study, arabinose was chosen as the starting sugar as this pentose is readily available as both the D and L enantiomers, thus affording maximum versatility in accessible stereochemical variants of the target carbocycles.

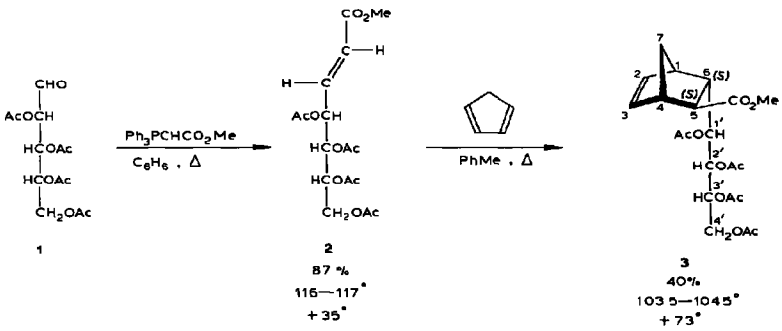
The results indeed confirmed the validity of the hypotheses; use of an arabinose-derived dienophile of *E* configuration allows isolation of a single, crystalline Diels–Alder adduct in the absence of catalyst, and of a different one when a Lewis acid is used; all four possible chiral adducts are thus obtainable by use of the appropriate D- or L-arabinose precursor. One of these four products was readily converted, in good yield, into an optically pure, tetra-*C*-substituted cyclopentane derivative. This product has the relative and absolute configurations present in the carbocyclic nucleus of 9,11-bishomo derivatives of prostaglandin $F_{1\alpha}$.

Although numerous syntheses of prostaglandins or important intermediates have been developed[6], as, for example, from α-tropolone methyl ether[7], many of them require resolution of racemic products and, also, separation of C-15 diastereoisomers. A key, intermediate epoxy-lactone had been synthesized from D-glucose[8]. Fried and co-workers[9] used a Diels–Alder approach to generate racemic 9,11-bis(hydroxymethyl)prostaglandin $F_{1\alpha}$, and found it to be biologically active, but they did not report resolution of the product.

RESULTS AND DISCUSSION

Wittig condensation of 2,3,4,5-tetra-*O*-acetyl-*aldehydo*-D-arabinose[10] (**1**) with Ph_3PCHCO_2Me in boiling benzene gave methyl (*E*)-4,5,6,7-tetra-*O*-acetyl-

2,3-dideoxy-D-*arabino*-hept-2-enonate (**2**), m.p. 116–117°, $[\alpha]_D$ +35°, in 87% yield. The dienophile **2** was treated with a large excess (13 mol. equiv.) of cyclopentadiene in the presence of a small proportion of hydroquinone in boiling toluene for 40 h. From the product mixture, the optically pure norbornene adduct **3** was obtained crystalline, m.p. 103.5–104.5°, $[\alpha]_D$ +73°, in 40% yield. The relative configuration of **3** was determined by ^{1}H-n.m.r. spectroscopy, which indicated the ester group to be *exo* and the C_4 side-chain to be *endo*. The H-5 resonance appeared at δ 1.88 as a doublet of doublets ($J_{5,6}$ 4.7, $J_{5,7syn}$ 1.5 Hz), whereas $J_{4,5}$ was almost zero. These coupling constants indicated that H-5 is *endo*. The H-6 signal appeared at δ 2.82 as a doubled doublet of doublets ($J_{1,6}$ 3.2, $J_{5,6}$ 4.7, and $J_{6,1'}$ 10.5 Hz). No long-range coupling was observed between H-6 and the bridge protons, indicating H-6 to be *exo*. In the norbornene system, it is known[11] that *exo* protons re-

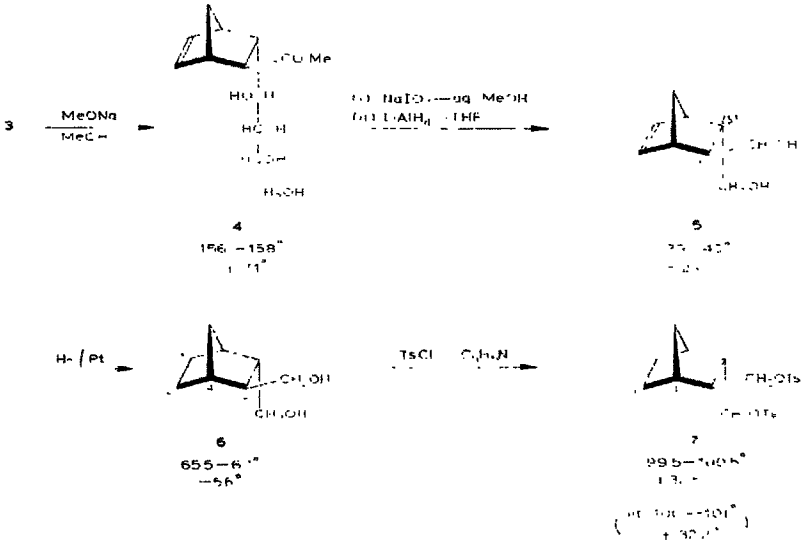


sonate at lower field than *endo* protons, and the foregoing chemical-shift data are in accord with this generalization.

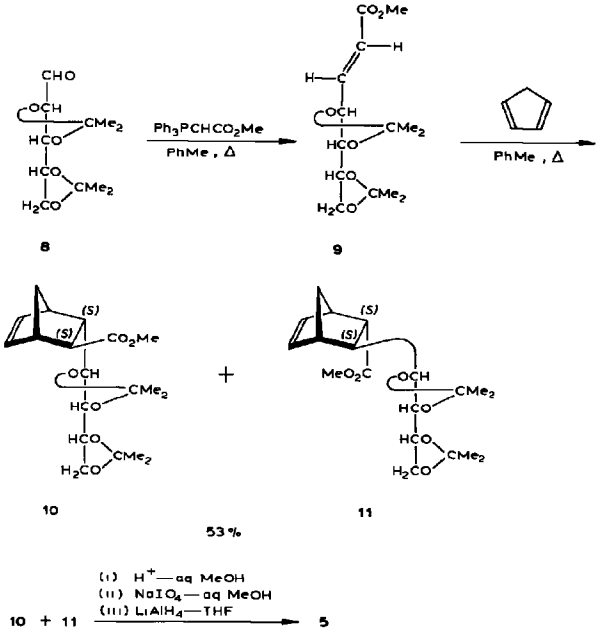
The absolute configuration of **3** was unambiguously confirmed by X-ray crystallographic analysis[3], based on the known D-*arabino* stereochemistry of the side chain, and this established that **3** has the (5*S*)-*exo* ester, (6*S*)-*endo* side-chain structure.

The norbornene adduct **3** was converted into the corresponding bis(hydroxymethyl)-norbornene and -norbornane derivatives. *O*-Deacetylation of **3** with methanolic sodium methoxide gave the crystalline tetrol **4**. The ^{1}H-n.m.r. spectrum of **4** showed the H-6 signal at lower field than that of H-5, and both protons showed coupling constants similar to those of **3**, establishing that no epimerization had occurred during the catalytic transesterification. The tetrol **4** was oxidized with sodium metaperiodate to give an aldehyde that was reduced with lithium aluminum hydride to give the optically pure (5*S*,6*S*)-bis(hydroxymethyl)bicyclo[2.2.1]hept-2-ene (**5**), $[\alpha]_D$ −23° in chloroform. The ^{1}H-n.m.r. spectrum of **5** indicated the two hydroxymethyl groups to be *trans*-disposed. The unsaturated diol **5** was hy-

drogenated in the presence of platinum, to give (2*S*,3*S*)-bis(hydroxymethyl)norbornane (**6**), m.p. 65.5–67°, $[\alpha]_D$ −56° (chloroform). Compound **6** was conventionally *p*-toluenesulfonylated, to give the disulfonate **7**, whose m.p. (99.5–100.5°) and specific rotation ($[\alpha]_D$ +32.5° in acetone) were essentially identical to those of an authentic, optically pure sample reported in the literature[12] (m.p. 100–101°, $[\alpha]_D$ +32.2°).



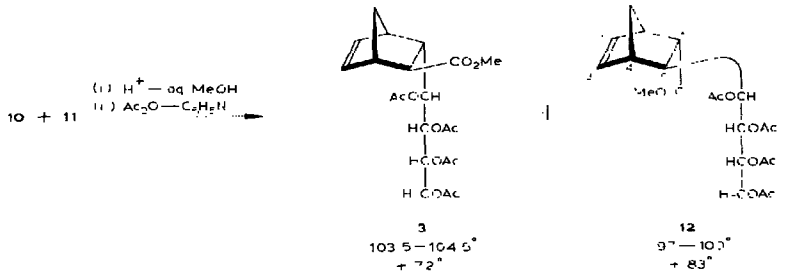
2,3:4,5-Di-*O*-isopropylidene-*aldehydo*-D-arabinose[13] (**8**) underwent the Wittig reaction with Ph_3PCHCO_2Me in boiling toluene to give methyl (*E*)-2,3-dideoxy-4,5:6,7-di-*O*-isopropylidene-D-*arabino*-hept-2-enonate (**9**) as the major product. The dienophile **9** reacted with cyclopentadiene under the conditions used for **2**, and crystalline material, m.p. 83–86°, was obtained in 53% yield. Although this product migrated as a single spot in t.l.c., its ^{1}H-n.m.r. spectrum indicated that it was a mixture of two diastereomers, **10** and **11**, in the ratio of 5:4. To determine the configurations of **10** and **11**, the mixture was transformed into the corresponding bis(hydroxymethyl)norbornene. Acid-catalyzed deacetonation of the mixture, followed by periodate oxidation and subsequent reduction with lithium aluminum hydride, afforded compound **5** ($[\alpha]_D$ −24° in chloroform), indistinguishable from a sample of **5** prepared from the adduct **3**. This result showed that the adducts **10** and **11** had the (5*S*,6*S*) configuration. Deacetonation of the mixture of **10** and **11** and acetylation gave two readily separable compounds, the previously charac-



terized compound **3** and an isomer **12**, m.p. 97–100°, $[\alpha]_D$ +83° (chloroform), in the ratio of 1.1:1. The former product had physical constants and spectra identical to those of compound **3** prepared from **2**. By correlating the degradation study just noted with the ^{1}H-n.m.r. spectrum of **12**, the absolute configuration of isomer **12** was established as that having the (5*S*)-*exo* side-chain, (6*S*)-*endo* ester orientations.

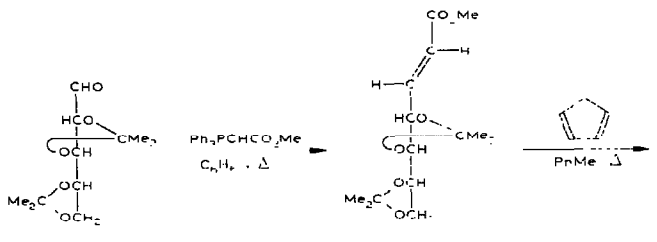
Diels–Alder addition of methyl (*E*)-2,3-dideoxy-4,5:6,7-di-*O*-isopropylidene-L-*arabino*-hept-2-enonate (**14**) (obtained* from 2,3:4,5-di-*O*-isopropylidene-*aldehydo*-L-arabinose[14] by the Wittig reaction with Ph_3PCHCO_2Me) with cyclopentadiene under the conditions used with the D enantiomer **9**, afforded a crystalline, inseparable mixture of two products (**15** and **16**) that were the enan-

*In the preliminary report[2], the names and structures given as L-*arabino* should be corrected to read D-*arabino*, as it was subsequently found that the commercial material used in that work, supplied as "L-arabinose", was actually D-arabinose. All stereochemical attributions given[2] for the carbocyclic products remain valid, and the present independent correlation *via* compound **7** reaffirms the optical purity of the crystalline products. The data and yields given in the present report were verified in several repetitions of each experiment.



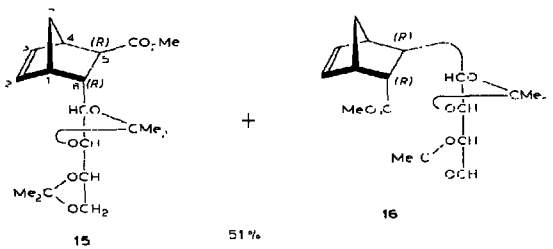
3
103.5—104.5°
+ 72°

12
97—100°
+ 83°



13

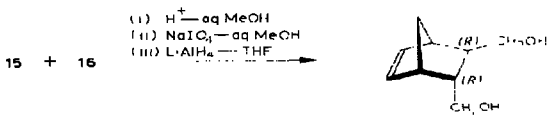
14
+5°



15

51%

16

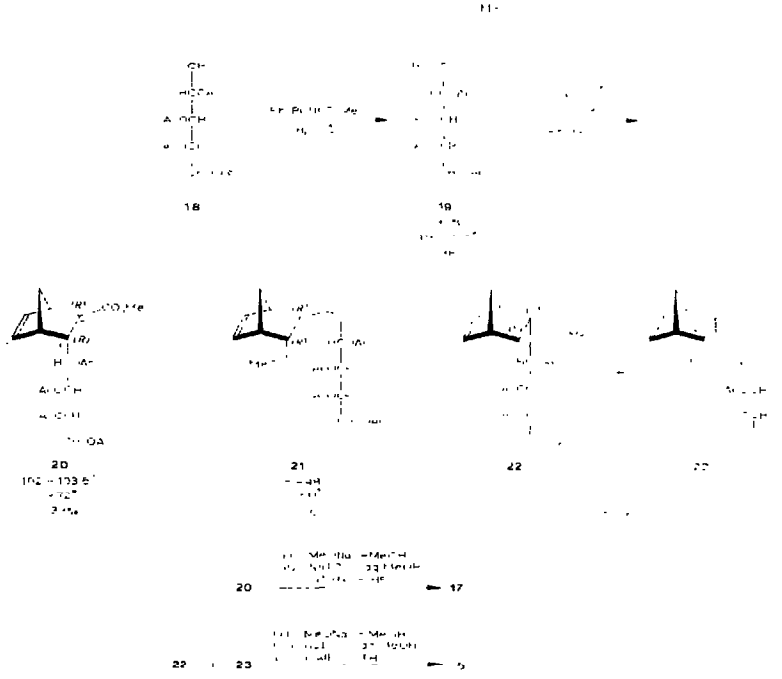


17
36—38°
+ 23°

tiomers of compounds **10** and **11**. The mixture was subjected to a reaction sequence similar to that used for the mixture **10** and **11** to afford the enantiomeric diol, (5*R*,6*R*)-bis(hydroxymethyl)bicyclo[2.2.1]hept-2-ene (**17**), $[\alpha]_D$ +23° (chloroform).

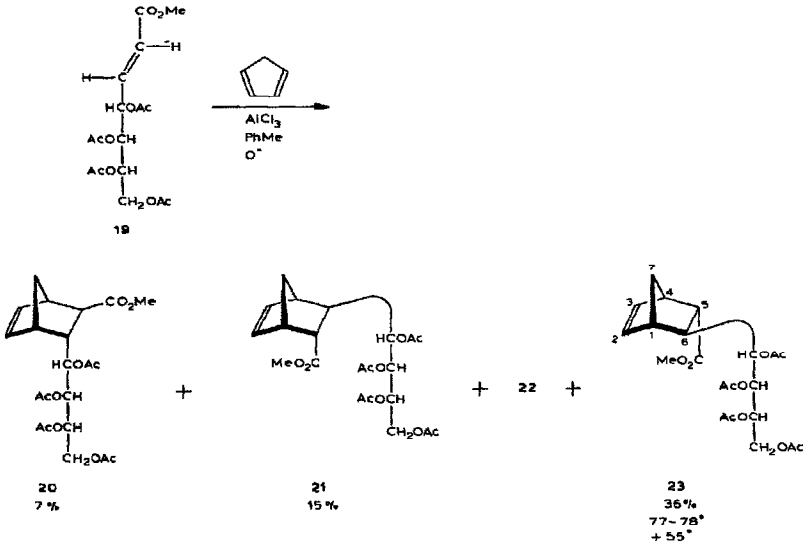
Methyl (*E*)-4,5,6,7-tetra-*O*-acetyl-2,3-dideoxy-L-*arabino*-hept-2-enonate (**19**), m.p. 116–117°, $[\alpha]_D$ −36° (chloroform), which was obtained* from 2,3,4,5-tetra-*O*-acetyl-*aldehydo*-L-arabinose[15] (**18**) by Wittig reaction with Ph_3PCHCO_2Me in boiling benzene, was treated with cyclopentadiene under the conditions used for the enantiomer **2**. The total reaction-mixture was resolved as completely as possible by careful column chromatography on silica gel, and by liquid chromatography, and two optically pure, crystalline norbornene adducts, **20**, m.p. 102–103.5°, $[\alpha]_D$ −72° (chloroform), and **21**, m.p. 95–98°, $[\alpha]_D$ −80° (chloroform), plus a syrupy mixture of two others (**22** and **23**, in the ratio of 8:5 as determined by ^{1}H-n.m.r. spectroscopy) were obtained in yields of 33, 5, and 30%, respectively. Compound **20** had i.r. and n.m.r. spectra superposable on those of compound **3**, and its physical constants indicated it to be the enantiomer of **3**. Thus, the absolute configuration of **20** was established as that of the (5*R*)-*exo* ester, (6*R*)-*endo* side-chain. The structure was further confirmed by converting **20** into the (5*R*,6*R*)-diol (**17**) by successive deacetylation, periodate oxidation, and reduction with lithium aluminum hydride. Compound **21** was shown from its i.r. and n.m.r. spectra and other physical constants to be the enantiomer of **12**. The syrupy mixture (**22** and **23**) was converted into the (5*S*,6*S*)-diol (**5**) by the same reaction sequence as used for **20**, indicating that the syrup was a mixture of two diastereomers having the (5*S*,6*S*) configuration. Although adduct **23**, whose configuration is that of the (5*S*)-*endo* ester, (6*S*)-*exo* side-chain, is a desirable compound that could be convertible into a prostaglandin precursor, it is only a minor component of the product mixture formed under the reaction conditions used.

Many examples have shown[16] that the addition of a Lewis acid not only accelerates the Diels–Alder reaction remarkably, but also affects the diastereomeric distribution of the resulting adducts, sometimes leading to a major adduct of reversed orientation. Thus, Lewis-acid catalysis of the Diels–Alder reaction of cyclopentadiene with acrylate or methacrylate increases the *endo* selectivity of the addition[17]. Inukai *et al.*[17(a)] attributed this rate acceleration and increased *endo* selectivity to enhanced π interaction between the unsaturated centers of the addends and to polarity effects introduced by formation of an ester-$AlCl_3$ complex. Houk *et al.*[17(d)] rationalized both rate acceleration and increased *endo* selectivity from considerations of frontier-orbital theory. By Lewis-acid complexation, the LUMO energy of the dienophile is lowered substantially, thus making the HOMO(diene)–LUMO(dienophile) interaction larger, and, consequently, accelerating the reaction. The complexation also has the effect of increasing the frontier-orbital coefficient at the carbonyl carbon atom. As a result, the secondary orbital-interaction between the carbonyl carbon atom and C-2 of the diene is increased, making the *endo* transition-state favored.



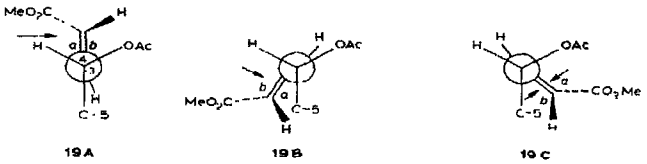
When dienophile **19** was subjected to the Diels–Alder reaction under catalysis by aluminum chloride, the ratio of adducts was reversed, and adduct **23** could be isolated as the major product. Compound **19** was treated with 5 mol.equiv. of cyclopentadiene in the presence of 1 mol. equiv. of $AlCl_3$ in toluene for 4 h at 0°. After separation of the products by chromatography on silica gel, the adducts **20** and **21**, and a mixture of **22** and **23** were obtained in 7, 15, and 57% yields, respectively. From the comigrating mixture of **22** and **23**, which was shown by its ^{1}H-n.m.r. spectrum to be a 1:6.5 mixture of the two diastereomers, pure compound **23**, m.p. 77–78°, $[\alpha]_D$ +55° (chloroform), crystallized from 2-propanol in 36% net yield, based on the dienophile **19**. The chemical shifts and coupling constants observed in its ^{1}H-n.m.r. spectrum supported the *exo* side-chain, *endo* ester structure. Under these reaction conditions, the (5*S*,6*S*)-adducts (**22** and **23**) preponderated, in contrast to the outcome of the uncatalyzed reaction, and, furthermore, the *endo* ester orientation (**21** and **23**) was favored, in line with the results reported for comparable reactions of cyclopentadiene with acrylates. A smaller ex-

cess of cyclopentadiene was needed for the addition to proceed to completion, and the reaction rate was higher. Although the Lewis acid-catalyzed reaction at room temperature afforded similar results, the yields were slightly lower. At −30°, no reaction occurred. When the reaction was performed in dichloromethane, similar results were obtained, but extensive formation [16(c)] of polymerized diene made separation of the product mixture difficult. When $BF_3 \cdot OEt_2$ was used as the Lewis acid, practically no reaction occurred, even at room temperature, and the reaction catalyzed by stannic chloride was so slow that it was not a practical procedure.



The preponderance of the (*S,S*) configuration in the $AlCl_3$-catalyzed reaction may be attributed to steric hindrance[18] in the dienophile **19**. Three possible conformers, **19A**, **19B**, and **19C**, may be considered in the transition state.

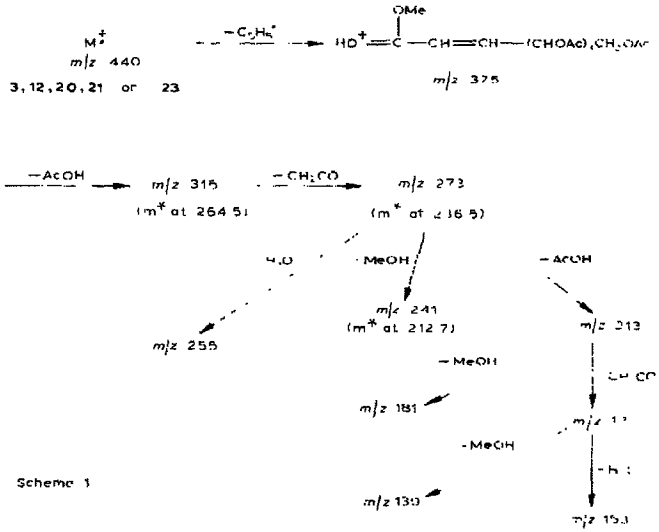
In the case of conformer**19A**, attack of cyclopentadiene would occur at face *a* (the less-hindered face) to give adducts having the (*S,S*) conguration. With conformer **19B**, attack at face *b* would appear favored, and lead to (*R,R*)-adducts, because face *a* is hindered by the OAc-5 group. In the (presumably least stable) conformer **19C**, both faces are hindered to a similar extent by the C-5 chain and the OAc-4 group, and, therefore, attack should occur at both faces, to give a mixture of (*R,R*) and (*S,S*) adducts. Conformer **19A** appears to be the most stable one, and it may be further stabilized by complexation with $AlCl_3$, so that, in catalyzed reac-



19A 19B 19C

tions at low temperature, the (*S,S*)-adducts preponderate. At elevated temperatures in the absence of catalyst, the other conformers (especially **19B**) contribute more extensively to the transition state, so that the proportion of (*R,R*)-adducts formed increases.

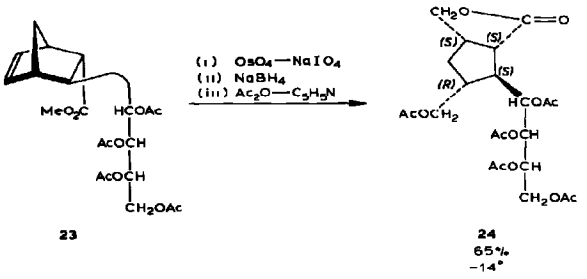
When compound **23**, the main adduct in the catalyzed reaction, was boiled under reflux in toluene in the presence of a large excess of cyclopentadiene for 36 h, no transformation into other adducts occurred, as shown by t.l.c. and by ^{1}H-n.m.r. spectroscopy. This result indicated that, even under the thermal conditions used in these studies, repeated dissociation and recombination of addends does not take place. The distribution of adducts thus does not depend on their relative thermodynamic stabilities, but on kinetic considerations based on the favored conformations of the dienophile **19** in the transition state.

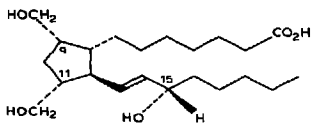


Scheme 1

Mass-spectrometric data for the derivatives **3, 12, 20, 21,** and **23** showed a characteristic fragmentation-pathway initiated by hydrogen rearrangement and by the loss of a C_5H_5 · radical from the molecular ion (see Scheme I).

Oxidative double-bond cleavage[19] of the (6*S*)-*exo* side-chain, (5*S*)-*endo* ester adduct (**23**) with osmium tetraoxide–sodium metaperiodate, followed by reduction with sodium borohydride and by acetylation, gave 65% of the crystalline, chiral tetra-*C*-substituted cyclopentane derivative **24**, m.p. 92–94°, $[\alpha]_D$ −14° (chloroform), having the (1*S*,5*S*,7*R*,8*S*) configuration of the ring substituents. Compound **24** showed i.r. absorption at 1765 cm^{-1}, indicating the presence of a 1,4-lactone. In the ^{13}C-n.m.r. spectrum, the resonance of the carbonyl carbon atom of the 1,4-lactone appeared at lower field[20] (179.4 p.p.m.) than those of the acetoxyl groups [171.0, 170.8, 170.4, and 170.0 p.p.m. (double intensity)]. Compound **24** has the correct relative stereochemistry of all five chiral centers of 9,11-dideoxy-9,11-bis(hydroxymethyl)prostaglandin[9] $F_{1\alpha}$ and also the same absolute stereochemistry as these corresponding centers in prostaglandin $F_{1\alpha}$ itself.





9,11-Dideoxy-9,11-bis(hydroxymethyl)prostaglandin $F_{1\alpha}$

As the dialdehydes resulting from hydroxylation–glycol cleavage of 5,6-*trans*-dialkylnorbornenes may be transformed[21] by a Baeyer–Villiger route into the diacetoxy analogs with net retention of stereochemistry, the chiral core of the parent prostaglandins is likewise accessible by the sugar-based syntheses described here.

EXPERIMENTAL

General methods. — Melting points were determined with a Thomas–Hoover apparatus and are uncorrected. Optical rotations were measured with a Perkin–Elmer 141 polarimeter. T.l.c. was performed on precoated glass plates (0.25 mm) coated with Silica Gel 60 F-254 (E. Merck, Darmstadt, G.F.R.); components were detected by spraying the plates with 10% sulfuric acid, with subsequent heating, and by u.v. light. Evaporations were conducted under diminished pressure. Column chromatography was performed with Silica Gel 60 (70–230 and 230–400 mesh; E. Merck, Darmstadt, G.F.R.). I.r. spectra were recorded with a Perkin–Elmer 457 grating spectrophotometer. ^{1}H-N.m.r. spectra were recorded, unless stated otherwise, at 200 MHz with a Bruker WP-200 spectrometer, for solutions in chloroform-*d*. Spectra at 90 MHz were recorded with a Varian EM-390, and 300-MHz spectra, with a Bruker WM-300 instrument. ^{13}C-N.m.r. spectra were recorded, unless stated otherwise, at 50.2 MHz with a Bruker WP-200 spectrometer for solutions in chloroform-*d*. Spectra at 75.4 MHz were recorded with a Bruker WM-300 instrument. Assignments were verified by heteronuclear decoupling. N.m.r. spectra were recorded by Dr. O. Mols. Chemical shifts refer to an internal standard of tetramethylsilane (δ = 0.00). Mass spectra were recorded by C. R. Weisenberger with an AEI MS9 double-focusing instrument equipped with a direct-inlet probe (140°), at an ionization potential of 70 eV and an accelerating potential of 8 kV. Elemental analyses were performed by Dr. O. Mols. X-Ray powder diffraction data give interplanar spacings, Å, for CuKα radiation. The camera diameter was 114.59 mm; relative intensities were estimated visually: m, moderate; s, strong; v, very; w, weak. The strongest lines are numbered (1, strongest); double numbers indicate approximately equal intensities.

Methyl (E)-*4,5,6,7-tetra*-O-*acetyl-2,3-dideoxy*-D-arabino-*hept-2-enonate* (**2**). — To a solution of 2,3,4,5-tetra-*O*-acetyl-*aldehydo*-D-arabinose[10] (**1**; 1.20 g, 3.77 mmol) in benzene (12 mL) was added methyl (triphenylphosphoranylidene)acetate (1.51 g, 4.52 mmol), and the mixture was boiled under reflux for 1 h. T.l.c. in 2:1 hexane–ethyl acetate then indicated conversion into a single product (R_f 0.33). A small amount of insoluble material was filtered off, and the filtrate was evaporated to give a solid that was recrystallized from 2-propanol, to afford compound **2** as pure crystals; yield 1.22 g (87%); m.p. 116–117°, $[\alpha]_D^{26}$ +35° (*c* 1, chloroform); ν_{max}^{KBr} 1745, 1730 (C=O), 1375, and 1235 cm^{-1}; ^{1}H-n.m.r.: δ 6.78 (dd, 1 H, $J_{2,3}$ 15.9, $J_{3,4}$ 4.9 Hz, H-3), 5.96 (dd, 1 H, $J_{2,4}$ 1.7 Hz, H-2), 5.70 (ddd, 1 H, $J_{4,5}$ 3.0 Hz, H-4), 5.40 (dd, 1 H, $J_{5,6}$ 8.6 Hz, H-5), 5.20 (ddd, 1 H, $J_{6,7}$ 2.9, $J_{6,7'}$ 4.6 Hz, H-6), 4.26 (dd, 1 H, $J_{7,7'}$ 12.5 Hz, H-7), 4.15 (dd, 1 H, H-7'), 3.74 (s, 3 H, CO_2Me), and 2.128, 2.069 (double intensity), and 2.059 (s, 12 H, 4 OAc); *m/z* (rel. intensity): 374 (0.4, M^+), 315 (2.7, $M^+ - CH_3OCO\cdot$), 301 (1.6, $M^+ - AcOCH_2\cdot$), 272 ($M^+ - AcOH - CH_2CO$), 241 (2.7, 301 − AcOH; m^* at 193.0, calc. 193.0), 217 (9.2), 212 (2.9, 272 − AcOH; m^* at 165.3, calc. 165.2), 200 (4.0), 199 (2.0, 241 − CH_2CO), 170 (6.3, 212 − CH_2CO; m^* at 136.3, calc. 136.3), 158 (23,

AcOCH=CHCH$_2$CO$_2$CH$_3$$^{+}$), 145 (2.2, Ac$_3O^+$), 139 (2.5, 170 − MeO·), 116 (31, 158 − CH$_2$CO; m* at 85.2, calc. 85.2), 115 (18), 111 (1.8, 139 − CO), 103 (2.5, Ac$_2$O$^+$H), and 43 (100, Ac$^+$); X-ray powder diffraction data: 9.63 w, 8.77 s (2,2) 7.66 vw, 5.57 w, 5.30 vs (1,1), 4.90 vs (1,1), 4.67 w, 4.47 w, 4.26 m, 4.03 m, 3.75 m, 3.50 s (2,2) 3.29 m, 3.14 vw, 3.00 w, 2.83 m, and 2.67 w.

Anal. Calc. for C$_{16}$H$_{22}$O$_{10}$ (374.36): C, 51.34; H, 5.92. Found: C, 51.52; H, 6.04.

*Methyl (5S,6S)-6-*endo*-(1,2,3,4-tetra-*O*-acetyl-*D*-arabino-tetritol-1-yl)bicyclo[2.2.1]hept-2-eno-5-*exo*-carboxylate* (**3**). — To a mixture of the acetylated alkene **2** (5.03 g, 13.4 mmol) in toluene (50 mL) were added hydroquinone (30 mg, 0.27 mmol) and cyclopentadiene (freshly distilled from dicyclopentadiene; 1.7 mL, 20.7 mmol), and the mixture was boiled under reflux in an atmosphere of argon. Additional cyclopentadiene (13.1 mL, 159 mmol) and hydroquinone (62 mg, 0.56 mmol) were added to the mixture in 4 portions, with monitoring of the reaction by t.l.c. in 2:1 hexane–ethyl acetate. After 40 h, t.l.c. revealed two major spots (R_F 0.38 and 0.29). Solvent (50 mL) was distilled off, and the resultant solution was evaporated with addition of water and then of ethanol, to give a brown syrup that was dissolved in hot ethanol. From this ethanolic solution, crude crystals of **3** were obtained. The crystals were recrystallized from ethanol to give pure **3**, yield 1.46 g. The mother liquors were combined, and evaporated to a syrup; this was charged onto a column of silica gel that was eluted with 3:1 hexane–ethyl acetate. The first fractions afforded a further crop of compound **3**, which was recrystallized from ethanol; yield 0.90 g. The total yield of compound **3** was 2.36 g (40%). Evaporation of later fractions gave a syrup that contained two diastereomers in the ratio of 2:1 (from the ^{1}H-n.m.r. methyl-proton signals of the methoxycarbonyl group).

Compound **3** had m.p. 103.5–104.5°, $[\alpha]_D^{16}$ +73° (*c* 0.7, chloroform); R_F 0.38 (2:1 hexane–ethyl acetate); ν_{max}^{KBr} 1755, 1740, 1730 (C=O), 1370, 1230, and 1210 cm^{-1}; ^{1}H-n.m.r.: δ 6.27 (broad dd, 1 H, $J_{2,3}$ 5.6, $J_{3,4}$ 3.1 Hz, H-3), 6.13 (broad dd, 1 H, $J_{1,2}$ 2.7 Hz, H-2), 5.11 (dd, 1 H, $J_{1',2'}$ 1.7, $J_{2',3'}$ 8.5 Hz, H-2'), 5.00 (ddd, 1 H, $J_{3',4'}$ 2.8, $J_{3',4''}$ 5.3 Hz, H-3'), 4.65 (dd, 1 H, $J_{1',6}$ 10.5 Hz, H-1'), 4.18 (dd, 1 H, $J_{4',4''}$ 12.3 Hz, H-4'), 3.97 (dd, 1 H, H-4''), 3.67 (s, 3 H, CO$_2$Me), 2.96 (m, 1 H, H-4), 2.82 (ddd, 1 H, $J_{1,6}$ 3.2, $J_{5,6}$ 4.7 Hz, H-6), 2.76 (m, 1 H, H-1), 2.107, 2.102, 2.028, 2.023 (s, 12 H, 4 OAc), 1.88 (broad dd, 1 H, $J_{4,5}$ ~0, $J_{5,7syn}$ 1.5 Hz, H-5), 1.64 (dt, 1 H, $J_{1,7anti} = J_{4,7anti} = 1.4$, $J_{7syn,7anti}$ 8.7 Hz, H-7*anti*), and 1.40 (dq, 1 H, $J_{1,7syn} = J_{4,7syn} = 1.6$ Hz, H-7*syn*); *m/z* (rel. intensity): 440 (2.3, M$^+$), 409 (1.2, M$^+$ − MeO·), 381 (0.4, M$^+$ − MeOCO·), 380 (0.3, M$^+$ − AcOH), 375 [4.9, HO$^+$=C(OCH$_3$)CH=CH(CHOAc)$_3$CH$_2$OAc], 367 (0.5, M$^+$ − AcOCH$_2$·), 315 (25, 375 − AcOH; m* at 264.5, calc. 264.6), 273 (3.3, 315 − CH$_2$CO; m* at 236.5, calc. 236.6), 255 (1.5, 273 − H$_2$O), 241 (4.0, 273 − MeOH; m* at 212.7, calc. 212.8), 213 (4.2, 273 − AcOH), 181 (2.7, 213 − MeOH), 171 (3.3, 213 − CH$_2$CO), 153 (10, 171 − H$_2$O), 145 (1.6, Ac$_3$O$^+$), 139 (3.5, 171 − MeOH), 103 (2.3, Ac$_2$O$^+$H), 66 (60, cyclopentadiene^{+}), and 43 (100, Ac$^+$); X-ray powder diffraction data: 10.77 m, 7.96 m, 7.15 s (2), 6.71 w, 6.13 m, 5.83 vw, 5.56 vw, 5.30 vw, 4.95 vs (1), 4.59 w, 4.26 w, 4.09 m, 3.75 w, 3.55 s (3), 3.38 w, and 3.25 w.

Anal. Calc. for $C_{21}H_{28}O_{10}$ (440.45): C, 57.27; H, 6.41. Found: C, 57.67; H, 6.61.

Methyl (5S,6S)-6-endo-(D-arabino-tetritol-1-yl)bicyclo[2.2.1]hept-2-eno-5-exo-carboxylate (**4**). — To a suspension of the Diels–Alder adduct **3** (506 mg, 1.1 mmol) in dry methanol (5 mL) was added a solution of sodium methoxide in methanol (25%, 0.13 mL), and the mixture was kept for 30 min at room temperature. T.l.c. (5:1 chloroform–methanol) then indicated conversion into a single product having R_F 0.5. The resultant solution was made neutral with Amberlite IR-120 (H^+) resin, and evaporated to a solid that was recrystallized from methanol to give **4** as crystals, yield 248 mg (79%); m.p. 156–158°, $[\alpha]_D^{26}$ +71° (*c* 0.8, methanol); ν_{max}^{KBr} 3320 (OH), 1730 (C=O), 1160, 1075, and 1045 cm^{-1}; ^{1}H-n.m.r. (pyridine-d_5–D_2O): δ 6.39 (dd, 1 H, $J_{1,2}$ 2.8, $J_{2,3}$ 5.4 Hz, H-2), 6.13 (dd, 1 H, $J_{3,4}$ 3 Hz, H-3), 4.57–4.42 (m, 2 H, H-3′,4′), 4.31 (dd, 1 H, $J_{3',4'}$ 6, $J_{4',4''}$ 10.5 Hz, H-4″), 4.19 (d, 1 H, $J_{1',2'}$ ~0, $J_{2',3'}$ 7.7 Hz, H-2′), 3.99 (d, 1 H, $J_{1',6}$ 10.5 Hz, H-1′), 3.56 (s, 3 H, CO_2Me), 3.45 (m, 1 H, H-1), 3.35 (ddd, 1 H, $J_{1,6}$ 3.5, $J_{5,6}$ 4.5 Hz, H-6), 3.01 (m, 1 H, H-4), 2.13 (dd, 1 H, $J_{4,5}$ ~0, $J_{5,7syn}$ ~1.5 Hz, H-5), 1.94 (dt, 1 H, $J_{1,7anti}$ = $J_{4,7anti}$ = ~1.5 $J_{7syn,7anti}$ 8.2 Hz, H-7*anti*), and 1.46 (dq, 1 H, $J_{1,7syn}$ = $J_{4,7syn}$ = ~1.5 Hz, H-7*syn*); ^{13}C-n.m.r. (pyridine-d_5): δ 176.5 (C=O), 136.9, 136.4 (C-2,3), 74.0, 73.3, 73.2 (C-1′,2′,3′), 65.3 (C-4′), 51.5 (CO_2CH_3), 48.2, 48.1, 47.2, 47.0, and 44.8 (C-1,4,5,6,7); *m/z* (rel. intensity): 223 (1.7, $M^+ - HOCH_2\cdot - H_2O$), 211 [2.3, $M^+ - HOCH_2(HO)CH\cdot$], 207 [2.6, $HO^+{=}C(OMe)CH{=}CH(CHOH)_3CH_2OH$], 189 (3.4, 207 − H_2O), 181, (13, $M^+ - HOCH_2(HOCH)_2\cdot$), 175 (2.7, 207 − MeOH), 157 (7.2, 175 − H_2O or 189 − MeOH), 121 [5.8, $HO^+{=}CH(CHOH)_2CH_2OH$], 115 (14, 181 − C_5H_6), 97 (8.4, 115 − H_2O), 91 [11, $HO^+{=}CHCH(OH)CH_2OH$], and 66 [100, $C_5H_6^+$]; X-ray powder diffraction data: 12.62 vs (1,1,1), 9.85 vs (1,1,1), 9.09 vs (1,1,1), 7.82 w, 6.66 w, 5.98 vw, 5.39 s (2), 5.11 m, 4.75 s (3,3), 4.37 s (3,3), 4.14 m, 3.96 m, 3.80 w, 3.62 vw, 3.49 m, 3.25 w, 3.08 w, and 2.97 w.

Anal. Calc. for $C_{13}H_{20}O_6$ (272.30): C, 57.34; H, 7.40. Found: C, 57.31; H, 7.48.

(5S,6S)-Bis(hydroxymethyl)bicyclo[2.2.1]hept-2-ene (**5**). — To a solution of the tetrol **4** (164 mg, 0.60 mmol) in aqueous methanol (1:1, 13 mL) was added sodium metaperiodate (600 mg, 2.8 mmol), and the mixture was stirred for 3 h at room temperature. T.l.c. (20:1 benzene–butanone) then showed one major product (R_F 0.4). Inorganic material was filtered off, and the filtrate was concentrated (<35°) to low volume. The concentrate was extracted with dichloromethane, and the extracts were washed with water, dried (sodium sulfate), and evaporated to a syrup (90 mg). A solution of the syrup (90 mg) in dry oxolane (tetrahydrofuran; 1.5 mL) was slowly added to a suspension of lithium aluminum hydride (65 mg) in dry oxolane (1 mL), and the mixture was stirred for 1 h at room temperature. T.l.c. (3:1 ethyl acetate–benzene) showed the presence of a major compound (**5**, R_F 0.23) together with a small proportion of a by-product (R_F 0.60). Saturated aqueous ammonium chloride was slowly added to the mixture in an ice bath, and the inorganic material was filtered off. The filtrate was evaporated to a syrup that was dissolved in dichloromethane, and the solution was washed once with a small vol-

ume of cold water, dried (sodium sulfate), and evaporated to a syrup (60.8 mg). The water layer was evaporated to a syrup that was dissolved in dichloromethane, and the solution was processed as before, to afford additional syrup (13 mg). The combined syrups were charged onto a column of silica gel that was eluted with 3:1 ethyl acetate–benzene. The second fractions gave pure compound **5** as a syrup that afforded hygroscopic crystals on keeping for 2 days at 0°; yield 56.4 mg (61%, based on compound **4**); m.p. 39–40°. $[\alpha]_D^{23}$ −23° (*c* 0.8, chloroform); ν_{max}^{film} 3300 (OH), 2950, 2860, 1630, 1340, 1055, and 1020 cm^{-1}; ^{1}H-n.m.r.: δ 6.23 (ddd, 1 H, $J_{1,3}$ 0.8, $J_{2,3}$ 5.7, $J_{3,4}$ 3.2 Hz, H-3), 5.98 (ddd, 1 H, $J_{1,2}$ 2.9, $J_{2,4}$ <0.5 Hz, H-2), 3.77 (dd, 1 H, $J_{5,b}$ 5.5, $J_{a,b}$ 9.5 Hz, Hb*), 3.65 (ddd, 1 H, $J_{4,b'}$ 0.7, $J_{6,b'}$ 5.2, $J_{a',b'}$ 9.5 Hz, Hb'*), 3.43 (t, 1 H, $J_{5,a}$ 9.5 Hz, Ha*), 3.05 (t, 1 H, $J_{6,a'}$ 9.5 Hz, Ha'*), 2.93–2.85 (broad, 2 H, OH), 2.83 (m, 1 H, H-1), 2.61 (m, 1 H, H-4), 1.95 (dddd, 1 H, $J_{1,6}$ 3.2, $J_{5,6}$ 4.3 Hz, H-6), 1.45 (m, 2 H, H-7*syn* and H-7*anti*), and 1.32 (dddd, $J_{4,5}$ ~0, $J_{5,7syn}$ ~1 Hz, H-5); ^{13}-n.m.r.: δ 138.0 (C-3), 133.4 (C-2), 66.5 (CH_2OH), 66.0 (CH_2OH), 47.9 (C-6), 47.1 (C-7), 46.9 (C-5), 44.6 (C-1 or C-4), and 44.5 (C-4 or C-1)[22]; *m/z* (rel. intensity): 154.0999 (1.5, M^+; calc. for $C_9H_{14}O_2$: 154.0994), 136 (7.7, $M^+ - H_2O$: m* at 120.2, calc. 120.1), and 66 (100, $C_5H_6^{1}$). For the racemate of **5**, the following ^{13}C-n.m.r. values have been recorded[22] (assignments identical to those given here): 138.0, 133.5, 66.4, 66.2, 47.9, 47.1, 46.9, 44.8, and 44.6.

Anal. Calc. for $C_9H_{14}O_2$ (154.10): C, 70.10; H, 9.15. Found: C, 70.15; H, 9.50.

(2S,3S)-Bis(hydroxymethyl)bicyclo[2.2.1]heptane (**6**). — A solution of the norbornenedimethanol **5** (40 mg) in methanol (1.6 mL) was hydrogenated in the presence of platinum for 2.5 h. T.l.c. (2:1 ethyl acetate–benzene) then indicated conversion into a single compound (R_F 0.29; compound **5** had R_F 0.26). The catalyst was filtered off, and the filtrate evaporated to a syrup that was passed through a short column of silica gel. The eluate was evaporated to afford pure **6** as a syrup that crystallized spontaneously after 3 days; yield 38 mg (94%). Recrystallized from chloroform–hexane, compound **6** had m.p. 65.5–67°, $[\alpha]_D^{27}$ −56° (*c* 0.5, chloroform); ν_{max}^{KBr} 3280 (OH), 2960, 2880, 2860, 1460, 1205, 1075, 1050, 1030, and 985 cm^{-1}; ^{1}H-n.m.r. (300 MHz): δ 3.71 (dd, 1 H, J_{gem} 9.9, J_{vic} 4.8 Hz, CH_2OH), 3.67 (dd, 1 H, J_{gem} 9.6, J_{vic} 5.5 Hz, CH_2OH), 3.47 (t, 1 H, $J_{gem} = J_{vic}$ 9.6 Hz, CH_2OH), 3.23 (t, 1 H, $J_{gem} = J_{vic}$ 9.9 Hz, CH_2OH), 3.09 (broad s, 2 H, OH), 2.27 (m, 1 H, H-4 or H-1), 2.01 (m, 1 H, H-1 or H-4), 1.75 (m, 1 H, H-3 or H-2), 1.58 (m, 1 H, H-2 or H-3), and 1.47–1.16 (m, 6 H, H-5,5', H-6,6', and H-7,7'); ^{13}C-n.m.r.: δ 66.2 (CH_2OH), 64.5 (CH_2OH), 50.8 (C-3 or C-2), 49.2 (C-2 or C-3), 39.4 (C-4 or C-1), 39.1 (C-1 or C-4), and 37.6, 30.2, and 22.4 (C-5,6,7); *m/z* (rel. intensity): 138.1053 (8.5, $M^+ - H_2O$; calc. for $C_9H_{14}O$: 138.1045), 120 (16, 138 − H_2O; m* at 104.4, calc. 104.3), and 79 (100); X-ray powder diffraction data: 10.68 vw, 9.76 s (2,2), 6.03 vw, 5.52 vs (1), 4.73 vw, 4.26 s (3), 4.07 vw, 3.89 s (2,2), 3.76 vw,

*Methylene protons of the *exo*-hydroxymethyl group are denoted by a and b, and those of the *endo* group, by a' and b'.

3.67 m, 3.20 m, 3.10 w, 2.89 w, 2.81 w, 2.70 w, 2.49 w, 2.44 w, 2.29 w, 2.12 m, and 2.08 w.

Anal. Calc. for $C_9H_{16}O_2 \cdot 0.25\ H_2O$: C, 67.25; H, 10.35. Found: C, 67.24; H, 10.34.

*(2S,3S)-Bis(*p*-tolylsulfonyloxymethyl)bicyclo[2.2.1]heptane* (**7**). — To a solution of the norbornanedimethanol **6** (70 mg, 0.45 mmol) in dry pyridine (1.5 mL) was added *p*-toluenesulfonyl chloride (280 mg, 1.47 mmol), and the solution was kept for 15 h at room temperature. T.l.c. (chloroform) then indicated conversion into a single compound (R_f 0.28). After the addition of water (0.1 mL), the solution was evaporated to a syrup that was dissolved in dichloromethane. The solution was successively washed with saturated aqueous potassium hydrogensulfate, saturated sodium hydrogencarbonate, and water, dried (sodium sulfate), and evaporated to a syrup that crystallized rapidly on addition of ethanol. Recrystallization from ethanol afforded **7** as needles; 166 mg (79%); m.p. 99.5–100.5°, $[\alpha]_D^{29}$ +29° (*c* 0.5, chloroform), $[\alpha]_D^{30}$ +32.5° (*c* 0.5, acetone) (lit.[12] m.p. 100–101°, $[\alpha]_D$ +32.2°, solvent not reported); ν_{max}^{KBr} 1600, 1365 (*v*as SO_2), 1175 (*v*s SO_2), 950, 865, and 820 cm^{-1}; ^{1}H-n.m.r. (300 MHz; C_6D_6): δ 7.82 (d, 2 H, *J* 8.4 Hz, aromatic), 7.81 (d, 2 H, *J* 8.4 Hz, aromatic), 6.77 (d, 4 H, *J* 8.4 Hz, aromatic), 3.92 (dd, 1 H, J_{gem} 9.9, J_{2,CH_2O} 6.8 Hz, *endo* CH_2OTs), 3.69 (dd, 1 H, J_{2,CH_2O} 9.0 Hz, *endo* CH_2OTs), 3.58 (d, 2 H, J_{3,CH_2O} 7.5 Hz, A_2 part of A_2X, *exo* CH_2OTs), 1.90 (m, 1 H, H-1), 1.84 (s, 6 H, CH_3 of Ts), 1.71 (m, 1 H, H-4), 1.38 (ddddd, 1 H, $J_{5,6}$ 6, $J_{1,2}$ 3.7, $J_{2,6exo}$ ~1.2 Hz, H-2), 1.08 (m, 1 H, H-5*exo*), 0.98–0.90 (m, 2 H, H-6*exo* and H-5*endo* or H-6*endo*), 0.89 (tdd, 1 H, $J_{3,7anti}$ ~1.5, $J_{3,4}$ ~0 Hz, H-3), 0.83 (dq, 1 H, J_{gem} 10, $J_{1,7syn} = J_{4,7syn} = J_{5endo,7syn} = J_{6endo,7syn}$ ~1.7 Hz, H-7*syn*), 0.71 (dt, 1 H, $J_{1,7anti} = J_{4,7anti} = J_{3,7anti}$ = ~1.5 Hz, H-7*anti*), and 0.57 (m, 1 H, H-5*endo* or H-6*endo*); ^{13}C-n.m.r. (75.4 Hz; C_6D_6): δ 129.9, 128.1 (aromatic), 72.3 (*exo* CH_2OTs), 70.8 (*endo* CH_2OTs), 45.2 (C-3), 43.6 (C-2), 38.9 (C-4), 38.4 (C-1), 36.6 (C-7), 29.4 (C-5), 21.9 (C-6), and 21.1 (CH_3 of Ts); *m/z* (rel. intensity): 466 (3.9, M + 2), 465 (7.2, M + 1), 464.1339 (26, M^+; calc. for $C_{23}H_{28}O_6S_2$: 464.1327), 309 (3.3, $M^+ - CH_3C_6H_4SO_2^\cdot$), 293 (11, $M^+ - CH_3C_6H_4SO_3^\cdot$), 292 (12, $M^+ - CH_3C_6H_4SO_3H$), 172 (83, $CH_3C_6H_4SO_3H^{\cdot+}$), 155 (24, $CH_3C_6H_4SO_2^+$), 149 (23), 137 (14, 292 − $CH_3C_6H_4SO_2^\cdot$), 121 (62, 292 − $CH_3C_6H_4SO_3^\cdot$), 108 (57), 107 (79), 92 (64), 91 (100, $CH_3C_6H_4^{\cdot+}$), 79 (94), 77 (85), 65 (98), 63 (79), 51 (60), and 41 (87); X-ray powder diffraction data: 14.54 w, 7.45 m, 6.63 s (2,2,2), 6.15 vw, 5.46 s (2,2,2), 5.15 m, 5.02 s (2,2,2), 4.77 s (3), 4.42 vs (1,1), 4.01 vs (1,1), 3.69 m, 3.58 w, 3.37 m, 3.24 m, and 3.09 m.

Anal. Calc. for $C_{23}H_{28}O_6S_2$ (464.13): C, 59.46; H, 6.07; S, 13.80. Found: C, 59.58; H, 6.39; S, 13.69.

Methyl (E)-*2,3-dideoxy-4,5:6,7-di-O-isopropylidene*-D-arabino-*hept-2-enonate* (**9**). — To a solution of 2,3:4,5-di-*O*-isopropylidene-*aldehydo*-D-arabinose[13] (**8**; 1.53 g, 6.64 mmol) in toluene (16 mL) was added methyl (triphenylphosphoranylidene)acetate (2.73 g, 8.16 mmol), and the mixture was boiled under reflux for 1 h. T.l.c. (30:1 chloroform–ethyl acetate) then showed the presence of two compounds having similar R_f values (R_f 0.27, major, **9**; R_f 0.23, minor *Z*

isomer). A small amount of insoluble material was filtered off, and the filtrate was evaporated. The residue was extracted with hexane, and the extract evaporated, to give a syrup (1.65 g) that was shown by its n.m.r. spectrum to contain ~25% of the *Z* isomer. The syrup was resolved by column chromatography on silica gel (30:1 chloroform–ethyl acetate). The first fraction afforded crude **9** as a syrup, which was shown to contain ~10% of the *Z* isomer by its n.m.r. spectrum; yield 896 mg (47%). A sample of pure compound **9** was obtained from the earlier-eluted portion of the first fraction: yield 212 mg; $[\alpha]_D^{21}$ −1.5° (*c* 0.6, chloroform); ν_{max}^{film} 2995, 1730 (C=O), 1665, 1440, 1385, 1375, and 1065 cm^{-1}; ^{1}H-n.m.r.: δ 7.02 (dd, 1 H, $J_{2,3}$ 15.6, $J_{3,4}$ 4.6 Hz, H-3), 6.17 (dd, 1 H, $J_{2,4}$ 1.7 Hz, H-2), 4.54 (ddd, 1 H, $J_{4,5}$ 7.7 Hz, H-4), 4.20–4.08 (m, 2 H, H-7,7'), 4.03–3.90 (m, 1 H, H-6), 3.75 (s, 3 H, CO_2Me), 3.68 (t, 1 H, $J_{5,6}$ 7.7 Hz, H-5), 1.43, 1.41 (double intensity), and 1.35 (s, 12 H, 2 CMe_2); ^{13}C-n.m.r.: δ 166.8 (C=O), 145.5 (C-3), 121.2 (C-2), 110.4, 110.0 (CMe_2), 81.3 (C-5), 79.0 (C-4), 77.0 (C-6), 67.5 (C-7), 51.5 (CO_2CH_3), 26.8, 26.6 (double intensity), and 25.0 (Me); *m/z* (rel. intensity): 286 (0.1, M^+), 285 (0.1, $M^+ - 1$), 271.1190 (30, $M^+ - Me\cdot$; calc. for $C_{13}H_{19}O_6$: 271.1182), 255 (1.0, $M^+ - MeO\cdot$), 228 (0.6, $M^+ - Me_2CO$), 213 (4.3, 271 − Me_2CO), 197 (3.1, 255 − Me_2CO), 185 (8.7, $Me_2\overset{\overset{O}{\frown}}{C}O^+=CHCH-CH=CHCO_2Me$), 156 (18), 127 (7.7, 185 − Me_2CO), 101 (62, $Me_2\overset{\overset{O}{\frown}}{C}O^+=CHCH_2$), 98 (43, 156 − Me_2CO; m* at 61.6, calc. 61.6), 73 (14), 59 (11, Me_2CO^+H), and 43 (100, 101 − Me_2CO).

Anal. Calc. for $C_{14}H_{22}O_6$ (286.16): C, 58.73; H, 7.75. Found: C, 58.93; H, 7.94.

*Methyl (5S,6S)-6-*endo*-(1,2:3,4-di-O-isopropylidene-*D*-*arabino*-tetritol-1-yl)-bicyclo[2.2.1]hept-2-eno-5-*exo*-carboxylate* (**10**) *and methyl (5S,6S)-5-*exo*-(1,2:3,4-di-O-isopropylidene-*D*-*arabino*-tetritol-1-yl)bicyclo[2.2.1]hept-2-eno-6-*endo*-carboxylate* (**11**). — To a solution of the isopropylidenated alkene **9** (830 mg, 2.90 mmol, containing ~10% of the *Z* isomer) in toluene (10 mL) were added hydroquinone (7 mg, 64 μmol) and cyclopentadiene (freshly distilled from dicyclopentadiene; 0.35 mL, 4.37 mmol), and the mixture was boiled in an atmosphere of argon under reflux. Additional cyclopentadiene (2.35 mL, 28.5 mmol) and hydroquinone (13 mg, 0.12 mmol) were added to the solution in 5 portions, while monitoring the reaction by t.l.c. (5:1 hexane–ethyl acetate). After boiling for 27 h under reflux, t.l.c. showed a major component (R_F 0.45, **10** + **11**) and a minor one (R_F 0.40). Although the minor component and the starting compound **9** had the same R_F value, they could be differentiated by their sensitivity to u.v. light (254 nm); the former component was u.v.-negative, whereas **9** was positive. It was determined that **9** was absent. A 10-mL portion of the solvent was distilled off, and the resultant solution was evaporated, with periodical additions of water, to give a pale-yellow syrup. This syrup was dissolved in hot hexane and kept for 15 h at −20°. The crude crystals obtained were recrystallized from hexane, to give a crystalline mixture of **10** and **11**; yield 376 mg. The mother liquors were combined, and

evaporated to a syrup that was resolved by column chromatography on silica gel (7:1 hexane–ethyl acetate). Fractions containing compounds **10** and **11** as the main components were evaporated to a syrup that was recrystallized from hexane to give additional crystalline mixture of **10** and **11**; yield 165 mg. The total yield of mixed compounds **10** and **11** was 541 mg (53%); m.p. 83–86°, $[\alpha]_D^{30}$ +91° (*c* 0.8, chloroform). The ^{1}H-n.m.r. spectrum (90 MHz) of the product showed two singlets, at δ 3.67 and 3.60, assigned to methyl protons of the methoxycarbonyl group of **10** and **11**, respectively, in the ratio of 5:4.

Anal. Calc. for $C_{19}H_{28}O_6$ (352.43): C, 64.75; H, 8.01. Found: C, 64.61; H, 7.88.

(5S,6S)-Bis(hydroxymethyl)bicyclo[2.2.1]hept-2-ene (**5**) *from the mixture of* **10** *and* **11**. — A suspension of the foregoing mixture of Diels–Alder adducts **10** and **11** (813 mg, 2.31 mmol) in a mixture of methanol (8 mL) and M aqueous hydrochloric acid (2 mL) was stirred for 4 h at 60°. T.l.c. (5:1 chloroform–methanol) of the resultant, clear solution then showed a major (R_F 0.44) and a minor component (R_F 0.47). The solution was evaporated, with periodical additions of water and then of toluene, to afford a colorless solid (618 mg). To a solution of this deisopropylidenated derivative in 50% aqueous methanol (48 mL) was added sodium metaperiodate (2.08 g, 9.72 mmol), and the mixture was stirred for 3 h at room temperature. T.l.c. (20:1 benzene–butanone) then showed one major spot (R_f 0.41). Inorganic material was filtered off, the filtrate was concentrated (<35°) to low volume, and the concentrate extracted with dichloromethane; the extracts were combined, washed with water, dried (sodium sulfate), and evaporated to give a syrup (323 mg). A solution of the syrup in dry oxolane (6 mL) was slowly added to a suspension of lithium aluminum hydride (219 mg) in dry oxolane (3.5 mL), and the mixture was stirred for 1 h at room temperature, and processed as described for the preparation of **5** from **4**. Purification by column chromatography on silica gel (3:1 ethyl acetate–benzene) gave pure **5** as a syrup that crystallized on being kept for 2 d at −20°; yield 221 mg (62%, based on compounds **10** and **11**). $[\alpha]_D^{21}$ −24° (*c* 0.8, chloroform). The specific rotation of **5** derived from compound **4** was $[\alpha]_D^{23}$ −23° (*c* 0.8, chloroform). The i.r. and ^{1}H-n.m.r. spectra of the product were identical to those of **5** derived from **4**.

*Methyl (5S,6S)-6-*endo*-(1,2,3,4-tetra-O-acetyl-*D*-*arabino*-tetritol-1-yl)bicyclo[2.2.1]hept-2-eno-5-*exo*-carboxylate* (**3**) *and methyl (5S,6S)-5-*exo*-(1,2,3,4-tetra-O-acetyl-*D*-*arabino*-tetritol-1-yl)bicyclo[2.2.1]hept-2-eno-6-*endo*-carboxylate* (**12**) *from the mixture* **10** *and* **11**. — A suspension of the mixture of Diels–Alder adducts **10** and **11** (330 mg, 0.94 mmol) in a mixture of methanol (3.2 mL) and M aqueous hydrochloric acid (0.8 mL) was stirred for 5 h at 60°. The resultant, clear solution was evaporated, with periodical additions of water and then of toluene, to give a solid (258 mg) which was acetylated with acetic anhydride (1 mL) in pyridine (5 mL) at room temperature, to give (t.l.c., 2:1 hexane–ethyl acetate) two major products (**3** and **12**, R_F 0.38 and 0.32, respectively) together with small amounts of by-products. Water (0.6 mL) was added, the solution was concentrated to low vol-

ume, the concentrate poured into water, and the mixture extracted with dichloromethane. The extract was successively washed with saturated aqueous potassium hydrogensulfate, sodium hydrogencarbonate, and water, dried (sodium sulfate), and evaporated to a pale-brown syrup which was resolved by column chromatography on silica gel (2:1 hexane–ethyl acetate). The first fractions afforded crystalline compound **3**, yield 132 mg (31%, based on **10** + **11**), which was recrystallized from ethanol; m.p. 103.5–104.5°, $[\alpha]_D^{30}$ +72° (*c* 0.8, chloroform). The i.r. and ^{1}H-n.m.r. spectra were identical to those of **3** obtained from **2**.

Evaporation of later fractions from the column afforded compound **12** as crystals, yield 118 mg (29%, based on **10** + **11**), which were recrystallized from ethanol; m.p. 97–100°, $[\alpha]_D^{29}$ +83° (*c* 0.7, chloroform); ν_{max}^{KBr} 1740 (C=O), 1370, and 1235 cm^{-1}; ^{1}H-n.m.r.: δ 6.26 (broad dd, 1 H, $J_{2,3}$ 5.5, $J_{3,4}$ 3.3 Hz, H-3), 5.94 (broad dd, 1 H, $J_{1,2}$ 2.8 Hz, H-2), 5.29 (dd, 1 H, $J_{1',2'}$ 2.2, $J_{2',3'}$ 8.5 Hz, H-2'), 5.12 (dd, 1 H, $J_{5,1'}$ 10 Hz, H-1'), 5.08 (ddd, 1 H, $J_{3',4'}$ 3, $J_{3',4''}$ 5.7 Hz, H-3'), 4.22 (dd, 1 H, $J_{4',4''}$ 12.2 Hz, H-4'), 4.00 (dd, 1 H, H-4''), 3.60 (s, 3 H, CO_2Me), 3.18 (m, 1 H, H-1), 2.60 (dt, 1 H, $J_{4,5}$ ~0, $J_{4,7syn}$ 1.7, $J_{4,7anti}$ 1.5 Hz, H-4), 2.58 (dd, 1 H, $J_{1,6}$ 3.7, $J_{5,6}$ 4.5 Hz, H-6), 2.14 (ddd, 1 H, $J_{5,7syn}$ 1.7 Hz, H-5), 2.13, 2.09, 2.05, 2.04 (s, 12 H, 4 OAc), 1.61 (dt, 1 H, $J_{1,7anti}$ 1.5, $J_{7syn,7anti}$ 8.9 Hz, H-7*anti*), and 1.45 (dq, 1 H, $J_{1,7syn}$ 1.7 Hz, H-7*syn*); *m/z* (rel. intensity): 440 (1.9, M^+), 381 (0.1, M^+ − MeOCO·), 380 (0.3, M^+ − AcOH), 375 [4.1, HO^+= $C(OCH_3)CH{=}CH(CHOAc)_3CH_2OAc$], 367 (0.4, M^+ − $AcOCH_2$·), 315 (27, 375 − AcOH; m* at 264.5, calc. 264.6), 273 (3.4, 315 − CH_2CO; m* at 236.5, calc. 236.6), 255 (1.5, 273 − H_2O), 241 (3.8, 273 − MeOH), 213 (4.2, 273 − AcOH), 181 (2.6, 213 − MeOH), 171 (3.5, 213 − CH_2CO), 153 (10, 171 − H_2O), 145 (1.9, Ac_3O^+), 139 (3.6, 171 − MeOH), 103 (3.0, Ac_2O^+H), 66 (67, $C_5H_6^+$), and 43 (100, Ac^+); X-ray powder diffraction data: 9.82 s (2), 8.40 m, 6.59 w, 5.66 vs (1), 5.37 w, 5.20 vw, 4.98 m, 4.73 w, 4.40 w, 4.20 w, 4.00 w, 3.69 w, 3.51 m, 3.36 w, 3.25 m, 3.13 w, and 3.02 w.

Anal. Calc. for $C_{21}H_{28}O_{10}$ (440.45): C, 57.27; H, 6.41. Found: C, 57.02; H, 6.54.

Methyl (E)-*2,3-dideoxy-4,5:6,7-di-*O*-isopropylidene*-L-arabino-*hept-2-enonate* (**14**). — To a solution of 2,3:4,5-di-*O*-isopropylidene-*aldehydo*-L-arabinose[14] (**13**; 1.68 g, 7.29 mmol) in benzene (20 mL) was added methyl (triphenylphosphoranylidene)acetate (2.95 g, 8.82 mmol), and the mixture was boiled under reflux for 1 h. T.l.c. (20:1 toluene–ethyl acetate) then indicated the presence of two components having similar R_F values (the less-polar one, R_F 0.25, was preponderant). A small amount of insoluble material was filtered off, and the filtrate was evaporated. The residue was extracted with hexane, and the extract evaporated to a syrup (2.08 g) that was resolved by column chromatography on silica gel (20:1 toluene–ethyl acetate). The first fraction afforded pure **14** as a syrup; yield 1.16 g (56%); $[\alpha]_D^{25}$ +5° (*c* 0.7, chloroform). The i.r., ^{1}H-n.m.r., and mass spectra were identical to those of the enantiomer **9**.

Anal. Calc. for $C_{14}H_{22}O_6$ (286.16): C, 58.73; H, 7.75. Found: C, 58.43; H, 7.78.

Methyl (5R,6R)-6-endo-(1,2:3,4-di-O-isopropylidene-L-arabino-tetritol-1-yl)-bicyclo[2.2.1]hept-2-eno-5-exo-carboxylate (**15**) *and methyl (5R,6R)-5-exo-(1,2:3,4-di-O-isopropylidene-L-arabino-tetritol-1-yl)bicyclo[2.2.1]hept-2-eno-6-endo-carboxylate* (**16**). — To a solution of the isopropylidenated alkene **14** (1.04 g, 3.63 mmol) in toluene (11 mL) were added hydroquinone (8 mg, 73 μmol) and cyclopentadiene (freshly distilled from dicyclopentadiene; 0.45 mL, 5.46 mmol), and the mixture was boiled under reflux in an atmosphere of argon. Additional cyclopentadiene (2.5 mL, 30.33 mmol) and hydroquinone (8.4 mg, 76 μmol) were added to the solution in 5 portions, and the reaction was monitored by t.l.c. (5:1 hexane–ethyl acetate). After the mixture had been boiled for 38 h under reflux, t.l.c. showed a major component (R_f 0.45; **15** + **16**) and a minor one (R_f 0.40). The minor component and the starting compound **14** had the same R_f value, but the former was not visible under u.v. light (254 nm), whereas compound **14** was; it was absent from the reaction product. Solvent (~10 mL) was distilled off, and the residue evaporated, with periodical additions of water, to give a pale-brown syrup, which was dissolved in a small amount of hot hexane and kept for 15 h at −20°. The crude crystals obtained from hexane were recrystallized from hexane, to give a crystalline mixture of **15** and **16** (289 mg). The mother liquors were combined, and evaporated to a syrup that was purified by column chromatography on silica gel (7:1 hexane–ethyl acetate). Fractions containing **15** and **16** as the main components were evaporated to a syrup that crystallized from hexane, to give a crystalline mixture (354 mg) of **15** and **16**. The total yield of compounds **15** and **16** was 643 mg (50%); m.p. 77–82°, $[\alpha]_D^{25}$ −77° (*c* 0.9, chloroform). The ^{1}H-n.m.r. spectrum of the mixture showed two singlets, at δ 3.69 and 3.62 (assigned to the methyl protons of the methoxycarbonyl group of **15** and **16**, respectively), in the ratio of 1.9:1.

Anal. Calc. for $C_{16}H_{24}O_6$ (352.43): C, 64.75; H, 8.01. Found: C, 64.72; H, 8.10.

(5R,6R)-Bis(hydroxymethyl)bicyclo[2.2.1]hept-2-ene (**17**) *from the mixture of* **15** *and* **16**. — A suspension of the foregoing mixture of Diels–Alder adducts **15** and **16** (256 mg, 0.73 mmol) in a mixture of methanol (2.5 mL) and M hydrochloric acid (0.65 mL) was stirred for 3 h at 65°. T.l.c. (5:1 chloroform–methanol) of the resultant, clear solution then showed a major (R_f 0.44) and a minor component (R_f 0.47). The solution was evaporated, with periodical additions of water and then toluene, to afford a pale-yellow solid (196 mg). To a solution of this solid in 50% aqueous methanol (16 mL) was added sodium metaperiodate (630 mg, 2.95 mmol), and the mixture was stirred for 3 h at room temperature. T.l.c. (20:1 benzene–butanone) then showed one major component (R_f 0.4). The mixture was processed as described for the preparation of **5**, to give the syrupy aldehyde (106 mg). A solution of this syrup in dry oxolane (1.5 mL) was slowly added to a suspension of lithium aluminum hydride (66 mg) in dry oxolane (1 mL), and the mixture was stirred for 1 h at room temperature. T.l.c. (3:1 ethyl acetate–benzene) then showed the presence of a major component (**17**, R_f 0.23), together with traces of a by-product (R_f 0.56). The mixture was further processed as described for the prepara-

tion of **5**, to give pure **17** as a syrup, yield 64 mg (57%, based on compounds **15** and **16**), which afforded hygroscopic crystals by keeping for 15 h at −20°; m.p. 36–38°, $[\alpha]_D^{22}$ +23° (*c* 0.6, chloroform); *m/z* (rel. intensity): 154 (0.3, M^+), 136.0892 (2.2, $M^+ - H_2O$; calc. for $C_9H_{12}O$: 136.0888), and 66 (100, $C_5H_6^+$). The i.r. and ^{1}H-n.m.r. spectra were superposable on those of compound **5**.

Anal. Calc. for $C_9H_{14}O_2 \cdot 0.25\ H_2O$: C, 68.11; H, 9.21. Found: C, 67.73; H, 9.33.

Methyl (E)-*4,5,6,7-tetra*-O-*acetyl-2,3-dideoxy*-L-arabino-*hept-2-enonate* (**19**). — To a solution of 2,3,4,5-tetra-*O*-acetyl-*aldehydo*-L-arabinose[15] **18** (854 mg, 2.68 mmol) in benzene (9 mL) was added methyl (triphenylphosphoranylidene)acetate (1.1 g, 3.29 mmol), and the mixture was boiled under reflux for 1 h. T.l.c. (2:1 hexane–ethyl acetate) then indicated conversion into a single product (R_F 0.33). A small amount of insoluble material was filtered off, and the filtrate was evaporated to a solid that was recrystallized from 2-propanol, to afford pure, crystalline **19**; yield 916 mg (91%); m.p. 116–117°, $[\alpha]_D^{25}$ −36° (*c* 0.3, chloroform); ^{13}C-n.m.r.: δ 170.6, 169.8, 169.7, 169.5 (C=O of OAc), 165.8 (C=O of CO_2Me), 141.1 (C-3), 123.4 (C-2), 69.8 (C-4), 69.7 (C-5), 68.3 (C-6), 61.7 (C-7), 51.7 (CO_2CH_3), 20.47, 20.36, 20.31, and 20.27 (OAc); X-ray powder diffraction data: 9.66 vw, 8.84 s (2,2), 7.66 vw, 5.53 w, 5.32 vs (1,1), 4.91 vs (1,1), 4.70 w, 4.48 w, 4.27 m, 4.04 m, 3.77 m, 3.51 s (2,2) 3.29 m, 3.14 vw, 3.02 w, 2.84 m, and 2.67 w. The i.r., mass, and ^{1}H-n.m.r. spectra of **19** were superposable on those of its enantimer **2**.

Anal. Calc. for $C_{16}H_{22}O_{10}$ (374.36): C, 51.34; H, 5.92. Found: C, 51.09; H, 5.94.

Diels–Alder reaction of **19** *with cyclopentadiene in boiling toluene to give* methyl (5R,6R)-*6*-endo-*(1,2,3,4-tetra*-O-*acetyl*-L-arabino-*tetritol-1-yl)bicyclo-[2.2.1]hept-2-eno-5*-exo-*carboxylate* (**20**), *methyl* (5R,6R)-*5*-exo-*(1,2,3,4-tetra*-O-*acetyl*-L-arabino-*tetritol-1-yl)bicyclo[2.2.1]hept-2-eno-6*-endo-*carboxylate* (**21**), *and a mixture of methyl* (5S,6S)-*5*-endo-*(1,2,3,4-tetra*-O-*acetyl*-L-arabino-*tetritol-1-yl)bicyclo[2.2.1]hept-2-eno-6*-exo-*carboxylate* (**22**), *and methyl* (5S,6S)-*6*-exo-*(1,2,3,4-tetra*-O-*acetyl*-L-arabino-*tetritol-1-yl)bicyclo[2.2.1]hept-2-eno-5*-endo-*carboxylate* (**23**). — To a mixture of the acetylated alkene **19** (880 mg, 2.35 mmol) and toluene (9 mL) were added hydroquinone (6 mg, 45 μmol) and cyclopentadiene (freshly distilled from dicyclopentadiene; 0.45 mL, 5.46 mmol), and the mixture was boiled under reflux in an atmosphere of argon. Additional cyclopentadiene (2.50 mL, 30.33 mmol) and hydroquinone (13.5 mg, 0.12 mmol) were added to the solution in 6 portions, the reaction being monitored by t.l.c. (3:1 hexane–ethyl acetate). After 40 h, t.l.c. showed two (apparently major) components [R_F 0.25 (**20**) and ~0.2; after removal of the excess of reagent, the latter fraction was shown to comprise two components, having R_F 0.21 (**21**) and 0.19 (**22** + **23**)]; only a trace of the starting material **19** (R_F 0.16) remained. Solvent (8 mL) was distilled off, and the resultant solution was evaporated, with periodical additions of water and then of ethanol, to give a pale-brown syrup that crystallized from ethanol by keeping the solution for 15 h at 0°. The crude crystals were recrystallized from ethanol, to af-

ford pure, crystalline **20** (242 mg). The mother liquors were combined, and evaporated, to give a brown syrup that was purified by column chromatography on silica gel (3:1 hexane–ethyl acetate). Fractions containing the less-polar constituent were evaporated, to give a syrup that crystallized from ethanol to afford additional crystalline **20** (96 mg); the total yield of compound **20** was 338 mg (33%); m.p. 102–103.5°, $[\alpha]_D^{25}$ −72° (*c* 0.5, chloroform). The i.r., ^{1}H-n.m.r., and mass spectra of **20** were identical to those of its enantiomer **3**; ^{13}C-n.m.r.: δ 175.0 (C=O of CO_2Me), 170.6, 170.0 (double intensity), 169.9 (C=O of OAc), 136.8, 136.6 (C-2,3), 73.2 (C-1'), 69.6 (C-2'), 68.6 (C-3'), 62.0 (C-4'), 51.8 (CO_2CH_3), 48.6 (C-4), 46.5 (C-5), 46.0 (C-7), 44.1 (C-6), 43.7 (C-1), 20.5 (double intensity), 20.4, and 20.3 (OAc); X-ray powder diffraction data: 13.75 vw, 10.81 m, 9.43 m, 8.02 m, 7.22 s (2), 6.78 w, 6.21 m, 5.83 vw, 5.57 vw, 5.28 m, 4.93 vs (1), 4.57 w, 4.26 m, 4.12 m, 3.86 vw, 3.74 w, 3.55 s (3), 3.38 w, 3.26 w, and 3.18 vw.

Anal. Calc. for $C_{21}H_{28}O_{10}$ (440.45): C, 57.27; H, 6.41. Found: C, 57.44; H, 6.78.

Evaporation of the later fractions from the column afforded a syrup containing **22** + **23** (R_F 0.19, major), **21** (R_F 0.21, minor), and **20** (R_F 0.25, trace), which was resolved on a second column (3:1 hexane–ethyl acetate). The second fractions from the second column were evaporated, to give **21** as a syrup that crystallized on being kept for 5 days at 0°; yield 48 mg (5%). An analytical sample of **21** was obtained by l.c. on a column (4.6 mm × 25 cm) of LiChrosorb SI-100, 5 μm, with 3:1 hexane–ethyl acetate as the eluant, at a flow rate of 1.5 mL/min and a pressure of 4.8 MPa (700 lb.in.$^{-2}$); retention time, 8.3 min. It was recrystallized from ethanol; m.p. 95–98°, $[\alpha]_D^{26}$ −80° (*c* 0.7, chloroform). The i.r., ^{1}H-n.m.r., and mass spectra of **21** were identical to those of its enantiomer **12**; ^{13}C-n.m.r. data for **21**: 173.8 (C=O of CO_2Me), 170.8, 170.7, 170.3, 170.1, (C=O of OAc), 138.1 (C-3), 134.1 (C-2), 73.0 (C-1'), 69.7 (C-2'), 68.8 (C-3'), 62.2 (C-4'), 51.7 (CO_2CH_3), 47.0 (C-4 or C-6), 46.8 (double intensity) (C-1 and C-7), 44.6 (C-6 or C-4), 43.0 (C-5), 20.6 (double intensity), 20.5, and 20.4 (OAc); X-ray powder diffraction data: 15.16 w, 10.01 s (2), 8.13 w, 6.51 w, 5.68 vs (1), 5.25 m, 4.99 m, 4.70 m, 4.53 vw, 4.36 w, 4.15 w, 4.02 w, 3.81 w, 3.56 m, 3.47 vw, 3.32 m, 3.20 w, 3.11 w, and 3.04 w.

Anal. Calc. for $C_{21}H_{28}O_{10}$ (440.45): C, 57.27; H, 6.41. Found: C, 57.62; H, 6.33.

The third fractions from the second column were evaporated to give crude **22** + **23** as a syrup (307 mg, 30%). According to l.c. analysis under the foregoing conditions (retention time of **21**, 8.3 min; of **22** + **23**, 9.3 min), and the ^{1}H-n.m.r. spectrum, the syrup was contaminated with ~9% of compound **21**. The ^{1}H-n.m.r. spectrum of the syrup showed three singlets, at 3.682, 3.618, and 3.605 p.p.m., assigned to the methyl protons of the methoxycarbonyl group of **22**, **23**, and **21**, respectively, in the ratios of 1.59:1:0.26.

(5R,6R)-Bis(hydroxymethyl)bicyclo[2.2.1]hept-2-ene (**17**) *from* **20**. — To a suspension of the Diels–Alder adduct **20** (292 mg, 0.66 mmol) in dry methanol (3 mL) was added a 25% solution of sodium methoxide in methanol (80 μL), and the

mixture was kept for 3 h at room temperature. T.l.c. (5:1 chloroform–methanol) then indicated conversion into a single product having R_F 0.5. The resultant solution was made neutral with Amberlite IR-120 (H^+) resin, and evaporated to a solid that was recrystallized from methanol to give the crystalline, *O*-deacetylated compound; yield 142 mg. To a solution of the crystals in 50% aqueous methanol (11 mL) was added sodium metaperiodate (546 mg, 2.55 mmol), and the mixture was stirred for 3 h at room temperature. T.l.c. (20 :1 benzene–butanone) then showed one major product (R_F 0.4). The mixture was processed as described for the preparation of **5**, to afford a syrupy aldehyde (93 mg). A solution of this syrup in dry oxolane (1.7 mL) was slowly added to a suspension of lithium aluminum hydride (70 mg) in dry oxolane (1 mL), and the mixture was stirred for 1.5 h at room temperature, and processed as described for the preparation of **5**, to give pure **17** as a syrup, yield 53 mg (52%, based on **20**); this afforded hygroscopic crystals on keeping for 15 h at −20°; $[\alpha]_D^{22}$ +22° (*c* 0.8, chloroform); R_F 0.23 (3:1 ethyl acetate–benzene). The ^{1}H-n.m.r. spectrum was identical to that of **17** obtained from **15** + **16**.

(5S,6S)-Bis(hydroxymethyl)bicyclo[2.2.1]hept-2-ene (**5**) *from the mixture of* **22** *and* **23**. — The mixed (5*S*,6*S*)-Diels–Alder adducts **22** + **23** (213 mg, 0.48 mmol), containing ~9% of the (5*R*,6*R*)-adduct **21**, were deacetylated with 25% methanolic sodium methoxide (60 μL) in dry methanol (2.5 mL) as described for the preparaion of **17** from **20**, affording a solid (120 mg). This solid was treated with sodium metaperiodate (460 mg, 2.15 mmol) in aqueous methanol (1:1; 10 mL) as already described, to give a syrupy aldehyde (72 mg). The syrup was reduced with lithium aluminum hydride (54 mg) in dry oxolane (2.3 mL) as already described, to afford **5** as a syrup (which was expected to contain 10% of its enantiomer **17**); $[\alpha]_D^{27}$ −17.4° (*c* 0.7, chloroform). The value for optically pure **5** calculated from this observed value is thus −21.8°. This value is in good accord with the value observed for optically pure **5** ($[\alpha]_D^{23}$ −23° in chloroform) derived from **3**.

Diels–Alder reaction of **19** *with cyclopentadiene in toluene at 0° in the presence of aluminum chloride, to give methyl* (5R,6R)-6-endo-*(1,2,3,4-tetra*-O-*acetyl*-L-arabino-*tetritol-1-yl)bicyclo[2.2.1]hept-2-eno-5*-exo-*carboxylate* (**20**), *methyl* (5R,6R)-5-exo-*(1,2,3,4-tetra*-O-*acetyl*-L-arabino-*tetritol-1-yl)bicyclo[2.2.1]hept-2-eno-6*-endo-*carboxylate* (**21**), *and methyl* (5S,6S)-6-exo-*(1,2,3,4-tetra*-O-*acetyl*-L-arabino-*tetritol-1-yl)bicyclo[2.2.1]hept-2-eno-5*-endo-*carboxylate* (**23**). — To a suspension of aluminum chloride (364 mg, 2.73 mmol) in dry toluene was added the acetylated alkene **19** (1.02 g, 2.72 mmol), and the mixture was stirred for 30 min at 0° in an atmosphere of argon. To the suspension was added cyclopentadiene (freshly distilled from dicyclopentadiene; 0.7 mL, 8.49 mmol), and the resultant pale-yellow suspension was stirred for 3 h at 0°. Additional cyclopentadiene (0.5 mL, 6.07 mmol) was added to the mixture, which was stirred for a further 1.5 h at 0°. T.l.c. (3:1 hexane–ethyl acetate) then showed the adducts as two minor components [R_F 0.25 (**20**), and 0.21 (**21**)], and a major one (R_F 0.19, **22** + **23**); the starting compound **19** (R_F 0.16) was absent. The mixture was poured into M hydro-

chloric acid (50 mL), and extracted 3 times with benzene. The extracts were combined, washed 6 times with brine, dried (sodium sulfate), and filtered through Celite, and the filtrate was evaporated to give a residue (1.94 g) which was resolved by column chromatography on silica gel (3:1 hexane–ethyl acetate). A syrup (102 mg), insoluble in the t.l.c. solvent, arose from side reactions of the reagent.

After initial elution of cyclopentadiene related side products, the first fractions were evaporated to afford crystalline **20** (47 mg). The second fractions afforded crystals of **21** (74 mg) containing a small proportion of **20**. The third fractions afforded a mixture of compounds **22** + **23** (major), **21** (minor), and **20** (trace), as a syrup 771 mg). The fourth fractions afforded a crude syrupy mixture of **22** + **23**, which partially crystallized on being kept for 3 days at room temperature; yield 304 mg. The syrup from the third fractions were resubjected to column chromatography on silica gel with the same solvent system as before, and the fractions from this second column afforded another crop of compound **20** (35 mg; total yield of **20**, 84 mg, 7%), compound **21** (103 mg, total yield 177 mg, 15%), and crude **22** + **23** (377 mg; total yield 681 mg, 57%). The crude mixture **22** + **23** was found to contain a small amount of compound **21** by its ^{1}H-n.m.r. spectrum which showed three singlets, at 3.682, 3.618, and 3.606 p.p.m., assigned to methyl protons of the methoxycarbonyl group of **22**, **23**, and **21**, in the ratios of 1:6.46:0.86.

The partially crystallized syrup (681 mg) of **22** and **23** was recrystallized from 2-propanol, to afford pure, crystalline **23**, yield 435 mg (36%, based on **19**), m.p. 77–78°, $[\alpha]_D^{25}$ +55° (*c* 0.6, chloroform). R_f 0.19 (3:1 hexane–ethyl acetate). ν_{max}^{KBr} 1745 (C=O), 1375, 1240, and 1220 cm^{-1}; ^{1}H-n.m.r. δ (C$_6$D$_6$) (broad dd, 1 H, $J_{1,2}$ 5.6, $J_{1,7}$ 3.2 Hz, H-2), 6.02 (broad dd, 1 H, $J_{3,4}$ 2.7 Hz, H-3), 5.7 (dd, 1 H, $J_{2',3'}$ 2.2, $J_{2',4'}$ 9.0 Hz, H-2'), 5.15 (dd, 1 H, $J_{0,1'}$ 10.3 Hz, H-1'), 5.08 (ddd, 1 H, $J_{3,4}$ 2.8, $J_{3',4'}$ 4.5 Hz, H-3'), 4.22 (dd, 1 H, $J_{4',4''}$ 12.5 Hz, H-4'), 4.13 (dd, 1 H, H-4''), 3.62 (s, 3 H, CO$_2$Me), 3.14 (m, 1 H, H-4), 2.84 (apparent dq, 1 H, $J_{1,7anti}$ 1.5, $J_{1,4}$ = $J_{1,7anti}$ = 1.5 Hz, H-1), 2.71 (dd, 1 H, $J_{4,5}$ 3.6, $J_{5,6}$ 4.7 Hz, H-5), 2.136, 2.067 (double intensity), 2.038 (s, 12 H, 4 OAc), 1.93 (ddd, 1 H, $J_{6,7syn}$ 4 Hz, H-6), 1.57 (dt, 1 H, $J_{1,7anti}$ 1.5, $J_{7syn,7anti}$ 8.8 Hz, H-7*anti*), and 1.49 (dq, 1 H, $J_{1,7syn}$ 1.7 Hz, H-7*syn*); ^{13}C-n.m.r.: δ 174.4 (C=O of CO$_2$Me), 171.0, 170.7, 170.6 (double intensity; C=O of OAc), 137.8 (C-2), 134.5 (C-3), 73.3 (C-1'), 69.5 (C-2'), 68.4 (C-3'), 61.9 (C-4'), 51.5 (CO_2CH_3), 46.9 (C-7), 46.7 (C-5), 46.2 (C-4), 44.9 (C-1), 44.8 (C-6), 20.63, 20.56, 20.45, and 20.38 (OAc). *m/z* (rel. intensity): 440 (2.6, M$^+$), 409 (1.1, M$^+$ − MeO·), 381 (0.2, M$^+$ − MeOCO·), 380 (0.3, M$^+$ − AcOH), 375 [3.4, HO$^+$=C(OCH$_3$)CH=CH(CHOAc)$_3$CH$_2$OAc], 367 (0.4, M$^+$ − AcOCH$_2$·), 315 (24, 375 − AcOH; m$^+$ at 264.5, calc. 264.6), 273 (3.2, 315 − CH$_2$CO; m$^+$ at 236.5, calc. 236.6), 255 (1.6, 273 − H$_2$O), 241 (4.5, 273 − MeOH), 213 (4.3, 273 − AcOH), 181 (2.7, 213 − MeOH), 171 (3.6, 213 − CH$_2$CO), 153 (9.7, 171 − H$_2$O), 145 (2.1, Ac$_2$O$^+$), 139 (3.5, 171 − MeOH), 103 (2.6, Ac$_2$O$^+$H), 66 (70, C$_5$H$_6^+$), and 43 (100, Ac$^+$). X-ray powder diffraction data: 9.25 m, 8.60 w, 7.88 m, 7.37 m, 6.40 vw, 5.89 vs (1), 5.62 vw, 4.85 s (2), 4.59 m, 4.39 vw, 4.27 w, 4.12 m, 4.00 m, 3.70 w, 3.49 vw, 3.41 vw, 3.34 vw, 3.20 w, 3.12 m, 3.05 w, and 2.84 w.

Anal. Calc. for $C_{21}H_{28}O_{10}$ (440.45): C, 57.27; H, 6.41. Found: C, 57.15; H, 6.58.

*(1S,5S,7R,8S)-7-(Acetoxymethyl)-8-(1,2,3,4-tetra-O-acetyl-*L*-arabino-tetritol-1-yl)-2-oxo-3-oxabicyclo[3.3.0]octane* (**24**). — To a solution of the Diels–Alder adduct **23** (248 mg, 0.56 mmol) in oxolane (4 mL) was added osmium tetraoxide (2% solution in butanol; 0.4 mL, 0.03 mmol). The solution was kept for 15 min at room temperature, and then water (0.5 mL) was added. Sodium metaperiodate (307 mg, 1.44 mmol) in water (2 mL) was now added to the solution during 20 min, and the resultant suspension was stirred for 15 h at room temperature. T.l.c. (3:1 ethyl acetate–hexane) showed that the starting material (**23**) was absent, and that several polar compounds were present; these may be attributed to partial formation of hydrated forms of the aldehydes. Inorganic material was filtered off, the filtrate was concentrated (<30°) to low volume, and the concentrate extracted with ethyl acetate. The extracts were combined, washed with water, dried (sodium sulfate), and concentrated (<30°) to ~5 mL. The concentrate was diluted with methanol (2.5 mL), sodium borohydride (89 mg, 2.35 mmol) was slowly added to the solution, and the mixture was stirred for 20 min at room temperature. T.l.c. (3:1 ethyl acetate–hexane) then showed the presence of a major product (R_F 0.25). Aqueous hydrochloric acid (M; 1 mL) was added to the mixture, which was then evaporated (<30°) to a dark syrup that was extracted with dichloromethane. The extracts were combined, washed once with water, dried (sodium sulfate), and evaporated to a syrup (182 mg) which was acetylated with acetic anhydride (0.45 mL) in pyridine (3.5 mL) for 15 h at room temperature. T.l.c. (3:2 ethyl acetate–hexane) then showed the presence of a major product (R_F 0.30), together with a small proportion of a byproduct (R_F 0.40). Water (0.4 mL) was added, and the solution was evaporated to a syrup that was dissolved in dichloromethane. The solution was successively washed with saturated aqueous potassium hydrogensulfate, saturated sodium hydrogencarbonate, and water, dried (sodium sulfate), and evaporated to a syrup which was purified by column chromatography on silica gel (3:2 ethyl acetate–hexane). The second fraction from the column was evaporated, to afford pure **24** as a syrup that crystallized on being kept for 10 days at 0°; yield 179 mg (65%, based on **23**). It was recrystallized from 2-propanol; m.p. 92–94°, $[\alpha]_D^{29}$ −14° (*c* 1.1, chloroform); ν_{max}^{KBr} 2970, 1765 (C=O of 5-membered lactone), 1745, 1735 (C=O of OAc), 1385, 1225, and 1045 cm^{-1}; ^{1}H-n.m.r.: δ 5.48–5.38 (m, 2 H, H-1′,2′), 5.24 (apparent td, 1 H, $J_{2',3'}$ 6.3, $J_{3',(4')}$ 3.1, $J_{3',(4'')}$ 5.9 Hz, H-3′), 4.36 (dd, 1 H, $J_{4,4'}$ 9.5, $J_{4,5}$ 5.8 Hz, H-4*), 4.33 [dd, 1 H, $J_{(4'),(4'')}$ 12.4 Hz, H-(4′)*], 4.25 (dd, 1 H, $J_{7,7a}$ 4.9, $J_{7a,7a'}$ 11.3 Hz, H-7a*), 4.16 (dd, 1 H, $J_{4',5}$ ~1 Hz, H-4′*), 4.07 [dd, 1 H, H-(4″)*], 3.95 (dd, 1 H, $J_{7,7a'}$ 5.8 Hz, H-7a′*), 3.28 (dd, 1 H, $J_{1,5}$ 8.7, $J_{1,8}$ 3.5 Hz, H-1), 2.78 (m, 1 H, $J_{5,6}$ ~6.5, $J_{5,6'}$ ~9 Hz, H-5), 2.38 (ddd, 1 H, $J_{7,8}$ 8.0, $J_{8,1'}$ 2.0 Hz, H-8), 2.23–2.16 (m, 1 H, H-7), 2.092, 2.088, 2.081, 2.070, 2.067

*Protons attached to C-4 are denoted by H-4 and H-4′, and those attached to C-4′ are denoted by H-(4′) and H-(4″); methylene protons of the acetoxymethyl group attached to C-7 are denoted by H-7a and H-7a′.

(s, 15 H, 5 OAc), 1.28 (m, 1 H, H-6′ or H-6); (300 MHz; C_6D_6): δ 5.75 (dd, 1 H, $J_{1',2'}$ 5.1, $J_{2',3'}$ 6.6 Hz, H-2′), 5.60 (ddd, 1 H, $J_{3',(4')}$ 2.9, $J_{3',(4'')}$ 6.3 Hz, H-3′) 5.58 (dd, 1 H, $J_{8,1'}$ 2.6 Hz, H-1′), 4.56 [dd, 1 H, $J_{(4'),(4'')}$ 12.5 Hz, H-(4′)], 4.19 [dd, 1 H, H-(4″)], 4.15 (dd, 1 H, $J_{7,7a}$ 4.8, $J_{7a,7a'}$ 11.4 Hz, H-7a), 3.60 (dd, 1 H, $J_{7,7a'}$ 6.6 Hz, H-7a′), 3.45 (dd, 1 H, $J_{4,4'}$ ~9.5, $J_{4,5}$ ~5 7 Hz, H-4), 3.36 (dd 1 H, $J_{4',5}$ ~1 Hz, H-4′), 3.02 (ddd, 1 H, $J_{1,5}$ 8.8, $J_{1,8}$ 3.4, $J_{1,6}$ ~1 Hz, H-1), 2.44 (ddd, 1 H, $J_{7,8}$ 8.4 Hz, H-8), 1.98-1.85 (m, 2 H, H-5,7), 1.841, 1.818, 1.811, 1.774, 1.765 (s, 15 H, 5 OAc), 1.31 (dddd, 1 H, $J_{5,6 \text{ or } 6,7}$ ~6, $J_{6,7 \text{ or } 5,6}$ ~7, $J_{6,6'}$ ~13 Hz, H-6)[1], and 0.67 (ddd, 1 H, $J_{5,6' \text{ or } 6',7}$ ~11.5, $J_{6',7 \text{ or } 5,6'}$ ~10.5 Hz, H-6′). ^{13}C-n.m.r.: δ 179.4 (C=O of lactone), 171.0, 170.8, 170.4, 170.0 (double intensity; C=O of OAc), 71.4 (C-1′or C-2′), 70.7, 70.6 (C-2′ or C-1′, C-4 or C-4′), 69.3 (C-3′), 65 3 (C-7a), 61.7 (C-4′ or C-4), 47.2 (C-8), 45.6 (C-1), 43 5 (C-7), 40.5 (C-5), 34.0 (C-6), 20.6, and 20.5 (OAc); *m/z* (rel. intensity): 486 (<0.1, M^+), 426 (0.7, M^+ − AcOH), 413 (2.2, M^+ − $AcOCH_2$·), 384 (1.1, 426 − CH_2CO), 366 (1.2, 426 − AcOH), 341 (13), 324 (4.2, 384 − AcOH), 299 (10), 282 (4.6, 324 − CH_2CO), 269 (15), 227 (29), 217 (20), 167 (23), 145 (6.1, Ac_3O^+H), 103 (4.1, Ac_2O^+H), and 43 (100, Ac^+); X-ray powder diffraction data. 10.97 w, 8.32 m, 7.16 vs (1), 6.80 w, 6.18 m, 5.73 w, 5.40 vw, 5.19 m, 4.91 s (3), 4.79 vw, 4.60 m, 4.43 vw, 4.07 w, 3 78 s (2), 3.53 m, 3.34 w, 3.22 vw, and 3.12 w.

Anal. Calc. for $C_{22}H_{30}O_{12}$ (486.48): C, 54.32; H, 6.22. Found: C, 54.39; H, 6.49.

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